DETECTING AND MEASURING INDIVIDUAL TREES WITH LASER SCANNING IN MIXED MOUNTAIN FOREST OF CENTRAL EUROPE USING AN ALGORITHM DEVELOPED FOR SWEDISH BOREAL FOREST CONDITIONS

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KEY WORDS: Forestry, Remote sensing, Laser Scanner, Individual Tree Detection

ABSTRACT:

Airborne remote sensing data from different types of sensors are tested within the Bavarian Forest National Park for estimation of forest attributes using several analysis methodologies. In this study, one algorithm that earlier has been validated for Swedish conditions was applied. The algorithm estimates tree position, tree height, and crown diameter of individual trees. The Bavarian Forest National Park is located in southeastern Germany. Three major forest zones are found at different elevations: (1) sub alpine spruce forests with Norway spruce (*Picea abies*) and partly Mountain ash (*Sorbus aucuparia*) above 1100 m, (2) mixed forests with Norway spruce, White fir (*Abies alba*), European beech (*Fagus sylvatica*) and Sycamore maple (*Acer pseudoplatanus*) on slopes between 600 and 1100 m, and (3) spruce forests with Norway spruce, Mountain ash and birches (*Betula pendula, Betula pubescens*) that are found in valley bottoms. Twenty-eight sample plots were field measured in all forest zones of the National Park during May and September 2002. Laser data were acquired using the Toposys II airborne laser scanner system recording first and last pulse. The number of trees that were detected using laser data was compared with field measurements. The overall detection rate was 44.2 %. In the top layer 67.9 %, in the middle layer 5.9 % and in the lower layer 2.5 % of the trees were detected. The percentage of detected volume was 85.2 % of the total volume measured in the field. The best results were obtained for a pure spruce stands and the worst for dense beech and spruce stands. High correlations were found between laser and ground measured tree height, with RMSE values of 1.40 m for all trees, of 1.37 m for coniferous trees and 1.41 m for deciduous trees. The correlation was also high between laser measured and field measured crown radius. For trees within 20 stands, the RMSE was 0.93 m. The measurements for the coniferous trees (RMSE 0.53 m) were more accurate than for the deciduous trees (RMSE 0.94 m). The volume was calculated by regression models on a single tree level. Overall 96.7 % of the volume was estimated.

1. INTRODUCTION

The development of airborne laser scanners with increased measuring frequencies has made it possible to efficiently detect and measure small objects on the ground. Detection of individual trees was first demonstrated five years ago (e.g., Brandtberg, 1999; Hyyppä & Inkinen, 1999). The early tests were performed within forests dominated by coniferous trees within boreal forests. The results show that most from above visible trees can be detected in mature coniferous dominated forests but difficulties usually are found in dense young forest or in groups of deciduous trees. The tree height and crown diameter were estimated with sub-meter accuracy. Laser data based estimates of tree height and crown area can be used as input to standard models for estimation of stem volume of the detected trees (Hyyppä et al., 2001; Persson et al., 2002). However, stem volume estimations at stand level will become biased because not all trees can be detected. Malatamo et al. (2004) combined the Weibull distribution with tree height distributions obtained from laser data in order to correct for trees that were not detected.

Only recently results are reported from tree detection and tree height estimation of individual trees within hardwood forests, e.g., Brandtberg (2003) analysing data from the eastern deciduous forest in North America and Gaveau & Hill (2003) analysing data from the United Kingdom. Because of the more spherical crown shape and sometimes many treetops for each tree of deciduous trees, tree detection will become more difficult. Also, because of the different crown shape, results from estimation of tree height are expected to differ from results obtained in coniferous forest.

In order to make detection and measurements of individual trees efficient for estimation of forest variables different methodologies need to be validated for different forest conditions. An extensive ground truth dataset with high precision measurements of tree positions is available within the Bavarian Forest National Park in southern Germany. Quite different forest types are found at different elevations in the park with a variety of composition of tree species forming different types of forest structures (Heurich et al., 2003). In this study, an algorithm developed and validated for Swedish conditions (Persson, 2001; Persson et al., 2002) was tested for the different forest conditions. The algorithm automatically estimates tree position, tree height, and crown diameter of individual trees based on laser data. The objective of this study was to validate tree detection, tree height estimation, crown diameter estimation, and volume estimation for different forest types within the Bavarian Forest National Park.

