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Forest delineation based on LiDAR data and vertical accuracy of the terrain model in forest and non-forest area

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Abstract. This paper deals with the use of airborne laser scanning data (ALS) in the process of the automatic delineation of forest and the generation of digital terrain models (DTM) in forested and non-forested areas. The study area where the procedures presented were examined is part of the University Forest Enterprise, Technical University in Zvolen (48° 37' N, 19° 04' E). A partial modification of existing solutions that iteratively takes into account the criteria of minimum area, height, width and crown coverage is presented within the forest delineation. At the same time this approach also evaluates the mutual distance of identified crowns and the presence of buildings. Compared with manually identified forest boundaries, the accuracy of the automated procedure in the study area reached the value of 93%. In the DTM generation, various alternative methods of interpolation and conversion were used, while ALS data from the summer and winter seasons were also available. The results showed that laser scanning in the area of interest provided systematically overestimated data for the DTM generation. The largest deviations of the DTM were found in terrains based on ALS data from the summer season, with a significant slope, regardless of the complexity of the afforestation structure (except for the youngest forest). In older stands and unforested areas, both with a moderate slope, the DTM accuracy achieved was in the range ±6-17 cm.
Keywords forestry, forest boundary, remote sensing, geoinformatics.

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Introduction

Stratification of the land on forest and non-forest area has a broader meaning. Firstly, it is source of primary information for geopolitical activity in the sector of water and agriculture management, environmental protection, and urban development. Simultaneously, such information also constitutes national reports about forest cover, carbon stocks, forest health, and so on. Secondly, it is a source of primary data for other more specific geo-applications.

For these reasons it is important that accurate and mutually comparable determination of forest location and size is ascertained. The information provided nevertheless often contains errors, resulting from two major reasons. The first "methodical" reason is the global and often also the national inconsistencies in forest definition. At present there are clearly defined criteria that implicitly define what can be considered forest from the assessment of forest vegetation cover: minimum height, width, area, crown coverage "CC" (FAO 2007) and based on land use: agriculture, forestry and other land use (FAO 1993). However, these criteria are not obligatory by law and are not used universally. The result is then a situation where there are about 800 national definitions of forest (Lund 2012). The second "technical" reason is linked to the direct realization of forest delineation. Traditionally, this process is performed manually on the basis of field measurements or on the basis of remote sensing data, and this is considerably subjective mainly in stands with unclear borders of forest.

Workflows based on automated identification of forest boundaries represent a potential solution of technical shortcomings in traditional methods of forest delineation. There are also suggestions of automated approaches based solely on data from remote sensing (e.g. Leckie et al. 2003, Radoux & Defourny 2007, Leppänen et al. 2008, Wang et al. 2011, Eysn et al. 2010, 2011). These suggestions more or less objectify the process of forest delineation, because they eliminate the subjective approach of an operator, who traditionally performs this workflow.

From the Remote Sensing methods, the technology of airborne laser scanning (ALS) is currently a highly efficient source of geospatial data suitable for this process. This method works on the principle of sending and receiving laser pulses, while simultaneously recording the position and inclination of the carrying device, the direction of the pulse and the duration of the emission. Individual pulses are transmitted at high frequency and with specific beam footprint size. From the single pulse thus more returns can be produced, which in turn allow the objects that partially overlap to be recorded. This capability is very significant because it is also possible to record objects, for example, under forest vegetation (Hyyppä et al. 2000). The primary laser scanning data are points which create a so-called „point cloud". After processing, these points can be filtered and classified into point classes: ground, buildings, vegetation or other objects (Chen et al. 2007). Processed and classified points can be used for the generation of the final digital terrain model (DTM) or digital surface model (DSM) in a regular or irregular data structure. This process is carried out mainly through interpolation and extrapolation techniques, while the method used must be chosen with respect to the source data.

A digital terrain model is one possible representation of relief, which describes the Earth without objects located on its surface. An important factor in a representative utilization is its accuracy, and thus how the values of the attributes in the DTM differ from reality. The accuracy of the DTM generated from ALS data depends on many factors. Skaloud & Schaer (2012) aggregated them into groups, which include: characteristics of the obtained point cloud (distribution of the points in space, the density of points on the area), method of classification of the point cloud into points representing the terrain and interpolation method of the classified terrain points into the terrain model. The impact of each has been examined in detail by several authors. They concluded that the vertical accuracy characterized by the root mean square error reaches values of ±10 - 20 cm, while the error increases in the data from the summer season, acquired from higher elevations and mainly in areas with a significant slope (Akkay & Sessions 2005, 2008, Hyyppä et al. 2005, Gomes Pereira & Goncalves 2010, Cibulka & Mikita 2011, Divín 2011).

The primary objective of this study is to present and evaluate the proposal of our own solution of forest delineation. The basis of the procedure is an algorithm that uses laser scanning data to perform automated forest boundary identification. For this purpose the basic criteria defining forest are iteratively evaluated (minimum area, height, width, crown coverage). It also simultaneously evaluates the mutual distance of trees and the presence of buildings in the area. The procedure is examined in the study area. Part of the paper includes an evaluation of possibilities and shortcomings of this workflow, which result from its direct application.

A secondary objective of the study is evaluation of vertical accuracy of terrain models derived from ALS data (leaf on/off) in so-defined areas (forest/non-forest). The differences in terrain models created on the basis of ALS and measured data are evaluated. At the same time there is evaluation of the differences in terrain models generated only on the basis of ALS data but from the winter (leaf-off) and also the summer (leaf-on) season. The study thus offers an overview of the attainable accuracy of such achieved terrain models, which is affected by various quality of ALS data and various geomorphological and biological conditions.

Materials and methods

Study area

The research activities were realized in the University Forest Enterprise, Technical University in Zvolen, which serves for the purpose of scientific research and practical examples for teaching technical subjects at the Technical University in Zvolen (48° 37' N, 19° 04' E). The main part of the landbase, is situated in the mountain orographic unit of the Kremnické and Štiavnické Mountains, through which the Hron River flows. The dominating exposures are south, east and south-west. The lowest point above mean sea level is at Jelná (280 m amsl) and the highest is the Lavrín peak (1,150 m amsl). Phytogeographically, the area of interest belongs to the district of Slovenské Stredohorie and two sub-districts: Kremnické Mountains and Poľana (left side of the Hron River). The southern parts of the valley are characterized by thermophile species, while the north slopes and ridges have typical mountain species. The territory consists of following forest vegetation zones: oak, beech and oak, beech, fir-beech and spruce-fir-beech. The area of managed forest area is 9,964 ha, of which 9,090 ha are in state ownership.

ALS data

The ALS data was acquired at two different time points, using identical technology. The periods were chosen in order to capture the study area, when the trees are leafed (summer season, leaf-on) and when they are not (winter season, leaf-off); the area was not covered with snow. Detailed characteristics of the acquisition of ALS data are shown in Table 1.

