Original scientific paper

The Effect of Mounting Height on GNSS Receiver Positioning Accuracy in Forest Conditions

Michał Brach, Michał Zasada

Abstract

In spite of the high prices of GNSS receivers, many users decide to invest in this equipment because of the high accuracy of X, Y and Z data capture. Measurements in forested environments are affected by the increased positional error because of the signal multipath effect caused by trees. The main idea of this paper is to raise the antenna of a GNSS receiver during measurements, in order to reduce the multipath effect in the highest part of forests. A 15 meter pole was used in order to capture the GNSS signal at a height of 5, 10 and 15 m above ground level, in various forest conditions. The main factor, which determines the precision and accuracy, is the operational mode of the receiver. When in the FIXED mode, the results obtained are more reliable than those obtained when in the FLOAT mode. Due to difficult conditions in the forest stand, FIXED mode occurrence is not always possible, but much more likely at higher elevations. The FLOAT mode, however, is more likely to occur in the forest conditions and the obtained accuracy of the X and Y coordinates was ±0.81 m and 1.11 m for the elevation (Z coordinate). The best results were achieved for X and Y coordinates at an altitude of 10 m in a leafless state with an average error of ±0.54 m for the FLOAT mode. We cannot assume, therefore, that raising the GNSS antenna will improve the precision and accuracy in every case.

Keywords: GNSS, accuracy, precision forestry, survey, ANOVA

1. Introduction

The Global Navigation Satellite System (GNSS) has become one of the most popular techniques for fast and accurate positioning in open spaces. This method has been used in many areas of mapping because of the low cost and simplicity of its use, compared to the standard way of surveying (Mauro et al. 2010). Taking into account the diversity of the forest structure (Puettmann et al. 2009) and accessibility of digital maps as a main source of land use information (Bach et al. 2006), there is a real need to be able to gather up-to-date and accurate positioning data in forests (Suarez et al. 2005).

The GNSS technology works well in unobstructed open spaces and all GNSS manufacturers provide the accuracy of their receivers assuming that they work without any obstacles. The fact that forest may suppress or even completely block the satellite signal is not taken into account (Næsset and Jonmeister 2002). The low accuracy of GNSS receivers in forestry conditions has been widely discussed in many research papers. There are a lot of factors caused by forest conditions which can influence positioning accuracy. Forests are a barrier for signal propagation so the final radio wave is weak and the reflection causes an elevated signal-to-noise ratio, which is caused by the so called multipath effect (Hasegawa and Yoshimura 2007, Pirti et al. 2010, Valbuena 2012). The base idea of multipath is strictly connected to signal reflections from objects located near the receiver, which ultimately causes an error in distance measurements. There are many software and hardware solutions to weaken this effect, however it still does not solve the strong forest influence (Valbuena 2014). Additionally, the multipath effect is multiplied by high moisture (Sigrist et al. 1999) and the presence of leaves (Valbuena et al. 2012). One of the first conclusions concerning navigation accuracy in the forest was formulated by Næsset (1999), who concluded that high density sites, tree species, satellite constellation and observation times, are important factors for accurate positioning. When compared to open sky conditions, leaves decreased a number of visible satellites, and hence geometry (PDOP value) was deteriorating. The PDOP factor corresponds to the general uncertainty of coordinate calculations. The desirable low value of PDOP depends on angled satellite constellation (Valbuena 2014). Forest conditions have little impact on PDOP, so this is why the observation session should be carefully planned and the final data processed afterwards (Wing et al. 2009). Planning is also very important in mountainous terrains, which can block satellite signals (Deckert and Bolstad 1996). GNSS data capture may be obstructed by tall trees and large basal areas, especially in mixed coniferous stands (Georges et al. 2004). Analyzing the differences between deciduous and coniferous trees, it can be concluded that needles and trunks have significant influence on positioning accuracy (Sawaguchi et al. 2003). When considering the impact of forest characteristics on satellite navigation, Ordóñez Galán (2011) carried out complex research on dasymetric and GPS parameters. It turned out that the slenderness coefficient, Hart-Becking spacing index, wood volume and dominant height are the most important variables that can be used for the description and prediction of the horizontal and vertical measurement accuracy. Basal area can better describe forest conditions than tree height and density (Næsset 2001) and this value can be better for assessing the absolute error (Næsset 2000). The complex research by Valbuena et al. (2012) confirms the relative spacing index (RSI) and wood volume as values that can explain GNSS positional variability. It was also mentioned that the leaf area index (LAI) can be used as an accuracy prediction factor. Taking into account the close connection between signal-to-noise ratio (SNR) and positioning precision, it can be assumed that wood resistance, quantity and satellite elevation angles should also be considered (Sawaguchi et al. 2005). Finally, the best way to conduct data capture in forest conditions is to use dual frequency receivers operated in the fixed mode (Hasegawa 2007). The DGNSS technique is one of the best and economically justified methods to improve positioning accuracy (Næsset 2001) and it can reduce errors caused by atmospheric delay (Næsset and Jonmeister 2002). Nowadays there are a lot of reference stations with coverage varying from local to global, which can transmit corrections directly to the GNSS receiver by the Internet. This method is far more efficient than the post-processing procedure (Andersen et al. 2009, Valbuena 2014) and it is better than setting up your own reference station (Valbuena et al. 2010).