2. MATERIAL

2.1 Study Area

The study area is located in the Bavarian Forest National Park, which is situated in southeastern Germany along the border to the Czech Republic (49° 3' N, 13° 12' E). Within the park three major forest types exist: (1) sub alpine spruce forests with Norway spruce (*Picea abies*) and partly Mountain ash (*Sorbus aucuparia*) above 1100 m; (2), mixed mountain forests with Norway spruce, White fir (*Abies alba*), European beech (*Fagus sylvatica*) and Sycamore maple (*Acer pseudoplatanus*) on slopes between 600 m and 1100 m altitude, and (3) spruce forests with Norway spruce, Mountain ash and birches (*Betula pendula, Betula pubescens*) in wet depressions often evidencing cold air ponds in the valley bottoms.

2.2 Field Data

Twenty-eight sample plots with a size of 20 by 50 m to 50 by 50 m were selected in all of the described forest zones (Table 1). The field data was collected from May to November 2002. Two plots (19 and 20) were measured in 1999 and for these two plots height measurements were only performed for a sample of the trees. Several tree parameters like the diameter at breast height, total tree height and starting point of crown were determined for each tree being higher than 5 m. The height measurements were carried out with the Vertex III system following the definitions of Kramer & Akca (1995). To determine the projection of the crown the radii along the 8 main axes were measured with a crown mirror (Röhle & Huber, 1985; Röhle, 1986). Out of these measurements the geometric mean for the crown radius was calculated. Each stem position was precisely measured by tachometry and DGPS. The absolute accuracy was comprehensively checked and was estimated to 1-2 cm. The volume of each single tree was determined by volume equations derived by Kennel (1973).

ID	age	height a.s.l.	slope %	decid. %	N / ha	stock dens.	V / ha	H dom	SD height
1	170	860	6.4	86	260	0.86	449	32.9	13.22
2	170	885	29.8	71	250	1.05	668	36.3	11.86
3	160	1240	9.5	0	225	1.0	472	27.0	3.36
4	135	1225	1.5	0	370	1.25	563	27.2	4.73
5	165	1220	11.5	0	300	1.01	453	27.1	7.7
6	65	1235	24.2	1	1950	1.59	344	17.6	3.44
7	70	1160	20.2	100	1880	2.08	365	20.1	4.45
8	250	610	0.4	1	810	1.14	793	43.5	11.07
9	170	640	16.9	4	475	1.42	124	49.0	14.88
10	95	765	13.1	0	410	1.03	121	42.1	3.63
11	90	710	13.6	10	320	0.86	982	44.5	13.88
12	40	810	2.7	6	1610	1.29	588	27.8	6.33
13	110	890	15.3	100	320	1.12	577	34.5	7.89
14	120	850	16.8	74	280	1.17	713	36.6	8.91
15	145	784	3.0	0	390	0.89	824	36.9	11.75
16	75	805	2.9	41	792	1.23	742	35.6	9.08
17	105	835	4.6	100	258	0.69	290	30.8	8.81
18	95	875	13.0	96	758	1.36	582	33.2	8.69
19	85	710	26.7	23	717	1.41	100	36.4	5.58
20	70	690	26.6	100	783	1.18	385	26.6	5.05
21	110	760	15.7	65	258	0.68	498	38.2	11.9
22	110	760	13.3	100	180	0.65	394	36.4	10.78
23	110	760	14.3	61	236	0.8	610	38.0	14.2
24	110	760	15.7	99	253	0.79	447	35.6	11.09
25	110	760	16	4	244	0.67	762	41.2	8.31
26	110	760	16.9	49	310	0.88	683	34.6	12.45
27	110	760	13.9	83	270	0.82	447	33.2	8.84
28	110	760	16	100	230	0.67	398	36.9	12.81

