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Impacts of forest spatial structure on variation of the multipath phenomenon of navigation satellite signals

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Abstract

The GNSS (Global Navigation Satellite System) receivers are commonly used in forest management in order to determine objects coordinates, area or length assessment and many other tasks which need accurate positioning. Unfortunately, the forest structure strongly limits access to satellite signals, which makes the positioning accuracy much weak comparing to the open areas. The main reason for this issue is the multipath phenomenon of satellite signal. It causes radio waves reflections from surrounding obstacles so the signal do not reach directly to the GNSS receiver's antenna. Around 50% of error in GNSS positioning in the forest is because of multipath effect. In this research study, an attempt was made to quantify the forest stand features that may influence the multipath variability. The ground truth data was collected in six Forest Districts located in different part of Poland. The total amount of data was processed for over 2,700 study inventory plots with performed GNSS measurements. On every plot over 25 forest metrics were calculated and over 25 minutes of raw GNSS observations (1500 epochs) were captured. The main goal of this study was to find the way of multipath quantification and search the relationship between multipath variability and forest structure. It was reported that forest stand merchantable volume is the most important factor which influence the multipath phenomenon. Even though the similar geodetic class GNSS receivers were used it was observed significant difference of multipath values in similar conditions.

Key words

GNSS, multipath, random forest, Borut, forest structure, LiDAR

Introduction

The availability of satellite navigation has become a permanent fact of life and exercises a practical impact on the effective functioning of many aspects of the economy (Closas et al. 2009). The concept of the linear intersection technique introduced in the 1960s – realized through a measurement of distances from a minimum of four satellites (Teng et al. 2016) – has undergone continual improvement. The Global Positioning System

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(GPS – the original name NAVSTAR-GPS) launched by the United States Department of Defense provided the foundations for the dynamic development of such technology by other countries. The best example of this is the Russian GLONASS (GLObalnaja NAvigatsionnaja Sputnikovaja Sistema) that reached full operational capacity in 2011 (Kaartinen et al. 2015). Although it is significantly weaker than the US American system (Blum et al. 2016), it meaningfully complements it by increasing the possibilities for precise positioning in places of limited accessibility to a satellite signal (Al-Shaery et al. 2013). The existence of two independent navigation systems enabled the creation of GNSS (Global Navigation Satellite System) devices, characterized by receivers capable of registering signals from more than one system. Dynamic development of the technologies and the economic growth of developing countries have caused GNSS to undergo a major transformation in recent years. The Chinese system BeiDou-2 and the European system Galileo (26 satellites on the space in December 2018 were reported on European Space Agency web page) will soon achieve operational capacity, which in practice translates into access to over 70 satellites today and roughly 120 within the next few years (Li et al. 2015). The benefits for potential users are clear and will be manifested primarily through an increase in accuracy and stability of positioning, as well as through a reduction in registration time and an increase in the distances allowable between a receiver and reference stations (Paziewski and Wielgosz 2014). This means that researchers and engineers face significant new challenges related to improving receivers and further developing navigation systems.

GNSS has eliminated traditional navigation and become an everyday practice in surveying, as well as in fields connected with the monitoring of environmental resources. The system's abilities have also been noted in forestry, because of its high capacity and simplicity in the effective collection of spatial data (Liu et al. 2017). The precise measurement of a forest is one of the key elements in accurately estimating forest resources (Liu et al. 2016). GNSS technology fits perfectly with the concept of precision forestry that requires detailed measurement of a forest and whose effects are seen in the accurate estimation of forest resources (Holopainen et al. 2014). The ability to use navigational devices has become a necessity and is one of the criteria for evaluating prospective employees applying for jobs in organizations performing forest management (Bettinger and Merry 2018). The basic tasks executed with this method still include the measuring of lengths and areas, which in practice is achieved by use of the simplest consumer-grade receivers. Problems relating to the precision of the receivers deployed and the selection of appropriate measuring techniques remain open and require further study (Unger et al. 2013). The increased need for spatial data causes navigational receivers to be used for ever more varied tasks with varying levels of expected accuracy, in areas such as fire prevention, forest utilization, forest conservation, spraying, and boundary determination (Pirti 2016). The popularization of laser scanning technologies has made it possible to obtain forest descriptions of previously unmatched detail like vegetation height, crown cover, amount of trees, biomass and general stand structure (Luo et al. 2017; Stereńczak et al. 2017; Kamińska et al. 2018; Szostak et al. 2018), which has opened new possibilities for precision forest utilization (Stereńczak and Moskalik 2015; Erfanifard et al. 2018; Mielcarek et al. 2018). In this context, accuracy of positioning becomes key, because it impacts the functioning of systems used for estimating the mass of harvested timber (Frank and Wing 2014), and GNSS receivers are deployed in the steering of forestry machines and in semiautomated tree-felling (Holden et al. 2001). Unfortunately, a satellite signal traveling a distance of ca. 20,000 kilometers undergoes multiple deformations, and the forest environment (Closas et al. 2009) and even cosmic weather (Hapgood 2017) can constitute obstacles that prevent any measurement altogether. In spite of continuous technological development and the millimeter precision achieved by GNSS receivers, it is only possible to eliminate a portion of the factors degrading the signal, including clock biases, ephemeris errors, and ionospheric and tropospheric delay (Suski 2012). In practice, the surrounding forest structure (of which a forest is an especially structurally complex type) offers decidedly more factors that may affect triangulation. Rain and the elevated humidity accumulated amidst trees weakens access to satellite signals, which results in a decreased number of visible satellites and worsening of the constellation defined by a rise in the PDOP (Position Dilution of Precision) coefficient and the need for a different configuration of the GNSS receiver (Frank and

Wing 2014). The concealing of the sky by nearby plants and trees is a key factor (Weaver et al. 2015). The presence of trees can also impact the precision of positioning by affecting the state of foliage (Dogan et al. 2014; Ucar et al. 2014), temperature, cloud cover (Danskin et al. 2009b), and the occurrence of forest roads or aspect which cause number of satellite limitation (Zimbelman and Keefe 2018). The complexity of forest spatial structures, combined with a continuously growing need for accurate positioning, provides the justification for further – and more detailed – research into the problem of the functioning of satellite navigation in forest environments. Contributors to GNSS positing errors have been identified in the number of trees, their diameter at breast height (Sigrist et al. 1999; Kaartinen et al. 2015), and the biomass and volume of trees, which have a direct influence on increasing signal noise and changing the polarization of the carrier wave (Liu et al. 2016). Wright (2018) has proposed the index of absorption of the navigational signal by the tree stand. Liang et al. (2014) was unable to obtain a centimeter precision even when using a modern terrestrial laser scanner equipped with an advanced IMU (Inertial Measurement Unit) module and performing differential correction. One of the best method to improve accuracy in the forest base on differential correction technique which can be realized in real time on in post-processing mode. The research conducted by Szostak and Wężyk (2013) suggest differential correction and extended epochs acquisition usage in forest condition. The results have showed the twofold increase of positioning accuracy however the limitation of Internet coverage in the forest is one of the key problem of this method.