In most known cases, researches used standard GNSS receivers mounted on poles up to 5 m high (Næsset 1999, Næsset and Jonmeister 2002, Cole 2004, Rodriguez-Perez et al. 2006, Wing 2009, Valbuena et al. 2010). Such antenna locations cannot guarantee access to open sky in the forest. Næsset and Jonmeister (2002) suggest that receiver location is changed to close open areas, which is not easy in dense forests. The alternative approach was presented by Sigrist et al. (1999), who recommended using a mast for the antenna as a solution to open sky access. One of the most well-known and comprehensive studies considering the influence of antenna height on positioning accuracy was presented by Yoshimura (2005). In his research he concluded that using a sophisticated GNSS receiver mounted at high heights and DGNSS correction can result in a significant increase in the accuracy of the position measurements in forest conditions.

Our goal was to determine whether the measurement height has an effect on the positioning accuracy in the forest stands that are typical for Eastern Europe. The key to improve accuracy is to increase the access to open sky. This can be realized by using an exceptionally high mast. In this way the significant influence of forest characteristics on GNSS positioning accuracy can be reduced. The second goal was to assess the possibility of using the high accuracy FIXED GNSS receiver mode and its comparison with the less accurate FLOAT mode.

2. Materials and methods

The experimental site was located in the Głuchów forest district belonging to the Warsaw University of Life Sciences-SGGW. The site location was 51°45'13.01" N and 20° 6'33.72" E. The network of reference points was created and stabilized along main roads crossing the Głuchów forest district. The traverse technique was used in order to assess error propagation. All points were measured using classical geodetic surveying techniques and adjusted to reference points located outside of the forest (Valbuena 2014). They formed a reference base in order to set 36 sample plots in different forestry sites. The sample plots were measured using trigonometric (for Z value - elevation) and polar (for X, Y values) methods. All coordinates were expressed and calculated in the 2000 zone 7 Polish coordinate system (EPSG code 2178). The maximum horizontal error for the sample point was 0.09 m. In order to correct any elevation errors, additional leveling measurements were carried out. The final results of the vertical calculations gave a maximum elevation error of 0.05 m, expressed and calculated in Kroonstad 1986 reference frame. At each of the 36 sample points grouped by main species, age and stand height, an aluminum mast with a GNSS receiver was set. The detailed characteristics of the research stands are given in Table 1.

Table 1 Categorization of sample points based on stand characteristics

Stand category	Main species	Age, years	Average height, m	Stocking
Brz 19–42	Birch	19–42	14–20	Full
Św 50	Spruce	50	21	Full
So 72–110	Pine	72–110	25–26	Moderate
So 17	Pine	17	3	Moderate
So 61–88	Pine	61–88	23–25	Full
Db 80–84	Oak	80–84	23–24	Full

The dual-frequency, geodetic class surveying GNSS receiver Topcon HiperPro was used for obtaining the positioning coordinates. Valbuena et al. (2010) research based on this receiver, reports it as one of the best in horizontal and vertical absolute error and practically independent on data capture time in forest conditions. The receiver was mounted on an aluminum mast at three different heights: 5, 10 and 15 m (Fig. 1). All measurements were differentially corrected by the Polish network of reference stations (ASG-EUPOS) by the NAWGEO service. This service provides real-time correction data by using a virtual reference station (VRS) technique (Landau et al. 2002).

During measurements in the forest, two basic measurement modes were used: FLOAT and FIXED, which provide significantly different positioning accuracy (Teunissen et al. 2008). FLOAT mode is based on a real value of sequences for the carrier phase between the receiver and satellite. This is only an approximate value which does not correspond to the reality, so the expected positioning accuracy is about 0.5 m (Cellmer et al. 2010). FIXED mode is a measurement mode in which the search for the carrier phase ambiguity has been solved as an integer value. This solution is the most reliable and most accurate. Depending on the data correction service, it is possible to achieve a 0.03 m horizontal position accuracy and 0.05 m vertical position accuracy (by the accuracy of

Fig. 1 An aluminum telescopic mast with the GNSS receiver in the Głuchów forest district (photo: Dariusz Górscy)

the system claimed by ASG-EUPOS) (Oruba et al. 2009). The default measurement mode is FIXED, but if the phase ambiguity has not been solved because of forest conditions, the mode is automatically switched to FLOAT.

The construction was stabilized by an aluminum tripod. Considering the mast weight (18 kg), height (15 m) and weight of GNSS antenna (1.74 kg), it was necessary to check whether the mast was vertically oriented at 5, 10 and 15 m. In order to receive the final results, the measurements by total station were carried out in an open space from two directions. It was found that, at a height of 10 m and 15 m, the average GNSS receiver deflection was 0.04 m and 0.08 m, respectively. There was no deflection when the mast was extended to 5 m.

The complete error analysis consists of a calculation for accuracy and precision (Yoshimura 2003, Valbuena 2014). In order to analyze horizontal positioning accuracy the following equation was used:

$$\sigma_{\mathrm{H\_accuracy}} = \sqrt{\left(\bar{x} - x_{\mathrm{true}}\right)^2 + \left(\bar{y} - y_{\mathrm{true}}\right)^2} \quad (1)$$

Where:

x_{true}, y_{true} reference coordinates,

$\bar{x}, \bar{y}$ mean coordinates captured at different heights.

