Comparison of GPS Receiver Accuracy and Precision in Forest Environments. Practical Recommendations Regarding Methods and Receiver Selection

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Key words: GPS, accuracy, positioning under forest canopy.

SUMMARY

Selecting the appropriate receiver and methods might be complicated when a major portion of GPS data collection is below forest canopies. This study compares recreational GPS receivers (GARMIN eTrex Euro, GARMIN 12XL, GARMIN Summit, GARMIN Geko 201) and more precise GPS receivers (Topcon Hiper+). It was aimed to determine the most suitable method and receiver for position assessment under different forest canopy covers, in terms of easiness of use, accuracy, reliability, and the ratio accuracy/cost. Data were collected in 17 forest locations and consisted of 3 measurements with each receiver per plot and positioning method. Each plot was visited 11 times; therefore there were 33 measurements per receiver, plot and method. Several positioning techniques were compared: autonomous, real-time differential, and post-processed differential modes, as well as the effect of using an augmentation system. Data were described and analyzed through a sample comparison analysis at 95% confidence level (Dunnet test for normal data, and Mann-Whitney test for data which do not fit a normal distribution), in order to validate the following null hypothesis: (i) all receivers have the same accuracy and precision at measuring horizontal coordinates, (ii) all receivers have the same accuracy and precision determining altitudes, (iii) accuracy and precision do not depend on characteristics of forest canopy, and (iv) differences in accuracy and precision between receivers are independent of forest canopy characteristics. Results showed that there were significant differences between the receivers regarding accuracy and precision measuring coordinates; moreover, accuracies were different depending on the canopy cover and forest characteristics. Therefore, practical recommendations for each case were settled in order to help foresters to select the most suitable receiver.

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1. INTRODUCTION

GPS receivers are frequently useful to forest management activities related with locating or mapping boundaries as monitoring harvesting machinery (McDonald et al, 2002), topography and cadastral forest surveys (Yoshimura et al., 2002), forest inventory, resources and special management areas (Wing and Kellogg, 2004), forest area and perimeter estimations (Tachiki et al., 2005) and GIS forest applications (Wing and Bettinger, 2003).

Against a handheld digital range finders and digital total station GPS receivers are quicker and easier to digitally capture a target point; however a handheld digital range finders is cheaper and a digital total station is more accuracy and precise that a GPS receiver (Wing and Kellogg, 2004). Its principal problem is GPS receivers require satellite signal that is often unachievable under forest canopy.

It is known that the positioning precision and accuracy under forest canopy are markedly lower than in areas with unobstructed sky conditions because trees attenuate or brake GPS signals. The precision and accuracy in GPS positioning can be expressed as a percent of the data is better than the specification. The more common terms used in previous works to estimate GPS accuracy and precision are Circular Error Probable (CEP), Root Mean Square error (RMS) and Distance Root Mean Square error (DRMS). Sawaguchi et al. (2003) define CEP as the value witch a half of the data points fall within a circle of this radius centered on truth and a half lie outside this circle and use CEP to estimate GPS positioning a different forest type, antenna height, and season, and to clarify the relationship between sampling number and the convergence of positioning precision. RMS value mean that approximately 68 percent of the data points occur within this distance of truth. Yoshimura and Hasegawa (2003) use RMS testing on horizontal and vertical positional errors of GPS positioning at different points in forested areas. DRMS should be expressed clearly whether the accuracy value refers only to horizontal or to both horizontal and vertical and indicates that approximately 95 percent of the data points occur with this distance of truth (Dana, 1997). It is the method proposed to calculate accuracy in the Standard Positioning Service (SPS) (Kaplan, 1996). Dana (1997) defines 2DRMS as Estimated Positional Error (EPE) and is used to compare differences between GPS receiver under forest canopies (Karsky et al., 2000).

There are techniques as differential global positioning system (DGPS) that improve precision and accuracy under tree canopies. Hasegawa and Yoshimura (2003) achieved a mean error of a 1 to 30-min observation varied between 0.029-0.226 m (without closed tree canopies) and it was 0.415-0.894 m (with closed tree canopies), using Dual-frequency GPS receivers by carrier phase DGPS static surveying. Sawaguchi et al. (2003) using DGPS got mean CEP95= 2.80 m for deciduous broadleaved trees and 4.99 m for conifers. Additionally they demonstrated that positioning precision was not noticeably improved if the sampling number was around ten. So DGPS improve GPS positioning in precision, accuracy and efficiency because the observation time is shorter (Næsset et al, 2001; Næsset and Jonmeister, 2002).

2. MATERIALS AND METHODS

2.1 Study area

The study area was located on Vega de Espinareda municipality (El Bierzo Region), close to University of León in Ponferrada (North East of Spain), at a latitude of 42º41'50.6"-42º43'4.9''N and a longitude of 6º37'10.0" - 6º39'24.9" W (WGS-84) with a geodetic height of 824-1082 m. The test course consisted of nineteen points sited under different tree canopies and one point without any obstacle (table 1). Stand variables were calculated to characterize each stand regarding canopy. Stand density (N) and Hart-Becking Index (Hart) were calculated as forest variables which, *a priori*, have an effect on GPS signal. Hart-Becking Index (%) describes stand density depending on average spacing (*a*) and Assmann dominant height (H_o) and was calculated as follows:

$$Hart(\%) = \frac{a}{H_0} \cdot 100 \qquad \text{Ec.1}$$

Table 1. Summary of forest characteristics for 18 stand tested and 0

Point	Species	Stand density (stems/ha)	H_0 (m)	Hart (%)	Canopy
1	*P. radiata*	2990	18.27	10.78	Closed
2	*P. radiata*	1463	16.37	15.94	Closed
3	*P. sylvestris*	572	19.93	28.15	Small gap
4	*P. sylvestris*	443	18.17	28.12	Small gap
5	*P. sylvestris*	507	19.27	24.75	Small gap
6	*P. sylvestris*	381	18.03	28.40	Small gap
7	*P. radiata*	2069	18.13	12.13	Closed
8	*P. radiata*	3787	17.13	10.22	Closed
9	*P. sylvestris*	2831	5.8	45.00	Closed
10	*P. radiata*	2131	20.57	10.55	Closed
11	*P. radiata*	1177	9.67	30.09	Large gap
12	*P. radiata*	1846	10.83	21.51	Closed
13	*P. radiata*	1527	11.3	22.65	Small gap
14	*P. radiata*	2196	7.67	27.77	Large gap
15	*P. radiata*	1464	3.67	71.12	Treeless
16	*P. radiata*	1527	7.53	34.00	Large gap
17	*P. radiata*	1464	3.67	71.12	Treeless