Multipath satellite signal phenomenon

A prevailing majority of similar studies have focused on discovering the spatial characteristics of forest stands that affect the final accuracy of GNSS positioning. In fact, about 50% of the error results from a phenomenon of the satellite signal reflection, which is referred in literature to as the “multipath effect” (Akbulut et al. 2017) and causes deviations that can exceed 100 meters (Giremus et al. 2007). The main factor impacting the variation in the signal’s reflection is the immediate surroundings of the GNSS receiver, which is particularly significant in a forest environment (Cheng et al. 2016a), as well in the vicinity of pools of water, mountains, or buildings (Titouni et al. 2017) or, more generally, of any smooth surfaces (Strode and Groves 2016). In order to analyze the essence of the multipath phenomenon (MP) in forest environment, it is first necessary to distinguish the part of the GNSS signal that reaches the receiver antenna directly, from that reaches it as reflected off of surrounding objects. A partial loss of satellite signal in the forest is also often explained by the Lambert-Beer law which, in its basic form, describes the absorption of light by an absorbing medium (Wright et al. 2017). The reflected signal has lower power and is delayed, the amplitude of the carrier wave is diminished, the angle of its arrival at the receiver is reduced, and it has an altered polarization (Pirsiavash et al. 2017). The factors described primarily have an effect on interference in the correct correlation of code and phase between the GNSS receiver and the GNSS satellite, thereby introducing significant errors in the measurement of distance between them (Groves et al. 2013). Since the geometry of satellites repeats with the cycle of the sidereal day, the value of reflection at the same measurement point and given the same observation conditions should be the same, with a systemic error of up to a few seconds (Wang et al. 2018a). Determination of the value of reflection of signals MP1 and MP2 is possible through a combination of code and phase observation for frequencies L1 (GPS: 1575.42 MHz, GLONASS: 1602 MHz) and L2 (GPS: 1227.60 MHz, GLONASS: 1246 MHz) emitted independently by the GPS and GLONASS systems, which can be described by the following formula (Bakula et al. 2015):

$$MP1 \equiv P_1 - \left(1 + \frac{2}{\propto -1}\right) L1 + \left(\frac{2}{\propto -1}\right) L2 =$$

$$= M_1 + B_1 - \left(1 + \frac{2}{\propto -1}\right) m_1 + \left(\frac{2}{\propto -1}\right) m_2$$

$$MP2 \equiv P_2 - \left(\frac{2\alpha}{\propto -1}\right) L1 + \left(\frac{2\alpha}{\propto -1} - 1\right) L2 =$$

$$= M_2 + B_2 - \left(\frac{2\alpha}{\propto -1}\right) m_1 + \left(\frac{2\alpha}{\propto -1} - 1\right) m_2$$

where:

$$B_1 \equiv -\left(1 + \frac{2}{\propto -1}\right) n_1 \lambda_1 + \left(\frac{2}{\propto -1}\right) n_2 \lambda_2$$

$$B_2 \equiv -\left(\frac{2\alpha}{\propto -1}\right) n_1 \lambda_1 + \left(\frac{2\alpha}{\propto -1} - 1\right) n_2 \lambda_2$$

$$\alpha \equiv \frac{f_1^2}{f_2^2}$$

f_1 – frequency L_1 for GPS or GLONASS satellites,
f_2 – frequency L_2 for GPS or GLONASS satellites,
$n_i \lambda_i$ – full value of uncertainty for a phase cycle at frequency *i*,
P_i – pseudo-distances for frequency *i*,
Li – wavelength for frequency *i*,
M_i – multipath value for code measurement at frequency *i*,
m_i – multipath value for phase measurement at frequency *i*.

The values of MP1 and MP2 have a sinusoidal character (Fig. 1) and depend on the satellites' location in the sky and on the observational smoothing model implemented in the receiver, which typically remains a secret of the manufacturer (Irsigler 2010). Knowledge about MP variability allows for a partial elimination of receiver and satellite clock errors and compensation for tropospheric and ionospheric delay (Hilla and Cline 2004). The multipath phenomenon has, for many years, been a subject of numerous studies whose main goal was the greatest possible elimination of the occurrence of oscillations (Weill 2003; Ragheb et al. 2007; Ziedan 2011; Rabaoui et al. 2012; Jgouta and Nsiri 2015). Proposed solutions find practical applications in new GNSS receivers, in both the structure of their electronics and construction of their antennas (Danskin et al. 2009a; Cheng et al. 2016b). Despite that fact, there is still no effective method for solving the problem of multipath GNSS navigational signals in the forest environment (Wang et al. 2018b).

This study evaluates the impact of selected elements of the forest environment on modeling the MP1 and MP2 values. Forest stand characteristics are relatively simple to determine in the field and on the basis of data given in forest appraisal descriptions. On that basis, it is possible to estimate the conditions for satellite signal observation in a given forest unit.

Object of study

GNSS signals were recorded in 2015 in the forest districts of Milicz, Pieńsk, Gorlice and Supraśl. In 2016 in the district of Herby and the sub-district Katrynka. Only the Gorlice forest district was of mountainous character (minimum elevation 300 meters, maximum elevation 830 meters above sea level), the others possess local elevations that do not have a significant impact on the canopy or forest management. The resources of a decided majority of objects are based on a coniferous

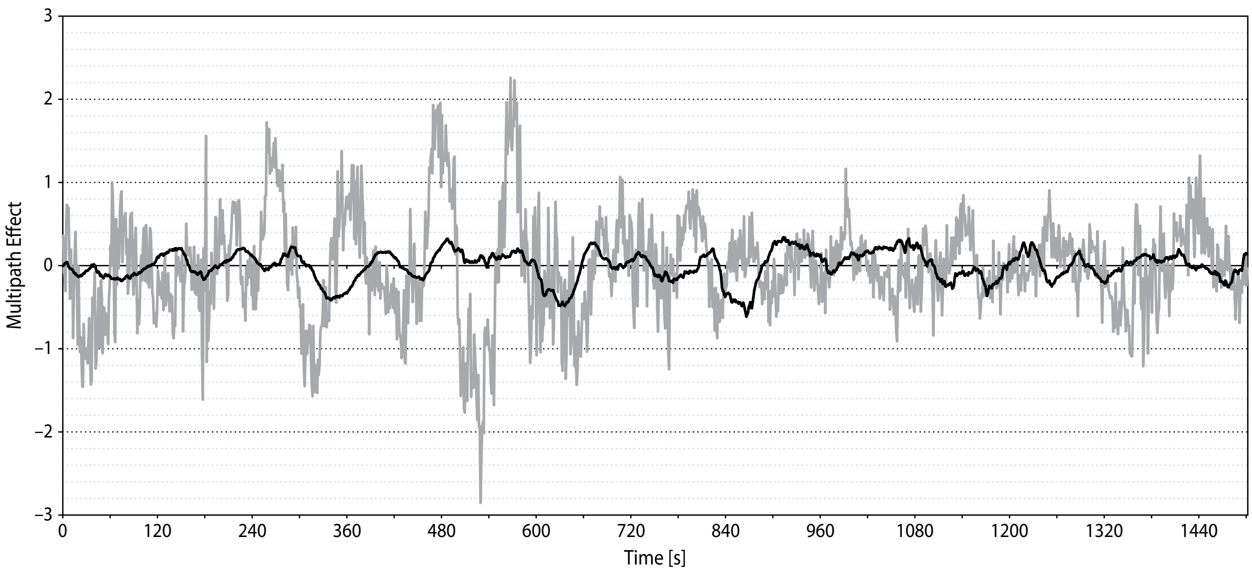

Figure 1. Juxtaposition of multipath values in an open area (black line) and on a study plot (grey line)

