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# Accuracy and precision of GPS receivers under forest canopies in a mountainous environment

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## Abstract

Georeferencing field plots by means of GPS/GLONASS techniques is becoming compulsory for many applications concerning forest management and inventory. True coordinates obtained in a total station traverse were compared against GPS/GLONASS occupations computed from one navigation-grade and three survey-grade receivers. Records were taken under a high *Pinus sylvestris* L. forest canopy situated in a mountainous area in central Spain. The horizontal component of the absolute error was a better descriptor of the performance of GPS/GLONASS receivers compared to the precision computed by the proprietary software. The vertical component of absolute error also failed to show the effects revealed when the horizontal one was studied. These differences might be critical for applications involving high-demanding surveys, in which a comparison against a terrestrially surveyed ground truth is still mandatory for accuracy assessment in forested mountainous areas. Moreover, a comparison of diverse Differential GPS/GLONASS techniques showed that the effect of lengthening the baseline and lowering the logging rate was not significant in this study. Differences among methods and receivers were only observed for recording periods between 5 and 15 minutes. The hand-held receiver was inappropriate for plot establishment due to its inaccuracy and a low rate of fixed solutions, though it may be used for forest campaigns tolerating low precision or permitting the employment of periods of 20 minutes or longer for plot mensuration.

**Additional key words**: forest inventory; georeferencing; global navigation satellite system (GNSS) (GLONASS); optimum observing time.

## Resumen

### Exactitud y precisión de receptores GPS bajo cubiertas forestales en ambientes montañosos

La georreferenciación de trabajos de campo por medio de GPS/GLONASS es cada vez más necesaria para muchas aplicaciones en la gestión e inventario forestal. Se compararon coordenadas reales levantadas con estación total con las obtenidas por un navegador y tres equipos de calidad topográfica. Los registros se efectuaron bajo una masa de *Pinus sylvestris* L. del Sistema Central, España. La componente horizontal del error absoluto resultó ser un mejor descriptor de la calidad de las mediciones de los receptores GPS/GLONASS que los valores de precisión proporcionados por el *software* de los equipos. La componente vertical del error absoluto no mostró los efectos revelados por la componente horizontal. Estas diferencias pueden ser críticas para trabajos que requieran levantamientos topográficos de precisión, en los cuáles un contraste con itinerarios de validación sobre el terreno sigue siendo indispensable para calcular la exactitud en áreas forestales montañosas. Por otro lado, la comparación de diversas técnicas de GPS/GLONASS diferencial mostró que los cambios en la longitud de la línea base y de la tasa de registros no fueron significativos en este estudio. Sólo se observaron diferencias ente los métodos y receptores para tiempos de registro de 5 a 15 minutos. El navegador no resultó adecuado para el establecimiento de parcelas debido a la inexactitud y baja tasa de soluciones fijadas, pero puede ser utilizado en campañas que toleren bajas precisiones y permitan tiempos de registro iguales o superiores a 20 minutos para las medias forestales.

**Palabras clave adicionales**: georreferenciación; inventario forestal; sistemas de navegación global por satélite (GNSS) (GLONASS); tiempo óptimo de observación.

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Abbreviations used: C/A (coarse acquisition, so-called civilian code), DGNSS (differentially corrected global navigation satellite systems), GNSS (global navigation satellite systems), HDOP (horizontal dilution of precision), L1 (1575.42 MHz GPS carrier frequency), L2 (1227.60 MHz GPS carrier frequency), PDOP (position dilution of precision), RMSE (root mean square error), TS (total station), VDOP (vertical dilution of precision), WAAS (wide area augmentation system).

## Introduction

Global Navigation Satellite Systems (GNSS) have nowadays become compulsory for a wide range of activities concerning forest management and research, including plot establishment for forest inventory (Naesset, 1999), surveying control points in remote sensing (Green, 1992), forest stand boundary determination (Tachiki *et al.*, 2005), transect sampling (Ståhl *et al.*, 1999), and forest road management and machinery tracking (Rodríguez-Solano and Peces, 2002), to name but some applications. Nonetheless, forest environments located in mountainous and steep terrain present a number of obstacles to accurate and unbiased GNSS positioning (Deckert and Bolstad, 1996), thus increasing surveying errors. In addition to signal propagation delays due to ionospherical and tropospherical effects, ephemeris, differences between satellite and receiver clock, and numerical errors, which are common issues in all cases, the forest canopy adds other obstacles to wave propagation, such as complete blockage or attenuation of the signal and a strong multipath effect. Recent developments in GNSS-based positioning techniques aim at providing solutions to all those issues. Current dual-frequency receivers remove the ionospherical delay error, unlike single-frequency receivers. The addition of observations from GLONASS constellation expands the number of available signals, increasing the possibilities of obtaining a good geometrical position of satellites and therefore contributing to improved accuracy and precision (Habrich *et al.*, 1999). A measurement of the availability and geometry of satellites is given by the dimensionless parameter Position Dilution of Precision (PDOP), which decreases when conditions are favourable. Solutions obtained from C/A code and carrier phase observations can be fixed by means of differentially corrected GPS/GLONASS (hereby DGNSS). The accuracy of the coordinates obtained by DGNSS may range from meters in code-solutions to centimetres in float and fixed-solutions (Naesset and Jonmeister, 2002). However, accuracy may be affected by a multiplicity of synergic factors. For example, Naesset (2001) found that fixed dual-frequency solutions are the most accurate, while no significant differences were found between float dual-frequency and fixed single-frequency solutions.

