JOURNAL OF FOREST SCIENCE, *63*, 2017 (9): 433–441

doi: 10.17221/28/2017-JFS

Estimation of diameter at breast height from mobile laser scanning data collected under a heavy forest canopy

Juraj ČERŇAVA, Ján TUČEK, Milan KOREŇ, Martin MOKROŠ*

Department of Forest Management and Geodesy, Faculty of Forestry, Technical University in Zvolen, Zvolen, Slovak Republic

**Corresponding author: juraj.cernava@tuzvo.sk*

Abstract

Čerňava J., Tuček J., Koreň M., Mokroš M. (2017): Estimation of diameter at breast height from mobile laser scanning data collected under a heavy forest canopy. J. For. Sci., 63: 433–441.

Mobile laser scanning (MLS) is time-efficient technology of geospatial data collection that proved its ability to provide accurate measurements in many fields. Mobile innovation of the terrestrial laser scanning has a potential to collect forest inventory data on a tree level from large plots in a short time. Valuable data, collected using mobile mapping system (MMS), becomes very difficult to process when Global Navigation Satellite System (GNSS) outages become too long. A heavy forest canopy blocking the GNSS signal and limited accessibility can make mobile mapping very difficult. This paper presents processing of data collected by MMS under a heavy forest canopy. DBH was estimated from MLS point cloud using three different methods. Root mean squared error varied between 2.65 and 5.57 cm. Our research resulted in verification of the influence of MLS coverage of tree stem on the accuracy of DBH data.

Keywords: mobile mapping system; clustering; point cloud; circle fit

After more than a decade of research in the field of the use of terrestrial laser scanning (TLS) for forestry, conclusions of many research papers presented TLS lack of mobility as the greatest disadvantage of this technology (Liang et al. 2014, 2016; Kelbe et al. 2015). Mobile mapping systems (MMS), which include mobile laser scanner and additional cameras, can provide point clouds with density similar to TLS. These systems are usually mounted on a mobile platform such as cars. Despite the fact that the first systems were mounted on cars, a mobile mapping system can be mounted on any vehicle that is capable to carry its weight.

Forested areas usually consist of various types of terrains that in most cases do not allow road vehicles to pass through. If we want to collect data from the forest using a mobile mapping system, we have to mount it on the vehicle that is adapted to the forest terrain.

Besides the accessibility issues we are dealing with the issue of Global Navigation Satellite System (GNSS) signal availability under more or less dense forest canopy while collecting the data by MMS. Orientation and location of MMS are calculated by an inertial navigation system (INS) which provides coordinates for returns of laser pulse. Under favourable conditions GNSS ensures high accuracy measurements of sensed objects, but forested areas covered by canopy do not allow GNSS to measure correctly during the whole data collection. When the GNSS signal becomes too weak, inertial measurement unit (IMU) and odometer data is used to correct the trajectory of mobile mapping system movement. Not even this smart cooperation of INS

Supported by the Scientific Grant Agency of the Ministry of Education of the Slovak Republic and Slovak Academy of Sciences – VEGA, Grant No. 1/0953/13.

devices synchronized by a control unit ensures the correct position of sensed objects under a heavy forest canopy. The location measured using GNSS under varying forest canopy is recorded at an accuracy of about 3 m (Rasinmäki, Melkas 2005). Holopainen et al. (2014) believed that mobile laser scanning (MLS) based tree mapping is capable of providing accurate tree maps (less than 1 m mean error of *xy*-coordinates) for mature stands. Tang et al. (2015) dealt with the issue of canopy covered tree stem mapping and proposed an adequate solution. Gillet et al. (2000) used an Applanix POS LS device for a seismic survey and achieved sub-meter position error. Reutebuch et al. (2003) tested the Applanix POS LS system under a heavy forest canopy. They were able to improve system's average real-time position accuracy from 2.3 ft position to 1.4 ft after post-processing.

Several studies showed the potential of MLS to provide accurate DBH estimations (Wu et al. 2013; Liang et al. 2014; Forsman et al. 2016). MLS has already been tested for mapping larger forest plots (Holopainen et al. 2013; Liang et al. 2014). It is obvious that MLS can ensure the sample size, which is more than necessary for the following total stem volume calculation on an operational level. The aims of this study are to compare methods of DBH estimation from MLS data and to evaluate the influence of the MLS coverage of tree stem (i.e. the percentage of a stem cross-section that is covered by the MLS point cloud) (Wang et al. 2016) on the accuracy of DBH estimation. We present a reduction of the sample size based on MLS coverage of tree stem and its influence on relative root mean squared error (RMSE) of DBH estimation using three different methods.

MATERIAL AND METHODS

Study area. Data collection was carried out in the territory of the Technical University in Zvolen Forest Enterprise in July 2015. The study area is covered by mature beech, oak-beech and hornbeam-oak-beech forests. The flat terrain is typical of mapped forests. The slope in the area varies between 15 and 35%. Terrain conditions allowed us to use a tractor for mobile mapping.

