

The integration of the terrestrial and airborne laser scanning technologies in the semi-automated process of retrieving selected trees and forest stand parameters

Integração das tecnologias terrestre e aerotransportada de scanner laser no processo semi-automático de recuperação de árvores selecionadas e de parâmetros de povoamentos florestais

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Abstract

The traditional forest inventory based usually on thousands of the circle plots (radius = 12.62m; area 500 sq m) set in regular network. On every inventory plot, the basic tree and forest stand parameters have to be collected using calliper and hypsometer or even human eye (i.e. crown closure) as well. The modern multifunctional forestry models requires more and more: dens and accurate data to deliver as fast as possible the precise information on the amount of wood stock or other selected forest stand and tree parameters. One of the promising remote sensing technologies is LiDAR collecting the 3D point cloud data. The TLS technology is very precise and fast but is limited to relatively small areas like forest inventory plot. The ALS is more focused on wide-area data collection. Both technologies are complementary, therefore it is a need for the fusion of those two sources of information to enhance the accuracy of tree parameters and enlarge the results for the wide forest areas with statistical models. Paper presents a method of the TLS and ALS point cloud registration and transformation to one coordinate system. The goal of the data fusion was the semi-automatic extraction of the trees selected parameter (height, DBH, basal area, crown closure, base of crown, 2D and 3D tree crown surface) of the TR2 transect in Niepolomice Forest (Krakow, Poland). The results showed that the big potential of the enhancement of height and crown closure or base of the crown exists.

Key words: TLS; ALS; LiDAR point clouds integration; forest taxation parameters.

Resumo

O inventário florestal tradicional baseia-se normalmente em milhares de parcelas circulares (raio = 12,62 m, área 500 m²) dispostas em uma malha regular. Em cada parcela do inventário, os parâmetros básicos da árvore e do povoamento devem ser

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coletados usando suta e hipsômetro ou até mesmo o olho humano (densidade de copa). Os modernos modelos florestais multifuncionais requerem cada vez mais: dados densos e acurados para gerar o mais rápido possível a informação precisa da quantidade de estoque de madeira ou outro parâmetro selecionado do povoamento e da árvore. Uma das tecnologias promissoras de sensoriamento remoto é o LiDAR coletando os dados da nuvem de pontos 3D. A tecnologia TLS é muito precisa e rápida mas limitada a áreas relativamente pequenas como as parcelas de inventários florestais. A ALS é mais focada na coleta de dados em grandes áreas. Ambas as tecnologias são complementares portanto, é necessário para a fusão das duas fontes de informação aumentar a acurácia dos parâmetros de árvore e ampliar os resultados para grandes áreas florestais com modelos estatísticos. O artigo apresenta um método de registro e transformação do TLS e nuvem de pontos do ALS para um sistema de coordenadas. O objetivo da fusão dos dados foi a extração semi automática de parâmetros selecionados de árvores (altura, DAP, área basal, densidade de copa, base da copa, área 2D e 3D da copa da árvore) do transecto TR2 da Floresta Niepolomice (Krakow, Polônia). Os resultados mostraram que o grande potencial do aprimoramento da altura e do densidade de copa ou da base da copa existe.

Palavras-chave: TLS; ALS; integração da nuvem de pontos LiDAR; parâmetros.

Introduction

Sustainable forest economy demands very precise data on vertical and horizontal structure of the tree stand and biomass of forest resources. The measurements of trees carried out with traditional methods on inventory circle plots, usually refer to the tree diameter at breast height (DBH), height (h) and the number of trees (e.g. density parameter) of tree species per unit of the area. The forest inventory campaigns are very time and cost consuming, thus, there is a need to use the methods based on remote sensing technologies, which would speed up the measurements and significantly reduce the costs (KOK; WEZYK, 2008; WEIDENBACH et al., 2008). One of such dynamically developing technologies is LiDAR (Light Detection And Ranging), both in airborne (ALS) as well as terrestrial laser scanning (TLS; MLS – Mobile Laser Scanning). The LiDAR technology allows

quick obtaining information in the form of the 3D point clouds (XYZ) representing the vertical and horizontal structure of tree stands. TLS and ALS are obtained from the opposite localizations, which results in the case of each of them in certain failures referring to precise determine of the taxation parameter, or even completely excludes this. These methods are not contradictory, but complementary, like: LiDAR and Photogrammetry. The key to the success of using the advantages of each of LiDAR technologies is the data fusion by correct registration often achieved by manual geometric transformation of TLS scanner coordinate system into the ALS coordinate system (DONEUS et al., 2010). The development of technology causes that more and more data (e.g. LiDAR, multi- and hyperspectral images) collected by the devices mount on different platforms (terrestrial, mobile, airborne, UAV) can be integrated in CAD/GIS systems, using the position and time pattern (GPS), IMU/INS, detection of

the edges of buildings (HANSEN et al., 2008) or surveying transformations using the direct measurement of the objects (plains/surfaces) (PERRY; CHILDS, 2009) or scanner stands (DONEUS et al., 2010) as well.