18	*P. radiata*	1559	13.13	19.27	Closed

2.2 Materials

The four receivers tested (made by GARMIN) in this work were: GPS 12XL, eTrex, eTrex Summit and Geko 201. All receivers have twelve channel receiver and technical specifications are different in shape, size and weight, but position accuracy are 15 m (RMS) for GPS 12XL and eTrex and below 15 m (RMS) for eTrex Summit and Geko 201. eTrex Summit built-in a electronic compass and a barometric altimeter. Geko 201 adds WAAS/EGNOS capability with an accuracy of 3 m. True positions were calculated using a surveying receiver Topcon Hiper+ with a position accuracy of 10mm + 1.0ppm.

2.3 Methods

Test procedure was identical for all twenty points, days and receivers. GPS positioning was repeated five times at each test point using, twenty minutes before receivers were turned on to insure that current almanac was stored in the receiver (Karsky et al., 2000). When the positions were measured the receiver was located at 1.7 m above the ground. No external antennas were used because our aim objective was tested receivers using the simplest performance in order to achieve useful and practical results. In addition Estimated Position Error (EPE) and number of satellites were monitored to determine their influence in positioning.

The field test was conducted for ten days (on September 16, 20, 21, 25, 27, 30 and October 4, 5, 8, 9), from 7:00 am to 14:00 pm. True positions of the tested points were measured on June 26th by a survey with dual-frequency GPS receivers: we calculated the coordinates as average of thirty fixed positions.
In this work RMS calculated to estimate GPS positional error in terms of precision and accuracy.

For RMS calculations horizontal precision was calculated by the following equations:

$$\sigma_{H\_pre} = \sqrt{\sigma_N^2 + \sigma_E^2} \qquad \text{Ec.2}$$

where σ_{N_pre} is RMS; σ_N and σ_E are the standard deviation of the positional error along Northing an Easting directions respectively, that are calculated by equations:

$$\sigma_N^2 = \frac{\sum_{i=1}^{n}(N_i - \overline{N})}{n-1} \qquad \text{Ec.3}$$

$$\sigma_E^2 = \frac{\sum_{i=1}^{n}(E_i - \overline{E})}{n-1} \qquad \text{Ec.4}$$

n is the total number of epochs; E_i and N_i indicate the location of ith epoch along Northing and Easting directions, respectively; $\overline{E}$ and $\overline{N}$ are the sample mean of the measurements along Northing and Easting directions, respectively.

Vertical precision was calculated by the following equations:

$$\sigma_{V\_pre} = \sqrt{\frac{\sum_{i=1}^{n}(V_i - \bar{V})^2}{n-1}} \qquad \text{Ec.5}$$

n is the total number of epochs; V_i indicates the vertical location of ith epoch; $\bar{V}$ is the sample mean of the vertical measurements.

Horizontal and vertical accuracies were calculated by equations:

$$\sigma_{H\_acc} = \sqrt{(\bar{N} - N_{true})^2 + (\bar{E} - E_{true})^2} \qquad \text{Ec.6}$$

$$\sigma_{V\_acc} = \left|\bar{V} - V_{true}\right| \qquad \text{Ec.7}$$

where σ_{H_acc} and σ_{V_acc} indicate horizontal and vertical accuracy, respectively; N_{true}, E_{true} and V_{true} are the true positions along the Northing, Easting and Verticals directions, respectively.

Data were analyzed through a sample comparison analysis at 95% confidence level, in order to validate the following null hypothesis: (i) all receivers have the same accuracy (σ_{H_acc}) and precision (σ_{H_pre}) at measuring coordinates, (ii) all receivers have the same accuracy and precision determining altitudes, (iii) accuracy and precision (σ_{H_acc}, σ_{H_pre}, σ_{V_acc}, σ_{V_pre}) do not depend on characteristics of forest canopy, and (iv) differences in accuracy and precision (σ_{H_acc}, σ_{H_pre}, σ_{V_acc}, σ_{V_pre}) between receivers are independent of forest canopy characteristics. Therefore, the Kolmogorov-Smirnov and Shapiro-Wilk normality tests were performed, at 95% confidence level, to determine if the four variables were normally distributed, as a previous step to select the most appropriate method to compare the different groups. A significant test meant the fit was poor and therefore data were not normal.

If data are normally distributed but variances are not assumed to be equal, the Dunnet's C was calculated to test the null hypothesis that the means are equal when comparing the different groups. Otherwise, when the mean is a non representative statistic for the sample, non-parametric tests are more suitable to compare groups. The nonparametric Mann-Whitney test of location for two independent samples was carried out to determine whether or not the values of a particular variable differ between two groups. This test does not assume normality in data and can be used regardless data distribution. Each two-tailed significance value estimates the probability of obtaining a Z statistic as or more extreme (in absolute value) as the one displayed, if there truly is the null hypothesis that the two groups come from the same population. For those groups significantly different according to the Dunnet or Mann-Whitney tests, the error bars with the confidence intervals at 95% for the individual variables were plotted, as an aid to interpret the tests results.