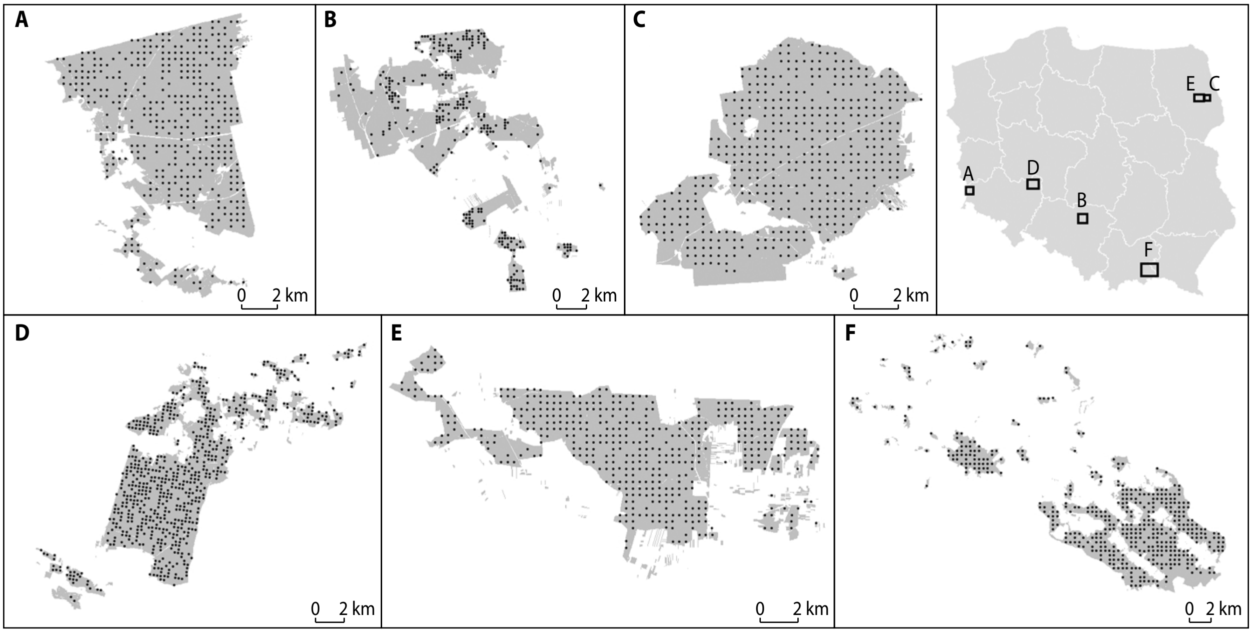

Figure 2. Location of objects of study (A – Pieńsk, B – Herby, C – Supraśl, D – Milicz, E – Katrynka, F – Gorlice) and of study plots

tree stand with prevalence of Scots pine (70%). A dominant share of broadleaf species occurs in the Pieńsk forest district located in the western part of Poland and in Gorlice, where nearly 45% of the stand area was covered by beech. Due to a diversity in aggregation of forest objects, study plots were located in areas of between 10,000 and 40,000 hectares. In total, 2,704 points were used for investigation of the GNSS signal multipath effect ongoing under the canopy (Fig. 2).

For each survey GNSS point, a forest stand inventory was carried out to a diameter of 12.62 m, which encompassed an area of 500 square meter. The inventory included, among other things, determination of tree species, age, height of trees with diameter at breast height (DBH) bigger than 0.07 meter, DBH, and situation of the trunk with regard to the center of the plot and with regard to the center of the crown, for trees leaning more than 10 degrees. These inventory data were used to determine a number of tree stand characteristics (Tab. 1). Tree stand resources per object were determined with regressive methods based on data from ALS (Airborne Laser Scanning) point clouds and field measurements done at the study circle plots. Based on the digital terrain model (DTM) obtained from the ALS data, the mean degrees slope and aspect (8 classes) were indicated (Tab. 1).

Study method

Four different models of dual-frequency GNSS surveyor-class receivers were used for registering raw data in the RINEX (Receiver Independent Exchange System) format (Gurtner and Estey 2007). These were the Trimble R8 GNSS (used no May to November 2015 and March to July 2016), Stonex S9 (used on May to December 2015 and on April to June 2016), Topcon HiperPro (used on November 2015) and Leica Viva GS08plus (used on august to November 2015). The antennas were mounted on a mast with a variable length of 2.5 to 5 m, depending on the technical abilities of the measuring team. Twenty-five minutes (1,500 epochs) of observations were recorded at each observation point with the elevation cutoff set to 10 degrees, which slightly exceeds norms used for open areas (Hofmann-Wellenhof et al. 2008) and is standard for forest areas (Hasegawa and Yoshimura 2003). Selected authors claim that a navigational receiver reaches its maximum precision after about 10–15 minutes of operation

Table 1. List of canopy characteristics gathered in study plots

Characteristic	Description of characteristic
tree.account	Number of trees in circular plot
h.max	Maximum tree height in circular plot
h.mean	Mean height calculated from all tree heights in circular plot
h.100	Maximum height in circular plot
h.mean.t	Mean height weighted by the breast height cross-sectional trunk area
h.100.t	Maximum height weighted by the breast height cross-sectional trunk area
w1.tree.account	Number of trees in the first canopy layer
w1.h.max	Maximum tree height in the first layer in circular plot area
w1.h.mean	Mean height of the first layer
w1.h.100	Maximum height of the first layer
w1.h.mean.t	Mean height of the first layer weighted by the breast height cross-sectional trunk area
w1.h.100.t	Maximum height of the first layer weighted by the breast height cross-sectional trunk area
v.bul	Reference tree stand resource from BULiGL measurements
v.lidar	Tree stand resource global model for each object
main.species	Main species attributed to each division
prec.main.species	Share of main species
age.main.species	Age of main species
class.age	20 year age class; 6 indicates sixth class or higher
species.typ	Canopy type based on main species: coniferous/broadleaf
species.typ.2	Species group calculated on the basis of the share of main species PURE CONIFEROUS share of dominant coniferous species ≥ 7% PURE BROADLEAF share of dominant broadleaf species ≥ 7% MIXED CONIFEROUS share of dominant coniferous species < 7% MIXED BROADLEAF share of dominant broadleaf species < 7%
prec.conif	Share of coniferous species based on LMN from divisions
structure	Structure attributed from LMN
slope	Mean terrain slope
aspect	Mean terrain aspect
aspect.class	Aspect with a division into 8 directional classes: 1 (337.5°–22.5°), 2 (22.5°–67.5°), 3 (67.5°–112.5°), 4 (112.5°–157.5°), 5 (157.5°–202.5°), 6 (202.5°–247.5°), 7 (247.5°–292.5°), 8 (292.5°–337.5°)

(Bastos and Hasegawa 2013; McGaughey et al. 2017). In practice, the time used for forest inventory the plots was much longer, which allowed authors for gathering surplus data and was compatible with the assertion that any additional time for the registration of signals increases the accuracy of static positioning (Bettinger and Merry 2012). Raw observation data were subjected to a post-processing differential correction process based on reference data obtained from the three nearest base stations of the ASG-EUPOS network (Bosy et al. 2007). This allowed the calculation of coordinates indicating the center of the inventory plot and estimation of the precision of measurement described by the standard deviation value for the north axis (std.n), east axis (std.e), shift vector (std.hz), and height (std.n). Calculations were performed with the Magnet Tools (Topcon Inc. 2013) software, which also allows determination of basic satellite signal observation parameters (Tab.2). The

Table 2. List of navigational characteristics obtained by processing raw satellite data in the Magnet Tools program

Characteristic	Description of characteristic
x	X axis
y	Y axis
z	Height
std.n	X precision
std.e	Y precision
std.hz	HZ shift vector
std.z	Height precision
time	Measurement time
g.sat	Number of GPS satellites
r.sat	Number of GLONASS satellites
pdop	Dimensionless coefficient of three-dimensional Position Dilution of Precision
hdop	Dimensionless coefficient of Horizontal Dilution of Precision
vdop	Dimensionless coefficient of Vertical Dilution of Precision
antenna.H	Height of antenna mounting
receiver	Model of GNSS navigational receiver
month	Month of measurement
District	Object of study

set of data was divided into leaf-off and leaf-on periods on the basis of photographic documentation of the sky.

