Folia Forestalia Polonica, series A, 2009, Vol. 51 (2), 123–137

ORIGINAL ARTICLE

Application and statistical analysis of terrestrial laser scanning and forest growth simulations to determine selected characteristics of Douglas-Fir stands

Jakob Weiß

University of Applied Sciences Eberswalde, Faculty of Forest and Environment, Alfred-Möller-Straße 1, 16225 Eberswalde, Germany, phone/fax: +49 30 971 51 08, e-mail: jakob.weiss@eva-verein.de

Abstract

Among others, the dbh, basal area, and tree height are the most important parameters to describe tree dimensions in forest inventories. In traditional forest inventories, these parameters are measured manually. In times of forest staff reduction and amalgamation of forest districts, terrestrial laser scanning (TLS) could evolve as a fast, efficient and automatic tool for the determination of basic inventory parameters such as the number of trees, diameter at breast height (dbh), basal area, tree height as well as stem and crown shape parameters. Since there has so far been little attention drawn to the accuracy and precision of TLS itself, we statistically investigated TLS in comparison with traditional inventory methods. We developed an investigation procedure, exemplified for a 49-year-old Douglas-Fir stand (*Pseudotsuga menziesii var. Viridis* Mirb.) near Eberswalde in the northeastern part of Germany to analyse the potential of TLS in terms of diameter at breast height (dbh) and height measurements. The results of the study suggest that the precision of the dbh measured from the laser scan point cloud return is sufficient. However, TLS was linked to an underestimation of dbh in comparison to the reference values measured with a diameter tape. Stand volume was accurately measured only if multiple scan positions were distributed in the forest stand.

Keywords

terrestrial laser scanning, forest inventory, diameter at breast height (dbh), precision, accuracy

Introduction

Laser scanners are used more and more as surveying instruments for various applications. Behera and Roy (2002) recognized the enormous potential of laser technology for forest ecological research, because the technology is able to represent spatial patterns in three-dimensional space. In connection with aerial laser scanning it could evolve as a modern technology to estimate suistainable use of forest biomass for different forest types.

The investigation of single trees in a forest using terrestrial laser scanning (TLS) techniques is of increasing interest. Traditionally, the exact dimensions and volumes of boles are typically measured after felling. Laser technology enables non-destructive determination of standing timber (Bienert 2007). From that perspective, TLS can be a valuable tool for forest planning

Received 5 August 2009 / Accepted 10 November 2009

and pre-harvest timber measurement (Keene 2008). Information derived from scanning can expand traditional measurement data and aid in marketing and optimising returns from harvest operations.

TLS could hold practical advantages over traditional inventory or monitoring methods. For example, while TLS is an objective method independent of an operator, traditional field measurements generally lack automation, since the measurements are often carried out by different personnel over time (Pfeifer 2004). As a complete snapshot of a given site the laser data provides an invaluable archive resource for routine monitoring or future operations.

TLS offers the capability of collecting thousands of points per second on highly irregular surfaces independently of the sun or additional light sources. This is a striking opportunity, but questions concerning the quality and accuracy of the recorded points have so far received little attention. At the moment, many manufacturers do specify the accuracies on the range measurements but not on the system at all, which implies much different accuracy specification (ranging, mirrors, temperature etc.). Manufacturers have not defined any common specifications, as typical for geodetic instruments (Fröhlich and Mettenleiter 2004).

The aim of the study is not only to compare dbh and height measurements done by traditional and laser measurements, but also to asses other aspects of TLS-based inventory using statistical-mathematical methods. The valuation of TLS will be judged by the grade of accuracy compared to the conventional inventory method and by the precision of the laser instrument used in the field.

Materials and Methods

Study Area

The study was carried out on the grounds of the research area "Chorin 85", approximately 7 km north-east of Eberswalde, Germany (Fig. 1). The research area was established in 1958 as part of a provenance study on Douglas-Fir. The size of each plot is 0.1 ha (30.0 m x 33.3 m) with 2.5 or 3.5 m skidding lanes in between. Each of the 26 provenances was seeded in three repetitions to allow for statistical – mathematical evaluations.

Fig. 1. Location of the study – near Horin, Germany

The area around Chorin is a part of the north-eastern lowland, in the range of the last glacial period of the Weichsel glaciation. Laying in the extent of the northern Barnim and the Thorun-Eberswalde glacial valley, it belongs to the zone of young moraine plates and glacial valleys (Marcinek and Nitz 1973). The area is a typical example for landscapes formed during the Pleistocene epoch characterised by depositional and erosion glacial landforms such as glacial moraines and U-shaped valleys (Panka 2000).

The Barnim, like the surrounding regions, is located in the transitional area of the oceanic climate of Western Europe and the continental climate of Eastern Europe. The average annual precipitation is 540 mm. Air temperature has an average annual fluctuation of 19°C. Mean temperature in January is –0.8°C in Eberswalde, the highest monthly average of 18.5°C is reached in July.

The sites show a strong trophic level with strong nutrient and moderate water supply (K2). The predominating local soil form is Kahlenberger sandy-brown soil, which is accompanied by Heegermühler and Jabeler sandy-brown podzolic soil.

From the present 41 parcels in the proving ground we chose three parcels with identical provenance for this study to ensure that variability between measurement plots would not be influenced by the provenance. The decision was made in favour of the Coombs provenance (Vancouver Island, British Columbia, Canada; 49° 15′ N, 124° 40′ W). It belongs to seed zone 1020a, which was recommended by Dittmar (1985) for establishing Douglas-Fir in coastal regions of Germany.

Basic forest inventory parameters based on the traditional inventory method are presented in Table 1. All trees in the plots have been artificially pruned except for the tree 65 in plot 71. Detailed information about the development of Chorin 85 was published by Panka (2000).

Tab. 1. Stand information based on the conventional inventory method in May 2008. The stand is 49 years old. Dg = quadratic mean diameter; Hg = height of the quadratic mean diameter; Ddom = quadratic mean diameter of the 100 biggest trees per ha; Hdom = height of Ddom; v = volume (> 7 cm) / ha

Parameter	Sample Plot			Average
	18	48	71	
Dgv (cm)	35,60	34,70	33,10	34,47
Hg (m)	25,90	28,90	26,30	27,03
Ddom (cm)	43,00	41,20	38,70	40,97
Hdom (m)	27,70	30,30	27,70	28,57
n/ha	280	350	390	340
basal area/ha (m^2)	27,90	33,10	33,50	31,50
v/ha (m^3)	309,60	404,50	376,80	**363,63**

Conceptual Design of the Experimental Study

Two scanning principles were investigated: single-scan and multiple-scan. In the single-scan mode the plot is just scanned once from the plot center position (referred to as position Z). In multiple-scan mode, we scanned from four peripheral positions inside the plot (position A, B, C and D). The multiple-scan mode is more time consuming but reveals information about the trees from more than one direction (Thies and Spieker 2004).