3. RESULTS AND DISCUSSION

3.1 Normality tests

The Kolmogorov-Smirnov and Shapiro-Wilk normality tests showed that the four variables considered (σ_{H_acc}, σ_{H_pre}, σ_{V_acc}, σ_{H_pre}) were not normally distributed (table 2). Therefore the Mann-Whitney non-parametric test was used to test the null hypothesis.

Table 2. Results of Kolmogorov-Smirnov and Shapiro-Wilk normality tests.

Variable	**Kolmogorov-Smirnov**			**Shapiro-Wilk**		
	Statistic	**df**	**Sig.**	**Statistic**	**df**	**Sig.**
σ_{H_pre}	0.452	702	0.000	0.092	702	0.000
σ_{H_acc}	0.184	702	0.000	0.624	702	0.000
σ_{V_pre}	0.308	558	0.000	0.428	558	0.000
σ_{V_acc}	0.097	558	0.000	0.892	558	0.000

3.2 Measuring horizontal coordinates and altitude: accuracy and precision

Table 3 shows the results of testing the null hypothesis that all receivers have the same accuracy and precision at (i) measuring horizontal coordinates (σ_{H_acc}, σ_{H_pre}) and (ii) altitude (σ_{V_acc}, σ_{V_pre}), by using Mann-Whitney test (U statistic). Significance values (Sig.) lower than 0.05 indicated that the null hypothesis that the two compared groups come from the same population had to be rejected; those values are displayed in bold. Receivers (GPS) were recoded as follows: GPS 12XL (1), eTrex (2), eTrex Summit (3) and Geko 201 (4).

Table 3. Result of Mann-Whitney test (U statistic) to compare receivers measuring horizontal position and altitude

GPS	**St.**	**eTrex (2)**		**eTrex Summit (3)**				**Geko 201 (4)**			
		σ_{H_pre}	σ_{H_acc}	σ_{H_pre}	σ_{H_acc}	σ_{V_pre}	σ_{V_acc}	σ_{H_pre}	σ_{H_acc}	σ_{V_pre}	σ_{V_acc}
1	U	12649	8337	10164	12009			12256	13511		
	Sig.	**0.005**	**0.000**	**0.000**	**0.000**			**0.001**	0.057		
2	U			12926	10836	12537	14750	13967	10285	7517	17158
	Sig.			**0.007**	**0.000**	**0.000**	**0.014**	0.111	**0.000**	**0.000**	0.893
3	U							15385	14143	3942	14859
	Sig.							0.914	0.159	**0.000**	**0.019**

Error bars with the confidence intervals at 95% for horizontal (H) and vertical (V) precisions and accuracies, regarding receivers are showed at Figure 2. Vertical accuracy and precision were compared among 3 receivers, because GPS 12XL (1) does not register altitudes.

Table 3 shows that different horizontal precisions (σ_{H_pre}) and accuracies (σ_{H_acc}) were achieved depending on the receiver. However, differences in σ_{H_pre} are not significant between receivers eTrex (2) and Geko 201 (4), or between eTrex Summit (3) and Geko 201 (4). Horizontal accuracies were different among all receivers but accuracies of 12XL (1) and eTrex Summit (3) were not statistically different than Geko 201 (4). Therefore, and according to table 3 and figure 2, eTrex Summit (3) achieved the best results regarding horizontal precision. With regard to σ_{H_acc} the worst distributions of accuracies were obtained by using receivers eTrex (2) and Geko 201 (4), while GPS 12XL (1) attained the best values.

Vertical accuracy and precision were different depending on the receiver, as showed at table 3 by the Mann-Whitney test values (Sig.<0.05). There were significant differences regarding vertical precision among all receivers; best results were achieved by using eTrex Summit (3), which was also significantly better than the two other receivers with regard to vertical accuracy. There were not significant differences between eTrex (2) and Geko 201 (4) for vertical accuracy. According to table 3 and Figure 2, eTrex Summit (3) achieved the best results determining altitude, considering both precision and accuracy: this is expected due to this model incorporates a barometric altimeter.

In this study the receiver Geko 201 showed a high variance in the errors (Figure 2), which advises against recommending this receiver concerning horizontal precision, because this model incorporates Augmentation System capability. This fact could be explain because the GPS Geko received two different correction signals in the field, one from EGNOS and other one from WAAS. Both differential corrections are calculated by master stations in Europe (EGNOS) and North America (WAAS) and it have to be used in appropriate region. Hence, if Geko receiver work only using EGNOS, accuracy and precision will be better.