Many studies have been carried out for evaluating the performance of DGNSS receivers under forest canopies. This assessment can be done by means of either a mere estimation of the dispersion from the mean of the observations recorded (Tachiki *et al.*, 2005; Zengin and Yeşil, 200), or an estimation of absolute error by comparing them against a ground-truth dataset generated by a conventional traverse survey (Liu and Brantigan, 1995; Sigrist *et al.*, 1999; Naesset and Jonmeister, 2002; Tuček and Ligoš, 200). Since the initial staking of such traverse has to be determined by means of GNSS positioning too, two reference positions must be measured under conditions considered standard, *i.e.* in the absence of canopy cover (Andersen *et al.*, 2009). In this paper a similar methodology for quality control is followed, further contributing in explaining the effects of forest cover and steep terrain in plot establishment with updated state-of-the-art receivers and techniques. As most research has been focused on evaluating accuracy by means of the horizontal component of absolute error, little attention has been paid on whether studying the vertical component would report the same results under forest canopies. This is logical since many forest studies depending on GNSS observations would produce the same outcome regardless of the vertical coordinate (Mauro *et al.*, 2009). Yet vertical accuracy might be a key factor in some cases (James *et al.*, 2007; Wing and Eklund, 2007). The present study also aimed at clarifying whether the terrestrial traverse surveying is compulsory for accuracy assessment or a faster evaluation throughout the precision computed by the proprietary software would result in the same outcome. Furthermore, since forest conditions significantly affect the probability of signal interruption (Hasegawa and Yoshimura, 2007), canopy may prevent from receiving a continuous array of epochs which is sufficiently long to fix the phase ambiguity. We therefore hypothesised that higher logging rates could increase the probability for fixing ambiguities. Based on these hypotheses, the main objective was to select the optimal observation parameters —logging rate and observing time— in order to plan further inventory plot establishment in the same study area.

## Material and methods

### Survey instrumentation

Four different types of commercial GNSS equipment were used: Leica GS50 and SR530 (Leica Geosystems AG, Switzerland), Topcon HiperPro and GMS2 (Topcon Positioning Systems Inc., California), all of them recording both pseudorange and carrier phase. Table 1 summarizes key technical specifications for each

**Table 1.** Manufacturer's specifications for global navigation satellite systems (GNSS) receivers

| Manufacturer | Receiver | Frequencies | # channels | GNSS | Survey type | WAAS[1] |
|---|---|---|---|---|---|---|
| Leica | GS50 | Single (L1) | 12 | GPS | Topogr/Geod | No |
| Leica | SR530 | Dual (L1-L2) | 12 | GPS | Topogr/Geod | No |
| Topcon | HiperPro | Dual (L1-L2) | 20 | GPS+GLONASS | Topogr/Geod | Yes |
| Topcon | GMS2 | Single (L1) | 50 | GPS+GLONASS | Navigator | Yes |

[1] WAAS: wide area augmentation system.

receiver. Elevations were calculated above European Terrestrial Reference System Geodetic *Datum* of 1989 (ETRS89), and coordinates projected on Universal Transverse Mercator (zone 30-North). The instrument employed for topographic surveys was a Topcon GPT-3005N pulse Total Station (hereby TS).

## Study area

The study was conducted in the Valsaín forest (Fig. 1), a public-owned forest managed by the National Parks Body of the Ministry of Environment and located at about 60 km north-west from Madrid (Spain). The site consists of high mature Scots pine (*Pinus sylvestris* L.) forest stands located in the northern slopes of the Guadarrama Mountains, with elevations between 1,298 and 1,475 m a.s.l. and slope gradients ranging between 10 and 20%. Figure 1 illustrates the vicinity of mountains obstructing the horizon approximately 10° in directions W-S-NE. The exact coordinates of landmarks situated under the canopy were obtained with diverse DGNSS receivers and differential correction techniques as described below. Since this study aims at assessing GNSS measurement accuracy for detailed forest inventory, these GNSS occupations computed at each landmark were compared to what were considered ground-truth coordinates, as they were obtained by means of a TS survey.

## Ground-truth data collection

The starting point for generating the ground-truth dataset was to identify areas with absence of canopy cover which were situated at a practical distance from the inventory plots. Two additional reference-landmarks were placed in each one of these areas and their exact coordinates were determined by means of DGNSS under standard conditions. Two log-landing sites and a bridge over a river were the openings chosen for setting a total of six reference-landmarks. Satellites under a cut-off angle of 15° were disregarded, and static observations were recorded at 1 s rate with a Topcon HiperPro rover-receiver during at least one hour at each reference-landmark. We recorded simultaneous tandem observations by setting up our own Topcon HiperPro base-receiver at the beacon Coberteros (IGN, 2008; baseline length = 12,690-13,130 m). Observations from two other independent permanent base-stations were also employed: SGVA (ITACYL, 2008; baseline length = 16,340-16,820 m), and VILL (IGS, 2008; baseline