Reference data

To assess the possibility of forest boundaries identification based on the ALS data, in the study area was selected a continuous reference

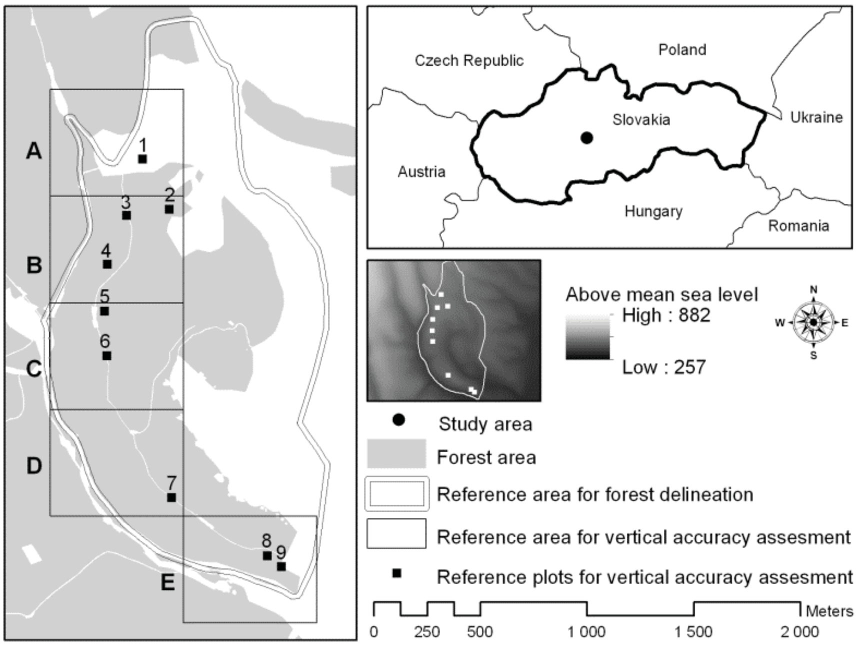

Figure 1 Study area

Table 1 Scanning characteristics

Scanning period I	15.-16.09.2011
Point density (point class "ground")	1.7 point/m^2
Scanning period II	16.4.2012
Point density (point class "ground")	2.5 point/m^2
Scanning device	Riegl LMS-Q680i
Carrying device	Cessna 206G
Average flying height (m)	700
FOV (DEG)	50
PRR (kHz)	320
Returns per beam	1 - 7

Note. FOV – field of view, PRR – laser pulse frequency.

territory with an area of 236 ha (Fig. 1). An important factor within the selection of this territory was the presence of a variety of forest stand edges and gaps (artificially and naturally created with a continuous or discontinuous edge), as well as the presence of structures (buildings). This ensured a wide range of possible alternatives to mark out the boundary of the forest.

For the purpose of vertical accuracy assessment, in the study area were allocated 5 reference areas (A-E) and 9 reference plots (1-9) in order to capture different morphological and biological conditions (Fig. 1). The basic attribute that defined the geomorphological conditions was the average slope of the terrain and its variability. Biological conditions were defined by the presence of forest vegetation, the forest developmental stage, the vertical structure of stands, and the composition of tree species. The reference areas, which were used in the analysis of the differences between the terrain models created in the summer season and the models created in the winter season, together covered an area of 156 ha, which means a 312,490 m^2/reference area (DTM leaf-on vs. DTM leaf-off). Reference plots were used in the analysis of the differences between the terrain models created in the winter and summer seasons with field data (DTM leaf-on/off vs. ground data). Particular reference plots were defined so as to represent terrains with moderate or strong slopes, both uniform and non-uniform. At the same time, between them were represented terrains with and without forest vegetation. In case of forested plots, stands were purposely chosen with a specific tree species composition (dominant coniferous trees, dominant deciduous trees, approximately equal representation of coniferous and deciduous trees) and with complex vertical structure (multi-layer stands). The sizes of the plots were defined by the number of registered points measured within the field surveying during the year 2012, so that each plot consisted of at least 50 points with an approximately 5 metre grid (59 to 161 points/RP). Then 802 points from all the nine reference plots were measured by the method of polar coordinates using a total station Topcon GPT 9003M. Calculation of heights was carried out using the trigonometric method, as a result of which a realistic achievement of accuracies of ±1 cm was set. The ground survey consisted of one traverse, which follows the forest road. Traverse originated at reference points that had been established using survey-grade GNSS (global navigation satellite system). After adjustment of the traverse, its height enclosure reached a value of 0.01 m. The points of the traverse fulfilled the criterion of the 3rd accuracy class of geodetic points determination (mxy = 0.06 m), based on the technical standard nr. 730415 valid in Slovakia. An overview of the differential characteristics of the individual reference plots is presented in Table 2.

Forest delineation

In this study a forested area was defined as an area greater than 0.3 ha and does not contain gaps smaller than 300 m^2, width greater than 20 m, height greater than 2 m and crown coverage "CC" (the percentage of the forest area covered by vertically projected tree crowns) more than 20%. Criteria selection was based on a combination of methodologies by Schoene et al. (2007) and NFI SR 2005-2006 (Šmelko et al. 2008, Moravčík et al. 2010). In order to take into account all these criteria, it was necessary to create several data integrity outputs, with the combinations of applications ArcGIS Desktop 10.1 (ESRI), Terrascan (Terrasolid Ltd.), OPALS (TU Wien, I. P. F.) and LiS Desktop 2.1.0 (Laserdata GmbH).

The process of automatic forest delineation

Table 2 Characteristics of the reference plots

RP	Slope (%)		Vegetation					RP	Slope (%)		Vegetation				
	$\bar{x}$	s_x	Species	Sp.c	Age	d_s	St.d		$\bar{x}$	s_x	Species	Sp.c	Age	d_s	St.d
RP1	6.84	24	-	-	-	-	-	RP6	6.29	22	SP	80	100	48	0.9
RP2	6.39	32	SP	61	80	47	0.8				BE	10	80	40	
			FR	6	80	40					OK	10	50	28	
			HB	9	80	21		RP7	9.04	48	OK	10	20	20	0.8
			OK	24	80	28					PN	10	60	34	
RP3	15.89	25	BE	30	80	38	0.8				SP	5	60	32	
			SP	30	80	40					HB	75	20	15	
			FR	10	40	18		RP8	20.75	45	LR	90	40	25	0.9
			OK	30	30	30					HB	5	10	12	
RP4	9.63	24	BE	100	10	0	-				OK	5	15	16	
RP5	6.83	37	BE	100	0	0	-	RP9	31.25	28	PN	100	60	28	0.6

Note. RP – reference plot, $\bar{x}$ – arithmetic mean, s_x – standard deviation, Sp.c – species composition, d_s – mean thickness, St.d – stem density, $RP_{i=1...9}$ – reference plot number, BE – beech, OK – oak, HB – hornbeam, SP – spruce, FR – fir, PN – pine, LR – larch.

was derived from the workflow described by Eysn et al. (2012) with partial modifications. The basis of this workflow is the correctly made classification and filtering of the point cloud into point classes "ground" and "vegetation", which subsequently serve for the generation of the digital terrain model (DTM) and the surface model (DSM). Then the normalized digital surface model (nDSM) is created from these models using the map algebra tools. A so-called "vegetation mask" is created, which is a raster layer where each cell contains an attribute of measured height and represents only identified vegetation. Consequently, it is possible to apply restrictive criteria defining the forest on this data output, and thus reduce the "vegetation mask" to the so-called "forest mask". Criteria for minimum area, width and height are applied. The criterion of minimum CC requires the creation of specific geoinformatic workflows, since it is necessary to identify individual tree crowns and determine their area. The proposed algorithm works on the principle of finding the local maxima in the "vegetation mask", and the estimation of the crown area is made based on the empirical function. Then tree triples of the nearest identified crowns are created using the Delaunnay triangulation and the coverage for each of them is calculated as a proportion of the surface area of the crowns and their convex hull.

The original workflow was partially modified in this study. The first modification was the identification of the tree crowns needed to determine the criteria for coverage. For our study empirical functions were not used, but only the evaluation of local maxima, where were grouped local maximas less than 20 cm difference in the analyzed radius. Next, similarly as in the original workflow, triads of the nearest identified crowns were created. Then their areas were computed and also their mutual distance was evaluated. Then, if the maximum distance is 2 times greater than the minimum distance, the trio of trees does not enter into the calculation of coverage. This was done to prevent from calculating of coverage between the trees that are on one side closest to each other, but at the same time they are spaced at more than twice their shortest distance. Otherwise, the area of crown coverage and also the area between the trio trees is calculated, which is given by the line around the perimeter of their crowns (convex hull). The value of coverage is computed as the proportion of crown area and hull area, and the raster layer is created that is the final restriction criterion for the forest delineation, respectively the creation of the "forest mask". The second modification of the original workflow was the use of so-called "building mask", which is a raster layer exclusively representing buildings. Identification of the buildings took place in the initial classification and point cloud filtering. The created layer containing buildings was used for the final trimming of the automatic delineation of the forest layer (reduced such cases where the forest mask passes through built-up areas).

