Article

Rapid Static Positioning Using a Four System GNSS Receivers in the Forest Environment

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Abstract: Global Navigation Satellite Systems (GNSS) are crucial elements used in forest inventories. Forest metrics modeling efficacy depends on the accuracy of determining sample plot locations by GNSS. As of 2021, the GNSS consists of 120 active satellites, ostensibly improving position acquisition in forest conditions. The main idea of this article was to evaluate GIS-class and geodetic class GNSS receivers on 33 control points located in the forest. The main assumptions were operating on four GNSS systems (GPS, GLONASS, Galileo, and BeiDou), keeping a continuous online connection to the network of reference stations, maintaining occupation time-limited to 60 epochs, and repeating all the measurements three times. Rapid static positioning was tested, as it compares the true performance of the four GNSS systems receivers. Statistical differences between the receivers were confirmed. The GIS-class receiver achieved an accuracy of 1.38 m and a precision of 1.29 m, while the geodetic class receiver reached 0.74 m and 0.91 m respectively. Even though the research was conducted under the same data capture conditions, the large variability of positioning results were found to be caused by cycle slips and the multipath effect.

Keywords: GNSS; Galileo; BeiDou; forest; accuracy; precision

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1. Introduction

The global need for accurate information concerning forests' impact on the dynamic development of precision forestry is immense [1]. Not only satellite imagery [2] but also LiDAR (Light Detection and Ranging) [3] and UAV (Unmanned Aerial Vehicle) technologies [4], used for forest inventories, are of great interest to researchers all around the world. All these techniques require the use of reference measurements on the ground. To correctly match the above data with the ground references, the geometric center of each sample plot must be measured with the highest accuracy possible. In all aforementioned cases, GNSS technology is the source for coordinate acquisition [5]. This factor is critical because it determines the results of the research and influences final conclusions. Taking into account fast GNSS development, which is progressing due to the new operational satellite segments like BeiDou or Galileo, [6] an important question should be asked: what is the present state of the possible accuracy of GNSS receivers? More than 25 years have passed since the first important research on GPS usage in forest environments was conducted by Deckert and Bolstad [7], who confirmed the accuracy of positioning on the level of 3.1 to 4.4 m. A few years later Naesset [8] repeated this experiment and extended the measurements through the use of GLONASS. The results were quite impressive, the dual-frequency receiver reached the accuracies from 0.08 m to 1.35 m. Since then, differential methods have been used to improve the position quality and to minimize large errors. The importance and wide applicability of GNSS technology in forest practices [9,10] have led many researchers to seek further improvements, not only in accuracy and precision but also in error identification and detection. The forest metrics, such as tree species, number of trees, diameter at breast height [11], basal area [12], the density of forest height, site condition and positioning mode [13] are only examples of factors that can influence the quality of measurements. In practice, the main cause of the errors is represented by the multipath effect and cycle

slips, which are both connected with complicated tree structures [14]. Over the years many solutions have been proposed aiming to reduce multipath effects [15–18]. Some of them have been implemented in new GNSS receivers [19]. Increased antenna heights also reported favorable results for reducing positioning errors, [20] however, the practical usage of a high and heavy mast in dense forests depreciated this idea. Unquestionably the most important and most suggested method which helped in achieving the highest accuracy is averaging the registered coordinates. McGaughey [21] proved that increasing the occupation time helps in lowering the root mean square error (RMSE). In conclusion, it was suggested to limit the occupation time to 15 min. However, it is worth mentioning the mean horizontal error, in that case, was 1.43 m after 1 h of continuous measurements for a Trimble GeoXH6000 and 0.83 m for a Triumph1 receiver, respectively. Moving forward after June 2020 this situation should begin to change because of the new era of navigation which has started through the operation of new global systems [22]. The Chinese navigation system BeiDou has reached full operational capability (FOC) and 22 European Galileo satellites have also started operation. As of summer 2021, the total number of satellites consisting of GPS, GLONASS, BeiDou and Galileo systems exceeded 120 [23]. Most global manufacturers of GNSS receivers preemptively prepared their navigation chipsets for new systems in the future, so there was no need to invest in new devices. The confirmed advantages of GNSS multi-constellation are: location accuracy, improved satellite geometry and signal availability, which are especially useful in both urban and forested areas [24]. Even though the BeiDou system should be improved in the areas of orbital inclination and ionospheric delay correction [25], the final performance in open spaces for long term monitoring on the open space was on the 1 mm level for horizontal direction and 2–3 mm for the vertical respectively [26]. These results were achieved on the short baseline length in standard positioning system (SPS) mode and were postprocessed by BeiDou software. Unfortunately, the complex research conducted by Yan et al. [27] who used the BeiDou and GPS receiver, does not confirm strong improvement in the positioning accuracy within forested environment. Their mean horizontal accuracy for broad-leaved forest was around 3.5 m and for coniferous forest around 2 m. Nevertheless, authors confirm that there is not only a significant increase in the number of available satellites, but that they also managed to obtain stronger satellite signal expressed by higher values of signal to noise ratio (SNR). It is also expected that FOC of Galileo will shorten the observation time and extend the baseline length between rover and base station [28]. The development of satellite systems contributes to the growing role of the smartphones for forest measurements [29]. These measurements and their results in forest conditions show they still need a longer observation time and large errors occur frequently [30,31].