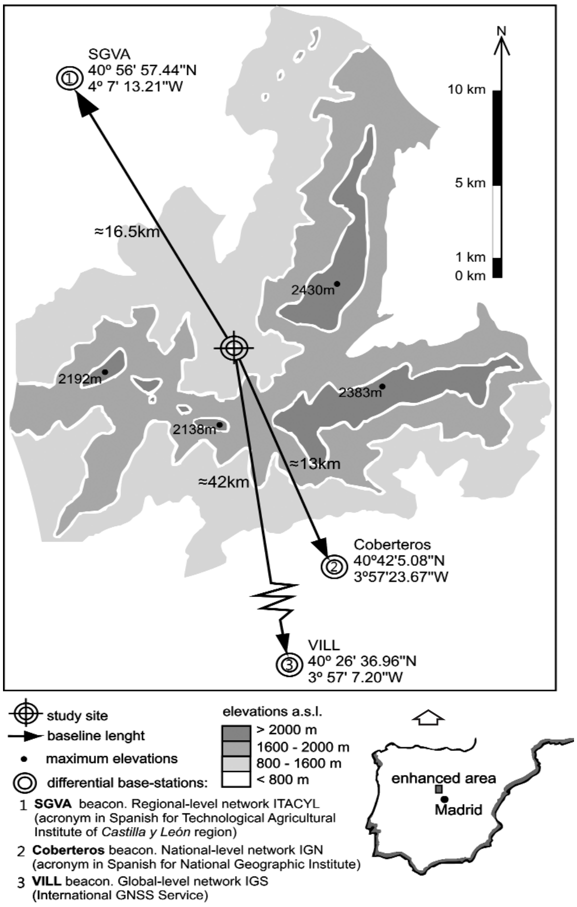


**Figure 1.** Draft map illustrating the relative position of the study area (approx. latitude, 40° 53' 31''-41° 15' 22'' N; longitude, 3° 59' 33''-4° 17' 34'' W), the base-stations and the surrounding topography.

length = 41,730-42,340 m), all of them recording from both GPS and GLONASS constellations (Dow *et al.*, 2005). The differential correction was performed at post-processing stage from all base-stations combined (Fig. 1). Under these standard conditions we may expect precisions of 1.0 cm in plan and 1.2 cm in height, according to the nominal precision stated by the vendor (Anonymous, 2006). The exact coordinates of the reference-landmarks were therefore considered to have been determined. A TS-traverse survey linked the reference-landmarks with the plot-landmarks situated under the canopy. The reference-landmarks were used as initial staking of the alignment of four different polygonal closed traverses which included the plot-landmarks (Fig. 2). The reason for operating in separate traverses was to prevent cumulative errors. Final ground truth coordinates of all landmarks were computed from a compass rule (Bowditch method) traverse adjustment (Wolf and Brinker, 1994), allowing for the acquisition of real coordinates for them with a reasonably high level of confidence. Misclosure root mean squared error (RMSE) was 0.034, 0.012, 0.018 and 0.008 m for each of the four traverses, which were 1,929.91, 650.10, 624.26, and 448.62 m long respectively.