Similarly for the elevation:

$$\sigma_{\mathrm{v\_accuracy}} = \left|\bar{z} - z_{\mathrm{true}}\right| \quad (2)$$

Where:

z_{true} reference elevation,

$\bar{z}$ mean elevation value at different heights.

In order to assess the relation of the measurements to the true value, the root mean square (RMS) estimator can be used (Sigrist et al. 1999, Rodrigez-Perez et al. 2006). The precision calculation by the RMS error was used for horizontal coordinates:

$$\sigma_{\mathrm{H\_precision}} = \sqrt{\sigma_{\mathrm{x}}^2 + \sigma_{\mathrm{y}}^2} \quad (3)$$

The values of σ_x and σ_y were calculated using the following equations:

$$\sigma_{\mathrm{x}}^2 = \frac{\sum_{k=1}^{n}\left(x_{\mathrm{k}} - \bar{x}\right)^2}{n-1} \quad (4)$$

$$\sigma_{\mathrm{y}}^2 = \frac{\sum_{k=1}^{n}\left(y_{\mathrm{k}} - \bar{y}\right)^2}{n-1} \quad (5)$$

Where:

x_k, y_k horizontal coordinates captured for a sample point,

$\bar{x}, \bar{y}$ mean horizontal coordinates captured for a sample point,

n a number of observations made at every mast height.

The precision for elevation was calculated using the following formula:

$$\sigma_{\mathrm{v\_precision}}^2 = \frac{\sum_{k=1}^{n}\left(z_{\mathrm{k}} - \bar{z}\right)^2}{n-1} \quad (6)$$

Where:

z_k elevation captured for a sample point,

$\bar{z}$ mean elevation captured for a sample point,

N number of observations made at every mast height.

Analyses of accuracy and precision were made separately for GNSS receiver modes FLOAT and FIXED. Because of a large number of deciduous stands in the Głuchów district, the observations were made in two vegetation seasons, so the final result could be analyzed in leaf on and leaf off conditions. Measurements at all sample points were repeated 10 times, so all in all, considering 36 sample points and 3 antenna heights (5, 10 and 15 m), a total of 1,080 observations were recorded.

One of the main hypothesis for this research is that the amount of light, which can reach the ground in the forest, may be correlated with positioning accuracy (Valbuena et al. 2012). This factor was examined by hemispherical photographs, which allowed us to determine a percentage of light (canopy openness) on the ground at each sample point in leaf on and leaf off conditions (Jonckheere et al. 2005). The idea of hemispherical photography was successfully used by Sigrist et al. (1999), who highlighted canopy closure as a good estimator of satellite signal blocking. The complete set of photographs was used for leaf-on and leaf-off seasons in order to compare final positioning errors with canopy openness.

During the GNSS measurements, the dilution of precision (DOP) value was also recorded. This value describes the satellite geometry. The high value of DOP means that the satellites are located close to the straight line and a potential error propagation by the triangulation calculation can lead to higher positioning uncertainty (Valbuena et al. 2014). Under the forest canopy, the DOP value can increase, so it can be an important factor in final positioning results (Lewis et al. 2007).

The influence of the antenna height and the presence of leaves (leaf-on/leaf-off season) on the horizontal and vertical accuracy was investigated by the two-way analysis of variance (ANOVA) with power transformation of dependent variables to comply with ANOVA assumptions.

3. Results

The mean canopy openness for sample points depending on antenna height was 19.2–41.7% for a leaf-on season and 56.7–68.7% for a leaf-off season. These values varied depending on the stand category (Fig. 2, 3). The mean value of DOP was 3.31, so it was close to optimal (Duncan et al. 2013, Puente et al. 2013). Peyret (2000) states that DOP value can give information about the repeatability of measurements, so a slight advantage of leafless and bigger antenna height can be observed (Fig. 4).

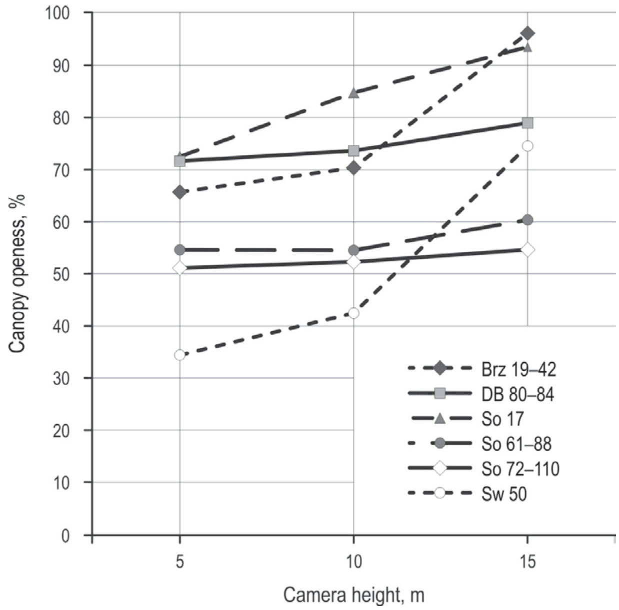

Fig. 2 Canopy openness for different stand category and hemispherical camera height in a leaf-off season

