A VOXEL-BASED APPROACH FOR CANOPY STRUCTURE CHARACTERIZATION USING FULL-WAVEFORM AIRBORNE LASER SCANNING

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ABSTRACT

Forests play a significant role in the global biogeochemical and -physical cycles and particularly the complex three-dimensional forest canopy structure influences the fluxes of energy and matter between the atmosphere and forests. Assessing this structure quantitatively using conventional fieldwork or traditional remote sensing methods is difficult, whereas airborne laser scanning (ALS) systems have proven to be suitable for providing explicit vertical information for large areas. However, most existing ALS based approaches include manual processing steps or need additional data about stand characteristics. To solve these issues, a robust and automatic multi-dimensional clustering method was developed to derive forest canopy structure types (CSTs) based on full-waveform ALS data. The results show that it is possible to develop an automatic, self-sustained and transferable method for: the extraction of CSTs without any previous knowledge about the forest stand; and the extraction of bio-physical parameters based on the resulting CSTs.

***Index Terms* —** 3D vegetation structure, full-waveform LiDAR, remote sensing, biophysical parameters

1. INTRODUCTION

Forests cover almost one third of the total land surface of the Earth. Therefore, they play a globally significant role in the biogeochemical and -physical cycles between atmosphere and the land surface [1,2]. Understanding, assessing and quantifying forest ecosystem goods and services and their underlying processes, helps to project the development of biogeochemical cycles under changing climate conditions and to develop sustainable management strategies [3,4,5]. Particularly the complex three-dimensional distribution of geometric objects and their topology within forest canopies, here termed *forest canopy structure* [6], influences the fluxes of energy and matter between the atmosphere and forests [7,8]. Relating to sustainable management strategies, forest canopy structure is one of the critical variables, e.g. to determine forest stand resistance to disturbances and to estimate the conservation potential for forest biodiversity [9,10]. Airborne laser scanning (ALS) systems were shown to be appropriate for providing horizontal as well as explicit vertical information of forest canopy structure due to the penetration of the emitted signal through gaps in the canopy [11,12,13].

Canopy structure metrics derived by ALS include dimensional variables on tree-level such as canopy height, volume, width, base height or density, as well as biophysical parameters such as the Leaf Area Index (LAI), gap fraction or foliage profiles [14,15]. However, existing approaches mostly include manual processing steps or need additional data about stand characteristics (e.g. management type and tree species) [16,17,18]. Therefore, we developed an automated, self-sustained and transferable method to support a more efficient monitoring of forest canopy structure on various spatial scales, as well as to improve the robustness and reliability of derived canopy structure information as input for environmental modeling.

2. AREA OF INTEREST AND DATA

In the approach presented in this study, we make use of full-waveform ALS data in a 300 x 300 m test site. The data acquisition was performed under leaf-on (using RIEGL's© LMS-Q680i scanner) and leaf-off (using RIEGL's© LMS-Q560 scanner) canopy conditions in a mainly semi-natural, deciduous-dominated forest stand in Laegeren (Swiss Jura – 47°28'N, 8°21'E), yielding in two independent datasets. The used flight strips have an overlap of approximately 50%. The relevant sensor characteristics of the applied ALS systems are summarized in Table 1 [13,19]. The dense forest stand is characterized by steep topographic relief (slope up to 60°) and high diversity of species (mostly *Fagus sylvatica (L.), Picea abies (L.) Karst, Fraxinus excelsior (L.)* and *Acer pseudoplatanus (L.)*), age (55 - 160 years), and diameter distribution (7 - 120 cm) [20].

Table 1: Sensor specifications of LMS-Q560/Q680i.

	Q560	Q680i
wavelength [nm]	1550	
scanning method	rotating multi-facet mirror	
pulse length [ns]	< 4	
pulse frequency [Hz]	200 000	
pulse detection method	full-waveform processing	
sampling interval [ns]	1	
scan angle [deg]	± 15	
avg. flight altitude (AGL)[m]	500	
mean point density for the area of interest [pts/ m^2]	20	40
date of acquisition	10.04.2010	01.08.2010

For the investigated area, an extensive set of ground based reference data is available, mainly measured during field campaigns in September 2011: Digital Hemispherical Photographies (DHPs), Terrestrial Laser Scanning (TLS – Z+F IMAGER© 5006), Field-Map system data and plant sociology classifications. All ground based measurements were georeferenced and co-registered based on traditional terrestrial land surveying methods.