We used all available forest roads, and also skid trails inside the forests, for data collection. About 5.3 km of forest roads and skid trails were mapped as the length of the trajectory shows.

Data processing was focused on the 110 years old forest stand consisting mainly of beech (*Fagus sylvatica* Linnaeus), oak (*Quercus petraea* Linnaeus) and hornbeam (*Carpinus betulus* Linnaeus) (Fig. 1). This forest stand consists of 909 trees and DBH calculated from a sample of 692 trees varies between 8.85 and 85 cm. The stand has relative density of 0.7. About 330 m of forest road is located along the north border of the forest stand and about 964 m of skid trails is located inside the forest stand. These values were estimated from the trajectory of MMS movement.

Field data. Reference data was collected in December 2015. DBH was measured at a height of 1.3 m in two perpendicular directions. Directions of measurement were adapted to the terrain. The first DBH was measured along the terrain contour line and the second was measured perpendicularly to the first direction of measurement.

Circumference data was calculated from diameters at breast height using the average value of two perpendicular measurements and standard form for the equation of a circle circumference.

Field data were imported manually based on the point cloud cross-section and a rough map of stem positions was created in the field during the reference data collection.

Mobile mapping system. RIEGL VMX-250 (RIEGL Laser Measurement Systems GmbH, Austria) mobile mapping system was used for data collection (Fig. 2). The system includes two integrated mobile laser scanners VQ-250, one panoramic camera and two additional digital cameras with high resolution (2,452 × 2,056 pixels). Scanner frequency was set to 300 kHz, which is the highest possible frequency. The navigation system consists of Applanix GNSS-POS LV 510 and IMU-31, odometer and control unit, which synchronizes navigation data. The Applanix INS-GNSS navigation system, integrated in the RIEGL VMX-250 system, is specified only for outages up to 1 min·km^{-1} (Boavida et al. 2012). The mobile mapping system was mounted on a Zetor Horal 7245 tractor (Zetor Tractors, a.s., Czech Republic).

Mapping technique. We can achieve an output similar to the output produced by the TLS single scan method used only on a forest road network. This can lead to less precise DBH estimation (Čerňava 2015). Similar result was obtained by Liang et al. (2014) or Forsman et al. (2016). We assumed that we can improve the accuracy of DBH estimation by sensing the stem from multiple positions. We also assumed that by returning to the open field with decent GNSS signal availability, data for the objects scanned from multiple positions will be correctly registered using only the navigation system and usual post-processing.