The forestry application of TLS in obtaining selected taxation parameters of trees in a manual or automatic way have been known for only a few years (BIENERT et al., 2007; HOPKINSON et al., 2004; WEZYK et al., 2008, 2010c; WEZYK; TOMPALSKI, 2010). The results obtained by individual authors depended mainly on a specific type of the scanner and its integration with other devices like ALS (CHASMER et al., 2006, as well as on the parameters of the tree stand itself (DANSON et al., 2006). TLS technology allows getting such taxation features and parameters of trees such as: the location of the tree, DBH, the tree (g) and stand (G) basal area, tree height, length and width of the tree crown, length of the branchless part of the trunk, canopy density, tree stem density, taper of the trunk and its curvature, the leaf area index (LAI), the angle of branches, trunk thickness, vertical profile of the variability of tree stands biomass, trunk quality (texture of wood fibres, damages), detection of understory and natural regeneration, etc. (ASCHOFF; SPIECKER, 2004; HOPKINSON et al., 2004; DANSON et al., 2006; BIENERT et al., 2007; MAAS et al., 2008). While the application of TLS technology has a limited range (usually forest inventory circle plots), the use of ALS refers to wide-area projects. In tree stands of high density ALS point cloud can often provide more precise information than TLS data on the height of the tree stand or provide basis for the canopy modelling (ANDERSEN et al., 2006; CHASMER et al., 2006; WEZYK et al., 2008, 2010b).

Some limitations of ALS refer to the space of the tree stand under the canopy, i.e. lower parts of the tree crown, trunk and ground as well. While the percentage of ALS impulses reaching the forest ground usually allows a precise Digital Terrain Model (DTM), both obtaining information on trunk location, DBH or the basis of the tree crown is very limited, although possible by the prediction of the relationship of DBH with the height of the tree and the density (size of crown) of tree stand (WEZYK et al., 2010a). Other taxation parameters of trees and tree stands as well as the spatial features can be successfully defined by the analysis of the ALS point cloud. The following features can be included: the horizontal range of the tree stand, height (e.g. maxZ, 95 percentile), density or penetration of canopy, the number and location of trees, biomass, the base of the crown, 2D and 3D surface of the crown and others such as the crown volume (HYYPÄ et al., 2004; HOLLAUS et al., 2007; WEZYK, 2008; WEZYK; SIECZKA, 2010; WEZYK et al., 2010a, 2010b; McGAUGHEY, 2012). Mutual supplementation of the information originating from two sources of data, i.e.: very precise local TLS and wide-area ALS now become almost the requirement in constructing correct statistical models describing e.g. the development of tree stands and their characteristic.

The purpose of the paper was to demonstrate the added value of the integration of the point clouds from complementary systems: terrestrial laser scanning with airborne laser scanning - to enhance the supplementation and information in terms of the semi-automatic extraction of selected taxation parameters of trees and tree stands.

Test Area

The presented study was performed on the research transect (100 m x 125 m) on the so called “TR2”, established in the mixed oak–pine stands (*Pino-Quercetum* community) of the Niepolomice Forest (wooded area: 10,507 ha; N: 50°02'26.28"; E: 20°23'06.18"; South Poland, figure1) in the framework of the FOREMMS project (5FP UE) in the 2001 year (SOCHA; WEZYK, 2007). The main forest tree species here are: Scots pine (*Pinus sylvestris* L.) occupying 64.5% of total wooded area, common oak (*Quercus robur* L.) and sessile oak (*Quercus sessilis* L.) - together 20.4% and European black alder (*Alnus glutinosa* Gaertn.) with an area of 10.9%. The mean age of the stands in Niepolomice Forest stands is 65 years and the biomass reaches approx. 282 m³/ha with increment of 5.02 m³/ha/year.

The radius of TR2_TLS was 4 times bigger (radius: 25 m; area: 1963.5 m²) than common forest inventory plot used in Polish State Forest (radius: 12.62 m; area: 500 m²). On the TR2_TLS plot, the 44 trees with DBH > 7 cm were found, i.e.: 24 Scots pines, 19 common oaks (5 trees in the storey II of the tree stand) and 1 Silver birch. All the trees (of DBH > 7 cm) were numbered on the whole TR2 area in 2001 and measured on the circle plot TR2_TLS with traditional methods. The DBH was defined in 5 directions with the calliper (accuracy 0.01 m) in 2006. The first measurement marked DBH_1 means the transverse measurement towards the direction of falling laser beam on the tree trunk from the scanner stand S_1. The subsequent referred to: DBH_2 – according to the direction of the laser and subsequent DBH_3÷5 transversely to the remaining stands of scanner (S_2÷5) and the perimeter of the tree was measured with the tape (0.01

