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Measurement of fine-spatial-resolution 3D vegetation structure with airborne waveform lidar: Calibration and validation with voxelised terrestrial lidar

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Vegetation structure controls habitat availability, ecosystem services, weather, climate and microclimate, but current landscape scale vegetation maps have lacked details of understorey vegetation and within-canopy structure at resolutions finer than a few tens of metres. In this paper, a novel signal processing method is used to correctly measure 3D voxelised vegetation cover from full-waveform ALS data at 1.5 m horizontal and 50 cm vertical resolution, including understorey vegetation and within-canopy structure. A new method for calibrating and validating the instrument specific ALS processing using high resolution TLS data is also presented and used to calibrate and validate the ALS derived data products over a wide range of land cover types within a heterogeneous urban area, including woodland, gardens and streets. This showed the method to accurately retrieve voxelised canopy cover maps with less than 0.4% of voxels containing false negatives, 10% of voxels containing false positives and a canopy cover accuracy within voxels of 24%. The method was applied across 100 km^2 and the resulting structure maps were compared to the more widely used discrete return ALS and Gaussian decomposed waveform ALS data products. These products were found to give little information on the within-canopy structure and so are only capable of deriving coarse resolution, plot-scale structure metrics. The detailed 3D canopy maps derived from the new method allow landscape scale ecosystem processes to be examined in more detail than has previously been possible, and the new method reveals details about the canopy understorey, creating opportunities for ecological investigations. The calibration method can be applied to any waveform ALS instrument and processing method. All code used in this paper is freely available online through bitbucket (https://bitbucket.org/StevenHancock/voxel_lidar).

1. Introduction

The 3D structure of vegetation canopies is a key determinant of ecological function and processes, providing an indicator of habitat (Ashcroft et al., 2014), biomass (Calders et al., 2015), impacting on weather and climate (Ni-Meister and Gao, 2011) and modulating microclimate (Clinton, 2003). For example, in urban systems the pattern and distribution of greenspace mitigates the "heat island" effect (Myint et al., 2015), with implications for human health. The distribution and quality of greenspace affect mental well-being, directly and by providing corridors for wildlife (Vaz et al., 2015; Shanahan et al., 2017). Understanding and quantifying how vegetation drives these processes requires accurate maps of structure, the vertical and horizontal distribution of vegetation cover above ground, over landscape scales (several kilometres) at sufficient resolution to resolve features of interest, which can be as small as 1–2 m horizontally and vertically for urban wildlife corridors and under-canopy paths (Zeller et al., 2012).

Measuring three-dimensional vegetation structure over large areas is challenging. Manually characterising structure is time consuming and impractical over more than a few metres (Bréda, 2003; Thomas and Winner, 2000). Terrestrial laser scanning (TLS) has been used to produce high resolution (10 cm) 3D vegetation maps (Hosoi and Omasa, 2006; Béland et al., 2011; Raumonen et al., 2013, Seidel et al., 2012) over plots a few tens of metres across and the results from TLS have been shown to be more consistent and accurate than those from manual methods (Ashcroft et al., 2014; Hancock et al., 2014; Calders et al., 2015). TLS does not provide a realistic option for

