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Investigating assumptions of crown archetypes for modelling LiDAR returns

Kim Calders [a,*], Philip Lewis [b], Mathias Disney [b], Jan Verbesselt [a], Martin Herold [a]

[a] Laboratory of Geo-Information Science and Remote Sensing, Wageningen University, Droevendaalsesteeg 3, Wageningen 6708 PB, The Netherlands
[b] Department of Geography, University College London, Gower Street, London WC1E 6BT, UK

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ABSTRACT

LiDAR has the potential to derive canopy structural information such as tree height and leaf area index (LAI), via models of the LiDAR signal. Such models often make assumptions regarding crown shape to simplify parameter retrieval and crown archetypes are typically assumed to contain a turbid medium to account for within-crown scattering. However, these assumptions may make it difficult to relate derived structural parameters to measurable canopy properties. Here, we test the impact of crown archetype assumptions by developing a new set of analytical expressions for modelling LiDAR signals. The expressions for three crown archetypes (cuboids, cones and spheroids) are derived from the radiative transfer solution for single order scattering in the optical case and are a function of crown macro-structure (height and crown extent) and LAI. We test these expressions against waveforms simulated using a highly-detailed 3D radiative transfer model, for LAI ranging from one to six. This allows us to control all aspects of the crown structure and LiDAR characteristics. The analytical expressions are fitted to both the original and the cumulative simulated LiDAR waveforms and the CV(RMSE) of model fit over archetype trees ranges from 0.3% to 21.2%. The absolute prediction error (APE) for LAI is 7.1% for cuboid archetypes, 18.6% for conical archetypes and 4.5% for spheroid archetypes. We then test the analytical expressions against more realistic 3D representations of broadleaved deciduous (birch) and evergreen needle-leaved (Sitka spruce) tree crowns. The analytical expressions perform more poorly (APE values up to 260.9%, typically ranging from 39.4% to 78.6%) than for the archetype shapes and ignoring clumping and lower branches has a significant influence on the performance of waveform inversion of realistic trees. The poor performance is important as it suggests that the assumption of crown archetypes can result in significant errors in retrieved crown parameters due to these assumptions not being met in real trees. Seemingly reasonable inferred values may arise due to coupling between parameters. Our results suggest care is needed in inferring biophysical properties based on crown archetypes. Relationships between the derived parameters and their physical counterparts need further elucidation.

1. Introduction

Forest structure plays an important role in forest ecosystems. Leaf area index (LAI) is a meaningful structural parameter, since several biological and physical processes are related to the total leaf surface. For example, photosynthesis, respiration, transpiration, carbon and nutrient cycles, and rainfall interception are functions of forest structure and LAI.

Active sensors such as LiDAR (light detection and ranging) can measure something approximating retroreflectance as a time or distance resolved signal over forest canopies. LiDAR therefore can serve as an excellent tool to assess forest structure and the three-dimensional distribution of plant canopies (Koch et al., 2006; Lefsky et al., 1999; Nelson, 1997; Vauhkonen et al., 2009). Although many studies have examined the possibilities that LiDAR offers in structure assessment, little work has been conducted on quantitative LiDAR data interpretation, i.e. relating the LiDAR signal to the fundamental principles governing the scattered signal. Barbier et al. (2011) studied how canopy structure interacts with physical signals (light) at forest stand level. However, a better understanding of the physical underpinnings of light interaction with canopy structure at tree level is needed, for example, to optimise fusion with optical and LiDAR data. In this study, we will therefore look at single tree LiDAR signals in an effort to understand the information content of such LiDAR signals. Here, the relationship between LiDAR and vegetation structure is studied and quantified in the nadir direction.

