Using Airborne Laser Scanner Data and CIR Orthophotos to Estimate the Stem Volume of Forest Stands

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Summary: Accurate assessment of timber resources is of great importance for forest management. This article evaluates a combination of airborne laser scanning and color infrared (CIR) orthophotos to estimate the stem volume of forest stands using growth and yield tables recommended for the Federal State of Baden-Württemberg, Germany. The stand height, which was estimated based on a canopy height model (computed from the laser scanner data), was used as the input variable into a volume function, which was derived from the yield tables. In order to improve the volume estimation, coniferous and deciduous trees were classified automatically using optical data. Different parameters for coniferous and deciduous trees were derived from the yield tables for stem volume estimation. Finally, the derived timber volume was "corrected" using the canopy cover as an estimate for the "degree of stocking". The method was verified in a forest area in Southern Germany with 300 circular inventory plots each with a radius of 12 m. The relation between estimated timber volume and the volume calculated from the inventory data reached a correlation coefficient of r = 0.73 (RMSE = 31%). The plot values were averaged within forest stands with the same age class and a correlation of r = 0.83 (RMSE = 17%) was achieved. The results show that the method can provide valuable information for standwise forest inventories over large areas.

Zusammenfassung: *Verwendung von flugzeuggetragenen Laserscannerdaten und CIR Orthobildern zur Schätzung des Stammholzvolumens von Waldbeständen.* Die präzise Abschätzung von Holzressourcen ist von großer Bedeutung für die Waldbewirtschaftung. Dieser Artikel evaluiert eine kombinierte Auswertung von flugzeuggetragenen Laserscannerdaten und Farb-Infrarot (CIR) Orthobildern zur Abschätzung des Derbholzvolumens von Waldbeständen unter Verwendung von empfohlenen Ertragstafeln für Baden-Württemberg. Die Höhe von Waldbeständen, welche basierend auf einem Vegetationshöhenmodell aus Laserscannerdaten geschätzt wurde, diente als Eingangsvariable in eine aus den Ertragstafeln abgeleitete Volumenfunktion. Zur Verbesserung der Volumenschätzung wurden Nadel- und Laubbäume unter Verwendung von optischen Daten automatisch klassifiziert. Unterschiedliche Parameter für Laub- und Nadelholz wurden zur Schätzung des Derbholzvolumens von Waldbeständen aus den Ertragstafeln abgeleitet. Abschließend wurde das abgeleitete Holzvolumen „korrigiert" über den Überschirmungsgrad als Schätzgröße für den Bestockungsgrad. Eine Verifizierung der Methode erfolgte in einer Waldfläche in Süddeutschland mit 300 kreisförmigen Inventurpunkten der Forstverwaltung (Radius: 12 m). Der Zusammenhang zwischen geschätztem Holzvolumen und dem Volumen aus den Inventurdaten zeigte eine Korrelation von r = 0.73 (RMSE = 31%). Nachdem die Werte innerhalb von Waldbeständen mit der gleichen Altersklasse gemittelt wurden, konnte eine Korrelation von r = 0.83 (RMSE = 17%) erreicht werden. Die Ergebnisse zeigen, dass die Methode wertvolle flächige Informationen für einzelbestandsweise Forstinventuren liefern kann.

1 Introduction

Forest management and planning requires reliable information regarding the forest status and forest production potential. For this reason, forest inventories with extensive field measurements and observations are carried out. In the state forests of the Federal State of Baden-Württemberg in Germany, which are larger than 1500 ha, permanent sample plots

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are usually used to estimate dendrometrical parameters. In smaller forest properties, as well as in private forests, often no sample plot inventories are implemented and other techniques are required to assess forest characteristics. In this study, measurements from Airborne Laser Scanning (ALS) and optical data were evaluated for stem volume estimation (as one of the most important quantitative parameters to characterize a forest stand) using existing forest growth and yield tables.