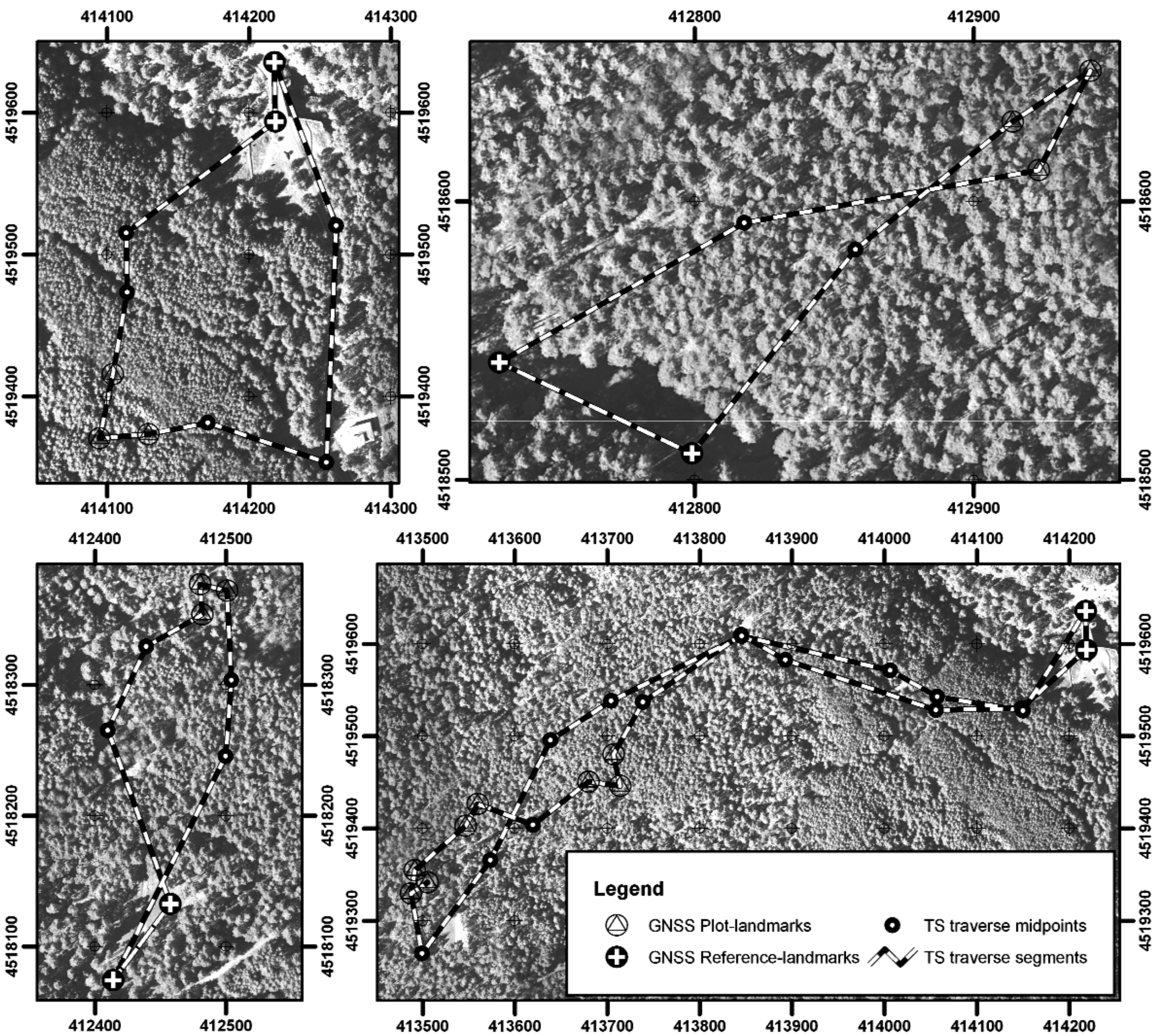


**Figure 2.** Detailed map of the total station-surveyed closed traverses linking the reference occupations with the plot-landmarks situated under the canopy. The watermark background from aerial photography illustrates the differences in canopy coverage between the different positions.

### Subcanopy GNSS observations

GNSS observations for 16 plot-landmarks situated under the canopy were acquired in May and June 2007 [day of year (DOY) 139 and 153] with GS50 and SR530 receivers at a 1 s logging rate. In July 2008 (DOY 196 and 213), rover observations were repeated by setting up an SR530, a HiperPro and a GMS2 rover-receivers at each plot-landmark. They were logging at 0.5 s intervals in order to test the effect of an increase in logging rate. The observations were obtained with all rover receivers at the same time, by shifting them from one plot-landmark to the next, so that it can be assumed no differences in their recording conditions. Observations at each plot-landmark were taken during 30 minutes with all the receivers, and antenna heights ranged from 1.01 to 1.86 m.

### GNSS data post-processing and analysis

GNSS epochs were recorded in the field, and all coordinates were computed from static observations by calculating the differential correction at post-processing stage with proprietary software, either Leica GeoOffice 5.0 or Topcon Tools 6.04. Similarly to the method followed for the reference dataset, a base-receiver was set up at the beacon Coberteros (IGN, 2008). Logging interval was set at 1 s for the first campaign, whereas 0.5 s was chosen for the second. Observations from the permanent stations SGVA (ITACYL, 2008) and VILL (IGS, 2008) were also downloaded from the internet, but data was available only at a 1 s rate. When logging at 0.5 s intervals during 30 min, a maximum of 3,600 epochs per survey were obtained. However, differential corrections arranged with SGVA or VILL had to use only one of each two epochs recorded by the rover. The effect of these changes in baseline length and logging rate was evaluated by comparing three methods for differential correction: (a) coordinates of landmarks were corrected by means of static observations at 1 s from all base-stations: Coberteros (IGN), SGVA (ITACYL) and VILL (IGS); (b) coordinates of landmarks were also computed only with the synchronized static observation obtained each 1 s at SGVA; (c) solutions were computed by using all records at 0.5 s intervals from our own base at the beacon Coberteros only.

When post-processing static observations, records were taken on whether they were fixed solutions or the initial phase ambiguity was just approximated in a float solution. Cut-off angle was set to 10° as long as the type of solution was not affected. The raw data was trimmed down to smaller intervals (25, 20, 15, 10 and 5 min) in order to identify the time needed for obtaining a reliable fixed solution. Accuracy and precision differences were considered among all the possible combinations of post-processing correction and recording times. The effect of these factors and satellite geometry was studied by analysis of variance (ANOVA) with Statistica 6.0 (StatSoft Inc., Oklahoma). For each time interval, the proprietary software computed arithmetic mean values for the position dilution of precision (*PDOP*), and their vertical (*VDOP*) and horizontal (*HDOP*) components. The optimum observation time for each receiver was identified by means of least significant differences (LSD) post-hoc analysis interval-by-interval.

The accuracy of each measurement was evaluated by means of the horizontal ($e_h$, cm) and vertical ($e_v$, cm) positional absolute errors, *i.e.* the distance between each GNSS occupation ($x$, $y$, $z$) and the TS-surveyed true landmark positions ($x_{truth}$, $y_{truth}$, $z_{truth}$):

$$e_h = \sqrt{\left(x - x_{truth}\right)^2 + \left(y - y_{truth}\right)^2} \quad [1]$$

$$e_v = \left|z - z_{truth}\right| \quad [2]$$

The dispersion of the observations is the standard deviation ($\sigma_x$, $\sigma_y$, $\sigma_z$). The precision of each survey was described as the standard deviation in its horizontal ($\sigma_h$) and vertical ($\sigma_v$) components. Being $n$ the number of epochs recorded, the proprietary software computed precision as:

$$\sigma_h = \sqrt{\sigma_x^2 + \sigma_y^2} = \sqrt{\frac{1}{n-1}\left(\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2 + \left(y_i - \bar{y}\right)^2\right)} \quad [3]$$

$$\sigma_v = \sigma_z = \sqrt{\frac{1}{n-1}\left(\sum_{i=1}^{n}\left(z_i - \bar{z}\right)^2\right)} \quad [4]$$

## Results

### Single *vs.* dual-frequency

First comparisons were generated for the full dataset occupied by means of the differential correction type (a), which adjusted the coordinates according to the three networks described ITACYL-IGN-IGS. Results for a one-way ANOVA among receivers suggested no significant differences ($p = 0.555$ and 0.834, for $e_h$ and $e_v$ resp.). Unexpectedly, single-frequency GS50 obtained results statistically similar to those of dual-frequency SR530 ($p = 0.599$ and 0.784, for $e_h$ and $e_v$ resp.). Moreover, selected contrasts demonstrated no systematic effects between campaigns ($p = 0.641$ and 0.439, for $e_h$ and $e_v$ resp.). No significant differences were found between SR530 occupations which were repeated in 2007 and 2008 ($p = 0.284$ and 0.229, for $e_h$ and $e_v$ resp.). Although results remained statistically unchanged between campaigns, further analyses were performed with the 2008 dataset, with the intention of limiting the sources of variation.