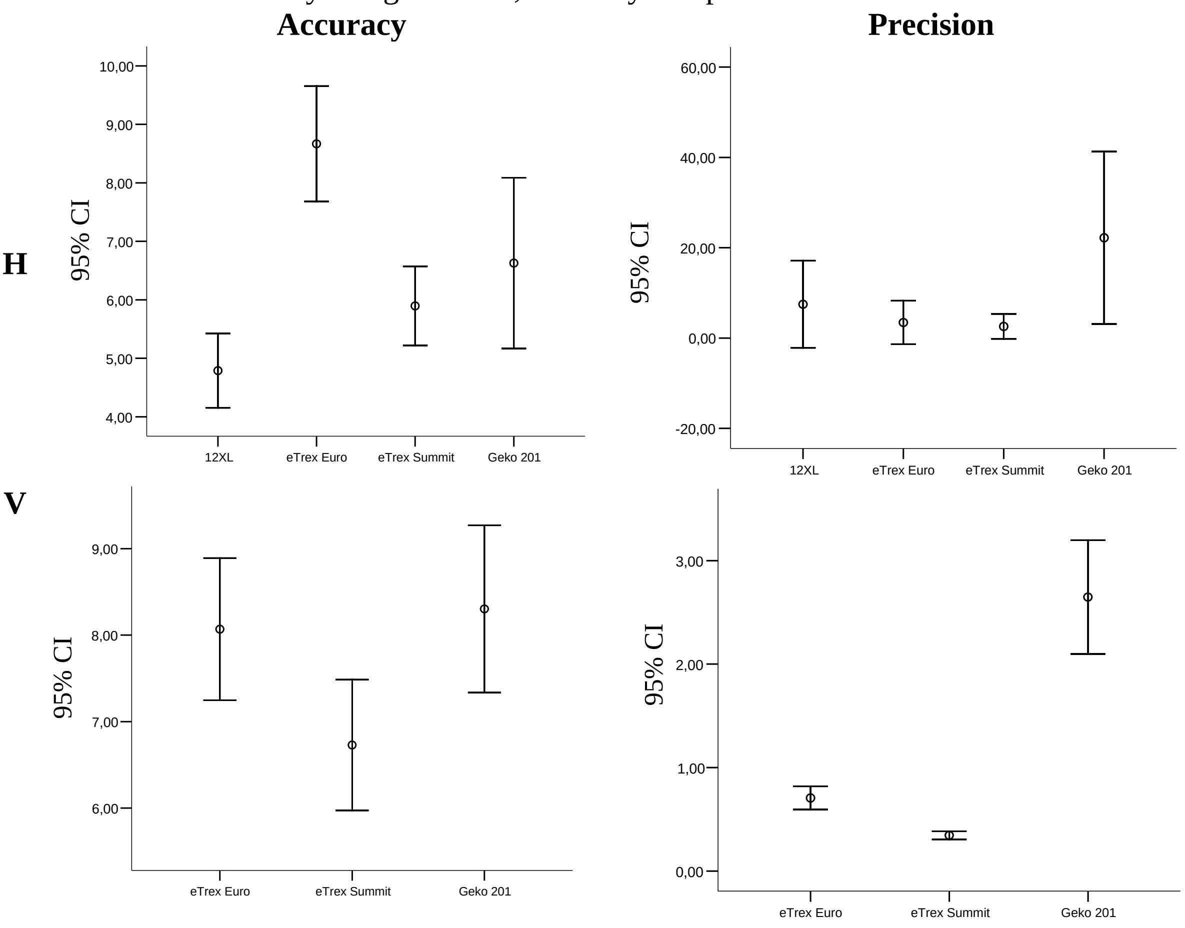


Figure 2. Error bars with the confidence intervals at 95% for horizontal (H) and vertical (V)

precisions and accuracies, regarding receivers.

3.3 Accuracy and precision regarding forest canopy characteristics

The influence of forest canopy characteristics in accuracy and precision (horizontal and vertical) was studied by differencing forest stands regarding two variables: stand density and Hart-Becking index, calculated as showed above.

Mann-Whitney test (U statistic) was applied to assess the null hypotheses that all receivers have the same accuracy and precision (σ_{H_acc}, σ_{H_pre}, σ_{V_acc}, σ_{V_pre}) at sparse stands (N<500 stems/ha) that at dense stands (N<500 stems/ha). Table 4 shows that horizontal accuracy (σ_{H_acc}) is significantly different for the two types of stands tested, while the significance values greater than 0.05 indicated that there were not differences for vertical accuracy and precision, neither for horizontal precision. Horizontal accuracy (σ_{H_acc}) values were smaller (i.e. more accurate) at sparse stands than at dense stands.

Table 4. Result of Mann-Whitney test (U statistic) to compare sparse and dense stands

Statistic	σ_{H_pre}	σ_{H_acc}	σ_{V_pre}	σ_{V_acc}
U	52303	46759	34020	34605
Sig.	0.380	**0.002**	0.249	0.413

Table 5 compares accuracies and precisions achieved in stands with stand density (1) lower than 500 stems/ha, (2) 500-1500 stems/ha and (3) greater than 1500 stems/ha. It is showed that horizontal accuracy (σ_{H_acc}) and horizontal precision (σ_{H_pre}) are significantly different when comparing sparse stands (<500 stems/ha) to the other two classes, which agrees with the results above. Nevertheless, there are not differences between type 2 and type 3 stands. In addition, there were not differences for vertical accuracy or vertical precision.

Table 5. Results of Mann-Whitney test (U statistic) to test the null hypotheses that all receivers have the same accuracy and precision (σ_{H_acc}, σ_{H_pre}, σ_{V_acc}, σ_{V_pre}) at stands with stand density (1) lower than 500 stems/ha, (2) 500-1500 stems/ha, and (3) greater than 1500 stems/ha.

N (stands/ha)	Statistic	500-1500 (2)		>1500 (3)	
		σ_{H_pre}	σ_{H_acc}	σ_{H_pre}	σ_{H_acc}
<500 (1)	U	32626	30105	23373	20834
	Sig.	**0.021**	**0.000**	**0.011**	**0.000**
500-1500 (2)	U			26209	25701
	Sig.			0.603	0.385

Table 6. Results of Mann-Whitney test (U statistic) to test the null hypotheses that all receivers have the same accuracy and precision (σ_{H_acc}, σ_{H_pre}, σ_{V_acc}, σ_{V_pre}) despite Hart-Becking Index; the selected threshold was the Hart-Becking Index of 20%.

