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Simulating the impact of discrete-return lidar system and survey characteristics over young conifer and broadleaf forests

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ABSTRACT

We present a model-based investigation of the effect of discrete-return lidar system and survey characteristics on the signal recorded over young forest environments. A Monte Carlo ray tracing (MCRT) model of canopy scattering was used to examine the sensitivity of model estimates of lidar-derived canopy height, h_{lidar} to signal triggering method, canopy structure, footprint size, sampling density and scanning angle, for broadleaf and conifer canopies of varying density. Detailed 3D models of Scots pine (*Pinus sylvestris*) and Downy birch (*Betula pubescens*) were used to simulate lidar response, with minimal assumptions about canopy structure. Use of such models allowed the impact of lidar parameters on canopy height retrieval to be tested under a range of conditions typically not possible in practice. Retrieved h_{lidar} was generally found to be an underestimate of 'true' canopy height, h_{canopy}, but with exceptions. Choice of signal triggering method caused h_{lidar} to underestimate h_{canopy} by ~4% for birch and ~7% for pine (up to 66% in extreme cases). Variations in canopy structure resulted on average in underestimation of h_{canopy} by 13% for birch and between 29 and 48% for pine depending on age, but with over-estimates in some cases of up to 10%. Increasing footprint diameter from 0.1 to 1 m increased retrieved h_{lidar} from significant underestimates of h_{canopy} to values indistinguishable from h_{canopy}. Increased sampling density led to slightly increased values of h_{lidar} to close to h_{canopy}, but not significantly. Increasing scan angle increased h_{lidar} by up to 8% for birch, and 19% for pine at a scan angle of 30°. The impact of scan angle was greater for conifers as a result of large variation in crown height. Results showed that interactions between physically modelled (hypothetical) within canopy returns are similar to findings made in other studies using actual lidar systems, and that these modelled returns can depend strongly on the type of canopy and the lidar acquisition characteristics, as well as interactions between these properties. Physical models of laser pulse/canopy interactions may provide additional information on pulse interactions within the canopy, but require validation and testing before they are applied to actual survey planning and logistics.

1. Introduction

During the last few years airborne laser scanning became a common technique to obtain stand or individual tree height information (Næsset, 1997a; Magnussen and Boudewyn, 1998; St-Onge, 1999; Næsset and Bjerknes, 2001; Lim et al., 2001; Persson et al., 2002; St-Onge et al., 2003; Hollaus et al., 2006). Canopy height (at the stand or tree scale) is a very important forest parameter due to its statistical connection with other biometric variables (Ketterings et al., 2001; Brown, 2002). As a result, lidar data have been increasingly employed to aid derivation of other forest stand variables such as basal area, stem volume, forest growth rate and biomass (Næsset, 1997b; Næsset, 2005; Nelson et al., 1988a,b, 1997; Schardt et al., 2002; Popescu et al., 2003; Yu et al., 2004a; Næsset and Gobakken, 2005; Hopkinson et al., 2008). The majority of commercial lidar instruments are generally mounted on fixed-wing or helicopter platforms and utilise the discrete-return logic i.e. a small number of returns is used to down-sample the dominant reflections, usually the first and last-returns. This is in contrast to full-waveform instruments where the lidar return is sampled at high frequency, providing much greater information on the vertical profile of the returned signal. Baltsavias (1999) provides a comprehensive review of the lidar systems available at that time. While full-waveform capability lidar systems have increased in number and are an important development, recent progress has typically been aimed at producing finer point spacing

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and increased temporal sampling of the first/last return signal, rather than full-waveform capability. Other improvements in lidar technologies include greater storage capacities and improved positional accuracy (Lim et al., 2003).

Most discrete-return lidar studies of vegetation have tended to use empirical, semi-empirical or statistical relationships between lidar returns and tree-level or forest stand-level parameters (Lefsky et al., 1999; Holmgren et al., 2003; McCombs et al., 2003; Riaño et al., 2003). Often in such studies, lidar system characteristics such as scan angle, footprint size, signal triggering threshold, variations in canopy structure etc. are not accounted for and are ignored (Brandtberg et al., 2003; Riaño et al., 2003; Zimble et al., 2003; Koetz et al., 2007), or included implicitly through the expression of lidar canopy height as percentile values. Even where the impact of 3D canopy structural information is considered explicitly in examining the lidar signal, this tends to take the form of statistical distributions in a 3D 'voxel' space of parameters such as leaf area index (LAI) and leaf angle distribution (LAD) (Houldcroft et al., 2005), or via the use of simple geometric primitives representing individual tree crowns, with some statistical description of extinction within and between tree crowns (Sun and Ranson, 2000; Goodwin et al., 2007). Other studies have used region-growing methods to explore the impact of canopy structure on lidar returns at the individual tree-level (Hyyppä et al., 2001). The problem in all these cases lies in deciding what the appropriate 'equivalent' structural parameters (LAI, LAD, extinction coefficient etc.) should be for a given canopy. Hopkinson and Chasmer (2009) showed the impacts of canopy structure and system characteristics on estimates of canopy cover from discrete-return lidar. Lefsky et al. (2002) review issues of canopy structure (in particular the vertical and horizontal amount and distribution of vegetation) on the lidar signal, particularly for ecosystem applications.