ArcGIS 9.2 was used to visualise tree positions and to locate scanner positions prior to field work. Both the x- and y-coordinates of plot borders and of all living trees were provided by the Eberswalde Forestry competence center (LFE). The peripheral scanner positions were to comply with the following preconditions:

- to maintain same distance between peripheral scanner and plot center and in-between peripheral scanners,
- to allow practical and fast set-up in the field,
- to cover as much plot area as possible provided by even distribution within 1000 m^2 plots,
- minimum distance between the scanner and closest tree should not fall below approx. 1.2–1.5 m to prevent the restricted scanner field of vision caused by trees too close to the scanner (shadow effects).

In Arc GIS the peripheral scanner distance to the plot center was fixed at 11.2 m. The peripheral scanner positions A to D were located along this radius to allow the maximum distance between each other. In the plots 18 and 71, the scanner positions were established between opposite plot corners. Due to unfavourable tree positions in the plot 48, the peripheral scanners were rotated along 11.2 m radius until the positions were found that provided maximum distance to the nearest tree from each scanner (Fig. 2). The scanner positions were later found in the field based on the calculated tree distances in the ArcGis – sketch.

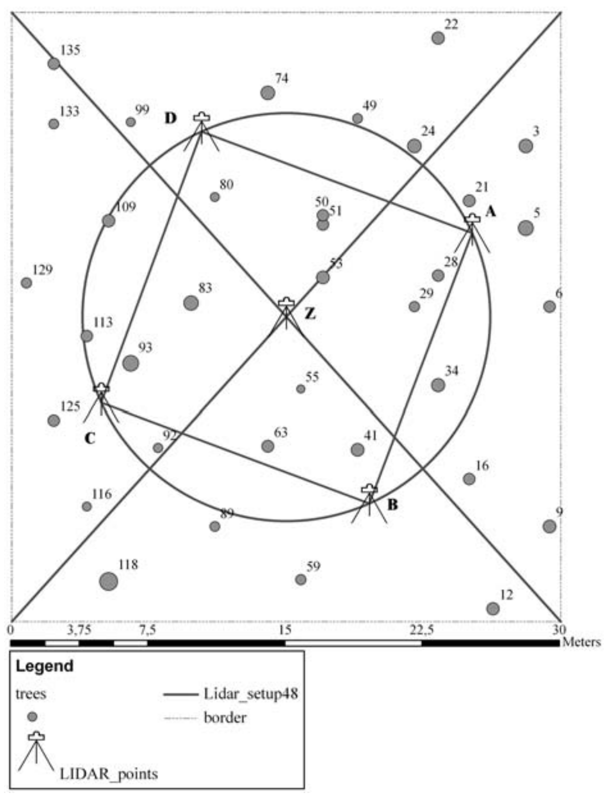

Fig. 2. Experimental set-up in the plot 48. In the plots 18 and 71 the peripheral scanner positions (A, B, C and D) were placed between opposite plot corners on circle line 11.2 m from the plot centre position.

Plot borders were designated according to the information generated in ArcGIS. Plot corners were found in the field using measuring tape, angle prism and survey poles, and finally marked with 0.5 meter stakes.

The plot center (central scanner position Z) was established at the intersection of the two diagonals from plot corners and aligned using survey poles.

All conventional measurements were performed at the beginning of May 2008 before the start of the growing season and are referred to as reference inventory or measurements in following.

The tree heights were measured using a TruPulse200 laser rangefinder by LaserTechnology. The manufacturer specifies the distance accuracy of the instrument with +/– 30 cm or +/– 1 m for high quality targets and low quality targets, respectively (LaserTechnologies 2009).

The dbh measurements were taken with diameter tape measures at exactly 1.3 m using a wooden board which was held vertically from the base of the tree. Diameter tape measurement is often mentioned as superior to calliper measurement (Nagel 2001), especially in experimental research and when dealing with extremely strong trees. Trees were marked with matte creped paper (2 cm) at dbh. This allowed direct comparison between conventionally measured dbh and TLS measurements. Trees were numbered with white paint at an eye level in such way that they were visible from all five scanner positions.

Practical Application of Terrestrial Laser Scanning using FARO Laser Scanner LS 880 HE 80

Most laser scanners normally consist of a combination of one dimensional measurement system with a mechanical deflection system, directing the laser beam into the direction to be measured. The laser beam is emitted and the reflected laser light is detected.

The scanner model FARO LS 880 HE 80 was used in the three plots. It is based on the phase-shift technology, registering up to 120.000 points per second[1]. With phase-based continuous wave technology, the laser beam measures the distance to an object by determining the phase-shift of the return beam to the sensors. The phase measurement principle is commonly used for medium ranges of up to one hundred meters. The manufacturer specifies the systematic distance measurement error with ± 3 mm at 20 m distance measured on a fixed reference paper with 90% reflectivity in vertical position (FARO 2009). The technical data of the scanner, taken from FARO (2009) are presented in Table 2.

Tab. 2. Technical specifications of FARO Laser Scanner LS 880

Specification	**LS 880**
Range finder	Phase shift
Field of view (horizontal x vertical)	360° x 320°
Resolution	0.6 mm – 17 Bit distance
Measurement range	0.6 m to 76 m
Distance accuracy	± 3 mm at 20 m distance and 90% reflectivity
Reproducibility (RMS)	4.2 mm at 10 m distance and 90% reflectivity
Repeatability (RMS)	0.7/2.6 mm at 10 m distance and 90% reflectivity
Sampling rate	120.000 points per second
Beam radius at discharge	3 mm
Beam divergence	0.25 mrad (0.014°)
Weight	14.5 kg
Speciality	integrated PC: Pentium III, 700 MHz, 256 MB RAM, 40 GB hard-disk and Windows 2000 operating system

Multiple repetitions were conducted in all three plots in order to assess the precision of the laser scanner. A series of three repetitions was scanned from each position without moving the scanner. These scans are referred to as repetitions 1 to 3.

Two further repetitions were exclusively performed in the plot 71. The scanner was moved in-between scanner readings and placed back into the previous position. This procedure better reflects conditions of a repeated inventory, since it is unlikely that in a real-world situation the scanner would be placed in exactly the same position as in the previous inventory. These repetitions are referred to as repetitions 4 and 5.

The time of the scanner's 360° rotation was about 7 minutes. The recording time of a given plot depended

[1] Laser scanners are categorised into two fundamenental technologies of the distance measurement system: the time of flight technology and the phase-based continuous wave technology.

on the selected scan mode. In multiple-scan mode, the time spent to relocate the scanner equipment to the next scan position must be added to the total scanning time. In our study it was about 2 minutes.