Statistic	σ_{H_pre}	σ_{H_acc}	σ_{V_pre}	σ_{V_acc}
U	52099	50836	33204	33806
Sig.	**0.000**	**0.000**	.085	0.170

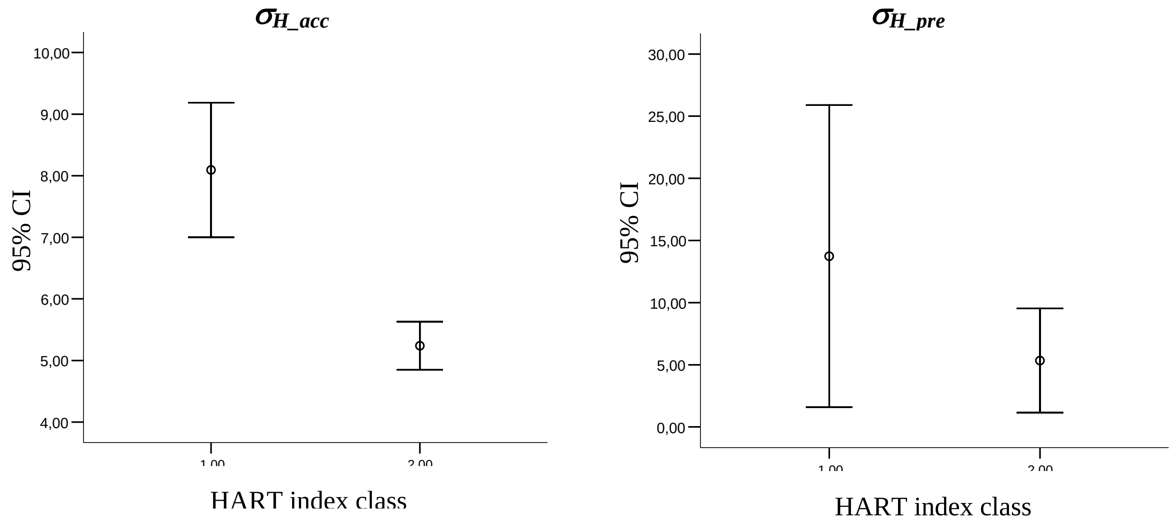


Figure 3. Error bars with the confidence intervals at 95% for horizontal accuracy and precision, regarding Hart-Becking Index.

Vertical and horizontal accuracies and precisions achieved in stands with Hart-Becking Index lower than 20% were compared to those values recorded in stands with a greater Hart-Becking Index (Table 6). Mann-Whitney test shows that horizontal accuracy and precision are significantly different for the two types of stands tested, while the significance values greater than 0.05 indicated that there were not differences for vertical accuracy and precision.

Horizontal accuracy and precision were therefore significantly smaller (i.e. more accurate) at stands with greater Hart-Becking Index (coded as 2 in Figure 3). This result agrees to the fact that low Hart-Becking Index values usually indicate more dense stands, small average spacing and/or tall trees, which makes more difficult GPS signal reception.

3.4 Accuracy and precision regarding forest canopy characteristics and GPS receivers

The previous paragraphs showed that accuracy and precision for horizontal coordinates and altitude were different depending on receivers and forest canopy characteristics. Moreover, it was aimed to test differences combining both factors, and determine whether differences between receivers depending on forest canopy characteristics.

Table 7 shows the results of performing the Mann-Whitney test to compare receivers' accuracy and precision (σ_{H_acc}, σ_{H_pre}, σ_{V_acc}, σ_{V_pre}) at dense and sparse stands (N>500 stems/ha or N<500 stems/ha).

Table 7. Results of the Mann-Whitney test regarding receivers' accuracy and precision at dense and sparse stands (N>500 stems/ha or N<500 stems/ha).

			eTrex (2)		**eTrex Summit (3)**				**Geko 201 (4)**			
N	**GPS**	**St.**	σ_{H_pre}	σ_{H_acc}	σ_{H_pre}	σ_{H_acc}	σ_{V_pre}	σ_{V_acc}	σ_{H_pre}	σ_{H_acc}	σ_{V_pre}	σ_{V_acc}
<500	**1**	U	1808	1666	1780	1918			1996	2001		

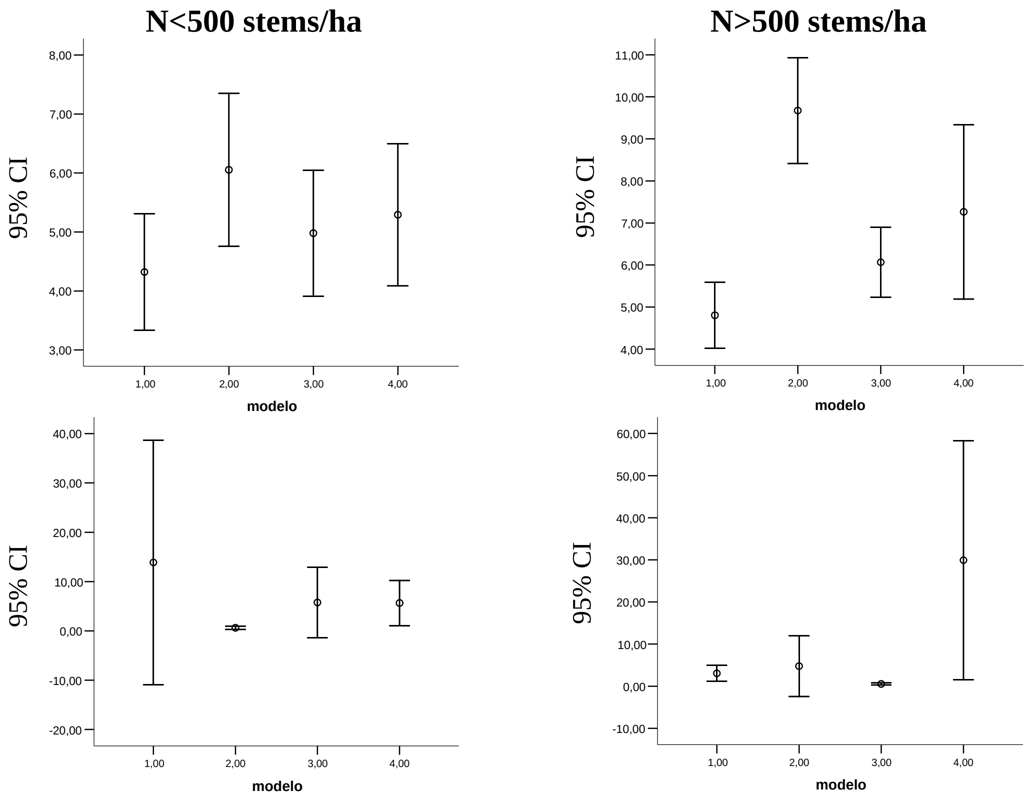
		Sig.	**0.028**	**0.005**	**0.021**	0.087			0.168	0.177		
	2	U			2239	1992	2187	1842	2306	2015	1056	2075
		Sig.			0.750	0.164	0.576	**0.041**	0.979	0.197	**0.000**	0.302
	3	U							2292	2233	808	1582
		Sig.							0.932	0.731	**0.000**	**0.001**
>500	1	U	5920	3056	4368	5250			5419	5758		
		Sig.	0.074	**0.000**	**0.000**	**0.002**			**0.006**	**0.036**		
	2	U			5433	4249	4188	6089	6041	4144	2882	6531
		Sig.			**0.004**	**0.000**	**0.000**	0.096	0.079	**0.000**	**0.000**	0.411
	3	U							6884	6557	1161	6575
		Sig.							0.882	0.440	**0.000**	0.461