Many LiDAR studies are based on the assumptions of crown archetypes and some examples are listed in Table 1. Ferraz et al. (2012), Riaño et al. (2004), Lim et al. (2003) and Ni-Meister et al. (2001) assumed ellipsoidal crowns. North et al. (2010) and Wang and Glenn (2008) used both conical and ellipsoidal crown shapes to characterise the crown. Goodwin et al. (2007) described crowns as hemi-ellipsoids and Koetz et al. (2007) also assumed crowns were shaped as hemi-ellipsoids when simulating large footprint LiDAR over simulated forest stands. Hyde et al. (2005) used four archetypes to characterise the trees in their study area: elliptical, umbrella-shaped, conical and cylindrical. They used vegetation type as a proxy for crown shape, e.g. stands of

* Corresponding author. Tel.: +31 317 485257; fax: +31 317 419000.
E-mail address: kim.calders@wur.nl (K. Calders).

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Table 1
Examples of LiDAR studies using crown archetypes.

Reference	Crown archetype
Ferraz et al. (2012)	Ellipsoidal
North et al. (2010)	Ellipsoidal & Conical
Wang and Glenn (2008)	Ellipsoidal & Conical
Koetz et al. (2007)	Hemi-ellipsoidal
Goodwin et al. (2007)	Hemi-ellipsoidal
Hyde et al. (2005)	Elliptical, Umbrella-shaped, Conical & Cylindrical
Riaño et al. (2004)	Ellipsoidal
Lim et al. (2003)	Ellipsoidal
Ni-Meister et al. (2001)	Ellipsoidal
Sun and Ranson (2000)	Ellipsoidal, Conical & Hemi-ellipsoidal

pure red fir were assumed to be conical or pointed, while deciduous crowns were assumed to be more rounded. Sun and Ranson (2000) modelled crown shapes as cones, ellipsoids and hemi-ellipsoids. Kato et al. (2009) did not make assumptions about some sort of archetype but used a wrapped surface reconstruction approach based on the LiDAR point cloud to generate the crown shape. A common approach to describe the distribution of foliage within archetype crowns is to use a turbid medium model, which assumes a constant leaf area density throughout the crown (Koetz et al., 2007; North et al., 2010; Sun & Ranson, 2000).

Earlier work on complex modelling approaches for LiDAR waveforms mainly focused on understanding some of the influences on the waveform. Sun and Ranson (2000) presented a 3D model for simulating LiDAR waveforms from forest stands. Their results showed that LiDAR waveforms are an indication of both horizontal and vertical structures of forest canopies. Kotchenova et al. (2003) introduced a time-dependent stochastic radiative transfer theory, which allowed for a more realistic description of clumping and gaps. Ni-Meister et al. (2001) used a hybrid geometric optical and radiative transfer model (GORT) to interpret the LiDAR waveforms with respect to canopy structure and validated their findings using SLICER data. Gap probability was identified as the most important link between canopy structure and modelling LiDAR waveforms. LiDAR simulations in Blair and Hofton (1999) suggested that multiple scattering in vegetation canopies did not contribute significantly to the LiDAR waveform shape and several other LiDAR modelling studies also assumed single scattering only (Goodwin et al., 2007; Ni-Meister et al., 2001; Sun & Ranson, 2000).

Empirical relationships often make assumptions, which lead us away from the fundamental scattering properties, making it hard to relate the derived structural parameters to real canopies. In this study we return to a limited number of assumptions based on radiative transfer (RT). These assumptions are: crown archetypes, constant leaf area density throughout the crown and first order scattering. We adopt these widely-used assumptions in order to quantify their impact in deriving canopy parameters from LiDAR observations. We address the question of whether simple crown archetype assumptions can be used to model LiDAR scattering. If these assumptions hold up, analytical expressions for LiDAR scattering would be preferred over empirical relationships, because those analytical solutions will allow retrieval of crown parameters that are physically interpretable. If such crown archetype assumptions are shown not to be valid, the analytical expressions will give insight into why this is and what implications this will have for inverting LiDAR signals using these assumptions. The main objectives of this paper are:

1. The derivation of analytical formulae that express LiDAR reflectivity as a function of crown macro-structure parameters and crown leaf area density for a nadir configuration;
2. The testing of these formulae against realistic LiDAR simulations; and
3. The quantification of impact of crown archetype assumptions on retrieval of LAI.