Answering the demand for improving the forest estimation accuracy [32], the main goal of this research was to check the real accuracy and precision of the latest commercial multi-GNSS receivers, in forest conditions. The basic assumption was that both rover receivers and the network of reference stations must be operated in GPS, GLONASS, Galileo and BeiDou. In order to keep the reliable and repeatable conditions for the experiment, measurements were reinitialized after the sidereal day and corrected by the same network of reference stations. Taking into account the price, implemented algorithm of positioning and the antenna quality [31], two different receivers were tested: a geodetic class (Stonex S900A) and a GIS class (CHC tablet model LT700H). The selection of the receivers was not dictated by the manufacturer but by the real interest of the foresters and researchers who use GNSS navigation daily. Another factor that was taken into consideration was the distinct improvement of GIS class receivers, which are close to geodetic receivers in accuracy and precision. Larger numbers of available satellites, better signal-to-noise ratios and the need for fast measurements justify the reduction of observation time to 60 epochs. The results of this research may be a valuable guide for foresters as well as for other researchers.

2. Materials and Methods

The research area was located in the Warsaw University of Life Sciences' experimental forests in—Rogów, Poland (51°49'10.92" N, 19°54'27.81" E). The 33 control points, separated by around 15 m, were located alongside a narrow forest road under the forest canopy (Figure 1). The whole research campaign was conducted at the beginning of June 2021 during an intensive growing season. The surrounding forests consist of two different dominant species types. The forest district located to the south of the research area is 90% dominated by 153-year-old Scots pine (*Pinus silvestris*), with average heights around 30 m and of medium stem density. To the north of the road, 60% of the forest is occupied by 60-year-old European Larch (*Larix decidua*) with average heights of 28 m and 30% is covered by 64-year-old Common Oak (*Quercus robur*) with heights around 23 m. Based on the official forest documentation, which was prepared in 2019 after the field inventory, the density of trees in this area is described as high.

Figure 1. The location of control points on the background of UAV orthomosaics.

The canopy cover was documented by hemispherical photographs which are very reliable, according to the assessment of the light conditions in the forest [33]. The Canon EOS 5D (Canon, Tokyo, Japan) camera along with the Sigma 8 mm f/35 circular fisheye lens (SIGMA, Aizu, Japan) was used for taking photos. The 180-degree lens located at the same height as the GNSS antenna allowed to completely document the light conditions for the control points. The Hemisfer 3.1 software [34] was used in order to extract the canopy openness and leaf area index (LAI) values, according to the Gonsamo et al. methodology [35]. Two stabilized ground points were used as a base for surveying. They were established during the winter season by the GNSS receiver Topcon Hiper SR (Topcon, Tokyo, Japan), over 20 min of continuous real time kinematic (RTK) observations in FIX mode, corrected by the Polish network of reference stations ASG-EUPOS. The expected horizontal accuracy is within ± 0.03 m [36]. Based on these two ground points, classic surveying polar methods were used to determine the final coordinates of the control points. The Topcon GTS 105N (Topcon, Tokyo, Japan) was used with an angular accuracy of 5" and distance accuracy $\pm (2 \text{ mm} + 2 \text{ ppm})$. This method practically operates independently of forest conditions, and therefore, guarantees reliable results [37].

The studies were conducted based on two GNSS receivers represented by the geodetic class Stonex S900A (Stonex, Paderno Dugnano, Italy) and GIS class CHC tablet model LT700H (CHC Navigation, Shanghai, China) (Table 1). In both cases, the receivers' antennas were mounted on a 2-m tall pole and stabilized above the control points by a bipod. In the case of the Stonex S900A, the android controller SH5A with the Cube-a software was used to gather the field observations. Along with two batteries, the receiver located in the antenna's case weighed 1.3 kg. It also used phase measurements which is the main difference compared to the GIS class receiver, which mostly relies on positioning via the C/A code. The LT700H tablet contains a navigation chipset, resulting in a very light additional external antenna. Both these components weigh around 675 g, thus, making them easily portable. The GIS class receiver was equipped with mLas Inżynier software developed by TAXUS IT company. Because of a software limitation, the height value was not recorded during research. Taking into account the coverage of LiDAR data for Poland, with the mean elevation error equal 0.15 m, [38] there is no need to capture the height by GNSS.