3. METHOD

The benefit of full-waveform data is the approximation of the entire backscattered signal by digitization, which facilitates the extraction of additional features of each reflecting object within the ALS footprint. To detect and extract specific object reflections, Gaussian pulse estimation was applied in order to obtain representative echo descriptions. In particular, this includes the derivation of the point cloud with its basic and established geometrical characteristics of reflectors but additionally the physical description of each reflector with information such as amplitude and width of the specific echo as well as the resulting intensity values [21].

3.1. Derivation of terrain and canopy height model

Based on the single and last echoes and their geometrical characteristics and echo width information, we developed a new adaptive multi-scale algorithm to extract the ground returns. As part of an iterative filter process, a kernel based query was applied to the selected ground return echoes to detect areas with high slope deviations. Within these areas a combination of optimized spline function analyses and a scale dependent multi-point triangulation was applied to exclude non-ground points from the point cloud. The remaining points were interpolated applying an ordinary kriging to a 1 x 1 m digital terrain model (DTM) and verified based on accurately fixed control points of the Swiss national land survey. A 1 x 1 m digital surface model (DSM) was processed using the first echo reflections and their corresponding echo width. Afterwards, the canopy height model (CHM) was calculated from the difference between DSM and DTM. Figure 1 shows the resulting DTM and the DSM colored with the CHM values.

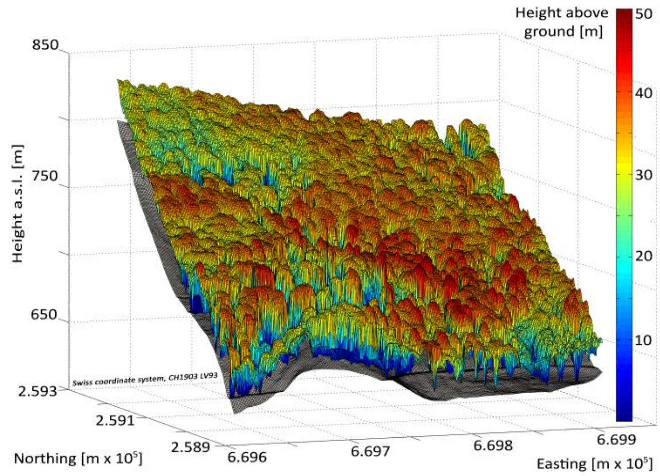

Figure 1: DTM, DSM and CHM for the area of interest.

Finally, for each point of the point cloud we determined the height above ground as well as the according DTM, DSM and CHM values.

3.2. Multi-scale clustering of forest canopy structure

Forest structure variables can characterize canopies on different spatial scales [22]. In this study, forest canopy structure was investigated on the individual tree as well as on a regular grid (5 x 5 m) level.

For the regular grid level, a 1 x 1 m voxel based representation was derived using the specific echo characteristics. In this representation, each voxel contains information based on the statistical properties and the distribution of reflectors within each voxel. The derived thematic attributes include, inter alia, the leaf-on / leaf-off varieties of point densities, the amount of different echo types (e.g., first echo, last echo, intermediate echoes) and intensity and echo width variations. Using a hierarchical multi-dimensional (three spatial dimensions and n-thematic ones) fuzzy clustering approach, thematically homogenous volume layers were calculated. The seed points and the number of expected clusters respectively, were determined based on the vertical distribution of point densities.

The characterization of the crown structure of individual trees requires the segmentation of the full point cloud into specific point clouds of the single trees. To detect understory trees as well, we applied an iterative grayscale dilation based on an ellipsoid-shaped structuring element S with a pre-defined domain D_S [23]. The general form of grayscale dilation for each voxel position $V(x,y)$ by $S(x,y)$ is defined as:

$$(V \oplus S)(x,y) = \max\{V(x-x', y-y') + S(x',y') | (x',y') \notin D_S\}$$

The resulting local maxima were used as seed points for the clustering algorithm. Additionally, a scaling argument for the z-coordinate was introduced due to the high variations in the vertical extent of the point cloud. The tree detection accuracy and the delineation of tree crown dimension were assessed based on a stratified random sampling approach using ortho-images and the Field-Map system data. Following the tree segmentation, we applied the same hierarchical clustering of the grid-based approach for each individual tree point cloud.

