A FULLY AUTOMATED PROCEDURE FOR DELINEATION AND CLASSIFICATION OF FOREST AND NON-FOREST VEGETATION BASED ON FULL WAVEFORM LASER SCANNER DATA

C. Straub [a] *, H. Weinacker [a], B. Koch [a]

[a]Department of Remote Sensing and Landscape Information Systems, University of Freiburg, 79106 Freiburg, Germany-(Christoph.Straub, Holger.Weinacker, Barbara.Koch)@felis.uni-freiburg.de

KEY WORDS: Laser scanning (LiDAR), Classification, Aerial Survey, Feature extraction, Environmental monitoring, Forestry

ABSTRACT:

Detailed geo-referenced information on the distribution and occurrence of forest and non-forest vegetation is essential for many different disciplines e.g. forestry, nature conservation, agriculture, landscaping and urban planning. This article presents a digital image processing procedure for automated delineation and classification of forest and non-forest vegetation which is solely using full waveform laser scanner data as input. The delineation of regions covered by vegetation is based on the assumption that many laser reflections will be found inside of vegetation from different vegetation layers between the top of the canopy and the bare earth which particularly applies to multiple echoes from full waveform data. The vegetation regions are classified into forest and non-forest vegetation based on criteria which are generally used for vegetation mapping such as height of the vegetation, tree crown cover, size and width of vegetation objects. Non-Forest vegetation is further classified into single tree objects or connected groups of trees based on geometrical features. To verify the applicability for large areas the procedure was tested in a study site in the Southern Black Forest Nature Park, Germany with a total size of 7.68 km². An accuracy assessment of the automated method is given with a comparison to a delineation and classification result done by a human operator based on RGB true-orthophotos and with a terrestrial survey. An error matrix was used to verify the classification result. An overall accuracy of 97.73% was reached. The capability and the limitations of the method are discussed.

1. INTRODUCTION

Mapping and monitoring of forest and non-forest vegetation are important for many applications related to sustainable forest and landscape management such as change statistics, stem volume, biomass and carbon stock estimates, study and understanding of environmental problems, clear cut mapping, regeneration activities or regeneration failures. Remote sensing techniques provide valuable information to support the mapping process.

In Germany nationwide information on topographic objects of the landscape including forests and non-forest vegetation are provided as Digital Landscape Model (DLM) by the state surveying authorities which are managed in digital form in the databases of the nationally standardised Authorative Topographic-Cartographic Information System (ATKIS®) (AdV 2008). Orthophotos and topographical maps are currently used to digitize the landscape objects which are intensively used in administration, economy and for scientific projects. The topographic information has to be updated regularly.

Airborne Laser Scanning (ALS) is a largely automated active remote sensing technique for the capturing of topographic data. The survey area is scanned strip by strip with the help of short infrared pulses emitted by a laserscanner which is mounted on a helicopter or an aeroplane. The result of the measurement is a point cloud which provides 3D information of the landscape for the derivation of a digital terrain model - DTM (which represents the bare earth) and a digital surface model - DSM (which represents objects on top of the bare earth like vegetation cover or buildings).

In recent years full wave scanners, which record the complete echo waveform for each emitted laser pulse, gain more importance. Commercial wafeform-digitization startet in 2004 (Wagner et al. 2007).

Numerous studies have shown the capability of ALS to accurately estimate important forest inventory parameters such as canopy heights and stem volume (Hyyppä et al. 2006, Hyyppä et al. 2004, Næsset 2002, Means et al. 2000). Several studies can be found on automatic single tree delineation. Some approaches make use of the surface model and apply different versions of watershed segmentations or region growing techniques to delineate crown polygons. As an example local maxima are extracted from the DSM to locate potential tree tops. The maxima are used as seed points for an expansion using a "pouring algorithm" (the segmentation is based on the idea that water is running downwards from the tree tops in all directions) to detect the borderline of tree crowns. To enhance the delineation result shape features and geometric relations between tree crowns are implied (Koch et al. 2006, Weinacker et al. 2004). Other approaches extract tree crowns directly from the raw data using a voxel based approach (Wang et al. 2007). In general good results can be achieved for coniferous trees but a high point density is required to be able to model single trees e.g. at least 1 point per m². Moreover automated approaches to subdivide the forest area into "homogeneous units" (which may be characterized as stands or sub-stand units) according to height classes, surface roughness and different tree types were developed and verified (Koch et al. 2008, Straub et al. 2006, Diedershagen et al. 2004). Before segmentation of the forest into stand units and single trees can be realized, a delineation of

