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Quantification of hidden canopy volume of airborne laser scanning data using a voxel traversal algorithm

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ABSTRACT

Accurate three-dimensional information on canopy structure contributes to better understanding of radiation fluxes within the canopy and the physiological processes associated with them. Small-footprint airborne laser scanning (ALS) data proved valuable for characterising the three-dimensional structure of forest canopies and the retrieval of biophysical parameters such as plant and leaf area index (PAI and LAI), fractional cover or canopy layering. Nevertheless, few studies analysed combined occluded and observed canopy elements in dense vegetation as a result of airborne laser scanning geometries. The occluded space contains a substantial amount of vegetation elements (i.e. leaf, needle and wood material), which are missing in the analysis of the three-dimensional canopy structure. Consequently, this will lead to erroneous retrieval of biophysical parameters. In this study, we introduce a voxel traversal algorithm to characterise ALS observation patterns inside a voxel grid. We analyse the dependence of occluded and unobserved canopy volume on pulse density, flight strip overlap and season of overflight in a temperate mixed forest. ALS measurements under leaf-on and leaf-off conditions were used. For cross-comparison purposes, terrestrial laser scanning (TLS) measurements on a 50×50 m^2 subplot under leaf-on conditions were used. TLS acquisitions were able to depict the three-dimensional structure of the forest plot in high detail, ranging up to the top-most canopy layer.

Our results at 1 m voxel size show that even with the highest average pulse density of 11 pulses/m^2, at least 25% of the forest canopy volume remains occluded in the ALS acquisition under leaf-on conditions. Comparison with TLS acquisitions further showed that roughly 28% of the vegetation elements detected by the TLS acquisitions were not detected by the ALS system due to occlusion effects. By combining leaf-on and leaf-off acquisitions, we were able to recover roughly 7% of the occluded vegetation elements from the leaf-on acquisition. We find that larger flight strip overlap can significantly increase the amount of observed canopy volume due to the added observation angles and increased pulse density.

1. Introduction

Forests cover approximately one third of the Earth's total land area (FAO, 2010), accounting for 75% of terrestrial gross primary production (Beer et al., 2010), 80% of plant biomass (Kindermann et al., 2008), and the majority of species on Earth (Pan et al., 2013). Therefore, forests play a crucial role in the global biogeochemical and biophysical cycles (Betts et al., 2001; Bonan, 2008; Ross, 2012). The importance of understanding and monitoring these complex ecosystems in the face of a changing climate is therefore ever increasing. In order to understand and manage forests, we need to describe and categorise their complex and dynamic structural and spatial components (Robertson, 1987; Groffman and Tiedje, 1989; Martens et al., 1991), as well as their biochemical properties (Asner, 1998). Monitoring and assessing canopy structure is of special interest as it highly influences the energy fluxes between the atmosphere and forests (Yang and Friedl, 2003; Shugart et al., 2010; Xue et al., 2011) and therefore has important implications for forest growth, productivity and biodiversity (e.g. Givnish, 1988; Ishii et al., 2004; Zellweger et al., 2014, 2015).

Canopy structure is often defined as the three-dimensional distribution of structural elements such as leaves, branches, and tree trunks (Pan et al., 2013; Nadkarni et al., 2008; Disney et al., 2006). It is often assessed by measuring tree height, tree diameter distribution, foliage and wood density, or stand volume (McElhinny et al., 2005). Traditionally, canopy structure is assessed by time-consuming and

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occasionally subjective fieldwork on relatively small sampling areas (McElhinny et al., 2005; Haara and Leskinen, 2009; Foody, 2010). Recent advances in the field of remote sensing have greatly improved medium to large scale assessment of canopy-structure variables, not only in the horizontal, but also in the vertical dimension (Roberts et al., 2007; Asner et al., 2012; Jones et al., 2012). Light detection and ranging (LiDAR), with airborne laser scanning (ALS) systems in particular, have shown promising results in retrieval of canopy structure variables such as canopy height, fractional cover, and leaf area index (LAI) (e.g. Morsdorf et al., 2006; Coops et al., 2007; Solberg et al., 2009), as well as in mapping tree positions and species (e.g. Morsdorf et al., 2004; Lee and Lucas, 2007; Suratno et al., 2009). Moreover, LiDAR data is increasingly used for parameterising ecological or radiative transfer models due to its ability to depict the horizontal and vertical distribution of vegetation elements (i.e. leaf, needle, and wood material) (Antonarakis et al., 2014; Schneider et al., 2014).

Very few studies have actually analysed occlusion from ALS due to dense vegetation or scanning patterns (Korpela et al., 2012). Nevertheless, several studies have identified occlusion to be a major source of uncertainty for retrieval of canopy structure variables both from ALS (e.g. Morsdorf et al., 2009; Musselman et al., 2013) as well as terrestrial laser scanner (TLS) measurements (e.g. Béland et al., 2011; Côté et al., 2011; Béland et al., 2014a). An approach to map and quantify occluded volume inside forest canopy is therefore of particular interest for canopy structure variable retrieval.

Occlusion in ALS measurements is often caused by very dense vegetation in the top-most canopy layers, obstructing the laser pulses from reaching lower canopy layers. Additionally, inappropriate scanning configurations, such as too low pulse density, partly caused by a lack of flight strip overlap, can be a cause for occlusion. Whereas occlusion in ALS measurements mostly occurs in the lower canopy layers (Korpela et al., 2012), TLS measurements show an increase in occlusion towards the top of the canopy as well as in the middle of tree crowns (Béland et al., 2011, 2014a). With an adequate scan pattern and well defined scan positions, the amount of occlusion in TLS measurements can be minimised (Hilker et al., 2010).