Table 1. GNSS receiver specification.

	LT700H	Stonex S900A
Channels	184	800
Constellations	GPS: L1C/A, L2C, GLONASS: L1C/A, L2C/A Galileo: E1, E5B, BieDou: B1, B2	GPS: L1C/A, L1C, L1P, L2C, L2P, L5G LONASS: L1C/A, L1P, L2C/A, L2P, L3 Galileo: E1, E5A, E5B, ALTBOC, E6 BieDou: B1, B2, B3. ACEBOC
Horizontal RTK accuracy	0.02 m	0.005 m
Dust and Water Proof	IP67	IP67 or IP68 ¹
Battery	8000 mAh	3400 mAh
LTE modem and Wi-Fi	YES	YES
Weight	675 g	1300 g

¹ On demand.

Each of the receivers recorded data for three days. In order to omit the multipath effect [39,40] which strongly influences positioning [41], the next measurement was repeated after one sidereal day which is equal to 23 h 56 m 04 s [42]. The GNSS receivers were powered on outside of the forest to avoid cold start problems [43]. After stabilizing the receiver on the control point, there was about 1 min of delay before data recording was started. The main assumption of the research was to test the receivers in fast rapid static measurements, so the 60 epochs were recorded for every point. This idea is congruent with previous research results [27,44] and corresponds with the need for fast data capture. The receivers were connected online to the ASG-EUPOS network of reference stations and operated in the RTK technique. The receivers were configured for storing the data only in FIX and FLOAT mode. To keep the sidereal day interval and the precise start of data recording for every receiver the measurements were conducted sequentially during six days—three days for each receiver. In total, close to 12,000 epochs were recorded for further analyses. Sunny skies and calm weather conditions do not influence the results of positioning. The analysis of the data based on the accuracy factor expressed in the equations [45]:

$$M_{ACC} = \sqrt{M_X^2 + M_Y^2}, \quad (1)$$

Values of the variables of the accuracy equation were calculated as follows:

$$M_X = \sqrt{\frac{\sum_{i=1}^n (X_{GNSS} - X_{REF})^2}{n}}, \quad (2)$$

$$M_Y = \sqrt{\frac{\sum_{i=1}^n (Y_{GNSS} - Y_{REF})^2}{n}}, \quad (3)$$

where, X, Y_{GNSS} —the X, Y coordinates from the GNSS field measurements, X, Y_{REF} —the X, Y coordinates of control points. The distribution of recorded coordinates around the mean value can be described as the precision of measurements and was calculated by the expression [46]:

$$M_{PRE} = \sqrt{\sigma_X^2 + \sigma_Y^2}, \quad (4)$$

The variables of the precision were calculated by:

$$\sigma_X = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n - 1}}, \quad (5)$$

$$\sigma_Y = \sqrt{\frac{\sum_{i=1}^n (Y_i - \bar{Y})^2}{n - 1}} \quad (6)$$

where, σ_X, σ_Y —represent the standard deviation in the horizontal direction for X and Y respectively, n —number of measurements on the control points

Accuracy and precision results were examined by the Pearson correlation coefficient to a number of visible satellites (NVS), position dilution of precision (PDOP), canopy openness, and LAI. The Shapiro–Wilk test of normality was performed for accuracy (M_{ACC}) and precision (M_{PRE}) with a significance level of 0.05. The differences between the receivers were verified by the Wilcoxon test. The analysis of variance was realized by the non-parametric Kruskal–Wallis test and posthoc Dunn test with Bonferroni adjustment to assess the statistical differences between the observation sessions.

3. Results

The average canopy openness was 6.7% and the 30 control points range from 3% to 10%. In the case of the LAI value, the mean and the median were very similar and reached around 3.3. There were no large differences for this index as it ranged between 2.43 and 4.06. Internet access was stable during the whole experiment; therefore, there was no disturbance in the online differential corrections. More than 27% of total observations were registered in the FIX mode for the LT700H receiver, and 15% for the Stonex S900A respectively. The mean accuracy for the GIS class receiver was 1.38 m, however, the standard deviation (StD) for both measurement modes was around 0.96 m and the maximum error exceeded 3 m on the 6 control points. A smaller standard deviation (0.84 m) and mean (0.74 m) for accuracy were recorded by Stonex S900A for both operating modes. The geodetic class receiver reached only 0.16 m for FIX mode and 0.84 m for the FLOAT respectively (Table 2).