Validation was performed on the basis of a simple comparison of outputs of the automatic and manual forest delineation (accuracy, kappa index). Validation data were created by the manual vectorization of the forest borders on the basis of aerial photos with a resolution of 30 cm, which was obtained in the same period as the ALS data. The information spectrum was improved by the layer of forest area from the cadastral data, on the basis of which it was possible to evaluate the proportion of forest area and forested agricultural land in the created forest mask.

Accuracy evaluation of the DTM

The Digital Terrain Model was created from the ALS data. Processing these data meant their relative and absolute adjustment, classification and export to LAS format version 1.2. These activities were carried out using software Riprocess (Riegl Laser Measurement System GmbH) and software Terrascan (Terrasolid Ltd). The modified data was processed into raster terrain model structures with a resolution of 2 x 2 m. Selection of raster resolution was based on the ALS point density achieved (about 1.7 points/m^2 in the summer season and about 2.5 points/m^2 in the winter season), and on the condition of having a pixel with at least 3 points. This process was performed using the software ArcGIS Desktop 10.1 (ESRI), as well as through the application LiS Desktop (Laserdata GmbH). Five alternative raster models were created separately for the winter and summer seasons, with two being created based on spatial interpolation techniques and three on the basis of conversion. For the interpolation, the inverse distances method and the natural neighbour method were used. From the conversion methods, the function that creates a raster structure of the minimum, average and maximum values of the points was used. During this procedure it was then necessary to use the focal statistics function to complete the empty parts of the generated grid.

Evaluation of the DTM's accuracy was done in two ways. First, the absolute differences (e_i) between the values of the generated terrain models in the summer (zSDTM) and winter (zWDTM) seasons with the terrain data (zTER) were analysed. To do this work, for each measured terrain point the height value was extracted from the created rasters (coordinate "z"). Then the height values for each point were paired on the reference plots, and could be statistically evaluated (i = 1, ...n).

$$e_i = zSDTM_i - zTER_i \quad e_i = zWDTM_i - zTER_i \tag{1}$$

Secondly, the absolute differences (e_i) between the values of generated terrain models in the summer (zSDTM) and winter (zWDTM) seasons were analysed. For this purpose, map algebra functions were used, while each pixel of the resulting grid contained the value of the difference between the "z" coordinates from the summer and winter DTMs (i = 1, ...n).

$$e_i = zSDTM_i - zWDTM_i \tag{2}$$

Statistical evaluation in both cases meant finding the size of mean difference ($\bar{e}$), mean error (s_e) and the root mean square error (RMSE) at a given confidence level.

$$\bar{e} = \frac{\sum_{i=1}^{n} e_i}{n} \tag{3}$$

$$s_e = \sqrt{\frac{\sum_{i=1}^{n}(e_i - \bar{e})^2}{n-1}} \tag{4}$$

$$RMSE = \sqrt{s_e^{\,2} + \bar{e}^2} \tag{5}$$

It was also possible to evaluate, using the statistical test, whether differences in the determined pair values were just random or were statistically significant. In order to choose the correct statistical test, a verification of the assumptions made about the data was first performed. This meant first evaluating the shape of the probability distribution of differences values, which was performed using the Shapiro-Wilks W test. Based on the results of this verification of assumptions about the data and the fact that the ranges of the analysed data sets are equal ($n_1 = n_2$), further analyses of the significance of differences were conducted using the Student's parametric pair test (a individual differences have normal distribution), where the hypothesis H_0: $\bar{e} = 0$ against H_1: $\bar{e} \neq 0$ at $\alpha = 0.05$ significance level and at f = n-1 degrees of freedom is tested, or then a non-parametric Wilcoxon pair test (a individual differences have not normal distribution), where the hypothesis H_0: $\tilde{e} = 0$ against H_1: $\tilde{e} \neq 0$ at $\alpha = 0.05$ significance level and at f = n-1 degrees of freedom is tested.

Results

Forest delineation

The result of the automatic forest delineation is shown in Figures 2 and 3. Map layer "Forest

Mask", respectively "Forest delineation - automatically" represent the forest that meets the restrictive criteria. Forest area is greater than 0.3 hectares and doesn't contain gaps smaller than 300 m^2, has a width greater than 20 m, height greater than 2 m and more than 20% of its total area is covered by tree crowns. Figure 2 also illustrates examples of the automatic identification of various forest boundaries. Specifically, it is an example of clearly (Fig. 2a) and ambiguous (Fig. 2b) recognizable forest boundary. Then there's an example of un/assignment of vegetation to forest mask after the (non)compliance with criteria defining forest (Fig. 2c). Finally, there's an example of the use of "building mask" at the correction of achieved forest mask (Fig. 2d). Figure 3 provides a simple comparison of the verified process of forest mapping (Fig. 3a) with commonly used methods. In Figure 3b is a comparison with the workflow of the manual vectorization of forest boundaries based on aerial photography, and in Figure 3c is a comparison with the data layer of forest area resulting from the cadaster.

A numerical overview of the presented figure outputs is shown in Table 3. It shows that the difference between the results of automatic and manual (reference) forest delineation are only 3 hectares, which causes a relatively small, only 2% difference in the declared forest cover between these workflows. Moreover, Table 4 provides a detailed overview of the validation of the proposed solution. The overall achieved accuracy is 93%, while the statistical compliance, which excludes the correspondence between the reference and comparison data due to chance, represents the value of 0.85 (Kappa). This means that above-average correspondence was achieved in compared data, as it applies to K> 0.6 (Altman 1998). According to Landis & Koch (1977) the classi-

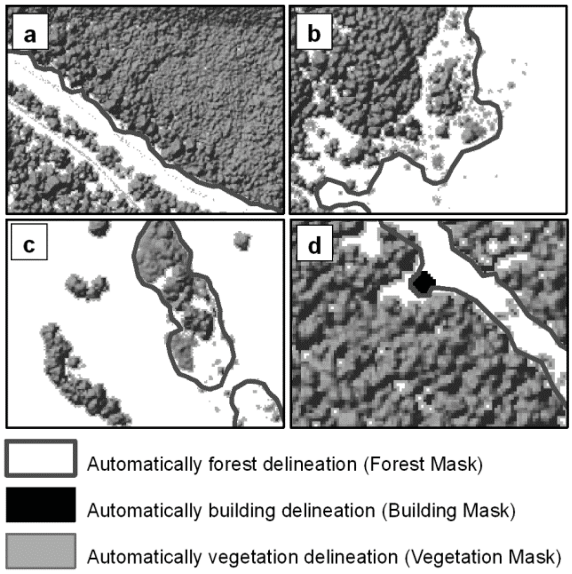

Figure 2 Examples of automatic delineation: a) clear course of the forest boundary, b) ambiguous course of the forest boundary, c) non/forest in vegetation mask, d) use of "Building mask" in forest delineation

