Remote Sensing of Environment 115 (2011) 2798–2809

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Impact of footprint diameter and off-nadir pointing on the precision of canopy height estimates from spaceborne lidar

Yong Pang [a,b], Michael Lefsky [a,*], Guoqing Sun [c], Jon Ranson [d]

[a] Center for Ecological Applications of Lidar, Warner College of Natural Resources, Colorado State University, Fort Collins, CO 80523, USA
[b] Institute of Forest Resource Information Technique, Chinese Academy of Forestry, Beijing 100091, China
[c] Department of Geography, University of Maryland, College Park, MD 20742, USA
[d] Biospheric Sciences Branch, Code 614.4, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA

ARTICLE INFO

Article history:
Received 13 June 2009
Received in revised form 30 August 2010
Accepted 31 August 2010
Available online 12 May 2011

Keywords:
Spaceborne lidar
Lidar waveform simulation
Off-nadir pointing
Footprint diameter
Canopy height
DESDynI
ICESat-II

ABSTRACT

A spaceborne lidar mission could serve multiple scientific purposes including remote sensing of ecosystem structure, carbon storage, terrestrial topography and ice sheet monitoring. The measurement requirements of these different goals will require compromises in sensor design. Footprint diameters that would be larger than optimal for vegetation studies have been proposed. Some spaceborne lidar mission designs include the possibility that a lidar sensor would share a platform with another sensor, which might require off-nadir pointing at angles of up to 16°. To resolve multiple mission goals and sensor requirements, detailed knowledge of the sensitivity of sensor performance to these aspects of mission design is required.

This research used a radiative transfer model to investigate the sensitivity of forest height estimates to footprint diameter, off-nadir pointing and their interaction over a range of forest canopy properties. An individual-based forest model was used to simulate stands of mixed conifer forest in the Tahoe National Forest (Northern California, USA) and stands of deciduous forests in the Bartlett Experimental Forest (New Hampshire, USA). Waveforms were simulated for stands generated by a forest succession model using footprint diameters of 20 m to 70 m. Off-nadir angles of 0 to 16° were considered for a 25 m diameter footprint diameter.

Footprint diameters in the range of 25 m to 30 m were optimal for estimates of maximum forest height (R^2 of 0.95 and RMSE of 3 m). As expected, the contribution of vegetation height to the vertical extent of the waveform decreased with larger footprints, while the contribution of terrain slope increased. Precision of estimates decreased with an increasing off-nadir pointing angle, but off-nadir pointing had less impact on height estimates in deciduous forests than in coniferous forests. When pointing off-nadir, the decrease in precision was dependent on local incidence angle (the angle between the off-nadir beam and a line normal to the terrain surface) which is dependent on the off-nadir pointing angle, terrain slope, and the difference between the laser pointing azimuth and terrain aspect; the effect was larger when the sensor was aligned with the terrain azimuth but when aspect and azimuth are opposed, there was virtually no effect on R^2 or RMSE. A second effect of off-nadir pointing is that the laser beam will intersect individual crowns and the canopy as a whole from a different angle which had a distinct effect on the precision of lidar estimates of height, decreasing R^2 and increasing RMSE, although the effect was most pronounced for coniferous crowns.

1. Introduction

1.1. Spaceborne lidar

Lidar sensors emit a short duration laser pulse and digitize the reflected return signal yielding a waveform that records the range and intensity of returns from intercepted surfaces (Lefsky et al., 2002; Sun & Ranson, 2000). Each scatterer in a scene produces a return signal which is recorded in a series of bins; the total signal will be the summation of these signals according to their time delay in the laser pulse direction. The power of the waveform is a function of the vertical arrangement and reflectance of intercepted surfaces within the forest canopy and terrain surface and the distribution of energy within the footprint.

Lidar systems provide a direct measurement of forest canopy height, the vertical structure of vegetation, and terrain elevations beneath the canopy. Over the past decade there have been dramatic improvements in lidar technology and it has been successfully used to estimate many forest structure parameters. While airborne discrete return lidar has been used for forest structure estimates since 1984

* Corresponding author. Tel.: +1 970 491 0602.
E-mail address: lefsky@cnr.colostate.edu (M. Lefsky).

0034-4257/$ – see front matter
doi:10.1016/j.rse.2010.08.025

(Nelson et al., 1984) in relatively small regions (<1000 km^2, Lefsky et al., 2002), applications of lidar over larger extents have only recently become possible using large footprint lidar data from the Shuttle Laser Altimeter missions in 1996 and 1997 (Sun et al., 2003) and ICESat GLAS sensor operations in 2003 (Lefsky et al., 2005, 2007; Nelson et al., 2008; Pflugmacher et al., 2008; Rosette et al., 2008; Sun et al., 2008).

