Combining airborne laser scanning and GIS data to estimate timber volume of forest stands based on yield models

Christoph Straub[1], Matthias Dees[1], Holger Weinacker[1] & Barbara Koch[1]

[1] University of Freiburg, Dept. of Remote Sensing and Landscape Information Systems, christoph.straub@felis.uni-freiburg.de, matthias.dees@felis.uni-freiburg.de holger.weinacker@felis.uni-freiburg.de, barbara.koch@felis.uni-freiburg.de

Abstract

Timber Volume is one of the most important quantitative parameters to characterize a forest stand. This article evaluates a combination of Airborne Laser Scanning and GIS data to estimate timber volume of forest stands using standard forestry yield models. The input parameters into the models are the stand height and canopy density which are both derived from a normalized digital surface model. For the selection of suitable yield models, information about tree species composition from digital stand maps was used. The method was verified in a forest area in Southern Germany with 313 circular inventory plots each with a size of 452m². The relation between estimated timber volume and the volume calculated from the inventory data reached a correlation coefficient of r = 0.74 when regarding all sample plots. The plot values were averaged within forest stands of the same age class and a correlation of r = 0.91 was achieved. The relation for averaged values only for single-storied stands reached a correlation of r = 0.98.

Keywords: Airborne Laser Scanning, forestry, timber volume, yield models, inventory

1. Introduction

Airborne Laser Scanning (ALS) is an active remote sensing technique for the capturing of topographic data. Laser Mapping is based on a multi-sensor system whose main components are a laser scanner to measure the range/distance from the scanner in the aeroplane to the terrain surface, a Global Positioning System (GPS) and an Inertial Navigation System (INS). These components are usually mounted on a helicopter or an aeroplane. The survey area is scanned strip by strip and the range measurements are converted into a local coordinate system. The result is a point cloud, often referred to as “raw data”. Besides conventional ALS systems which record the first and last echo for each emitted laser beam, full wave scanners (which record the whole echo waveform) gain more importance (Wagner *et al.* 2008). In forests the laser pulses usually have multiple reflections from different vegetation layers and a certain amount of pulses will penetrate to the ground. Using a suitable filtering technique a digital terrain model - DTM (which represents the bare earth) and a digital surface model - DSM (which represents the height of objects on top of the bare earth like vegetation cover or buildings) can be derived from the point cloud. A large number of studies have shown the capability of ALS technology to accurately estimate important forest inventory parameters such as stand heights, basal area, and stand volume (Hyyppä *et al.* 2006, Koch *et al.* 2006, Hyyppä *et al.* 2004, Næsset 2002). A widely used approach is to relate laser-derived variables, representing canopy height and density, to ground-truth data from inventory plots for the calibration of regression models. The models are used in a second step to estimate forest inventory parameters e.g. timber volume for the entire study area (Hollaus *et al.* 2007, Næsset 2002, Means *et al.* 2000, Næsset 1997).

In the following paragraphs a method is described which combines ALS and additional information from GIS data to estimate timber volume of forest stands using standard forestry yield models. Yield models were developed in the past from extensive field measurements and are summarized into yield tables which give information about structural forest parameters like timber volume attainable under certain conditions. First ideas of the method are described in (Dees *et al.* 2006).

2. Method

2.1 Study Area

The method, presented in the following paragraphs, was verified in a forest area with a size of 9.24 km² in Southern Germany located north of the city of Karlsruhe (coordinates of the upper left corner in Gauss Krüger: 3456300 (easting) / 5436100 (northing)). The tree species composition is shown in table 1.

Table 1: Tree species composition of the study site

Tree Species	Percentage
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 such as birch (Betula pendula), spruce (Picea abies), larch (Larix europaea), lime tree (Tilia cordata), sycamore maple (Acer pseudoplatanus)	6 %

2.2 Remote Sensing Data

Full-wave laser scanner data and aerial images 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. Important flight and system parameters are listed in table 2.