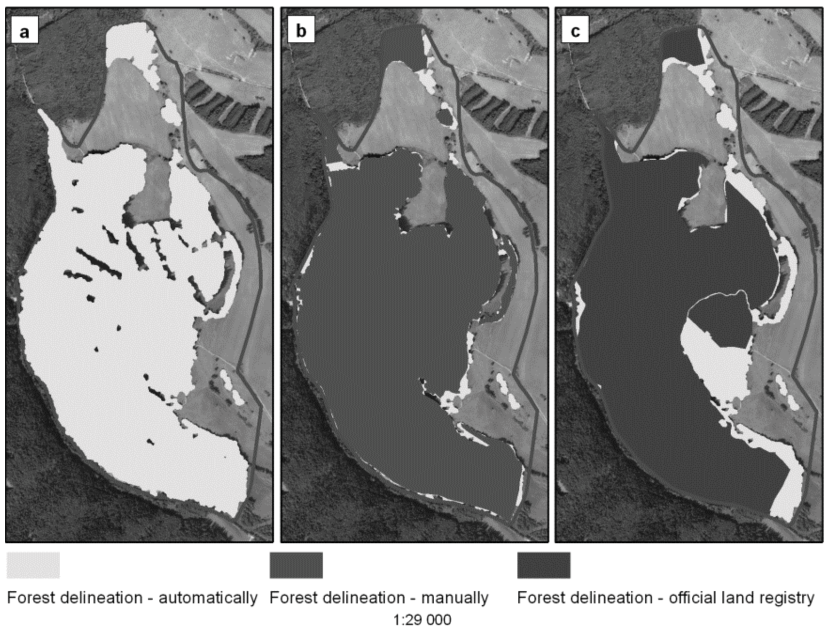

Figure 3 Forest delineation: a) automatically, b) automatically and manually, c) automatically and official land registry

fication results can be evaluated as almost perfect. Table 3 also provides information from the official land registry about forest area, hence the forested areas, temporarily deforested or deforested but necessary for forest management. The difference between these data and the automatically and manually stratified land into forested and deforested area represents 23 ha, respectively 20 ha, which causes 10% respectively 8% difference in the total woodiness of the area.

Accuracy evaluation of the DTM

An overview of the various differences between the height values extracted from the DTMs (leaf-on, leaf-off) and the height determined from the field survey for all reference plots is shown in Figure 4.

The terrain model generated from the ALS data in the summer season showed an overestimation of the height compared to the measured value in all methods of its creation. The lowest mean difference (2 cm ±15) was observed in the method when the DTM was created through the conversion of minimum point values. This method also provided outputs with the highest variability of deviations around their mean, which fluctuated in the range of -13 to +17 cm, and the extremes reached range from -73 to +80 cm (Fig. 5a). However, this method achieved the lowest difference between the estimated terrain height and the measured value, which with a 68 % confidence level was in the range of ±15 cm. Methods based on the DTM generation based on linear combinations, which significantly overestimated terrain height values (IDW, NN), do not produce significantly worse results (±18 cm). Therefore, these methods can also be considered relevant for the DTM generation.

The terrain model generated from the ALS data in the winter season showed height overestimation compared to the measured values in all methods of data creation, except when the DTM was created through the conversion of minimum point values. The lowest mean difference (5 cm ±12) was observed when the DTM was created by the inverse distance interpolation and natural neighbour functions, while a similar value (5 cm ±13) was also achieved in the method of conversion of average point values. From these methods of DTM generation, the lowest extremes were found in the natural neighbour method, which achieved a range of -72 to +88 cm (Fig. 5b). Root mean square error, which is achievable with these methods, is with 68% probability in the range of ±13 cm, or ±14 cm.

The conclusions drawn from the assessment

Table 3 Influence of forest delineation method on woodiness

Methods of forest delineation	Area (ha)	Woodiness (%)
Forest delineation - automatically	162	69
Forest delineation - manually	159	67
Forest delineation - official land registry	139	59

Table 4 Comparison of the automatically and manually forest delineation

Classified data	Reference - Manually delineated forest			
	Non-forest (ha)	Forest (ha)	Totals (ha)	User's accuracy (%)
Non-forest (ha)	68	6	74	92
Forest (ha)	9	153	162	94
Totals (ha)	77	159	236	
Producer's accuracy (%)	88	96		
Overall accuracy (%)	93	Kappa	0.85	

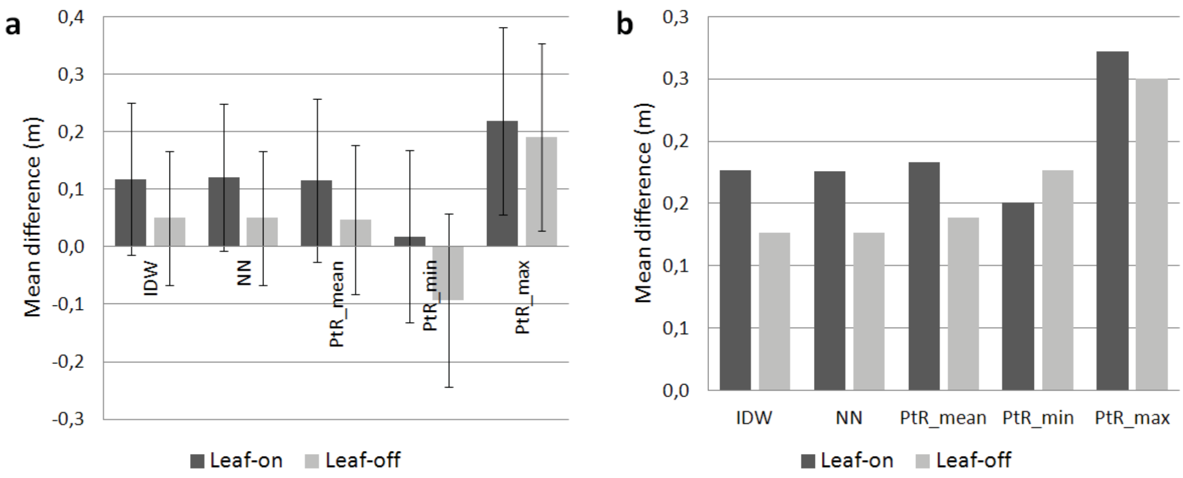

Figure 4 Summary of differences between DTM_Leaf-on, DTM_Leaf-off and terrain data from all reference plots: a) mean difference, mean error, b) root mean square error
Note. IDW – inverse distance weighting, NN – natural neighbour, PtR – Point to raster from minimal, mean, maximal point value.

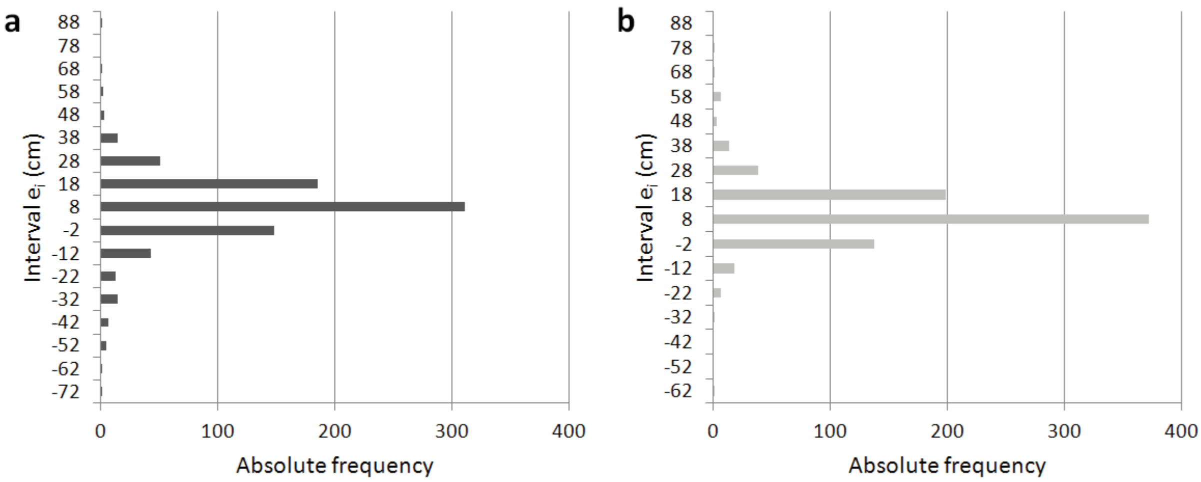

Figure 5 Frequency distribution of individual differences for DTM generation methods with the lowest root mean square error achieved in the winter and summer season of all reference plots: a) Point to raster from minimal value (Leaf-on), b) Natural neighbour (Leaf-off)
Note. e_i – individual differences.

