International Journal of Applied Earth Observation and Geoinformation 23 (2013) 109–118

Contents lists available at SciVerse ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

A novel approach to estimate canopy height using ICESat/GLAS data: A case study in the New Forest National Park, UK

Irfan Akhtar Iqbal[a], Jadunandan Dash[a], Saleem Ullah[b,*], Ghayyas Ahmad[c]

[a] School of Geography, University of Southampton, Highfield, Southampton SO17 1BJ, UK
[b] Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, 7500 AA Enschede, The Netherlands
[c] Pakistan Forest Institute, Peshawar, Khyber Pakhtunkhwa, Pakistan

ARTICLE INFO

Article history:
Received 21 August 2012
Accepted 18 December 2012

Keywords:
Canopy height
LiDAR
Remote sensing

ABSTRACT

The Geoscience Laser Altimeter System (GLAS) aboard Ice, Cloud and land Elevation Satellite (ICESat) is a spaceborne LiDAR sensor. It is the first LiDAR instrument which can digitize the backscattered waveform and offer near global coverage. Among others, scientific objectives of the mission include precise measurement of vegetation canopy heights. Existing approaches of waveform processing for canopy height estimation suggest Gaussian decomposition of the waveform which has the limitation to properly characterize significant peaks and results in discrepant information. Moreover, in most cases, Digital Terrain Models (DTMs) are required for canopy height estimation. This paper presents a new automated method of GLAS waveform processing for extracting vegetation canopy height in the absence of a DTM. Canopy heights retrieved from GLAS waveforms were validated with field measured heights. The newly proposed method was able to explain 79% of variation in canopy heights with an RMSE of 3.18 m, in the study area. The unexplained variation in canopy heights retrieved from GLAS data can be due to errors introduced by footprint eccentricity, decay of energy between emitted and received signals, uncertainty in the field measurements and limited number of sampled footprints.

Results achieved with the newly proposed method were encouraging and demonstrated its potential of processing full-waveform LiDAR data for estimating forest canopy height. The study also had implications on future full-waveform spaceborne missions and their utility in vegetation studies.

1. Introduction

Geoscience Laser Altimeter System (GLAS), the first of a new generation spaceborne LiDAR onboard the Ice, Cloud and land Elevation Satellite (ICESat) mission, was launched on January 13, 2003. GLAS is the first spaceborne instrument which can fully digitize the backscattered waveform from incident surfaces (Wagner et al., 2006). GLAS offers near-global coverage by carrying three laser instruments (Laser 1, 2 and 3) with only one operational at a time. After the failure of Laser 1 in March 2003 (Schutz et al., 2005), GLAS followed a modified plan of 33 days sub-cycle with a 91 days repeat orbit (Abshire et al., 2005). Under the revised plan, Laser 3 acquired data during February–March, May–June, and October–November each year (Schutz et al., 2005), until its failure in October, 2008. Laser 2 also ceased emitting light on October 11, 2009 (NASA, 2009). After seven years of near-global coverage and 15 laser-operation campaigns, ICESat has stopped collecting science data. However, data from these historical acquisitions can be exploited to evaluate the potential of these data in other terrestrial applications and thus, can have useful implications for the next generation of sensor development, for example ICESat-2, DESDynI. Originally, ICESat was launched to monitor polar ice-sheet dynamics and its role in changing the global sea-level (Zwally et al., 2002). However, other scientific objectives of this mission also include surface reflectivity, precise measurement of land topography and vegetation canopy heights.

Light Amplification by Stimulated Emission of Radiation (LASER) altimetry has supplemented the existing remote sensing techniques because of its high precision and capability to estimate canopy height. Light Detection and Ranging (LiDAR) directly measures the vertical component of vegetation, thus has the potential to measure the structural attributes of vegetation (Dubayah et al., 2000; Lefsky et al., 2002; Nelson, 2010). It has the capability to provide information at both canopy and subcanopy levels which is crucial for understanding forest health and regeneration capacity (Stone et al., 2000; Todd et al., 2003), forest fires (Andersen et al., 2005; Riaño et al., 2003) and present and future carbon stock

* Corresponding author at: Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands. Tel.: +31 53 4874 372.

E-mail addresses: irfanswat@hotmail.com (I.A. Iqbal), ullah19488@itc.nl (S. Ullah).

0303-2434/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jag.2012.12.009

estimation (Dean et al., 2004). Moreover, tree heights and vegetation density derived from LiDARs prove to be important inputs for aboveground biomass estimation, understanding global carbon cycle and ecosystem dynamics (Ranson et al., 2004).

Forests, being important for their role in the global climate (UNFCCC, 1997, 2009a), need to be quantitatively as well as qualitatively analyzed. By estimating the structural attributes (e.g. aboveground biomass) of these ecosystems, the amount of carbon stored can be calculated as half the dry weight of biomass (Drake et al., 2002; Houghton, 2008; IPCC, 2003; UNFCCC, 2009b). Conventionally, aboveground biomass is estimated by using the DBH (Keller et al., 2001), though straightforward, estimation of aboveground biomass (using DBH) on ground is time consuming as well as expensive (Houghton, 2005) and mostly involves destructive sampling (Hiratsuka et al., 2003). Alternatively, due to its spatial and temporal coverage, remote sensing provides opportunity to derive vegetation biophysical variables and some of them are related to vegetation structure. Although DBH cannot be directly measured from remotely sensed data; other biophysical parameters like canopy height and canopy cover can serve as a proxy for estimating the amount of aboveground biomass. Several studies have attempted to use remotely sensed data (both passive and active (RADAR)) for estimating the biophysical parameters of vegetation and in turn, to estimate aboveground biomass e.g. (Dobson et al., 1992; Kaufman et al., 1990; Muukkonen and Heiskanen, 2007). However, the accuracy and sensitivity of these data types drop-off in areas of closed canopies and high-biomass (Waring et al., 1995; Mitchard et al., 2012).