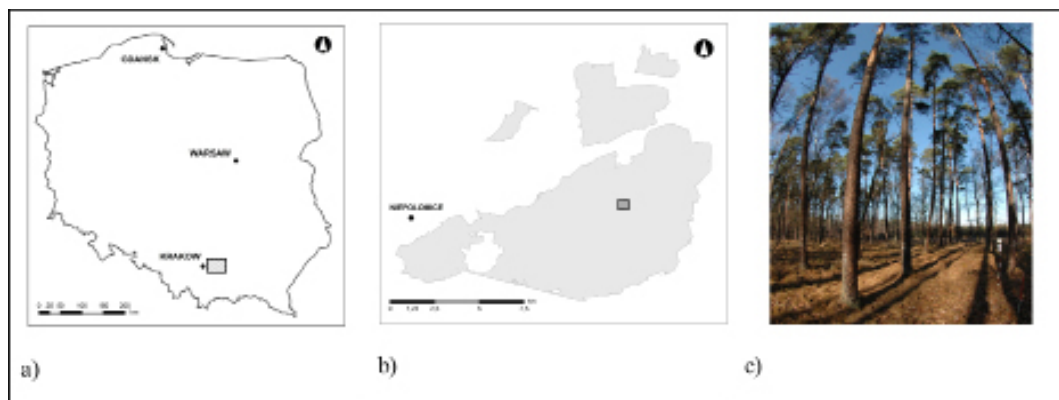


Figure 1. Localization of the test site in Niepolomice Forest near from Krakow, South Poland (a), the research transect TR2 in forest compartment I 13d (b) and the view of the TR2_TLS inventory plot (c).

Material and Methods

Reference Measurements

In November 2006 the localization of the experimental forest inventory plot, called TR2_TLS was chosen and stabilized in the central part of the research transect TR2.

cm). The height of the tree was defined by the hypsometers of Vertex II (Haglöf). All the locations of tree trunks were measured with the polar method from stand S_1.

On the “King’s road” lying near the transect TR2, in the places of significantly uncovered horizon, two survey points were permanently stabilized. The first of them

- GPS_10 made the beginning and end of the traverse. Point GPS_11 making the reference of the traverse located on the cross road (distance 192.36 m; azimuth 245.43). To make GPS static observation, the Leica receivers: GX1230GG (GPS_10) and GS15 VIVA (GPS_11) were used (GEOSAT Krakow). Reference measurements of the centre of the TR2_TLS circle plot (S_1) were made with the method of the traverse (Total Station: Topcon GTS 212). The observations of the distances and directions in subsequent points: GPS_10, 03, 02, 01, S_1, 01, 02, 03 and GPS_10 (Figure 2) were done.

Airborne Laser Scanning

ALS data were obtained with scanner REIALS data were obtained with

scanner REIGL LMS-Q560 in September 2006 from the Eurocopter (Milan Flug; Germany), at the height 450 m over the ground. Two strips of the flight (width of about 500 m, density approx. 3 pts/m²; FE/LE) covered the study area TR2, so that, the density of the ALS cloud points in total was ca. 6 pts/m² (Figure 3). Due to the lack of buildings typically used as georeferencing KAGER, 2004), in the direct proximity of the flight, height and situation adjustment was carried out based on IMU/GPS and measured GCP's (dGPS/tachymetry) and plains of adjustment located on the forest roads fragments with open horizon. ALS point cloud (Figure 3) was written in the projection UTM 34N and the Polish height reference system (Kronsztad 86; MSL).

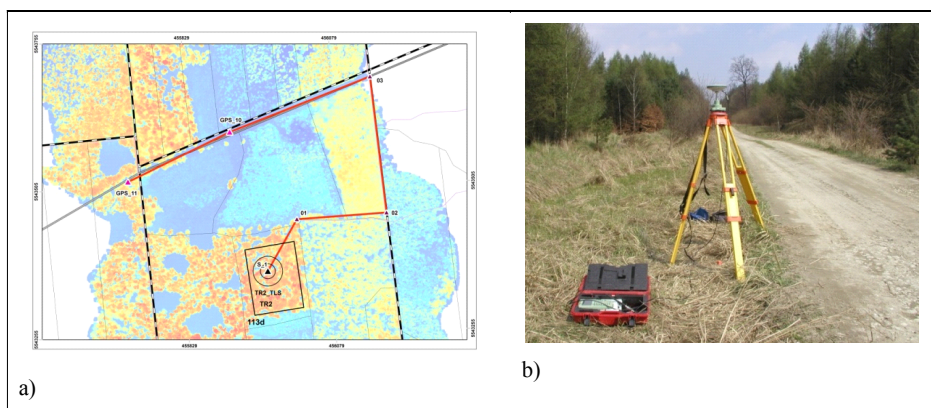


Figure 2. The traverse from GPS_10 to S_1 done with Total Station Topcon GTS 212 (a) and the dGPS static RTK survey of GPS_10 using the GX1230GG Leica GPS receiver (b)

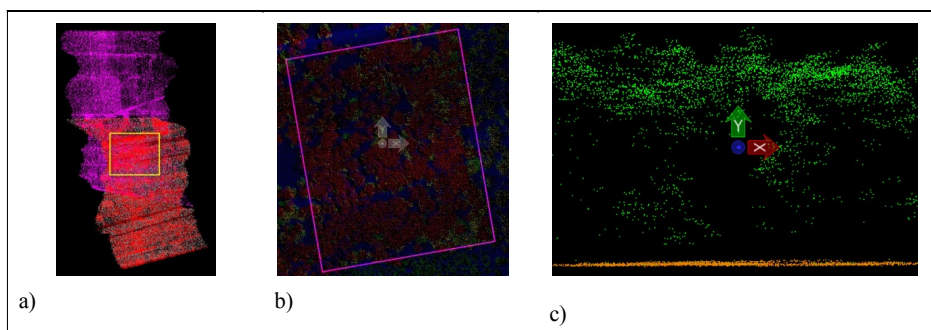


Figure 3. The two ALS strips (magenta ID=6; red ID=7) (a) and enlarged area of TR2 transect (b; colors by absolute elevation) and profile of classified data set (c)

TLS Hardware

In November 2006 the scanner FARO LS880 HE80, based on phase shift technology, was used. FARO operates within the range 360° (H) and 320° (V). The option ¼ of full resolution was applied (size of single scan ~160 MB; scanning time of about 7 minutes). To manage the scans and combine them, based on 5 reference spheres (radius: 7.25 cm), the software FARO Scene ver. 4.0 was applied.