of the differences identified separately for each reference plot (Table 5) are not fully consistent with the conclusions that were based on a review of differences of the entire set of values. In the case of estimated terrain height from the ALS data acquired in the summer season, this relates to areas with significantly higher slope (RP3, RP8, RP9), where the method of conversion of points with minimum height value, compared with the other methods, doesn't provide the most accurate estimations, and is moreover the only method that underestimates the measured values of the terrain height. In the case of terrain models created using data from the winter season, this discrepancy lies in the quality of the terrain height estimation in areas with the youngest stages of forest development (RP4, RP5), where the method of point conversion with minimum height values proved to be the most accurate. At the same time, on unforested area (RP1) there was an underestimation of the determined height of the ALS data compared to the measured values, except for the conversion method (PtR_min) and also the interpolation methods (IDW, NN).

The influence of the biological and geomorphological conditions as well as the term of scanning on the size of the root mean square error of terrain height determination from the ALS data can be evaluated on the basis of Table 6. Each reference plot is classified in the table into accuracy classes with the interval of 5 cm particularly for both terms of scanning.

From the table it can be seen that the terrain height was least correctly determined, thus with the highest deviations from reality, on plots with significant slope. This confirmed the results from plots RP8 and RP9, where in spite of the relatively simple vertical structure of the homogeneous, predominantly coniferous stand, the highest value of the root mean square error (RMSE > ±20 cm leaf-on; RMSE

Table 5 Summary of differences between DTM_Leaf-on, DTM_Leaf-off and terrain data from each reference plot

		Leaf-on					Leaf-off				
RP	(m)	IDW	NN	PtR_mean	PtR_min	PtR_max	IDW	NN	PtR_mean	PtR_min	PtR_max
RP1	$\bar{e}$	0.11	0.10	0.10	0.01	0.20	-0.03	-0.03	-0.03	-0.11	0.05
	s_e	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	RMSE	0.12	0.12	0.11	0.06	0.20	0.06	0.06	0.06	0.12	0.07
RP2	$\bar{e}$	0.14	0.13	0.14	0.08	0.21	0.08	0.08	0.09	0.00	0.19
	s_e	0.08	0.07	0.08	0.08	0.08	0.07	0.07	0.07	0.08	0.08
	RMSE	0.16	0.15	0.16	0.11	0.22	0.11	0.11	0.12	0.08	0.20
RP3	$\bar{e}$	0.05	0.06	0.06	-0.04	0.17	0.04	0.04	0.04	-0.13	0.21
	s_e	0.12	0.12	0.12	0.13	0.14	0.10	0.09	0.10	0.11	0.11
	RMSE	0.13	0.13	0.14	0.13	0.22	0.10	0.10	0.11	0.17	0.24
RP4	$\bar{e}$	0.17	0.18	0.17	0.08	0.26	0.09	0.09	0.09	-0.04	0.21
	s_e	0.10	0.10	0.09	0.10	0.09	0.08	0.08	0.08	0.08	0.09
	RMSE	0.20	0.20	0.19	0.13	0.28	0.12	0.12	0.12	0.09	0.23
RP5	$\bar{e}$	0.20	0.19	0.21	0.12	0.30	0.06	0.06	0.07	-0.02	0.18
	s_e	0,10	0.11	0.09	0.10	0.10	0.06	0.06	0.04	0.06	0.06
	RMSE	0.22	0.22	0.23	0.15	0.31	0.09	0.08	0.08	0.06	0.19
RP6	$\bar{e}$	0.08	0.08	0.08	0.02	0.14	0.02	0.02	0.02	-0.06	0.11
	s_e	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05
	RMSE	0.10	0.10	0.10	0.06	0.16	0.06	0.06	0.06	0.08	0.12
RP7	$\bar{e}$	0.10	0.10	0.10	0.02	0.18	0.06	0.05	0.05	-0.07	0.18
	s_e	0.08	0.07	0.08	0.08	0.09	0.07	0.07	0.08	0.08	0.10
	RMSE	0.12	0.13	0.13	0.08	0.20	0.09	0.09	0.09	0.11	0.21
RP8	$\bar{e}$	0.08	0.08	0.06	-0.08	0.21	0.04	0.04	0.00	-0.24	0.25
	s_e	0.20	0.19	0.21	0.22	0.23	0.19	0.19	0.21	0.22	0.23
	RMSE	0.22	0.20	0.22	0.23	0.31	0.19	0.19	0.21	0.32	0.34
RP9	$\bar{e}$	0.19	0.20	0.18	-0.06	0.43	0.10	0.09	0.08	-0.24	0.41
	s_e	0.26	0.25	0.31	0.32	0.33	0.24	0.24	0.30	0.29	0.33
	RMSE	0.32	0.32	0.36	0.32	0.54	0.26	0.26	0.31	0.38	0.53

Note. RP – reference plot, IDW – inverse distance weighting, NN – natural neighbour, PtR – point to raster from minimal, mean, maximal point value, RP1-9 – reference plot nr. 1-9, $\bar{e}$ – mean difference, s_e – standard error of mean difference, RMSE – root mean square error.

> ±19 cm leaf-off) was recorded. This conclusion was also confirmed in the inverted form, as the terrains with the lowest slope also showed the smallest deviation between the height of the terrain observed from the ALS data and the real terrain height. An example was plot RP6, the forest stand of which similarly consisted of predominantly coniferous trees, but the value of the root mean square error was more than a half lower (RMSE ±6-10 cm leaf-on; RMSE ±6 cm leaf-off).

The significant impact of the shading of the terrain by forest vegetation on the accuracy of the generated terrain model was demonstrated only in cases where the area under forest cover was completely obscured. Examples are plots RP4 and RP5. These represented slight slope terrains with deciduous stands in the earliest stage of development, characterized by the use of the whole production space. The research plot RP4 was one of the least correct both in terms of scanning (RMSE ±13-20 cm leaf-on; RMSE ±9-12 cm leaf-off), while at research plot RP5 only the scanning in the summer season was affected (RMSE ±15-23 cm leaf-on; RMSE ±6-9 cm leaf-off). The probable reason for this was that research plot RP5 was formed only of sprouted seedlings of beech, which creates dense vegetation cover up to 50 cm above the ground during the growing season, while the trunk and branches outside the growing season when they lose assimilative organs, are still below a dimension that could prevent the penetration of laser pulses on the ground. This

Table 6 Classification of reference plots by root mean square error achieved

RMSE (cm)	Leaf-on					Leaf-off				
	IDW	NN	PtR_mean	PtR_min	PtR_max	IDW	NN	PtR_mean	PtR_min	PtR_max
5.1-10	RP6	RP6	RP6	RP1		RP1	RP1	RP1	RP5	RP1
				RP6		RP6	RP6	RP6	RP6	
				RP7		RP5	RP5	RP5	RP2	
						RP7	RP7	RP7	RP4	
						RP3	RP3			
10.1-15	RP3	RP1	RP1	RP2		RP2	RP2	RP3	RP7	RP6
	RP1	RP7	RP7	RP4		RP4	RP4	RP2	RP1	
	RP7	RP3	RP3	RP3				RP4		
		RP2		RP5						
		RP4								
15.1-20	RP2		RP2		RP6	RP8	RP8		RP3	RP5
	RP4		RP4		RP1					RP2
					RP7					
20.1-25	RP8	RP8	RP8	RP8	RP3			RP8		RP7
	RP5	RP5	RP5		RP2					RP4
										RP3
25.1-30					RP4	RP9	RP9			
30.1-35	RP9	RP9	RP9	RP9	RP8			RP9	RP8	RP8
					RP5					
35.1-40									RP9	
40.1-45										
45.1-50										
50.1-55					RP9					RP9

Note. IDW – inverse distance weighting, NN – natural neighbour, PtR – point to raster from minimal, mean, maximal point value, $RP_{i=1...9}$ – reference plot.

was the substantial difference from research plot RP4, the forest cover of which was formed by more developed individuals 50-150 cm in height. For older stands located in terrain with a slight slope, it was confirmed that the DTM created from ALS data belonged to the same or neighbouring accuracy class as the DTM created from ALS data on the unforested research plot. The range of the root mean square error at these locations reached the level of RMSE = ±6-17 cm.

