Area-based parameterization of forest structure using full-waveform airborne laser scanning data

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Abstract

Small-footprint airborne laser scanning (ALS) is increasingly used in vegetation and forest related applications. This paper explores the potential of full-waveform (FWF) ALS information (i.e. echo width and backscatter cross section) for tree species classification and forest structure parameterization. In order to obtain defined physical quantities, radiometric calibration of the recorded FWF data is performed by using a natural radiometric reference target (asphalt road). Based on a segmentation of the canopy surface, descriptive statistical values of laser echo attributes are derived and attached to the segment polygons, which represent large crown parts or even single trees. We found that average segment-based values of echo width and cross section are well suited to separate larch from deciduous trees (i.e. oak and beech). Additionally, the vertical distribution of the FWF information within a segment is specific for each tree species. On forest stand level a visual agreement of the segment-based FWF values with forest inventory reference data exists. We expect that with further investigation on the laser beam's interaction with vegetation calibrated FWF information can assist tree species classification and forest inventory.

Keywords: Airborne Laser Scanning, Waveform, Calibration, Segmentation, Vegetation

1. Introduction

Small-footprint Airborne Laser Scanning (ALS) has evolved to a state-of-the-art technique for topographic data retrieval with major utilization in Digital Terrain Model (DTM) generation, forestry and urban applications (e.g. building detection and modeling). The fields of applications steadily increase (e.g. glaciology, hydrology) but also developments in sensor design allow for improved data analysis in already established fields of applications, as for example full-waveform (FWF) recording systems have shown in the last few years. In forestry a large range of applications using ALS data have been presented in the last years (see proceedings of Natscan in Freiburg 2004, 3D Remote Sensing in Forestry in Vienna 2006, and previous Silvilaser conferences).

Two major methodological approaches for the extraction of forest information are predominant. The (1) distribution-based methods (e.g. Næsset 2004; Maltamo *et al.* 2004; Hollaus *et al.* 2007) use the canopy height or vertical distribution of laser echoes for estimating area-based forest inventory parameters (e.g. Lorey's mean height, stem number, basal area, and volume) by statistical means, which require an extensive set of field reference data. The (2) single-tree-based methods (e.g. Hyyppä *et al.* 2001; Morsdorf *et al.* 2004) rely on the detection of individual trees and their geometrical reconstruction (e.g. tree height, crown shape), for which ALS data with high point densities are required. In contrast to these summarized methods, which use mainly the geometric information of discrete ALS data, the radiometric information content of ALS data seems to be a promising data source for tree species classification. For example Moffiet *et al.*

(2005) analyzed the so-called intensity of discrete echo digitization systems for classification. Also Brandtberg (2007) investigated the vertical distribution of intensities for different tree species under leaf-off and leaf-on conditions. Furthermore, Reitberger *et al.* (2008) and Litkey *et al.* (2007) analyzed full-waveform (FWF) ALS data for tree species identification.

However, if radiometric information of ALS data is used, an appropriate calibration of the data is required. For example Höfle and Pfeifer (2007) described data and model-driven approaches to correct the intensity values from discrete ALS systems. For the radiometric calibration of FWF ALS data Wagner *et al.* (2006) presents the theoretical basis for modeling the waveform as series of Gaussian pulses and proposed a calibration equation to estimate the backscatter cross section of each target. Briese *et al.* (2008) point out that natural reference targets (e.g. asphalt, gravel), whose reflectance is determined in situ by a reflectometer, can be used for radiometric calibration.

In this paper a new approach is introduced for area-based parameterization of forest structure with major focus on the additional information provided by FWF ALS systems (e.g. echo width, amplitude, and backscatter cross section). Through exploratory data analysis the distributions of the FWF point cloud attributes will be assessed, which is fundamental for understanding the backscattering characteristics of individual tree species. The proposed investigations are done for deciduous tree dominated forest stands in the West of Vienna.