## Factors affecting absolute error and precision

The effects of receiver type (Leica SR530, Topcon HiperPro, or GMS2), differential correction [(a) all base-stations, (b) SGVA only, or (c) Coberteros only], and recording time (30, 25, 20, 15, 10, or 5 min) on the accuracy (Figs. 3a, 3b) and precision (Figs. 3c, 3d) of DGNSS positioning were studied by means of ANOVA. Most variables studied suggested significant differences among receivers, while the method used for differential correction had no significant effects (Tables 2 and 3). Figure 3a provided a comprehensive explanation of the interactive effect that receiver and time had on the absolute error in planimetry. Fisher's LSD analysis emphasized that hand-held GMS2 differs from the survey-grade receivers ($p < 0.001$), whereas no significant differences were found between SR530 and HiperPro ($p = 0.358$). Results showed that the recording time also had significant effects on both absolute error and precision. However, only when observing horizontal absolute error the effect of recording time seemed to be receiver-dependent (Fig. 3a), whereas this interaction was not significant when studying precision (Table 3).

## Assessing optimum observation time

The horizontal component of absolute error was used for determining the optimum observing time,

**Table 2.** Summary of factorial analysis of variance (ANOVA) for the absolute error of global navigation satellite systems (GNSS) occupations

| Source of variation | df | Horizontal absolute error ($e_h$) | | | | Vertical absolute error ($e_v$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean square | F-statistic | $p$ | | Mean square | F-statistic | $p$ | |
| Receiver type (A) | 2 | 19.147 | 6.052 | 0.002 | * | 1.459 | 0.517 | 0.597 | (ns) |
| Differential correction (B) | 2 | 0.386 | 0.122 | 0.885 | (ns) | 1.744 | 0.618 | 0.540 | (ns) |
| Recording time (C) | 5 | 18.559 | 5.866 | < 0.001 | ** | 15.593 | 5.521 | < 0.001 | ** |
| A × B | 4 | 0.419 | 0.132 | 0.970 | (ns) | 3.125 | 1.107 | 0.352 | (ns) |
| A × C | 10 | 6.396 | 2.022 | 0.029 | * | 4.880 | 1.728 | 0.070 | (ns) |
| B × C | 10 | 0.137 | 0.043 | 0.999 | (ns) | 0.433 | 0.153 | 0.999 | (ns) |
| Error | 780 | 3.164 | | | | 2.824 | | | |

**Table 3.** Summary of factorial analysis of variance (ANOVA) for the precision of global navigation satellite systems (GNSS) occupations

| Source of variation | df | Horizontal precision ($\sigma_h$) | | | | Vertical precision ($\sigma_v$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean square | F-statistic | $p$ | | Mean square | F-statistic | $p$ | |
| Receiver type (A) | 2 | 2.684 | 10.662 | < 0.001 | ** | 1.946 | 5.056 | 0.007 | * |
| Differential correction (B) | 2 | 0.104 | 0.412 | 0.521 | (ns) | 0.053 | 0.139 | 0.710 | (ns) |
| Recording time (C) | 5 | 2.848 | 11.312 | < 0.001 | ** | 4.481 | 11.642 | < 0.001 | ** |
| A × B | 4 | 0.443 | 1.760 | 0.173 | (ns) | 0.290 | 0.755 | 0.471 | (ns) |
| A × C | 10 | 0.243 | 0.964 | 0.474 | (ns) | 0.447 | 1.162 | 0.315 | (ns) |
| B × C | 10 | 0.146 | 0.581 | 0.715 | (ns) | 0.081 | 0.209 | 0.959 | (ns) |
| Error | 780 | 0.252 | | | | 0.385 | | | |

regarded as the moment when no further improvement was obtained. Post-hoc tests were generated separately for each receiver (Table 4), since the interaction between receiver and time was significant (Table 2). Longer recording times failed to improve the performance of HiperPro, whereas the other receivers showed signifi-