Table 2: Flight and system parameters of the flight campaign in summer 2007 with the “Harrier 56”

Parameter	Value
Range Capture	Full waveform digitization
Measurement rate	100 kHz
Field of view	45°
Swath width	370m
Flying height	450m AGL
Flying speed	30m/s
Point density	16 points / m²
Vertical accuracy	< ±0.20 [m]
Horizontal accuracy	< ±0.5 [m]

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 (Weinacker *et al.* 2004). A normalized digital surface model (nDSM), in forests often referred to as canopy height model (CHM), was derived by subtracting the DTM from the DSM. True orthophotos (RGB and CIR) with 20 cm ground resolution were delivered by TopoSys GmbH.

2.3 Reference Data

Forest inventory data from summer 2006 was provided by the Department of Forestry of the Federal State of Baden-Württemberg. Permanent georeferenced sample plots were distributed over the study area on the intersections of a regular 100x200m raster. For each of the plots trees were measured in the field within concentric circles using the following different radii: 2m, 3m, 6m and 12m. Within each concentric circle trees with a diameter at breast height (DBH) greater than 7cm, 10cm, 15cm and 30cm were measured. Two top heights of the main crop and one top height of the dominated crop were measured using a Vertex® instrument. As an average top height for each plot the arithmetic mean of those height measurements was calculated. Stand height curves with the DBH as input parameter were used to estimate the heights of the remaining trees (Korn-Allan 2004). Based on these measurements the volume of single trees was computed and the timber volume in solid cubic meter per hectare (defined as the sum of all stems and branches with a diameter above 7cm) was derived for each plot. The position accuracy of the centre point of the sample plots was quantified in a current study with an average deviation of 3,77m compared to very accurate measurements using a theodolite (Breidenbach 2008).

2.4 Methodology

Yield models, developed and recommended for the Federal State of Baden-Württemberg, Southern Germany (MLR 1993) were used to estimate timber volume with metrics from ALS and GIS data as input parameters. The models describe the development of a forest stand throughout lifetime based on a specific forestry concept (treatment of a stand like moderate or strong thinning) and were set up for 16 different tree species. For each species several yield classes are defined which describe the influence of environmental conditions (climate, topography and soil). They are given in a tabular form and provide forestry parameters such as tree number per hectare, top height, basal area, mean diameter or volume as a function of the age. Due to the fact that ALS data provides very accurate height measurements the yield models were used to estimate timber volume as a function of top height. In general the following information is necessary for the application of yield models:

1. Tree species composition of a stand: Necessary for the selection of suitable models. Due to the fact that species classification from ALS data is still a challenge, except for the classification of coniferous and deciduous forest during leaf-off (winter) conditions (Straub 2006), tree species percentages of the forest management plan (formatted as GIS data) were integrated. For each species a separate function was derived from the yield tables. The species percentage was used as weighting factor.
2. Yield class: Describes the influence of environmental conditions and is necessary for the selection of a suitable model. As described in (Mette *et al.* 2002) 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 only a small effect. The statistical relation between (mid) height and (stem) volume of a stand is also known as the "law of Eichhorn" (Pretsch 2001). Thus the yield class was not further considered in this study.
3. "Degree of stocking": The timber volume derived from a yield table is multiplied with the degree of stocking DS defined as the ratio of real basal area BA_{real} to the corresponding basal area from a yield table BA_{table} for moderate thinning (Kramer and Akça 1995):

$$DS = \frac{BA_{real}}{BA_{table}} \qquad (1)$$

The result is an estimate of the actual volume of the stand. According to (Huss 1984) the degree of stocking can be estimated with remote sensing data using the tree crown cover also referred to as canopy density.

2.4.1 Top Height Estimation of Forest Stands using ALS Data

Top height is defined as the height of the hundred trees with largest diameter per hectare within a stand (Burschel and Huss 1997). Due to the fact that trees with the largest diameter are usually the highest trees, the top height represents the height of trees in the upper canopy level which can be modelled with ALS data. Several variables both derived from the point cloud/raw data (after subtracting the ground surface height) and the nDSM were verified 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 from the raw data Raw_{60}, Raw_{70}, Raw_{80}, Raw_{90}, Raw_{max} (unlike previous studies no differentiation between first and last echo was made) and from the nDSM $nDSM_{60}$, $nDSM_{70}$, $nDSM_{80}$, $nDSM_{90}$, $nDSM_{max}$. The correlations of the laser metrics with the field data (as shown in table 3) were computed for 305 inventory plots (all plots with actual tree height measurements).

