

Detection of Individual Tree Crowns in Airborne Lidar Data

Barbara Koch, Ursula Heyder, and Holger Weinacker

Abstract

Laser scanning provides a good means to collect information on forest stands. This paper presents an approach to delineate single trees automatically in small footprint light detection and ranging (lidar) data in deciduous and mixed temperate forests. In rasterized laser data possible tree tops are detected with a local maximum filter. Afterwards the crowns are delineated with a combination of a pouring algorithm, knowledge-based assumptions on the shape of trees, and a final detection of the crown-edges by searching vectors starting from the trees' tops. The segmentation results are assessed by comparison with terrestrial measured crown projections and with photogrammetrically delineated trees. The segmentation algorithm works well for coniferous stands. However, the implemented method tends to merge crowns in dense stands of deciduous trees.

Introduction

For sustainable forest management, a great amount of information is required both for planning of future forest management and for documenting the activities of the last decade. Parameters, such as tree species and tree species distribution, timber volume, increment of timber volume, and mean tree height are usually needed. In a number of European countries these single tree-related parameters are the basis for a forest inventory, which is conducted every ten years. Currently, most of those variables are estimated by measuring sample plots manually in field surveys, thus, forest inventories are rather expensive. During the last several years more effort has been put into decreasing costs by developing inventory systems that are based on remote sensing.

Airborne lidar (light detection and ranging) is becoming a promising technique for modeling the forest's canopy and thus for completing several inventory tasks. Brandtberg (1999) and Hyyppä and Inkinen (1999) proved that single tree delineation in forest stands of Nordic countries can be detected by high-density laser data. Popescu *et al.* (2002) estimated plot level tree heights with lidar data based on local filtering with a canopy height-based variable window size with good success. Persson *et al.* (2002), Leckie *et al.* (2003), and Hyyppä *et al.* (2000) have demonstrated that tree heights can be measured with high accuracy from airborne lidar data. Yu *et al.* (2003) were the first to demonstrate the use of laser scanner data for change detection assessment of single trees in boreal forests.

Several authors have shown mostly for coniferous forests that airborne lidar is also a good means for estimating other forest stand parameters (like volume or mean tree height)

with an averaging, stand-wise approach (Naesset, 1997; Magnussen and Boudewyn, 1998; Lefsky *et al.*, 1999). However, under typical conditions in temperate forests a stand-wise approach comprises many difficulties. As several tree species with different growing behavior can occur in one stand, *a-priori* knowledge of stem number and tree-species distribution would be necessary for calculating stand parameters. Additionally, in diverse forests, a stand-wise result is usually not sufficient for forest management planning as established in a number of European countries. Especially for harvest management purposes, information on single trees is required. Therefore, single tree delineation and tree species classification seem to be a prerequisite to use remote sensing technologies for large-scale forest inventories under typical conditions in temperate forests especially in respect for calculation of timber volume, as well as harvesting and silvicultural treatment schemes. First approaches of single tree delineation showed promising results for conifer forests with multispectral imagery (Gougeon, 1995; Pollock, 1996), as well as with lidar data (Hyyppä and Hyyppä, 2001; Persson *et al.*, 2002; Brandtberg *et al.* 2003) or by fusing both type of data (Popescu *et al.* 2004; Popescu and Wynne, 2004).

The objective of this paper is to develop a robust algorithm to detect and delineate tree crowns and tree heights that is suitable for coniferous stands, as well as for deciduous and mixed, vertically-structured, temperate forests. The correct delineation of crowns is a prerequisite for other derived parameters like tree position, tree height, crown diameter, or crown volume. Even the extraction of tree species type from multispectral data needs the correct delineation of tree crowns to achieve good results (Koch *et al.* 2002). Due to the fact that in temperate forests the tree crown delineation is still a topic that needs to be improved, the presented study focuses on the refinement of algorithms to improve the tree crown delineation for dense and multilayered stands.

The fusion of multispectral data with laser scanner data is also an important objective under investigation, but not the topic of this article. It also has to be taken into consideration that information extraction based on laser scanner data will provide more flexibility in the flight scheme. Therefore, the knowledge what may be exclusively based on laser scanner data has high priority for data provider and users.

Study Areas

The two study areas are located in the Southwest of Germany close to the City of Freiburg/Breisgau (Figure 1). They were

Department of Remote Sensing and Landscape Information Systems, Albert-Ludwigs University of Freiburg, Tennenbacherstr. 4, 79085 Freiburg, Germany (barbara.koch@felis.uni-freiburg.de).

Photogrammetric Engineering & Remote Sensing
Vol. 72, No. 4, April 2006, pp. 357–363.