2. Study area and datasets

The study area is located in the western part of Vienna, in the so-called Wienerwald (Vienna Woods), and covers about 80 hectares of forest. The used full-waveform ALS data are provided by the city of Vienna (MA41-Stadtvermessung) and were retrieved in the framework of the city-wide ALS project. The ALS data were acquired using a RIEGL LMS-Q560 full-waveform scanner during the winter and spring season 2006/2007 under leaf-off conditions. The LMS-Q560 uses near infrared (1500 nm) laser pulses with a pulse width of 4 ns while the scan angle range is ±22.5°. Full-waveform decomposition has been performed by using the Riegl software Rianalyze[1]. With full-waveform recording the number echoes that can be extracted is not limited beforehand as it is with discrete echo recording systems (e.g. mostly two echoes). Therefore, the number of echoes per shot is generally higher in full-waveform data, as for example the relatively high percentage of intermediate echoes shows (i.e. extracted echoes between first and last reflection). The average echo density is 16 laser echoes per m², with about 31.5% first echoes, 11% intermediate echoes (e.g. 2nd, 3rd echo), 31.5% last echoes and 26% single echoes (i.e. shots with only one reflection).

For the investigated forests, stand-level forest inventory (FI) data were provided by the ÖBf AG, which is the largest forest owner in Austria. The dominating tree species are red beech (*Fagus sylvatica*) with ~51%, oaks (*Quercus robur, Quercus petraea*) with ~23% and hornbeam (*Carpinus betulus*) with ~16%. The remaining areas are covered with ~6% larch (*Larix decidua*), 2% clearings and other deciduous and coniferous tree species. For the current analyses tree species (i.e. beech, oak, and larch) were classified for several single trees during a field trip.

[1] http://www.riegl.com/airborne_scannerss/lms_s560/rianalyze.htm

3. Methods

The high point density (>16 echoes/m^2) of the used full-waveform ALS dataset together with the large areas that should be covered in operational forest inventory management require the application of methods, which are able to combine both, fast raster processing as well as detailed ("interpolation-free") point cloud based information retrieval. Furthermore, the high point density allows generating high resolution raster datasets (e.g. 0.5m cell size), which guarantee sufficient spatial accuracy for area-wide forest analysis. Hence, an object-based raster analysis method combined with FWF point cloud information retrieval is introduced.

The workflow of the proposed analysis comprises the following steps:

1. Radiometric calibration and retrieval of FWF echo parameters using a defined calibration area;
2. Object-based raster analysis of the forest canopy using an edge-based segmentation procedure;
3. Building of an extensive segment feature (i.e. attribute) database;
4. Exploratory segment feature analysis using reference data on single tree and forest stand level.

3.1 Radiometric calibration

The physical observables after processing the full-waveform for each laser shot are the echo width and the amplitude for each echo. These observables are not only affected by the target properties (e.g. reflectance) but also by sensor (e.g. emitted pulse energy) and flight parameters (e.g. flying height). Therefore, it is advantageous for segmentation and classification purposes to switch to physical quantities, which take these dependencies into account, such as the backscatter cross section σ given in m^2. If no calibration is performed, the investigation of the FWF information (e.g. echo amplitude) suffers from the drawback that the found quantities are not applicable for different sensors, flight parameters, flying dates, study areas, and flight strips (Wagner *et al*. 2008). The basic relation for the received power P_r, which is proportional to the product of the amplitude and echo width, is given in the radar equation (Eq. 1):

$$P_r = \frac{P_t D_r^2}{4\pi R^4 \beta^2} \cdot \eta_{sys} \eta_{atm} \cdot \sigma \quad \text{with} \quad \sigma = \frac{4\pi}{\Omega} \rho \; A \qquad (1)$$

where P_t represents the transmitted power, D_r the receiving aperture diameter, R the path length, β the beam divergence, η_{sys} a system and η_{atm} an atmospheric transmission factor and σ the backscatter cross section, which combines all target parameters like illuminated area A, reflectivity ρ and directionality of the scattering of the surface Ω (Wagner *et al*. 2006; Briese *et al.* 2008). Some parameters can be assumed to be constant during one flight mission and therefore be combined in the calibration constant C_{cal}. Estimating the cross section of a reference surface allows determining C_{cal} (Eq. 2) by using path length, amplitude and echo width of echoes, which hit the reference surface. Then the backscatter cross section can be calculated for every single echo as following:

$$\sigma = C_{cal} R^4 P_r \quad \text{with} \quad C_{cal} = \frac{4\pi\beta^2}{P_t D_r^2 \eta_{sys} \eta_{atm}} \qquad (2)$$

The calibration was carried out based on an asphalt road as reference target. The reflectance of the target was estimated by in situ measurements using a reflectometer (cf. Briese *et al.* 2008). Assuming Lambertian scattering of the reference target allows deriving the cross section of the reference target. Due to the lack of simultaneous meteorological data, the atmospheric attenuation effects are included in the calibration constant (Eq. 2). For echoes within the target, C_{cal} can be computed and an average value of the resulting calibration constants can be used for the calculation of σ for the whole data set.