* Corresponding author.

the forest area itself is required. A method to discriminate between vegetation and non-vegetation points using full-waveform laser scanning was demonstrated by (Ducic et al. 2006). An approach for forest boundary delineation using a combination of aerial images and LIDAR data is proposed by (Wang et al. 2007).

The following article presents a procedure for automated delineation and classification of forest and non-forest vegetation solely using full waveform laser scanner data as input. Non-forest vegetation regions are further classified into single tree objects and connected groups of trees.

2. MATERIAL AND METHODS

2.1 Study Area

The procedure presented in the following paragraphs was tested in a study area which is located in the Southern Black Forest Nature Park, Germany with a total size of 7.68 km². The study site is dominated by forest area (5.69 km²) besides other land use types: rural area (1.69 km²) and urban area (0.30 km²). The forest comprises of coniferous and deciduous stands as well as mixed forest. Different vegetation types can be found in the rural area like riverine vegetation, organic orchards, shrubs, vegetation along roads with different species and sizes. A true-orthophoto of the study area is shown in figure 1.

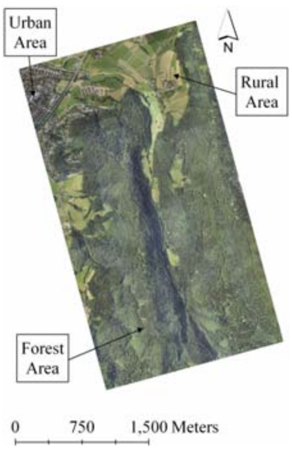

Figure 1. True-Orthophoto of the study area

2.2 Datasets

The fullwave data used in this study was acquired in summer 2005 by IGI mbH using the LiteMapper 5600 laser measurement system mounted on a helicopter. Important flight and system parameters are shown in table 1:

The laser scanner used in this system is the RIEGL LMS-Q560. The range finding is realized with nanosecond infrared pulses and fast opto-mechanical beam scanning which results in linear, unidirectional and parallel scan lines (Hug et al. 2004).

Time of acquisition	August 2005
Flying height	400m AGL
Ground point spacing	8 points / m²
Surface point accuracy (horizontal/vertical), excluding GPS errors	0.1m / 0.03m (1 sigma) for 800m AGL
Laser pulse frequency	100.000 Hz
Scan angle	22.5°
Swath width	330m
Special features	Full waveform digitization

Table 1. Flight and system parameters of the LiteMapper 5600

2.3 Methods

The procedure can be classified into two main parts:

1. Delineation of regions covered by vegetation.
2. Classification of vegetation regions into the classes a) forest vegetation and non-forest vegetation which is further classified into b) connected groups of trees and c) single trees.

2.3.1 Delineation of regions covered by vegetation:

Compared to conventional ALS systems which record the first and last echo for each laser beam, the LiteMapper 5600 system (used in this study) has the ability to record the entire echo wafeform. As a result several single laser returns can be extracted per laser beam which is achieved by modelling the waveform data as a series of Gaussian pulses (Wagner et al. 2006). Simultaneous gauss fitting is used for the detection of echoes which delivers a special amount of pulses per laser beam in conjunction with their range, amplitude and width. The corresponding xyz coordinates are calculated for each echo to derive a point cloud.

A DSM (which represents the top of the canopy in a forest) and a DTM (which represents the bare earth) are derived from the laser points using an “Active Surface Filtering Algorithm” implemented in the software TreesVis. Details about the filtering technique can be found in (Weinacker et al. 2004).

