Describing the selected canopy layer parameters of the Scots pine stands using ALS data

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Abstract

The purpose of the study was to determine the usefulness and improve understanding of ALS technology in acquisition of selected parameters of canopy layers for individual trees and whole stands. This approach based on ALS data (TopoSys fiber scanner) was compared to reference data from forest inventory (432 Scots pines). The results of our study indicate the following: (1) height for single trees derived from ALS data leads to underestimation (mean difference -0.90 m or +0.12 m depending on CHM generation algorithm); (2) mean height for a stand was higher (+0.85 m) than the height from SILP database what can results in whole Milicz Forest district in underestimation of the wood volume; (3) mean height of a stand (understanding as 95th percentile of the FE point cloud) was +0.46 m higher than the height from SILP inventory database; (4) it was possible to estimate the base of crown with underestimation of 0.52 m; (5) length of crown measured during the forest inventory was +0.42 m higher if compared to ALS data (analysis of histogram); (6) crown surface area was slightly greater and crown volume was slightly smaller than the reference; (7) homogeneity of an even-aged-pine stand is questionable. In the very near future the new approach of forest inventory supported with ALS data is expected as a list of the new parameters and guidelines.

Keywords: tree height, base of crown, tree crown length, surface area and volume, homogeneity

1. Introduction

One of the most significant parameters used by foresters is the tree stand height. The definition of timber volume of a single tree or stand is based on formulas which use mainly the diameter at breast height (DBH) and tree height, thus the accuracy in the estimation of the timber stock is directly linked with the quality of these parameters. In management forests, particularly single-species and even-age tree stands, artificially renewed from homogenous genetic material, height should not vary too much, provided the forest site conditions are the same and human treatments (e.g. thinning) are identical. The traditional measurement of tree height with hypsometer is affected by the instrument error and subjectivity in pointing the tree top by the operator. In some situations, high density of the stand, windy weather or a small number of leaves may cause additional errors. Methods using the remote sensing technologies (e.g. photogrammetry) have been known for decades, but they have always been work intensive. Nowadays these methods become more and more competitive due to the technology of digital airborne cameras and the process of automatic stereo-matching (Baltsavias *et al.* 2008). Other technologies, such as radar or LiDAR offer a completely new approach in forest practice in the measurement of selected parameters. LiDAR is not limited to the circular inventory plot, on which foresters used to describe the whole stand, but validation studies are generally performed at the plot level or at the tree level (Means *et al.* 2000) because of the reference data. The measurements of the stand height with ALS have already been studied by many authors (Næsset 1997, 2004, Kwak *et al.* 2007). Given that the accuracies of the estimation of tree stand height

(h) are usually different, there is a general trend towards underestimation of this feature (Hyyppä et al. 2004, Maltamo et al. 2004, Rönnholm et al. 2004, Yu et al. 2004). Only few studies (Næsset and Økland 2002, McGaughey *et al.* 2004) show a reverse trend of overestimation. ALS data is also used in the definition of other parameters, such as: base of crown (Næsset and Økland 2002, Hall *et al.* 2005, Popescu and Zhao 2008), crown depth/L (Næsset and Økland 2002, Maltamo *et al.* 2006), crown diameter (Popescu *et al.* 2003), density of stems in a stand (Riaño et al. 2003, Hall et al. 2005), biomass (Lim and Treitz 2004, Popescu 2007) or timber volume (Næsset 2004, Hollaus et al. 2007).

2. Method

2.1 Study area

For this study we chose forest stands located in a central-west part of Poland (51°27' N; 17°12' E) belonging to the Forest District of Milicz and owned by the Wroclaw Regional Directorate of the Polish State Forest National Holding. In this area different GI technologies (ALS, TLS, photogrammetry) are tested in terms of their usefulness in forest inventory (Wezyk *et al.* 2007). In this paper we present the results from our studies based on 21 inventory plots covered with Scots pine. Depending on the stand age, the plot size varies from 50m^2 (26 years) to 500m^2 (107 years).