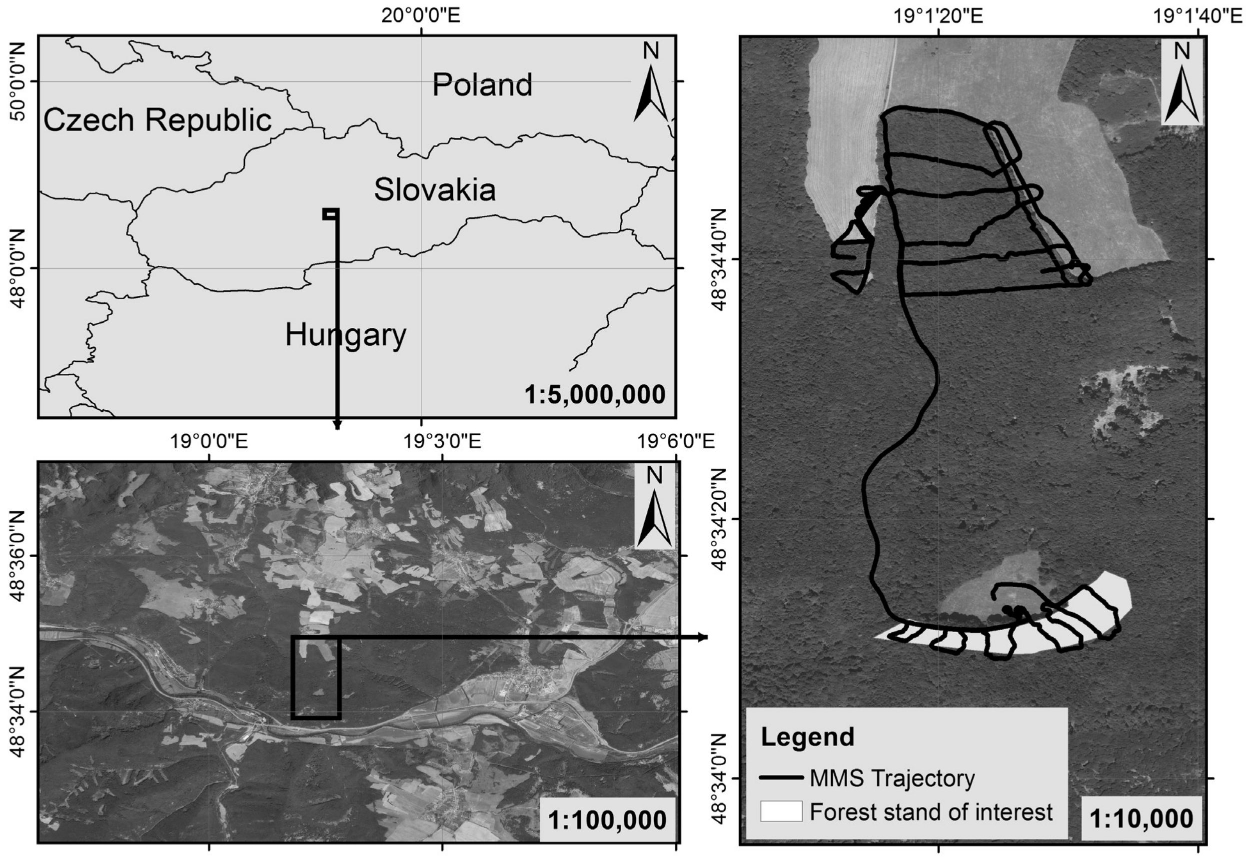

Fig. 1. Study site located in Zvolen district in central Slovakia. The forest stand of interest (white polygon) is located at the southern part of the complete trajectory (black polyline) of mobile mapping system (MMS) movement presented in the right figure

Mobile laser scanning data. Mean density for the point clouds collected within the forest stand of interest was 663 points per square meter. Collected point clouds were saved into LAS files (Version 1.2) (American Society for Photogrammetry and Remote Sensing Board 2008). Data was divided into multiple files based on the date of acquisition and scanner.

Fig. 2. RIEGL VMX-250 mobile mapping system – MMS (RIEGL Laser Measurement Systems GmbH, Austria) mounted on a Zetor Horal 7245 tractor (Zetor Tractors, a.s., Czech Republic). Two digital cameras (1) and VQ-250 mobile laser scanners (2) are placed on the side of the MMS measuring head, GPS antenna (3) is placed on the top and panoramic camera (4) above the MMS measuring head

Data processing. Ground points, which are necessary for the calculation of normalized height, were classified using LAStools application package (Version 160429, 2016). LASground application, which is a part of the application package, offers a complex algorithm of ground point classification. We can ensure a compact set of ground points without points from tree crowns or higher parts of the understory by optimization of the custom settings of ground point classification.

Next steps of data processing were executed using a modular program system developed by University of Technology in Vienna called OPALS, Version 2.1.5, 2015 (Mandlburger et al. 2009; Pfeifer et al. 2014). The system requires a digital terrain model (DTM) in the form of a raster for normalized height calculation. Ground points were converted into Tagged Image File Format with 4 m cell size in OPALS using a Grid module. The SNAP method was used for the interpolation of height values. Relatively large grid size was chosen to generate DTM without holes with respect to slope conditions in the forest stand.

Normalized height was calculated using the OPALS module AddInfo. Data on relative height starts from points located at the same height as DTM raster with 0 value of normalized height and continues higher with values based on the vertical distance from DTM.

Using data on normalized height added in the previous step points in normalized height from 1.27 to 1.33 m are extracted. The created segment of points with 6 cm thickness extracted from the whole point cloud (Fig. 3) is then used for DBH estimation.

The point cloud cross-section in the form of a 6-cm thick set of points was imported into DendroCloud software (Version 1.23.0.0, 2016). Distance-based spatial clustering (DiBSC) was used to identify individual stems. DiBSC requires the setting of two parameters – maximum distance between the points of the cluster and minimum number of points of the cluster. The point cloud cross-section was divided into small clusters which represent individual tree stems.

DBH estimation. The "Monte Carlo" method was used for DBH estimation as the first of three methods. Monte Carlo searches for the circle that best fits to the tree stem point cluster. The first estimation of the circle centre represents the middle point of the line which connects the two most distant points of the cluster. The circle centre and the radius are then adjusted by the function which utilizes the least squares method. Centres of estimated circles located incorrectly or too far from the tree stem centre were removed. These errors occurred mainly because of dense noise surrounding tree stem point clusters (e.g. occurrence of dense undergrowth near the tree stem). Another cause of this issue was overlapping of clusters from the same tree stem scanned from two or more different positions with weak, no or basically different GNSS signal.

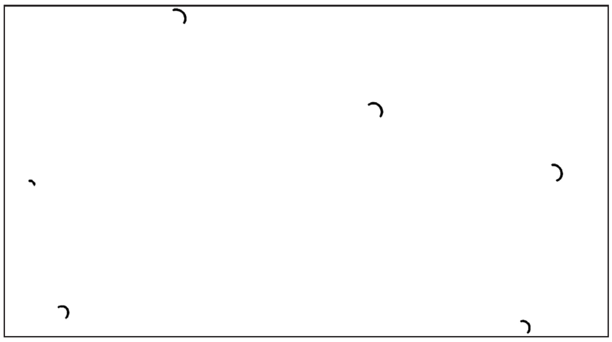

Fig. 3. Point cloud cross-section. The presented part of point cloud intersection represents an average scene obtained by one mobile laser scanner, scanned from one position

Another method used for DBH estimation was maximum distance, which was also provided by DendroCloud. This method simply estimates diameter using a distance between the two most distant points of the tree stem cluster. Estimations of DBH by maximum distance and Monte Carlo are presented in Fig. 4.