A tolerance zone is created for both models, which defines a maximum distance Δh_{DSM} beneath the DSM and a maximum distance Δh_{DTM} above the DTM to classify the single laser returns into: 1. Ground points (within the zone above the DTM), 2. Surface points (within the zone below the DSM) and 3. “Intermediate points” (points with height values between the tolerance zone above the DTM and the zone below the DSM). Assuming that A is the set of all laser points

$$A = \{ p_1, p_2, ..., p_n \} \quad (1)$$

where $p_1, p_2, ..., p_n$ are the single laser reflections defined as

$$p_i = (p_{i_x}, p_{i_y}, p_{i_z}) \quad (2)$$

where p_{i_x} , p_{i_y} are the planar coordinates and p_{i_z} represents the height value. The selection of “intermediate points” as subset A_1 is defined as

$$A_1 = \{ p_i \in A : (DTM_i + \Delta h_{DTM}) \leq p_{i_z} \leq (DSM_i - \Delta h_{DSM}) \} \quad (3)$$

Where p_{i_z} represents the height value of point p_i, DTM_i and DSM_i are the height values of the DTM and DSM at position p_i.

Figure 2 and 3 show cross sections of DSM, DTM and "intermediate points". Both cross sections reveal that many "intermediate points" will be found in vegetation due to the naturally heterogeneous structure as well as gaps in the canopy, which results in several reflections from branches and stems from different vegetation layers. This particularly applies to multiple echoes from full waveform data. No "intermediate points" will be found within artificial non-ground objects like buildings (because of the impenetrable roofs). Multiple echoes will only be found at the edges of buildings.

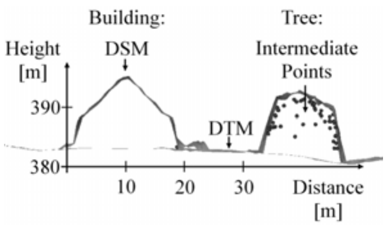

Figure 2. Cross-section of intermediate points (as defined by equation 3), DTM and DSM for a building and a single tree

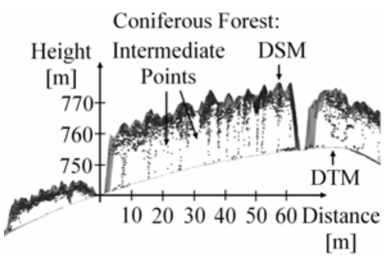

Figure 3. Cross-section of intermediate points, DTM and DSM in a forest area

The irregularly distributed points are grouped using a grid with a cell size of 1x1m² and with the extent of the study area. The number of points found within each grid cell are counted and assigned as grey value to an image. Thus the image shows the local density of laser reflections. Two different images are generated: 1. image showing the number of all points/echoes of the dataset (*AllPointsImage*) and 2. image showing the number of "intermediate points/echoes" (*IntermediatePointsImage*). Due to the fact that many more points will be found in overlapping flight strips compared with single flight strips the gray values g_1 of the *IntermediatePointsImage* are normalized with the gray values g_2 of the *AllPointsImage*. The gray values (g_1, g_2) of the images are transformed as follows:

$$g' = g_1 / g_2 \tag{4}$$

where g' is the output value of the "normalized image".

A median filter with a 5x5 pixel window is used to reduce noise in the normalized image. Finally a global threshold (which was defined by empirical tests) is applied to extract regions which are covered by vegetation. Connected components (pixels) are grouped into vegetation objects. Morphological closing with a circular structuring element (radius 3m) is used for boundary smoothing and to fill small holes.

2.3.2 Classification of vegetation objects into forest and non-forest vegetation:

The following general definition for forest vegetation is used: Forest vegetation is dominated by trees and other woody plants. The area covered by forest vegetation has to be large enough for the development of a "characteristic forest climate" (Burschel & Huss 1997). The criterion "forest climate" will depend on the following vegetation features which can be measured or estimated with ALS data:

1. Height of the vegetation
2. Tree crown cover
3. Size of the vegetation region
4. Width of the vegetation region

Forest vegetation must have a minimum height, tree crown cover, size and minimum width. All vegetation objects which do not fulfill the criteria for forest vegetation will be classified as non-forest vegetation. The mentioned features are computed with the following approaches:

1. A pixel based computation of the vegetation height is done using a normalized digital surface model (nDSM) which is derived by subtracting the DTM from the DSM (nDSM = DSM-DTM). In forests it is often described as canopy height model (CHM). Due to the fact that the values of the nDSM represent the object heights for each xy position a threshold operation (selection of height values within a defined interval) is used to extract non-ground pixels. The threshold operation is defined as

$$S = \{(x, y) \in R : \Delta h_{\min} \le nDSM_{x,y} \le \Delta h_{\max}\} \tag{5}$$

Where S is the output region (non-ground pixels), R is the Region of Interest (ROI), $nDSM_{x,y}$ are the height values of the nDSM for each xy position, $\Delta h_{\min}$ is the minimum height and $\Delta h_{\max}$ the maximum height threshold.

