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Data acquisition considerations for Terrestrial Laser Scanning of forest plots

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ABSTRACT

The poor constraint of forest Above Ground Biomass (AGB) is responsible, in part, for large uncertainties in modelling future climate scenarios. Terrestrial Laser Scanning (TLS) can be used to derive unbiased and non-destructive estimates of tree structure and volume and can, therefore, be used to address key uncertainties in forest AGB estimates. Here we review our experience of TLS sampling strategies from 27 campaigns conducted over the past 5 years, across tropical and temperate forest plots, where data was captured with a RIEGL VZ-400 laser scanner. The focus is on strategies to derive *Geometrical Modelling* metrics (e.g. tree volume) over forest plots ($\geq$1 ha) which require the accurate co-registration of 10s to 100s of individual point clouds. We recommend a 10 m × 10 m sampling grid as an approach to produce a point cloud with a uniform point distribution, that can resolve higher order branches (down to a few cm in diameter) towards the top of 30+ m canopies and can be captured in a timely fashion i.e. ~3–6 days per ha. A data acquisition protocol, such as presented here, would facilitate data interoperability and inter-comparison of metrics between instruments/groups, from plot to plot and over time.

1. Introduction

Uncertainty when modelling the impacts of future climate scenarios is, in a large part, a result of uncertainty in the contribution of the terrestrial ecosystem (Friedlingstein et al., 2006; Sitch et al., 2008). Forests are the predominant terrestrial source and sink of carbon, varying greatly across time and space, and there has been much effort to constrain estimates of the terrestrial carbon pool (Bombelli et al., 2008). Methods to do so have typically involved detailed *in-situ* measurements at the tree or plot level (Chave et al., 2014). More recently these methods have been augmented with remote sensing, including aircraft and satellite observations, particularly airborne LiDAR (Asner et al., 2010). However, all these methods rely on empirical models to generate estimates of Above-Ground Biomass (AGB) and as a result tend to suffer from non-optimal sampling, including small numbers of harvested trees or biased sample size distributions e.g. under-sampling large trees which contain disproportionate biomass (Clark and Kellner, 2012; Duncanson et al., 2015).

Over the past fifteen years, Terrestrial Laser Scanning (TLS) has proven to be an increasingly practical option for providing precise, accurate, timely and non-destructive estimates of forest biophysical metrics, including AGB (Lovell et al., 2003; Hopkinson et al., 2004; Thies and Spiecker, 2004; Jupp et al., 2008; Calders et al., 2015b; Newnham et al., 2015). Falling instrument costs, improved range, precision and accuracy of measurements and increased capability of software and computing infrastructure to process large datasets, have facilitated operational acquisition of TLS data at a forest plot scale. Increased uptake presents opportunities for inter-comparison of techniques and metrics, as well as establishing longer-term measurements of forest structure for the calibration and validation of satellite products. To improve data-interoperability between campaigns, it is suggested that a minimum data standard and a data acquisition protocol for capturing TLS data in forests is adopted (Calders et al., 2015a). A minimum data standard is dictated by the metric being acquired, this will in turn inform the sample design and the specifications of the instrument used. A formal approach to data

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acquisition is already common in other disciplines, such as national forest inventories (Tomppo et al., 2010), forest ecology e.g. the Global Ecosystem Monitoring (GEM) network or remote sensing validation e.g. BigFoot.

As the name suggests, TLS instruments are ground-based laser scanners, which have typically been developed for precision surveying applications. Depending on the make and model, TLS instruments scan a Field of View (FoV) ranging from a fixed sector to a complete hemisphere where the angular resolution is configurable in azimuth and zenith resolution to a minimum sampling step. Instruments use either a pulsed (time-of-flight) or continuous frequency modulated (phase-shift) laser that measure the distance to an intercepting surface (Newnham et al., 2015). This, combined with measurements of the scanning mirror's orientation, allows for the precise location of an intercepting surface to be determined. State of the art instruments can fire many millions of laser pulses per scan which create a highly detailed 3D point cloud representation of the scanning domain. Some instruments also have a waveform recording capability which records the intensity of the backscattered signal as a function of time. This can be used to identify multiple interceptions (or returns) from a single outgoing pulse which can be important to penetrate occluding foreground vegetation in dense forests (Calders et al., 2014; Lovell et al., 2003). There are currently no commercially available scanners that are specifically designed for deployment in forests, however, commercial surveying instruments have been used successfully to measure forest structure in great detail (Newnham et al., 2012). Additionally, there are several prototype experimental TLS instruments that have been developed specifically for forest applications, including the single wavelength Echidna (Strahler et al., 2008) and its successor, the Dual Wavelength Echidna Laser scanner (DWEL) (Douglas et al., 2015), and the Salford Advanced Laser Canopy Analyser (SALCA) instruments (Danson et al., 2014; Gaulton et al., 2010).