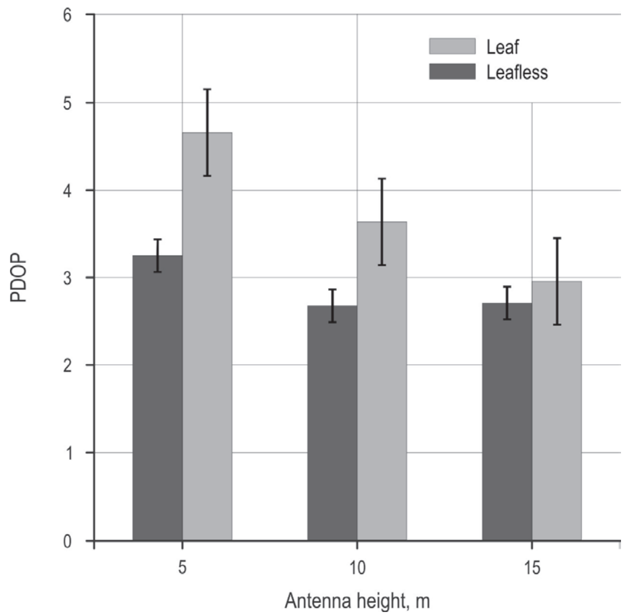

Fig. 4 PDOP value depending on antenna height and vegetation season

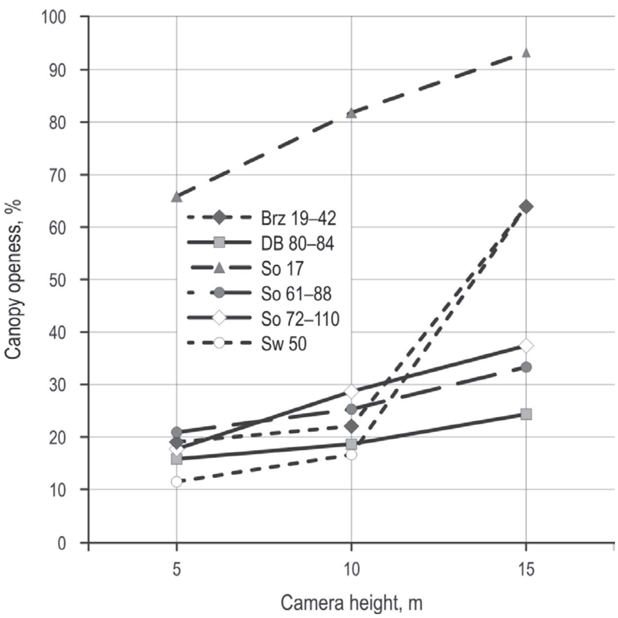

Fig. 3 Canopy openness for different stand category and hemispherical camera height in a leaf-on season

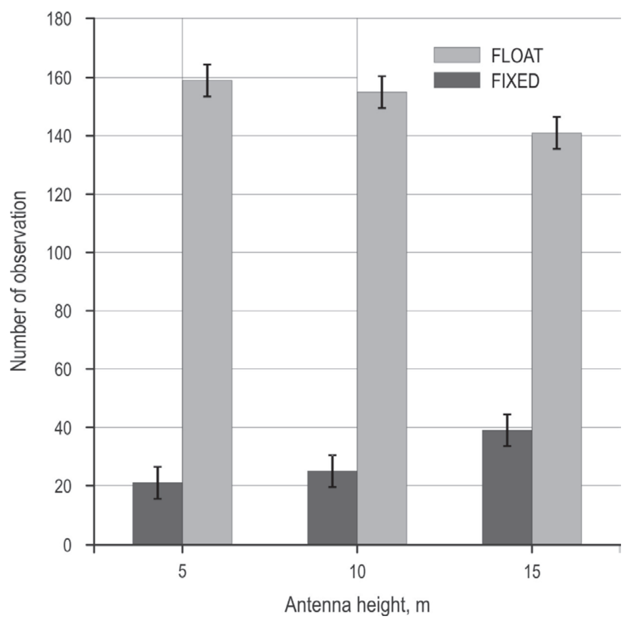

Fig. 5 Number of observations depending on measurement mode in leaf season

The main factor which affects GNSS accuracy in the forest is the measurement mode. The total number of FIXED mode measurements was 344 (32%) and 736 (68%) for FLOAT mode, respectively. These values change, however, depending on antenna height and vegetation season. The number of FIXED positions increase very slowly with the height, but in practice FLOAT mode is more probable (Fig. 5, 6).