TLS Forest Inventory Method

Multi-stand method of scanning (WEZYK et al., 2007) assumes 1 central position S_1 and 3 additional ones (S_2, S_3 and S_4) located out of the radius of the standard circle plot (r=12.62 m; area: 500 m²) but not further than 16÷17 m from spheres, was applied. Such a location of TLS scanners regarding the visibility of minimum 3 spheres

from each position, allows the imaging tree trunks as 3D, almost from every side (Figure 4).

Relative Orientation of TLS Point Cloud

The cloud of points from 4 stands of FARO scanner were connected by identifying and numbering the spheres in FARO Scene software. The matched data were exported to ASCII (XYZI) file format in the local coordinates system of the scanner LSRS (Local Scanner Reference System) (0,0,0). In the next step, the imported point cloud TLS was written into binary format and LAS 1.2 (TerraScan, Terrasolid).

Registration of TLS Point Cloud

The key step of the integration of the ALS and TLS point clouds is their registration to common coordinates system. ALS point cloud is transferred by the supplier

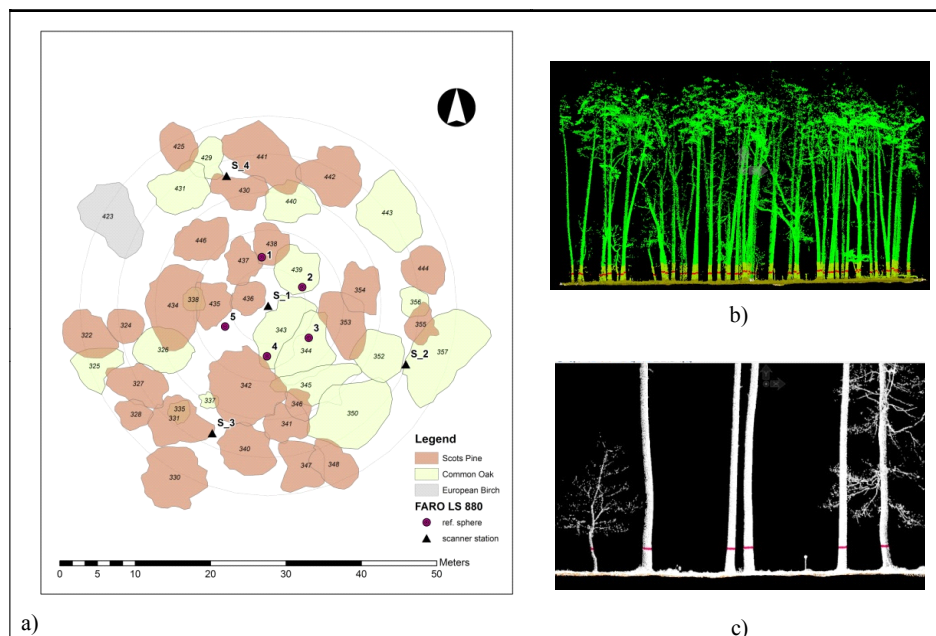


Figure 4. Map of FARO scanner stations, spheres and tree crowns on the experimental 25 m radius inventory plot (a), the N-S Profile trough TLS classified point cloud data (b) and enlarged part (magenta slices: DBH 1.28-1.32 m above DTM; (c)).

in a defined coordinate system, thus it is easier to make transformation from LSRS (0,0,0) into ALS (UTM34N). In the first step the translation of the height system of the TLS point cloud was made (TerraScan, Terrasolid). This requires the classification of the ground (*TScan/Classify/Routine/Ground*) in the TLS data set. The DTM quality is crucial for further analyses e.g. automatic classification of points of the high vegetation above the ground or to generate the slices of the trunk (DBH) or define the height of the trees (Z_{max} ; 95 percentile). In the study the active model method triangulated irregular network (TIN) was applied (AXELSSON, 2000; Terrasolid). The Z value on the ground in the closest point from S_1 (FARO Scene) indicated that the mirror of the scanner was on the height +1.66 over the local DTM. The TLS point cloud was raise on the axis Z to obtain the value $Z = 0.0$ m (DTM relative level). As the ultimate value Z the heights of points of ground ALS were accepted in the same localizations covered by TLS and ALS (measurement on the ground in the gaps). Due to different grass vegetation (Sept. and Nov. 2006) on TR2, this method turned out to have an error of about 0.32 m. It was replaced by a static measurement of scanner stand (S_1) made by dGPS and total station (UTM34N; X=455965.05, Y=5543361.17, Z=196.67 MSL; Figure 4).