2.2. Reference data

The reference data used in this project came from several sources. One of them, the most often quoted, is later on referred to as forest inventory. This measurement, based on the Polish State Forests inventory guidelines (IUL PGLP 2003), was carried out in August 2006 by the company Taxus SI Ltd. The inventory campaign delivered the selected tree taxation parameters like: tree species, position on the inventory plot (polar measurement), height of tree (h_t), base of crown, DBH, diameter at 5.0 m, centre of the crown position and shape of the crown. Height of tree and base of crown were measured using the hypsometer Vertex III (Haglöf, Sweden) with 0.1 m accuracy. Another set of reference data comes from the SILP database (the descriptive database of the Polish State Forest) and was updated in year 2005 (regular forest inventory). However, SILP database provides information for a whole stand as an average height, DBH, volume and other parameters. The centres of the plots were determined with dGPS survey (Trimble Pathfinder ProXRS). Data collected with Terrestrial Laser Scanning (TLS; FARO LS 880) was also used (Wezyk *et al.* 2007).

2.3. ALS data

The airborne campaign was carried out in July 2007 using the TopoSys glass fiber scanner Falcon II with a so called "swing mode". The mean relative height of flight was about 550 meters above the ground. The mean point density was ca. 14 pts/m^2 (varied from 9 to 18 pts). Single scans were delivered in ASCII format (raw data) and raster format data as well (DSM and DTM).

2.4. Hardware and software

In this project Terrascan and Terramodeler (Terrasolid Ltd.) software was used in the processing and classification of the point cloud (ASCII XYZ) and DTM generating. In calculating of the canopy metrics, the FUSION (McGaughey 2007) was used. The LASEdit (Cloud Peak) software was used to control the correctness of the file structure *.LAS, the ArcViewGIS 9.1 (ESRI) in 3D GIS analyses (GRID) and Statistica 8.0 (StatSoft Inc.) for statistical purpose.

2.5. Canopy surface and height

Surfaces representing the forest canopy were generated using the FUSION software

(McGaughey 2007). Two different crown models (called: CHM1 and CHM2) were saved in *.dtm format. The CHM1 surface was generated without preserving the local maxima from point cloud but with two filters - median and smoothing filter. The CHM2 surface was generated with the additional option of "preserve the local maxima and minima". The canopy surfaces were exported to the ASCII GRID (ESRI) and in this environment the 3D analyses, like calculating the volume and surface area of the canopy layer, were performed. The heights of single trees (h_t) were defined by GIS analysis overlaying the polygons representing the outline of the crown with layer CHM2 (GRID zonal statistic). For the needs of the vertical structure analysis (histogram generation) and the prediction of base-of-living-crown, ALS was used as point cloud XYZ. Similarly, the mean height for selected compartments was calculated as 95th percentile (FUSION software) of the ALS point cloud and not from the modelled CHM1 and CHM2 surfaces. In this case we accepted size of pixel representing the tree crown as 10 by 10 meters.

2.6. Estimation of the base-of-crown based on the ALS histograms

Based on the percentage distribution (above 1%) of the number of LiDAR impulses from the point cloud in height gradient (0.5m intervals) the histogram of the base of crown for individual tree and for the whole compartment was made. These results were compared to the visual interpretation made by 7 operators. The length of green crown may be defined as the vertical distance from the tree top to the lowest living branch. While the upper limit (tree height) can be objectively defined, the base of crown is often very subjective to ascertain.

2.7. Tree crown shape

The centre of the crown and the edges of 8 opposite sites of the crown were projected vertically to the ground by forest inventory in July 2006. Some trees between forest inventory (2006) and LiDAR flight (2007) were cut down (thinning) so authors decided to use the crown shapes collected from TLS (2006), which had more accurate outlines. Crown TLS outlines were used in defining e.g. density of points in individual crowns, maximal high point inside the crown polygon or the crown base, with the methods available in FUSION program and 3D GIS spatial analysis.