2. Application of GLAS data in vegetation studies

GLAS transmits short pulses (4 ns width equivalent to 60 cm in surface elevation) of infrared (1064 nm) and green (532 nm) light at a frequency of 40 Hz. The nominal diameter of the illuminated spot, the footprint, is ~70 m, space at 172 m along the track; however, its size and ellipticity have varied through the time (Pang et al., 2008). The reflected photons are collected by a telescope of 1 m diameter, and their intensities are binned every nanosecond. Height (or range) can be worked out as the product of speed of light (3×10^8 m/s) and one-way travel time of the photons. Intensities of the reflected photons are stored in 544 bins over ice sheet and land, corresponding to a height of 81.6 m (Brenner et al., 2003). In steeply sloped areas and/or areas where feature heights exceed 81.6 m, GLAS waveform would truncate, making it inconvenient to derive range information. For this reason, in later operations height extent was increased to 150 m over land, using a 'waveform compression scheme' (Harding and Carabajal, 2005) according to which the first 152 bins correspond to 60 cm each.

Fig. 1 shows the waveform components, used to estimate various physical attributes, which will be referred to in the succeeding text. The numbers 25, 50, 75 and 100 indicate height quartiles where respective percentage of waveform intensity is concentrated.

GLAS products, typically GLA01 and GLA14, have been used for vegetation classification and biomass estimation (Boudreau et al., 2008; Lefsky et al., 2005; Ranson et al., 2004), and seasonal changes in vegetation (Duong et al., 2008), where most of the information is retrieved from GLA01 (the 'raw' waveform). Particular to vegetation studies, Ranson et al. (2004) found the front slope angle (Fig. 1) strongly correlated to canopy density and vertical variability of upper canopy. These relationships were further exploited in a classification of forests in central Siberia.

Aboveground biomass estimation from GLAS data has been demonstrated to have agreement with field based or airborne measurements (Boudreau et al., 2008; Helmer and Lefsky, 2006; Lefsky et al., 2005). Extraction of canopy height from raw waveform is complicated in areas of varied topography due to slope effects (Harding and Carabajal, 2005). GLAS returns from flat surfaces can be represented by a Gaussian curve; while flat areas with homogeneous vegetation can be approximated by two Gaussian curves. With increasing topographic variation and vegetation heterogeneity, the number of Gaussian peaks increases (Duncanson et al., 2010). To allow for such complexities, methods for canopy height estimation have been developed which are generally classified (Chen, 2010b) as (i) statistical methods and (ii) direct methods. In statistical methods, waveform processing is supplemented by additional information from the underlying terrain. So-called terrain indices are extracted either from the available Digital Terrain Models (DTMs) (Lefsky et al., 2005; Rosette et al., 2008) or derived from the waveforms (Lefsky et al., 2007; Pang et al., 2008). Direct methods concentrate on waveform processing for accurate identification of canopy top and the ground return with less, if any, assistance from auxiliary data, e.g. DTMs. Lefsky et al. (2005) derived canopy height as a linear function of waveform extent and terrain index. Waveform extent was taken as the difference between the first and last threshold crossings of the waveform; whereas terrain index was calculated, from Shuttle RADAR Topography Mission (SRTM) data, as the difference between minimum and maximum elevations within a footprint. Having both waveform extent and terrain index identified, canopy height was modelled as given in the equation:

$$H = b_0(w - b_1 g) \quad (1)$$

where, H is the measured canopy height, w is the waveform extent in m, g is the terrain index in m, b_0 and b_1 are coefficients applied to the waveform and terrain index, respectively. With their method, Lefsky et al. (2005) were able to explain a maximum variation of 68% with an RMSE of 4.85 m in canopy heights. They attributed the unexplained variance in canopy height estimation to the 'measurement' of waveform extent, more importantly, the identification of ground return (or peak) in the raw waveform.

For efficient ground peak detection, Gaussian components are fitted to the raw waveform (Brenner et al., 2003) and iteratively reduced to six (Sun et al., 2008), using the Least Squares approach (Markwardt, 2009). Harding and Carabajal (2005) showed that out of the six peaks, the last peak with the highest amplitude is a representative of the ground. However, in densely vegetated areas, due to energy attenuation through the canopy (Parker et al., 2001),

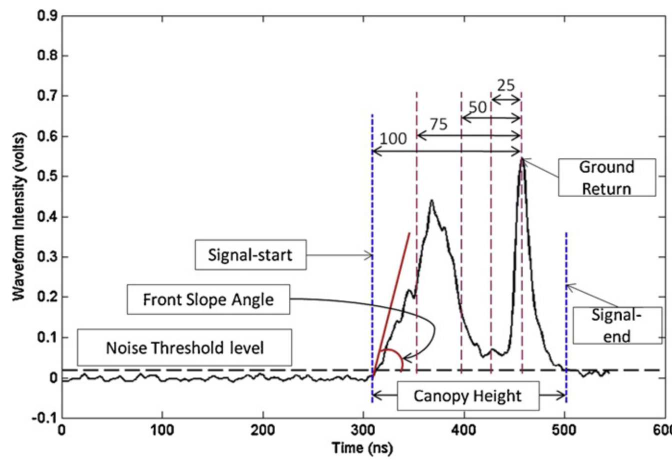

Fig. 1. Illustration of waveform components used to estimate canopy height. The waveform has been smoothed with a moving average of 5 to reduce noise and favour clarity. The numbers 25, 50, 75 and 100 indicate height quartiles where respective percentage of waveform intensity is concentrated. The distance between the two dotted blue lines is the waveform extent. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)