Table 3: Correlations of height percentiles from raw data and nDSM with height measurements from 305 inventory plots to estimate the top height of forest stands

Height percentiles from nDSM	Correlation Coefficient (r)	Height percentiles from raw data	Correlation Coefficient (r)
$nDSM_{max}$	0.84	Raw_{max}	0.84
$nDSM_{90}$	0.87	Raw_{90}	0.84
$nDSM_{80}$	0.84	Raw_{80}	0.78
$nDSM_{70}$	0.80	Raw_{70}	0.62
$nDSM_{60}$	0.74	Raw_{60}	0.44

The 90th percentile of the nDSM ($nDSM_{90}$) showed the highest correlation with the field data. The regression is shown in figure 1:

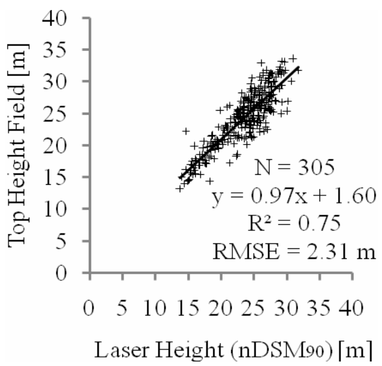

Figure 1: Estimation of the top height of forest stands from 90th percentile of the nDSM

2.4.2 Estimation of the Canopy Density from ALS data

Canopy density is defined as the ground covered by a vertical projection of tree crowns. For each sample plot the canopy density 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

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

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

Timber volume is defined by stems with a minimum diameter of 7cm. If a general relation of *height = diameter · 100* is assumed (for young trees), the minimum height of trees to be measured will be 7m which was defined for $\Delta h_{\min}$ whereas $\Delta h_{\max}$ was set to the maximum height value within the sample plots. The ratio of the size of extracted crown regions *CR* to the plot area was used as an estimate for canopy density.

2.4.3 Tree Species Information from GIS Data

A digital stand map was provided by the Department of Forestry. A total number of 101 stands are located in the study site. Tree species percentages of the forest management plan were assigned as attributes to the stands. The percentages are estimated in field based on the area covered by the crowns of each individual species in a stand and are given in units of 5 %. The accuracy of the estimation is not quantified but is assumed to be less than ±5 %. Finally the tree species percentages were allocated to all sample plots located within each stand.

2.4.4 Estimation of the Timber Volume

A polynomial of second order was used to estimate timber volume as a function of top height:

$$V = a + bH + cH^2 \tag{3}$$

where V = Timber volume
H = Top height
a, b, c = Individual parameters for a tree species

Different parameters were derived from the yield tables for eight species using regression analysis (see table 4).

Table 4: Parameters derived from yield tables to estimate timber volume as a function of top height

						Range	
Tree species	Number of yield tables	a [m³/ha]	b [m²/ha]	c [m/ha]	R^2	Min. Height [m]	Max. Height [m]
Scotch pine (Pinus sylvestris)	7	- 90.2971	18.0819	-0.0022	0.98	8.3	37.5
Oak (Quercus petraea)	7	- 145.3082	16.4528	0.0684	0.99	7.8	40
Beech (Fagus sylvatica)	8	- 160.3876	17.8205	0.0629	0.98	6.6	45.5
Red oak (Quercus rubra)	5	- 88.6174	8.5654	0.2272	0.97	6	33.5
Douglas fir (Pseudotsuga menziesii)	12	33.0444	0.3091	0.4372	1	9.5	51.1
Spruce (Picea abies)	11	- 154.5544	21.5093	0.1245	0.97	6.9	43.1
Larch (Larix Europaea)	5	- 17.7444	7.1107	0.2381	0.99	11.1	43.2
Lime tree (Tilia cordata)	5	25.2515	8.2378	0.1333	1	13.2	32.6

For some deciduous species no yield models were available and the parameters for beech were used. 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:

$$V = DS \cdot \sum_{i=1}^{n} \left[(a_i + b_i H + c_i H^2) \cdot \frac{P_i}{100} \right] \quad (4)$$

where V = Estimated Timber volume in m³/ha

a_i, b_i, c_i = Parameters for different tree species $(i = 1,..., n)$

H = Top height in meter (estimated from ALS and calibrated with field data)