The TLS point cloud was transformed from the LSRS using macro: Transformation/Linear (TerraScan) into the real UTM 34N projection. Then it was necessary to rotate the TLS data, due to a small angular difference (connected with indicating the direction of the scan beginning, i.e. North with the use of compass). From stand S_1, the azimuth angles to the closest 4 tree trunks (436, 437, 438 and 439) were determined and compared to the readings of the planar view (FARO Scene

ver. 4.0). The values of angular difference were calculated into radians and the TLS point cloud was rotate by macro Transformation/3D translate & rotate (TerraScan).

Measurement DBH in the Point Cloud TLS

In the planar view (FARO Scene) the measurements of tree diameter at breast height (DBH) were carried out with a reference manual method (later on called PIXEL) and semi-automatic methods (so-called PIPE). The first method meant indicating edges pixels representing the tree trunk at the height 1.3 over the local ground. The second method meant indicating the vertical and horizontal axes of the trunk running through the point of the stem height of 1.3 m above the ground. Another method applied was fully automatic and meant the application of the author's algorithm „Slice” to define the basal area of 4 cm-thick slice of the TLS point cloud cut from the tree trunk (WEZYK et al., 2007). The TLS data was subdued to automatic classification with the application of macro, which allowed create the class DBH_1.3 (1.28÷1.32 m above DTM; Figure 4c; TerraScan).

Results

The dGPS and Tachymetry Survey

Static observations of dGPS were calculated and equalized in the software Leica Geo Office (ver. 7.0) in the reference to the closest reference stations (KRAW and PROSZ) of network ASG-EUPOS. The series of static dGPS measurements referred to precise marking the position and direction of the initial point of transverse GPS_10

and reference GPS_11. The measurement observations of these points lasted 3h 45'30" and 3h 13'05" respectively on the Ionosphere-free frequency (phase observation L3) with the application of measurement solution "Phase: all fix" (horizontal mask: 15°). The error of the dGPS static measurement did not exceed the value 0.01 m. The applied corrections (Lat./Long./Hgt.) were only: +0.0002, -0.0014 and -0.0012 m. The traverse made using the total station had acceptable angle-linear deviations on the level of $\pm 0.03 \text{ m} \div 0.05 \text{ m}$ (XYZ). Defined by total station azimuths to 4 trees allowed the rotation of the point cloud TLS by 5.5° (0.09599 radians). This way a TLS point cloud was prepared to direct integration, artificially adding to each TLS point attribute a „1" (ALS data received = "2") by the automatic order „Flightline numbering/

Assign constant" (TerraScan), which allows the visualization of points in distinct colours and the control of the integration process.

The Statistics of Point Cloud TLS and ALS

The TLS and ALS point clouds (Figure 5) were subdued to automatic macros, the result of which is presented below (Table 1). Inside the inventory circle plot of the radius of 25 m (area ca. 2000 m² and volume ~60.000 m³) about 2172 times more TLS beams were recorded than ALS echo's. Counting these values into density (volume) units indicates that TLS points are about 420 pts/m³ and ALS points are only 0.2 pts/m³.

Based on the selected (from the TLS point cloud) sets of single trees



Figure 5. Profiles of the: ALS (a), TLS (b) and integrated A&T Laser Scanning (c) point cloud.

Table 1. Base statistic of the TLS, ALS and integrated (A&TLS) point clouds

Class	TLS (pts.)	TLS class (%)	ALS (pts.)	ALS class (%)	all A&T LS (pts.)	% TLS of all pts.	% ALS of all pts
ground (0.00m)	93650.00	0.38	1808	15.84	95458.00	98.11	1.89
low veg. (0.0÷0.5m)	19130708.00	77.18	2222	19.47	19132930.00	99.99	0.01
medium veg. (+0.5÷2.5m)	867580.00	3.50	3	0.03	867583.00	100.00	0.00
high veg. (>2.50m)	4596483.00	18.54	7378	64.66	4603861.00	99.84	0.16
DBH_1.3 (+1.28÷1.32)	98928.00	0.40	-	-	98 928.00	100.00	0.00
SUM	24787349.00		11411		24798760.00	-	-

(inside the outlines of crowns) without the representation of ground class, it was calculated that on the trunks of Scots pine and common oak there were 77.5% and 81.4% of the total points, respectively. The crowns were represented by 21.1% and 9.4% points TLS, respectively (oaks were scanned in November; the “leaf-off” period) and thicker branches by 1.4% and 7.6%.

The below presented histogram (FUSION-GRIDMETRIS;McGAUGHEY, 2012) of the vertical distribution of the integrated A&TLS point cloud of a single Scots pine (ID=342; DBH= 69.2 cm; HALS=30.65 m) with very dense crown, demonstrates that TLS and ALS technologies are complementary. In the top part of the pine crown (Figure 6a), it can be noticed many ALS laser hits, while in the

lower part of the crown the domination of TLS points can be observed (Figure 6b).