ALS is an active remote sensing technique which allows accurate height measurements of the earth's surface, vegetation cover or other natural and man-made objects. Due to the fact that the laser penetrates through gaps in the canopy, which allows measuring the canopy height as well as the elevation of the terrain underneath, it is of great interest for forest mapping and monitoring. Most ALS systems use short laser pulses to determine the range to an object by measuring the time of flight between transmission of a pulse and detection of the reflected signal. In addition to the range measurements the scan angle is required. The absolute position and orientation of the sensor is determined using a Global Positioning System (GPS) receiver and an Inertial Measurement Unit (IMU) to calculate the 3D coordinates of the reflected signals in a local coordinate system (Kraus 2004). The result is an irregular point cloud. The point density depends on flight and system parameters. Besides conventional ALS systems, which record the first and last echo for each emitted laser beam, full-waveform scanners, which record the whole echo waveform, have become more important for applications in forestry (Mallet & Bretar 2009, Reitberger et al. 2008). A digital terrain model DTM (which represents the bare earth) and a digital surface model DSM (consisting of the earth and any other objects like vegetation, buildings, etc.) can be derived from the point cloud. Many different filtering algorithms have been developed during the past years for terrain modelling (Sithole 2005). Various studies have already proven the potential of ALS for accurate estimation of forest inventory parameters such as stand heights, basal area, and timber volume (Hyyppä et al. 2006, Koch et al. 2006, Næsset 2002). Regression analyses have been used in many studies concerning forest parameter estimation to identify the relationship between laser-derived variables (representing canopy height and density) and ground-truth data from field plots to calibrate models. The models are used in a second step to estimate inventory parameters, e.g., timber volume for the entire study area (Hollaus et al. 2007, Næsset 2002, Means et al. 2000).

The idea of this study was to develop and verify a method to estimate the stem volume of forest stands based on information from ALS and optical data in combination with existing yield tables. A "stand" is a relatively homogeneous formation of a forest (e.g., uniform in species composition or age) and is managed as a single unit. Thus, information on a stand level is of high importance for forest management. Yield tables were developed in the past from extensive field measurements and give information about structural forest parameters like timber volume attainable under certain conditions. First ideas of the method are described in (Straub et al. 2008a) and (Dees et al. 2006). After a characterization of the study area, and the remote sensing data, and the reference data a description of the methodology is given. The method is designed to be of use for practical forestry applications. Results are presented and, finally, the potential to provide information for forest inventories is discussed.

2 Study Area

The method was verified in a forest area with a size of 9.24 km² in Southern Germany, lo-

Tab. 1: Tree species composition of the study site (source: forest management plan).

Tree Species	Proportion
Scotch pine (Pinus sylvestris)	51 %
Oak (Quercus petraea)	14 %
Beech (Fagus sylvatica)	10 %
Red oak (Quercus rubra)	10 %
Douglas fir (Pseudotsuga menziesii)	5 %
Hornbeam (Carpinus betulus)	4 %
Other species	6 %

cated north of the city of Karlsruhe (coordinates of the upper left corner in Gauss Krüger: 3456300 (easting) / 5436100 (northing)). The tree species composition (derived from the forest management plan) is listed in Tab. 1. The proportions per species were estimated in the field, based on the area covered by the crowns of each individual species in a stand.

3 Remote Sensing Data

Full-waveform laser scanner data were acquired in August 2007 by TopoSys GmbH using the "Harrier 56" LIDAR system mounted on a helicopter. The scanner used in this system is the Riegl LMS-Q560. To achieve a high point density, the study area was flown twice and a large side lap of more than 50% was used. Important flight and system parameters are listed in Tab. 2.

The software "RiANALYZE 560" was used by the data provider to process the full-waveform data. The data was delivered in ASCII format with 3D coordinates of the reflections and additional information such as the echo signal intensity and the echo pulse width.

Both a terrain and a surface model with 1m resolution were derived from the point cloud. An "Active Surface Algorithm", implemented in the software "TreesVis", was used for filtering and interpolation. Details about the filtering technique can be found in (Elmqvist et al. 2001) and (Weinacker et al. 2004). A normalized digital surface model (nDSM), often referred to as canopy height model (CHM) in forests, was derived by subtracting the DTM from the DSM.

Tab. 2: Flight and system parameters of the flight campaign in summer 2007 with the "Harrier 56" (AGL = above ground level).

Parameter	**Value**
Measurement rate	100 [kHz]
Field of view	45 [°]
Flying height	450 [m] AGL
Flying speed	30 [m/s]
Point density	16 [points/m²]
Vertical / horizontal accuracy	< 0.20 [m] / < 0.50 [m]

Tab. 3: Flight and technical parameters of the RGB/NIR line scanner of the flight campaign in summer 2008 with the "Falcon II system" (AGL = above ground level).