A height of 3m was defined as a minimum height $\Delta h_{\min}$ for non-ground pixels. The non-ground pixels are intersected with the regions covered by vegetation (which were delineated by the method described under 2.3.1). The resulting region represents potential vegetation pixels above 3m.

2. The tree crown cover, also referred to as canopy density, is generally defined as the ground covered by a vertical projection of tree crowns - a parameter used in forestry to characterize the density of forest stands. To be able to characterize the local tree crown cover of a vegetation area, a grid with a cell size of 20x20m is generated and intersected with the vegetation pixels above 3m. The result is a mixture of regular and individually shaped grid cells. Within each single grid cell the tree crown cover is computed based on the following approach: Potential canopy gaps are extracted from the nDSM which represents the area not covered by tree crowns which is achieved by "thresholding" all pixels below 5m from the nDSM. By subtracting the surface percentage of gaps from each individual cell the area covered by tree crowns is derived and expressed as a percentage of total ground area of each grid cell. Only cells

with a tree crown cover of at least 50% are accepted as forest vegetation.

3. The size of a vegetation region (a group of connected cells/pixels) is calculated from the number of pixels multiplied with the corresponding ground resolution. A minimum size of 1000m² was defined for forest vegetation.

4. The width of the irregularly shaped vegetation regions is measured with the help of profiles along the medial axis which is obtained by "skeletonization" (each vegetation region is reduced to a line that is one pixel thick and lies in the centre of the region). The skeleton is computed by fitting circles into a vegetation region with the largest radius possible. A circle *C* has the largest radius in the input region *R* if there is no other circle in *R* that is a superset of *C*. The skeleton is derived from the centre points of those maximal circles. There will be at least two points on the region boundary to which a centre point will have the same shortest distance (Steger et al. 2008). Further details about "skeletonization algorithms" can be found in (Soille 2003).

Due to the fact that vegetation objects can have high variations in their shape, post-filtering is necessary to remove irrelevant branches from the skeleton. Based on the skeleton the longest connected chain of pixels is computed which finally is a single one-pixel-wide centre line without any other branches. Raster to vector conversion is used to convert the one pixel-wide centre lines into vector lines which are smoothed using a method which projects the points of the centre line onto a local regression line (a least-squares approximating line) fitted to a defined number of original points. For each point of the vectorized and smoothed centre line a profile is generated to measure the local width of the vegetation object as shown in figure 4.

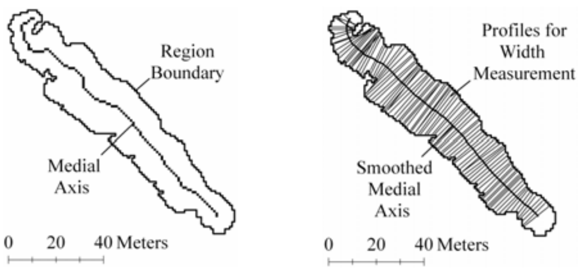

Figure 4. Width measurement of an elongated vegetation region using profiles along the medial axis

Finally the median of all width measurements is computed as an average width for each object and is used for classification. A minimum width of 30m was defined for forest vegetation.
Objects which were classified as non-forest vegetation will be further classified into single tree objects or a connected group of trees based on their size and shape. Due to the fact that single tree crowns will have the similarity to a circle the circularity *C* is used as shape factor for classification. Circularity is defined as follows:

$$C = \frac{A}{D_{max}^{2} \cdot \pi} \qquad (6)$$

where A is the area and D_{max} is the maximum distance from the center to all contour pixels of the vegetation region.
Finally vegetation objects are slightly modified. Areas surrounded by forest vegetation without trees and smaller than 0.5 hectares are extracted and merged with the forest mask.