The third method of DBH estimation was random sample consensus (RANSAC) for a cylinder integrated in the CloudCompare software, Version 2.6.2, 2015 (Figs 5 and 6) (Schnabel et al. 2007). This method requires the setting of four parameters. For minimum support points per primitive we

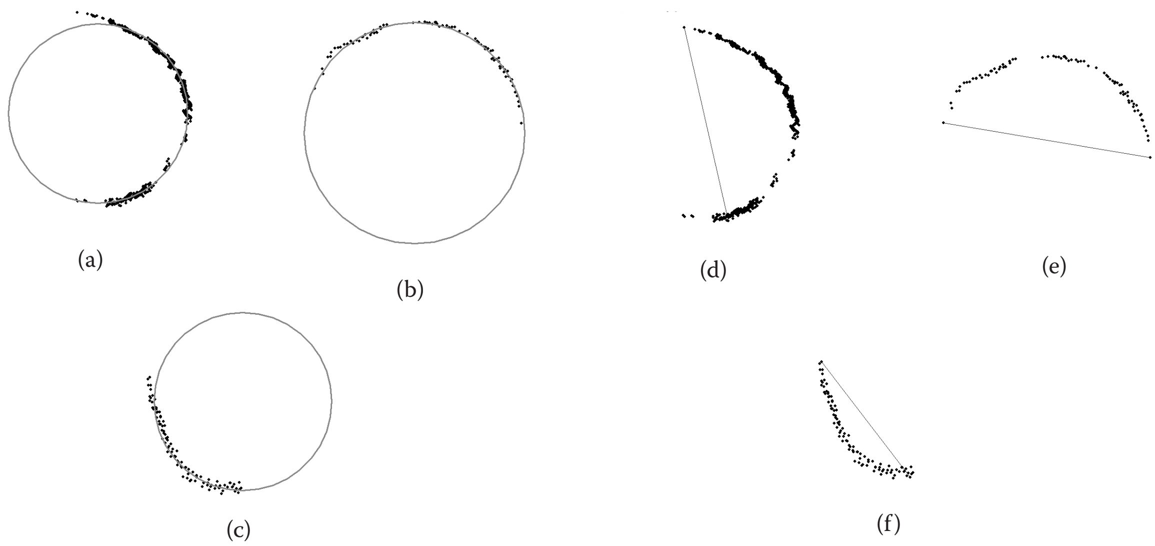

Fig. 4. Circle estimated using the Monte Carlo method of DBH estimation (a–c), diameter estimated using the maximum distance method of DBH estimation (d–f); mobile laser scanning coverage of tree stem: 60.49% (a, d), 44.76% (b, e), 34.05% (c, f)

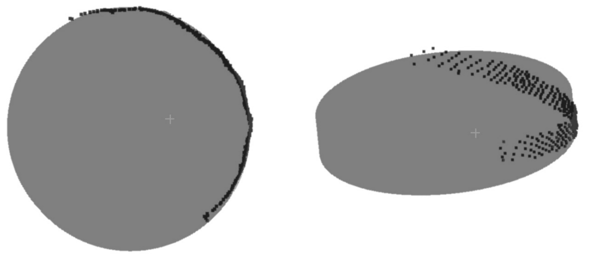

Fig. 5. Visualization of cylinder fitting to the tree stem point cluster in CloudCompare (Version 2.6.2, 2015). Points that appear larger meet the conditions of maximum distance to the cylinder and maximum normal deviation from the ideal shape of the cylinder. Darker points are located inside the cylinder, lighter outside

used the same number of points as that we used for the minimum number of points in DiBSC (i.e. 50). Maximum distance to the primitive was set to 3 cm. Sampling resolution works exactly in the same way as maximum distance between points using DiBSC and was also set to the same value as it was in DiBSC (i.e. 8 cm). Maximum normal deviation is the maximum allowed deviation of a point cluster from the ideal cylinder in degrees and was set to 15°. The probability of overlooking is a probability that no better candidate was overlooked during sampling (Schnabel et al. 2007) and was set to 0.001. The above-mentioned parameters can reduce the number of tree stems for which DBH will be estimated. We tried to keep the sample size as large as possible with respect to adequate accuracy which this method can provide.

Construction of convex hull and calculation of MLS coverage of tree stem. By examining the point cloud cross-section we were able to detect noticeable position errors for most of the scanned tree stems. Accuracy of measurement differs as the GNSS signal availability changes. The control unit is able to correct these errors only for a limited time. Identical tree stem was represented by multiple point clusters in the point cloud cross-section. Multiplications of the tree stem point cluster are results of scanning from multiple positions with different accuracy caused by different GNSS signal availability and also by the existence of two mobile laser scanners integrated in the mobile mapping system. This caused multiple DBH estimation for the identical tree stem.