Error bars with the confidence intervals at 95% for horizontal and vertical precisions and accuracies (σ_{H_acc}, σ_{H_pre}, σ_{V_acc}, σ_{V_pre}), regarding stand density and receivers are showed at Figure 4.

According to table 7 and figure 4, in sparse stands there were significant differences in horizontal accuracy between receivers 12XL (1) and eTrex (2); in that case 12XL achieved the most accurate horizontal measures. It would be also feasible to use eTrex Summit (3) and Geko 201 (4) to get accurate horizontal position. Regarding horizontal precision, 12XL (1) got the least precise values, and eTrex (2) receiver was recommended considering the smaller confidence interval, in comparison with the two other receivers, which are not less precise.

σ_{H_acc}

σ_{H_pre}



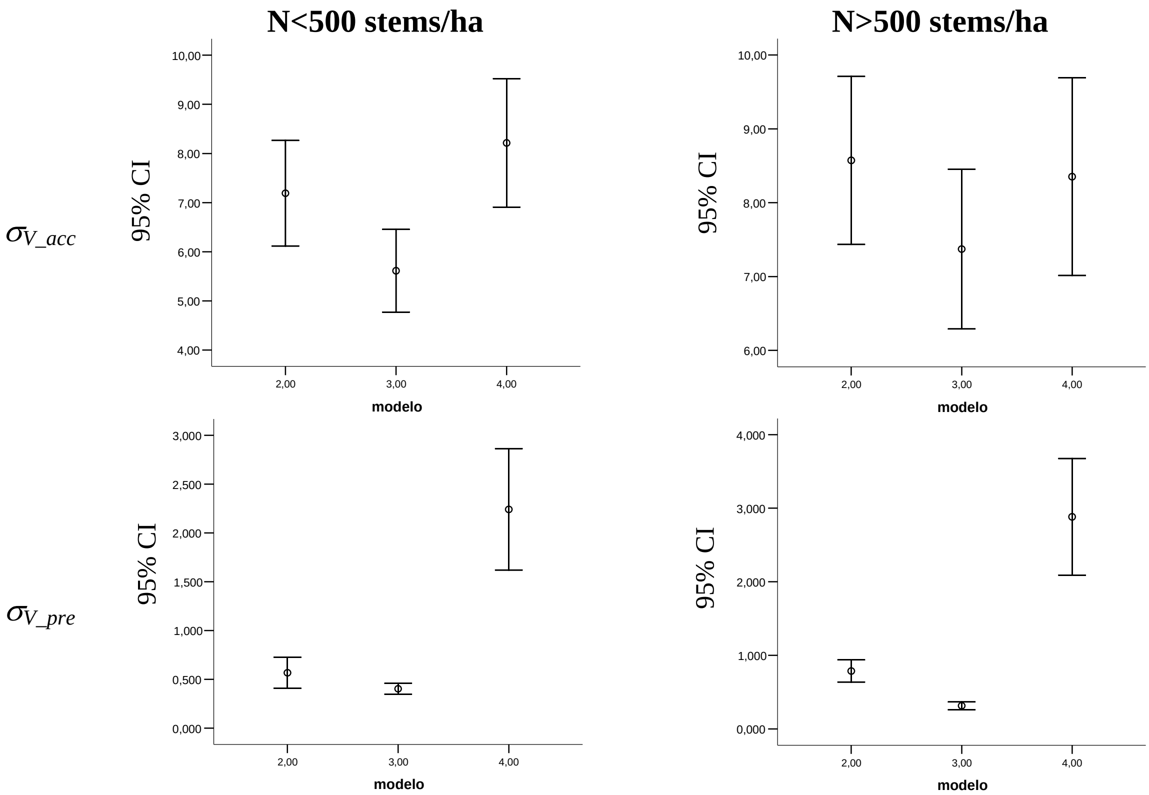


Figure 4. Error bars with the confidence intervals at 95% for horizontal accuracy and precision, regarding receivers and stand density.

Concerning vertical measurements, eTrex Summit (3) was significantly most accurate than the other receivers, while regarding precision there were not differences between eTrex Summit (3) and Geko 201 (4) and eTrex (2). Nevertheless eTrex Summit (3) is also recommended due to the narrower confidence interval. Therefore eTrex Summit (3) is the best option to measure altitude at sparse stands, considering accuracy and precision.

