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Highlights: Estimating exact 3D distribution of canopy components using terrestrial lidar in forest is limited by signal occlusion. We propose a method to address this limitation: it uses voxels, beam returns and beam propagation through the scene. The proposed method was validated using simulated forest scenes and a lidar simulator.

Key words: *terrestrial laser scanner, signal occlusion, forest components, 3D spatial distribution, point cloud processing.*

Introduction

Terrestrial lidar scanner (TLS) can be used in forest stands to investigate fine structural attributes at the stand- and tree-level. Visual inspection of the point cloud from a single scan taken by a TLS shows many areas with no points due to signal occlusion. The impact of signal occlusion is more important as the distance from the scanner increases. It also increases with stand structural complexity. One way to reduce the occluded areas in the point cloud of a forest plot is to produce a co-registered (or aligned) point cloud from several scans at different locations inside and around the plot. This way to proceed reduces but does not eliminate occluded areas. However merging multiple scans introduces oversampling: i.e. the possibility that one component may be probed from several directions. Oversampling is also likely to occur in a single scan for targets close from the scanner for which laser beams may overlap. Overall, signal occlusion and oversampling is present in all point clouds of forest plots taken by TLS and it alters the estimation of an exact 3D spatial distribution of the forest components if this estimation is based on point density. This situation is so prevalent that one can assume that the number of lidar returns is biased compared with true component distribution: it is proportionally higher for objects closer to the sensor and conversely lower with increasing distance from the sensor. This results in a misrepresentation of the number of returns compared with the real distribution of the forest components. For instance the vertical profile drawn from TLS data artificially inflates the number of returns from lower canopy and does not provide a proper account of the components from the upper part of the canopy for which the laser beam is strongly occluded. A similar effect exists with airborne lidar data [1]. At this point no correction method exists for this bias of representation of component distribution.

Enhanced forest inventory are expected from new methods of processing TLS data designed to estimate forest attributes [2]. For example, assessing stem shape (DBH and stem taper) is not affected by point oversampling from multiple scans, if the scans are well aligned, but it may be affected by signal occlusion. Several methods proposed replicating detailed tree structure from raw TLS data ([3]). These methods are promising but they require extensive computing to provide a 3D spatially-explicit structural representation of the forest. A simpler method to process the TLS point cloud is required to help estimating the exact 3D distribution of forest components. Voxel representation may be a way to reduce the complexity of point clouds while retaining a sufficient level of details for further analyses. The representation of the point cloud into voxels can allow estimation of many structural attributes such as LAI [4] or metrics describing asymmetry [5] or linked to the quality of wood fiber attributes [6]. The main objective of this study is to develop and validate a method to process the TLS point cloud taken in forest stands, using voxel representation, to allow estimating reliable 3D forest component distribution, consequently removing the impact of signal occlusion and oversampling.

Materials and Methods

The study objective was met by following four methodological steps: (1) simulating detailed forest structure for a range of documented conditions, (2) simulating the point cloud resulting from multiple TLS scans acquisition for the simulated forest scenes, (3) developing a two-step method to deal with signal occlusion and oversampling, and (4) estimating error of the results from the two-step method. These efforts were therefore concentrated towards the development of a method to estimate the component distributions in 3D using the Plant Area Density (PAD in m^2/m^3) in a voxel-based environment.

Simulation of forest canopy: It is virtually impossible to have direct in situ measurements of forest component distribution in 3D to serve as a reference. Consequently we decided to simulate realistic forest scenes with the fine-scale architectural model L-Architect [3]. We reproduced 12 realistic forest scenes over a range of documented conditions typical of boreal forests of Eastern Canada largely dominated by black spruce (Picea mariana) and balsam fir (Abies balsamea) [3].

Simulation of the TLS point cloud: All the simulated forest scenes were *"*scanned*"* by a TLS-simulator based on a ray-tracing algorithm and in similar conditions typically performed during field acquisitions. The TLS-simulator replicated a hemispherical geometry and technical characteristics similar to the Faro© and the Zoller+Fröhlich© sensors in high resolution mode, which recorded only the first return. All plots were scanned from 5 positions, including one at the plot centre and the 4 others placed at an equal distance near the plot edge. The resulting five scans of each plot were aligned, clipped on the plot dimension and assembled.

A two-step method to address signal occlusion and oversampling: The datasets were processed and analysed for voxel sizes of 5, 10, 15 and 20 cm edges, respectively, to assess if voxel resolution had an impact on the quality of the results. The method was composed of two distinct steps. The first step provided an estimate of the PAD within each voxel according to the number of lidar beams crossing the voxel and the number of returns. This step combined two procedures: procedure 1 used the L-Vox algorithm that estimates the theoretical number of lidar beams crossing each voxel and calculates a density index using the number of returns ([7], [3]), and procedure 2 processed the number of incident lidar beams and their path in the voxel following the method suggested by [4] to estimate the PAD for every voxel. These procedures both required defining a minimum number of lidar beams entering the voxel. After several preliminary tests, we set the threshold at ten. This allowed processing voxels with moderate beam occlusion, but not voxels severely occluded. The second step of the method involved assigning missing value for voxels severely occluded with at least one return but less than 10 lidar beams crossing them. All these voxels were assigned with the average PAD value of the corresponding voxels located within a 1-m slice in height (z).