P_i = Percentage of tree species (from digital stand map) $(i = 1,..., n)$

DS = Degree of stocking (derived from the estimated canopy density)

n = Number of different tree species within a stand

3. Result

Forest inventory plots (as described under 2.3) were used for verification. The comparison of estimated timber volume and inventory data was done for all sample plots as well as for averaged values which were derived from plots located within stands of the same age class. The age class was taken from the stand map. A correlation coefficient of r = 0.74 was reached when regarding all sample plots (a scatter plot with regression and RMSE is shown in figure 2). After averaging the estimated and the reference values for all stands with the same age class (both for single and multi-storied stands) a correlation of r = 0.91 was achieved (the scatter plot is shown in figure 3). The correlation with averaged values only for single-storied stands in the study site reached the highest correlation of r = 0.98 (the scatter plot is shown in figure 4). Information about the vertical stand structure was taken from the forest management plan.

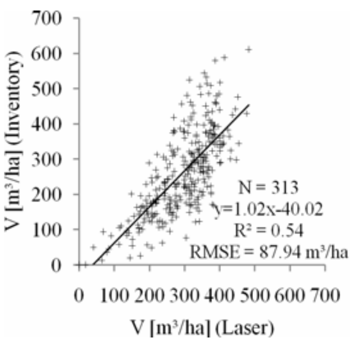

Figure 2: Timber volume estimation regarding all inventory plots

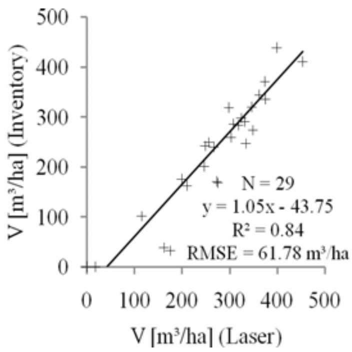

Figure 3: Timber volume estimation with averaged values for age classes (including both single and multi-storied stands)

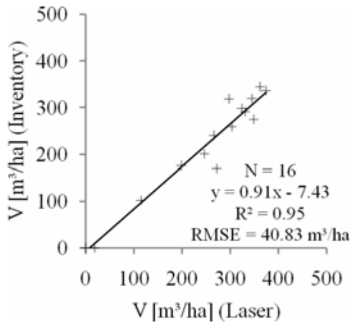

Figure 4: Timber volume estimation with averaged values for age classes (only single-storied stands)

4. Discussion

A method to estimate timber volume of forest stands based on ALS and GIS data using standard forestry yield models was presented. Inventory plots were used for verification. Top height of forest stands as one of the input parameter into the yield models was estimated from the 90th percentile of the nDSM. The relation of the height estimation on plot level reached a correlation coefficient of $r = 0.87$ and coefficient of determination of $R^2 = 0.75$. As second parameter the canopy density (tree crown cover) was estimated based on the nDSM by extracting all pixels with a height above 7m. The canopy density was used as an estimate for the degree of stocking to correct the timber volume derived from a yield model. For the selection of suitable yield models tree species information of the forest management plan (assigned as attributes to digital stand maps) were utilized. Parameter sets for eight tree species were derived from the yield tables as recommended for the Federal State of Baden-Württemberg, Germany.

A relation of $r = 0.74$ ($R^2 = 0.54$) was reached for timber volume estimation when regarding all sample plots. The high scatter on plot level can be explained by local variations of the forest structure which have a high influence if timber volume is estimated for small regions like the sample plots used in this study with a size of 452m². However the variation was compensated when plot values were averaged for larger units (here: stands of the same age class). The estimation for all stands located in the study area (both single-storied and multi-storied stands) reached a very satisfying accuracy of $r = 0.91$ ($R^2 = 0.84$). The variance can be further reduced if plot values are averaged only for single-storied stands of the study site with a very close relation of $r = 0.98$ ($R^2 = 0.95$). This may emphasize that yield models were originally developed for pure even-aged stands (homogeneous structure with small differences in age among individual trees).

Yield models attempt to quantify the development of a forest but nowadays higher growth rates are assumed than given by the models used in this study which were established between the years 1936 to 1992. Nevertheless the relation between height and volume will not change significantly (Mette *et al.* 2002).