Measurements of Selected Taxation Teatures in the TLS Point Cloud

The mean DBH for the analyzed trees on a typical circle plot radius ($r=12.62$ m) was 44.46 cm (Scots pine) and 38.34 cm (common oak). The reference values of mean tree trunk perimeter were for these species 134.88 cm and 115.49 cm respectively. The perimeter measured with a tape increased DBH of the Scots pine by about +0.69 cm (reference: mean of 5 different measurements of $DBH_{1\div 5}$) and by +0.79 cm for the common oak. The DBH carried out in FARO Scene were different from the reference values of about 0.03% (PIXEL) and 2.30% (PIPE; Table 2). The PIXEL method increased the

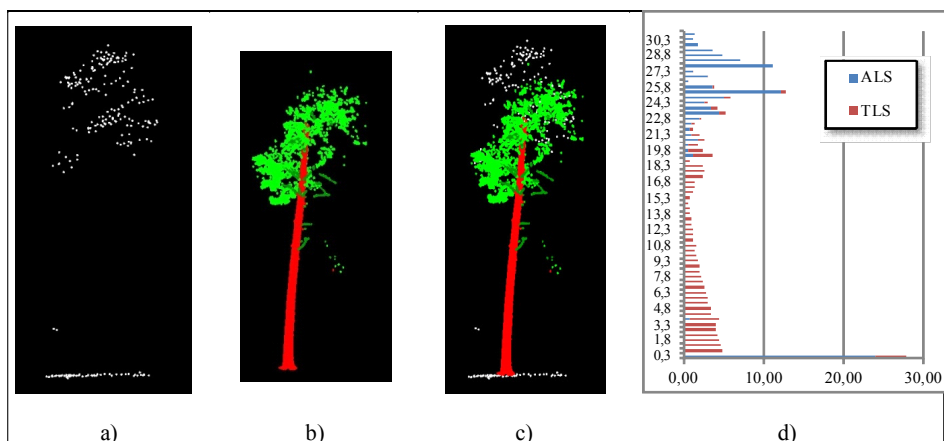


Figure 6. Profiles of the:ALS (Scots pine ID=342; white 445pts.; (a)), TLS with classes: stem (232.247 pts), branches (10.357 pts.), crown (46.106 pts.) (b) and A&T LS integrated point cloud (c) with the histogram (d).

Table 2. Differences of DBH deriving from the TLS point cloud with different methods

Tree species	PIXEL DBH mean (%)	PIXEL DBH mean% (mode)	PIPE mean DBH (%)	PIPE DBH mean% (mode)	„slice” DBH1 (cm)	„slice” DBH1 (%)	„slice” DBH_1 % (mode)	„slice” DBH mean (cm)	„slice” DBH mean (%)	„slice” DBH mean % (mode)
pine	1.27	2.90	200	5.61	-1.44	-2.77	4.93	-1.48	-2.23	3.70
oak	-1.06	3.06	1.82	4.06	-0.57	-1.60	2.30	-0.88	-3.05	2.78
all trees	0.03	3.20	2.30	5.28	-1.10	-2.67	4.21	-1.24	-2.83	3.60

DBH values of about 1.27% for the Scots pine, which could be caused by the bark peeling on the trunk. In case of the common oak the opposite trend was observed, which can indicate the limited resolution of TLS data. In case of the semi-automatic PIPE method, the formed cylinders increased the real DBH value by almost 2.0% both for the Scots pine as well as common oak. Such situation is caused by adjusting the cylinder into the point cloud of an irregular part of the tree trunk (e.g. slightly twisted or with the defects of the wood). Mean absolute values for these differences were significantly higher and equaled 3.20% for methods PIXEL and 5.28% for PIPE, respectively.

The applied method of automatic definition of DBH with „Slice” algorithm (WEZYK et al. 2007) based on TLS point class “DBH_1.3” (Figure 4c), in the first step leads to the definition of the area of the convex hull, i.e. „g” (basal area), which is sought by the foresters to define the

wood volume of tree stands. Based on “g”, the DBH or radius can be calculated in reverse method if necessary. It turns out that comparing the value of DBH_Slice with reference measurement DBH_1 (calliper) the error was -1.10 cm (Table 2; calliper measurement lowered for all the trees of about 2.67%; for the Scots pine 2.77%, common oak 1.6%;). The comparison of methods with the use of algorithm „Slice” to 5 reference measurements with the calliper (DBH_mean) gave very similar results, slightly higher for the common oak (lowering 0.88 cm; -3.05%). Analyzing the mean absolute values of the differences showed that for all the species it was 3.60% (Scots pine 3.7%; common oak 2.78%) in case of the comparison with the mean of 5 measurements with the calliper.

Based on the DBH point class (Figure 7b,c) the „Slice” algorithm, returned the precise coordinates of the centroid of the created convex hull and the map of tree