0099-1112/06/7204-0357/\$3.00/0
© 2006 American Society for Photogrammetry and Remote Sensing

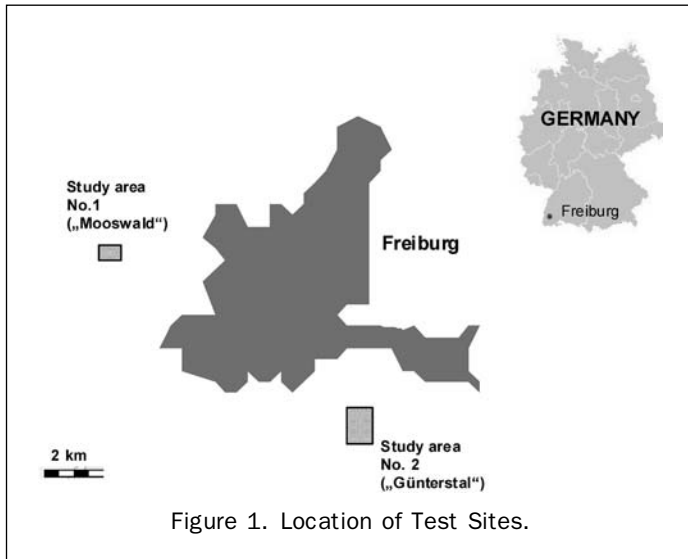


Figure 1. Location of Test Sites.

selected to cover as many different characteristics of forest stands as possible. The first area ("Mooswald") is situated in the Northwest of Freiburg and covers a planar region of 20 ha at an elevation of about 200 m above sea level. The mean yearly temperature is 10°C and the total yearly precipitation is 850 mm. This regional forest consists of oak mixed forest and floodplain multilayer forest with the exception of one stand of 30-year old Douglas fir (*Pseudotsuga menziesii*). The dominating species are English oak (*Quercus robur*) and hornbeam (*Carpinus betulus*) with a changing proportion of other deciduous species, such as red oak (*Quercus rubra*), ash (*Fraxinus excelsior*), or Norway maple (*Acer pseudoplatanus*). Most stands have formerly been managed as coppice with standards. Thus, the trees are of very uneven age, and the forest is rich in structure; canopy gaps alternate with very dense and double layered parts of tightly interlocked tree crowns. Selecting this test site provides a multi-storey mixed species forest structure situation. Investigations of airborne laser scanner data described in articles have not focused on such a complex forest situation.

The second test site ("Günterstal") is Southeast of Freiburg. It is a mountainous area of 70 ha at an elevation of 500 m to 800 m above sea level. This zonal forest placed in the submontane level consists of Atlantic Submontane Beach with fir and sessile-oak. The mean yearly temperature is between 5.1°C and 9.4°C depending on the altitude, which varies within the test site. Also, the total yearly precipitation varies between 950 mm and 1,800 mm dependent on the altitude. Within this site, very steep slopes appear. In detail, the vegetation consists mainly of a mixed mountain forest, which is characteristic for this climate. Tree species are mostly beech (*Fagus sylvatica*, approximately 60 percent), fir (*Abies alba*, 25 percent), and spruce (*Picea abies*, 10 percent). Most stands are of uneven age, many have an understorey.

Data

The laser scanning data were acquired with the Falcon System (TopoSys, 2003) by TopoSys, Inc. during spring and summer of 2002. While the data from the spring flights, without leaves on the broadleaf trees, have been used for the calculation of a precise Digital Terrain Model (DTM), the data captured during the summer have been used for the tree delineation and tree height estimation. The lidar-sensor of the Toposys system sends out laser pulses with 127 optical fibres, giving an overall pulse frequency of 83 kHz. The first and the last echo

of each pulse are recorded. An average altitude of 400 m in Mooswald and of 850 m in Günterstal was flown, resulting in a ground cross-sectional diameter (footprint) for each laser beam of 40 cm and 85 cm, respectively, and an average point sampling density of 5 to 10 points/m². As the test sites were covered with multiple overlapping laser strips, dense point distributions up to 20 points/m² were achieved. However, due to the structure of the sensor, the points are irregularly spaced in a line pattern. According to TopoSys, Inc., the location of each laser point has a relative horizontal accuracy of less than 0.5 m, and a relative vertical accuracy of less than 0.15 m.

For all echoes, the (x, y, and z) position of the reflecting object points were stored. The ground points (DTM) and the canopy surface points were identified each with an active surface algorithm similar to that developed by Elmkvist (2000). The developed algorithm is based on an energy minimization process that introduces a surface with inner and outer forces. This surface acts as a magnetic object that will be attracted by the laser spots which also act as small magnets. Additionally, the surface is affected by gravitational forces. An elasticity strength is introduced finally as an interior force. By simultaneously minimizing all these forces, a balance is achieved by an iterative minimization process. The final result of this process is a Digital Surface Model (DSM) or a DTM depending on the parameter settings, the laser spots used, and the direction the forces act. The process is done with a surface sampled into a regular grid. The two models are stored in a 2D raster image, where greyscale values represent the height. The height resolution alone is 1 cm.