Depending on the antenna height, the mean horizontal accuracy for a FIXED mode varied from ±0.09 to ±0.25 m and 0.13 to 0.15 m for elevation, respectively. Considering the FLOAT mode, the mean error

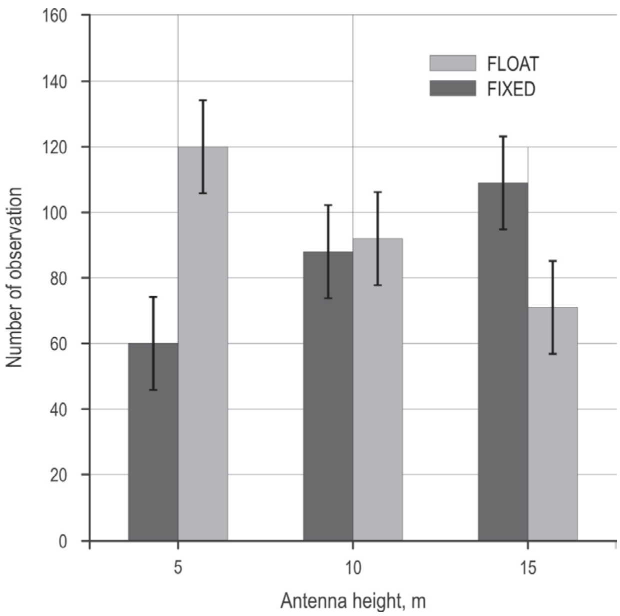

Fig. 6 Number of observations depending on measurement mode in leafless season

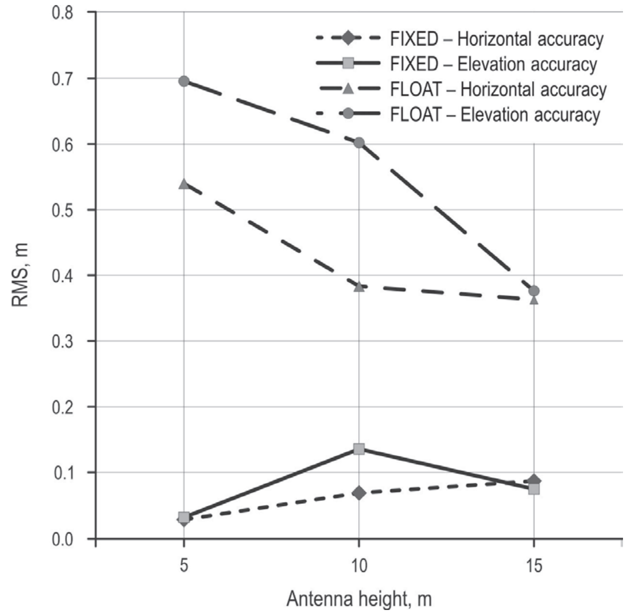

Fig. 8 RMS value depending on measurement mode and antenna height

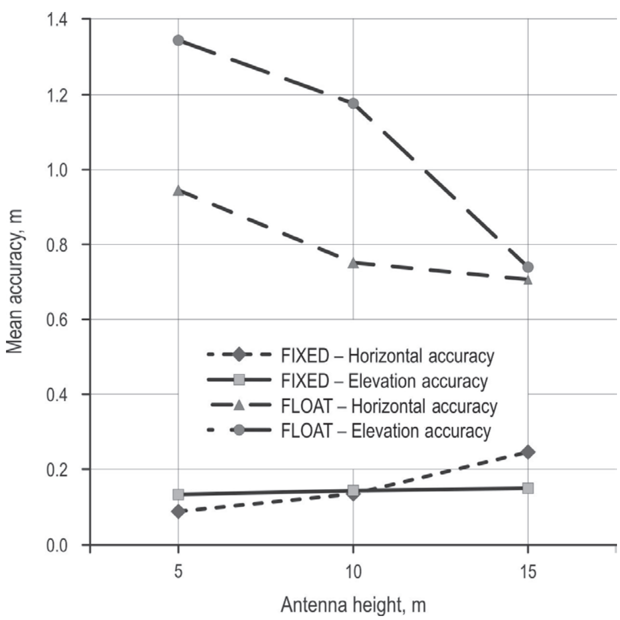

Fig. 7 Mean horizontal and vertical accuracy depending on measurement mode and antenna height

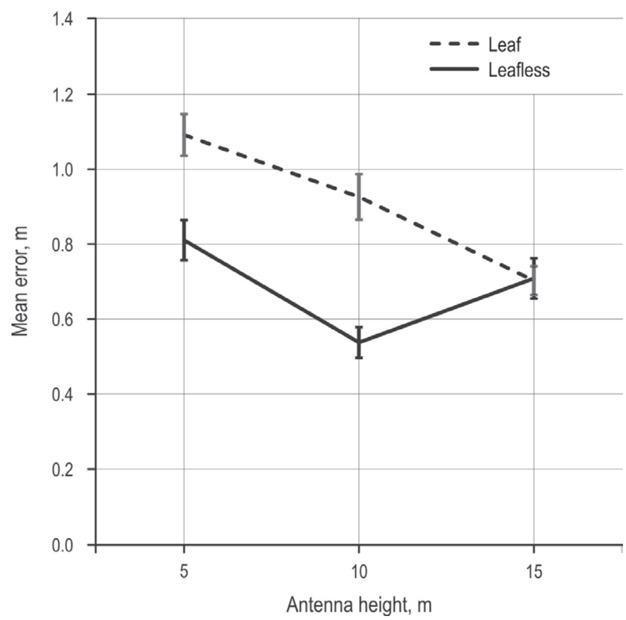

Fig. 9 Relationship between the mean error of the XY coordinate determination and antenna height for various seasons in the FLOAT mode

was a few times higher and decreased from ±0.96 m for low antenna locations to ±0.70 m for the antenna located on the mast extended to the maximum. For an elevation, the error in the FLOAT mode varied from 0.74 to 1.35 m (Fig. 7). Analysis of the horizontal precision gave the RMS error for the FIXED mode ranging from ±0.05 meter for a leaf-off season to ±0.09 m for a leaf-on season and for the FLOAT mode from ±0.36 to ±0.48 m, respectively. The RMS error for elevation in the FIXED mode varied from 0.07 meter in a leaf-off season to 0.10 m for a leaf-on season and from 0.46 to 0.63 m for the FLOAT mode, respectively (Fig. 8).