Reflection of the satellite signal expressed by the MP1 and MP2 values was obtained with the TEQC software (Estey and Meertens 1999), which provides advanced processing of RINEX files. The GPS satellites in RINEX files are recognized with G abbreviation and GLONASS with R respectively. Multipath statistics were determined in two groups:

1. for all satellite signals recorded on a study plot with division into MP1, MP2, and GPS and GLONASS systems,
2. satellite signals received from the single satellite characterized by the longest continuous observation time, with division into MP1 and MP2.

The statistics for both groups were calculated with the R program (R Core Team 2013). Additionally, the percentage share of registered signals (prec.positive.sig) obtained from all satellites with relation to the signals blocked by the specific forest environment (Tab. 3) was calculated.

In order to compare the impacts of different parameters of the forest complex environment on the digital value capturing the GNSS signal's multipath phenomenon, the Borut algorithm was used (Kursa and Rudnicki 2010, 2015). This algorithm, based on the random forests (RF) model (Breiman et al. 1999), creates a ranking of analyzed independent variables arranged with regard

Table 3. List of statistics for the multipath satellite signal effect

Characteristics group	Characteristic	Description of characteristic
All satellite signals	mean.12.g, median.12.g, max.12.g, min.12.g, std.12.g	Mean, median, maximum, minimum, and standard deviation for MP1 multipath effect for the GPS system
	mean.12.r, median.12.r, max.12.r, min.12.r, std.12.r	Mean, median, maximum, minimum, and standard deviation for MP1 multipath effect for the GLONASS system
	mean.21.g, median.21.g, max.21.g, min.21.g, std.21.g	Mean, median, maximum, minimum, and standard deviation for MP2 multipath effect for the GPS system
	mean.21.r, median.21.r, max.21.r, min.21.r, std.21.r	Mean, median, maximum, minimum, and standard deviation for MP2 multipath effect for the GLONASS system
	prec.positive.sig.12, prec.positive.sig.21	Percentage share of signals registered at the point in relation to signals blocked by the forest environment for MP1 and MP2 values
Satellite signals for single satellite	mean.sat.12, median.sat.12, max.sat.12, min.sat.12, std.sat.12	Mean, median, maximum, minimum, and standard deviation for MP1 multipath effect
	mean.sat.21, median.sat.21, max.sat.21, min.sat.21, std.sat.21	Mean, median, maximum, minimum, and standard deviation for MP2 multipath effect

to their capacity for explaining the indicated dependent variable. Results from the calculations make it possible to determine the Importance of a given characteristic that represents the number of selections of the given independent variable by particular decision trees generated by the RF algorithm (Strobl et al. 2007). This algorithm allows comparison of variables of differing characters (quantitative and qualitative), as well as indicating variables that do not have an impact on the value of the dependent variable. Independent variables are divided into three main categories: significant (marked in green in Fig. 3), uncertain (yellow), and insignificant (red) (Rai 2017). In the case of each analysis conducted, the algorithm delivered results after 10,000 iterations, unless it unequivocally attributed all uncertain variables to the significant or insignificant category earlier. In addition, the RF model (Liaw et al. 2018) was used for estimating the percentage share of variation of the numerical value for the multipath phenomenon that is explicable with information gathered in the studied independent variables.

Results

A set of scripts written in the R language was created as part of the study. They allow fast processing of data obtained from the TEQC program created for the interpretation of RINEX files. These scripts facilitated the rapid processing of over 30,000 text files of a total volume exceeding 5GB. The possibility of calculating basic statistics for MP1 and MP2 values for all satellites registered on each study plot and for the single satellite signal characterized by the longest registration time is the main result of this procedure. Separate visual interpretations of the results of the multipath value for the GPS or GLONASS satellites are an additional element (Fig. 4). Due to the standard formats of RINEX files and results of the TEQC program's operation, the scripts developed can be successfully used for further studies in the open environment of the R program.

The amount of leaves and needles in tree crowns has key significance for interpreting the results of the

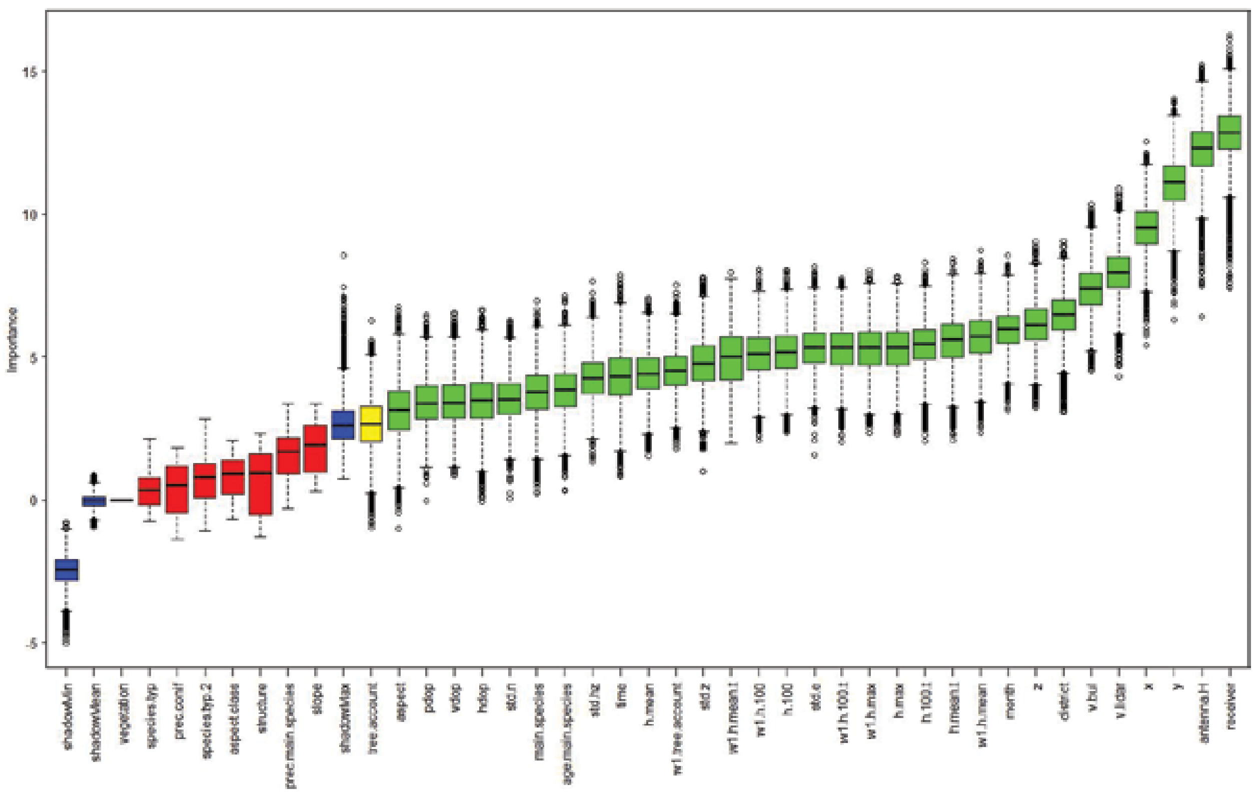

Figure 3. Example of a result of application of the Borut algorithm with signals from one satellite and MP2 multipath values that characterizes the Importance of independent variables in leaf-off season