Table 1: Characteristics of the field plots: height a.s.l. (height above sea level), slope (slope measured in percent), % decid.(percentage of deciduous trees), stock dens. (stock density), N/ha (number of trees per ha), V/ha (volume per ha), h dom (dominant height, average height of the 100 tallest trees per hectar), SD heigh (standard deviation of tree heights measured in the field)

2.3 Laser Data

There were two flights with the "Toposys II" airborne laser scanner system from TopSys (Topografische Systemdaten GmbH) in the spring and summer 2002. The TopoSys System is based on two separate glass fibre arrays of 127 fibres each. Its specific design produces a push-broom measurement pattern on ground. For further details see Wehr and Lohr (1999). For this analysis, only the data of the flight in the summer was used. The average point density within this flight was 10 pts/m². First and last pulse data was collected during the flight.

Sensor type	Pulsed fibre scanner
Wave length	1560 nm
Pulse length	5 nsec
Scan rate	653 Hz
Pulse repetition rate	83 000 Hz
Scan with	14.3°
Data recording	first and last pulse
Flight height	800 m
Size of footprint	0.8 m

Table 2: System parameters of the laser scanner flight

3. METHODS

3.1 Estimation Method

The applied method for identifying individual trees and estimating the height and crown diameter of these trees consists of six parts: (1) a digital surface model (DSM) is created, (2) a digital terrain model (DTM) is created, (3) the canopy of trees is modelled and a digital canopy model is created (DCM), (4) the canopy of the trees is smoothed with different scales, (5) a parabolic surface is fitted to the elevation data to determine which scale to choose for different parts of the image, (6) the height and crown diameter are estimated for the identified trees. Detailed information about the algorithm can be found in Persson (2001). For the volume estimation two methods were used. For method A, the volume (V) was directly predicted using the laser measurements of tree height (H_L) and crown radius (D_C) according to Equation 1.

$$V = b_0 + b_1 * H_L + b_2 * H_L^2 + b_3 * D_C + b_4 * D_C^2 \qquad (1)$$

For method B, the volume was calculated with standard volume functions (Kennel 1973) using stem diameter (D_S) and tree height (H_F) as variables that were predicted by linear regression model according to Equation 2 and 3. The parameters b_0, b_1, b_2, b_3 and b_4 were estimated using the least-squares method.

$$D_S = b_0 + b_1 * H_L + b_2 * H_L^2 + b_3 * D_C + b_4 * D_C^2 \qquad (2)$$

$$H_F = b_0 + b_1 * H_L + b_2 * H_L^2 + b_3 * D_C + b_4 * D_C^2 \qquad (3)$$

For the estimation of volume, diameter and height the data was divided in three groups: deciduous trees, coniferous trees low elevations, coniferous high elevations.

3.2 Accuracy Assessment

For evaluation of the results, the field measured trees were linked to the laser measured trees using their position. In a first step, all field measured trees within a derived crown polygon were selected. To take asymmetric crowns into consideration, all laser measured trees within a distance of 3 m from a specific field measured tree were selected in a second step. Three different cases could occur: (1) a laser measured tree was linked to one field measured tree, (2) a laser measured tree was linked to several field measured trees, (3) a laser measured tree could not be linked to any field measured tree. For case (1) the laser measured tree was linked to the single field measured tree. For case (2) the laser measured tree with a height closest to the height of the field tree was linked. However, to avoid incorrect linking of trees, trees were only linked if the height difference was less than 5 m. The non-linked field measured trees were considered as not detected. For the last case (3), the laser measured tree was judged as false positive. The linkage of the individual laser trees with the according field trees offered the possibility to analyse the detection rate and the accuracy of the laser system for height and crown radius measurements. For the detection rate of the trees, three different height classes were distinguished, upper layer: largest tree height to 2/3 of dominant height, middle layer: 2/3 to 1/3 of the dominant height, lower layer: 1/3 of dominant height to 5 m. The RMSE was calculated as the root-mean-square of the difference between field-measured and estimated values.