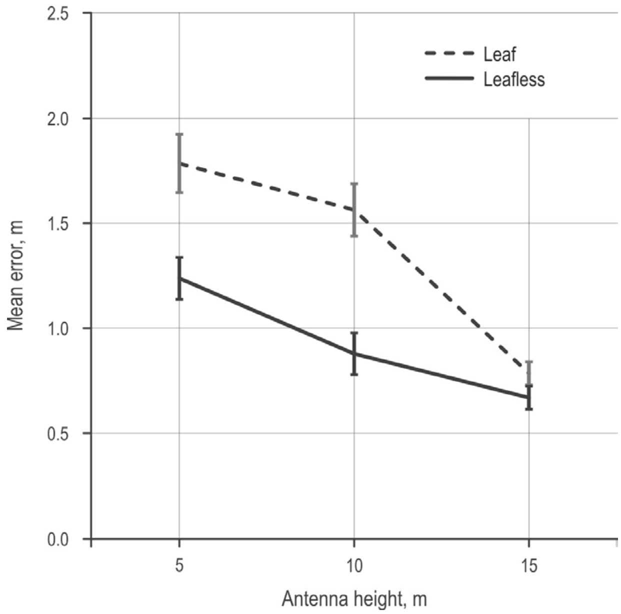

Fig. 10 Relationship between the mean error of the Z coordinate determination and antenna height for various seasons in the FLOAT mode

No significant relationships were found between the accuracy and DOP or canopy openness value. Measurements taken in the FIXED mode had very low variability. Taking into account these factors and the small number of FIXED observations (32%), it was decided to make statistical analysis for the FLOAT mode only.

The analysis showed that, for the FLOAT mode, both factors: antenna height and season (presence of leaves) significantly influence the measurement accuracy of XY coordinates (p=0.0000, Fig. 9). There is an interaction between the analyzed factors: the influence of the antenna height on the accuracy differs significantly for leaf-on and leaf-off seasons (p=0.0000). The ANOVA analysis for the height coordinate (Z) revealed that, in the FLOAT mode, the influence of both factors was also significant (p=0.0000, Fig. 10). The influence of the antenna height on the accuracy of Z-coordinate determination had the same characteristics in both analyzed seasons (p=0.126), i.e. there was no interaction between the two observed factors.

4. Discussion and conclusions

Increasing the height of the GNSS receiver antenna enables achieving significantly better horizontal and vertical positioning accuracy in the stands in both seasons (leaf-on and leaf-off). These conclusions correspond to other published research: by elevating the antenna one can expect the increased number of visible satellites (Næsset 2001, Arslan and Demirel 2008), decreased influence of foliage (Valbuena 2014) and faster activation of the receiver (Sigrist et al. 1999), hence, improved positioning accuracy (Yoshimura and Nakanishi 2005).

One of the main factors determining the accuracy and precision of coordinates is the measurement mode. The best results are expected in the FIXED mode supported by the DGNSS technique. In forest conditions, however, this mode may be uncertain in some situations (Næsset 2001), due to the relatively small number of FIXED observations. The conditions for collecting data in the stands are much worse than in open spaces, so the measurement mode of the receiver is random and does not depend on the observer. The leafless state of the forests has a good influence on the total accuracy because the number of FIXED measurements is higher, which was confirmed by Sigrist et al. (1999) amongst others. Taking into account the statement by Deckert and Bolstad (1996), that the number of fixes are very important for accurate measurements, we can assume the leaf-off season as the best time for taking measurements. It was also found that the number of observations in the FIXED mode is associated with canopy openness and the height of the measurement. This is because access to satellite signals becomes easier, hence the probability of making measurements in the FIXED mode increases and thus replaces the FLOAT mode. It is also worth mentioning that in some cases elevating the antenna does not necessarily lead to accuracy improvement. At 15 meters over ground the accuracy of the FIXED measurement is slightly decreased compared to lower antenna positions. This can be explained by the presence of the antenna in the zone of tree crowns, in the close proximity of leaves. This may cause an increased sensitivity of the receiver readings to the multipath especially in wet conditions, which was also noticed by Sigrist et al. (1999) and Valbuena et al. (2012). Thus, when taking measurements in forest conditions with an elevated antenna, it is necessary to pay attention to its location in relation to tree crowns, i.e. to take into account not only measures of stocking (wood volume, tree density, basal area), but also stand and tree characteristics, such as the dominant height, crown base height, crown length, density of foliage, etc.