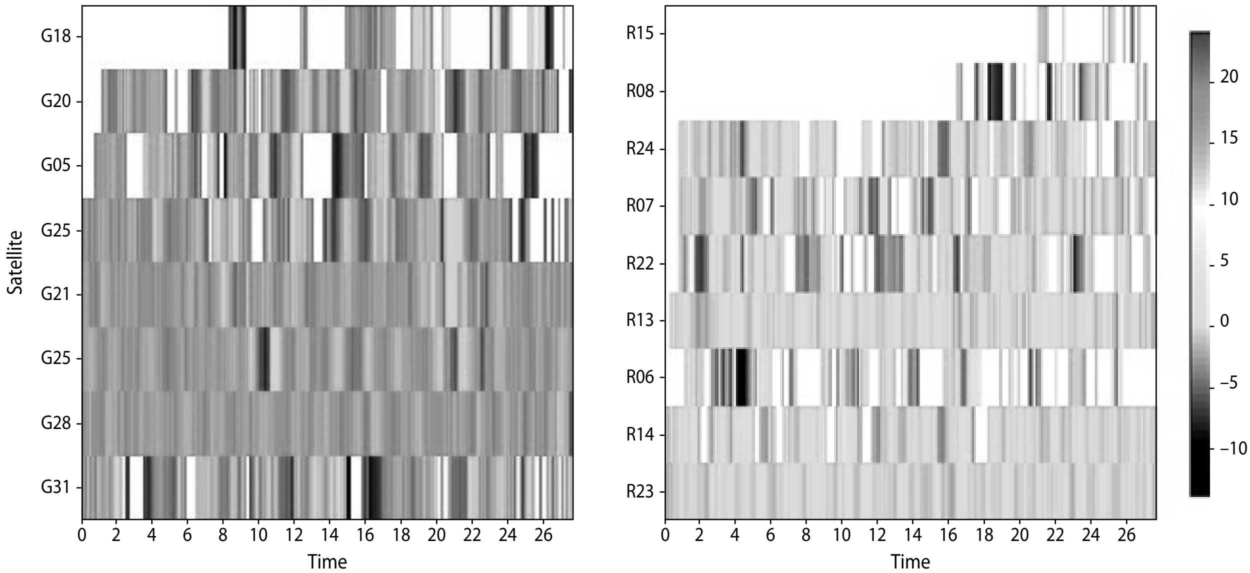

Figure 4. Example of results of the functioning of the script written in R to interpret the signal's multipath effect for the first frequency (L1) for the GPS (left) and GLONASS (right) systems

Table 4. Comparison of the percentage share of variation explaining the multipath phenomenon for selected statistics registered by all available satellites

Wave	L1			L2					
System	GPS	GLONASS	GNSS	GPS	GLONASS				GNSS
Characteristic	median. 12.g	std. 12.r	prec.positive. sig.12	min. 21.g	min. 21.r	max 21.r	mean. 21.r	std. 21.r	prec.positive. sig.21
Leaf-off	31.5	28.06	69.11	14.79	37.98	35.92	28.57	59.34	68.95
Leaf-on	18.74	41.13	48.62	38.03	8.29	10.71	2.14	30.52	48.46

multipath effect, because it determines the strength and number of signals registered by receiver the antenna. This phenomenon can be expressed more simply by the amount of light reaching the forest floor, it allows a better understanding of the complexity of the canopy structure (Olpenda et al. 2018). On this basis, the obtained results have been analyzed in two groups with regard to the state of the leaf cover (leaf-on and leaf-off). Multipath oscillations are demonstrated quite well by the sets of readings registered in open areas and under canopy (Fig. 1). Both mean as well as minimum and maximum values are multiple times greater in cases where the receiver is surrounded by numerous obstacles. It is also noticeable that multipath variation is significantly less dynamic in cases of a lack of cover.

Based on the obtained percentage share of variation that explains the studied characteristics, those statistics from Table 3 were selected whose value exceeded 20 for at least one of the vegetation periods (Tab. 4 and 5).

Table 5. Comparison of the percentage share of variation explaining the multipath phenomenon for selected statistics registered by a single satellite

Wave	L1			L2		
System	GNSS					
Characteristic	min. sat. 12	max. sat. 12	std.sat. 12	min. sat. 21	max. sat. 21	std.sat. 21
Leaf-off	6.29	2.82	19.35	19.19	8.89	13.67
Leaf-on	26.66	27.21	33.2	24.24	26.56	32.47

In the case of the initially selected 22 statistics for all satellites, the percentage share of variation allowed elimination of 13 characteristics that indicated very weak correlation. A greater number of characteristics available for detailed analyses occurs at the L2 frequency and for the GLONASS system. The leaf-off season is difficult to characterize, if all registered satellites are taken into account. The opposite is observed in all cases when only one satellite registering data continuously through over 97% of the operating time on the study plot is taken into account. Selected characteristics in this case display an average share of variation of ca. 30% distributed evenly between frequency L1 and L2. In all analyzed cases, the GLONASS system's standard deviation displays decidedly better results for both frequencies. The total capacity for registering signals is higher in the leaf-off season by ca. 20% in comparison to the height of the vegetation period.

The results of the Borut algorithm enabled identification of the independent variables that can impact the selected 15 statistical characteristics. The independent variables were classified into two thematic groups delineating tree stand characteristics (Tab. 1) and navigational characteristics (Tab. 2). The presented results take into account these characteristics, which were not registered for a maximum of two of the multipath effect statistics. The remaining characteristics occurred significantly less frequently or were not selected by the algorithm at all. For the leaf-off season, a total of 12 tree stand characteristics and 12 navigational characteristics were selected (Tab. 6), and for the leaf-on season 16 and 14, respectively (Tab. 7). For both types of vegetation seasons, tree volume and maximum height (h100) are characterized by a high value of importance. In the case of navigational characteristics, independent variables such as the antenna height (antenna.h) and model of navigational receiver (receiver) are significant. In comparison to other statistics, the standard deviation of the GLONASS system for both frequencies is characterized by higher capacities for explaining variation through independent variables. The values of Importance of one analyzed satellite and of all observed signals span similar levels for the analyzed statistics. Only in the case of the leaf-on season and navigational characteristics was a doubly high value of Importance observed for all satellite signals in comparison to the data from a single satellite. The highest values of Importance (29) were observed in the case of the type of navigational receiver (receiver) for statistics defining the percentage share of signals registered in the leaf-off season. In the case of this statistic, a strong correlation with time occurs for all vegetation states of the tree stand. A strong correlation was noted between the percentage share of the number of registered signals (prec.positive.sig) and the time of operation of a receiver (time). These values of Importance are at the level of 23 for the leaf-off season and 24 for the height of vegetation season.

Among characteristics related to terrain relief, a small impact was noted for the hill slope. The variation in standard deviation for L1 and L2 is almost half as great for the object located in the Gorlice District, where mean slopes are three times larger than at other objects of study (Fig. 5).