At dense stands (N>500 stems/ha), the most accurate receiver for horizontal position was 12XL (1), while the most precise were 12XL (1) and eTrex Summit (3). In addition, the latter showed the narrowest confidence interval. Regarding accuracy the Mann-Whitney test pointed out the inexistence of significant differences among receivers. However, vertical precision was different depending on the receiver, so that the most precise measurements were recorded by eTrex Summit (3). Therefore this receiver was recommended to determine altitudes in all types of stands regarding stand density.

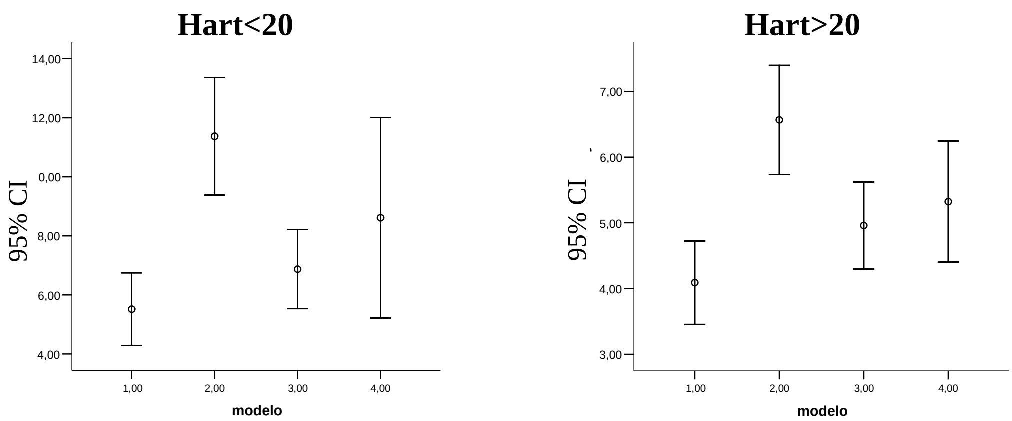
The results of comparing receivers' accuracy and precision (σ_{H_acc}, σ_{H_pre}, σ_{V_acc}, σ_{V_pre}) at different stands regarding Hart-Becking Index (20% as thresholding value) are showed at Table 8. Significance values (Sig.) lower than 0.05 indicated that the null hypothesis that the two compared groups come from the same population had to be rejected; those values are displayed in bold.

Table 8. Results of the Mann-Whitney test regarding receivers' accuracy and precision at stands classified regarding Hart-Becking Index (20% as thresholding value).

			eTrex (2)		eTrex Summit (3)				Geko 201 (4)			
Hart	**GPS**	**St.**	σ_{H_pre}	σ_{H_acc}	σ_{H_pre}	σ_{H_acc}	σ_{V_pre}	σ_{V_acc}	σ_{H_pre}	σ_{H_acc}	σ_{V_pre}	σ_{V_acc}
<20	**1**	U	1916.	1200	1484	1948			2007	2037		
		Sig.	**0.048**	**0.000**	**0.000**	0.066			0.112	0.144		
	2	U			1939	1514	1298	2163	2334	1471	1153	2161
		Sig.			0.060	**0.000**	**0.000**	0.360	0.840	**0.000**	**0.000**	0.350
	3	U							2183	2304	421.50	2348
		Sig.							0.400	0.750	**0.000**	0.890
>20	**1**	U	5680	3846	4779	5157			5468	5760		
		Sig.	**0.040**	**0.000**	**0.000**	**0.002**			**0.014**	0.059		
	2	U			5872	5051	5784	5609	6054	5055.50	2747	6573
		Sig.			0.060	**0.001**	**0.034**	**0.017**	0.126	**0.001**	**0.000**	0.601
	3	U							6639	6377	1788	5182
		Sig.							0.691	0.367	**0.000**	**0.001**

According to table 8 and figure 5, in stands with a low Hart-Becking index (<20%) eTrex (2) was the least accurate receiver for measuring Easting, Northing coordinates, while the other three receivers presented similar accuracies. Regarding horizontal precision eTrex (2) or eTrex Summit (3) achieved the best values (lowest), similar to 12XL (1). Geko 201 (4) showed a wide confidence interval, maybe because the WAAS mode was activated in for some measurements. There were also significant differences in vertical precision between receivers, achieving eTrex Summit (3) the most precise values. Nevertheless, the Mann-Whitney test showed the inexistence of significant differences in vertical accuracy.