In TLS studies, several approaches have been introduced to quantify and map occluded areas inside forest canopies (e.g. Béland et al., 2011, 2014a; Bienert et al., 2010). Also attempts to compensate occluded volume have been made by using light transmission models (Béland et al., 2011) or by statistical methods (e.g. Lovell et al., 2011; Strahler et al., 2008). However, for ALS measurements, such an occlusion mapping and quantification approach is still missing.

One way to map and quantify occlusion in ALS acquisitions is the reconstruction of the path of each laser pulse via ray tracing. Ray tracing is a commonly used tool to simulate and analyse data acquisition of different sensors (e.g. Disney et al., 2006, 2010; Hovi and Korpela, 2014). A simple and computationally inexpensive way to trace laser pulses is a voxel traversal algorithm as introduced by Amanatides and Woo (1987). The algorithm divides the three-dimensional space into small rectangular cubes, also known as voxels and traces each pulse through the voxel grid. By knowing the exact location of each laser return as well as the origin of the pulse, one is able to analyse the laser acquisition pattern inside the forest canopy for a given voxel size, allowing to quantify occluded and observed volumes. Béland et al. (2014b) introduced a parametric model using computational geometry instead of a complex ray tracing algorithm in order to estimate leaf area density at the voxel scale and showed in Béland et al. (2014a) that this model can also be used to map occluded areas.

In this study, we introduce an approach to map and quantify occluded forest canopy volume by tracing ALS laser pulses through a pre-defined voxel grid using a voxel traversal algorithm (Amanatides and Woo, 1987). The occlusion map has been analysed regarding (i) the influence of laser acquisition parameters such as pulse density or flight strip overlap on the amount of occlusion, (ii) seasonal influence (leaf-on vs. leaf-off) on the occluded canopy volume, and (iii) the quantification of hidden vegetation elements inside occluded forest volume by cross-comparing with voxelized TLS measurements.

2. Study site and materials

2.1. Study site

The Laegern site (47° 28′ N, 8° 21′ E) is a semi-natural mixed deciduous forest northwest of Zurich, Switzerland. It is an old-growth forest with a complex, multilayered canopy structure. The predominant tree species are the common beech (*Fagus sylvatica*), European ash (*Fraxinus excelsior*), and sycamore maple (*Acer pseudoplatanus*), with scattered silver fir (*Abies alba*) and Norway spruce (*Picea abies*) trees (Leiterer et al., 2015a). The canopy is well structured with distinct background, understory, and overstory layering. Trees are up to 165 years old, with a diameter at breast height (DBH) distribution of up to 150 cm (Eugster et al., 2007). The study site shows significant variation in canopy structure, including areas undergoing different forest management practices (ranging from semi-natural forests to highly intensive regimes with silvicultural interventions) (Leiterer et al., 2015a).

The site is approximately 400 ha in size and the elevation ranges from 515 to 860 m above sea level, with primarily north- and south-facing slopes with inclinations between 10° to 65°. A 300×300 m^2 core study site located on the south-facing slope of the Laegern mountain and centered around the FLUXNET site ('Laegeren', site CH-Lae) was chosen for in-depth analysis (i.e. voxel size influence and beam width influence on occlusion). The core study site is representative for the whole 400 ha large study site showing a diverse mixture of deciduous and coniferous forest stands (Leiterer et al., 2015a).

2.2. ALS data

The full-waveform ALS data acquired over the Laegern site was part of a larger ALS flight campaign in 2014 covering an area of 180,000 ha. The area was flown both under foliated (leaf-on) and defoliated (leaf-off) conditions. The sensor specifications are summarised in Table 1. The ALS acquisitions were acquired and processed by Milan Geoservice GmbH (Kamenz, Germany). The processing steps involved the extraction of laser returns from the full waveform data, transformation of the point cloud into the Swiss CH-1903 (LV03) Cartesian coordinate system, flight strip adjustment, filtering and

Table 1
Specifications for the ALS data acquisition.

<table>
<tr><th>ALS parameter</th><th>Leaf-off</th><th>Leaf-on</th></tr>
<tr><td>Acquisition date</td><td>March/April 2014</td><td>June/July 2014</td></tr>
<tr><td>ALS sensor</td><td colspan="2">LMS-Q680i</td></tr>
<tr><td>Operating platform</td><td colspan="2">Airplane</td></tr>
<tr><td>Mean operating altitude above ground [m]</td><td>600</td><td>700</td></tr>
<tr><td>Scanning method</td><td colspan="2">Rotating multi-facet mirror</td></tr>
<tr><td>Pulse detection method</td><td colspan="2">Full-waveform processing</td></tr>
<tr><td>Pulse length [ns]</td><td colspan="2"><4</td></tr>
<tr><td>Sampling interval [ns]</td><td colspan="2">1</td></tr>
<tr><td>Scan angle [deg]</td><td colspan="2">± 22</td></tr>
<tr><td>Mean point density [pts/m^2]</td><td>15</td><td>30</td></tr>
<tr><td>Mean pulse density [pls/m^2]</td><td>≈ 11</td><td>≈ 11</td></tr>
<tr><td>Pulse footprint [cm]</td><td>30</td><td>35</td></tr>
<tr><td>Laser wavelength [nm]</td><td colspan="2">1550</td></tr>
<tr><td>Scan rate [Hz]</td><td colspan="2">120</td></tr>
<tr><td>Pulse repetition frequency [kHz]</td><td colspan="2">300</td></tr>
<tr><td>Beam divergence [mrad]</td><td colspan="2">0.5</td></tr>
<tr><td>Angular step width [deg]</td><td colspan="2">0.0176</td></tr>
</table>

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