Measuring Diameter at Breast Height in FAROScene (Pixel method)

FAROScene is a software for viewing, administration, and working on extensive 3-D scan points from high resolution 3-D laser scanners. This tool allows the user to manipulate raw 3-D scan points and acquire initial point cloud data comprehension. Dbh was measured using a distance tool between the pixels forming the tree trunk in a planar view at 1.3m above the ground (marked with matte creped paper). In following, this method is referred to as "pixel method". Measurements were done on a Gericom Laptop with Windows XP operating system, 1.86 GHz processor with 512 MB RAM and 1024 x 768 pixel resolution.

Precision analysis of TLS

All statistical analysis were performed using the statistical software SPSS 11.5. Before comparing the accuracy of a new measurement technique, one should consider the precision of the new and the old method (Bland and Altman 1986). Precision refers to the degree to which repeated measurements or calculations show the same or similar results (Taylor 1997).

Repetitions of TLS were performed to analyse the precision of the TLS scanner system. Precision was measured as repeatability (Bland and Altman 1986), which is defined as the degree of agreement between independent measurements repeated under controlled conditions. It is a measure of consistency between the results of independent measurements taken by the same person and must fulfil the following conditions:

– application of the same measurement method,
– repetition by the same person and instrument,
– repetition from/in the same place,
– repetition under the same experimental conditions,
– repetition during a short period of time.

Bland and Altman (1986) introduced the so-called Coefficient of Repeatability (CR, Formula 1). It is a measure of precision that represents the value below which the absolute difference between two repeated test results may be expected to lie with probability of 95%. In other words, any difference above the calculated CR can be interpreted as a true difference at a 5% margin of error, which cannot be solely explained by measurement error.

Since the same method is used for the repeated measurements, the mean difference should be zero. We tested this with one-sample T-tests against zero. Therefore, the CR can be calculated as 1.96 (or 2) times the standard deviations of the differences between the two measurements (d2 and d1) under the assumption that the differences are normally distributed where 1.96 is the 97.5%-quartile of the normal distribution:

$$CR = 1.96 \times \sqrt{\frac{\sum (d_2 - d_1)^2}{n-1}}$$

Formula 1. Coefficient of Repeatability. D_1 and d_2 are independent measurements of the same object

In this study we made repeated TLS measurements three times from each scanner position in all plots and calculated the particular average dbh.

Following the concept of Bland and Altman (1986), we:

– calculated differences between Repetition (Rep) 1 and Repetition 2, Repetition 1 and Repetition 3, and Repetition 2 and Repetition 3, respectively,
– performed Kolmogorov-Smirnov-Tests for normal distribution of the differences,
– conducted one-sample T-Tests to test differences against zero,
– drew scatterplots showing dbh differences,
– calculated standard deviations of differences and Coefficients of Repeatability.

We carried out two additional measurement repetitions (Rep 4 and Rep 5) in the plot 71, moving the scanner before and after repetition 4. This was done to look if moving the scanner influences the precision of the TLS system. With the statistical procedure described above, we compared differences of dbh measurements between the fixed scanner (Rep 2 and Rep 3) and moved scanner (Rep 4 and Rep 5). We used data from the plot center position (Z) and four peripheral scanner positions (A, B, C, D).

Accuracy Analysis of TLS

Accuracy is the degree of conformity of a measured or calculated quantity to its actual (true) value. We regarded the measurements conducted in the traditional way as true values. We analysed the degree of closeness of the dbh measured with the pixel method to the dbh measured with diameter tape. Usually, the correlation coefficient (r) specifies the degree of relation between two variables. But a strong correlation does not always correspond to a high degree of agreement, because r measures the relation, not the agreement (Bland and Altman 1986). A high correlation can often conceal a considerable lack of agreement between two instruments.

Therefore, we focussed on the procedure introduced by Bland and Altman (1986)[2] and calculated the Coefficients of Repeatability. With this method it is possible to describe the differences between two measurement methods using rather simple calculations of differences, standard deviation, standard error, and confidence intervals. We used this method to investigate the degree of agreement between traditional inventory method and TLS regarding dbh measurement.

Although Bland and Altman (1986) recommend defining the limit values beforehand, we did not provide a limit for the maximum difference above which we would reject the TLS method. Instead, we drew attention to the relevance of the single-scan- and multiple-scan approach regarding accuracy of TLS dbh measurements.

The average measurements of repetitions 1 to 3 were used as a basis to draw conclusions on the accuracy of TLS. In examining the single-scan approach, we focussed on the central scanner position. The data of positions A, B, C and D were considered in the analysis of the multiple-scan method.

The relation between pixel-method measurement accuracy and the distance to the scanner was evaluated using correlation coefficients and linear regression. Assuming that trees closer to the scanner are more accurately measured, two different modes were tested within the multiple-scan method. We investigated the so-called "basic multiple-scan mode" by progressively adding more scanner positions into the calculation of the differences. In the so-called "optimized multiple-scan mode", the dbh was not simply averaged from measurements of different positions. Instead, for each tree only one dbh measurement was chosen from the peripheral position that was least distant to the respective tree.

We could capture the lack of compliance by calculating the bias that can be estimated by the mean difference (d) and the standard deviation (s). If the differences are normally distributed, 95% of the differences would lie between d – 1.96 s and d + 1.96 s. The calculated values constitute the so-called "limits of agreement" (Bland and Altman 1986). Assuming that the differences are normally distributed, the standard errors and confidence intervals would allow statements regarding the population. The standard error for d is calculated by (Formula 2):

$$d = \sqrt{\frac{s^2}{n}}$$

Formula 2. Standard error of difference, where s = standard deviation; n = sample size

Assessment of Forest Stand Parameters Using TLS in the Single-Scan and Multiple-Scan Mode

BWINPro[3] Version 7.5.2, an individual tree based forest growth simulation software, was used to calculate relevant forest stand parameters based on traditional and TLS measurements. The input values are the stand (tree) age, dbh, and height of individual trees. We assessed the stand parameters depending on the scanning method, i.e., single-scan and optimised multiple-scan mode in order to disclose the differences of the approaches regarding stand volume estimation. In order to investigate the effect of the different stem numbers in the stand, we analysed the three sample plots separately.

We were not able to measure any tree heights using FAROScene software because tree tops were not visible in the laser scans and solved this problem by using diameter-height functions to estimate the individual tree heights. We used the software "HöhenKurve" (Nagel 2006)[4] to draw the height curves and generate

[2] It was introduced for cases where the true value of a measured variable cannot be known, e.g. blood pressure measurements in medical science.

[3] BWINPro Version 7 is based on the project TreeGrOSS (Tree Growth Open Source Software). The programming language is Java (Sun) under the NetBeans development interface. The structure of the programme is object-oriented. The package runs under the General Public License model (GPL). Developed by Nagel (2006), Nordwestdeutsche Forstliche Versuchsanstalt.