An overview of the statistical pair test for the whole set of values achieved is presented in Table 7. The values of the attribute "z" from the created DTMs and the field survey, and the values of the attribute "z" from the DTMs produced by different methods were tested. The table presents the results of parametric or non-parametric testing using P-Value as a test criterion. These results show that, with 95% confidence, all the height values of the terrain achieved by the ALS in both scanning periods are statistically significantly different from the measured height value. It is also shown that the method of the inverse distances, natural neighbour and conversion of point average values give, with 95% probability, only randomly different terrain models. The exception was the comparison of the inverse distances and natural neighbour method in the winter season (p = 0.04). A similar conclusion was reached in a terrain model created from the ALS data from the summer and winter season on each reference plot.

From the previous results shown in Figure 4 and Table 5, it is possible to assess the impact of the scanning period on the accuracy of the terrain model. The conclusions derived from these results can be related only to the territory of the 802 reference points. A more representative sample of data for this type of analysis is therefore the reference areas that together provide 392,815 reference points.

The numerical results of the comparison of the "Leaf-on" and "Leaf-off" terrain models within the reference areas are shown in Table 8. A review of these values shows that "z" coordinates obtained in the scanning in the summer season are systematically overestimated compared with the "z" coordinates obtained in the winter season, which was confirmed by the statistical test for $\alpha = 0.05$ significance level.

Table 7 Review of the results of a statistical test of significance of differences of all reference plots ($\alpha = 0.05$)

n=802	Leaf-on						Leaf-off					
	Ground	IDW	NN	PtR (min)	PtR (mean)	PtR (max)	Ground	IDW	NN	PtR (min)	PtR (mean)	PtR (max)
Ground		<0.001	<0.001	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001	<0.001	<0.001
IDW	<0.001		0.124	<0.001	0.959	<0.001	<0.001		0.039	<0.001	0.841	<0.001
NN	<0.001	0.124		<0.001	0.37	<0.001	<0.001	0.039		<0.001	0.814	<0.001
PtR (min)	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001	<0.001	0.000		<0.001	<0.001
PtR (mean)	<0.001	0.959	0.37	0.000		<0.001	<0.001	0.841	0.814	<0.001		<0.001
PtR (max)	<0.001	<0.001	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001	<0.001	<0.001	

Note. n – range of the data set, Ground – terrain data, IDW – inverse distance weighting, NN – natural neighbour, PtR – point to raster from minimal, mean, maximal point value.

Results from the graphical comparison of the “Leaf-on” and “Leaf-off” terrain models within the reference areas are presented in Figure 6. Figure 6a represents part of the raster where each pixel has a value of the terrain height difference obtained in the summer and winter seasons. The area in white represents positive difference values and the area in black represents negative difference values. With the help of Figures 6b and 6c, it is then possible to analyze the cases where the terrain height values were overestimated and underestimated in the summer season compared with the values obtained in the winter season. The series of figures shows that the large positive differences occurred mainly on unforested areas. Large negative differences were again identified in the forested areas, but with a significant slope. Locally distributed differences were also found in the forested area, where mainly positive differences dominated.

Discussion and conclusions

The use of airborne laser scanning for forest delineation and for the generation of terrain models in forested and non-forested area is one of the many application possibilities of remote sensing in forestry.

The stratification of landscape to forest and non-forest has direct significance in a series of linked geo-operations, but it also has strategic international importance. The workflow of automatic forest delineation presented in this study, which is a modification of the procedure by Eysn et al. (2012), demonstrated the perspective in the objectification of identifying boundaries of forest stands based on the ALS data.

Classification of vegetation and the subsequent application of iterative restrictive criteria of minimum height, width, area, and crown coverage, also considering the spacing of tree crowns and the presence of buildings, ensured an overall accuracy of 93%. The result was thus somewhat worse than in similar studies which had achieved accuracy of 94% (Wang et al. 2011), 96% (Eysn et al. 2012) and 97% (Straub et al. 2008). Nevertheless in the presented approach, above average correspondence (K = 0.85) was achieved in the assess-

Table 8 Numerical review of each difference between DTM_Leaf-on and DTM_Leaf-off from each reference area

RA	(m)	IDW	NN	PtR_mean	PtR_min	PtR_max
A	$\bar{e}$	0.09	0.09	0.09	0.15	0.03
	s_e	0.13	0.10	0.11	0.15	0.16
	RMSE	0.16	0.13	0.14	0.21	0.16
B	$\bar{e}$	0.06	0.07	0.07	0.15	-0.01
	s_e	0.13	0.10	0.12	0.16	0.15
	RMSE	0.14	0.12	0.14	0.22	0.15
C	$\bar{e}$	0.05	0.05	0.05	0.12	0.00
	s_e	0.13	0.12	0.11	0.11	0.15
	RMSE	0.14	0.13	0.12	0.16	0.15
D	$\bar{e}$	0.07	0.06	0.06	0.14	-0.01
	s_e	0.14	0.11	0.11	0.13	0.15
	RMSE	0.16	0.13	0.13	0.19	0.15
E	$\bar{e}$	0.08	0.08	0.08	0.20	-0.02
	s_e	0.16	0.19	0.14	0.16	0.17
	RMSE	0.18	0.21	0.16	0.26	0.17

Note. RA – reference area, IDW – inverse distance weighting, NN – natural neighbour, PtR – point to raster from minimal, mean, maximal point value, $\bar{e}$- mean difference, s_e – standard error of mean difference, RMSE – root mean square error.

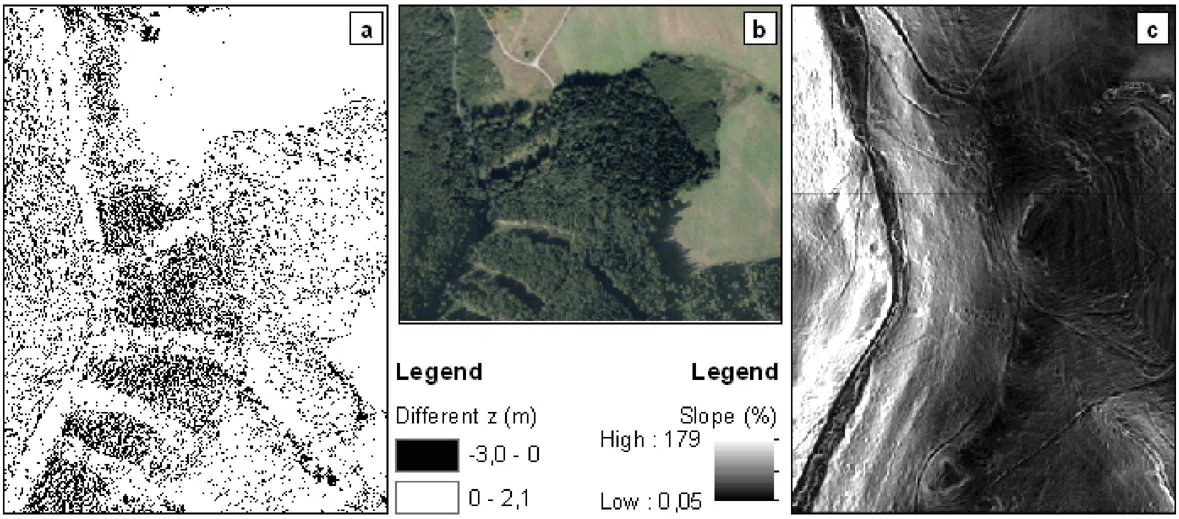

Figure 6 Review of differences between DTM_Leaf-on and DTM_Leaf-off from individual reference areas: a) individual difference, b) aerial photo, c) slope

