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# Waveform lidar over vegetation: An evaluation of inversion methods for estimating return energy

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ABSTRACT

Full waveform lidar has a unique capability to characterise vegetation in more detail than any other practical method. The reflectance, calculated from the energy of lidar returns, is a key parameter for a wide range of applications and so it is vital to extract it accurately. Fifteen separate methods have been proposed to extract return energy (the amount of light backscattered from a target), ranging from simple to mathematically complex, but the relative accuracies have not yet been assessed. This paper uses a simulator to compare all methods over a wide range of targets and lidar system parameters. For hard targets the simplest methods (windowed sum, peak and quadratic) gave the most consistent estimates. They did not have high accuracies, but low standard deviations show that they could be calibrated to give accurate energy. This may be why some commercial lidar developers use them, where the primary interest is in surveying solid objects. However, simulations showed that these methods are not appropriate over vegetation. The widely used Gaussian fitting performed well over hard targets (0.24% root mean square error, RMSE), as did the sum and spline methods (0.30% RMSE). Over vegetation, for large footprint (15 m) systems, Gaussian fitting performed the best (12.2% RMSE) followed closely by the sum and spline (both 12.7% RMSE). For smaller footprints (33 cm and 1 cm) over vegetation, the relative accuracies were reversed (0.56% RMSE for the sum and spline and 1.37% for Gaussian fitting). Gaussian fitting required heavy smoothing (convolution with an 8 m Gaussian) whereas none was needed for the sum and spline. These simpler methods were also more robust to noise and far less computationally expensive than Gaussian fitting. Therefore it was concluded that the sum and spline were the most accurate for extracting return energy from waveform lidar over vegetation, except for large footprint (15 m), where Gaussian fitting was slightly more accurate. These results suggest that small footprint ($\ll$15 m) lidar systems that use Gaussian fitting or proprietary algorithms may report inaccurate energies, and thus reflectances, over vegetation. In addition the effect of system pulse length, sampling interval and noise on accuracy for different targets was assessed, which has implications for sensor design.

## 1. Introduction

Lidar has been shown to be a valuable tool for characterising vegetation, offering many advantages over other techniques due to its non-destructive measurement of structural and spectral information (Dubayah & Drake, 2005). Maps of global forest height have been determined from the spaceborne ICESat (Harding & Carabajal, 2005; Los et al., 2012), forest cover can be accurately derived from airborne lidar without the need for site-specific calibration (Armston et al., 2013), airborne lidar's structural information improves land cover classification accuracy (Mallet, Bretar, Roux, Soergel, & Heipke, 2011), airborne and terrestrial laser scanners (TLS) have also been used to characterise vegetation canopies and their effect on hydrological processes (Musselman, Margulis, & Molotch, 2013; Reid et al., 2014) and TLS can accurately measure woody volume (Raumonen et al., 2013), potentially allowing rapid biomass measurement. All of these studies rely on accurately extracting target properties from lidar signals.

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Lidar directly measures the 3D distribution of energy reflected from a target surface. The vast majority of research has focused on determining the range to a single feature (Stilla & Jutzi, 2008; Wagner, Ullrich, Melzer, Briese, & Kraus, 2004), with very few studies assessing the accuracy of the estimated return energy (backscattered radiation from the target). Recent research has tried to identify targets through clutter, such as the ground surface under vegetation (Jalobeanu & Gonçalves, 2014; Los et al., 2012), but they still assumed that there was a hard feature that lay at a single range. Commercial lidar systems have been optimised to measure the range to hard features.

The return energy contains useful information about complex targets, such as vegetation. The amount of energy returned can be used to calculate the size of illuminated objects (Hancock et al., 2014; Ramirez, Armitage, & Danson, 2013) and determine canopy cover (Armston et al., 2013). The return energy of certain wavelengths is related to leaf biochemistry and can be used to calculate leaf moisture (Gaulton, Danson, Ramirez, & Gunawan, 2013) and chlorophyll content (Nevalainen et al., 2014). It has been shown that lidar return energy is the most important lidar metric when classifying land cover type (Mallet et al., 2011; Neuenschwander, Magruder, & Tyler, 2009). Therefore an accurate method for retrieving return energy from lidar is vital for making physically based measurements of vegetation. In addition, vegetation canopies contain many small elements, making it likely that a lidar beam will hit multiple targets within a single return feature, potentially violating the assumptions of methods developed for single targets.

