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Estimating forest canopy parameters from satellite waveform LiDAR by inversion of the FLIGHT three-dimensional radiative transfer model

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ABSTRACT

The Geoscience Laser Altimeter System (GLAS) has the potential to accurately map global vegetation heights and fractional cover metrics using active laser pulse emission/reception. However, large uncertainties in the derivation of data products exist, since multiple physically plausible interpretations of the data are possible. In this study a method is described and evaluated to derive vegetation height and fractional cover from GLAS waveforms by inversion of the FLIGHT radiative transfer model. A lookup-table is constructed giving expected waveforms for a comprehensive set of canopy realisations, and is used to determine the most likely set of biophysical parameters describing the forest structure, consistent with any given GLAS waveform. The parameters retrieved are canopy height, leaf area index (LAI), fractional cover and ground slope. The range of possible parameters consistent with the waveform is used to give a per-retrieval uncertainty estimate for each retrieved parameter. The retrieved estimates were evaluated first using a simulated data set and then validated against airborne laser scanning (ALS) products for three forest sites coincident with GLAS overpasses. Results for height retrieval show mean absolute error (MAE) of 3.71 m for a mixed temperate forest site within Forest of Dean (UK), 3.35 m for the Southern Old Aspen Site, Saskatchewan, Canada, and 5.13 m for a boreal coniferous site in Norunda, Sweden. Fractional cover showed MAE of 0.10 for Forest of Dean and 0.23 for Norunda. Coefficient of determination between ALS and GLAS estimates over the combined dataset gave R^2 values of 0.71 for height and 0.48 for fractional cover, with biases of −3.4 m and 0.02 respectively. Smallest errors were found where overpass dates for ALS data collection closely matched GLAS overpasses. Explicit instrument parameterisation means the method is readily adapted to future planned spaceborne LiDAR instruments such as GEDI.

1. Introduction

Satellite laser altimeters have the capacity to provide global estimates of vegetation height and structure (Lefsky, 2010; Simard et al., 2011; Los et al., 2012). This can provide an important baseline for future assessment and comparison of forest structural changes, including biomass. Such estimates are needed to inform and test models of carbon sequestration (Ciais et al., 2013), and to monitor changes in carbon stocks due to climatic change and both natural and human disturbance (Goetz and Dubayah, 2011).

While passive optical systems have been used extensively to observe vegetation covered land by measuring the spectral properties of the surfaces, such systems are limited in their ability to measure vertical structure below the upper surface of the canopy. Active light detection and ranging (LiDAR) systems have addressed this, providing information about the vertical profile of a forest canopy. Waveform LiDAR has been in use since the early 1980s, when the Wallops Flight Facility's AOL airborne laser scanner was used to profile a 14 km flight line near Doubling Gap, Pennsylvania (Nelson et al., 1984). Height and density metrics were compared with photogrammetry derived values and the results were encouraging; height means were within 0.6 m of their respective photointerpreted values. Aldred et al. (1985) also demonstrated that waveform recording LiDAR had the potential to mitigate one of the problems arising from the use of discrete-return LiDAR, which was the systematic underestimation of stand height. In the 1990s, first Scanning LiDAR Imager of Canopies by Echo Recovery (SLICER) (Means et al., 1999; Lefsky et al., 1999a; Lefsky et al., 1999b; Harding et al., 2001) and then Laser Vegetation Imaging Sensor (LVIS) (Blair et al., 1999; Drake et al., 2002) were developed by NASA as demonstrators for potential spaceborne LiDAR.

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In the decade following, the Geoscience Laser Altimeter System (GLAS), a space-borne waveform instrument, was carried on the ICESat mission (Brenner et al., 2003). While GLAS was primarily designed to measure ice sheet topography, secondary objectives included measurements of vegetation height and land surface elevation. Launched in January 2003, the mission lasted until October 2009 when its instrument failed. The mission platform was placed in a 183 day ground track repeat cycle, to provide a 15 km spacing between tracks at the equator and 2.5 km at 80° latitude. Using GLAS data, canopy height has been estimated directly from the Gaussian wave components of a decomposed LiDAR waveform (Harding and Carabajal, 2005; Lefsky et al., 2005; Lefsky et al., 2007; Rosette et al., 2009; Duncanson et al., 2010), and volume has also been successfully derived (Rosette et al., 2008a; Nelson et al., 2009; Popescu et al., 2011). More recently, near global datasets of height for forest (Lefsky, 2010; Simard et al., 2011) and total vegetation (Los et al., 2012) have demonstrated the importance of the near-global coverage of GLAS. Los et al. (2012) conclude that the GLAS height product appears to be better suited as an input to ecological and climate models than existing data sets based on land cover alone.

For the previous two decades, the use of LiDAR to map biomass has increased dramatically. It is likely that over the next decade, in combination with other forms of remote sensing, LiDAR will become increasingly central to mapping biomass at regional, national or continental scales (Goetz and Dubayah, 2011; Wulder et al., 2012; Neigh et al., 2013). In particular, upcoming space borne LiDAR missions, such as the Global Ecosystems Dynamics Investigation (GEDI) LiDAR (Dubayah et al., 2014; Coyle et al., 2015) and the second generation ICESat-2 (Abdalati et al., 2010; Montesano et al., 2015) will have the potential to improve and update a definitive baseline for global biomass stocks.