3. RESULTS

Both the classification and the delineation accuracy were verified. The aim was to assess the classification of regions into forest and non-forest vegetation objects and to analyze the accuracy of the object boundaries drawn by the automated procedure.

3.1 Accuracy Assessment of the Classification Result

For verification of the classification result all vegetation objects in the study site were digitized by a human operator based on RGB true-orthophotos. Analogously to the automated classification the objects were visually classified into 1. Forest vegetation and 2. Non-forest vegetation (groups of trees and single trees). Figure 5 and 6 show a part of the study area with the result obtained by the automatic and visual classification together with the true-orthophoto which was used for visual interpretation. Forest (F), Non-forest vegetation groups of trees (NFV-GT) and single trees (NFV-ST) are visualized with different hachures.

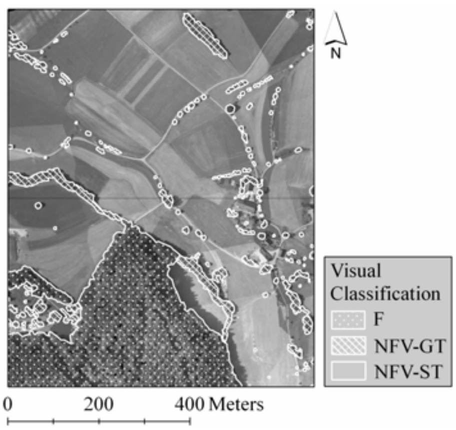

Figure 5. Result of the visual classification (Forest (F), Non-forest vegetation groups of trees (NFV-GT) and single trees (NFV-ST))

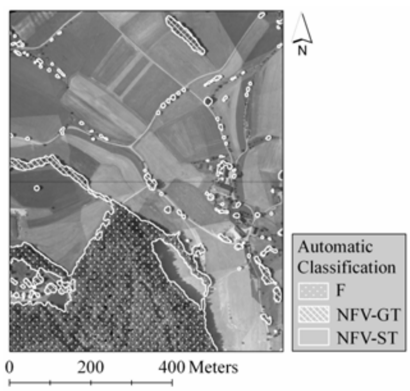

Figure 6. Result of the automatic classification (abbreviations are explained in figure 5)

A regular point raster was generated for the entire study area with a point spacing of 10m (in total 75400 points were generated). For each point the visual and the automated classification were compared. The result was summarized in an error matrix as shown in table 2. Descriptive measures obtained from the error matrix such as producer's accuracy, user's accuracy and overall accuracy are listed in table 3.

	Automatic Classification				
	NTV	F	NFV (GT)	NFV (ST)	Row Total
Visual Classification					
NTV	16198	336	293	23	16850
F	259	56012	60	2	56333
NFV-GT	415	219	1389	17	2040
NFV-ST	42	8	35	92	177
Column Total	16914	56575	1777	134	75400
Abbreviations: NTV: Non-Tree Vegetation, F: Forest, NFV-GT: Non-Forest Vegetation - groups of trees, NFV-ST: Non-Forest Vegetation – single trees					

Table 2. Error matrix showing the comparison of the visual and the corresponding automated classification using 75400 samples from a point raster for the entire study area (point spacing: 10m)

Producer's Accuracy		User's Accuracy	
NTV	96.13%	NTV	95.77%
F	99.43%	F	99.00%
NFV-GT	68.09%	NFV-GT	78.17%
NFV-ST	51.98%	NFV-ST	68.66%
Overall Accuracy: 97.73%			

Table 3. Descriptive measures such as producer's accuracy, user's accuracy and overall accuracy obtained from the error matrix as shown in table 2

A comparison of total areas for the different vegetation classes both for the automatic and the visual classification are shown in table 4:

Class	Total areas for the classes derived by the automatic procedure	Total areas for the classes derived by the visual interpretation
NTV	1688103 m²	1678847 m²
F	5659356 m²	5633410 m²
NFV-GT	180328 m²	207490 m²
NFV-ST	12562 m²	20436 m²

Table 4. Results of the total area computation of vegetation classes derived by the automatic and the visual classification (abbreviations are explained in table 2)

3.2 Accuracy Assessment of the Delineation Result

Point wise measurements of the forest boundary were done in the field using a differential GPS (dGPS). The accuracy of the GPS measurement system was verified with a survey point. Deviations of the survey point coordinates and the position measured with the differential GPS are shown in table 5.