3.2 Segmentation of the forest canopy

In order to enable an area-based investigation and parameterization of the forest structure larger spatial units have to be built. Firstly, this step should separate forested/vegetation areas from terrain as well as from other raised objects (e.g. buildings). Secondly, the object boundaries indicated in the normalized Digital Surface Model (nDSM) and lying within areas marked as vegetation should be preserved because they may represent the border between different tree species and forest types respectively, showing different signatures in the FWF data. Especially in dense deciduous forests with a mixture of small and large trees (in the sense of height and diameter) the detection of single trees can hardly succeed. Therefore, our approach aims at delineating convex objects elevated in the nDSM (i.e. canopy layer) using an over-segmentation, so that one tree can be represented by one, or more segments if a tree forms a crown with multiple tops. An edge-based segmentation procedure was implemented in the open source software GRASS GIS. The basic ideas behind the segmentation are that 1) convex objects of the canopy (i.e. nDSM) are separated by concave areas (i.e. valleys), 2) the normalized height of the vegetation exceeds a certain threshold (e.g. >2.0m above DTM), and 3) within vegetation multiple reflections occur. Since the segmentation is performed on the nDSM it is a 2.5D approach, which cannot delineate occluded objects in lower vegetation layers. Two raster layers are used as input for the segmentation (Figure 1ab) – the nDSM and an echo ratio raster (Eq. 3):

$$\text{echo ratio [\%] per cell} = (n_{\text{first}} + n_{\text{intermediate}}) / (n_{\text{last}} + n_{\text{single}}) \cdot 100.0 \qquad (3)$$

with echo ratio set to zero if no echo is within the cell and set to 100.0 if (n_{last}+n_{single}) is zero.

The edge detector is based on calculating the curvatures of the nDSM (minimum curvature in direction perpendicular to the direction of maximum curvature), threshold it (i.e. curvature<0.0) and further skeletonize the potential edge areas to finally get the edge map. The chosen window size and the threshold on curvature determine the degree of canopy structure detail that is regarded, i.e. controls over- and under-segmentation. These derived edges are the potentially most exterior boundaries of a segment. Then the edge map is intersected with the areas fulfilling the height and echo ratio threshold. As a last step the final segments are derived by connected components labeling and vectorization of the region outline (Figure 1c).

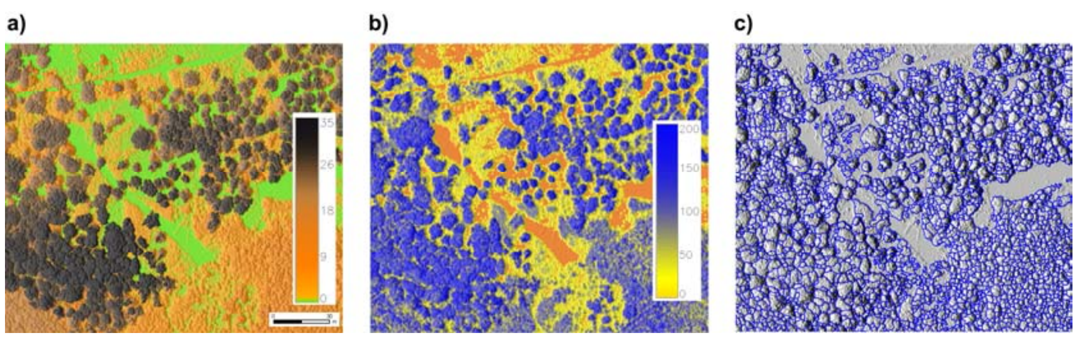

Figure 1: a) nDSM color-coded by normalized height, b) echo ratio raster, c) resulting segmentation of the canopy layer using the nDSM and the echo ratio raster (cf. Eq. 3).