To decide which DBH estimation should be the most precise we used a convex hull of the tree stem point cluster constructed in the last step of data processing. We assumed that the calculated length of the line which represents a part of the stem cross-section that is covered by the MLS point cloud should correlate with the error of DBH estimation mainly by methods which approximate the tree stem cross-section to some primitive (e.g. circle or cylinder).

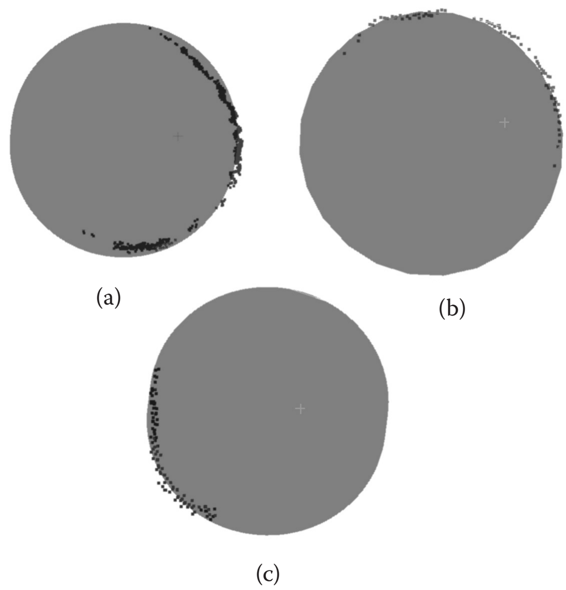

Fig. 6. Circular base of the cylinder estimated using random sample consensus for the cylinder method of DBH estimation. Mobile laser scanning coverage of tree stem: 60.49% (a), 44.76% (b), 34.05% (c)

MLS coverage of tree stem was estimated in the last step of data processing. Convex hulls of each point cluster were created using a minimum bounding geometry tool of ArcGIS (Version 10.12, 2013). Created polygons were converted to polylines and the longest segment of each polyline was removed. The final feature is presented in Fig. 7. The above-

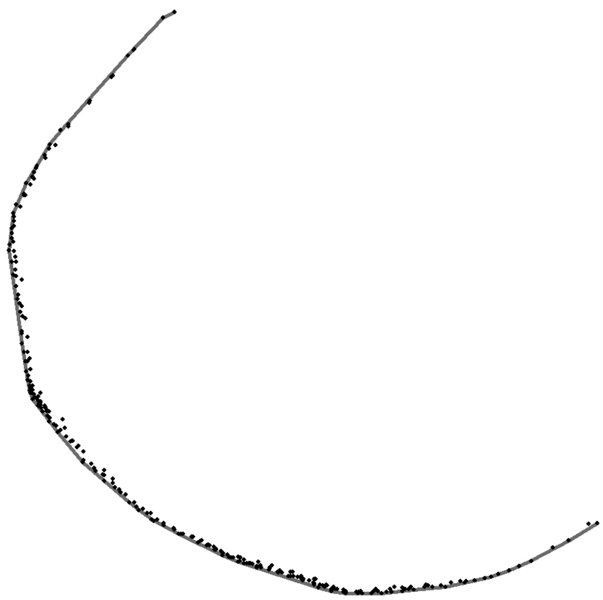

Fig. 7. Processed convex hull of the tree stem point cluster which represents mobile laser scanning coverage of tree stem

mentioned steps were put together using script based on ArcPy Python library as a complex workflow. Up to 10% of the created convex hulls needed to be corrected manually. Lengths of the created polylines were calculated.

Diameter estimated by each method was used to calculate the circumference of every stem. Division of the created line length by circumference calculated from reference data represents that part of stem circumference which can be derived from the point cloud using a 6-cm thick cross-section. This part is then converted into percentage (by multiplying the value by 100).

RESULTS

DBH estimation

Estimated diameters were compared with diameters measured using a calliper. A difference between the two values was used for the calculation of errors. We present results for a sample of 71 trees. MLS coverage of tree stem was calculated by dividing the length of the polyline created in the last step of data processing by the value of circumference calculated from reference data on DBH. The variable varies between 34.05 and 60.49% with an average of 48.27%.

The accuracies of the DBH and position estimations were evaluated using the bias, relative bias, RMSE, and relative RMSE as it was defined in Liang et al. (2014). The maximum distance method overestimates diameters with a bias of 1.13 cm. This method performs best with RMSE of 2.65 cm and relative RMSE of 6.57%. Student's *t*-test revealed a systematic error of DBH estimation using presented methods at the 95% confidence level. *P*-value was 0.000187.

The Monte Carlo method overestimates diameters with a bias of 1.08 cm. RMSE of DBH estimation using this method was 2.88 cm and relative RMSE was 7.14%. Student's *t*-test revealed a systematic error of DBH estimation using presented methods at the 95% confidence level. *P*-value was 0.0012270.

RANSAC cylinder fitting overestimates diameters with a bias of 2.74 cm. RMSE of DBH estimation for cylinder fitting was 5.57 cm and relative RMSE was 13.8%. Student's *t*-test revealed a systematic error of DBH estimation using presented methods at the 95% confidence level. *P*-value was 0.000012. Overview of the calculated errors is shown in Table 1.