[4] The programme "HöhenKurve" is part of the forest software package ForestTools2 developed by Nagel (2006), Nordwestdeutsche Forstliche Versuchsanstalt. It is subject to the Genral Public License (GPL).

the relevant coefficients and functions for the individual plots 18, 48 and 71. The input variables for the functions were dbh and height of the reference measurements.

In the next step, we selected the height function with the best model fit to the data. The quadratic mean deviations were to be as small as possible and the coefficients of determination (R^2) were to be as high as possible. The residual distribution had to be uniform.

We used the non-linear regression analysis in SPSS to determine the most appropriate height function based on the coefficients a_0 to a_2 generated by the software "HöhenKurve" for the reference height and dbh data.

In the next step, the height function with the best model-fit allowed calculation of the missing heights in the single-scan and optimised multiple-scan approaches. We used paired-sampled T-tests to compare true (reference) heights with heights predicted by different TLS-approaches treating all plots separately. Finally, the dbh and height values of individual trees were directly entered into BWINPro in order to calculate the forest stand parameters.

Results

Precision of Terrestrial Laser Scanning

Tree obstruction (Shadow Effects)

The degree of shadow effects is linked to stem abundance in the plots (Fig. 3). The highest stem numbers of all three plots was observed in the plot 71. Here, 6 out of 39 trees (more than 15%) could not be measured from the central scanner position. Only the combination of all four peripheral scan positions allowed recognition of all trees in the plot.

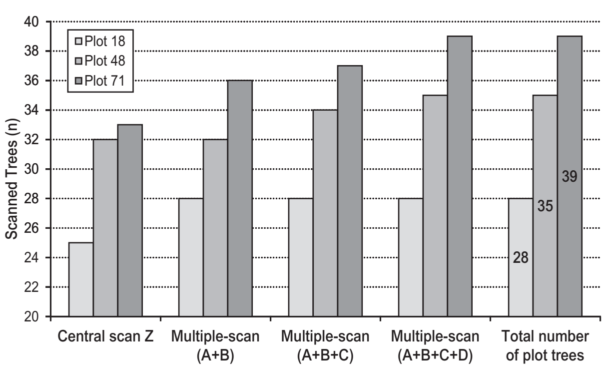

Fig. 3. Line-of-sight obstruction in the single-scan and multiple-scan mode in plots with different tree densities

Precision of DBH Measurements

The analysis of precision is based on 1171 individual on-screen measurements in FAROScene. For each repetition, the average dbh was calculated in all scanner positions in all plots. Differences between repetitions are normally distributed (significance: Rep1 – Rep2 = 0.936; Rep1 – Rep3 = 0.594; Rep2 – Rep3 = 0.992)[5].

We tested for difference against zero with one-sample T-tests for each combination of repetitions:

H_0: $\mu_{difference\_rep1Rep2} = 0$
H_0: $\mu_{difference\_rep1Rep3} = 0$
H_0: $\mu_{difference\_rep2Rep3} = 0$

In all three cases we could not reject $H_{0.}$ (significance = 0.152; 0.730; 0.276). According to Bland and Altman (1986) we could use the data to assess repeatability. Scatterplots plotting the difference of measurements in the pixel method between two repetitions revealed no relation between the differences and the size of average dbh.

The Coefficients of Repeatability (CR) are 0.39 cm, 0.56 cm and 0.43 cm for respective combinations of repetition (Tab. 3). This means that variation between measurements that exceed these coefficient cannot solely be explained by measurement error.

Tab. 3. Coefficients of Repeatability (CR) according to different combinations of repetition. The average CR is 0.46 cm

	Rep 1 vs. Rep 2	Rep 1 vs. Rep 3	Rep 2 vs. Rep 3
Standard deviation	0,1975	0,2866	0,2202
Coefficient of Repeatability	0,387	0,562	0,432

In order to assess the influence of moving the scanner between repetitions, the CR were calculated in the fixed-scanner repetition and the moved-scanner repetition in the plot 71.

The movement of the scanner increased the differences between the fourth and fifh repetition. Figure 4

[5] One-Sample Kolmogorov-Smirnov Test

compares the fixed scanner with the moved scanner mode. In average, the Coefficient of Repeatability is higher in the moved scanner mode (2.74 cm vs. 1.86 cm).

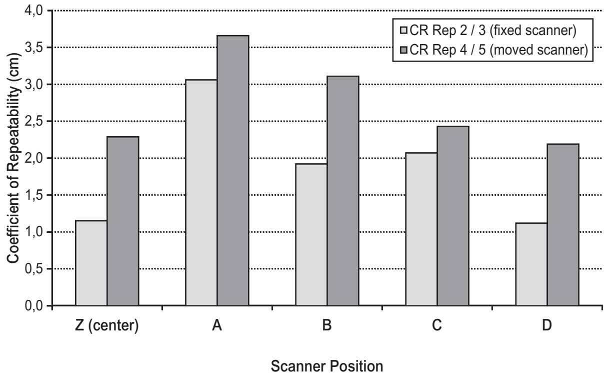

Fig. 4. Coefficients of Repeatability in the plot 71 at 95% confidence comparing "fixed scanner mode" with "moved scanner mode"

Accuracy of Terrestrial Laser Scanning

The relationship between the traditional measurement method and TLS was initially investigated by calculating the correlation coefficient for tape measurements and TLS from the plot centre position (Fig. 5). The correlation coefficient between the two methods is above 0.984 in all plots. We would have perfect agreement when all points lay on the line of equality (Fig. 5).

Table 4 summarises the results of different scanning approaches, i.e., single-scan-, basic- and optimized multiple-scan modes. In all plots, almost all TLS- measurements fall below the reference measurements. There is no considerable relationship between the measurement error and the mean of the two measurements. The difference does not increase or decrease with the increasing average dbh.

Figure 6 presents the average difference resulting from different scanning approaches in the plots 18, 48, and 71. In general, TLS underestimates the average dbh. The use of multiple scanner positions does not increase accuracy in the basic multiple-scan mode. Only the optimised multiple-scan mode leads to a significant reduction of the differences. The agreement increases with additional peripheral scanner positions.