To improve the volume estimation further studies will concentrate on the extraction of additional forest parameters from the full wave data e.g. the vertical stand structure. Automatic or semi-automatic classification of optical data will be tested to replace species information of the forest management plan by remote sensing data.

Acknowledgements

The authors would like to express their gratitude to the German environmental foundation - Deutsche Bundesstiftung Umwelt (DBU) which provided funding for the project.

References

Burschel, P. and Huss, J., 1997. *Grundriß des Waldbaus*. Parey, Berlin, 67-68.

Breidenbach, J., 2008. *Regionalisierung von Waldinventuren mittels aktiver Fernerkundungstechniken*. Doctoral Thesis (in press), 73.

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

Hollaus, M., Wagner, W., Maier, B. and Schadauer, K., 2007. Airborne Laser Scanning of Forest Stem Volume in a Mountaineous Environment. *Sensors*, 7, 1559-1577.

Huss, J., 1984. *Luftbildmessung und Fernerkundung in der Forstwirtschaft*. Wichmann. Karlsruhe, 285.

Hyyppä, J., Hyyppä, H., Litkey, P., Yu, X., Haggrén, H., Rönnholm, P., Pyysalo, U., Pitkänen, J. and Maltamo, M., 2004. Algorithms and Methods of Airborne Laser Scanning for Forest Measurements. In: M. Thies, B. Koch, H. Spiecker, H. Weinacker (Eds.). *Proceedings of ISPRS working group VIII/2 "Laser-Scanners for Forest and Landscape Assessment"*. Freiburg, University of Freiburg: 82-89.

Hyyppä, J. , Yu, X., Hyyppä H. and Maltamo, M., 2006. Methods of Airborne Laser Scanning for forest information extraction. In: T. Koukal, W. Schneider (Eds.). *Proceedings of International workshop "3D Remote Sensing in Forestry",* University of Natural Resources and Applied Life Sciences, Vienna: 63-78.

Kramer, H. and Akça, A., 1995. *Leitfaden zur Waldmesslehre*. J.D. Sauerländer's Verlag, Frankfuert am Main, 148.

Koch, B., Heyder, U. and 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. and Nothdurft, A., 2004. *Verfahrenshandbuch Betriebsinventur*. Version 1.1., Landesforstverwaltung Baden-Württemberg.

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

Mette, T., Papathanassiou, K.P., Hajnsek, I. and Zimmermann, R. 2002. Forest Biomass Estimation using Polarimetric SAR Interferometry. *Proceedings of IGARSS* 2002*,* Toronto, Canada, 2, 817-819.

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

Næsset, E., 1997. Estimating Timber Volume of Forest Stands Using Airborne Laser Scanner Data. *Remote Sensing of Environment*, 61, 246-253.

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, 88-99.

Pretzsch, H., 2001. *Modellierung des Waldwachstums*. Parey, Berlin.

Rieger, W., Eckmüllner O., Müllner, H. and Reiter, T., 1999. Laser-Scanning for the derivation of forest stand parameters. In: Beata M. Csatho (Ed.). *Proceedings of the ISPRS Workshop "Mapping Surface Structure and Topography by Airborne and Spaceborne Lasers"*. La Jolla, USA.

Straub, C., 2006. Automatic Delineation and Classification of Forest Stands based on Airborne Laser Scanner Data. Master Thesis, Stuttgart.

Wagner, W., Hyyppä, J., Ullrich, A., Lehner, H., Briese, C. and Kaasalainen, S., 2008. Radiometric Calibration of Full-Waveform Small-Footprint Airborne Laser Scanners, In: Chen, J., Jiang, J., Baudoin, A. (Eds.). *Proceedings of the XXI ISPRS Congress*, Beijing, China: 163-168.

Weinacker, H., Koch, B., Heyder, U. and Weinacker, R., 2004. Development of filtering, segmentation and modelling modules for LIDAR and multispectral data as a fundamental of an automatic forest inventory system. In: M. Thies, B. Koch, H. Spiecker, H. Weinacker (Eds.). *Proceedings of ISPRS working group VIII/2 "Laser-Scanners for Forest and Landscape Assessment"*. Freiburg, University of Freiburg: 90-95.