As reference data, stem coordinates, diameter at breast height and crown projections of 98 sample trees (49 Douglas firs, and 49 broadleaved trees (mainly hornbeam)) have been measured terrestrially in Opfingen in five evenly-spaced plots. The crown projections have been constructed as polygons from eight orthogonal projected crown edge points. These points represent the typical shape, but do not consider extreme branches. Therefore, it is a subjective method. Both data sets are geo-coded to the same reference system (Gauss-Krüger coordinates). Due to the fact, that for the high altitude test site "Günterstal" no ground projection data could be provided, alternatively stereo CIR images have been used for ground mapping. About 80 percent of the area was measured stereoscopically and used as reference data. The problems related to comparing aerial photograph data with laser scanner data, due to occlusions and shadows in the aerial photographs, as well as object matching between the different data types are known, but there was no alternative for verification. Furthermore, the single tree delineation based on aerial photographs is an accepted method to provide a good estimation on the number of dominant trees, so at least with this data base a verification on the assessment of dominant trees is possible. Within this section, five plots (each of 10,000 m²) have been chosen randomly for further analysis.

Data Processing and Analysis

The computer analyses were implemented in C++, with use of the libraries of the image-processing system HALCON (MVTec, 2003).

Preprocessing

First, a Digital Crown Height Model (DCHM) is calculated by subtracting the height value of the DTM at each pixel from the height value of the DSM, so that tree heights can be taken directly from the DCHM. The DCHM maps the rough surface of the canopy. Especially, large broad-leaved trees have large height variations within their crown topography. One crown might have several smaller tops, which makes single tree detection difficult. Gaussian smoothing of the DCHM levels

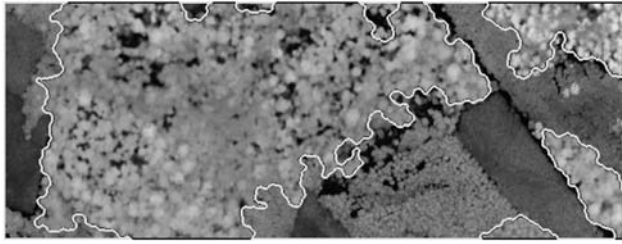


Figure 2. The Digital Crown Height Model is divided into two height classes and smoothed with adjusted intensity.

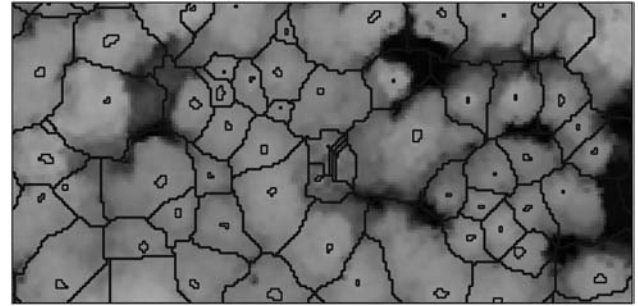


Figure 3. Result of the "Pouring" Algorithm. Starting from local maxima, regions are expanded as long as lower grey values exist. The tiny areas within the tree regions are the maxima or the plateau.

out minor height deviations, but small trees might be lost as well, if the image is smoothed too strongly.

To reduce such problems, the intensity of smoothing is adapted to the height of trees. With a threshold-operator the DCHM is divided into two height classes (≤ 20 m lower trees, and > 20 m, higher trees). Smaller holes within the area of one class are closed to decrease edge-effects. Each height class is filtered separately with a Gaussian function (with $\sigma = 0.81$ for the lower trees and $\sigma = 2.0$ for the higher trees, respectively), and both parts are merged afterwards (Figure 2). The optimal number of height classes, the height-threshold, and the smoothing intensity have been determined in pre-tests for the present data by visual judgement of preliminary segmentation results (Heyder, 2003).

Crown Delineation

In the smoothed DCHM tree tops are detected with a local maximum filter. A pixel counts as a local maximum, if all of its neighbours (in 4-connective neighborhood) have got a lower height-value or if all neighbors of some connected pixels with equal height (a "plateau") have got a lower height-value. Starting from those local maxima, regions are extended, as long as neighboring pixels with a lower or the same height value exist ("Pouring" Algorithm, already implemented in HALCON). Overlapping regions in "height-valleys" are finally distributed evenly to all involved trees. This algorithm resembles water being poured onto mountains, thus being similar to an inverted, classical watershed-algorithm (Soille, 1999). The pouring algorithm produces already a first approximation to the actual shape of the tree crown (Figure 3).

However, there still exists a lot of obviously "wrong" segments. Some regions are too small to be a tree, some have got shapes that are improbable to belong to a tree, some have unusual spatial relationships to each other, and some regions cover a tree as well as a neighboring canopy-gap. The following steps are conducted in order to remove such mistakes and to improve the segmentation result.

To adjust the thresholds for the ensuing steps according to the height of each tree, the crown regions are first split into two groups, depending on the height of their tree-top. Trees over 22 m are from now on referred to as "high trees," and below 22 m as "low trees".