Since there is no obvious relation between the differences and the means, we could summarise the lack of agreement for the scanning approaches by calcu-

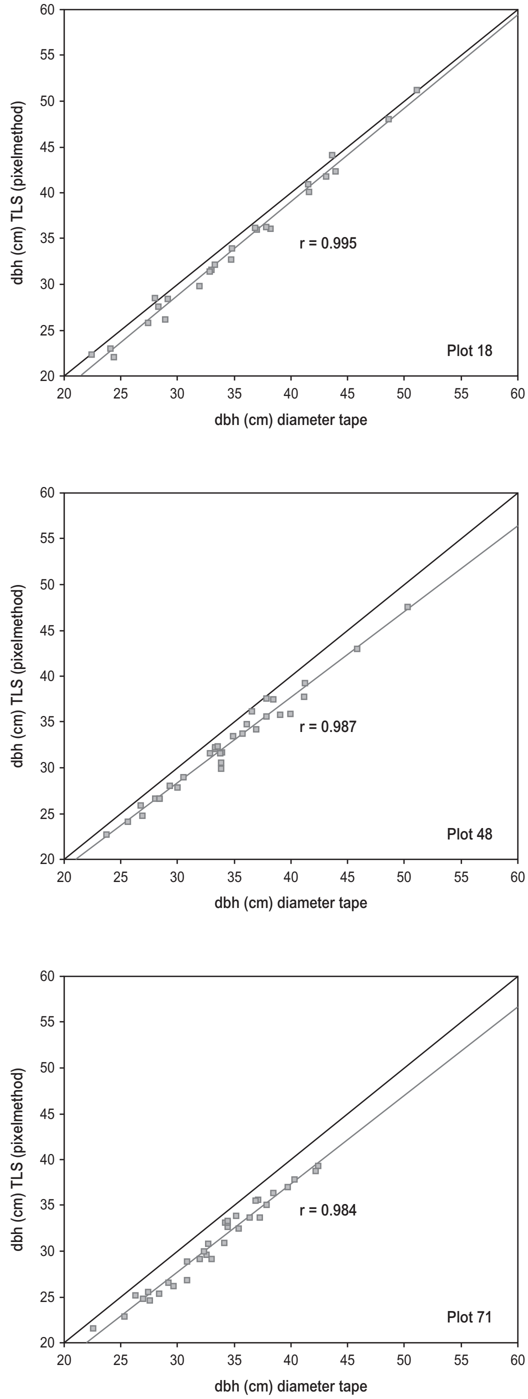

Fig. 5. Dbh measured with diameter tape (reference) and TLS in single-scan mode from the plot center position with line of equality (bold line)

Tab. 4. Descriptive statistics of dbh measurements (cm) using reference measurements and TLS with three different laser scanning approaches (single-scan-, basic multiple-scan- and optimised multiple-scan mode)

DBH (cm)							
		Reference	**Single-Scan-Mode**				
PLOT		Reference (Diameter Tape)	Z	A	B	C	D
18	Mean	34,89	33,93	33,97	33,43	32,81	33,53
	N	28	25	25	24	25	24
	Std. Deviation	7,37	7,88	7,88	7,64	6,55	7,82
	Minimum	22,40	22,10	21,43	21,83	21,33	21,03
	Maximum	51,10	51,20	49,70	50,10	48,20	49,77
	Std. Error of Mean	1,393	1,577	1,576	1,560	1,309	1,596
48	Mean	34,25	32,84	33,37	32,48	32,27	33,29
	N	35	32	23	24	27	29
	Std. Deviation	5,72	5,68	5,75	6,28	6,17	5,78
	Minimum	23,70	22,97	22,30	22,60	22,47	22,25
	Maximum	50,30	48,33	43,20	47,73	49,90	47,50
	Std. Error of Mean	0,967	1,005	1,198	1,283	1,188	1,074
71	Mean	32,73	31,53	31,35	32,38	31,23	31,56
	N	39	33	31	26	25	30
	Std. Deviation	4,95	4,98	5,29	4,99	4,98	4,74
	Minimum	22,10	21,87	18,90	21,20	21,10	21,77
	Maximum	42,20	40,20	42,10	41,50	41,43	40,07
	Std. Error of Mean	0,792	0,867	0,950	0,979	0,997	0,865
DBH (cm)							
		Multi-Scan-Mode			Optimized Multi-Scan-Mode		
PLOT		AB	ABC	AB	ABopt	ABCopt	ABCDopt
18	Mean	33,77	33,63	33,47	34,10	34,24	34,39
	N	28	28	28	28	28	28
	Std. Deviation	7,51	7,32	7,34	7,40	7,34	7,50
	Minimum	21,65	21,54	21,42	21,83	21,83	21,83
	Maximum	49,90	49,33	49,26	50,10	50,10	50,10
	Std. Error of Mean	1,418	1,384	1,387	1,399	1,387	1,417
48	Mean	32,97	32,97	32,84	33,13	33,55	33,64
	N	32	34	35	32	34	35
	Std. Deviation	6,08	5,93	5,76	6,07	6,00	5,77
	Minimum	22,47	22,47	22,41	22,60	22,63	22,63
	Maximum	47,73	48,82	48,38	47,73	49,90	49,90
	Std. Error of Mean	1,075	1,017	0,974	1,073	1,028	0,975
71	Mean	31,60	31,40	31,29	32,07	31,88	32,01
	N	36	37	39	36	37	39
	Std. Deviation	5,08	5,13	5,01	5,09	5,21	5,02
	Minimum	20,05	20,40	20,74	21,20	21,10	21,10
	Maximum	41,80	41,80	41,22	42,10	42,10	41,43
	Std. Error of Mean	0,846	0,843	0,802	0,848	0,857	0,804

lating the biases. The biases were estimated by the mean differences (d) and the standard deviations of the differences (s). The differences were in all cases normally distributed. We can expect that 95% of the difference would lie between d –1.96s and d +1.96s. The lower and upper values of the limits of agreement are provided in Table 5 to Table 7 for the plot 18, 48 and 71.

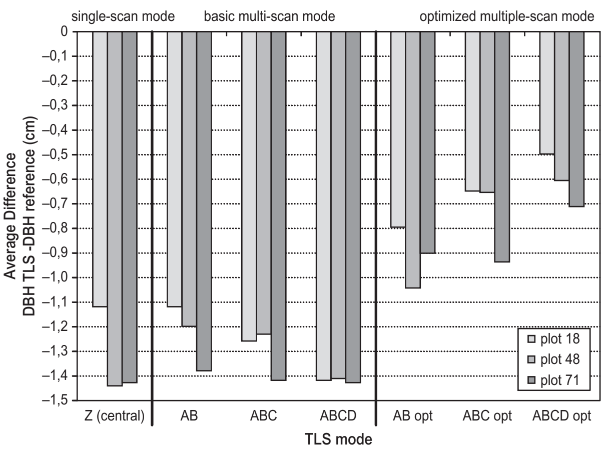

Fig. 6. Mean dbh difference between diameter tape measure and TLS measurements

The least agreement is found in the plot 48, where, in the single-scan approach, dbh may be between 3.3 cm below or 0.42 cm above the diameter tape measurement. The plot 18 (–2.78 to 0.54 cm) and the plot 71 (–3.21 to 0.35 cm) exhibit only slightly better agreement. This lack of agreement is characterised by a strong underestimation of dbh.

The limits of agreement are estimates based on our sample. Other samples would lead to different results. Calculating the standard errors and confidence intervals makes it possible to estimate at the population level.