σ_{H_acc}



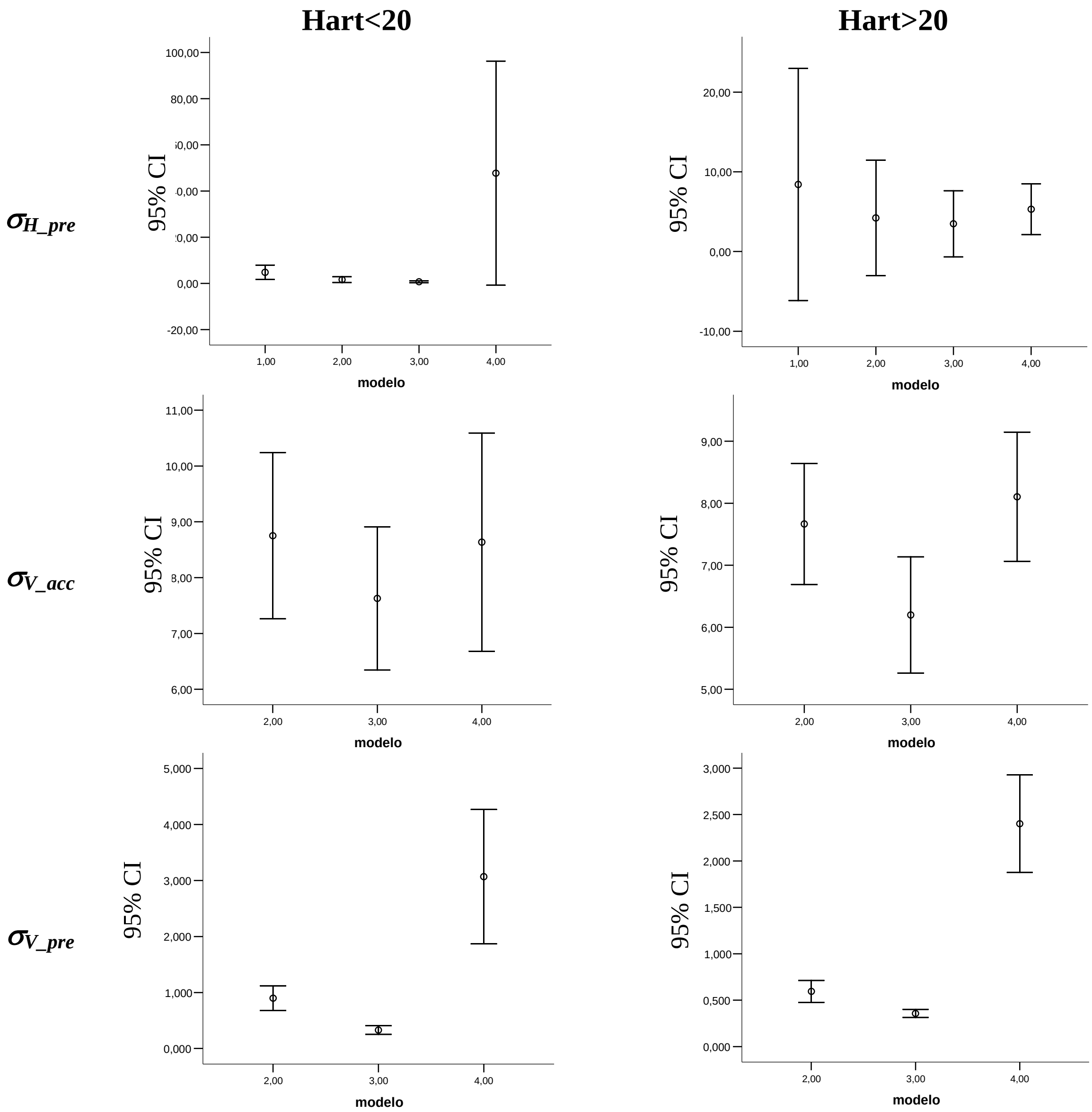


Figure 5. Error bars with the confidence intervals at 95% for horizontal accuracy and precision, regarding receivers and Hart-Becking index.

At stands with a greater Hart-Becking index (>20%), the most accurate receiver for horizontal position was 12XL (1), however this receiver was the least precise, as well as its confidence interval was the widest. There were not significant differences in horizontal precision among the other receivers. Regarding altitude, the most accurate and precise values were recorded by eTrex Summit (3). Therefore this receiver was recommended to determine altitudes in all types of stands regarding Hart-Becking Index, as reported when considering stand density.

In this study positional accuracy was affected by stand density because the lowering of signal noise ratio and signal interception caused by the electromagnetic waves penetrating the stem and canopies. Those results are according with previous research that related PGS positioning and canopy characteristics, as basal area (Næsset, 1999; 2001), wood resistance quantity and type of wood material (Sawaguchi et al, 2003), and tree specie and wood water content (Sawaguchi et al, 2005).

Additionally, accuracy and precision were sensitive to Hart-Becking Index (related to Assmann dominant height), which did not agree to other studies where height did not explain horizontal position error either after, during and before data collection (Næsset 2001; Næsset and Jonmeister, 2002).

Næsset and Jonmeister (2002) reported mean positions error ranged from 2.15 to 5.60 m but they based on differential postprocessing and used a receiver that observed pseudorange and carrier phase. Even the mean positional accuracy was improved to ranged 0.016 to 1.16 m using a 20-channel, dual-frequency receiver observing dual-frequency pseudorange and carrier phase of both GPS and GLONASS signals (Næsset, 2001). Similar results were reported by Næsset et al (2000) using a 24-channel GPS-GLONASS receiver. Measured horizontal positions for this work allowed accuracy ranged from 4.80 to 8.80 m depending on GPS receiver model, worse than cited studies, but we have used low-cost hand-held GPS receivers and on real time (no postprocessing neither long time observations). Vertical accuracy ranged from 6.80 to 8.50 m depending on GPS model, which are similar to valued achieved in other works (Yoshimura and Hasegawa, 2003).

Precisions for horizontal and vertical positioning were variable depending on model and canopy stand and were low, in general. This is a general problem using GPS under forest canopies and is solved increasing observation time period and applying DGPS (Næsset and Jonmeister, 2002; Sawaguchi et al, 2005).

According to the results, 12XL was the most accurate receiver nevertheless it was less precise than eTrex models. To get more precise measures with 12Xl we suggest activate the positioning averaging function, so that the receiver will provide more accurate and precise positions.

The eTrex Summit was the most precise for both horizontal and vertical position. Because coordinate standard deviation is the most important factor to explain positions error (Næsset et al, 2000; Næsset 2001; Næsset and Jonmeister, 2002), we recommend applying differential corrections after data acquisitions using this receiver to achieve accurate position under forest canopy .

The worst results were unexpectedly achieved by models eTrex and Geko 201, so that more research is suggested to check both receivers' performance. It is proposed to repeat a similar sampling but using Geko 201 with augmentation system function turned off and comparing results with receiving only EGNOS corrections.

4. CONCLUSIONS

This study shows that noticeable differences in accuracy and precision exist for four GARMIN receivers tested. Stand density and Hart-Becking Index, separately or considering both receivers and forest canopy characteristics, drive positional accuracy and precision. If accuracy requirements are moderate-low, tested receivers may provide valuable positional data under forest canopy if careful GPS data acquisition protocols are conducted.

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BIOGRAPHICAL NOTES

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