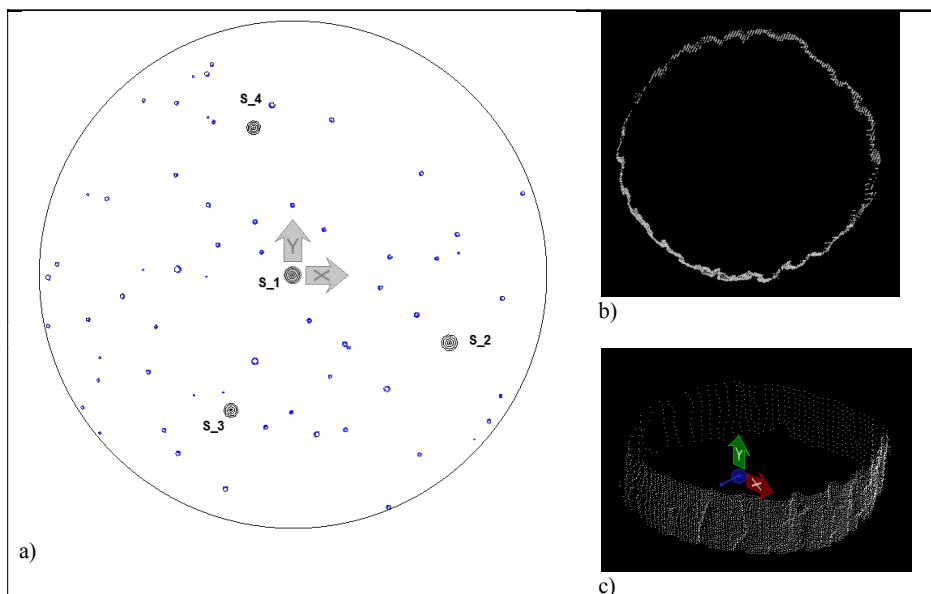


Figure 7. Map of tree stem positions (slices) at the TR2_TLS area (S_1 +4 scanner positions) (a), Slice trough pine ID=342 at the height 1.28-1.32 above DTM (b) and Isometric view of 4cm slice (c)

stem was done (Figure 7a). The CAD/GIS analyses allows making the azimuth table and distance table to every tree of S_1, even if it is concealed by another trunk. In the class “ground” and “low vegetation” the areas (diameter approx. 1.4 m) without the TLS points were detected as the scanner stands (S_2 was: 19.7 m and 112° form S_1 position, and subsequent ones: S_3: 17.5 m and 201.5° and S_4: 17.97 m and 341.5°). This allows to make the map of the scanner positions and spheres (Figure 7a).

Height of the Trees And the Characteristics of the Crowns (TLS & ALS)

The mean height of the common oak (I storey), derived on the TLS point cloud with the application GNOM (RATAJCZAK, 2010) was 23.70 m (5.99 m - II storey; 5 oaks), Scots pine: 26.15 m and silver birch 25.48 m. The same point cloud interpreted by the operator in TerraScan gave values: -1.0 m lower for Scots pine and the respective results for the oak and birch were: -0.27 m and -1.20 m. Automatic analyses carried out on the ALS point cloud showed mean height

for the common oak form Ist storey: 23.97 m (6.08 IIInd storey), the Scots pine: 27.10 m and silver birch: 26.65 m. The mean height differences between ALS and TLS data for all analyzed trees of I storey were approx. 0.63 m, indicating lowering this parameter by TLS technology. The main problem of TLS is in the limitation in the ability of laser beams to reach the tree top parts, limited scanning resolution and seasonal differences in LAI (oak).

Application GNOM in its subsequent modification is now able to define the base of crown (bc), diameter and maximal radius (one of 8 main directions). Based on these values the: length of crown (lc), 2D and 3D surfaces as well as volume (V/m³) of the tree crown can be calculated (Table 3).

Using the Cloudmetrix (FUSION; McGAUGHEY 2012; Table 4) it was possible to derive the characteristics of ALS and TLS point clouds, as well as integration of both data sources. The Cloudmetrix worked on the prepared point sets of single trees (files *.LAS) cut with the TLS outlines of tree crowns (function *Polyclipdata*; FUSION). On average the single Scots pine crown contained 189 impulses of ALS beams.

Table 3. The characteristics of the tree crowns of the I storey of the tree stand on TR2_TLS (r=25m)

Spec. /n [pcs.]	Statistics	h _t [m]	b _c [m]	l _c [m]	r _c [m]	area 2D [m ²]	area 3D** [m ²]	V _c *** [m ³]
Pine 23	mean	27.10	17.41	9.08	3.14	32.8	80.4	84.0
	std. dev.	1.69	2.42	2.74	0.76	16.23	43.04	69.55
Oak* 16	mean	23.97	13.24	11.40	3.77	46.15	159.4	288.7
	std. dev.	1.86	5.12	5.64	0.72	18.45	62.76	143.90
Birch 1	mean	27.25	20.25	7.00	4.1	53.80	105.7	111.3

Note: * only I storey, h_t [m] - height of tree top; b_c [m]- base of crown; l_c [m]- length of crown; r_c [m] - radius of crown; area 3D ** - cone; V_c - volume of crown [m³] *** paraboloid.