All confidence intervals for the bias (Tab. 5–7) cover the range below zero, indicating an underestimation of the true dbh. Obviously, the degree of underestimation depends on the scanning approach. For single-scan mode, the 95% confidence interval ranges in the worst case (sample plot 48) from –1.76 to –1.12 cm. In the same plot, the optimised multiple-scan mode clearly leads to an improved agreement. Here, the range of underestimation is –0.86 to –0.36 cm. As more scanner positions are included in the calculation, the agreement improves.

In the basic multiple-scan-approach the agreement decreases as more scanner positions are included in the average dbh calculation. The worst agreement was found when using all peripheral scanner positions (ABCD).

Figure 7 presents the range of the confidence intervals for the different scan-approaches without plot separation. While we have to assume the deviation of up to 1.65 cm (4.9%) in the single-scan mode, the optimised multiple-scan approach leads to the average underestimation of up to 0.89 cm (2.6%) using all available peripheral scanner positions.

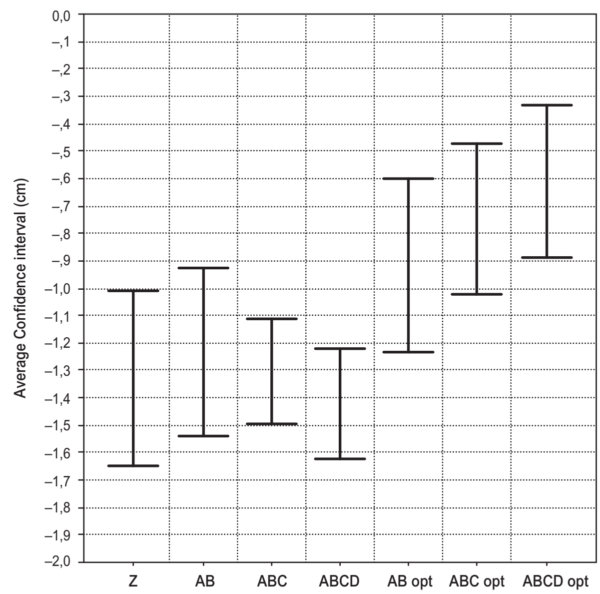

Fig. 7. Confidence intervals (95%) of differences between TLS and reference dbh without plot separation. Averages of plot 18, 48 and 71

TLS accuracy was lower measuring dbh from peripheral scanner positions. We assumed that this is connected to the higher average tree distance to the scanner. In general, larger tree distances were connected to larger dbh differences in all sample plots and from all scanner positions. The correlation coefficients were too small to allow linear regression. Nonetheless, we would calculate an average R^2 of 0.3, meaning that 30% of the variation in accuracy of the pixel-method could be explained by a change of the scanner distance. There is however no causal relationship.

Tab. 5. Statistics and estimated limits of agreement for plot 18

Plot 18	Single-Scan-Method	Basic Multi-Scan-Method			Optimized Multi-Scan-Method		
Scanner Position	Z (central)	A + B	A + B + C	A + B + C + D	A + B opt	A + B + C opt	A + B + C + D opt
Mean difference (d) (cm)	–1,120	–1,120	–1,260	–1,420	–0,800	–0,650	–0,500
Standard deviation (s)	0,830	0,890	0,380	0,500	0,933	0,833	0,806
Standard error	0,166	0,168	0,072	0,094	0,176	0,157	0,152
Confidence interval (–) at 95% confidence level	–1,460	–1,470	–1,410	–1,610	–1,160	–0,970	–0,820
Confidence interval (+) at 95% confidence level	–0,780	–0,770	–1,110	–1,230	–0,440	–0,330	–0,190
Limits of agreement (d – 2s)	–2,780	–2,900	–2,020	–2,420	–2,66	–2,320	–2,120
Limits of agreement (d + 2s)	0,540	0,660	–0,50	–0,420	1,070	1,020	1,110
Standard Error of limits	0,290	0,290	0,120	0,160	0,310	0,270	0,260

Tab. 6. Statistics and estimated limits of agreement for plot 48

Plot 48	Single-Scan-Method	Basic Multi-Scan-Method			Optimized Multi-Scan-Method		
Scanner Position	Z (central)	A + B	A + B + C	A + B + C + D	A + B opt	A + B + C opt	A + B + C + D opt
Mean difference (d) (cm)	–1,440	–1,20	–1,230	–1,410	–1,040	–0,650	–0,610
Standard deviation (s)	0,930	0,960	0,710	0,670	0,976	0,706	0,762
Standard error	0,164	0,170	0,122	0,113	0,172	0,121	0,129
Confidence interval (–) at 95% confidence level	–1,760	–1,530	–1,470	–1,630	–1,380	–0,890	–0,860
Confidence interval (+) at 95% confidence level	–1,120	–0,870	–0,990	–1,190	–0,700	–0,420	–0,360
Limits of agreement (d – 2s)	–3,300	–3,120	–2,650	–2,750	–2,990	–2,070	–2,130
Limits of agreement (d + 2s)	0,420	0,720	0,190	–0,070	0,910	0,760	0,910
Standard Error of limits	0,280	0,290	0,210	0,200	0,300	0,210	0,220

Tab. 7. Statistics and estimated limits of agreement for plot 71

Plot 71	Single-Scan-Method	Basic Multi-Scan-Method			Optimized Multi-Scan-Method		
Scanner Position	Z (central)	A + B	A + B + C	A + B + C + D	A + B opt	A + B + C opt	A + B + C + D opt
Mean difference (d) (cm)	–1,430	–1,380	–1,420	–1,430	–0,910	–0,940	–0,710
Standard deviation (s)	0,890	0,710	0,560	0,630	0,750	0,830	0,840
Standard error	0,155	0,118	0,092	0,101	0,126	0,136	0,135
Confidence interval (–) at 95% confidence level	–1,734	–1,612	–1,600	–1,628	–1,153	–1,203	–0,979
Confidence interval (+) at 95% confidence level	–1,126	–1,148	–1,240	–1,232	–0,660	–0,671	–0,450
Limits of agreement (d - 2s)	–3,210	–2,800	–2,540	–2,690	–2,410	–2,590	–2,400
Limits of agreement (d + 2s)	0,350	0,040	–0,300	–0,170	0,600	0,710	0,970
Standard Error of limits	0,270	0,200	0,160	0,170	0,220	0,240	0,230

Assessment of Forest Stand Parameters Using TLS in Single-Scan and Multiple-Scan Modes

Deriving Diameter-Height- Functions from Reference Inventory Data

Using the reference dbh and height data we looked for a proper height function to calculate the missing tree heights and stand volume in the single-scan and optimised multiple-scan approach, respectively. The parabolic height functions showed best model fit in all three sample plots (Formula 3).

$$h = a_0 + a_1 \times dbh + a_2 \times dbh^2$$

Formula 3. Parabolic height function, where a0, a1 and a2 are coefficients

Paired-sampled T-tests revealed no significant difference between reference heights measured in the field and estimated heights calculated with parabolic height function.