2.8. Tree crown surface area and volume

Crown surface area and volume can be approximated by assuming that the crown is a regular geometric solid like a cone or paraboloid. If we assume that a cone is a reasonable approximation for the Scots Pine crown, the surface area (Eqauation 1 after Avery and Burkhart 2002) and volume (Eqauation 3 after Avery and Burkhart 2002) can be computed. However, if a paraboloid is chosen, then crown surface and volume would be computed using different formulas Equation 2 after Laar & Akca (1997) and Equation 4 after Brack (2008) respectively. In each equation the same crown width value (CW) was used, determined on the TLS data.

$$CSA = \frac{\pi CW}{2} * \sqrt{L^2 + \left(\frac{CW}{2}\right)^2} \qquad (1)$$

$$CV = \frac{\pi CW^2 CL}{12} \qquad (3)$$

$$CSA = \frac{\pi CW}{12 CL^2}(4CL^2 + \frac{1}{4}CW^2)^{3/2} \qquad (2)$$

$$CV = \pi \frac{CW^2 CL}{8} \qquad (4)$$

where: CSA – crown surface area [m^2]; CV – crown volume [m^3]; CW – crown width [m]; CL – crown length [m]

3. Results and discussion

3.1 Height

Firstly the results of height measurements obtained with different methods (SILP descriptive data base, forest inventory = F.INV, TLS, CHM1 and CHM2) were subdued to a statistic variance analysis. The significance of differences was tested with a non-parametric Friedman's (ANOVA) test for many variables and a Wilcoxon test for two variables. Analyzing all the 432 pines, high and highly significant differences were found in comparison of two groups of methods: traditional measurement with hypsometer (forest inventory 2006) with TLS and ALS methods (CHM1 and CHM2) as well as SILP (2005). The analysis in age groups up to 60 years and above 60 year old trees showed significant differences ($0.01<p<0.05$) in comparison with CHM2 and forest inventory/TLS/CHM1 (up to 60 years old), and additionally for older tree stands (above 60 years old) with the pairs of forest inventory methods and TLS/CHM1.

Generally, a typical trend was observed in the comparison of traditional field measurements (Vertex; Haglöf) and ALS technology. Graph (Fig. 1) and Tab1 clearly shows that ALS (CHM1 and CHM2) method of individual trees height measurement result in underestimation up to -0.90 m (SD=1.77 m) in case of CHM1 surface and -0.12m (SD=1.81 m) for CHM2, respectively. The difference of height read from two surfaces: CHM1 and CHM2 were on average 0.75 m (CHM2 was generated with option "preserve local maxima"). The additional analysis on the ALS point cloud were made of first echo (FE) points to defining the highest point within the crown. This analysis showed that the CHM2 canopy surface was closer to highest points (+0.20m) than CHM1 (-0.50m).

The mean height of the Scots pine read from the SILP (2005) data base was 1.14 m lower than gathered during the forest inventory (2006), which could indicate inaccuracies of the previous measurements (the localizations of the inventory plots of 2005 are unknown). Yearly mean height increment was only about 0.15÷0.20 m in those pine stands. Mean difference between forest inventory (2006) and TLS showed -0.98 m value, which could indicate the underestimation of terrestrial laser scanner, however only assuming full correctness of reference data. This convinces the authors that the tree height reference, based on quite a subjective measurement, should not necessarily be taken as unquestionable, even when the state-of-the-art hypsometer was used. Considering the quality of height (h_t) from ALS, one should keep in mind that reference data are collected with a basically unknown error (estimated 5-10%). Therefore additional test was made in the field using the same hypsometer and 6 observers. The comparison was made on three conifer trees and its result confirms that height measurement is very subjective (st. dev. 0.56m, maximum difference from mean: +0.67m and -0.79m). The only reliable way to measure tree height, requires cutting down the tree or applying very accurate surveying with total station (Andersen *et al.* 2006).

A key factor in defining the tree height with ALS methods seems to be the selection of the algorithm to generate DTM. In case of the occurring understory or a small number of points (LE) on the ground due to a very dense forest canopy - the underestimation of tree height can take place (Pyysalo 1999). Another important step is generating the canopy surface model (CHM). The result of the comparison to the highest point within the crown indicates that CHM2 presents the reality rather accurately (-0.12m) then CHM1 surface, what results in a greater difference between CHM2 and the SILP database (+0.85 m; R^2=0.95; SD= 1.02 m; Tab.1). Concurrently, it has to be remembered that SILP data base (2005) values does not necessarily have to be reliable for a whole compartment.