Over the past 10–15 years, various studies have been carried out to assess the impact of lidar system and survey characteristics. Næsset (2009a) provides perhaps the most comprehensive attempt to quantify the impact of such effects practically, through a comparison of lidar returns from two different instruments at different flying altitudes and pulse repetition frequencies (PRFs). Yu et al. (2004a,b) studied the effect of flight altitude on the number of detected trees and on the estimation of tree height. The results suggest that increasing the flight altitude increases underestimation of tree height, and that pulse density is a crucial factor for tree height measurements (although this effect was not separated from the impact of using different pulse densities at different altitudes). In a similar study, Hirata (2004) examined footprint diameter (via changing altitude) in mountainous terrain and found that retrieved height increased with increasing footprint size. Hirata (2004) also studied different sampling density by subsampling existing data and showed the rate of extraction of treetops increased with sampling density. Maltamo et al. (2004) examined bias in estimating timber volume caused by footprint size.

Næsset (2004) found that first-pulse lidar returns did not vary much regardless of flight altitude/footprint diameter for footprints ranging between 16 and 26 cm, and that last-pulse returns were more sensitive to variations in footprint diameter. Goodwin et al. (2006) examined how canopy height profiles were affected when platform altitude was increased from 1000 to 3000 m (footprint size increased from 0.2 to 0.6 m) and found no significant differences. However, point spacing (i.e. PRF or sampling density) inferred from survey details was found to strongly affect retrieved attributes of individual trees, particularly height and canopy structure. Chasmer et al. (2006a,b) showed that PRF is associated with the ability of laser pulses to penetrate the canopy. Næsset (2009a) confirmed a general tendency of retrieved canopy height distribution to be shifted upwards when reducing PRF from 100 kHz to 50 kHz. Hopkinson et al. (2006) attempted to reduce the effects of lidar survey configuration on empirical lidar-derived canopy height estimates. Hopkinson (2007) used multiple surveys to examine the impact of altitude, beam divergence and PRF on pulse return intensity (and height distribution) for different vegetation canopies. Reducing peak laser pulse power (by increasing altitude, beam divergence or PRF) reduced penetration into short canopies, while increasing penetration slightly into tall canopies, where foliage tended to have slightly lower leaf area density. Hopkinson (2007) emphasises the need to account for system and survey-specific variations in peak pulse power as far as possible in order to make different lidar surveys more directly comparable and proposes an empirical correction for systematic biases. Hopkinson (2007) also suggests that if such variations cannot be accounted for directly, their impact should be estimated via sensitivity analysis.

The different technical specifications (and environmental impacts) among different surveys, and interdependencies between some of the parameters being investigated, make it difficult to generalise the impacts of system characteristics on the retrieval of canopy structural parameters, as noted by Hopkinson (2007). For example, platform altitude controls both lidar point spacing and footprint size (beam divergence), for fixed PRF; any alteration of altitude will change both point spacing (across track) and footprint size. Even for lidar points scanned from the same altitude, far-range (maximum off-nadir scan angle) points have larger footprints than those at nadir due to projection effects on the instantaneous field of view (IFOV). One method to separately investigate the effects of sampling density and footprint size is to apply thinning to the original lidar data in either a systematic (Yu et al., 2004a), random (Goodwin et al., 2006), or semi-random (Gobakken and Næsset, 2008) manner to keep a constant sampling density in order to make unbiased comparisons. Another method is to generate a reference survey, against which other surveys with varying properties can be normalised (Hopkinson, 2007).

In scanning lidar systems the scan angle can vary significantly across survey regions. Despite this, biases introduced by this angle variation are rarely considered as a source of information, or quantified (Hopkinson, 2007). Increasing scan angle tends to overestimate the mean, area-averaged canopy height, h_{canopy}, in empirical estimators of height from lidar, due to seeing a larger proportion of higher points in the canopy (Næsset, 1997a). However, the increased path length at greater scan angles will tend to cause greater attenuation of the signal, resulting in fewer ground returns, particularly in dense canopies (Lovell et al., 2005). Also, technical/electronic specifications (e.g. mono- or dual-receiver systems, scanning pattern, signal triggering method etc.) differ among airborne laser scanners (ALS), influencing the inter-comparability of lidar datasets acquired by various systems (Næsset, 2009a). Even ambient temperature and the hours of operation can introduce variations in the power of the laser (Moffiet et al., 2005).

In addition to the use of controlled lidar surveys, there have been studies of the impact of lidar instrument characteristics using 3D simulation models. The main advantage of this approach is that the effect of various lidar parameters can be studied independently across a wide range of parameter values and canopy scenarios in such a way that would prove prohibitively expensive, or technically difficult for a real lidar survey. Simulation studies can also be a valuable tool to improve understanding of the limits of parameter retrieval from lidar data, particularly if combined with knowledge gained from empirical surveys. Using a geometrical forest model, Lovell et al. (2005) found that lidar height retrieval is less accurate at the edge of a swath due to uneven spacing of the sample points. Holmgren et al. (2003) used a geometric forest model to study the effects of lidar scanning angle on the proportion of canopy returns and height percentiles. The results showed that the two metrics varied with increased scanning angle, especially for long crown species. However, they used solid geometric objects (half-ellipsoids) to represent 'trees' and the lidar signal was modelled without divergence (i.e. using a parallel beam). These assumptions (particularly the first) will have potentially important