Parameter	**Value**
Flying height	700 [m]
Spectral Channels	Blue: 450 – 490 [nm] Green: 500 – 580 [nm] Red: 580 – 660 [nm] Near infrared: 770 – 890 [nm]
Viewing angle	21.6 [°]
Line Rate	Up to 330 [Hz]
Pixel per line	682
Ground sampling distance	0.4 [m]

Additionally, optical data in four spectral channels were recorded in July 2008 by TopoSys GmbH with the aid of an RGB/NIR line scanner (integrated in the Falcon II system). The individual flight strips were rectified and georeferenced with the aid of a DSM, which was filtered from laserscanner data (6–7 points/m²) acquired at the same time with the optical data. Important flight and technical parameters of the RGB/NIR line scanner are listed in Tab. 3. Orthophotos were computed by the data provider ToposSys using the software "TopPIT" and were delivered with 25 cm resolution.

4 Reference Data

Forest inventory data (circular sample plots) from summer 2006 were provided by the state forest administration of the Federal State of Baden-Württemberg. These permanent geo referenced sample plots were distributed over the study area on the intersections of a regular 100×200 m raster. In each of the plots trees were measured in the field within concentric circles using the following radii: 2 m, 3 m, 6 m and 12 m. Within each concentric circle, trees with a diameter at breast height (DBH) greater than 7 cm (2 m radius), 10 cm (3 m radius), 15 cm (6 m radius) and 30 cm (12 m radius)

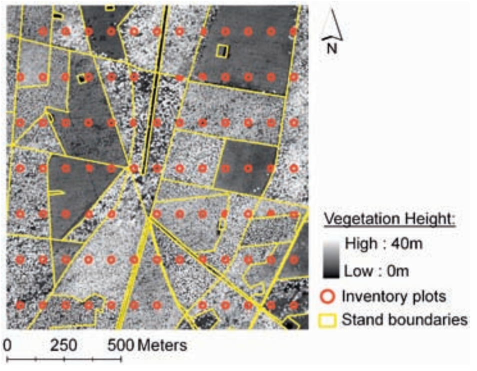

Fig. 1: Canopy height model with stand boundaries and position of inventory plots.

were measured. Two top heights of the main crop and one top height of the dominated crop were measured using a Vertex® instrument. The arithmetic mean of the height measurements was calculated as an average top height for each plot. Stand height curves with the DBH as input variable were used to estimate the heights of the remaining trees (Korn-Allan et al. 2004). Based on these measurements, the stem volume of single trees was computed using volume functions and the total timber volume in solid cubic meter per hectare (defined as the sum of all stems and branches with a diameter above 7 cm) was derived for each plot. Moreover, a digital stand map was provided by the forest administration. A total number of 108 stands are located completely within the study site. Fig. 1 shows a part of the study area with the CHM, stand boundaries and inventory plots.

5 Methodology

Yield tables, recommended for the Federal State of Baden-Württemberg (MLR 1993), were used to estimate the stem volume of forest stands in conjunction with variables derived from ALS and CIR orthophotos. The tables are grouped into 16 different tree species and describe the development and growth of forest stands based on a specific forestry concept (treatment of a stand like moderate or strong thinning). For each species, several yield classes are defined which describe the influence of environmental conditions (climate, topography and soil) and thus the production or growth potential of sites. The tables provide numerical forestry parameters related to the area unit of one hectare such as tree number, top height, basal area, mean diameter or volume as a function of the age. Due to the fact that ALS data provides very precise height measurements, the yield tables were used to estimate timber volume as a function of the stand height. The following variables have to be determined for the application of yield tables:

1. Tree species composition of a stand: Necessary for the selection of a suitable table. CIR orthophotos were used to identify and classify coniferous and deciduous trees. For both classes a separate volume function was derived from the tables.
2. Yield class: Describes the production or growth potential and is usually necessary for the selection of a suitable table. As described in (Mette 2007) information on the site condition is very important if stem biomass is estimated by the age of a stand. If stem biomass is estimated by the forest height the site condition has a rather small influence. This statistical relation between (mid) height and (stem) volume of a stand is known as the “law of Eichhorn” (Pretzsch 2001). Thus, the yield class was not further considered in this study.
3. Stand height: The stand height is estimated from ALS data and is used as input variable into a height based volume function derived from the yield tables.
4. “Degree of stocking”: The timber volume derived from a yield table is multiplied by the degree of stocking DS (reduction factor), defined by the quotient of actual basal area BA_{real} to the corresponding basal area of a suitable yield table BA_{table} for moderate thinning (Kramer & Akça 1995):

$$DS = BA_{real} / BA_{table} \quad (1)$$

The result is an estimate of the actual volume of a stand. According to (Huss 1984) the canopy cover, also referred to as canopy density, is appropriate to estimate the degree of stocking with remote sensing data.