The carried out regression analysis for all the pairs of measurement methods showed that the lowest value of the determination coefficient (R^2=0.73) was find for the group of variables:

SILP – forest inventory (Tab.1). Satisfactorily high indexes $R^2=0.95$ were obtained in the regression analysis for both variables CHM1 and CHM2 based on data obtained from ALS, in the relation to explanatory variable SILP.

There were not high differences between our results and other projects regarding the height determination of deciduous forest stands. In most papers, the mean error of the estimation of height took values below zero, indicating the underestimation of tree height based on ALS (Hyyppä *et al.* 2004, Maltamo *et al.* 2004, Rönnholm *et al.* 2004, Yu *et al.* 2004, Andersen and Breidenbach 2007) or close to zero; i.e. equal to the reference (Næsset 2004). Only results were obtained only by Næsset and Økland (2002) and McGaughey et al. (2004), show relatively small "overestimation" to the reference (respectively +0.18m and +0.29m).

Tab. 1 - Statistics of tree height (h_t) measured by selected methods. (**) – very high significant differences, $p<0.01$; (*) – significant differences, $0.01<p<0.05$; (n) – not significant differences; all 432 trees

		F. INV	SILP	TLS	CHM1	CHM2
	mean difference [m]		-1.14 $^{(**)}$	-0.98 $^{(**)}$	-0.90 $^{(**)}$	-0.12 $^{(n)}$
F. INV	R^2		0.73	0.81	0.81	0.80
	SD of difference		2.15	2.18	1.77	1.81
	mean difference [m]			0.02 $^{(n)}$	0.13 $^{(n)}$	0.85 $^{(*)}$
SILP	R^2			0.96	0.96	0.95
	SD of difference			1.01	0.94	1.02
	mean difference [m]				0.08 $^{(n)}$	0.83 $^{(**)}$
TLS	R^2				0.95	0.94
	SD of difference				0.86	0.94
	mean difference [m]					0.75 $^{(**)}$
CHM1	R^2					0.98
	SD of mean					0.58

3.2 Base and the length of crown

Mean difference between the base of crown determination using the traditional forest inventory method and ALS data was +0.52 m, indicating the underestimation by LiDAR (SD=1.5 m). The analysis of histograms on 0.5m slices of the point cloud ALS, e.g. for 214c (19.89 ha) showed that 82,30 % points (of over 2.5 million) remained in the layer, and only 12.5% of all impulses reached the ground. Regression analysis ($R^2=0.65$) indicates relation between field and ALS measurements (Fig. 2). Further analyses of the point cloud ALS showed that in compartment 214c (plots no.: 25, 27, 28 and 29) mean base of crown read from histogram by 7 operators was 15.9 m and thus was lower (-1.59 m) from that calculated automatically (17.49 m) for individual trees. It was found that mean base of crown differed by +1.65 m from the value defined for the whole compartment. There can be many causes for the problem of correct definition of the base of crown. First of all, the compactness of foliage conditions as well as the occurrence of dead branches on stems (underestimation +1.4 m above reference (Chasmer *et al.* 2006). Næsset & Økland (2002), Hall et al. (2005) and recently by Popescu & Zhao (2008) obtained similar coefficients R^2 equalling: 0.53, 0.80 and 0.79, respectively.

Additional test done during the field campaign on three conifer trees by the same 6 operators, showed that the base of crown measurement can vary from +1.11m to -0.76m (st. dev. 0.69) from the mean value. This result confirms that also the base of living crown measurement is very man-dependent.