Proceeding from the assumption (forest inventory directives) that a tree has a certain height dependent minimal area, high trees with an area below 3 m^2 and low trees with an area below 1 m^2 are selected. For each of those regions the neighbor region with the longest common border is selected and is merged with this neighboring region (Figure 4). The higher top of both trees becomes the top of the new tree.

Additionally, we assume that tree tops have got a certain minimal distance from each other. We chose 1 m for the low trees and 2 m for the high trees. If two tree tops are within

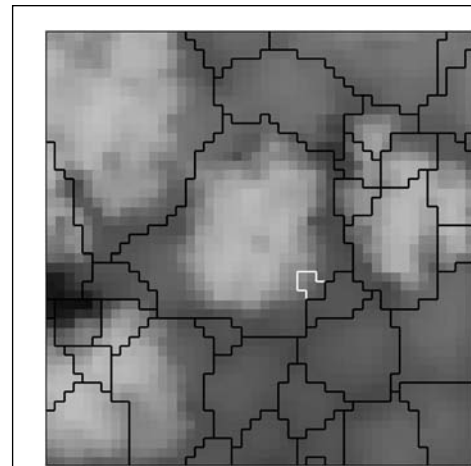


Figure 4. A very small tree (white border line) is merged with the neighbor tree region with the longest common border. The result is a new tree consisting of the two tree regions marked with the black border line. For the tree top, the higher top of the two merged regions is chosen.

this distance, the corresponding crown segments are merged (Figure 5). To avoid problems in very young stands with small trees, only four original regions can be merged to one new region in each step of the segmentation algorithm.

After the previous delineation steps, there still exist groups of trees that could not be separated. Elliptical groups are identified with a combination of a minimal area and the region's anisometry (the quotient of both radii of a fitted ellipse). If a region has got a length of at least 2.5 times its width and has got at least three times the respective minimal area for its height class, it is marked as a *group*. Those congregations are disjointed analogous to Straub and Heipke's (2001) approach, which has been developed for tree groups within settlements (Figure 6). For each tree group, the biggest inner circle is detected and subtracted from this region. Then, the biggest inner circle of the remaining region is identified and subtracted and so on, until the circle's area falls below the double minimal area for the height class. Subsequently, the circles are expanded as long as there are

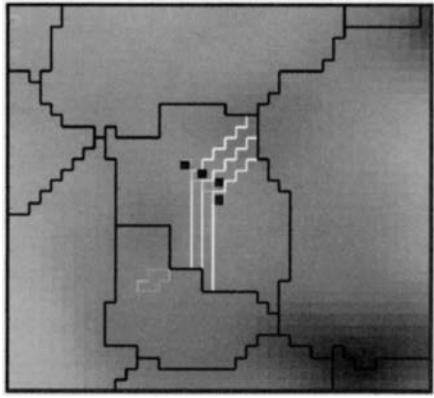


Figure 5. Shows four regions, which are bordered by a dark grey line and in between by white lines. The four very small black spots represent the four tree-tops. If the local maxima (black spots) of two segments are close together (less than 1 m for low and 2 m for high trees), the corresponding regions (white) are merged. In this special case, the four regions are merged to a new one. The highest tree top is chosen as the tree top for the merged tree.

no height differences above 60 cm between the new and the old border pixels, until the new regions touch each other or until the original group's border is reached.

The last part of the single-tree-detection-algorithm determines the actual crown edge to separate a tree from neighboring canopy gaps or from adjacent understorey trees. It is based on the algorithm developed from the group at University of Freiburg within the HighScan project (Hyypä *et al.* 2002, Friedländer 2002) idea of detecting tree crowns with searching vectors, but in contrary to this approach, it is only used to determine the final crown edge based on the previous segmentation results. It only reduces the area of a tree and does not enlarge it. Figure 7 gives an example for this algorithm. Starting from the tree's top, a vector to each border point is calculated. Proceeding in one pixel wide steps on each vector, the slope of the tree crown at each of these points is measured

as height difference between two points. If this height difference exceeds 2.5 m per 0.5 m distance, the vector breaks, and a new border point is generated. The crown edge is moved inside. Occasional occurring outliers are removed afterwards. Figure 8 summarizes the whole segmentation process.

Assessment of the Segmentation and Tree Type

Each automatically-detected tree lying within one of the terrestrially or photogrammetrically measured plots is visually classified into one of the following categories (Leckie *et al.*, 2003):

- Correct delineation
- Satisfactory delineation (one automatically detected tree corresponds to one reference tree, but the areas of both trees overlap less than 60 percent)
- Merged tree (more than one reference tree lies within the automatically delineated tree)
- Split tree (more than one automatically-delineated tree lies within one reference tree)
- Not found (there exists a reference tree, but no corresponding automatically delineated tree)

Each of the automatically detected trees is counted only once.

For all segmented trees based on a digital forest data base, an assignment to the three classes conifer, young and old broad leaf tree is carried out.