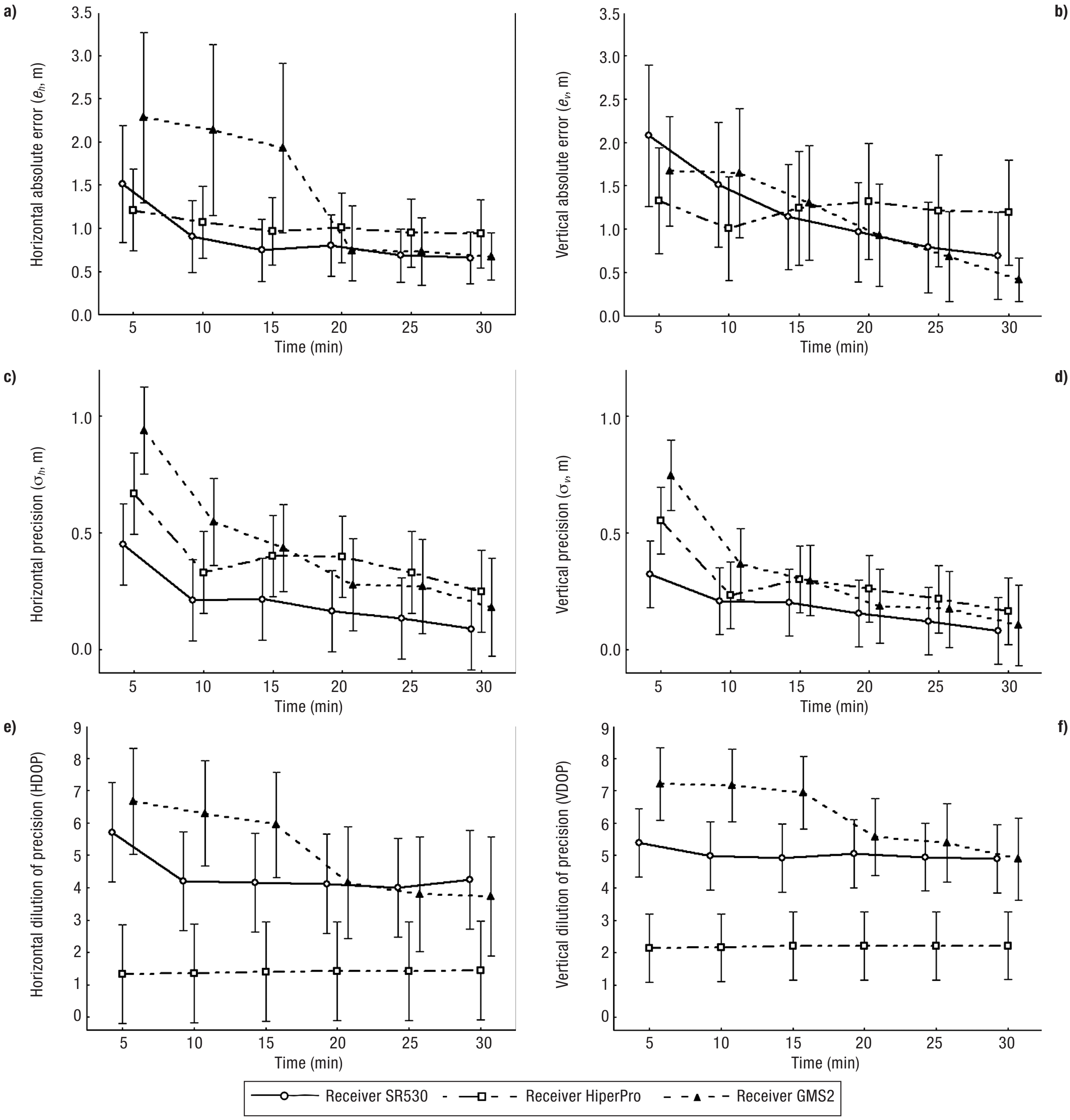


**Figure 3.** Interactions between global navigation satellite systems (GNSS) receiver types and increasing recording times for: a) horizontal component of accuracy $e_h$; b) vertical component of accuracy $e_v$; c) horizontal precision $\sigma_h$ ; d) vertical precision $\sigma_v$; e) horizontal dilution of precision (HDOP); and f) vertical dilution of precision (VDOP).

**Table 4.** Least significant difference (LSD) analysis of recording time influence in the horizontal absolute error for each receiver

| Recording time (min) | Leica SR530 | | | | | | Topcon HiperPro | | | | | | Topcon GMS2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 5 | 10 | 15 | 20 | 25 | 30 | 5 | 10 | 15 | 20 | 25 | 30 | 5 | 10 | 15 | 20 | 25 | 30 |
| 10 | 0.001* | | | | | | 0.341 | | | | | | 0.823 | | | | | |
| 15 | <0.001** | 0.392 | | | | | 0.094 | 0.469 | | | | | 0.584 | 0.745 | | | | |
| 20 | <0.001** | 0.582 | 0.760 | | | | 0.160 | 0.650 | 0.787 | | | | 0.022* | 0.037* | 0.077 | | | |
| 25 | <0.001** | 0.237 | 0.743 | 0.527 | | | 0.069 | 0.384 | 0.883 | 0.676 | | | 0.022* | 0.038* | 0.077 | 0.981 | | |
| 30 | <0.001** | 0.185 | 0.637 | 0.438 | 0.885 | | 0.060 | 0.351 | 0.834 | 0.631 | 0.950 | | 0.021* | 0.036* | 0.072 | 0.916 | 0.935 | |
| Mean $e_h$ (m) | 1.514 | 0.904 | 0.802 | 0.745 | 0.684 | 0.657 | 1.211 | 1.072 | 0.966 | 1.005 | 0.944 | 0.935 | 2.282 | 2.137 | 1.927 | 0.747 | 0.731 | 0.672 |