The use of MLS coverage of tree stem for DBH estimation

Correlation and regression analysis was used to verify MLS coverage of tree stem point cluster for reducing RMSE of DBH data. A relationship between the MLS coverage of tree stem as an independent variable and the relative error as a dependent variable was examined.

Correlation and regression analysis revealed a strong downhill linear relationship between the MLS coverage of tree stem and the relative error of DBH estimation using the cylinder fitting method (Fig. 8a). Pearson correlation coefficient for this method was –0.745 and coefficient of determination was 0.555.

Relative error of DBH estimation by Monte Carlo is moderately related to MLS coverage of tree stem with correlation coefficient of –0.575 and coefficient of determination of 0.331 (Fig. 8b).

Relative error of maximum distance based DBH estimation is not related to MLS coverage of tree stem (Fig. 8c). Correlation coefficient for this method was only –0.067 and coefficient of determination was 0.005.

DISCUSSION

RMSE of 2.88 cm obtained using the Monte Carlo circle fitting method is lower compared to RMSE of 3.7 cm (relative RMSE of 14%) reported by Forsman et al. (2016). We achieved the lower accuracy of DBH estimation using cylinder fitting with RMSE of 5.57 cm and relative RMSE of 13.08% compared

Table 1. Overview of obtained errors

Maximum distance					Monte Carlo					RANSAC cylinder				
Bias		*P*-value	RMSE		bias		*P*-value	RMSE		bias		*P*-value	RMSE	
absolute (cm)	relative (%)	(CI = 95%)	absolute (cm)	relative (%)	absolute (cm)	relative (%)	(CI = 95%)	absolute (cm)	relative (%)	absolute (cm)	relative (%)	(CI = 95%)	absolute (cm)	relative (%)
1.13	2.80	0.000187	2.65	6.57	1.08	2.67	0.001227	2.88	7.14	2.74	6.78	0.000012	5.57	13.80

CI – confidence interval, RMSE – root mean squared error

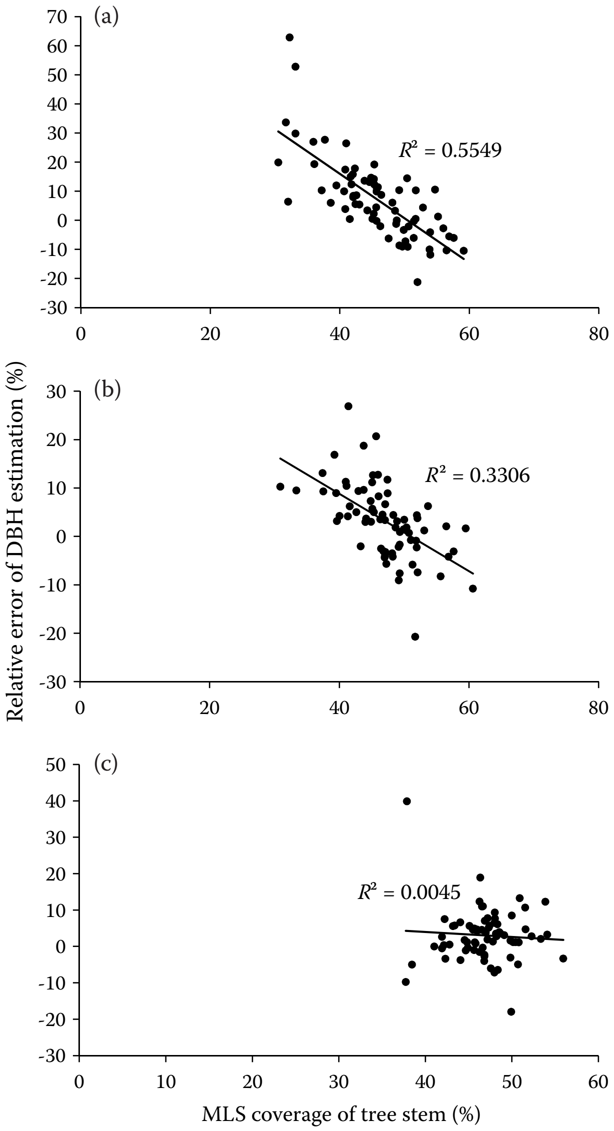

Fig. 8. The relationship between the mobile laser scanning (MLS) coverage of tree stem and the relative error of DBH estimation using cylinder fitting (a), Monte Carlo (b), maximum distance (c) method

to RMSE of 2.36 cm and relative RMSE of 8.17% calculated by Liang et al. (2014). Maximum distance performed best with RMSE of 2.65 cm and relative RMSE of 6.57%. Our results also showed that the accuracy of DBH estimation using this method cannot be improved by scanning a bigger part of the stem cross-section (Figs 8c and 9). On the other hand, a reduction of sample based on the MLS coverage of tree stem can improve accuracy especially in case of 35% minimum threshold value, if we use the method of DBH estimation that approximates the tree stem cross-section to some primitive (Fig. 9).