ment of the degree of statistical correlation of reference and comparison data. The difference in the observed forest coverage of the area by automated and manual forest delineation represented basically a minimal value (2%), in comparison with cadastre difference (10%). The thus found difference (cadastre vs. automatically forest delineation) can however be used to assess the amount of forested agricultural land, which has a practical importance in restoring the land evidence of the cadastre and of course in landscape management. This comparison also provides the opportunity to identify areas that are formally registered as non-forest, but in reality are forested.

A digital terrain model with the support of GIS analytical tools is an important database for a broad range of purposes (Burrough 1986, Tuček 1998). It can serve as a single source of data, such as within network or hydrologic analysis (Jaara & Lecordix 2011, Susaki 2012). An example of this utilization is the creation of a normalized digital surface model (nDSM) resulting from the difference between the surface and terrain models (Hollaus et al. 2009, 2010). The vertical accuracy of the DTM is its most important quality parameter, as it directly or indirectly affects all outputs generated from it or based on it.

One of the tasks of this paper was to evaluate the applicability of various methods of DTM generation from laser scanning data. Within this activity, the versatility of the "point cloud" in DTM generation with alternative methods has been demonstrated. The differences between the terrain models that were created by the method of inverse distances, natural neighbour and conversion of average values were with 95% probability only random. This means that in the area of interest, the DTM generation method that is simpler and economically more advantageous can be selected. Other authors e.g. Su & Bork (2006) found that the method of inverse distances is a simpler and more accurate interpolation method than kriging for DEM development, when high density of LiDAR data points is available (> 0.75 points/m^2 in their study).

The important fact identified was that at the $\alpha = 0.05$ significance level, all the terrain height values in the models differed significantly from their measured values. Thus, a systematic error was found in the terrain height estimated by both interpolation and conversion methods. This difference was usually positive, which means that the terrain height generated from the ALS data is overestimated in comparison to the real height. The reason for this finding may be the objects located above the ground (herbaceous cover, arable „disturbed“ soil, etc.) which are considered as the returns. However, we also have to take into account the manner of recording and processing the raw data, or the DTM generation method.

The next task of the paper was to evaluate the impact of various factors on the vertical accuracy of the DTM generated from the ALS data.

Based on the values of the root mean square error, it is then possible to assess the impact of the scanning period on its value, which is clearly lower for terrain models generated based on the data from the winter season. The complex difference between the estimated terrain height and the measured value will be located with 68% confidence at intervals of ±18 cm (DTM Leaf-on) and ±13-14 cm (DTM Leaf-off). This is due to the greater number of „terrain“ points that can be obtained when the trees are without leaves, allowing a larger part of the pulses to penetrate to the ground. The major impact of the vegetation on the DTM's vertical accuracy was demonstrated only in locations with totally covered terrain. In the area of interest, such areas were represented by forests in the earliest forest growth stage, which arose after cutting. Mature forest stands, even if vertically more complex, didn't cause a significant constraining element in the DTM quality. Other authors noted more or less different results, but the sample size was smaller in comparison to this study. Reutebuch et al. (2003) achieved RMSE of ±32 cm, but it was checked only at 347 check points. They also noted that the accuracy is eroded slightly by a heavy canopy and the height of near-ground vegetation, but with a weak effect. Kraus & Pfeifer (1998) achieved a RMSE of ±57 cm (466 reference points) in beech forests with bias of +20 cm; Evans & Hudak (2007) in coniferous forest with RMSE of ±70 cm (165 reference points), ±62 cm (39 reference points).

Geomorphological characteristics proved to be very influential on the final precision of the terrain model. In this case, slope greater than 30% in some areas nearly doubled the differences between the terrain height and the real terrain value. Hodgson et al. (2005) also identified a significant monotonic relationship between the mean absolute elevation error and increasing slope for a LiDAR derived DTM. Their final RMSE of ALS derived elevations points in leaf-off conditions achieved ±93 cm at the ground locations. Similar conclusions were presented by Hollaus et al. (2006); RMSE of ±10 cm on flat area, RMSE of ±50 cm on slope areas (>60˚). In contrast, Su & Bork (2006) found that mean error did not increase proportionally to slope gradient (like e.g. in Hodgson (2003)), where the largest signed error associated with intermediate slopes was between 2° to 5° and the total RMSE achieved was ±59 cm.

Based on the results shown in this paper, as well as the results of other authors, the prospect of automated forest delineation and generating digital terrain models on the basis of airborne laser scanning data can be confirmed. However, biological and geomorphological factors, as well as factors arising from the use of different methods of obtaining and processing data must be considered, because they affect these processes.

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References

Akkay A.E., Sessions J., 2005. Applying the decision support system, TRACER, to forest road design. Western Journal of Applied Forestry 20(3): 184–191.

Akkay A.E., Oğuz H., Karas I.R., Aruga K., 2008. Using LiDAR technology in forestry activities. Environmental Monitoring and Assessement 151(1-4): 117–125. DOI: 10.1007/s10661-008-0254-1.

Altman D.G., 1998. Some common problems in medical research: Practical stastistics for medical research. 8th ed. Chapman & Hall, London, 589 p.

Burrough P.A., 1986. Principles of GIS for land resources assessment. Oxford University Press, Oxford, 193 p.

Chen Q., Gong P., Baldocchi D., Xie G., 2007. Filtering airborne laser scanning data with morphological methods. Photogrammetric Engineering & Remote Sensing 73(2): 175-185. DOI: 10.14358/PERS.73.2.175.

Cibulka M., Mikita T., 2011. Využití leteckého laserového skenování pro digitální modelování terénu v lesních porostech. [CD-ROM]. Progresívne postupy spracovania náhodných ťažieb [Utilization of airborne laser scanning for digital terrain modelling in forest stands. Progressive methods for processing of incidental fellings]. ISBN 978-80-228-2286-2. s. 100-108.

Divín J., 2011. Porovnání přesnosti dat leteckého laserového skenování pro tvorbu digitálních modelů terénu [Comparison of accuracy of lidar data for DTM generation]. Bachelor thesis, Faculty of Forestry and Wood Technology, Mendel University, Brno, 48 p.

Evans J., Hudak A., 2007. A multiscale curvature algorithm for classifying discrete return LiDAR in forested environments. IEEE Trans. Geoscience and Remote Sensing 45(4): 1029–1038. DOI: 10.1109/TGRS.2006.890412.

Eysn L., Hollaus M., Vetter M., Mucke W., Pfeifer N., Regner B., 2010. Adapting α-shapes for forest delineation using ALS Data. In Koch B., Kändler G., Teguem Ch. (eds.), 10th International Conference on LiDAR Applications for Assessing Forest Ecosystems (Silvilaser 2010), 14–17 September 2010, Germany, Albert-Ludwigs- University, Freiburg, pp. 41-50.