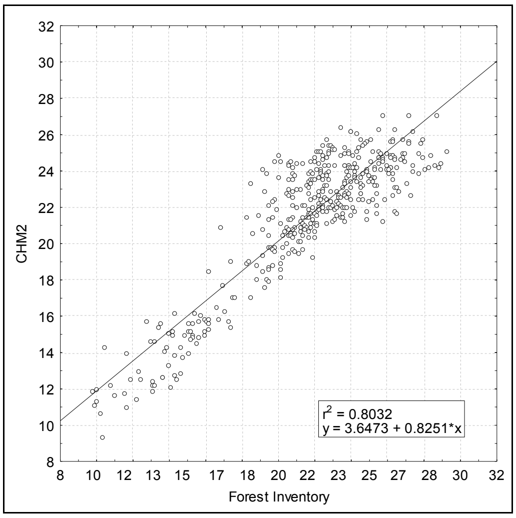

Fig. 1 - Regression analysis for the height (h_t) of the single tree for the CHM2 variable explained by the forest inventory ground truth data.

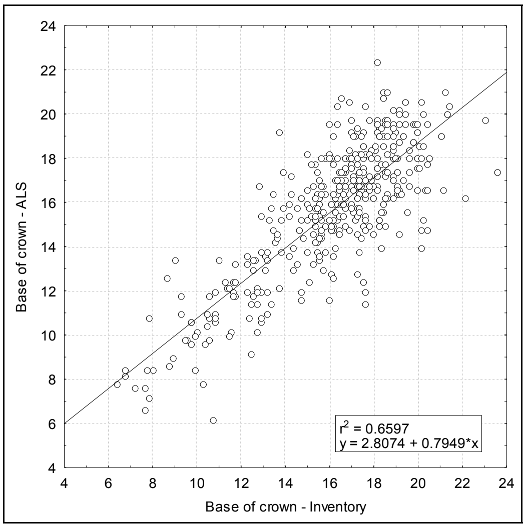

Fig. 2 - Linear regression for the base of living crown estimated form ALS (reference = Forest inventory)

The accuracy of the definition of crown length (L) was probably affected by the base of crown rather than the tree height estimation using ALS. Mean difference in the lengths (L) of crowns compared to reference data (forest inventory) was -0.42 m, which generally mean underestimation for the ALS method. For younger tree stands (<80 years) the difference in crown length (L) was only -0.22 m, while in older trees (>80 yr) as much as -0.56 m. Regression analysis showed relatively low value of coefficient R^2=0.28 The higher explaining value R^2=0.51 for crown lengths estimated from ALS was obtained by Næsset & Økland (2002) in their studies.

3.4 Crown area surface and volume of the tree and canopy layer

Carried out analysis of the crown surface area and crown volume were based on formulas (1, 3) for cone and (2, 4) for paraboloid.

Results for crown surface area indicate differences of about 15.1% and 36.6% (for cone and paraboloid method respectively) in the surface of the individual tree crowns. Crown surface area defined in GIS analyses for CHM (surface 3D + projection on a 2D surface) showed the differences reaching from 17.4% (cone) to 26.5% (paraboloid) compared to the sum of the crown areas of individual trees. Generating the canopy surface (CHM) makes the area of canopy layer differ by c.a. 11% to 28.6% compared to the sum of crown surface area calculated for individual crowns. Clear declining trend in crown surface area value with the age of the stand was also noticed.

The volume of the forest canopy defined from ALS surface is slightly smaller than the sum of individual crowns defined by the forest inventory (on average -9.0% for cone and -38.5% for paraboloid). The difference in volume between the solid generated from CHM (3D) with its base (2D) with the sum of individual crowns understood as paraboloid reached the average value of -38.7% (ALS) and -38.5% (forest inventory). Such differentiation resulted from the structure of the crown, difference in defining its length (L), and the CHM interpolation errors.

3.5 Homogeneity of the stand

Mean height of tree stands in analysed compartments, defined by authors as the 95th of the point cloud (FE only), varies from SILP data base (+0.47m; SD=0.60). It should be added that possibly the growth of tree stands from year 2005 to 2007 would partially equalize this difference. The authors did not know the localization of the sample plots used in defining the SILP height used in 2005. The differences in measured taxation features can be relatively high. This can result from the differentiation of a soil micro-site, cultivation procedures carried out during the forest stand lifetime, and random phenomena (breaking of the trees, pest invasion etc). Mean difference between height defined for the whole compartment and the mean height of the inventory plots was -0.37 m (SD=0.95). The spatial distribution of height (mean value H=20.96m) in a selected forest compartment 232b is presented in Fig. 3.