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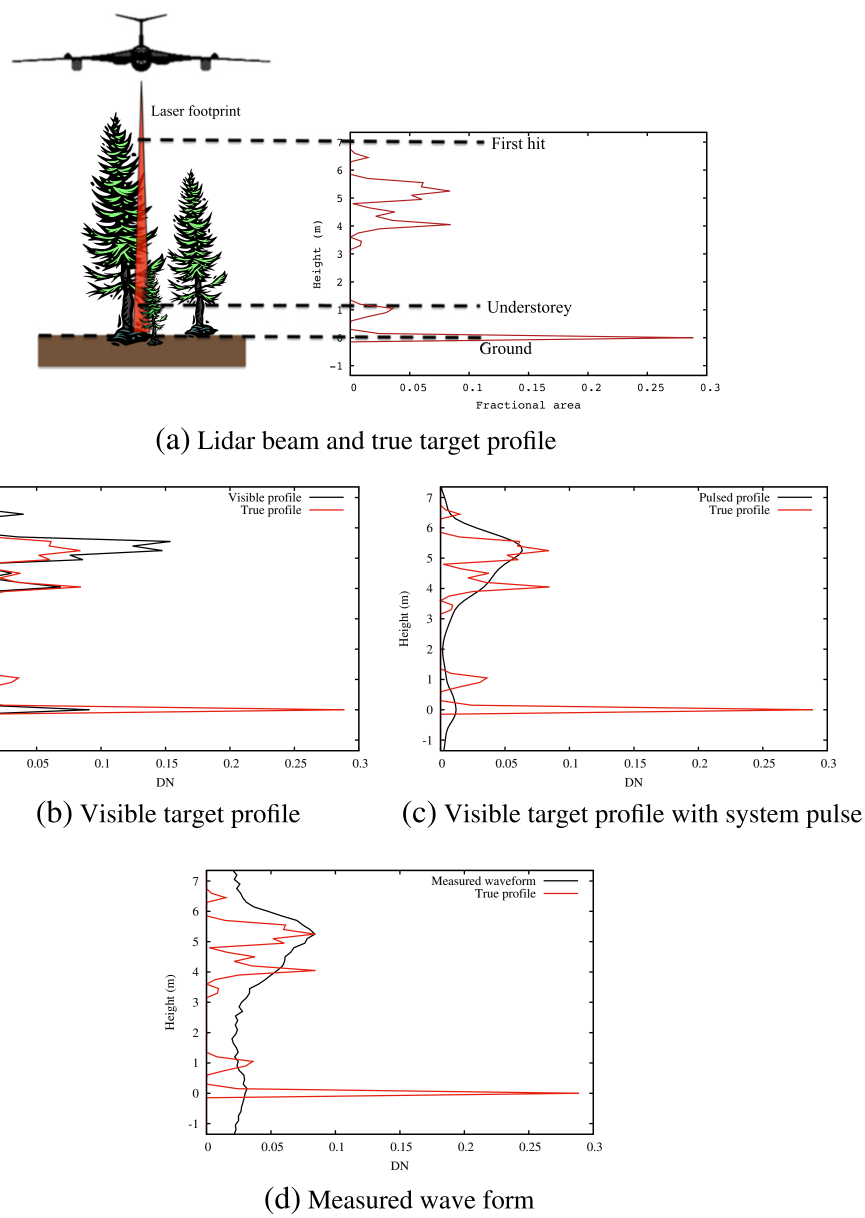
characterising 3D vegetation structure over large areas but can be used to calibrate and validate larger scale measurements (Hopkinson et al., 2013).

Airborne laser scanning (ALS) measures the location and radiometric properties of reflected laser light over landscape scales, allowing the characterisation of 3D structure. They operate in two different modes, “discrete return” and “waveform”. Discrete return uses proprietary algorithms to produce a point cloud (Disney et al., 2010). This allows measurement of canopy height (Li et al., 2015) and has been used to estimate canopy density from the ratio of points returned from the canopy and ground (Stark et al., 2012). However, these algorithms have been developed for measuring hard targets and can be biased over vegetation (Disney et al., 2010), requiring ground based calibration to correct (Li et al., 2015). In addition the return strength may not be related to target reflectance (Hancock et al., 2015), complicating its use in canopy characterisation. These discrete return instruments methods only return a few (around 4) points per laser shot with no way of knowing what is not being measured (Gaveau and Hill, 2003; Disney et al., 2010), potentially preventing the measurement of within-canopy and understorey structure.

Full-waveform lidar measures the reflected laser intensity as a function of range (Baltsavias, 1999). This gives information on all objects visible to the ALS but requires processing to extract target properties from the signal (Anderson et al., 2015). Fig. 1 illustrates how an ALS waveform is made up of the vertical distribution of objects that are to be measured, referred to as the “target profile”, (Fig. 1 (a)), attenuation as laser light is blocked by targets (black line in Fig. 1 (b)), blurring by the lidar system pulse (black line in Fig. 1 (c)) and noise to give the measured signal (red line in Fig. 1 (d)). The effects of noise, system pulse and attenuation must be removed in order to measure high resolution (<2 m) vegetation structure. The extra information available to waveform lidar has been used to measure leaf area index (Hopkinson et al., 2013), gap fraction



(a) Lidar beam and true target profile

(b) Visible target profile

(c) Visible target profile with system pulse

(d) Measured wave form

Fig. 1. Illustration of ALS waveform composition. The true target profile is shown (red line) in each graph to allow comparison to the different components of the measured wave (black line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).