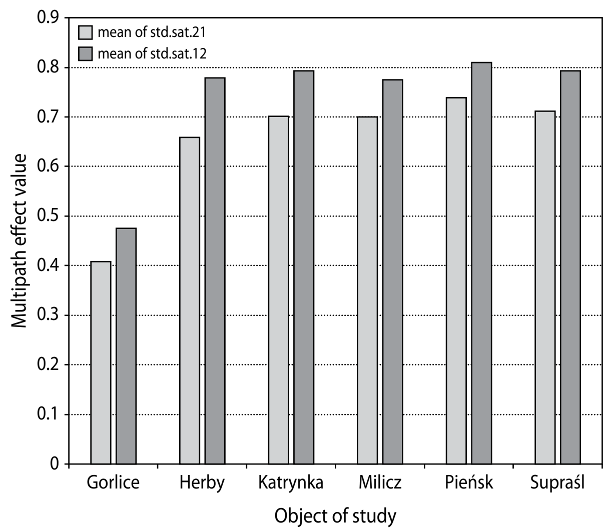

Figure 5. Values of standard deviation for a single satellite and L1 and L2 frequencies with respect to the object of study

The impact of the tree stand on the maximum values of the multipath signal effect is presented for six dominant species whose prevalence within the tree population of the study plots was the biggest. Broadleaf species maintain a reflection index of 14 during the leaf-off season, regardless of the navigational system or studied frequency, while during the height of the vegetation season these values are twice as high and exceed 30. Birch canopies are particularly worth mentioning, as they create conditions for a strong multipath signal effect, which is manifested in their maximum values (94) and the highest (over 7) standard deviation (Fig. 6 and Tab. 8).

The vegetation season does not play a significant role for coniferous canopies, although a slightly higher index was recorded for fir. Mean MP1 and MP2 values are lower by half for the GLONASS system in all cases (Fig. 6).

The temporal distribution for operation of the GNSS receivers used in the study was diverse. About 65% of measurements were carried out in the leaf-on season, except in the case of the Topcon receiver, which was only used in winter. Apart from the Leica model, receivers registered lower multipath signal values during the leaf-off season. The smallest range of standard deviation was observed for the Trimble receiver, while the greatest differences for L1 and L2 frequencies were observed for the Leica and Stonex receiver models (Fig. 7).

Table 6. List of the correlation of Importance values between selected statistics for the multipath effect and selected tree stand and navigational characteristics in the leaf-off season

	median.12.g	std.12.r	prec.positive.sig.12	min.21.g	min.21.r	max21.r	mean.21.r	std.21.r	prec.positive.sig.21	min.sat.12	max.sat.12	std.sat.12	min.sat.21	max.sat.21	std.sat.21	
	All satellites									One Satellite						
h.max	6.3	6.6	5	3.5	5.8	6.2	4.9	4.9	5	5.1	6	4.9	5.4	6.3	5.6	Tree stand characteristics
h.100	7.4	6.4	5	3.7	5.5	5.9	4.6	5.8	5	6.4	6	6.9	5.2	5.8	6.1	
h.mean.t	5.9	7.1	5	3.6	5.9	6.8	5	6.2	5	5.8	6.1	6.2	5.7	6.7	6.9	
h.100.t	7.2	6.9	5.1	3.4	5.5	5.9	4.6	5.6	5	6	5.9	6.4	5.5	5.4	6.5	
w1.tree.account	4.8	5.1	3.5	2.4	4.3	6	5.2	4.8	3.7	7	7	5	4.6	6.8	2.6	
w1.h.max	6.3	6.3	5	3.5	5.8	6.2	4.9	5	5	5.2	6	4.9	5.4	6.4	5.7	
w1.h.mean	5.5	8.7	5.8	3.8	5.8	6.5	5.4	6.4	5.4	6.5	6.1	6.1	5.8	7.2	7.1	
w1.h.100	7.5	6	5.1	3.3	6	6	4.4	6	5.1	5.6	5.1	5.8	5.1	5.9	5.5	
w1.h.mean.t	5.8	7.2	5.3	3.6	5.4	6.4		6	5.3	5.3	6.6	5.3	5	6.5	6.4	
w1.h.100.t	7.4	5.9	5.2	3	6	6.1	4.3	6	5.1	5.4	5.1	5.5	5.4	5.6	5.4	
v.bul	5.4	8.5	6	5	6.3	7	4.5	7.9	6	12	11	10	7.5	11	11	
v.lidar	6.2	9.9	6.9	5.6	6.2	7.2	4.4	7.2	6.8	12	11	11	8	10	10	
x	11	9.4	17	5.1	13	14	12	14	18	4.3	5.2	7	9.5	6.6	7.2	Navigational characteristics
y	15	8.1	21	4.3	14	15	11	16	21	6.8	5.8	8.8	11	8	8.3	
z	7	8.2	11	6.4	8.5	9.4	7	11	11		4	4.4	6.2	3	2.6	
std.n	4.8	12	7.5	2.9	6.7	6.1	4.2	9.6	7.1		3.6	5.1	3.6	3.5	6.2	
std.e	5.1	11	7	2.6	4.6	4.5	3.5	7	6.9	3.5	3.9	7.5	5.3	4.6	9.1	
std.hz	5.1	11	7.2	2.9	6	5.8	3.9	8.6	7	2.4	3.2	6.4	4.2	4.3	7.7	
std.z	4.5	10	5.6	3.3	7	6.5	4	8.5	5.5		3.3	4.4	4.8	5	7.1	
time	6.5	4	23	4	3	4	7.5	6.8	23	6.6		2.8	4.3	7.8	2.8	
pdop	4	6.5	8		5.2	4.1	3.8	6.1	8	2.9	3.8	4.5	3.3	4	2.8	
antenna.h	16	13	25	7.5	18	17	9.5	21	25	4.3	3	12	13	4.2	6.6	
receiver	23	3.2	29	5.9	21	21	22	26	29			8.7	13	3.8	5.1	
district	9	5.4	12	5.4	9.7	9.5	5.5	10	12		3.1	3.4	6.5		2.2	

Table 7. List of the correlation of Importance values between selected statistics for multipath effect and selected canopy and navigational statistics in the leaf-on season