**Table 5.** Summary of means for the number of satellites received from each constellation

| Recording time (min) | # GLONASS satellites | | | | # GPS satellites | | | | | | # GPS + GLONASS satellites | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | GMS2 | | HiperPro | | GMS2 | | HiperPro | | SR530 | | GMS2 | | HiperPro | | SR530 | |
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| 5 | 0.4 | 0.6 | 2.1 | 0.8 | 6.5 | 1.7 | 8.6 | 1.6 | 8.0 | 1.7 | 6.9 | 1.7 | 10.7 | 1.6 | 8.0 | 1.7 |
| 10 | 0.5 | 0.7 | 2.3 | 0.8 | 6.6 | 1.8 | 8.9 | 1.3 | 8.4 | 1.6 | 7.1 | 1.8 | 11.1 | 1.3 | 8.4 | 1.6 |
| 15 | 0.6 | 0.7 | 2.3 | 0.8 | 7.0 | 1.8 | 8.9 | 1.4 | 8.6 | 1.6 | 7.6 | 1.8 | 11.2 | 1.4 | 8.6 | 1.6 |
| 20 | 0.7 | 0.7 | 2.3 | 0.9 | 7.3 | 1.8 | 9.1 | 1.3 | 8.7 | 1.5 | 8.0 | 1.8 | 11.4 | 1.3 | 8.7 | 1.5 |
| 25 | 0.8 | 0.7 | 2.4 | 0.9 | 7.4 | 1.7 | 9.3 | 1.3 | 8.7 | 1.5 | 8.3 | 1.7 | 11.7 | 1.3 | 8.7 | 1.5 |
| 30 | 1.0 | 0.9 | 2.4 | 0.9 | 7.9 | 1.9 | 9.5 | 1.3 | 8.8 | 1.5 | 8.9 | 1.9 | 11.9 | 1.3 | 8.8 | 1.5 |

cant differences. In order to clarify the reasons, the dilution of precision (Fig. 3e, 3f), number of satellites per constellation (Table 5), and the capacity of each receiver for fixing solutions (Fig. 4) were studied.

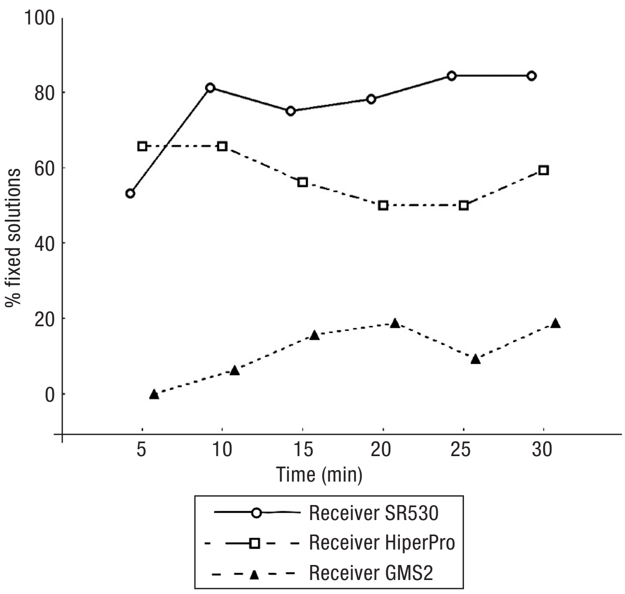


**Figure 4.** Temporal evolution of the rate of fixed solutions obtained.

# Discussion

## Factors affecting absolute error and precision

Figure 3 illustrates how some cases presenting high values of absolute error may show low values of precision. The analysis of horizontal absolute error is therefore suggested as a better descriptor of the performance of GNSS systems, rather than the precision computed by the proprietary software. Other authors also agree in considering insufficient the use of a measurement of the standard deviation for accuracy assessment (Liu and Brantigan, 1995; Sigrist *et al.*, 1999; Naesset and Jonmeister, 2002), so that a comparison with ground truth is still compulsory. These results emphasize how some effects may remain unveiled when considering the measurement of precision that the receivers provide while recording. However, when acquiring large inventory datasets, it does not make sense for forest managers to use terrestrial TS surveying methods in the whole of the study area. Following this methodology is therefore recommended as a part of any plot-establishment campaign requiring high positioning accuracies. This would be especially critical for some forestry applications requiring high accuracies, such as classifying very high resolution imagery, or when generating models between forest inventory and LiDAR-based parameters. Analysing the vertical component of absolute error was also ineffective for clarifying the effects involved in the survey (Fig. 3b). For this reason, elevations have to be considered only when required by the specific forest application, as it may be when estimating soil volumes, forest road mapping (Rodríguez-Solano and Peces, 2002) and terrain or stream profiling (James *et al*., 2007).

No significant effects due to the diverse methodologies used for differential correction were found, regardless of the variable studied (Tables 2 and 3). In most cases, the maximum number of epochs (3,600 for 0.5 s, and 1,800 for 1 s) were recorded by both SR530 and HiperPro. Hence, contrary to our hypothesis, signal interruption was not limiting in the described conditions. As the correction methods were dissimilar in both baseline and logging rate, we may therefore suggest that neither decreasing baseline length nor increasing logging rate led to a substantial improvement in survey's performance. However, these conclusions can be highly dependent on the exact methodologies described. For instance, Figure 1 shows how mountainous obstacles are likely to interfere more with the signal of satellites simultaneously received by Coberteros than with those received by SGVA, since the latter is situated in the direction of the main NW-aspect of the slopes. At the operational level, using downloaded observations from independently established permanent stations would be preferred in future studies, rather than setting up an own base-receiver at the nearest beacon. In addition, the error obtained by GS50 receiving L1 observations was no significantly worse than the SR530 receiver recording both L1-L2. This might have happened because, in a multipath environment such as dense forest in steep terrain, the signal-to-noise ratio may notably decrease for the L1-L2 linear combination (Arslan and Demirel, 2008). These results suggest that dual-frequency receivers might not necessary perform better when surveying in forested areas.