Results and Discussion

A comparison of the segmentation outcome with the reference trees gave the following results (Table 1). For 49 terrestrial measured Douglas firs (*Pseudotsuga menziesii*), 47 automatically-detected trees are found. 87.3 percent of them are identified correctly or at least satisfactory (Figure 9). The main mistake is the omission of some very small trees. Crown areas are overestimated: the mean crown area of the reference trees is 8.2 m², compared to 11 m² of the segmented trees. Corresponding to the 49 broad-leaved reference trees (*Carpinus betulus*, *Acer pseudoplatanus*, and *Fraxinus excelsior*), only 30 automatically-delineated trees are found. Of those, 50 percent are delineated well or satisfactory, and 43.3 percent include several merged reference trees. The merged trees combine mostly subdominant trees with an adjacent dominant tree. Partly dominant trees which build a dense, close, homogeneous canopy could not be separated. Figure 10 shows the results of one sample plot. Compared to the photogrammetrically measured reference crowns, 61.7 percent of the trees are delineated as correct or satisfactory, 25.6 percent merge two or more reference trees, and 4.2

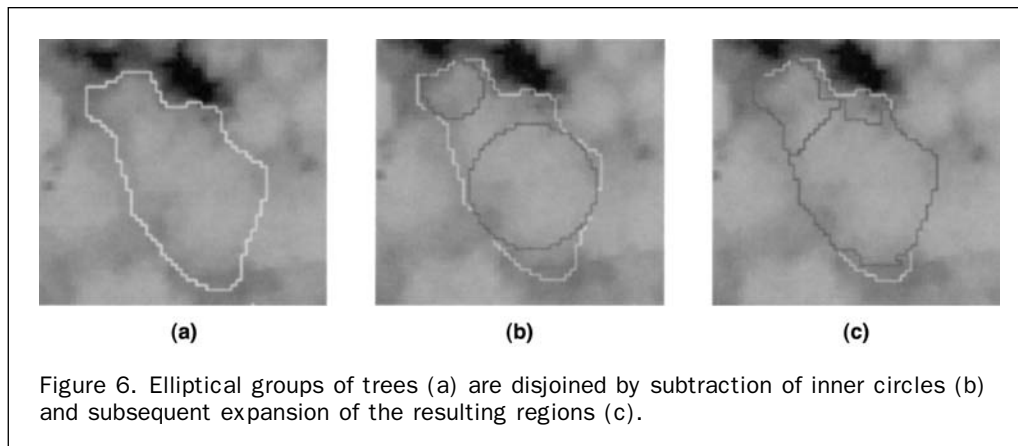


Figure 6. Elliptical groups of trees (a) are disjoined by subtraction of inner circles (b) and subsequent expansion of the resulting regions (c).

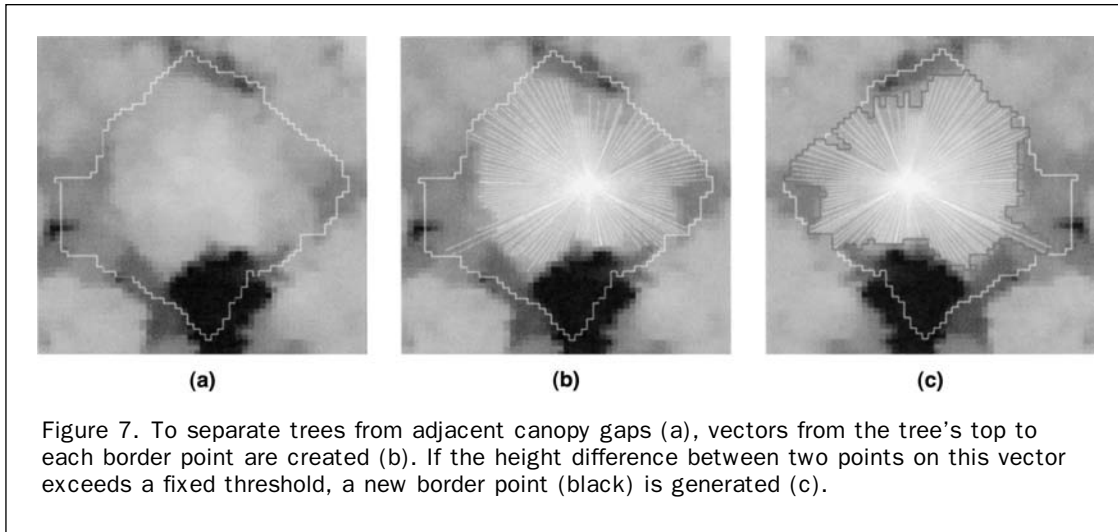


Figure 7. To separate trees from adjacent canopy gaps (a), vectors from the tree's top to each border point are created (b). If the height difference between two points on this vector exceeds a fixed threshold, a new border point (black) is generated (c).

percent are split; 39 reference trees (8.5 percent) have not been detected.