Table 4. The example of the values of indexes (metrix) obtained by the function Cloudmetrix (FUSION) on ALS datasets for single trees

Tree_id	342	326	425	324	429	423	434	354	341	348
ALS points [pts]	445	189	92	47	52	209	266	105	115	126
Elevation parameters:										
min. [m]	0.0	0.0	0.2	0.0	0.2	0.1	0.0	0.0	0.0	0.2
max. [m]	30.6	30.0	29.9	29.8	29.5	28.6	28.6	28.5	28.3	28.2
mean [m]	22.8	20.3	20.8	21.7	19.5	14.4	23.6	21.0	23.2	24.0
median [m]	25.6	23.0	25.9	27.7	24.4	21.2	27.3	25.0	23.5	24.7
mode [m]	27.7	0.0	0.2	27.4	23.9	0.1	27.2	25.8	22.9	24.6
std. dev. [m]	9.2	8.3	10.6	11.5	9.4	12.6	8.6	9.2	4.2	3.9
variance	84.6	69.6	113.4	132.3	89.0	158.0	74.7	85.1	17.7	15.0
Percentile 5	0.0	0.1	0.3	0.0	5.6	0.2	0.1	0.0	19.1	19.8
Percentile 10	0.1	0.2	0.5	0.0	6.1	0.2	0.1	0.1	20.6	21.0
Percentile 90	29.1	27.2	29.6	29.4	28.2	27.7	28.1	27.1	25.2	27.7
Percentile 95	29.6	28.6	29.8	29.6	28.7	27.9	28.2	27.9	25.7	28.0

The Density Of The Tree Stand

The reference value of canopy closure has based on vectorization of the TLS point cloud (range of the crown) and was 76.9%. Should they, however bear in mind that TLS was carried out during the leaf-off period, thus inaccuracies in the crown shape were possible. The nDSM (GSD 0.5 m; smoothed surface, median filter 3x3; FUSION) was generated automatically based on the ALS point cloud normalized using precise DTM. The model was exported as ASCII GRID

and in the ArcGIS10 Esri it was reclassified into two ranges separated by the height of the crown base (Figure 8). The crown base was automatically computed (GNOM): for the common oak as 13.24 m (only trees of I storey) and Scots pine: 17.41 m. The value of canopy closure of the TR2_TLS plot obtained by Spatial Analyst (Esri) for the base of the crown of 13.0 m was: 71.1% (gaps made 28.9%). This relatively small error of 5.8% can be totally neglected comparing to the traditional methods of crown closure estimation.

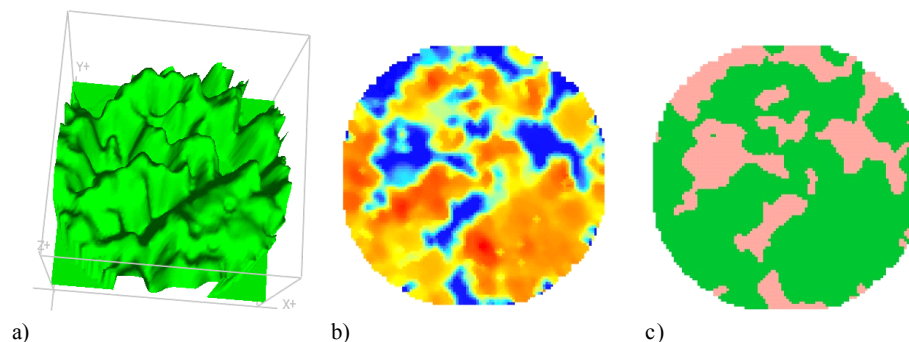


Figure 8. Isometric view of nDSM of TR2_ALS ($r=25$ m) inventory plot (a), nDSM of TR2_ALS inventory plot (b) and reclassified nDSM, green: crowns $h > 13$ m; pink: gaps $h < 13$ m < 0 (c)..

Discussion

A large part of the studies in the recent years focused on the increase of the speed and accuracy of automatic algorithms to apply the crown of trees on DSM or nDSM models (WEZYK et al., 2010; POPESCU; WYNNE, 2004) or automatic measurement of tree trunks. Bienert et al. (2007) with the TreeMetrics company made the program of AutoStem, allowing the automatic measurement of tree parameters (number of trees, area of cross-section at any height, the situation of the tree in the area and the height of the top) in the TLS point cloud. There were also attempts, described by Maas et al. (2008) of detection and measurement of trees with a method based on so called voxels (GORTE; PFEIFER, 2004). However, it turned out to be of little efficiency, because at best it was possible to detect only 52% trees, and the measurement of the trunk diameter was characterized by the standard deviation of 3.5cm. The integration of TLS and ALS clouds (A&T LS; Airoborne&Terrestrial Laser Scanning) based on surveying measurements is nowadays possible due to the development of GNSS technologies (the reception of satellites GPS-NAVSTAR and GLONASS) as well as the network

of reference stations (e.g. ASG-EUPOS). The precision of the transformation of TLS point clouds from the local system (0,0,0) to the system of coordinates exceeds many times (about 4-6x) the precision of ALS point cloud georeferencing, because the forest area are usually lacking planar surfaces (i.e.: buildings, infrastructure) where the adjustment in to the defined XYZ coordinate system is made. The integration of A&T LS data provides the increase of the accuracy of the measurement of the: tree top heights, density, crown base and length or storey structure and enables the transposition of the results on large forest areas, for which statistical models are constructed in order to estimate the wood biomass (WEZYK; SROGA, 2010). Looking at the research trends and the publications of other authors, the papers on the LiDAR application (like development of GNOM and other methods; WEZYK et al., 2009, 2010a) of in forestry carried out since 2006 in the Laboratory of Geomatics (Faculty of Forestry, Agricultural University in Krakow, Poland) looks very promising. The integration of TLS and ALS supported by the Photogrammetry (i.e. CIR) or VHRS images can offer much more to forest inventory techniques than the separated techniques.

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