Deviation of easting coordinate [m]	Deviation of northing coordinate [m]	Height deviation [m]
0.04	0.02	0.10

Table 5. Accuracy of the dGPS system validated with a survey point

A number of 66 point measurements were used to assess the accuracy of the delineation. For each point the shortest distance to the boundary delineated by the automated procedure as well as the visual delineation was calculated. A summary of the absolute deviations is given in table 6.

	Automatically delineated forest boundary compared to dGPS measurements:	Visually delineated forest boundary compared to dGPS measurements:
Count	66	66
Mean deviation	1.08m	0.82m
Standard deviation	1.41m	0.59m
Minimum deviation	0.01m	0.04m
Maximum deviation	9.12m	2.88m

Table 6. Summary of deviations from 66 GPS measurements for the automatically and visually delineated forest stand boundary

3.3 Discussion

It was shown that a high accuracy can be achieved using automated methods and full wave data for vegetation mapping for the delineation accuracy as well as for the classification into three different vegetation types. The delineation of vegetation regions was based on the assumption that numerous reflections will be found within vegetation (in this study referred to as "intermediate points") due to the heterogeneous structure as well as gaps in the canopy whereas no reflections will be obtained inside of artificial objects (like buildings). For the extraction of vegetation regions, the local density of "intermediate points" was assigned to an image. Filtering was necessary to eliminate the edges of buildings.

Due to the fact that multiple echoes can be extracted from fullwave data it is particularly suited for the extraction of vegetation regions using the method described in this article. Nevertheless the procedure will also be applicable to laser scanner data acquired by conventional ALS systems which record the first and last echo for each laser beam. However the point spacing (point density) of the scanning will be a significant factor which will have an influence on the accuracy of the method. If the point density is reduced the probability to detect points within vegetation is decreased.

A very high precision was achieved for forest boundary delineation which was evaluated with dGPS measurements. As shown in table 6 the mean deviation of the automatic delineation is very close to the visual delineation done by a human operator based on RGB true-orthophotos. However the automated technique shows a slightly higher variation.

Very high classification accuracies were reached for the classes "forest vegetation" and "non-tree vegetation". Good accuracy was achieved for "Non-Forest Vegetation - groups of trees". Challenges are elongated groups of trees connected with the boundary of the forest area which were interpreted as forest vegetation by the automated procedure whereas a human interpreter would rather classify them as trees not belonging to the forest.

Furthermore it was shown that small single trees are not always detectable using the full wave data. This is due to the fact that the possibilities to detect "intermediate points" (on which the delineation was based) decreases if the size and height of the vegetation object is reduced. Thus the number of single trees and groups of trees outside the forest is underestimated compared with a delineation result done by a human operator which can be seen in table 4. The total area for single trees and groups of trees derived by the automated method is smaller compared with the total area delineated by visual interpretation. The usage of ALS (as being an active system) for vegetation mapping will be less dependent on weather conditions compared with photogrammetry (passive system) (Baltsavias 1999). ALS is less influenced by background irradiation whereas in aerial images the date and time (the position of the sun) will have an influence on the applicability of a classification procedure which relies on a precondition of recognizable textures in the image.

4. CONCLUSION

This article describes a fast and efficient method for delineation and classification of regions covered by vegetation based on full waveform laser scanner data. A primary classification of vegetation objects is done with several features generally used for vegetation mapping. Future work will concentrate on the classification of elongated groups of trees connected with the boundary of the forest which are classified as forest vegetation with the current method but would generally be classified as trees outside of the forest by visual interpretation. The transferability to laser scanner data acquired by conventional ALS systems which record the first and last echo for each laser beam will be tested. Furthermore the integration of colour information for further classification will be considered.

REFERENCES

AdV, 2008. Working Committee of the Surveying Authorities of the States of the Federal Republic of Germany, Hannover, Germany, http://www.adv-online.de (accessed 27.04.2008)

Baltsavias, E., 1999. A comparison between photogrammetry and laser scanning. *ISPRS Journal of Photogrammetry & Remote Sensing*, 54, pp. 83-94.