Calculation of Forest Stand Parameters Based on Different TLS Scanning Approaches

Dbh and heights of the individual trees were entered into BWINPro in order to calculate the forest stand variables.

The stand volumes were underestimated in both approaches, but underestimation in the optimised multiple-scan mode is significantly lower compared to the single-scan mode. In the plot 18, optimised scanning underestimates volume by about 3% (8 m³/ha). In the plot 71, having the highest numbers of trees, the single-scan-mode results in a volume underestimation of about 22% (or 82 m³/ha) (Tab. 8).

On the average of all plots, optimised multiple-scanning underestimated the volume by about 4% (13 m³/ha) compared to 18% (65 m³/ha) in the single-scan mode.

Discussion

Compared to mixed-species and heterogeneous forest stands in steep terrain our test site represents the scenario where TLS seems well suitable. The pure 49-year old Douglas-Fir stand on level terrain has been pruned and is free from understorey vegetation. As much as the methods are successful in calculating the stocking volumes, they are more difficult to apply for complex forest scenarios. However, the results concerning the precision of the laser scanner and the use of the pixel-method for computing dbh may also be valuable for similar forest stand types since they directly address the precision of the technology in forest environment.

In this study, TLS achieved accurate estimates of forest parameters such as the tree diameter, basal area and density at a plot level. However, the tree heights could not be directly measured with the pixel-method. However, our study showed that height functions can be used to accurately predict the tree heights when tree height data is unavailable. Forest growth simulation

Tab. 8. Forest yield variables generated by single-scan and multiple-scan mode. Heights were predicted using parabolic height function. The last two columns present the deviation (underestimation) from the true sample plot volume per ha (Tab. 1). The bottom column displays average variables for the entire Douglas-Fir stand. Dg = quadratic mean diameter; Hg = height of the quadratic mean diameter; Ddom = quadratic mean diameter of the 100 biggest trees per ha; Hdom = height of Ddom; g = basal area; v = volume (> 7 cm) / ha.

height source: parabolic height function	Dgv (cm)		Hg (m)		Ddom (cm)		Hdom (m)		n/ha		g/ha (m²)		v/ha (m³)		% Difference to reference v/ha	
Scanning Approach	single-scan	multi-scan	single-scan	multi-scan	single-scan	multi-scan	single-scan	multi-scan	single-scan	multi-scan	single-scan	multi-scan	single-scan	multi-scan	single-scan	multi-scan
Plot 18	34,8	35,2	25,8	25,8	42,0	42,5	27,6	27,8	250	280	23,8	27,2	264	302	14,9	2,5
Plot 48	33,3	34,1	28,5	28,7	39,4	40,7	30,0	30,3	320	350	27,9	32,0	338	390	16,4	3,7
Plot 71	31,9	32,4	26,0	26,1	37,2	38,0	27,5	27,7	330	390	26,4	32,1	295	360	21,8	4,4
Average	33,3	33,9	26,8	26,9	39,5	40,4	28,37	28,60	300	340	26,0	30,4	299	351	17,8	3,6

software such as BWINPro is able to calculate the missing tree heights based on various height functions using just a small sample of tree heights. The tree diameters can be retrieved using TLS to calculate the stocking volume.

Our results demonstrate that the tree density has a significant influence at the level of information that can be retrieved from the laser data. In the plot 71 (390 trees per hectare), the shadow effect is diminished only when all four peripheral scanner positions are used. Smaller plot sizes could reduce the problem of shadow effects in dense stands using multiple scan positions. The advantage of multiple-scan positions was also found by Thies & Spieker (2004) who evaluated TLS for standardised forest inventories in the 30 m x 30 m plot on a 28° steep slope in the Southern Black Forest foothill range occupied by a mixed European Beech (*Fagus sylvatica* L.) and oak (Quercus spp.) stand. 26 out of 50 trees (52%) were detected based on five scanner positions. In the single-scan mode only 11 trees (22%) were detected.

The Coefficient of Repeatability (CR) represents an estimation of the minimal difference between repetitions above which variations may be interpreted as true difference. To evaluate the average dbh using TLS in the environment under study, the CR averages to 0.46 cm for all three plots at fixed scanner position. This is the relevant value in the case when TLS is used for forest inventory purposes to assess forest growth, especially diameter increment. Because the dbh differences of subsequent measurements can only be interpreted as true dbh increment when it exceeds 0.46 cm. Differences below this value could be caused by measurement errors immanent to the measuring system itself.

We found that moving the scanner increases the CR. Even if the scanner is positioned at almost exact position, the dbh difference can be interpreted as true dbh increment only if the dbh difference exceeds 2.74 cm. This value may appear critical assuming an inventory interval of 5 years. But it is well below the diameter increment expected in Douglas-Fir forests between forest inventories that are conducted in 10-year intervals[6]. We conclude, that the precision of the tested laser instrument is suitable to monitor dbh growth of Douglas-Fir in forest inventories.

Regarding the accuracy of TLS, a general trend was recognised: the pixel method tends to underestimate dbh. This phenomenon is also described in other TLS-related studies using however many fewer sample trees and different forest types. For example Watt *et al.* (2003) describes that individual trees were underestimated by up to 4 cm in coniferous forests. In the study by Thies and Spieker (2004), dbh was underestimated by 3.5%.

The best agreement was found in optimised multiple-scan mode using all four scan-positions. The basic multiple-scan mode led to poorer agreement with reference values even in comparison with the single-scan mode, and the negative effect was increased by adding more scan positions into the calculation of average dbh of individual trees. This could be explained by the increasing average tree distance using multiple peripheral scanner positions compared to the single position from the plot centre.

Various reasons may account for the dbh variations between repeated measurements in our study. Potential sources of error include the laser scanner itself, different light conditions during the scanning process and measurement inaccuracies in the pixel method of FAROScene.

The scanner produces various incorrect points in vicinity of tree edges. The range error may vary from just a few millimetres to the values of several decimetres (Boehler and Marbs 2004). This is because the laser spot of the scanner is not infinitely thin but has a certain diameter. When the spot hits the tree edge, only a part of it will be reflected there. The rest may be reflected from the adjacent surface, a different tree behind the edge, or not at all (i.e. when no further object is present within the possible range of the scanner). Unfortunately specifically these edges are critical points for estimating dbh using TLS. To measure a tree affected by the edge effect, one must chose a pixel that is closer to the center of the stem. This inevitably causes an underestimation of dbh.

We cannot recommend the single-scan approach for determining forest stand parameters.The different scanning approaches were the decisive factor for accurately estimating the stand volumes. Only the optimised multiple-scan mode provided at least one dbh measure-

[6] Growth simulation were conducted in BWINPro to verify average dbh increment in the plots 18, 48, and 71 assuming no intermediate thinning: plot 18: 2.9 cm in 5 years and 5.4 cm in 10 years; plot 48: 2.9 cm in 5 years and 5.5 cm in 10 years; plot 71: 2.4 cm in 5 years, 4.7 cm in 10 years.

ment for each tree, keeping the underestimation relatively low.