The segmentation results are very encouraging for coniferous species. Almost all dominant trees are found, and the crown delineation is very close to terrestrially-measured crown polygons, the crown's edge is sometimes even more precise, although the crown area is overestimated. It has to be taken into consideration that crown projections in the field have to deal with uncertainties, so the true value for crown area might be in between the two measurements. For deciduous species the automatic segmentation result underestimates the tree number significantly; many reference trees are merged. This is partly due to not found subdominant trees (which are not very important from the forester's point of view), but also some dominant tree crowns are merged. Very densely growing dominant hornbeams with a homogeneous height-distribution could not be separated. However, if the crowns of dominant deciduous trees are not tightly interlocked, the segmentation outcome is considerably improved. Possibly a more sophisticated adaptation of the filter intensity to the canopy conditions will improve the segmentation results.

Conclusions

Lidar data can play an important role for small scale forest inventories, especially for deriving tree heights and stand volume. In mixed forests single tree delineation and classification is necessary. As shown in this paper, automatic segmentation works well for coniferous stands and for more open deciduous forests. Crown areas are slightly overesti-

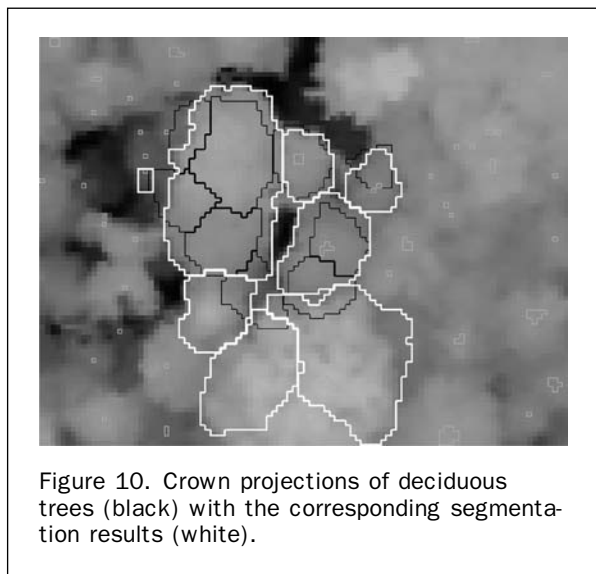
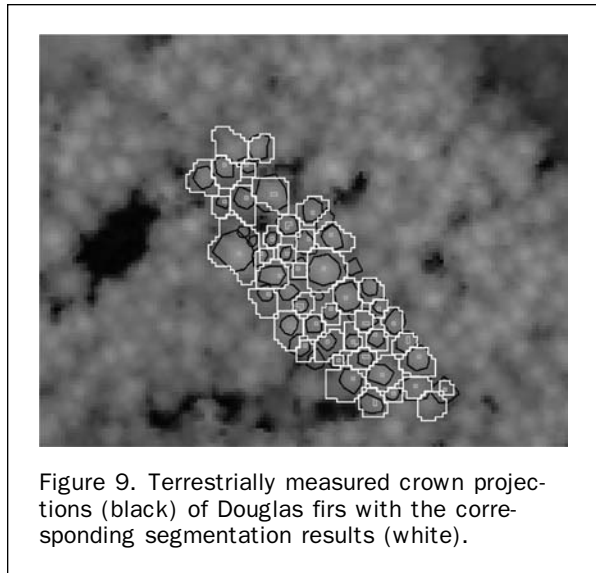
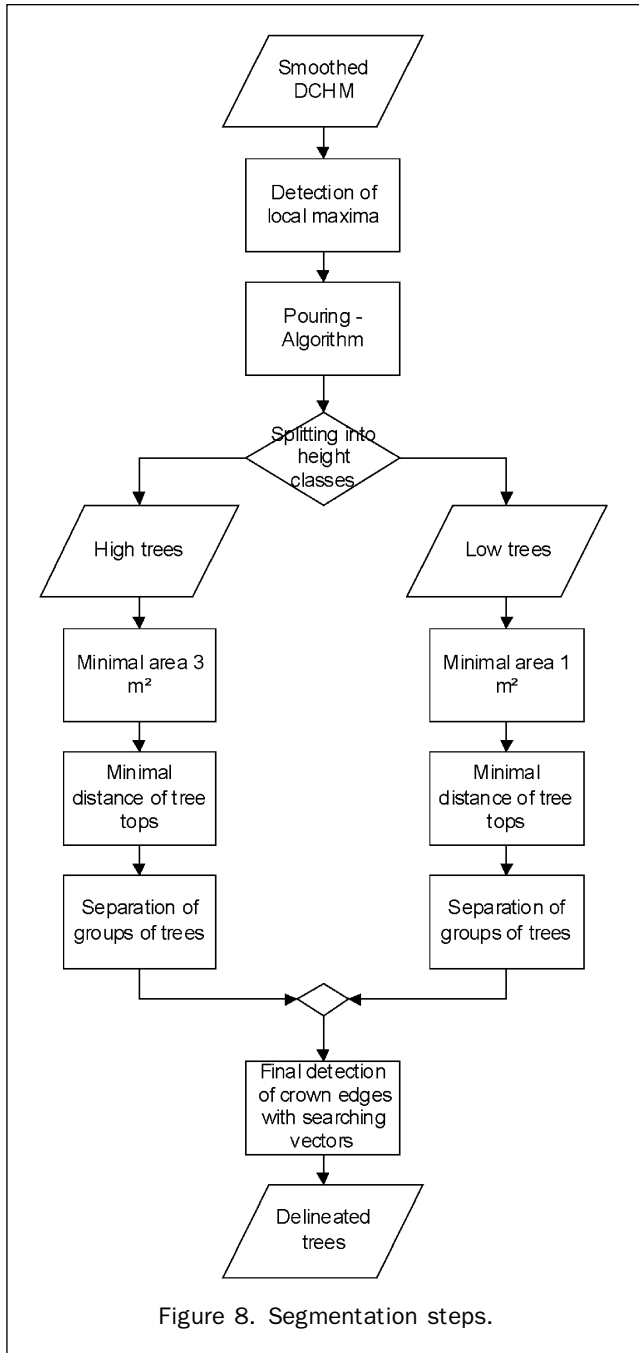
mated, but the number and the position of most trees is found correctly. Problems occur only with detecting very small or suppressed trees. In dense deciduous forests with a tightly interlocked, homogeneous canopy, it is difficult to separate tree crowns from each other. Thus, the stem number is underestimated. Stem counts in such stands might be improved by advanced full waveform lidar systems in combination with a multispectral camera, for example, the IGI Litemapper 5600 (Hug *et al.*, 2004). The increase of information of data from such systems is tremendous, and it will be a future challenge to select the relevant information from the data. Another possibility is to do the lidar registration during winter or springtime. The advantage is that many more laser spots will be reflected from within the tree crowns and/or the stem, and as a result, better tree separation might be possible. Some improvement might also be available with further development of the delineation algorithm. But even with an incomplete assessment of all stems, lidar will become an efficient means to support small scale inventories during the next years due to the fact that the reasonably correct and rapid assessment of information on dominant trees provided already gives a valuable basis for the derivation of forest parameters needed in the framework of sustainable forest management. In addition, the correct delineation of single or scattered trees in the landscape is also of high value for a number of management tasks.

