EFFECTS OF CLUMPING ON MODELLING LIDAR WAVEFORMS IN FOREST CANOPIES

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ABSTRACT
Empirical relations are frequently used to derive leaf area index (LAI). Such relations often make assumptions that make it hard to link the derived LAI to realistic trees and forest canopies. In previous work we developed a set of analytical expressions to describe LiDAR waveforms with only a limited number of assumptions based on radiative transfer. These expressions were a function of crown macro-structure and LAI. The expressions were successfully tested when applied on crown archetypes, but showed significant error when applied to more realistic crowns. In this study, we analyse the effect of clumping on inferring LAI from realistic trees. Despite the potential of the expressions to detect subtle changes in LAI, absolute inferred LAI values can be significantly off. However, the strong correlation between true and inferred LAI ($R^2 > 0.97$) for the two test cases in this study, allows for calibration of the inferred LAI values.

Index Terms— LiDAR waveforms, radiative transfer, canopy structure, LAI, clumping

1. INTRODUCTION
Leaf area index (LAI) is an important structural parameter in forest ecosystems. LAI closely relates to several biological and physical processes such as respiration, transpiration, photosynthesis, carbon and nutrient cycle and rainfall interception.

LiDAR (light detection and ranging) is an active remote sensing technique that can measure something approximating the retroreflectance as a time or distance resolved signal. LiDAR is therefore an excellent technique to assess forest structure and the three-dimensional distribution of plant canopies [1, 2]. Large footprint LiDAR has the potential to infer forest structural information related to the physical characteristics of the trees. This is in contrast with the more commonly used empirical relations, which often make assumptions that make it hard to relate the inferred structural parameters to realistic forest canopies. Two types of LiDAR systems are commonly used: discrete return LiDAR and waveform LiDAR. Discrete return LiDAR measures only a limited number of pulses returning from a particular object. Waveform LiDAR digitises the whole of the return signal and it can therefore provide additional information about the structure of vegetation.

2. MODELLING LIDAR WAVEFORMS
Modelling LiDAR waveforms is important to understand the effects of forest structure on deriving biophysical parameters. Previous studies on complex modelling approaches for LiDAR waveforms mainly focused on understanding some of the influences on the LiDAR waveform. [3] presented a 3D model for simulating LiDAR waveforms over forest stands. Their results demonstrated that LiDAR waveforms contain information of both horizontal and vertical structure of forest canopies. [4] introduced a time-dependent stochastic radiative transfer theory, which allowed for a more realistic description of clumping and gaps. [5] used a hybrid geometric optical and radiative transfer model (GORT) to understand LiDAR waveforms with respect to canopy structure and validated their results using SLICER data.

In [6] we looked at single tree LiDAR waveforms in an effort to understand the information content of such LiDAR signals. The relation between canopy structure and LiDAR was studied and quantified in the nadir direction. We returned to a limited number of assumptions based on radiative transfer. These assumptions included crown archetypes, constant leaf area density throughout the crown and first order scattering. We developed a new set of analytical expressions to describe
LiDAR waveforms and tested these against numerically simulated waveforms (wavelength 1064 nm) using an explicit 3D radiative transfer model. The librat Monte Carlo ray tracing model was used. This model is based on the ararat/drat MCRT model [7]. The expressions for three archetype crowns (i.e. cuboids, cones and spheroids) were derived based on the radiative transfer solution for single order scattering in the optical case and are a function of crown macro-structure and leaf area index (LAI). The analytical expressions were inverted against both the original and the cumulative LiDAR waveform. CV(RMSE) of fit between the analytical expressions and the simulated waveforms over archetype trees ranged from 21.2% to 0.3% and the absolute prediction error for LAI was 7.1% for cuboid archetypes, 18.6% for conical archetypes and 4.5% for spheroid archetypes.

3. EFFECTS OF CLUMPING ON LIDAR WAVEFORMS OF REALISTIC FOREST CANOPIES

The spatial arrangement of scattering elements in the canopy plays an important role in radiation transmission. Scattering elements can either be completely randomly distributed (as assumed in [6]) or clumped. Realistic forest canopies show a hierarchical clumping structure and all these levels of clumping contribute to heterogeneity of laser pulses propagating in the crown [8]. Applying the analytical expressions to more realistic 3D representations of broadleaved deciduous (birch) and evergreen needle-leaved (Sitka spruce) tree models indicated that ignoring clumping and gaps can have a significant impact on the performance of waveform inversion of real trees [6]. Consequently, inversion methods can be deceptive due to departure of real crowns (clumped) from archetypes (not clumped). Many of the existing applications in airborne laser scanning use some sort of assumption of crown archetype [5, 9, 10, 11]. The archetype crowns used in these studies did not account for clumping. Although the assumption of a crown archetype will provide a result, it can potentially be misleading when the real crowns depart from the archetypes. This is illustrated for a realistic 3D birch representation in fig. 1. The effect of clumping is clearly visible in the original LiDAR waveform. The cumulative waveform is more robust and hence less affected by clumping. The evaluation statistics in table 1 show that significant clumping means that the assumption of constant leaf area density is severely violated, so it is not surprising that results are poor. We need to account for canopy gaps when using the analytical equations because not only is the number density of leaves important, so too are the consequences of finite sized gaps that are present in the canopy [12]. The canopy of a tree can thus be seen as a binary medium consisting of aggregations of leaves distributed in free space. Leaves generally appear in the space around branches and hierarchical clumping is therefore dependent on the natural plant stand.