5.1 *Estimation of Forest Stand Height Using ALS Data*

The top height H of forest stands is defined as the height of the hundred trees with largest diameter per hectare (Burschel & Huss 1997). Since trees with the largest diameter are usually the highest trees, the top height represents the height of trees in the uppermost layer which can be modelled with ALS data. Due to the shorter time difference to the forest inventory in summer 2006, the full-waveform laser scanner data (acquired in August 2007) was used for top height estimation. Several variables related to vegetation height were derived from the point cloud (after subtracting the ground surface height), as well as the nDSM, and were analyzed in order to determine the best estimate for the top height. Similar to earlier findings (Næsset 2002, Means et al. 2000, Rieger et al. 1999) several height percentiles were calculated for each inventory plot based on the nDSM $nDSMhp_{60,}$ $nDSMhp_{70,}$ $nDSMhp_{80,}$ $nDSMhp_{90,}$ $nDSMhp_{max}$ and based on the point cloud. Percentiles were computed using all laser points ahp_{60}, $ahp_{70,}$ $ahp_{80,}$ ahp_{90}, ahp_{max} and for the first echo points (=first reflections detected in the waveforms by the RiANALYZE 560 software) fhp_{60}, $fhp_{70,}$ $fhp_{80,}$ $fhp_{90,}$ fhp_{max}. The results are shown in Tab. 4.

The 90th percentile of the nDSM ($nDSMhp_{90}$) showed the highest correlation with the field data and was used as an estimate for the top height.

5.2 *Estimation of the Canopy Cover from ALS Data*

Canopy cover CC was defined in this study as the ground covered by a vertical projection of tree crowns in the uppermost layer. For each sample plot, the canopy cover was estimated based on the nDSM, which represents the canopy heights for each xy position. A threshold operation (selection of pixels with height values within a defined interval) was used to extract potential crown regions. The threshold operation is defined as

$$CR = \{(xy) \in R \mid \Delta h_{min} \leq nDSM_{xy} \leq \Delta h_{max}\} \quad (2)$$

where CR = Output region (crown regions)
R = Region of Interest (ROI)
$nDSM_{xy}$ = Height values [m] of the nDSM for each xy position
Δh_{min} = Minimum height threshold [m]
Δh_{max} = Maximum height threshold [m]

The minimum height threshold Δh_{min} for each plot was calculated relative to the estimated top height H, assuming that height values above 50% of the top height belong to the uppermost layer ($\Delta h_{min} = H \cdot 0.5$) whereas Δh_{max} was set to the maximum height value within the sample plots. The ratio of the size of extracted crown regions CR to the plot size was used as an estimate for the canopy cover.

Tab. 4: Correlations of height percentiles from raw data and nDSM with field measurements (inventory plots) to estimate the top height of forest stands.

height percentiles nDSM	**Correlation coefficient (r)**	**height percentiles – raw data (all laser points)**	**Correlation coefficient (r)**	**height percentiles – raw data (only first echo points)**	**Correlation coefficient (r)**
$nDSMhp_{max}$	.835(**)	ahp_{max}	.839(**)	fhp_{max}	.839(**)
$nDSMhp_{90}$	.868(**)	ahp_{90}	.844(**)	fhp_{90}	.853(**)
$nDSMhp_{80}$	.837(**)	ahp_{80}	.778(**)	fhp_{80}	.813(**)
$nDSMhp_{70}$	.800(**)	ahp_{70}	.619(**)	fhp_{70}	.741(**)
$nDSMhp_{60}$	.735(**)	ahp_{60}	.441(**)	fhp_{60}	.580(**)

** Correlation is significant at the 0.01 level (2-tailed).

5.3 *Automatic Classification of Coniferous and Deciduous Trees Using CIR Orthophotos*

A widely acknowledged phenomenon is the generally observed lower spectral reflectance of coniferous stands when compared to deciduous stands especially for the near infrared wavelengths (Rautiainen 2005, Hildebrandt 1996, Huss 1984). CIR orthophotos were used to classify coniferous and deciduous trees. First, a vegetation mask was generated solely using the laser data. The segmentation of vegetation and non-vegetation areas is based on the assumption that many laser reflections will be found inside of the vegetation from different vegetation layers between the top of the canopy and the bare earth. Those points are referred to as "intermediate points". No "intermediate points" will be found within artificial non-ground objects like buildings because of the impenetrable surfaces. "Intermediate points" can be used for classification if multiple echoes (extracted from full-waveform data) are available. Further details regarding the segmentation method can be found in (Straub et al. 2008b).