Acknowledgments

The authors would like to express their gratitude to the German Federal Ministry of Education and Research (BMBF), which provides funding for the NATSCAN project.

TABLE 1. SEGMENTATION RESULTS COMPARED TO TERRESTRIALLY OR PHOTOGRAMMETRICALLY MEASURED REFERENCE TREES

Plot	No. of trees	Correct		Satisfactory		Merged		Split		Not detected	
			in %		in %		in %		in %		in %
Terrestrial measurements											
Douglas fir	47	28	59.6	13	27.7	1	2.1	0	0	5	10.6
Deciduous trees	30	6	20	9	30	13	43.3	2	6.7	0	0
Photogrammetric measurements											
Mixed forest	457	207	45.3	75	16.4	117	25.6	19	4.2	39	8.5
Total	534	241	45.1	97	18.2	131	24.5	21	3.9	44	8.2



References

Brandtberg, T. 1999. *Automatic Individual Tree-based Analysis of High Spatial Resolution Remotely Sensed Data*, Ph.D. dissertation, Acta Universitatis, Agriculturae Sueciae, Silvestria 118, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Brandtberg, T., T.A. Warner, R.E. Landenberger, and J.B. McGraw, 2003. Detection and analysis of individual leaf-off tree crowns in small footprint, high sampling density lidar data from the eastern deciduous forest in North America, *Remote Sensing of Environment*, 85:290–303.

Friedlaender, H., 2002. *Die Anwendung von flugzeuggetragenen Laserscannerdaten zur Ansprache dreidimensionaler Strukturelemente von Waldbeständen*, Ph.D. dissertation, University of Freiburg, Freiburg, Germany, 64 p.

Elmqvist, M., 2000. *Automatic Ground Modelling using Laser Radar Data*, Master thesis, Linköping University, Linköping, Sweden, 30 p.

Gougeon, F., 1995. A crown-following approach to the automatic delineation of individual tree crowns in high spatial resolution aerial images, *Canadian Journal of Remote Sensing*, 21(3): 274–284.

Heyder, U., 2003. *Automatische Delinierung und Klassifizierung von Bäumen aus Laser- und Multispektraldaten*, Diploma-Thesis, University of Freiburg, Freiburg, Germany, 87 p.

Hug, C., A. Ullrich, and A. Grimm, 2004. Litemapper 5600 - A waveform digitizing lidar terrain and vegetation mapping system, *Proceedings of the ISPRS Working Group VIII/2, Laser Scanners for Forest and Landscape Assessment*, Volume XXXVI, Part 8/W2:24–29

Hyypä, J., and M. Inkinen, 1999. Detecting and estimating attributes for single trees using laser scanner, *Laser Radar Technology and Applications IV*, 3707:57–69.