Presented accuracies of DBH estimation are much lower compared to the latest results from TLS using a more complex method of data processing and DBH estimation (You et al. 2016).

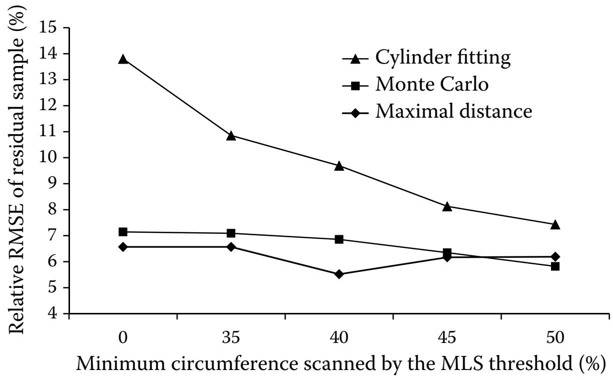

Fig. 9. The influence of different minimum mobile laser scanning (MLS) coverage of tree stem thresholds on the relative root mean squared error (RMSE) of residual sample using all three methods

Student's t-test has revealed that presented methods of MLS data processing and possibly methods of DBH estimation resulted in systematic error. Systematic error was revealed for all three methods of DBH estimation. Systematic error was caused mainly by the method of normalized height calculation. The normalized height value was interpolated using a bilinear method as it was set by default in OPALS. DTM generated in OPALS was used for normalized height calculation in LAStools. Visual examination of the created cross-section has shown that underestimation of normalized height values was eliminated or reduced. LAStools calculates normalized height using a triangulated irregular network.

Presented relationships can be used for optimization of DBH estimation for the purpose of total stem volume estimation. We present the impact of sample size reduction based on minimum MLS coverage of tree stem threshold on the tree stem point cluster to be included in the sample. Four threshold values were chosen for each method of DBH estimation.

For cylinder fitting 35% MLS coverage of tree stem minimum threshold value reduced relative RMSE from 13.8% for the whole sample to 10.85% for sample consisting of 65 trees. 40% minimum threshold value reduced relative RMSE to 9.69% for 59 trees. 45% minimum threshold value reduced relative RMSE to 8.13% for 41 trees. 50% minimum threshold value reduced relative RMSE to 7.43% for 20 trees.

For Monte Carlo 35% MLS coverage of tree stem minimum threshold value reduced relative RMSE from 7.14% for the whole sample to 7.09% for a sample of 69 trees. 40% minimum threshold value reduced relative RMSE to 6.86% for 64 trees. 45% minimum threshold value reduced relative RMSE to 6.35% for 49 trees. 50% minimum threshold value reduced relative RMSE to 5.82% for 19 trees.

For the maximum distance method of DBH estimation the threshold value of 35% did not change relative RMSE while the sample size did not change either. 40% minimum threshold value reduced relative RMSE from 6.57 to 5.52% for 68 trees. 45% minimum threshold value increased relative RMSE to 6.17% for 53 trees. 50% minimum threshold value increased relative RMSE to 6.19% for 12 trees. As linear regression showed before, there is no relationship between the MLS coverage of tree stem and the relative error of DBH estimation using the maximum distance method. The above-mentioned results for all three methods are presented in Fig. 9. Overview of the influence of MLS coverage rate on relative RMSE of DBH estimation is presented in Table 2.

Table 2. Overview of the influence of mobile laser scanning coverage rate on relative root mean squared error (RMSE) of DBH estimation

	Threshold (%)	Relative RMSE (%)	Sample size (stems)
Maximum distance	0	6.57	71
	35	6.57	71
	40	5.52	68
	45	6.17	53
	50	6.19	12
Monte Carlo	0	7.14	71
	35	7.09	69
	40	6.86	64
	45	6.35	49
	50	5.82	19
RANSAC cylinder	0	13.80	71
	35	10.85	65
	40	9.69	59
	45	8.13	41
	50	7.43	20

CONCLUSIONS

Nowadays research in the field of the use of MLS for forestry focuses mainly on an automated fusion of point clouds collected from multiple positions or scanners (Tang et al. 2015, Rönnholm et al. 2016). Results of our research showed that even partial data collected under unfavourable conditions can provide promising DBH estimations. We also presented the potential of limited data optimization for the purpose of total stem volume estimation. MLS offers very fast collection of data from large areas and sample size that can be reduced in the above-mentioned way to produce data on DBH with accuracy demanded on an operational level.

Our research showed that the accuracy of DBH estimation increases as the minimum MLS coverage of tree stem threshold increases. As we assumed, it was a general relationship between these two variables especially for methods which use primitives such as circle or cylinder for DBH estimation. Though some relationship between the error of DBH estimation and the MLS coverage of tree stem has been shown, the relationship between these two variables can be even stronger under more favourable conditions (e.g. leafless season and faster movement of a vehicle carrying the mobile mapping system).