3.3 Feature calculation

In order to extract the highest degree of information, feature extraction goes back to the 3D point cloud. For each segment the corresponding laser echoes are selected using a point-in-polygon test.

Descriptive statistical values (min., max., mean, and std. deviation) are derived individually per segment for normalized point height, echo width, and backscatter cross section. As the point cloud selection is performed in 2D the points of the highest vegetation layer have to be separated from the lower layers and the understory otherwise the segment features may not represent the tree species forming the canopy but a mixture of all trees in the vertical vegetation column of a segment. For this task a global minimum height threshold (e.g. > 3.0m) is defined, which should remove the understory. A dynamic minimum height threshold on normalized echo height – defined as percentage of the nDSM height (e.g. 50%) at the echo location – should further separate the top layer.

4. Results and discussion

4.1 Calibrated full-waveform information

Figure 2a shows an image of the study area with averaged echo cross sections where the brightest areas represent terrain (e.g. forest road and open grass) and dark areas mainly high vegetation. The grayscale variations within the forest coincide with different forest characteristics (e.g. tree species, age, canopy height and closure). Figure 2b shows averaged cross sections for echoes in the upper layer of the vegetation where major tree branches and stems become evident by their higher average cross section (light green color).

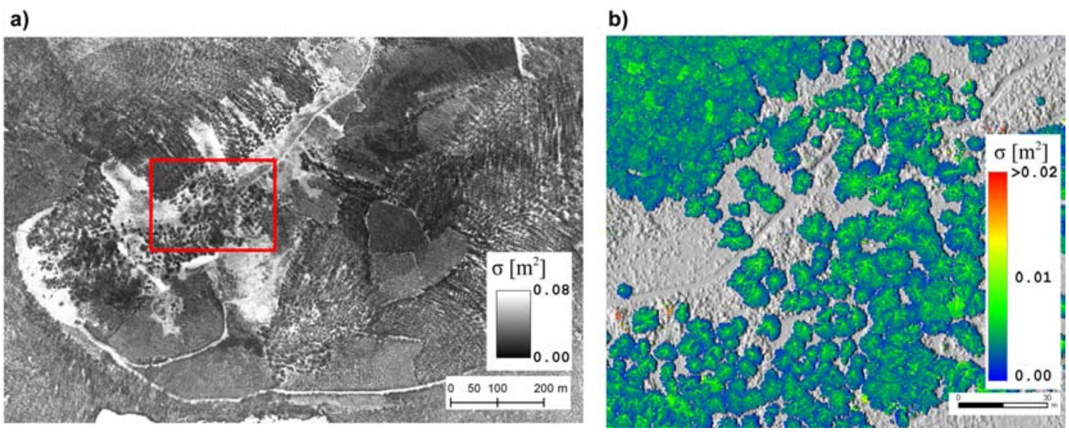

Figure 2: a) Average backscatter cross section per 0.5 x 0.5m cell using all laser echoes (red square shows extent of right subfigure) and b) average cross sections of echoes in the uppermost vegetation layer.

Extracting the target reflectance for vegetation echoes will be problematic because we do not know the illuminated area, the bidirectional reflectance distribution function (BRDF) of the target, as well as estimating the local incidence angles (e.g. on leaves) using the point cloud leads to great uncertainty. Hence, the backscatter cross section (BSC) and the echo width (EW) derived for each reflection are the parameters most suitable for further investigation in the field of vegetation analysis and forestry.

4.2 Canopy segmentation

The echo ratio is an appropriate parameter for separating solid objects (e.g. terrain, buildings) from vegetation indicated by high values. Visually evaluated this classification worked out very well (cf. Figure 1c) because the data acquisition was carried out under leaf-off conditions and deciduous trees are dominant within the area investigated. Dense canopies (e.g. coniferous trees or dense leaf canopy) where the laser beam is fully intercepted in the crown will cause low echo ratio values, and hence are not considered as vegetation. To overcome this problem other raster layers could be additionally included in the segmentation – such as surface roughness, echo width or backscatter cross section of points vertically close to the DSM. The applied segmentation delineates objects that are clearly represented in the canopy layer. These objects may correspond with single trees if they are detached and build a single distinct crown, respectively. Large deciduous trees tend to build multiple convex crown parts, which results in one segment for each part. In the analyzed data no grouping of different canopies into one segment (under-segmentation) could be observed. If aiming at single tree or stem detection in a forest comparable to our study area, it becomes necessary to consider the third dimension (i.e. point cloud) and FWF information already in the detection process (e.g. Reitberger *et al*. 2007).