3.3. Determination of canopy structure types

Finally, we used the extracted layer information of the respective cluster approaches and classified them into structural homogenous canopy structure types (CSTs). Based on the analysis of the vertical stratification of the CSTs, we derived the common tree and crown dimensional variables (e.g. tree height, crown length) as well as additional information such as tree species, crown cover and foliage distribution.

To evaluate the applicability of the derived CSTs, we estimated the bio-physical variables leaf area index (LAI) and gap fraction, utilizing different pulse penetration rate variables (e.g., fraction of echoes, fraction of full waveform return) depending on the specific layer combinations within the CSTs. For the validation of the estimated parameters, both point measurements with DHPs and plot-wise TLS measurements were carried out, resulting in grid based LAI and gap fraction layers.

4. RESULTS

The commission and omission errors of the tree detection are 5.2% and 13.1%, respectively, whereby the high omission errors have mainly been caused by understory trees. The cross-comparison of crown dimensions with the TLS measurements and ortho-images show a high consistency in the horizontal dimension. For the vertical extent the accuracy depends on the detection of the crown base, which involves - particularly in dense deciduous forests - a high level of uncertainty. Figure 2 shows an example of possible variable extractions on the individual tree level.

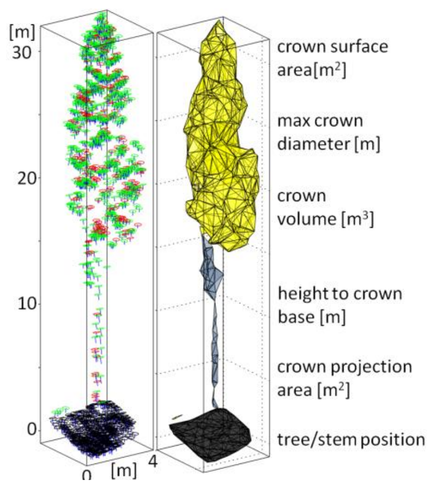

Figure 2: Alpha shape representation of the individual tree point cloud clustering and tree level specific variables.

Figure 3 shows an example of a 20 x 5 m profile for the grid based investigations. The distinction between deciduous and coniferous canopies based on the leaf-on/leaf-off variations in the vertical echo distribution. For the estimation of the foliage distribution we used the information about the penetration depth, intensity and echo width.

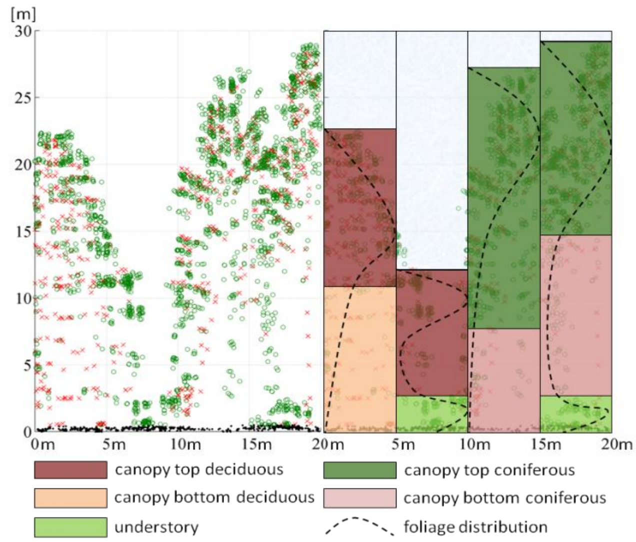

Figure 3: Grid based vertical stratification of canopy structure.

The comparison with the TLS measurements shows that the vertical boundaries of the layers within the tree canopy differ by a maximum of 2 m, whereas the vertical extent of the understory differs by a maximum of 1 m. However, the total number of detected layers as indicator for structural heterogeneity mainly corresponds to the reference information.

The cross-comparison of the bio-physical variables derived from the CSTs to the reference data also shows a high correlation, whereby the quantification based on absolute values requires additional calibration steps.

5. CONCLUSIONS

We introduced an automatic, self-sustained and transferable method for the extraction of canopy structure information in the form of CSTs without any previous knowledge about the forest stand. We could show, that the relative determination of bio-physical parameters based on CSTs agrees well with the ground based reference data. However, the CST product may still contain residual uncertainties resulting either from the measurement process or semantic ambiguities, which will be addressed in future studies.

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