Burschel, P., Huss, J., 1997. *Grundriß des Waldbaus*. Parey, Berlin, pp. 1.

Diedershagen, O., Koch, B., Weinacker, H., 2004. Automatic segmentation and characterisation of forest stand parameters using Airborne LIDAR data multispectral and FOGIS data. In: *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Freiburg, Germany, Vol. XXXVI, Part 8/W2, pp. 208-212.

Ducic, V., Hollaus, M., Ullrich, A., Wagner, W., Melzer, T., 2006. 3D Vegetation Mapping and Classification Using Full-Waveform Laser Scanning. *International Workshop "3D Remote Sensing in Forestry"*, Vienna, Austria, pp. 211-217.

Hug, C., Ullrich, A., Grimm, A., 2004. LiteMapper-5600 - A Waveform-Digitizing LIDAR Terrain and Vegetation Mapping System. In: *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Freiburg, Germany, Vol. XXXVI, Part 8/W2, pp. 24-29.

Hyyppä, J., Hyyppä, H., Litkey, P., Yu, X., Haggrén, H., Rönnholm, P., Pyysalo, U., Pitkänen, J., Maltamo, M., 2004. Algorithms and Methods of Airborne Laser-Scanning for Forest Measurements. In: *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Freiburg, Germany, Vol. XXXVI, Part 8/W2, pp. 82-89.

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"*, Vienna, Austria, pp. 63-78.

Koch, B., Heyder, U., Weinacker, H., 2006. Detection of individual tree crowns in airborne LIDAR data. An approach to delineate tree crowns in mixed and deciduous temperate forests. *Photogrammetric Engineering and Remote Sensing*, 72, (4), pp. 357-363.

Koch, B., Straub, C., Dees, M., Wang, Y., Weinacker, H., 2008. Airborne laser data for stand delineation and information extraction. *International Journal of Remote Sensing*, (accepted, November 2007)

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*, Vol. 66, No. 11, pp. 1367-1371.

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

Soille, P., 2003. *Morphological Image Analysis*. Springer-Verlag, Berlin, pp. 158-182.

Steger, C., Ulrich, M., Wiedemann, C., 2008. *Machine Vision Algorithms and Applications*. WILEY-VCH, Weinheim, pp. 137-138.

Straub, C., Weinacker, H., Diederhagen, O., Koch, B., 2006. Standwise Delineation based on 3D information from LIDAR. *International Workshop "3D Remote Sensing in Forestry"*, Vienna, Austria, pp. 243-247.

Wagner, W., Ullrich, A., Ducic, V., Melzer, T., Studnicka, N., 2006. Gaussian decomposition and calibration of a novel small-footprint full-waveform digitising airborne laser scanner. *ISPRS Journal of Photogrammetry & Remote Sensing*, 60, pp. 100-112.

Wagner, W., Roncat, A., Melzer, T., Ullrich, A., 2007. Waveform Analysis Techniques in Airborne Laser Scanning. In: *International Archives of Photogrammetry, Remote Sensing and*

Spatial Information Sciences, Espoo, Finland, Vol. XXXVI, Part 3/W52, pp. 413-418.

Wang, Y., Weinacker, H., Koch, B., 2007. Development of a procedure for vertical structure analysis and 3D-single tree extraction within forests based on LIDAR point cloud. In: *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Espoo, Finland, Vol. XXXVI, Part 3/W52, pp. 419-423.

Wang, Z., Boesch, R., Ginzler, C., 2007. Colour and LIDAR Data Fusion: Application to automated forest boundary delineation in aerial images. *ISPRS Hanover Workshop 2007 "High-Resolution Earth Imaging for Geospatial Information"*, Hannover, Germany.

Weinacker, H., Koch, B., Heyder, U., Weinacker, R., 2004. Development of filtering, segementation and modelling modules for LIDAR and multispectral data as a fundamental of an automatic forest inventory system. In: *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Freiburg, Germany, Vol. XXXVI, Part 8/W2, pp. 50-55.

ACKNOWLEDGEMENTS

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