4. RESULTS

4.1 Number and volume of detected trees

Out of all 2666 field measured trees 1178 (44.2%) were judged to be detected by the algorithm. A total number of 143 (5.4%) false trees were detected. Out of all deciduous trees 38.4% were detected and 7.6% were considered as false trees. Out of all coniferous trees 50.6% were detected and 2.8% were considered as false trees.

The reason for this relatively small amount of detected trees is that the applied method can hardly detect trees beneath the surface. In the middle layer only 5.9% and in the lower layer 2.5% of the trees were detected. However, the detection was much higher in the top layer with 67.9% of the trees detected.

Despite low detection rates the volume represented by the detected trees contribute to a large proportion of all volume. Across all stands with 85.2% of the volume detected. Only in stands with a high stem density (>1600 stems/ha) and / or a high proportion of deciduous trees (>95%) less than 80% of the volume was detected. For all forest stands, 80.5% and 88.1% of the volume were detected of deciduous and coniferous trees, respectively.

4.2 Tree height estimation

The mean value and the standard deviation of the height difference between laser trees and ground trees were determined for the 966 trees measured in 2002 (441 deciduous and 525 coniferous trees). The trees measured in 1999 were excluded for this analysis. The average of the difference between laser and field measured tree height was -0.55 m for all trees, -0.42 m for deciduous trees, and -0.65 m for coniferous trees. The standard deviation of the difference between laser and field measured tree height was 1.43 m, 1.42 m and 1.43 m respectively. The RMSE was 1.40 m for all trees, 1.41 m for deciduous trees and 1.37 m for coniferous trees. The coefficient of determination was 0.96 for deciduous and 0.98 for coniferous trees (Figure 1).

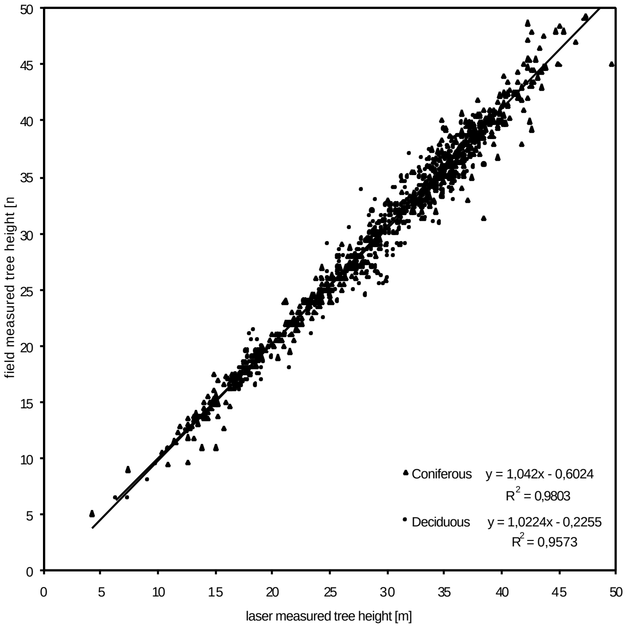

Figure 1: field height measurements versus laser height measurements (659 trees).

4.3 Tree crown estimation

Crown measurements were performed for 659 linked trees (361 deciduous trees and 298 coniferous trees). The average of the difference between laser and field measured crown diameter was –0,24 m for all trees, -0.61 m for the deciduous trees, and 0.22 m for the coniferous trees. The standard deviation of the