Table 2. Results of the field measurements by the LT700H and Stonex S900A receivers depending on the operating mode.

	LT700H		Stonex S900A	
	FIX	FLOAT	FIX	FLOAT
Mean M_{ACC}	1.32	1.41	0.16	0.84
StD M_{ACC}	0.99	0.93	0.09	0.88
Mean M_{PRE}	1.28	1.29	0.69	0.95
StD M_{PRE}	0.66	0.61	0.68	0.63
Mean NVS	30	30	16	12
Mean PDOP	0.55	0.55	1.02	1.03

The overall precision was better for the Stonex S900A and amounting to 0.91 m, while the LT700H reached 1.29 m. The standard deviations for both receivers were very similar and ranged between 0.61 and 0.68 m depending on the operating mode, so the aggregation of points was similar also. The direction of the precision errors varied mostly along the Y-axis of the coordinate system (Figure 2).

The NVS is doubled for the LT700H and it reached 30 much faster than the Stonex S900A, which was confirmed in the field by the readiness of this receiver and inferior PDOP factor (Table 2). The variability of errors on the control points is large and cannot be clearly explained by the forest metrics. Good examples of such errors are the results for the control point number 7 with a canopy openness of 13%, as well as number 25 where the canopy openness is 5%. The accuracy on the point with bigger accessibility to open sky reaches 2 m for both receivers while the dense canopy cover on point number 7 is around 0.5 m (Figure 3).

The Pearson correlation coefficients are very small for all forest and navigational metrics. The canopy openness has the strongest negative correlation (−0.26) for the precision of the Stonex S900A which proves the aggregation of coordinates is maybe better for the smaller canopy cover (Table 3).

Figure 2. The diversity of precision for the LT700H (red color) and Stonex S900A (green color) receivers is expressed in meters.

Figure 3. The mean, maximum and minimum accuracy of the LT700H (red color) and Stonex S900A (green color) receivers achieved on all control points during three observation sessions.

Table 3. The Pearson correlation coefficient results of forest and navigational metrics for the LT700H and Stonex S900A receiver.

Receiver	Errors	PDOP	NVS	LAI	Openness
LT700H	M _{ACC}	0.13	−0.03	−0.18	−0.08
	M _{PRE}	0.17	−0.01	−0.22	−0.09
Stonex S900A	M _{ACC}	0.06	−0.16	−0.05	−0.16
	M _{PRE}	0.21	−0.11	−0.15	−0.26

The analyzed data for both accuracy and precision do not have a normal distribution. The null hypothesis stating that there is no significant difference between LT700H and Stonex S900A accuracy and precision was rejected. The distance between the first and third percentile for the accuracy of the LT700H is 1.44 m while for the Stonex S900A it is 0.79 m

(Figure 4a). The lower difference can be observed in the precision dispersion (Figure 4b). The LT700H percentile range is slightly smaller (0.63 m) than Stonex S900A (0.84 m).

Figure 4. The overall accuracy (a) and precision (b) depending on the used receiver.

The GNSS receivers' accuracy was checked statistically with regard to the results from three independent observational sessions. The statistical difference for LT700H was confirmed between sessions 2 and 3 (p -value 0.0094), while in the case of the Stonex S900A the difference was significant for sessions 1 and 2 (p -value 0.0262) for 1 and 3 (p -value 0.0259) (Figure 5).

Figure 5. Accuracy for the LT700H (red color) and Stonex S900A (green color) divided by the three independent observation sessions.

4. Discussion

There is no doubt that the development of navigational technology increased the accuracy and precision of GNSS receivers. In comparison to the results of Deckert and