Besides optimization presented in this paper, MLS coverage of tree stem can be used as a variable which describes the success of mobile mapping campaign. MLS coverage of tree stem can also influence the method of DBH estimation or can be used during the selection of forest roads and paths that will be used for MMS data collection.

References

American Society for Photogrammetry and Remote Sensing Board (2008): LAS specification. Version 1.2. Available at http://www.asprs.org/wp-content/uploads/2010/12/asprs_las_format_v12.pdf

Boavida J., Oliveira A., Santos B. (2012): Precise tunnel survey using the RIEGL VMX-250 mobile laser scanning system. In: Licari S. (ed.): RIEGL Lidar 2012, Orlando, Feb 27–Mar 1, 2012: 1–13.

Čerňava J. (2015): Zisťovanie dendrometrických veličín pomocou údajov z mobilného mapovacieho systému. Acta Facultatis Forestalis Zvolen, 57: 161–171.

Forsman M., Holmgren J., Olofsson K. (2016): Tree stem diameter estimation from mobile laser scanning using line-wise intensity-based clustering. Forests, 7: 206.

Gillet J., Scherzinger B.M., Lithopoulos E. (2000): Inertial/GPS system for seismic survey. In: Liner L.C. (ed.): Proceedings of Society of Exploration Geophysicists, Calgary, June 4–7: 1–9.

Holopainen M., Vastaranta M., Hyyppä J. (2014): Outlook for the next generation's precision forestry in Finland. Forests, 5: 1682–1694.

Holopainen M., Kankare V., Vastaranta M., Liang X., Lin Y., Vaajac M., Yu X., Hyyppä J., Hyyppä H., Kaartinen H., Kukko A., Tanhuanpääa T., Alho P. (2013): Tree mapping using airborne, terrestrial and mobile laser scanning – a case study in a heterogeneous urban forest. Urban Forestry & Urban Greening, 12: 546–553.

Kelbe D., van Ardt J., Romanczyk P., van Leeuwen M., Cawse-Nicholson K. (2015): Single-scan stem reconstruction using low-resolution terrestrial laser scanner data. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 8: 3414–3427.

Liang X., Hyyppä J., Kukko A., Kaartinen H., Jaakkola A., Yu X. (2014): The use of a mobile laser scanning system for mapping large forest plots. IEEE Geoscience and Remote Sensing Letters, 11: 1504–1508.

Liang X., Kankare V., Hyyppä J., Wang Y., Kukko A., Haggrén H., Yu X., Kaartinen H., Jaakkola A., Guan F., Holopainen N., Vastaranta M. (2016): Terrestrial laser scanning in forest inventories. ISPRS Journal of Photogrammetry and Remote Sensing, 115: 63–77.

Mandlburger G., Otepka J., Karel W., Wagner W., Pfeifer N. (2009): Orientation and processing of airborne laser scanning data (OPALS) – concept and first results of a comprehensive ALS software. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVIII-3/W8: 55–60.

Pfeifer N., Mandlburger G., Otepka J., Karel W. (2014): OPALS – a framework for airborne laser scanning data analysis. Computers, Environment and Urban Systems, 45: 125–136.

Rasinmäki J., Melkas T. (2005): A method for estimating tree composition and volume using harvester data. Scandinavian Journal of Forest Research, 20: 85–95.

Reutebuch S.E., Carson W.W., Ahmed K.M. (2003): A test of the Applanix POS LS inertial positioning system for the collection of terrestrial coordinates under a heavy forest canopy. In: Haukaas J., O'Shea M. (eds): Precision Forestry. Proceedings of the 2nd International Precision Forestry Symposium, Seattle, June 15–17, 2003: 21–28.

Rönnholm P., Liang X., Kukko A., Jaakkola A., Hyyppä J. (2016): Quality analysis and correction of mobile backpack laser scanning data. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, III-1: 41–47.

Schnabel R., Wahl R., Klein R. (2007): Efficient RANSAC for point-cloud shape detection. Computer Graphics Forum, 26: 214–226.

Tang J., Chen Y., Kukko A., Kaartinen H., Jaakkola A., Khoramshahi E., Hakala T., Hyyppä J., Holopainen M., Hyyppä H. (2015): SLAM-aided stem mapping for forest inventory with small-footprint mobile LiDAR. Forests, 6: 4588–4606.

Wang D., Hollaus M., Puttonen E., Pfeifer N. (2016): Automatic and self-adaptive stem reconstruction in landslide-affected forests. Remote Sensing, 8: 974.

Wu B., Yu B., Yue W., Shu S., Tan W., Hu C., Huang Y., Wu J., Liu H. (2013): A voxel-based method for automated identification and morphological parameters estimation of individual street trees from mobile laser scanning data. Remote Sensing, 5: 584–611.

You L., Tang S., Song X., Lei Y., Zang H., Lou M., Zhuang C. (2016): Precise measurement of stem diameter by simulating the path of diameter tape from terrestrial laser scanning data. Remote Sensing, 8: 717.

Received for publication February 21, 2017
Accepted after corrections August 16, 2017