Within the vegetation mask, coniferous and deciduous trees were classified with the help of a "two-dimensional feature space image" as shown in Fig. 2. The value at one point $P(g_1,g_2)$ indicates the frequency of the gray value combination (g_1,g_2) with g_1 indicating the values of the green channel as row index and those values g_2 of the near infrared channel as column index. The two expected classes (for coniferous and deciduous trees) are clearly visible. A segmentation of the feature space image was achieved using a pouring algorithm which regards the input image as a topological surface and interprets the gray values as heights. First, local maxima are extracted which have larger values than their direct neighbors. The maxima are the starting points for an expansion (region growing) until "valley bottoms" are reached (like water running downhill from the maxima in all directions). In order to segment the input image into exactly two classes (representing coniferous and deciduous trees) the feature space image was iteratively smoothed with a moving average filter. For each iteration the filter size was enlarged until exactly two segments were delineated (boundaries of the segmented regions are visualized in Fig. 2).

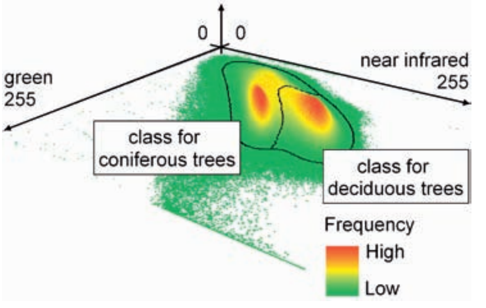

Fig. 2: 3D view of the two-dimensional feature space image showing the frequency of the gray value combination of near infrared and green channel with segmented classes for coniferous and deciduous trees.

Each point P of the study area with g_1 and g_2 as the respective gray values of green and near infrared channel (g_1 interpreted as row coordinate and g_2 as column coordinate) is classified according to its position in the feature space. If P is an element of the coniferous or deciduous class (as shown in Fig. 2) it is classified respectively. A result of the classification is shown in Fig. 3.

The classification accuracy was evaluated using the inventory plots. The comparison of the coniferous proportion classified by the automated method (within the reference plots) with the coniferous proportion of the field data yields a correlation of r = 0.87.

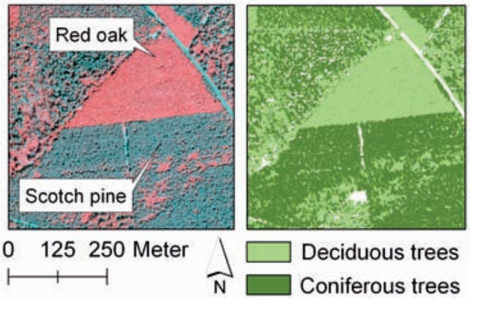

Fig. 3: CIR orthophoto and result of the classification into deciduous and coniferous trees.

5.4 *Retrieval of a Height Based Volume Function from Existing Yield Tables*

A polynomial of second order was used to estimate timber volume per hectare as a function of the forest stand height:

$$V = a + bH + cH^2 \quad (3)$$

where V = Timber volume [m³/ha]
H = Top height [m]
a,b,c = Individual parameters (depending on tree species composition)

Different parameters a,b,c were derived for coniferous as well as for deciduous trees from existing growth and yield tables as recommended for the Federal State of Baden-Württemberg, Southern Germany (MLR 1993). Scotch pine (Pinus sylvestris) is the major coniferous species within the study site (see Tab. 1). For this reason, it was used as a "reference species" for coniferous trees. As described in Section 5 several yield classes are defined for each species. For scotch pine, 7 different classes are defined and the corresponding height based volume function was derived as a regression through all of these classes. The most important deciduous tree species within the study site is oak (Quercus petraea), which was defined as "reference species" for deciduous trees. Analogous to the approach for coniferous trees, the corresponding volume function for deciduous trees was derived as a regression through all yield classes for oak (7 classes in total). Results of the regression analysis are summarized in Tab. 5.