Eysn L., Hollaus M., Schadauer K., Roncat A., 2011. Crown coverage calculation based on ALS data. In Hirata, Y., et al. (ed.), Proceedings of 11th International Conference on LiDAR Applications for Assessing Forest Ecosystems (Silvilaser 2011), 16–20 October 2011, Australia, Hobart, pp. 10.

Eysn L., Hollaus M., Schadauer K., Pfeifer N., 2012. Forest delineation based on airborne LIDAR data. Remote Sensing 4(3): 762-783. DOI: 10.3390/rs4030762.

FAO, 1993. Guidelines for land-use planning. Web: http://www.fao.org/docrep/t0715e/t0715e00.htm.Accessed 1993.

FAO, 2007. Guidelines for defining forest resources. Web: http://www.fao.org/docrep/w8212e/w8212e05.htm. Accessed 2007.

Gomes Pereira L., Goncalves G., 2010. Accuracy of a DTM derived from full-waveform laser scanning data under unstructured eucalypt forest: A case study. In: Staiger R., et al. (eds.), XXIV FIG International Congress 2010, April 2010, Australia, Sydney, pp. 1-16.

Hodgson M.E., Jensen J.R., Schmidt L., Schill S., Davis B., 2003. An evaluation of LIDAR- and IFSAR-derived digital elevation models in leaf-on conditions with USGS Level 1 and Level 2 DEMs. Remote Sensing of Environment 84 (2003): 295–308. DOI: 10.1016/S0034-4257(02)00114-1.

Hodgson M.E., Jensen J., Raber G., Tullis J., Davis B.A., Thompson G., Schuckman K., 2005. An evaluation of lidar-derived elevation and terrain slope in leaf-off conditions. Photogrammetric Engineering & Remote Sensing 71(7): 817–823. DOI: 10.14358/PERS.71.7.817.

Hollaus M., Wagner W., Schadauer K., Maier B., Gabler K., 2009. Growing stock estimation for alpine forests in Austria: a robust lidar-based approach. Canadian Journal of Forest Research 39(7): 1387-1400. DOI: 10.1139/X09-042.

Hollaus M., Mandlburger G., Pfeifer N., Mücke W., 2010. Land cover dependent derivation of digital surface models from airborne laser scanning data. In: Paparoditis N., Pierrot-Deseilligny M., Mallet C., Tournaire O. (eds.), IAPRS, Vol. XXXVIII, Part 3A – Saint-Mandé, September 1-3, France, pp. 221-226.

Hollaus M., Eysn L., Bauerhansl Ch., Riccabona F., Maier B., Jochem A., Petrini-Monteferri F., 2012. Accuracy assessment of ALS-derived stem volume and biomass maps. EARSel eProceedings 11(1): 74-86.

Hyyppä H., Xiaowei Y., Hyyppä J., Kaartinen H., Kaasalainen S., Honkavaara E., Rönnholm P., 2005. Factors affecting the quality of DTM generation in forested areas. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 36 (Part 3/W19), pp. 97–102.

Hyyppä J., Pyysalo U., Hyyppä H., Samberg A., 2000. Elevation accuracy of laser scanning-derived digital terrain and target models in forest environment. In: Reuter R., Babichenko S., Samberg A. (eds.), 4th Workshop on lidar remote sensing of land and sea, Germany, EARSeL, Dresden, pp. 139-147.

Jaara K., Lecordix F., 2011. Extraction of cartographic contour lines using digital terrain model (DTM). Cartographic Journal 48(2): 131-137. DOI: 10.1179/1743277411Y.0000000011.

Kraus K., Pfeifer N., 1998. Determination of terrain models in wooded areas with airborne laser scanner data. ISPRS Journal of Photogrammetry and Remote Sensing 53(4): 193–203. DOI: 10.1016/S0924-2716(98)00009-4.

Landis J., Koch G., 1977. The measurement of observer agreement for categorical data. Biometrics 33(1): 159–

174. DOI: 10.2307/2529310.

Leckie D.G., Gougeon F.A., Walsworth N., Paradine D., 2003. Stand delineation and composition estimation using semi-automated individual tree crown analysis. Remote Sensing of Environment 85(3): 355–369. DOI: 10.1016/S0034-4257(03)00013-0.

Leppänen V., Tokola T., Maltamo M., Mehtätalo L., Pusa T., Mustonen J., 2008. Automatic delineation of forest stands from LIDAR data. In: Hay J.G., Blaschke T., Marceau D. (eds.), GEOBIA 2008 – Pixels, Objects, Intelligence, GEOgraphic Object Based Image Analysis for the 21st Century, August 05-08, Canada, University of Calgary, Calgary Alberta, pp. 373. ISPRS Vol. XXXVIII-4/C1.

Lund H.G., 2012. National definitions of forest/forestland listed by country. Web: http://home.comcast.net/~gyde/national.definitions.of.forest.pdf. Accessed 10 June 2013.

Moravčík M., Čaboun V., Priwitzer T., 2010. National forest inventories – pathways for common reporting. In: Tomppo E., Gschwantner T., Lawrence M., McRoberts R. (eds.) Slovak Republic. Springer Science Business Medias B. V. pp. 609. ISBN 978-90-481-3232-4. DOI: 10.1007/978/90/481-3233-1.

Radoux J., Defourny P.A., 2007. Quantitative assessment of boundaries in automated forest stand delineation using very high resolution imagery. Remote Sens. Environ 110(4): 468-475. DOI: 10.1016/j.rse.2007.02.031.

Reutebuch S.E., McGaughey R.J., Andersen H.E., Carson W.W., 2003. Accuracy of a high-resolution LIDAR terrain model under a conifer forest canopy. Canadian Journal of Remote Sensing 29(5): 527–535. DOI: 10.5589/m03-022.

Schoene D., Killmann W., Lüpke H., Wilkie M.L., 2007. Forests and climate change working paper 5, Definitional issues related to reducing emissions from deforestation in developing countries. FAO, Rome, 29 p.

Skaloud J., Schaer P., 2012. Automated assessment of digital terrain models derived from airborne laser scanning. Photogrammetrie Fernerkundung Geoinformation 2012(2): 105-114.

Straub C., Weinacker H., Koch B., 2008. A fully automated procedure for delineation and classification of forest and non-forest vegetation based on full waveform laser ccanner data. International Archives of the Photogrammetry, Remote Sensing and Spatial Information sciences, Jul 3-11, China, ISPRS, Beijing, pp. 1013-1019.

Šmelko Š., Šebeň V., Bošeľa M., Merganič J., Jankovič J., 2008. Národná inventarizácia a monitoring lesov SR 2005-2006: Základná koncepcia a výber zo súhrnných informácií [National inventory and forest monitoring SR 2005-2006: The basic concept and the selection of summary information]. National Forest Centre, Zvolen, 15 p.

Susaki J., 2012. Adaptive slope filtering of airborne LiDAR data in urban areas for Digital Terrain Model (DTM) generation. Remote Sensing 4(6): 1804-1819. doi: 10.3390/rs4061804. DOI: 10.3390/rs4061804.

Su J.G., Bork E.W., 2006. Influence of vegetation, slope and LIDAR sampling angle on DEM accuracy. Photogrammetric Engineering and Remote Sensing 72: 1265–1274. DOI: 10.14358/PERS.72.11.1265.

Tuček J., 1988. Geografické informační systémy: Principy a praxe [Geographic information systems: Principles and practice]. Computer Press, Ostrava, 424 p.

Wang Z., Boesch R., Ginzler C., 2011. Forest delineation of aerial images with Gabor wavelets. International Journal of Remote Sensing 33(7): 2196-2213. DOI: 10.1080/01431161.2011.608087.