The underestimation of dbh and consequentially of true stocking volume is influenced by two major factors. First, the negative impact of tree obstruction in the single-scan mode. Independent from total stocking volume, plots with high tree numbers are more affected by shadow effects than plots with lower tree numbers. Secondly, the underestimation of dbh by the scanner system has an impact on volume underestimation.

Conclusions

This research project concentrated on accuracy and precision considerations using only one type of laser scanner. Different results should be expected using other scanners due to different system specifications. Besides the type of laser scanner system, the scan-mode (single-scan, multiple-scan) is also important in terms of data processing. The data collection time in the field is considerably faster using the single-scan mode but the amount of detail is restricted due to a single view position.

This research project may help to the clarifiy questions regarding the precision and accuracy of TLS in a forestry context. It is an extension of previously published studies where the statistical analysis is at best limited to the derivation of coefficient of determination to determine the relationship between reference and TLS measurements (Wezyk 2007). We followed the approach of Bland and Altman (1986) who argue, that correlation coefficients measure the strength of a relation but not the agreement. They point out that even the T-test for significance indicating a high level of agreement does not solve the problem: “It would be amazing if two methods designed to measure the same quantity were not related. The test of significance is irrelevant to the question of agreement” (Bland and Altman 1986).

From this point of view, our study provides an indication of the deviation from stand parameters measured with conventional forest inventory methods. For pure Douglas-Fir stands of similar age and density, the estimation of the measurement error is given that should be anticipated when applying TLS. It would make sense to expand the test arrangement introduced here to other types and stages of forests.

The fact that obtaining dbh manually by the pixel-method is time-consuming, raises the need for more automatic tools. Several approaches to model trees from 3D-point clouds have been made in the past years (Bienert 2007, Gorte and Winterhalder 2004, Pfeifer 2004, Simonse 2003, Wezyk 2007). Basically, all these efforts boil down to detect cylindrical structures in a point cloud that resemble stems, branches and trees. In order to reconstruct trees in a forest from a point cloud, algorithms need to be found that filter the point cloud to detect structures which represent trees. The reconstruction can be used, for example to calculate the tree and stand basal area (Wezyk 2007), wood volume or timber quality. It is also applicable for the analysis of forested structures and habitats (Gorte and Pfeifer 2004). However, TLS is hardly used in forest inventory and fully automatic tools are still under development.

Acknowledgements

Agata Wencel and Paweł Strzeliński (Department of Forest Management, University of Life Sciences in Poznan, Poland) provided the laser scanner and technical support. The author would like to express his gratitude to Stefan Panka (LFE – Eberswalde Forestry competence center) who provided guidance for this project.

References

Behera M. D., Roy P. S. 2002. Lidar remote sensing for forestry applications: The Indian context. Current Science, 83 (11).

Bienert A. 2007. Tree Detection and Diameter Estimations by Analysis of Terrestrial Laserscanner Point Clouds. IAPRS XXXVI. Part 3 / W52.

Bland J. M., Altman D. G. 1986. Statistical Methods For Assessing Agreement Between Two Methods Of Clinical Measurement. Lancet, 1 (8476), 307–310.

Boehler W., Marbs A. 2004. Investigating Laser Scanner Accuracy. XIX CIPA Symposium at Antalya, Turkey, (i3Mainz, Institute for Spatial Information and Surveying Technology, FH Mainz, Holzstrasse 36, 55116 Mainz, Germany), 30.09–04.10.2003.

Dittmar O. 1985. Ergebnisse des internationalen Douglasienprovenienzversuchs 1961 im Pleistozän der DDR. Beiträge für die Forstwirtschaft, 19, 8–18.

FARO. 2009. Techsheet of Laser Scanner FARO LS 880 HE 80. http://www.faro.com/content.aspx?ct=di&content=pro&item=5&subitem=12, date: 14.04.2009.

Fröhlich C., Mettenleiter M. 2004. Terrestrial Laser Scanning – New Perspectives in 3D Surveying. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences XXXVI – 8/W2.

Gorte B., Pfeifer N. 2004. Structuring laser-scanned trees using 3d mathematical morphology. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences XXXVI – 8/W2.

Gorte B., Winterhalder D. 2004. Reconstruction of Laser-Scanned Trees using Filter Operations in the 3D Raster Domain. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences XXXVI – 8/W2.

Keene E. 2008. Warehousing principle in Forest Management (ed.: J. Weiß), Cork, Laser Technologies, 2009. Techsheet of TruPulse 200 laser rangefinder. http://www.lasertech.com/TruPulse-200-Rangefinder.aspx, date: 21.04.2009.

Marcinek J., Nitz B. 1973. Das Tiefland der Deutschen Demokratischen Republik. VEB Hermann Haack, Geographisch-Kartographische Anstalt, Gotha/Leipzig, 288 pp.

Nagel J. 2001. Skript Waldmesslehre. Göttingen, 55 pp.

Nagel J. 2006. HöhenKurve – HeightDiameterCurve. P. In forest research and practice special regression functions (height curves or height functions) are used. The program HeightDiameterCurve helps to generate missing heights using these functions., Göttingen.

Panka S. 2000. Internationaler Douglasienprovenienzversuch CHORIN 85 – 38 Jahre Beobachtungszeit. *in* Tagungsband des Deutschen Verbands Forstlicher Versuchsanstalten, Sektion Ertragskunde, Kaiserslautern, 05–07.06.2000.

Pfeifer N. 2004. Automatic Reconstruction of Single Trees From Terrestrial Laser Scanner Data in ISPRS XX th Congress, Istanbul, Turkey, 12–23.07.2004.

Simonse M. 2003. Automatic Determination of Forest Inventory Parameters Using Terrestrial Laserscanning. [In:] ScandLaser Scientific Workshop on Airborne Laser Scanning of Forests, 251–257.

Taylor J. R. 1997. An Introduction to Error Analysis – The Study of Uncertainties in Physical Measurements. University Science Books, Sausalito, California.

Thies M., Spieker H. 2004. Evaluation and future prospects of terrestrial laser-scanning for standardized forest inventories. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 36, 192–197.

Watt P. J. 2003. Forest Parameter Extraction Using Terrestrial Laser Scanning. Proc. ScandLaser Scientific Workshop on Airborne Laser Scanning of Forests, Umeå, Sweden, 237–244.

Wezyk P. 2007. Terrestrial Laser Scanning versus Traditional Forest Inventory – First Results from the Polish Forests. ISPRS Workshop on Laser Scanning 2007 and SilviLaser 2007, Espoo, Finland, 12–14.09.