5.5 *Stem Volume Estimation*

For each sample plot the timber volume was estimated in solid cubic meter per hectare. The estimation of timber volume as a function of top height, tree species composition and degree of stocking can be written as:

$$V = CC \cdot \left[\left((a_c + b_c H + c_c H^2) \cdot \frac{P_c}{100} \right) + \left((a_d + b_d H + c_d H^2) \cdot \frac{P_d}{100} \right) \right] \quad (4)$$

where V = Estimated stem volume in [m³/ha]
H = Top height [m] (estimated from nDSM)
$a_c, b_c, c_c, a_d, b_d, c_d$ = Parameters for coniferous ($_c$) and for deciduous ($_d$) trees
P_c, P_d = Percentage of coniferous ($_c$) and for deciduous ($_d$) trees (automatically classified with optical data)
CC = Canopy cover derived from the nDSM as an estimate for the "degree of stocking"

6 Results

Forest inventory plots (as described in Section 4) were used for verification. The estimated timber volume and the volume derived from the inventory data were compared for all sample plots (n = 300) as well as for averaged values, which were computed from plots located within forest stands having the same age class. The age class was taken from the forest management plan. For accuracy assessment, the

Tab. 5: Parameters derived from yield tables (MLR 1993) by regression analysis to derive timber volume in [m³/ha] as a function of the stand height.

						Range	
Class	**Number of yield classes**	***a* [m³/ha]**	***b* [m²/ha]**	***c* [m/ha]**	**R^2 (coefficient of determination)**	**Min. Height [m]**	**Max. Height [m]**
Coniferous trees	7	−90.2971	18.0819	−0.0022	0.98	8.3	37.5
Deciduous trees	7	−145.3082	16.4528	0.0684	0.99	7.8	40

absolute and relative root mean square errors (RMSE) were calculated. The absolute RMSE is defined as:

$$\mathrm{RMSE}\ [\mathrm{m^3/ha}] = \sqrt{\frac{\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}{n}}, \qquad (5)$$

where y_i = the observed volume for plot i [m^3/ha]
$\hat{y}_i$ = the predicted volume for plot i [m^3/ha]
n = the number of sample plots used for validation

The relative RMSE is defined as the RMSE normalized to the mean y_{mean} of the observed values:

$$\mathrm{RMSE}\ [\%] = \frac{\mathrm{RMSE}}{y_{mean}} \cdot 100 \qquad (6)$$

A correlation coefficient of r = 0.73 and RMSE = 31% was reached when using all sample plots (a scatter plot is shown in Fig. 4a). The comparison of averaged values (for stands with the same age class) is shown in Fig. 4b. Only stands with a minimum of three plots were selected (n = 21) and a correlation of r = 0.83 and RMSE = 17% was achieved.

7 Discussion

A method was presented which combines ALS data and further information from optical data to assess the stem volume of forest stands. Due to the fact that existing growth and yield tables were used for volume estimation, the method can provide valuable information for forests without sample plot inventories. Forest inventory data (circular sample plots), which were acquired within the study area by the state forest administration in summer 2006, were solely used for verification of the developed method. Different variables (vegetation characteristics) were extracted from ALS data and CIR orthophotos. It was shown that ALS data provides very precise height measurements to estimate the top height of forest stands, which was used as input variable into a height based volume function derived from the yield tables. Using only one variable (the 90th percentile of the nDSM) a high correlation of r = 0.87 was reached for height estimation on plot level. To improve the volume estimation, coniferous and deciduous trees were classified fully automatically using optical data. The comparison of the coniferous proportion classified by the automated method with the coniferous proportion of the field data yields a high correlation of r = 0.87.

In order to derive different parameter sets from the yield tables it was necessary to define

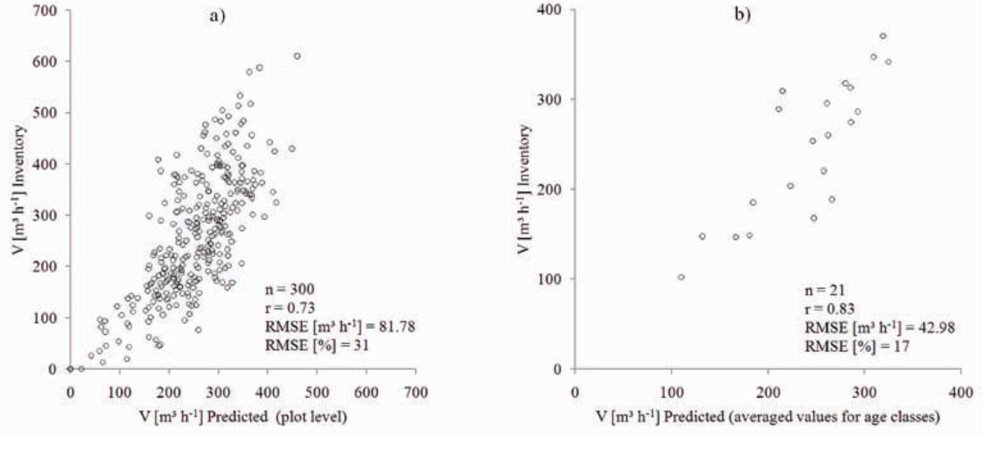

Fig. 4: Verification of the stem volume estimation a) using all inventory plots, b) estimation with averaged values for age classes.