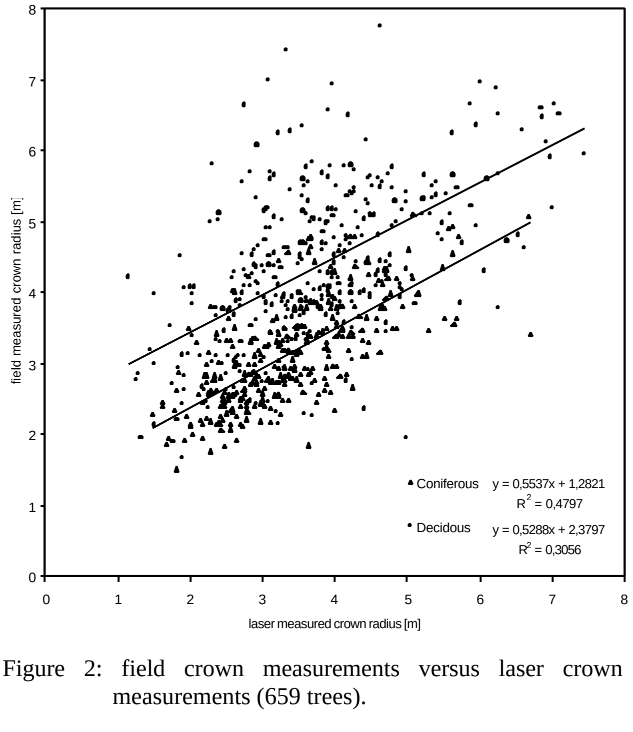

Figure 2: field crown measurements versus laser crown measurements (659 trees).

difference between laser and field measured tree height was 1.02 m for all trees, 1.09 m for deciduous trees, and 0.67 m for coniferous trees. The RMSE value was 0.93 m for all trees, 0.94 m for the deciduous trees and 0.53 m for the coniferous trees. The coefficient of determination for deciduous and coniferous trees was 0.31 and 0.48, respectively (Figure 2).

4.4 Stem diameter estimation

The diameter was estimated for 1174 trees (631 coniferous, 543 deciduous). The RMSE was 6.66 cm, 6.89 cm and 6.45 cm respectively. The coefficients of determination for all trees, deciduous trees and coniferous trees were 0.81, 0.63 and 0.85 (Figure 3). The coeffiecients of the regression model differed for the different forest types (Table 3).

	b_0	b_1	b_2	b_3	b_4
Deciduous	9.72	1.96	0.002	-0.11	0.02
Coniferous low	6.16	-0.64	0.30	0.38	0.02
Coniferous high	26.02	-1.32	0.25	-1.50	0.09

Table 3: Coefficients of the regression model for the prediction of the DBH. Coniferous low: spruce forests in the valley bottoms and coniferous trees of the mixed mountain forests zone. Coniferous high: sub alpine spruce forests

4.5 Volume estimation

The volume was estimated for 1174 trees (631 coniferous, 543 deciduous). For all trees the RMSE was 0.83 m³, for the deciduous trees 0.75 m³ and for the coniferous trees 0.89 m³. The coefficients of determination were 0.84, 0.69 and 0.86 for the three groups.

For method A, 96.7 % of the total volume of all trees measured on ground was predicted. When the false positives were not taken into account 86.8 % of the volume was predicted. For the coniferous trees 95.7 % of the volume was estimated with and 90.0 without false positives. The same values for the deciduous trees were 98.2 % and 81.8 % with and without false positives.

The results of method B were similar to the direct estimation. The RMSE was 0.86 m³ for all trees. For deciduous and coniferous trees the RMSE was 0.81 m³ and 0.90 m³, respectively. The coefficients of determination were 0.82, 0.65 and 0.86 for all trees, deciduous trees and coniferous trees, respectively. The coeffiecient of the regression model differed for the different forest types (Table 4).

	b_0	b_1	b_2	b_3	b_4
Deciduous	2.29	0.03	0.01	-0.25	0.01
Coniferous low	6.35	-0.52	0.07	-0.46	0.01
Coniferous high	2.4	-0.05	0.01	-0.34	0.01

Table 4: Coefficients of the regression model for the direct prediction of the volume. Coniferous low: spruce forests in the valley bottoms and coniferous trees of the mixed mountain forests zone. Coniferous high: sub alpine spruce forests.