Biophysical metrics estimated with TLS can be broadly grouped into two categories: *Gap Probability* and *Geometrical Modelling* metrics (Newnham et al., 2015). *Gap Probability* metrics assume that the canopy comprised small "soft" features that are distributed and oriented randomly throughout the scanning domain e.g. leaves and needles in a forest. Examples of *Gap Probability* metrics include direct estimates of gap probability (Danson et al., 2007) as well as derived metrics including Leaf Area Index (Lovell et al., 2003) and Plant Area Volume Density (Jupp et al., 2008). "Soft" features often result in only a fraction of the outgoing pulse being backscattered, therefore *Gap Probability* metrics are derived from the statistical probability of recording an intercept (as a function of scan angle). As *Gap Probability* metrics are derived from probability functions, scans can be treated as independent samples and, therefore, do not require co-registration. *Gap Probability* metrics are often derived from single scans (Jupp et al., 2008; Lovell et al., 2003) or multiple scans integrated to a single point (Calders et al., 2014; Schaefer et al., 2015).

Conversely, *Geometrical Modelling* metrics are derived assuming hard targets (e.g. tree stems and branches) which can be modelled explicitly. Examples include modelling tree structure (Bayer et al., 2013) and volume e.g. using the Quantitative Structure Models or QSM approach (Raumonen et al., 2013; Hackenberg et al., 2015), which in turn can be used to estimate AGB (Calders et al., 2015b). Tree models can also be used in a radiative transfer modelling framework to simulate forests for modelling terrestrial and spaceborne instruments (Calders et al., 2016). A single scan location can suffer from limited sampling of the forest canopy and occlusion of distant vegetation by objects in the foreground; (Hilker et al., 2010; Lovell et al., 2011); therefore a systematic multi-scan location approach and subsequent co-registration is necessary. Co-registration requires the accurate determination of scans relative position to a local datum, scans can then be roto-transformed into a common local reference coordinate system. Methods to achieve a coarse co-registration have involved the use of tree stem recognition (Henning and Radtke, 2006; Zhang et al., 2016; Liu et al., 2017) or artificial targets that are common between scans. Currently, combining only a handful of scans (<10 scans) covering tens or hundreds of square meters has been reported e.g. Calders et al. (2015b). However, as discussed below, with careful planning a large number of scans (>100) can be combined to provide detailed structural information across large forest plots over many hectares (Calders et al., 2016)(Fig. 1).

1.1. Overview

Here we aim to provide a summary of our experiences acquiring TLS data over forest plots to generate *Geometrical Modelling* metrics. This generally holds more challenges with respect to acquisition of *Gap Probability* metrics due to the requirement for accurate (sub-centimeter) co-registration of multiple scans (10s to 100s). The guidance is aimed at practitioners who are planning their own campaigns and, therefore, contains both theoretical and practical considerations. The following section introduces equipment, logistics and sampling considerations for undertaking a TLS campaign. This is followed by a summary of our TLS campaigns completed over the past 5 years, including analysis that highlights the benefits of selecting an appropriate sampling strategy. Finally, recommendations for future campaigns are discussed in Section 5. It should be noted that experience is drawn from using a high specification time-of-flight RIEGL VZ-400 TLS instrument (RIEGL Laser Measurement Systems GmbH), the conclusions drawn are intended for users of this instrument. However, we suggest that the presented sampling framework and other recommendations could be modified to suit coarser resolution or lower powered instruments.

2. Equipment, sample design and logistics

2.1. Equipment

2.1.1. Laser scanner

As stated above, the guidance provided is drawn from experience with a RIEGL VZ-400 scanner. However, there are a number of alternative laser scanners on the market and choosing the right scanner is a question of budget as well as theoretical and practical requirements. For example, the maximum distance at which a scanner is capable of recording an interception can range from a few to many hundreds of meters; this is an important consideration dependent on likely vegetation density and canopy height. The ability to record single or multiple returns may also preclude an instrument from consideration, if for example, it is to be utilised in dense vegetation where occlusion could significantly reduce range (Calders et al., 2014; Lovell et al., 2003). Scanners can also be heavy (≥ 10 kg) (Newnham et al., 2012), therefore, if field sites are a long distance from an access point then a lighter scanner may be more practical. Power access and battery life may also be important in remote locations; battery charging can take several hours, and power access can be intermittent, so multiple batteries and chargers may be vital. A comprehensive review of scanner technologies, capabilities and limitations are provided by Newnham et al. (2015) and Liang et al. (2016). Ongoing efforts by the Terrestrial LiDAR Scanning Research Coordination Network will also highlight the strengths of different commercial and research instruments, for example between time-of-flight and phase-shift scanners.

TLS instruments are normally mounted on a surveying tripod (Fig. 2). The scanner should be located securely on firm ground e.g. directly into the soil removing any duff where possible. It may then be necessary to level the scanner to within instrument tolerances. Many scanners have a panoramic (limited zenith) FoV and do not scan the complete hemisphere. To achieve full hemispheric coverage