Error estimation: The simulated scenes with L-Architect provided an exact account considered as the reference values of PAD and LAD (Leaf Area Density). It was therefore possible to use that information to compare the reference vertical profiles from the ones of the simulated scenes produced from the TLS-simulated datasets. Differences between vertical profiles quantified the impact of beam occlusion and object oversampling. Then, the reference PAD values of all scenes could be compared with the results from each step of the two-steps method. Lastly, the two-step method was adapted to process only returns associated with foliage. This allowed comparing how the two-step method could also be used to produce realistic spatial LAI distribution of a forest scene. Overall the error estimation quantified the error of the two-step method to process TLS point clouds for its ability to provide exact distribution of forest components, expressed in PAD and LAI.

Results and Discussion

Preliminary results suggest that the two-step method corrects the raw TLS data for the impact of beam occlusion and object oversampling by at least 95%. When vegetation density was assessed directly from point frequencies of raw TLS point clouds, most profiles showed important differences with the reference and the normalized profiles of the simulated scenes. For example, the peak of point density for the TLS-simulated data occurs mostly at 4 to 5 m below the one from the simulated scenes. This concurs with the general hypothesis that TLS returns tend to overestimate the quantity of component area on the lower part of the canopy and understorey (closer to the sensor) and underestimate this quantity in the upper part of the canopy [1] (Fig 1). Applying the first step of the method already improved greatly the normalized vertical profiles compared from the raw TLS data by repositioning the vertical maximum close to the one provided by the reference. Similarly, applying the first step of the method also improved greatly the general shape of the vertical profile compared to the raw TLS data with the reference values (Fig 1). Both the position of the maximum and the parametrized shape of the vertical profile are being improved to a 90% match or better for four varied scenes we tested so far. Furthermore, applying the second step of the method improved even more the results with a match reaching and beyond 95% for the tested scenes (Fig 1). These encouraging results will be further tested on twelve scenes and documented to assess the limitations of the methods. However, the preliminary results over four diversified scenes indicated that the two-step method is a good way to preprocess raw TLS data of forest scenes to recover the exact distribution of components through the PAD and LAD. We plan to implement these procedures in Computree (http://computree.onf.fr), an open source web platform to process TLS data. The two-step method will therefore be potentially useful to deal with signal occlusion and oversampling, but it will need to be adapted to specific sensors and for other forest scene configurations yet not tested.

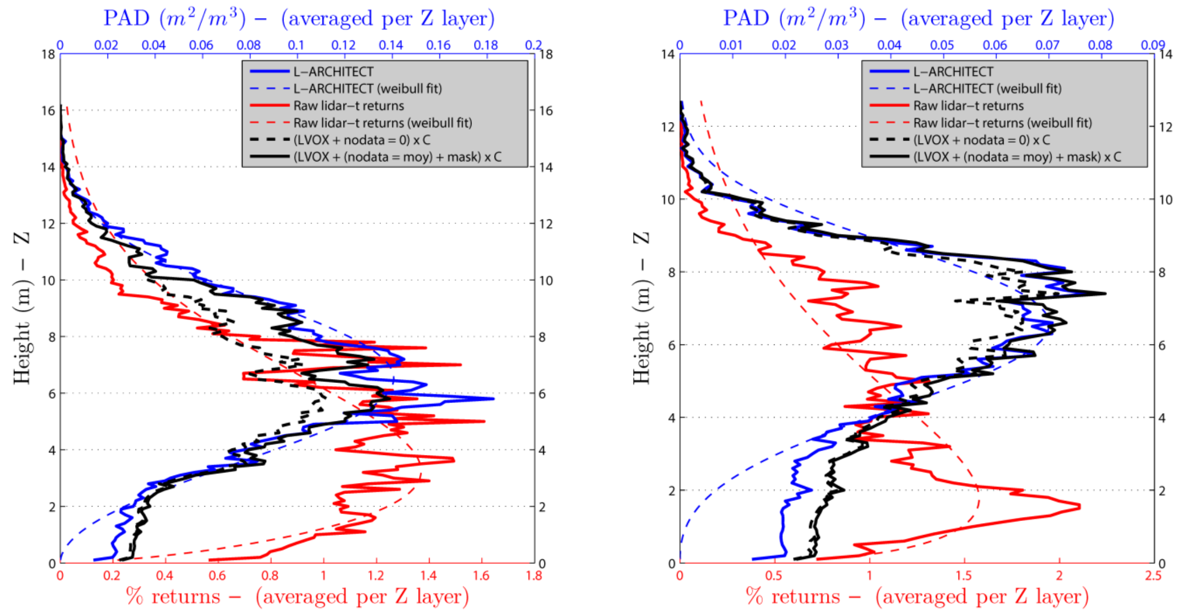

Figure 1. Four vertical profiles for two forest scenes simulated with 10 cm voxels: (blue line) the reference values in PAD from the simulated scenes with L-Architect, (red line) the raw TLS-simulated data normalized (density values) of the forest scenes, (dotted black line) the normalized values (density values) resulting from the first step of the method and (solid black line) the normalized values (% returns) from the two steps of the method.

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