a "reference species" for coniferous and deciduous trees. For the definition of a "reference species" it is helpful if information about the dominant tree species within the study site is available. In this study the species composition was derived from the forest management plan. As an alternative approach visual interpretation of optical data is suggested. As a further variable, the canopy cover (tree crown cover) was derived based on the nDSM by extracting all pixels above a threshold relative to the top height. The canopy cover was used as an estimate for the degree of stocking. The multiplication of the degree of stocking with the volume obtained from a yield table affords an estimate for the actual volume.

A correlation of r = 0.73 (RMSE = 31%) was reached for stem volume estimation when regarding all sample plots. The relatively high scatter on plot level can be explained to some extent by positional errors of the reference data (the plot locations) and local variations of the forest structure, which have a high influence if timber volume is estimated for small regions like the 452 m² sample plots used in this study. The position accuracy of the centre point of inventory plots was quantified in a recent study with an average deviation of 3.77 m compared to very accurate measurements using a theodolite (Breidenbach 2008). However, the variation was compensated when plot values were averaged for larger units (here: for stands with the same age class) and a very satisfying accuracy of r = 0.83 (RMSE = 17%) was reached.

The results show that information from ALS and CIR orthophotos can be used in conjunction with existing yield tables to estimate the stem volume of forests. Thus, the method can provide valuable information for standwise inventories, which is particularly interesting for forests without sample plot inventories. Many studies require reference data to identify relationships between laser-derived variables and ground-truth data from field plots to calibrate models. The advantage of forest attribute estimation based on yield tables is that such reference data is not mandatory.

The observed error (RMSE = 31%) of this study is in the range of those reported by (Breidenbach et al. 2008) (RMSE: 22.5% to 31.3%), who used mixed-effects models in combination with forest inventory plots (see Section 4) as ground truth data, to estimate stem volume for two different study sites located within the Federal State of Baden-Württemberg. In a study from (Packalén & Maltamo 2006) ALS data and aerial photographs were used in a boreal forest in Finland to predict the plot volume using the *k*-MSN method. They report a RMSE of 24% for estimates of total volume.

The current method does not utilize the full potential of full-waveform ALS data, but rather uses these data in the same way as conventional ranging systems. The advantage is that the method can be used with any type of ALS data, e. g., first/last echo data plus CIR orthophotos. However, further research will concentrate on the integration of additional information available from full-waveform ALS data, such as the echo signal intensity of each reflection. A study from (Reitberger et al. 2008) has recently shown that these additional parameters can be used for classification of coniferous and deciduous trees.

In order to improve the volume estimation for uneven-aged stands (that have a more complex forest structure) further studies will concentrate on the extraction of additional forest characteristics from the full waveform data, e. g., the vertical stand structure (different layers) or horizontal variability. In this study it was possible to delineate coniferous and deciduous trees using a fully automated approach, whereas the classification of species such as Scotch pine (Pinus sylvestris), Oak (Quercus petraea), or Beech (Fagus sylvatica) will need further research. Thus, automatic and/or semi-automatic classification procedures will be developed to extract additional information on tree species composition.

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References

Burschel, P. & Huss, J., 1997: Grundriß des Waldbaus. – Parey, Berlin.

Breidenbach, J., 2008: Regionalisierung von Waldinventuren mittels aktiver Fernerkundungstechniken. – Doctoral Thesis, Freiburg.

Breidenbach, J., Kublin, E., McGaughey, R.J., Andersen, H.E. & Reutebuch, S.E., 2008: Mixed-effects models for estimating stand volume by means of small footprint airborne laser scanner data. – Photogrammetric Journal of Finland **21** (1): 4–15.

Dees, M., Straub, C., Wang, Y., Koch, B. & Weinacker, H., 2006: Auswertung von zwei Laserscanner-Testdatensätzen: Waldkarten und Kenngrößen des Waldes. – Internal report of a demonstration project for E.ON-Ruhrgas, Essen.