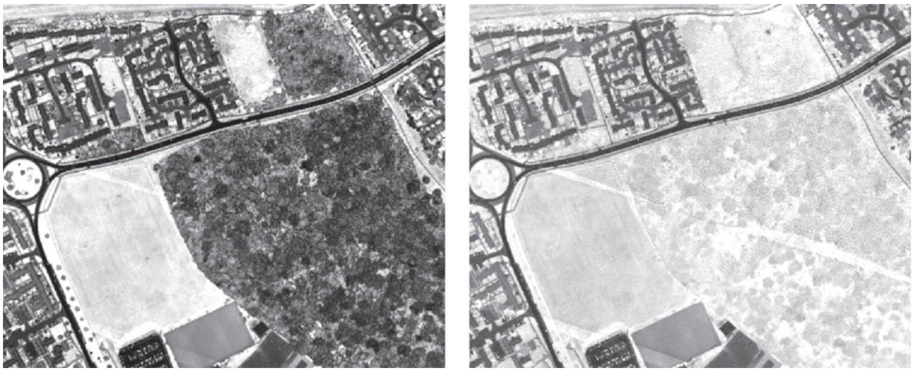
Many previous papers have assessed the accuracy of the range estimate from lidar data (Stilla & Jutzi, 2008; Wagner et al., 2004). Fewer have explored the accuracy of return energy and these previous energy extraction studies are described in Section 3.4. This study deals exclusively with methods for determining the energy of a return, with a view to improving the accuracy of physically based measurement methods of vegetation (which require no site specific calibration). This study assessed the methods in terms of their return energy accuracy, robustness and computational expense for both single, hard returns and for complex, vegetation returns. Return energy accuracy was assessed in terms of absolute accuracy and also in terms of consistency, as the value retrieved by a method can be calibrated to give true energy as long as there is a consistent, well defined relationship between the retrieved value and energy. Computational efficiency is an important consideration as Jalobeanu and Gonçalves (2014) state that “the best performing methods are too computationally intensive to be used on large datasets”.

Empirical methods have been proposed to characterise vegetation without the need for target biophysical parameters to be directly derived from the lidar signal, e.g. Height Of Median Energy, HOME (Drake et al., 2002) and the leading edge extent (Lefsky, Keller, Yong, de Camargo, & Hunter, 2007). However these empirical methods require local calibration. Physically based methods, directly extracting target properties from the lidar signal, require no external calibration and so can be applied globally. The resulting parameters have a physical meaning that can be directly measured on the ground such as canopy cover, tree height or leaf area.

Fig. 1 shows maps generated using two different methods for determining return strength from a Leica ALS50-II airborne lidar. Fig. 1(a) shows the intensity reported by Leica's proprietary discrete return algorithm (sum of multiple returns per beam) whilst Fig. 1(b) shows the sum of full waveform intensity. For both, the return strength was calculated per beam and averaged into a 2 m raster. These lead to very different outputs, with forests providing a stronger return in Fig. 1(b) than (a) and so researchers might draw different conclusions about the biophysical nature of the vegetation depending on which method they used. This paper will explore the different methods to measure lidar return energy and which are more accurate over different surfaces. Several new lidar systems optimised for vegetation are in development covering terrestrial, airborne and satellite based systems (Danson et al., 2014; Douglas et al., 2015; Murooka et al., 2013; Wallace, Nichol, & Woodhouse, 2012) and so this type of data will become ever more common.

## 2. Lidar systems

There are two broad classes of lidar, time of flight (TOF) and phase shift systems. Phase shift systems have been shown to struggle at determining if and where a hit occurs in diffuse targets, such as vegetation due to their assumption that all reflected light comes from a single surface (Newnham, Goodwin, Armston, Muir, & Culvenor, 2012), and so these systems will not be covered here. TOF lidar systems emit a short pulse of light and measure the reflected energy, allowing the range to, and apparent reflectance of, the target surface to be determined. Within TOF lidars there are two further categories, discrete return and full waveform systems. Discrete return systems use proprietary algorithms to extract the range and energy of one or more targets along the laser beam's path (Disney et al., 2010; Jalobeanu & Gonçalves, 2012). Full waveform systems record all the reflected energy as a function of range, giving a more complete description of the scattering event (Harding, Blair, Garvin, & Lawrence, 1994) and allowing more accurate measurement of target properties over diffuse targets such as vegetation (Hancock, Disney, Muller, Lewis, & Foster, 2011). The data and processing requirements are much greater for full waveform than for discrete return lidar, although some doubts have been raised about the accuracy of range and energy derived from the proprietary discrete return algorithms over vegetation (Disney et al., 2010). This study focuses on methods for full waveform lidar, where the energy can be extracted from waveform lidar in a number of ways, ensuring that the optimal information is available for the task.



(a) Discrete return intensity (b) Full wave form sum

**Fig. 1.** Two different ways to measure return strength from lidar. The site is an area in Luton, UK, with forest, grassland and buildings.