## Assessing optimum observation time

Results in Table 4 provided a comprehensive estimation of the optimum recording time. For SR530 receiver, no significant differences were found from ten minutes onwards. Thus, that recording time was determined as its optimum under the given conditions. Changes in recording time did not seem to affect the performance of HiperPro receiver when studied separately. It can be presumed that new developments implemented in HiperPro, such as the multipath correction or including GLONASS constellation and WAAS, might have improved the results obtained when measuring during short times only. GMS2 started offering reliable results under the canopy after fifteen minutes of recording (Fig. 3a). Since this receiver is intended for navigation purposes, this recording time was demonstrated unpractical. For that reason, using navigator-grade receivers is not recommended for plot establishment, except in the particular case that the time spent by the receiver has nevertheless to be used for plot mensuration as well. The high variability of the results obtained when recording with GMS2 for short times suggest that they are probably significantly depending on the characteristics of each forest plot. Further analysis should therefore clarify the relations between accuracy with forest variables, since diverse optima might be found for different forest stand characteristics (Deckert and Bolstad, 1996; Hasegawa and Yoshimura, 2007). It might be advisable not to employ this receiver under dense canopies and limit its use to less-requiring surveys in fairly open areas, for instance forest roads' positioning. This methodology estimated the optimum recording time by evaluating when logging more GPS epochs no longer offered significantly better results, regardless of the magnitude of the error itself. Similar future analysis might instead use values calculated of tolerable error as a threshold for optimum identification, as an alternative methodology that may provide results focused on the objectives of each survey. Some authors have calculated such admissible errors, which might depend on the forest variables themselves (Mauro *et al.,* 2009) or the remote sensing technique (Gobakken and Naesset, 2009).

## Effects of incorporating GLONASS

It may be supposed that the use of both GPS and GLONASS constellations allowed HiperPro receiver to obtain a constantly low dilution of precision (Figs. 3e, 3f), even when the receiver was observing during a short time. Table 5 illustrates the improvement obtained when incorporating GLONASS constellation. Naesset (2001) demonstrated that accuracy may highly depend on the number of available satellites when observing under difficult conditions. Thus, the addition of

GLONASS observations could have led to less biased measures of HiperPro when recording during 5 minutes only. Note that all receivers were shifted from one landmark to the next, taking their records simultaneously. Hence, it can be assumed that differences in *HDOP* and *VDOP* were motivated by conditions of the receivers themselves, while changes due to the status of the constellation or canopy distortion should be constant among groups. This may explain why some authors described no significant relations between accuracy and PDOP (Sigrist *et al*., 1999; Naesset and Jonmeister, 2002).

### Type of solution obtained

Figure 4 illustrates the percentage of fixed solutions obtained over the total of the occupations performed with each receiver, and the changes encountered when recording continuously during a longer time. Results may explain why HiperPro did not improve its performance when recording longer times, since more floating or code solutions were computed. The relative difficulties for fixing solutions that this receiver encountered are in contrast with the number of available satellites (Table 5) and the dilution of precision computed (Fig. 3e, 3f). Naesset (2001) suggested that recording under forest canopies may provide some solutions erroneously accepted as fixed. Further research would be needed in order to totally clarify the reasons. GMS2 demonstrated an especially poor performance in obtaining fixed solutions, and in many cases (15.18%) no solution was obtained at all when situated under dense canopies. Nevertheless, since its error decreased as the receiver stayed longer in its position, it may be deduced that floating and code solutions would become more reliable as the recording time increases, since a bigger sample size is obtained as well.

### Concluding remarks

The analysis of the horizontal component of absolute error was confirmed to be a better descriptor of the performance of GNSS receivers compared to the precision computed by the proprietary software, or its vertical component. For this reason, highly-demanding surveys, such as those supporting very high resolution imagery or LiDAR remote sensing techniques, would dramatically depend on the exactness of the results obtained in each area. We therefore suggest that similar surveys perform an analogous comparison against a ground-truth prior to arranging occupations at a larger scale. This way, compulsory TS-traverses can be also limited to an area close to an opening in the canopy, therefore saving time and effort. Hopefully, future developments in GLONASS and other satellite constellations, as well as in the available networks of permanent base-stations, will improve the results obtained in forested areas.

Significant differences between the survey-grade and navigation-grade receivers were found, though these differences became diluted when recording during long periods. Hence, the effects of recording time were significant as well, and in this paper the optimum recording time for each receiver was estimated by contrasting time groups one-by-one. Differences among the methodologies for differential correction were randomly oscillating. The effect of lengthening the baseline and lowering logging rate was not significant in this case. A cost-effective conclusion was that it is more advisable to download observations from established base-stations than setting up your own. Regardless of the factor, results tend to be similar when recording during periods longer than fifteen minutes. In addition, it was concluded that the hand-held receiver was inappropriate for plot establishment due to its inaccuracy and low rate of fixed solutions.

Further research would be needed on whether or not the performance of GNSS techniques can be explained and predicted by the characteristics of the forest at each plot. Similar studies in different forest plots would also be needed, especially in broadleaved stands. Nonetheless, this paper clarifies that significant differences may be apparent only when recording short times. Significant results might disappear when recording more than fifteen minutes, even when comparing fixed survey-grade occupations with a hand-held receiver obtaining mainly floating solutions. This is even more important when considering that such a long observation period is inefficient at operational level.

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