Taking into account all the sample points in all the stands, the horizontal coordinates may be affected by an error of ±0.17 m in the FIXED mode and ±0.81 m in the FLOAT mode. In the case of elevation, these values were 0.14 m in the FIXED mode and 1.11 m in the FLOAT mode, respectively. Results similar to Næsset and Jonmeister (2002) and Sigrist (1999) were observed for DOP value, which has no effect on the accuracy. Very poor results in terms of measurements were obtained in the spruce stands. Data gathered in these conditions should be subject to further analysis, especially in mountainous conditions, where terrain shape is an important factor (Sigrist et al. 1999). The overall conclusion is that the use of an aluminum mast gave significant benefits in improving the accuracy of measurement in the FLOAT mode, which is the dominant part in the total number of measurements. This mode will actually be the main one used for taking measurements in forest conditions. In the FLOAT mode, the influence of multipath on the accuracy is almost nonexistent. Additionally, by extending the FLOAT observation time, it is possible to achieve accuracy similar to the FIXED mode in the forest conditions (Valbuena et al. 2010).

It is worth mentioning, however, that increasing the height of the antenna does not affect the accuracy of measurement proportionally. In some stands, the density of the crowns and the proximity of leaves can influence measurement errors because of a low signal visibility. The final results allow us to conclude that the use of masts with GNSS receivers is justified in all types of forests and can significantly increase the accuracy at altitudes of 10 m in the leaf-off season. It is important, however, to take into account the characteristics of trees and stands, and to avoid placing the antenna in the close proximity of tree crowns and leaves causing the decrease of the measurement accuracy.

Using higher masts brings an increase in operating costs as well as technical difficulties, e.g. the weight of the mast, problems with electrical power, the mast tilt, etc. and shows insignificant improvement in terms of accuracy, especially in the leaf-off season. That is why, in the forest conditions, the use of light and shorter telescopic poles is recommended. One possible option to help eliminate positional error is to use the HD-GNSS technology (Carter 2013) or RTK-Net positioning (Bakula et al. 2012). These methods are expensive, however, as well as time-consuming and therefore need further analysis. Thus, using aluminum masts or poles currently seems to be the most efficient and accurate method of data capturing in the forests.

The present technology cannot predict the GNSS accuracy with full confidence in the forest conditions (Valbuena et al. 2012) and the use of standard surveying methods as a source for real coordinates will still be needed for reliable accuracy assessment. The increasing access to new satellite navigation technologies, however, can limit terrestrial surveying (Valbuena et al. 2014).

Acknowledgements

This research was funded by the Polish Ministry of Science and Higher Education in the frame of the N N309 114137 project titled »Accuracy analysis of GNSS receiver in forestry environment«. Many thanks to PhD Janusz Walo for his invaluble support in the realization of this project. Special appreciation and thanks to Natalia and Dariusz Górscy for their help in field work and data analysis.

5. References

Arslan N., Demirel H., 2008: The impact of temporal ionospheric gradients in Northern Europe on relative GPS positioning. J Atmos Sol-Terr Phy 70: 1382–1400.

Andersen H.E., Clarkin T., Witerberger K., Strunk J., 2009: An accuracy assessment of positions obtained using survey-grade global positioning system receivers across a range of forest conditions within the Tanana Valley of Interior Alaska. West J Appl For 24: 128–133.

Bach, M., Breuer, L., Frede, H. G., Huisman, J. A., Otte, A., Waldhardt, R., 2006: Accuracy and congruency of three different digital land-use maps. Landscape Urban Plan 78: 289–299.

Bakula, M., Pelc-Mieczkowska, R., Walawski, M., 2012: Reliable and redundant RTK positioning for applications in hard observational conditions. Artif satellites 47(1): 23–33.

Carter, R. A., 2013: Exploring the dimensions of digital solutions in mine mapping. Eng min j 214(1): 40–41.

Cellmer, S., Wielgosz, P., Rzepecka, Z., 2010: Modified ambiguity function approach for GPS carrier phase positioning. J of Geodesy 84(4): 267–275.

Cole, J. A., 2004: Global Positioning System Accuracy Under Varying Forest Canopy Conditions. College of Environmental Science and Forestry State University of New York.

Deckert, C., Bolstad, P.V., 1996: Forest canopy, terrain and distance effects on global positioning system point accuracy. Photogramm Eng Rem S 62: 317–321.

Duncan, S., Stewart, T.I., Oliver, M., Mavoa, S., MacRae, D., Badland, H.M., Duncan, M.J., 2013: Portable Global Positioning System Receivers. Am J Prev Med 442 :19–29.

Hasegawa, H., Yoshimura, T., 2007: Estimation of GPS positional accuracy under different forest conditions using signal interruption probability. J For Res 12: 1–7.

Jonckheere, I., Nackaerts, K., Muys, B., Coppin, P., 2005: Assessment of automatic gap fraction estimation of forests from digital hemispherical photography. Agr Forest Meteorol 132: 96–114.

Landau, H., Vollath, U., Chen, X., 2002: Virtual reference station systems. J Global Position Syst 1(2): 137–143.

Lewis, J. S., Rachlow, J. L., Garton, E. O., Vierling, L. A., 2007: Effects of habitat on GPS collar performance: using data screening to reduce location error. J of App Eco 44: 63–671.