Elmqvist, M., Jungert, E., Lantz, F., Persson, Å. & Söderman, U., 2001: Terrain Modelling and Analysis Using Laser Scanner Data. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **34** (3/W4): 219–226.

Hildebrandt, G., 1996: Fernerkundung und Luftbildmessung für Forstwirtschaft, Vegetationskartierung und Landschaftsökologie. – Wichmann, Heidelberg.

Hollaus, M., Wagner, W., Maier, B. & Schadauer, K., 2007: Airborne Laser Scanning of Forest Stem Volume in a Mountainous Environment. – Sensors **7:** 1559–1577.

Huss, J., 1984: Luftbildmessung und Fernerkundung in der Forstwirtschaft. – Wichmann, Karlsruhe.

Hyyppä, J., Yu, X., Hyyppä, H. & Maltamo, M., 2006: Methods of Airborne Laser Scanning for forest information extraction. –International workshop "3D Remote Sensing in Forestry", University of Natural Resources and Applied Life Sciences, Vienna, Austria: 63–78.

Koch, B., Heyder, U. & Weinacker, H., 2006: Detection of Individual Tree Crowns in Airborne Lidar Data. – Photogrammetric Engineering & Remote Sensing **72** (4): 357–363.

Korn-Allan, E., v.d. Goltz, H., Blust, M. & Nothdurft, A., 2004: Verfahrenshandbuch Betriebsinventur. – Version 1.1., Landesforstverwaltung Baden-Württemberg.

Kramer, H. & Akça, A., 1995: Leitfaden zur Waldmesslehre. – J.D. Sauerländer's Verlag, Frankfurt am Main.

Kraus, K., 2004: Photogrammetrie – Band 1. – De Gruyter, Berlin.

Mallet, C. & Bretar, F., 2009: Full-waveform topographic lidar: State-of-the-art. – Journal of Photogrammetry and Remote Sensing **64** (1): 1–16.

Means, J.E., Acker, S.A., Fitt, B.J., Renslow, M., Emerson, L. & Hendrix, C.J., 2000: Predicting Forest Stand Characteristics with Airborne Laser Scanning LIDAR. – Photogrammetric Engineering & Remote Sensing **66** (11): 1367–1371.

Mette, T., 2007: Forest Biomass Estimation from Polarimetric SAR Interferometry. – Doctoral Thesis, München.

MLR, 1993: Hilfstabellen für die Forsteinrichtung. – Ministerium für Ländlichen Raum, Ernährung, Landwirtschaft und Forsten Baden Württemberg, Stuttgart.

Næsset, E., 2002: Predicting forest stand characteristics with airborne scanning laser using a practical two-stage procedure and field data. – Remote Sensing of Environment **80** (1): 88–99.

Packalén, P. & Maltamo, M., 2006: Predicting the plot volume by tree species using airborne laser scanning and aerial photographs. – Forest Science **52** (6): 611–622.

Pretzsch, H., 2001: Modellierung des Waldwachstums. – Parey, Berlin.

Rautiainen, M., 2005: The spectral signature of coniferous forests: the role of stand structure and leaf area index. – Doctoral Thesis, Helsinki, Finland.

Reitberger, J., Krzystek, P. & Stilla, U., 2008: 3D segmentation and classification of single trees with full waveform LiDAR data. – SilviLaser 2008 conference, Edinburgh, UK: 216–225.

Rieger, W., Eckmüllner, O., Müllner, H. & Reiter, T., 1999: Laser-Scanning for the derivation of forest stand parameters. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **32** (3/W14): 193–201.

Sithole, G., 2005: Segmentation and Classification of Airborne Laser Scanner Data. – Publications on Geodesy, **59**, Delft, The Netherlands.

Straub, C., Dees, M., Weinacker, H. & Koch, B., 2008a: Combining Airborne Laser Scanning and GIS Data to estimate Timber Volume of Forest Stands based on Yield Models. – SilviLaser 2008 conference, Edinburgh, UK: 572–580.

Straub, C., Weinacker, H. & Koch, B., 2008b: A Fully Automated Procedure for Delineation and Classification of Forest and Non Forest Vegetation based on Full Waveform Laserscanner Data. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **37** (B8): 1013–1019.

Weinacker, H., Koch, B., Heyder, U. & Weinacker, R., 2004: Development of filtering, segmentation and modelling modules for LIDAR and multispectral data as a fundamental of an automatic forest inventory system. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **36** (8/W2): 90–95.

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