Such formulae, for single trees, are potentially of great value themselves for understanding and deriving information. Solving for canopy properties using analytical expressions allows crown structure to be extracted from LiDAR waveforms. We present analytical expressions for a nadir configuration obtained by solving the 3D integral for photon transport in a specific envelope crown shape. We test these expressions by comparison with realistic LiDAR simulations of which all variables are known. Various 3D tree models are created, which conform to the assumptions underlying our analytical expressions. LiDAR signals from these crowns are simulated using a Monte Carlo ray tracing radiative transfer model. In this way, we can control all aspects of the crown structure and the (simulated) signal properties, which would not be possible using measured LiDAR data. Trees with simple archetype crown shapes are analysed first to fully understand these waveforms. More realistic representations of broadleaved deciduous (birch) and evergreen needle-leaved (Sitka spruce) trees are then considered, which we use to elucidate some of the more interesting aspects of when and why simple models might fail. Finally, we discuss the likely impact of assumptions of crown archetypes on interpreting LiDAR signals and we outline ways in which these impacts can be quantified. This work is of importance due to the increasing requirement for accurate, physically-realistic retrieval of canopy parameters from LiDAR data.

2. Methods

2.1. Describing LiDAR reflectivity as a function of tree structure

In this section, we derive analytical formulae to describe LiDAR reflectivity as a function of different structural tree parameters for a nadir configuration. We use an approach based on the solution to the scalar radiative transfer equation for a plane parallel medium, which assumes vertical homogeneity within canopy layers and Lambertian scattering from objects. We then adjust the solution for the standard case for vertical heterogeneity inside the canopy. As a result, we can describe light passing through archetype crown shapes as cuboids, cones and prolate spheroids (hereafter referred to as spheroids). Several LiDAR studies (Goodwin et al., 2007; Ni-Meister et al., 2001; Sun & Ranson, 2000) assumed single scattering only and LiDAR simulations over vegetation canopies in Blair and Hofton (1999) suggested that there was no significant contribution of multiple scattering to the LiDAR waveform shape. We tested that for a spheroid archetype more than 98.5% of the returned LiDAR reflectance was coming from the first order scattering when there was a single tree in the LiDAR footprint. Testing over a canopy with multiple trees in the LiDAR footprint showed a first order scattering domination of 91.1%. All tests were done at wavelength of 1064 nm for plate leaf crowns using the *librat* radiative transfer model with settings specified in Section 2.2.2. It is therefore a reasonable assumption to only consider first order scattering (i.e. only one interaction with soil or canopy elements) in this study.

2.1.1. A solution to the scalar radiative transfer equation for a LiDAR signal

The solution for first order scattering in the optical case is used to reconstruct the LiDAR waveform over a plane parallel canopy medium theoretically (see Fig. 1). If Ω_s is the direction of scattering and Ω_0 the direction of the incident LiDAR pulse then $I(\Omega_s, z)$ is the received single scattering energy by the sensor at depth z in direction Ω_s over a plane parallel canopy.

$$
\begin{aligned}
I(\Omega_s, z) = {} & e^{\frac{-\kappa_e(\Omega_s)(z-(-H))}{\mu_s}} \rho_{soil}(\Omega_s, \Omega_0) e^{\frac{-\kappa_e(\Omega_0)(-H)}{\mu_0}} I_0 d(\Omega_s - \Omega_0) \\
& + \frac{I_0}{\mu_s} \int_{Z=-H}^{Z=z} e^{\frac{-\kappa_e(\Omega_s)(z-Z)}{\mu_s}} e^{\frac{\kappa_e(\Omega_0)Z}{\mu_0}} P(\Omega_0 \rightarrow \Omega_s) dZ
\end{aligned}
\tag{1}
$$

I_0 refers to the incident radiation intensity on top of the canopy. The volume scattering phase function is defined as $P(\Omega_0 \rightarrow \Omega_s) =$