Mauro, F., Valbuena, R., Manzanera, J. A., Garcı´a-Abril, A., 2010: Influence of Global Navigation Satellite System errors in positioning inventory plots for tree height distribution studies. Can J of For Res 41: 11–23.

Næsset, E., 1999: Point accuracy of combined pseudorange and carrier phase differential GPS under forest canopy. Can J of For Res 29: 547–553.

Næsset, E., Bjerke, T., Øvstedal, O., Ryan, L.H., 2000: Contributions of differential GPS and GLONASS observations to point accuracy under forest canopies. Photogramm Eng Rem S 66: 403– 407.

Næsset, E., 2001: Effects of differential single- and dualfrequency GPS and GLONASS observations on point accuracy under forest canopies. Photogramm Eng Rem S 67: 1021–1026.

Næsset, E., Jonmeister, T., 2002: Assessing point accuracy of DGPS under forest canopy before data acquisition, in the field and after postprocessing. Scand. J. For. Res. 17: 351–358.

Ordóñez Galán, C., Rodríguez-Pérez, J. R., Martínez Torres, J., García Nieto, P. J., 2011: Analysis of the influence of forest environments on the accuracy of GPS measurements by using genetic algorithms. Math Comput Model 54: 1829–1834.

Oruba, A., Leończyk, M., Ryczywolski, M., Wajda, S., 2009: ASG-EUPOS after year. Geodeta 4(167): 10–14.

Pirti, A., Gümüs, K., Erkaya, H., Ramazan, G. H., 2010: Evaluating Repeatability of RTK GPS/GLONASS Near/Under Forest Environment. Croatian Journal of Forest Engineering 31(1): 23–33.

Puente, I., González-Jorge, H., Martínez-Sánchez, J., Arias, P., 2013: Review of mobile mapping and surveying technologies. Measurement 46: 2127–2145.

Puettmann, K. J., Coates, K. D., Messier, C., 2009: A Critique of Silviculture: Managing for Complexity. Island Press Washington-Covelo-London.

Rodriguez-Perez, J. R., Alvarez, M. F., Sanz, E., Gavela, A., 2006: Comparison of GPS Receiver Accuracy and Precision in Forest Environments. Practical Recommendations Regarding Methods and Receiver Selection. Shaping the Changes, XXIII FIG Congress, Munich, Germany.

Sawaguchi, I., Nishida, K., Shishiuchi, M., Tatsukawa, S., 2003: Positioning precision and sampling number of DGPS under forest canopies. J For Res 8: 133–137.

Sawaguchi, I., Saitoh, Y., Tatsukawa, S., 2005: A study of the effects of stems and canopies on the signal to noise ratio of GPS signals. J For Res 10: 395–401.

Sigrist P., Coppin P., Hermy M., 1999: Impact of forest canopy on quality and accuracy of GPS measurements. Int J Remote Sens 20, 3595–3610.

Teunissen, P. J. G., Verhagen, S., 2008: GNSS Ambiguity Resolution: When and How to Fix or not to Fix? VI Hotine-Marussi Symposium on Theoretical and Computational Geodesy International Association of Geodesy Symposia 132: 143–148.

Valbuena, R., Mauro, F., Rodríguez-Solano, R., Manzanera. J.A., 2010: Accuracy and precision of GPS receivers under forest canopies in a mountainous environment. S. J. Agr. Res. 8(4): 1047–1057.

Valbuena, R., Mauro, F., Rodríguez-Solano, R., Manzanera. J.A., 2012: Partial Least Squares for Discriminating Variance Components in Global Navigation Satellite Systems Accuracy Obtained Under Scots Pine Canopies. Forest Science 582: 139–153.

Valbuena, R., 2014: Integrating ALS with other data sources: field GNSS and optical imagery. In: Maltamo M., Naesset E. & Vauhkonen J. (Eds.) Forestry applications of LIDAR remote sensing. Managing Forest Ecosystems Vol 27. Springer. ISBN 978-94-017-8662-1

Wing, M. G., 2009: Consumer-Grade Global Positioning System Performance in an Urban Forest Setting. J of For 209(107): 307–312.

Wing, M. G., Frank, J., 2011: Vertical measurement accuracy and reliability of mapping-grade GPS receivers. Comput Electro Agr 78:188–194.

Yoshimura, T., Hasegawa, H., 2003: Comparing the precision and accuracy of GPS positioning in forested areas. J For Res 8(3): 147–152.

Yoshimura, T., Nakanishi, A., 2005: Accuracy enhancement of GPS positioning antenna height. Asian Conference on Remote Sensing proceedings. Kyoto University.

Received: October 01, 2013
Accepted: April 10, 2014

Authors' address:

Michał Brach, PhD.*
e-mail: michal.brach@wl.sggw.pl
Department of Forest Management
Geomatics and Forest Economics
POLAND

Michał Zasada PhD.
e-mail: michal.zasada@wl.sggw.pl,
Laboratory of Dendrometry and Forest Productivity
Faculty of Forestry
Warsaw University of Life Sciences – SGGW
159 Nowoursynowska str.
02-776 Warszawa
POLAND

* Corresponding author