	median.12.g	std.12r	prec.positive.sig.12	min.21.g	min.21.r	max21.r	mean.21.r	std.21r	prec.positive.sig.21	min.sat.12	max.sat.12	std.sat.12	max.sat.21	min.sat.21	std.sat.21	
	All satellites									One satellite						
tree.account	3	3	6.2	5.7	6.8	5.7	2.6	5.2	6.2	5.5	8.4	6.3	7.4	7.3	5.7	Tree stand characteristics
h.max	6.7	7.1	7.2	4.5	7.3	5.9	6.2	7.4	7.3	4.4	5.9	5	5.5	6.9	5.9	
h.mean	4.8	9.1	8	5.9	11	8.9	7.2	14	7.6	5.8	7.6	8.7	9.4	9.9	10	
h.100	7.8	7.1	6.8	5	7.4	7.4	6.4	10	7	5	6.3	7	6.4	8.4	7.1	
h.mean.t	7.6	6.2	7.9	4.9	8.2	8.5	6	10	7.5	5.2	7.5	6.5	6.5	8.5	7.8	
h.100.t	7	6.9	6.5	5.2	7.9	7.9	6.1	9.2	6.6	4.5	5.9	6.1	5.7	8	6.7	
w1.tree.account	5.6	7.2	7	7.8	7.8	6.8	4.8	6.4	7.2	6.4	6.5	7.8	9.9	10	6	
w1.h.max	6.8	7.4	7.3	4.5	7.4	6	6.3	7.3	7.4	4.5	6	5.1	5.5	7	6.2	
w1.h.mean	7.3	7.5	7.5	5	7.5	8.4	7	10	7.5	5.3	7.1	7.2	7	8	7.4	
w1.h.100	7.8	6.8	6.6	6.9	6.6	7.5	6.9	9.4	6.7	4.9	6.7	7	6.6	8.2	7.2	
w1.h.mean.t	7.4	5.3	7	5.1	7.2	7.4	6.8	8.9	7	4.8	6.4	6.4	6	7.7	6.5	
w1.h.100.t	7.4	7	6.7	6.4	6.8	6.8	6.5	8.9	6.9	4.6	6.2	6.5	5.8	7.5	6.9	
v.bul	7	9.6	12	6.2	9.4	6.5	5.5	11	12	7.9	9.7	12	11	13	13	
v.lidar	9	14	14	6	12	7.9	6.3	14	13	8	8.8	12	11	13	12	
age.main. species	6.2	8	5.2	4.4	4.7	3.6	3.3	4	5.2	5.7	3.5	4	9	10	7.7	
slope	8.2	10	9	11	5.3	4	6.4	6.5	7.9	7	9	7.9	6.4	9.5	5.6	
x	14	20	13	13	8.3	6.1	8.5	14	13	12	13	15	16	11	15	Navigational characteristics
y	14	13	13	8.9	8.3	8.8	11	15	12	6	8	8.5	7.5	6.8	7.6	
z	12	18	9.8	12	7.7	5.7	11	11	9.7	12	13	14	15	12	14	
std.n	6.7	8.4	9		5.4	5.6	7.5	7.4	9.2	5.1	5.2	5.9	3.8	3.7	4	
std.e	4.6	9	10	4	5.2	5.9	6.7	7.4	10	4	3.2	3.8	4.6	4.9	5.5	
std.hz	6.2	9.5	10		6	5	7.1	7.8	10	5	5.1	5.2	4.4	4.8	5.2	
std.z	7.4	9.4	9		5.3	5.8	8.2	11	9	4.3	4.1	7	5.9	7.8	11	
time	8.9	6.6	24		6.7	7.9	6.1	11	24		6.7	4	8.6	4.3	6.6	
pdop	5.9	6.1	15	5.8	7	5.1	5.9	7.6	15	6.2	7.6	8.7	8.1	5	5.2	
hdop	6	8.4	19	7.1	7.6	5.4	5.4	9.8	18	6.5	7.7	9.5	8.6	6.7	8.8	
vdop	6	5.4	14	4.8	6.5	4.7	6	7.6	13	6.7	8.1	9	8	5.5	5	
antenna.h	13	15	13	8.4	8.6	6.8	8.3	10	13	9.5	9.8	10	9.6	9	9.8	
receiver	12	14	11	11	4	4	6	8.1	11	9	11	11	11	9.7	11	
district	10	15	10	11	8.2	6.4	6.2	9.9	10	9.7	12	11	11	9.8	12	

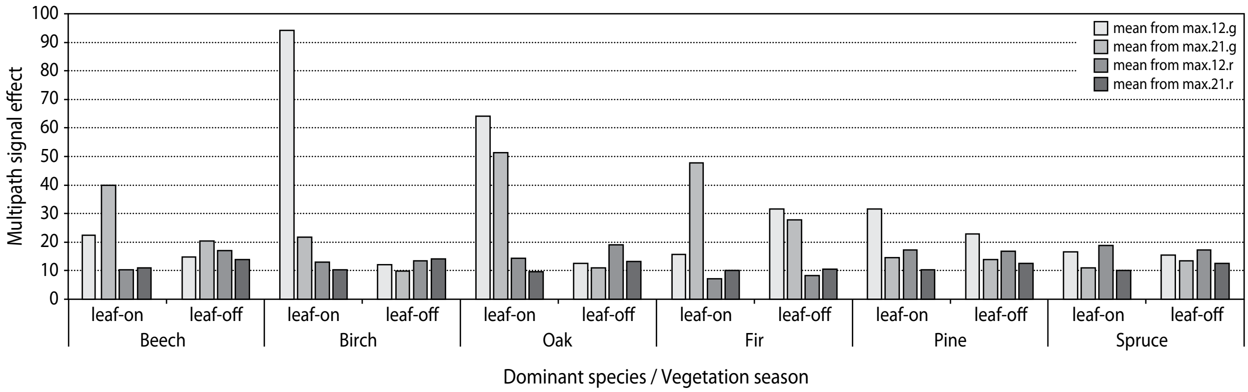

Figure 6. Comparison of maximum MP1 and MP2 values for GPS (g) and GLONASS (r) systems with regard to dominant species and vegetation season

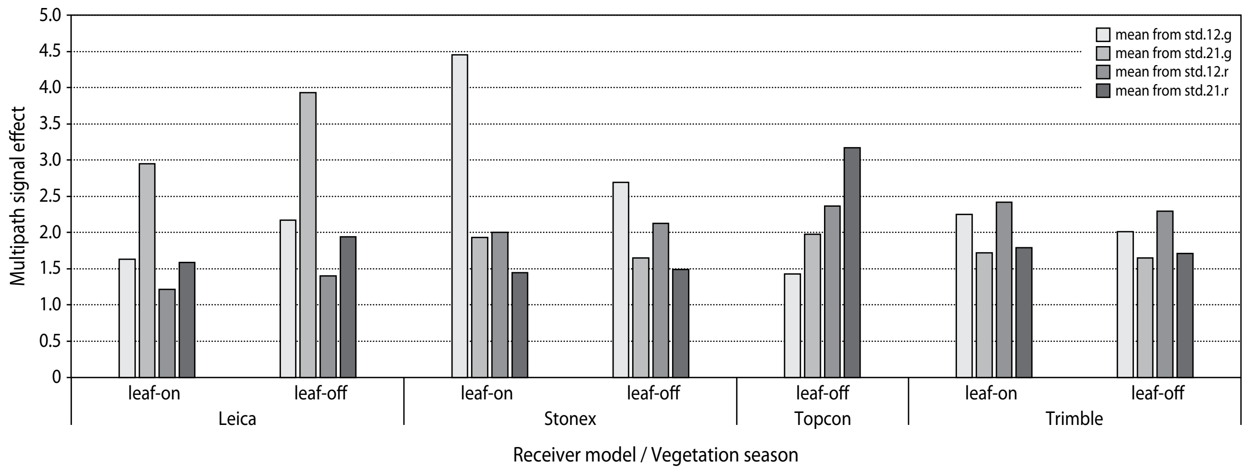

Figure 7. Comparison of maximum MP1 and MP2 values for GPS (g) and GLONASS (r) systems with regard to dominant species and GNSS receiver model

Discussion

The data presented in this text within the framework of the REMBIOFOR project titled "Remote Sensing Determination of Timber Biomass and Coal Resource in Forests" constitute an especially valuable set for analyses of the variation of satellite signals in forest environments. First of all, it is based on a significant number of plots (2,704), for which a large (around 1,500 epochs) collection of raw satellite data was made. It is a unique pool, as in most cases navigational measurements carried out in the forest are realized within short time intervals, and available correction methods are applied in real time or in post-processing. In the case of this project, use of a data-collection time reaching 25 minutes is congruent with standards for the registration of satellite signals (Hofmann-Wellenhof et al. 2008), which allowed appropriate post-processing and the gathering of surplus measurement data describing characteristics of carrier waves.