Bolstad [7], the rapid static accuracy for 60 epochs achieved in this research is almost six times lower. Considering the occupation time, the new GNSS receivers can reach the same accuracy as the Naesset [8] research did 20 years ago, but instead of doing it in 2.5 min, like before, they are now able to achieve it in just around 1 min. Overall, the accuracy is much better for both tested receivers, but there is still room for further improvement. One of the biggest problems is the reliability of measurements in forest environments. Even though the GNSS receivers were recording the epochs in almost the same conditions, only 10% of the results can be assumed as replicable. It is especially visible for the GIS class receiver, which is characterized by nearly 1 m of standard deviation and a maximum accuracy that can exceed 4 m. The biodiversity and forest stand structure surrounding the control points was not overly complex, which was confirmed by the canopy openness and LAI, however, the final results prove the rapid static positioning accuracy is still unpredictable (Table 2 and Figure 3). This conclusion can be also explained by the fact that these forest metrics are not correlated with the final results. Theoretically, the larger amounts of light in the should forest increase the NVS but in practice, it applies only to precision, not accuracy (Table 3). In the case of the GIS class receiver, despite large canopy openings (14–16) for a few control points, which nearly doubles that of mean canopy openness, positional accuracy showed minimal improvement. Only the Stonex S900A reacts positively to the amount of light, which was confirmed by the Pearson correlation coefficient. This is due to every part of the open horizon allowing stable phase measurements, hence better precision. Many investigations mention the positive influence of low PDOP on the positioning results [20,47,48]. The extension of GNSS segments by BeiDou and Galileo implemented in the four system navigation receivers caused significant decreases in the PDOP values [49]. In this research, the Pearson correlation between PDOP and positioning results does not confirm these conclusions (Table 3). Errors are generally smaller, but they do not depend on PDOP, which is generally low and stable. One of the main assumptions of this research was to avoid the multipath effect, caused by a tree structure, through the repetition of data acquisition after a sidereal day. The results of statistical tests did not explain this clearly because there was no significant difference in exactly 50% of cases (Figure 5). This leads to the conclusion that the multipath effect is a factor that is very vulnerable to change. During the whole field data capture, there was no wind, moisture, or other distortionary factors. Assuming the general presence of the multipath, it can be concluded that its variability depends on very small elements in the environment. What was clearly observed during the field data capture, was the receivers' ability to quickly acquire data. This observation is consistent with Santra et al. [50] who confirmed the advantages of multi-GNSS usage in an environment with obstacles. The availability of over 30 satellites guarantees that there is no delay in recording the epochs. Moreover, both operating modes, FLOAT and FIX, are easy to keep up with. Nevertheless, the development of GNSS has not increased the number of FIX modes, which could have strongly improved the accuracy. Considering 27% of FIX modes for LT700H and 15% for Stonex S900A we can assume that the possibility of centimeter accuracy in the forest is still rare. Furthermore, the LT700H receiver didn't provide reliable results in FIX mode. The 1.32 m accuracy and 1.28 m precision for the GIS class receiver clearly explained that the FIX mode is not based on the full carrier phase observations, but mostly on the C/A code. The advantage of code receivers is the lack of cycle slip effect [51], however, it is not directly transferred to the quality of positioning. This effect was not observed in the case of Stonex S900A. The geodetic class receiver uses a smaller number of satellites, but the majority of them are utilized for the assessment of the phase pseudorange. Even though the overall performance of Stonex S900A is not perfect in the forest, it needs to be mentioned that the availability of open horizons combined with the access to the network of reference stations allows for reliable and repeatable 0.03 m of horizontal accuracy. The research also confirms that there is a significant difference between LT700H and Stonex S900A regarding accuracy and precision. Given the better Stonex S900A positioning results in the forest, when compared to GIS class receiver, not a big difference in price, and very accurate

measurement results in the open horizon, proves the geodetic class solution worthwhile. There is no doubt that high accuracy and precision would not be achieved without the differential correction technique that was used in this research. Access to a network of reference stations allows capturing the data in real-time kinematic (RTK) mode, virtual reference stations (VRS) mode, or post-process observations after fieldwork. This was confirmed by many researchers all over the world [52–54] not only for GIS or geodetic class receivers but also for smartphones [55].

5. Conclusions

Breaking the barrier of the sub-centimeter positioning accuracy in the forest environment is still a challenge, nevertheless, slowly we are coming closer to reaching that goal. One of the important factors in this matter is the extension of the GNSS constellation by Galileo and BeiDou which resulted in the improvement of the rapid static accuracy and precision in forest stands; 60 epochs are enough to reach the accuracy of 1.38 m for the GIS class receiver and of 0.73 m for the geodetic class. The results of precision for both tested receivers are similar to those of accuracy and total 0.91 m for Stonex S900A and 1.29 m for LT700H. The comfort of recording forest measurements is much higher due to a large number of visible satellites and low PDOP values, resulting in the short time to data acquisition in FLOAT mode. Considering the immense demand for fast and accurate coordinates in the forest, the important question can still be asked: will GNSS receivers manage to deal with the task? Further development of GNSS segments should help in increasing the accuracy, however, the most important research must be primarily directed at mitigating the multipath and cycle slip in a forest environment.

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