4.3 Exploratory segment feature analysis

On single tree and segment level, respectively, the echo width and backscatter cross section of three different tree species are investigated. The segments of 11 red beeches (spread over two stands; >30 m avg. height), 10 oaks (4 stands; >27 m avg. height) and 4 larches (same stand; >18 m height) were identified in the field. The derived statistics are based on echoes in the upper vegetation layer (as defined in Section 3.3) in order to avoid a mixture with echoes from smaller neighboring trees and the understory. Looking at the average segment values for echo width and cross section clearly shows that larch (avg. EW=5.35 ns, avg. BSC=0.0096 m^2) is clearly separated from the deciduous species, whereas beech (avg. EW=4.44 ns, avg. BSC=0.0059 m^2) and oak (avg. EW=4.41 ns, avg. BSC=0.0055 m^2) show similar average values (cf. Figure 3a).

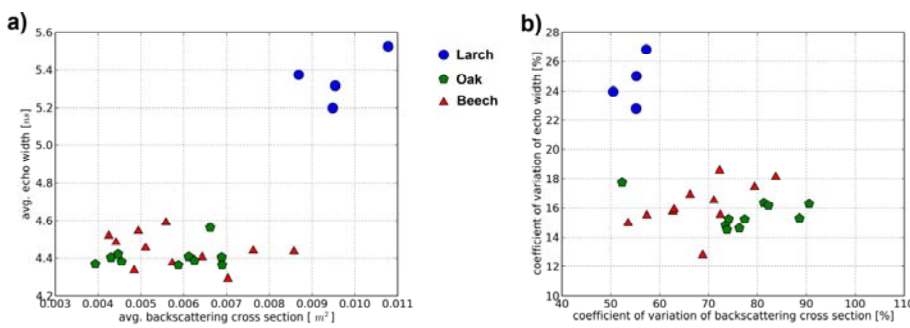

Figure 3: Tree species scatter plots of a) segment-based average of echo width vs. cross section and b) segment-based coefficient of variation (*CV*) of echo width vs. *CV* of cross section.

Concerning the variation of the FWF features oak shows a higher coefficient of variation (CV) in BSC and lower CV in EW than beech. In Figure 3b one oak tree with lower variation sticks out (CV of BSC=52%). In contrast to the other oaks (>27m height), the 'outlier' is a smaller tree with about 18 m height. This confirms that growth and age are an important factor, as important as tree species, for the backscattering properties parameterized by the FWF information.