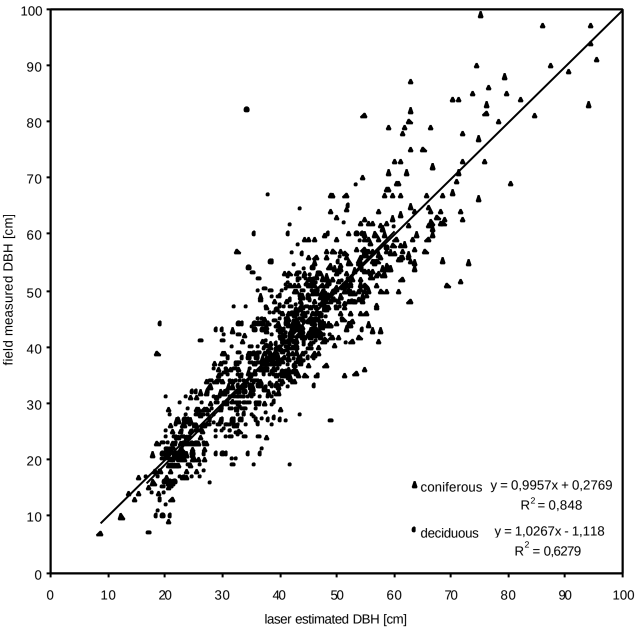

Figure 3: Field DBH measurements versus laser DBH estimations (1174 trees).

With this method 91.4 % of the volume measured in the field was predicted. When the false positives were not taken into account 82.9 % of the total volume was predicted. For the coniferous trees 89.3 % of the volume was estimated with false positives and 84.2 % without. The same values for the deciduous trees were 92.3 % and 78.2 % with and without false positives respectively.

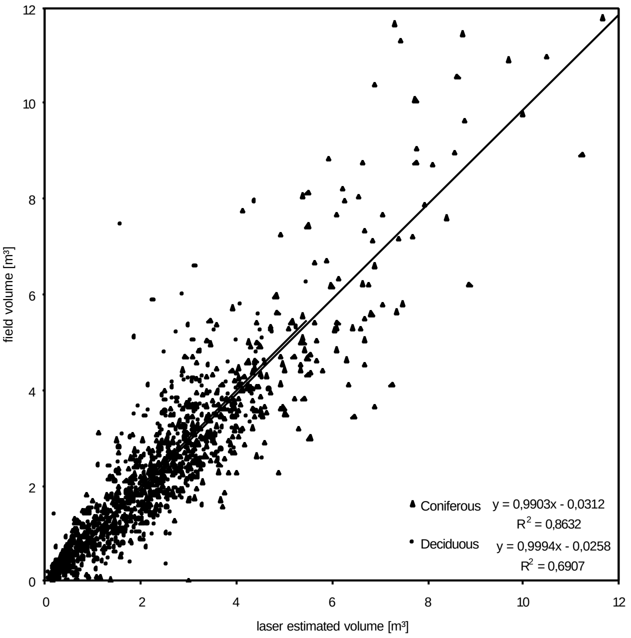

Figure 4: Field-measured volume versus laser-estimated volume (1174 trees).

5. DISCUSSION

High accuracy tree height estimations were achieved both for deciduous trees and coniferous trees. From tree height estimations in forest dominated by Norway spruce and Scots pine, Hyyppä et al (2000) report a RMSE of 0.98 m and a negative bias of 0.14 m. Persson et al. (2002), analysing data from a forest dominated by the same tree species report a RMSE of 0.63 m and a negative bias of 1.13 m. The negative bias can be explained by penetration through the canopy and failure to sample treetops caused by the conical shape of conifer trees. For broad-leaved forest Gaveau & Hill (2003) quantified the underestimation of canopy heights. They reported a negative bias of 1.08 m and a RMSE of 1.89 m for the tree height estimation of individual broad-leaved trees and shrubs. They concluded that the penetration of the upper canopy is dependent on the small-scale variation in closure of the upper canopy surface. According to field observations the upper canopy was denser and more closed for the shrubs than for the trees. Also Brandtberg et al. (2003) estimated hardwood tree heights, although in leaf-off condition, and found a tendency of overestimating the height of small trees and underestimating the height of tall trees. The applied regression model explained 69% of the variation for 48 sample trees. The height measurements show similar accuracy as conventional field survey. Bauer (2001) analysed the quality of height measurements that were performed during operational forest inventories under similar conditions. The mean of the differences between two successive height measurements was 0.07 m, with a standard deviation of 1.4 m. In this study the same value was achieved by an automatic procedure. The fact, that the mean value of the difference between laser measured and field measured height is highly correlated with the dominant height of the stand, is probably caused by erroneous field measurements. The reason for this is that tall trees are difficult to measure from the ground. It is hard to detect the shoots of the trees and the angle for the measurement becomes very steep, when the distance to the stem position cannot be far enough.