In this paper, we will look at how clumping in realistic crowns influences inferring LAI from large footprint LiDAR waveforms of single trees. We will evaluate the analytical expressions described in [6] and:

1. Analyse the effect of clumping on inferring LAI from realistic trees; and

2. Discuss their potential practical use in large scale monitoring applications.

Here, we used two species of broadleaved trees to analyse the clumping effect: birch (Betula pendula) and eucalyptus (Eucalyptus fraxinoides). We used the OnyxTREE© software (www.onyxtree.com) to derive the three-dimensional
tree models. The trees were then pruned from 100% to 0% leaves in steps of 10%. The pruning was done randomly throughout the canopy and this resulted in a series of 11 trees per species. These trees have the same tree macro-structure, but different amounts of leaves. LAI is defined as the one-sided area of leaf surface per unit ground surface area and true LAI values for each generated tree were calculated.

For each of these generated trees we inferred the LAI based on the inversion methodology described in [6]. First, we simulated the LiDAR waveforms using the librat Monte Carlo ray tracing model. The simulated waveforms were then compared against the analytical expression. LAI is inferred from the waveforms by inversion of the analytical expressions using the Levenberg-Marquardt algorithm and evaluated by the coefficient of variation of the root mean squared error, CV(RMSE), and the absolute prediction error (APE).

### 4. RESULTS & DISCUSSION

Fig. 2 shows the relation between true and inferred LAI for birch and eucalyptus. Based on the evaluation statistics, only the results from the spheroid and cuboid inversion are shown. The spheroid inversion fits best for both tree species. Compared to the spheroid inversion, the goodness of fit for the cuboid inversion is only a few percent less for the eucalyptus trees, but can be up to 25% less for the birch trees. The better fit with the spheroid expressions was consistent throughout the whole tree series and indicates that the tree macro-structure defines which analytical expressions fit best.

Results show that the absolute inferred LAI values can be significantly wrong. However, the relation between true and inferred LAI shows a linear trend. Inferred LAI values from the spheroid inversion show a larger range with respect to true LAI than the cuboid inversion. Linear regression applied on the whole tree series showed a minimum $R^2$ value of 0.93 for birch and 0.74 for eucalyptus. After removal of the 100% pruning value, the minimum $R^2$ value increased to 0.98 for birch and 0.97 for eucalyptus. Removing the 100% pruning value is a reasonable assumption because the derivation of the analytical expressions was based on leaf presence in the crown. Given the high $R^2$ values of the linear relations, calibration functions for a specific tree species can potentially be created to infer true LAI from LiDAR waveforms. These consistent inversion results suggest that the analytical expressions can be used to pick up subtle changes in LAI in a single tree. Future work should consider environment and system noise to get realistic estimates of error. Different types of change may also lead to less consistent results when LAI is inferred from the waveform. Such changes could be non-random removal of foliage from the crown, spectral changes in foliage or the death but not removal of leaves in the crown. A better understanding of these influencing factors will lead to a better understanding of the the potential use of large footprint LiDAR in monitoring applications.

It is important to note that the analytical expressions are derived for large footprint LiDAR over a single tree crown whereby the full horizontal extent of the crown is covered by the footprint. Further work should focus on exploring how these analytical expressions can be applied in real forests (i.e. multiple trees). We expect that the resulting waveform will be the summation of the waveforms of the individual trees, and therefore their shape might become less distinct. This could be solved by re-sampling smaller footprint LiDAR to mimic large footprint waveforms over single trees. This would depend on how reliable trees could be identified and isolated, but also on the forest type. Trees could be isolated more easily in open environments (e.g. savanna), but it will be harder to isolate trees in denser forest types (e.g. rainforest). More complex forest types such as rainforest also have multiple vertical strata: tree and shrub crown are present in one footprint. This suggests the need for a more robust method to delimit the correct tree crown signal within the waveform.

### 5. CONCLUSION

In this paper, the effect of clumping on inferring LAI from LiDAR waveforms of realistic trees is presented. We showed that waveform inversion is consistent for varying leaf area densities and analytical expressions can be used to detect subtle changes in LAI in single trees. The absolute values of the inferred LAI can be significantly off, but the linear relation ($R^2 > 0.97$) between true and inferred LAI allows for calibration of the inferred values.

### Table 1. Evaluation statistics for a realistic 3D birch representation: inferred LAI, coefficient of variation of the RMSE [CV(RMSE)] and absolute prediction error [APE]. True LAI was 4.4. Results for the conical inversion are omitted from the table due to unrealistic absolute prediction errors (APE > 10^4%) (modified from [6], birch: case 2)

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<th>Cuboid inversion</th>
<th>Spheroid inversion</th>
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<tr>
<td></td>
<td>Original</td>
<td>Cumulative</td>
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<tr>
<td>Inferred LAI</td>
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<td>APE [%]</td>
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Fig. 2. Regression between true LAI and inferred LAI from LiDAR waveform inversion. (left panel) birch; (right panel) eucalyptus.

6. REFERENCES