An initial analysis of the multipath signal effect drawing on the basic statistics and graphs obtained with the application of R scripts made it possible to conclude that the variation in this phenomenon is large and difficult to interpret. Although this variation is characterized by a certain cyclical temporal nature, the number of cycles and their value is quite variable and hard to predict. This state of affairs is a result not only of the forest en-

Table 8. Comparison of standard deviation of the multipath effect with regard to dominant species and vegetation season

		L1 Frequency		L2 Frequency	
		GPS System	GLONASS System	GPS System	GLONASS System
season	Species	std.12.g	std.12.r	std.21.g	std.21.r
leaf-off	Beech	1.61	2.39	2.13	2.05
	Birch	1.45	1.96	1.46	2.01
	Oak	1.56	2.50	1.52	2.13
	Fir	2.76	1.35	2.82	1.68
	Pine	2.31	2.24	1.76	1.93
	Spruce	1.84	2.28	1.64	1.72
leaf-on	Beech	1.98	1.44	2.96	1.65
	Birch	7.32	1.84	1.87	1.49
	Oak	4.84	1.89	4.21	1.52
	Fir	1.53	1.22	3.07	1.64
	Pine	3.07	2.16	1.73	1.61
	Spruce	1.86	2.13	1.48	1.64

vironment but also of the navigational receiver utilized, the leaf state, and the height of mounting of the antenna. Moreover, the dynamics of the satellite segment itself, which is in constant motion, makes it impossible to presume constant and unchangeable conditions. It seems, therefore, that the decision to seek correlations for the main statistics like minimum, maximum, and mean values or standard deviation is a correct one, because the multipath index constantly oscillates around a median equal to 0. Results obtained from the RF algorithm allowed a final determination of statistics that can be evaluated for their influence on the satellite signal. In most cases, the mean and median values do not significantly characterize the multipath satellite signal phenomenon. The case is different for minimum and maximum values and standard deviation. These characteristics have a smaller impact on the phenomenon during the leaf-on vegetation season, which is a logical consequence of the strong impact of the leaves on increasing the signal's multipath effect. This state of affairs is also reflected in the differences in the number of factors and their values between the leaf-on and leaf-off season (Tab. 6 and 7). It is much more difficult to find strong correlations between a chosen statistic and independent characteristics at the height of the vegetation season than in winter. The multipath effect is characterized by a greater variation, hence there are more characteristics that can explain it, but their Importance value is lower. The choice of one satellite whose signal is registered throughout the entire measurement process allows an easier demonstration of tree stand characteristics that may influence the multipath effect. It can be explained by the more frequent occurrence of breaks in the signal from satellites located closer to the horizon and by the necessity of a time-consuming re-initiation of acquisition. Interruptions in the recording of MP1 and MP2 values have a negative impact on the measures that represent them. Despite the large ranges of values, the Borut algorithm provided a way of distinguishing these tree stand characteristics that can contribute to an increase in the multipath signal phenomenon. Both in the leaf-off season and at the height of the vegetation season, these are the mean height of the first-layer trees (w1.h.mean) and tree stand merchantable volume (v.lidar and v. bul). It is, however, worth mentioning that the correlation for the volume is slightly weaker in the leaf-off season. This is a valuable conclusion, because by possessing knowledge about the dominant species and tree stand volume, one is able to partially reduce positioning errors through appropriate planning of the date of measurement and its location. It is clear that it is not the number of trees that determines signal refraction but their height and stand merchantable volume, which is consistent with the findings of other authors (Kaartinen et al. 2015; Liu et al. 2017). One of the main undertakings of this study was to determine these characteristics of tree stands that can strongly affect the multipath effect and that are relatively easy to determine directly in the field. While tree height can be presumed to be readily apparent, determining volume requires much experience. It is a variable that encompasses many tree stand characteristics, such as the number of trees, their height, crown diameter, and the tree species itself (Miścicki and Stereńczak 2013; Fassnacht et al. 2018). Taking into account the accessibility of this value in forest appraisal reports, it is possible to identify objects where the multipath signal effect will be higher. Among selected navigational characteristics, the impact of the model of receiver used and the height of the antenna are particularly notable. The impact of the height is a well-known factor documented in studies of the precision and accuracy of navigational receivers and is consistent with the results obtained by other scholars (Brach and Zasada 2014; Frank and Wing 2014). Information about the variation caused by models of GNSS receiver of the same class is, however, scarce. This means that when conducting research into the accuracy of a navigational receiver, it is worth carrying out an initial analysis of the multipath signal value, as it determines the final results of the research.

Even with the significant share of Scots pine tree stands (70%) in the study, taking the vegetation season into account is still justified. In over half the objects of study, stands comprised a main species with admixtures of other species at the level of 30%. Among broadleaf stands, the birch – as the species with the most flexible structure with a high number of leaves – has the greatest impact on the multipath signal phenomenon. In spite of the high LAIs (Leaf Area Index) for oak and beech (Gower et al. 1999; Le Dantec et al. 2000), their maximum values are lower, which provides a basis for obtaining better positioning results. The vegetation season does not significantly affect the MP1 and MP2 values during the period of study for coniferous canopies. Nevertheless, fir canopies obtain visibly worse results, which relates to the greater spatial density and build of the needles of that species (Robakowski et al. 2004). This causes greater obstruction of satellite signals.

Interestingly, significantly lower multipath signal effect values were recorded on areas with a high slope. The reasons for this can be found in the smaller number of satellites registered by the receiver. This especially concerns satellites with a low elevation, which are those that by rule generate the highest signal reflection. Moreover, the structure of the forest itself is, from the point of view of its three-dimensional space registered by the antenna, less complicated in a situation where a larger portion is filled with terrain and not sky.

The obtained results confirm the extraordinarily complex and hard-to-interpret specificity of the satellite signal multipath effect. In spite of significant study material, it is difficult to find strong correlations, which is due to the complexity of the study plots' structure. In practice, each of the areas, regardless of whether or not it has the same appraised features, is characterized by an entirely different state of spatial complexity. Adding to that the variations in the geometry of the satellite system, weather conditions, and the receiver model creates a matrix of variables that is very difficult to analyze. With all certainty, it has been confirmed that the multipath effect is partially explicable by tree stand volume, which is a characteristic defined in managed forests. It has also been confirmed that the elevation of the antenna at its maximum height, in combination with extended measurement time, is a factor that can significantly improve positioning quality. Enabling registration in the GNSS receiver during the work of inventorying study plots ensures the obtaining of at least 1500 epochs of raw observation data, which at a further stage can help achieve qualitatively better results.

Conclusions

– Increase of tree stand merchantable volume contributes to increase in carrier wave reflection and a decreased capacity for registering satellite signals.
– Selecting the model of GNSS receiver is one of the significant factors that impacts the accuracy of positioning.
– Forest stands with fir and birch during leaf season present difficulties for carrying out navigational measurements, but samples for both species were purely represented, thats why this conclusion should be future studied.
– Reducing the number of satellites on low horizontal elevation by increasing the height of the antenna or blocking access to a part of the sky improves the general quality of the data obtained.

– Taking into account knowledge about multipath phenomenon it possible to compensate for potential positioning errors by appropriately selecting the vegetation season and tree stand characteristics.

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