The complex structure of a vegetation canopy in combination with uncertainties arising from instrument, suggest that remote sensing of vegetation biophysical parameters is an ill-posed problem; that is, multiple interpretations of the measured radiative signal are possible. A physically based radiative transfer model (RTM) (e.g. Sun and Ranson, 2000; Ni-Meister et al., 2001b; Disney et al., 2006; North et al., 2010) can be used to describe the interaction of radiation with canopy elements and explicitly relate canopy parameters, observation and illumination variables and remote sensing signature.

Model inversion may be considered a multi parameter optimisation problem. However iterative numerical optimisation methods tend to be computationally intensive, and may not be appropriate for applications on a per-pixel basis for regional and global data (Kimes et al., 2002). An efficient approach to model inversion is the lookup table (LUT) method. It involves: generating of a table of reflectance signatures by varying the values of a set of reflectance model input parameters, comparing an observed signal against all signatures in the LUT to determine the best fit and corresponding set of parameters. Unlike iterative optimisation based approaches, LUTs can be applied to computationally expensive and complex models without any modifications, and so are particularly suitable for Monte Carlo or ray tracing models such as the 3D radiative transfer model, FLIGHT, we have used in this study (Weiss et al., 2000; Leonenko et al., 2013). Also, unlike iterative methods, LUTs do not require a set of initial values, preventing the chance of poor values leading to non-global minima. The effectiveness of the LUT approach to model inversion is sensitive to the accuracy of the RT model, but also to assumptions concerning choice of LUT generation parameters and crown macro-structure and shape. Turbid medium geometric primitives are typically used to model LUT canopy realisations due to their simplicity. However, studies (Calders et al., 2013; Widlowski et al., 2014) suggest that biophysical parameter retrieval may be sensitive to choice of crown shape or internal structure, and further work is recommended to improve understanding of this.

Several studies have applied model inversion to airborne LiDAR waveform (Koetz et al., 2006,2007; Ma et al., 2015). In particular LUTs have been used previously to invert LiDAR data with some success by Koetz et al. (2006), who inverted a 3D LiDAR waveform model (Sun and Ranson, 2000). Subsequently, Koetz et al. (2007) investigated the fusion of imaging spectrometer and LiDAR data, demonstrating greater constraint on LAI. The inversion was tested on both simulated data and waveform data synthesised from small-footprint data acquired in the Swiss National Park, showing good correlation with retrieved parameters.

Existing datasets of height derived from GLAS show higher disagreement for regions of dense forest cover and higher ground slopes (Los et al., 2012; Xing et al., 2010); a physically-based joint retrieval of slope, cover and height has potential to improve accuracy over such regions. Fractional cover has previously been estimated (Los et al., 2012) over wider regions by statistical sampling, assuming each footprint represents either zero or complete vegetation cover, rather than per-footprint. This study aims to develop and evaluate a model inversion method suitable for satellite LiDAR waveform observations, to retrieve simultaneously parameters such as maximum canopy height (H_{top}), fractional cover (F_c), underlying topography and estimates of their error. In the following sections we will describe a lookup table (LUT) based inversion of the three-dimensional radiative transfer model FLIGHT (North, 1996; North et al., 2010) and evaluate the retrieval using GLAS waveform data, validated against airborne laser scanning data.

2. Method

In this section we first describe the FLIGHT (North, 1996; North et al., 2010) radiative transfer model applied to simulation of GLAS waveforms. We next outline generation of a lookup table for performing model inversion. Finally we describe the method for determining the most likely set of biophysical parameters describing the forest structure for a given waveform, and error estimates associated with these parameters.

2.1. FLIGHT radiative transfer model

The FLIGHT radiative transfer model simulates vegetation bidirectional reflectance and LiDAR return by applying Monte Carlo simulation of photon transport within a three dimensional representation of vegetation structure. In the original radiative transfer mode of operation of FLIGHT (North, 1996), photon trajectories are traced forwards from the source, through a sequence of interactions between and within crown boundaries. At each interaction a photon may be absorbed, reflected or transmitted and this process is modelled with a continuous probability density function. On leaving the canopy boundary, energy is accumulated in bins defined for each solid angle of exit. The LiDAR mode of the model (North et al., 2010) samples the paths of individual photons received within the field of view of a given sensor position, accumulating path length and energy from both laser and solar sources and including multiple scattering events.

Large-scale forest structure is modelled by a set of geometric primitives, either ellipsoidal or conical, giving approximate extent of foliage vertical and horizontal extent. The representation is widely used to allow modelling of the main characteristics of three-dimensional forest canopies, but which remains computationally tractable by allowing a semi-analytic radiative transfer approach (Ni-Meister et al., 2001a; Duursma et al., 2012; North, 1996). A simple growth model is used to limit the degree of overlap between neighbouring crowns. Inside each crown, foliage is modelled using the parameters of leaf area density, leaf angle distribution (LAD), size and the optical parameters of reflectance and transmittance. The parameters are set to be homogeneous within a crown but are