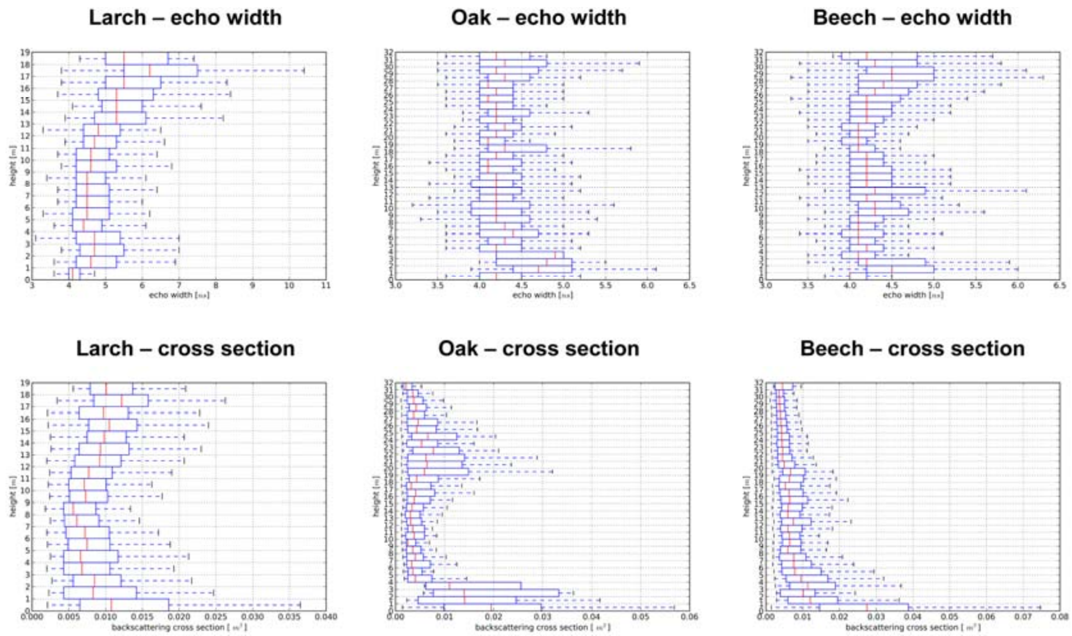

Figure 4: Boxplots in vertical profiles (1 m intervals) of echo width and cross section for the tree species larch, oak and beech. All echoes per tree segment are used.

For better understanding of the average segment values the vertical distribution of the FWF information for representative segments is shown in Figure 4. It can be seen that larch has the highest values of BSC in the uppermost part, which is strongly correlated with the echo width. Oak and beech show relatively constant average echo widths over the vertical profile but the BSC increases, which may be due to the increase of collision area (more and broader branches). Figure 5 gives a good impression how the segment FWF features could be used to find structurally homogeneous forest areas or could be used to determine the structural heterogeneity of defined units. It can be seen that the reference forest stand outlines generally coincide with a specific BSC and EW class, respectively, whereas some stands are characterized by a strong heterogeneity due to different tree species and age classes.

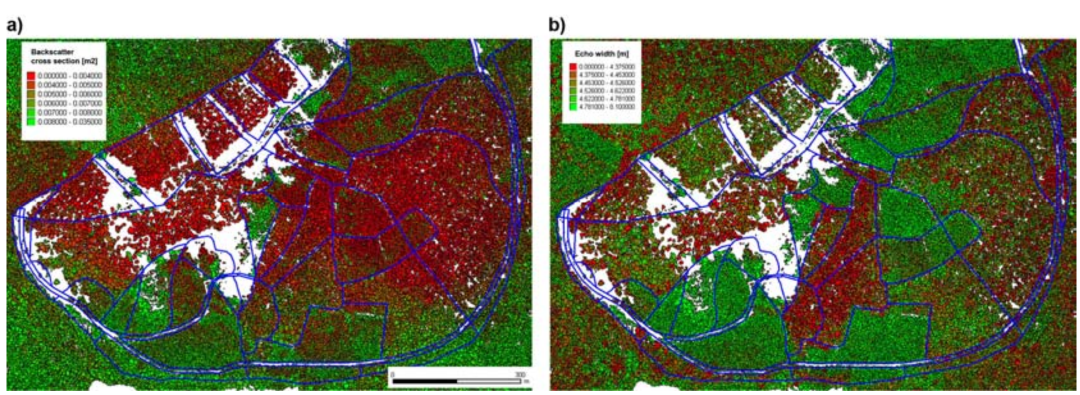

Figure 5: a) Segments colored by mean backscatter cross section of echoes in the upper vegetation layer. b) Segments colored by mean echo width. Blue boundaries are the forest stand outlines from the forest inventory reference data.

5. Conclusions

Up to now most studies utilize the geometric information of airborne laser scanning data to characterize forests at various scales (from single trees to forest stands). Recent studies have shown that the intensity data of discrete echo recording system is a supplementary source of information (e.g. Moffiet *et al*. 2005). The present paper shows that information provided by full-waveform laser scanning (e.g. echo width) and physical quantities derived by radiometric calibration of the recorded signal (e.g. backscatter cross section) have a great potential for tree species identification and large scale forest characterization, even under leaf-off conditions. Within the small selection of trees analyzed in detail a good separability between larch and deciduous trees (oak and beech) is found regarding average segment values of echo width and backscatter cross section. Additionally the vertical distribution of the FWF information yields specific characteristics for each tree species. In order to consolidate the findings more and extensive reference data has to be included. Furthermore, effects of different data acquisition settings (e.g. flight geometry) on echo width, amplitude, and cross section have to be quantified and separated from effects originating from the tree configuration (e.g. species, age).

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