The laser crown measurements show better results for coniferous trees than for deciduous trees. While the deciduous crowns were underestimated the algorithm overestimated the crowns of coniferous trees. Also the variability between field and laser measurements was much higher for the deciduous trees. The reason for this is the complex canopy structure in deciduous stands. While coniferous crowns are more or less separate the crowns of deciduous trees intertwine. The branches of the trees are growing into the crowns of its neighbours. This is the reason why it is difficult to separate the trees correctly. Even for a human interpreter it is difficult to identify single trees on an aerial photo. By using the laser scanner DSM the task of separating single deciduous trees is well performed. In comparison to Persson et al. (2002) the presented results for the coniferous trees were slightly worse. In the Swedish study a RMSE of 0.61 m and a coefficient of determination of 0.57 m was reported.

The percentage of the detected volume was 85.2 %. By applying the regression models 86.8% of the field measured volume was predicted when the false positives were not taken into consideration. For the coniferous trees the detected volume was 88.1% and the predicted volume was 90.0%. In comparison to these results Persson et al. (2002) detected 91% and estimated 89% of the volume. Problems with tree detection were usually encountered in forest stands with a high percentage of deciduous trees, in stands with high stem density and in stands with a high variability of tree heights. This is in accordance with observations reported from other studies. Thus, further improvement of the tree detection is needed in order to improve the tree detection for this type of forest stands. Another challenge is to reduce the amount of false tree detections. Coniferous trees are usually conical and with a single treetop whereas deciduous trees are more spherical and sometimes have several treetops for each tree. Using the algorithm efforts are made to handle this problem by symmetry of a tree in order to decide if a maximum of the canopy model is the apex of a tree or only one of many branches. This is done by fitting a parabolic surface to the laser height data but other decision rules should be tested in order to make a better decision whether there are one or several trees.

6. CONCLUSIONS

The analyses show very promising results even for very complex forest structures with multiple layers, with a large height variation and with a high percentage of deciduous trees. In the next step the data will be analysed in more detail, especially there will be a analysis on the stand level. The main focus for the further development of the algorithm has to be laid on an improved delineation of deciduous trees combined with a reduction of false positives. Also a method for tree species identification has to be developed and implemented for the main tree species occurring in Central Europe. With these improvements the method has a high potential to be introduced in practical forest inventory systems.

7. ACKNOWLEDGEMENTS

The financial support given by the Government of Lower Bavaria out of the program “High Tech Offensive Bayern” is gratefully acknowledged. We would like to thank Prof. Håkan Olsson for the possibility for Marco Heurich to work as a guest researcher at the Remote sensing laboratory at the Swedish University of Agricultural Sciences and to the Forest Research Environment in Umeå (FORE) for supporting him with a scholarship. We would also like to thank the field staff especially from the University of Applied Science Munich, from the Chair of Geodesy of the Technological University of Munich who conducted the surveying of the field plots and the Chair of forest yield science which provided us with the field data of its permanent research plots. Special thanks for the following individuals which added valuable contributions to the project: Leonhard Steinacker, Jens Czaja, Franziska Fischer, Hans Jehl, Oliver Knörzer, Achim Klein, Prof. Dr. Krzystek and Dr. Rall. Finally we would like to thank the administration of the Bavarian Forest National Park for supporting the project.

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