Hyypä, J., M. Schardt, H. Haggrén, B. Koch, U. Lohr, H.U. Scherrer, R. Paananen, H. Luukkonen, M. Ziegler, H. Hyypä, U. Pyysalo, H. Friedländer, J. Uuttera, S. Wagner, M. Inkinen, A. Wimmer, A. Kukko, E. Ahokas, and M. Karjalainen, 2001. HIGH-SCAN: The first European-wide attempt to derive single-tree information from laserscanner data, *The Photogrammetric Journal of Finland*, 17:58–68.

Hyypä, J., and H. Hyypä (editors), 2001. *HIGH-SCAN – Assessing Forest Stand Attributes by Integrated Use of High Resolution*

- Satellite Imagery and Laserscanner – Final Report*, ENV4-CT98-0747, EU-Kommission, DG XII.
- Hyypä, J., U. Pyysalo, H. Hyypä, and A. Samberg, 2000. Elevation accuracy of laser scanning-derived digital terrain and target models in forest environment, *Proceedings of the 20th EARSeL Symposium and Workshops, Lidar Remote Sensing of Land and Sea*, 14–16 June, Dresden, Germany.
- Koch, B., J. Svoboda, P. Adler, and M. Dees, 2002. Automatische baumartenerkennung auf der Grundlage digitalisierter CIR-luftbilder, *Allgemeine Forst- u. Jagd-Zeitung*, 173. Jg., 07–08: 131–140.
- Leckie, D., F. Gougeon, D. Hill, R. Quinn, L. Armstrong, and R. Shreenan, 2003. Combined high-density lidar and multispectral imagery for individual tree crown analysis, *Canadian Journal of Remote Sensing*, 29(5):633–649.
- Lefsky, M.A., D. Harding, W.B. Cohen, G. Parker, and H.H. Shugart, 1999. Surface lidar remote sensing of basal area and biomass in deciduous forests of Eastern Maryland, USA, *Remote Sensing of Environment*, 67:83–98.
- Magnussen, S., and P. Boudewyn, 1998. Derivations of stand heights from airborne laser scanner data with canopy-based quantile estimators, *Canadian Journal of Forest Research*, 28:1016–1031.
- MVtec, 2003. HALCON, URL: <http://www.mvtec.de/halcon/> (last date accessed: 10 January 2006).
- Naesset, E., 1997. Estimating timber volume of forest stands using airborne laser scanner data, *Remote Sensing of Environment*, 56:1–7.
- Persson, Å., J. Holmgren, and U. Södermann, 2002. Detecting and measuring individual trees using an airborne laser scanner, *Photogrammetric Engineering & Remote Sensing*, 68(9):925–932.
- Pollock, R., 1996. *The Automatic Recognition of Individual Trees in Aerial Images of Forests Based on a Synthetic Tree Crown Image Model*, Ph.D. dissertation, University of British Columbia, Vancouver, Canada.
- Popescu, S.C., R.H. Wynne, and R.H. Nelson, 2002. Estimating plot level tree heights with lidar: Local filtering with a canopy height based variable window size, *Computers and Electronics in Agriculture*, 37(1–3):71–95.
- Popescu, S., R. Wynne, and J. Scrivani, 2004. Fusion of small-footprint lidar and multispectral data to estimate plot-level volume and biomass in deciduous and pine forests in Virginia, USA, *Forest Science*, 50(4):551–565.
- Popescu, S., and R. Wynne, 2004. Seeing the trees in the forest: Using lidar and multispectral data fusion with local filtering and variable window size for estimating tree height, *Photogrammetric Engineering & Remote Sensing*, 70(5):589–604.
- Soille, P., 1999. *Morphological Image Analysis*, Springer, Berlin, 316 p.
- Straub, B.-M., and C. Heipke, 2001. Automatic Extraction of Trees for 3D-City Models from Images and Height Data, *Automatic Extraction of Man-Made Objects from Aerial and Space Images* (E. Baltsavias, A. Gruen, and L. van Gool, editors), pp. 267–277.
- TopoSys, 2003. FALCON LIDAR Sensor System, URL: <http://www.toposys.de/> (last date accessed: 10 January 2006).
- Yu, X., J. Hyypä, P. Rönholm, H. Kaartinen, M. Maltamo, and H. Hyypä, 2003. Detection for harvested trees and estimation of forest growth using laser scanning (J. Hyypä, E. Naesset, H. Olsson, T. Granqvist Pahlen, and H. Reese, editors), *Proceedings of Scandlaser Scientific Workshop on Airborne Laser Scanning of Forests*, 03–04 September, Umea, Sweden, Swedish University of Agricultural Sciences, Department of Forest Resource Management and Geomatics:115–124.

(Received 29 October 2004; accepted 11 January 2005; revised 16 March 2005)