It is well known that the distribution of the DBH in the forest stand is close to normal, therefore there are also differences in the tree heights. However, in many cases, the spatial distribution of tree height in a single compartment indicates that the borders do not contain homogeneous stands (as it is shown in Fig. 3) because of diversity of the soil, humidity, solar radiation, wind etc.

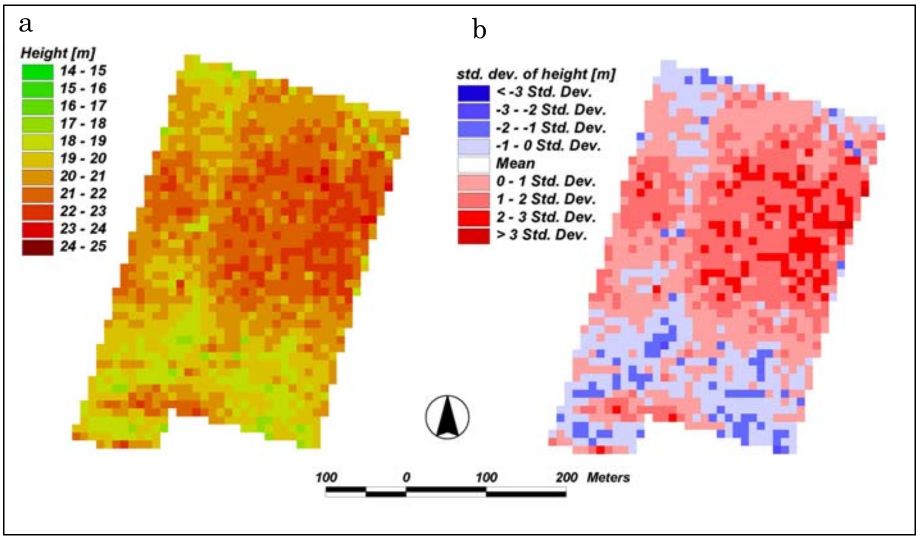

Fig. 3. Spatial distribution (a) and standard deviation (b) of height in compartment 232b.

4. Conclusions

Presented study addressed different questions related to the 3D spatial distribution of laser beams within a canopy of Scots pine stands using a different set of ground truth data, like forest inventory measurements, TLS, SILP databases, and ALS data. Seeking alternative methods of defining the base of crown height is encouraged by the fact that traditional methods are very time consuming and subjective. ALS technology for the first time gives the opportunities of describing the whole tree stand and not only its fragments represented by forest inventory plots. The results of our study indicate the following: (1) height for single trees derived from ALS data leads to small underestimation depending on CHM generation algorithm (e.g. 0.12 m for CHM2); (2) mean height for a stand was higher (+0.85 m) than the height from SILP database what can results in whole Milicz Forest district in underestimation of the wood volume; (3) mean height of a stand (understanding as 95th percentile of the FE point cloud) was +0.46 m higher than the height from SILP inventory database; (4) it was possible to estimate the base of crown with slight underestimation (-0.52 m) using the histogram of the ALS data; (5) length of crown measured from ALS was lower compared to reference data (0.42 m); (6) crown surface area was slightly greater and crown volume was smaller than the reference; (7) spatial homogeneity of height in the even-aged pine stand is questionable and lead to the urgent revision of the compartment borders. In the very near future new approaches of forest inventory supported with ALS data is expected as a list of new parameters and guidelines. Paper shows a need of further studies on ALS integration with other data sources (like TLS, digital aerial imageries) as a potential cost-effective operational forest inventory method for estimation of whole stand biomass. Future studies based on the single-tree approach should lead to precise forestry and to the optimization of forest inventory, like the new methodology in forest sampling.

Acknowledgements

Many thanks to the General Directorate of the Polish State Forest National Holding for financing of the RTD project: “Elaborating the method of forest inventory, based on the integration of selected geomatic techniques” managed by Warsaw Agricultural University (SGGW).

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