Current and planned spaceborne lidar systems collect data from sparsely distributed transects aligned with the spacecraft orbit, with either contiguous or noncontiguous footprints; their application is limited by low spatial density. The spatial density of transects can be increased by using several lasers as proposed for the Vegetation Canopy Lidar (VCL, Dubayah et al., 1997) and the Deformation, Ecosystem Structure and Dynamics of Ice missions (DESDynI, Donnellan et al., 2008);http://desdyni.jpl.nasa.gov/mission/). Continuous wall-to-wall mapping of forest structure will require data fusion between lidar data point samples and other image data sources (Baccini et al., 2008; Hese et al., 2005; Kimes et al., 2005; Nelson et al., 2008). One possibility is to mount a sampling lidar sensor and an imaging sensor on the same platform and use the data together as in the concept of DESDynl in the National Decadal Survey report (DESDynI Writing Committee, 2008; http://desdyni.jpl.nasa.gov/mission/). Conflicts would exist between the optimal configurations for each of DESDynI's sensors. For solid earth deformation studies, precisely repeated orbits with a high temporal resolution (e.g. 8–12 days) are required to map abrupt topographic change through SAR interferometery. Under this scenario, to achieve a high spatial density of transects at low latitudes, off-nadir laser pointing would be required to acquire data in the areas between orbits. It is generally understood that off-nadir pointing introduces a decrease in the precision of forest structure estimates, but the magnitude of this effect is unknown.

Off-nadir pointing has two effects on LiDAR waveforms from forests. Lidar waveforms are distorted by terrain fluctuations within a footprint (Brenner et al., 2003; Harding & Carabajal, 2005) and these phenomena become more complicated over forested slopes (Lefsky et al., 2005, 2007; Rosette et al., 2008). As slope increases, the vegetation return signals and the ground return signals can occur at the same elevation (Lefsky et al., 2007). This terrain effect is compounded by footprint diameter, terrain slope, forest height and crown geometry. With off-nadir pointing the azimuth of terrain and laser pointing must also be considered.

In addition to the terrain effect, the laser beam will intercept more vegetation elements with increasing off-nadir angle, which will increase the power of the vegetation signal and decrease the power of the ground signal. The laser beam will contain more trees with a part of the crown within the laser beam while their trunks are out of the footprint or trees whose trunks are located in the footprint while a part of their crowns are out of the laser beam. This results in a definition problem as forest structure measurements of all kinds use plots that are defined in the horizontal plane and extend from at or below the ground towards the zenith angle.

It would be costly and time-consuming to develop a database of measurements of actual forest stands that would allow us to examine the full range of these multiple conditions and their interactions. The combination of a forest succession model (to generate realistic forest structure for a range of stand ages and composition) and a waveform simulator (depicting the interactions of a laser pulse with the elements of vegetation structure generated from the succession model) can be used to explore the relationship between forest structure and lidar waveforms for numerous combinations of forest structure, terrain conditions and mission scenarios.

1.2. Modeling of lidar waveforms

Sun and Ranson (2000) developed a 3-D model to simulate lidar waveforms from measured or modeled forest stands. The shape of simulated waveforms was similar to observed waveforms from an airborne lidar. Ni-Meister et al. (2001) used the Geometric Optical and Radiative Transfer (GORT, Li et al., 1995) model to describe lidar waveforms from forests and analyzed the effect of foliage clumping on the simulated waveforms. Kotchenova et al. (2003) modeled lidar waveforms with time-dependent stochastic radiative transfer theory, which included multiple scattering mechanisms and had better results over dense forests. Pang and Lefsky (revised) revised the Sun and Ranson (2000) model, and used it to investigate the effect of terrain in detail.

These lidar waveform models simulate sensors with nadir pointing. The geometry of sensor and terrain becomes more complicated when a laser pulse coming from a given azimuth interacts with a forest on sloped terrain that can be oriented either towards or away from the sensor at any angle. Given terrain and lidar pointing described by zenith and azimuth angles (θ_o, ϕ_o) and (θ, ϕ), respectively, the local incidence angle α, which is the angle between the off-nadir beam and a line normal to the terrain surface, can be defined as:

$$\cos(\alpha) = \sin\theta_0 \sin\theta \cos(\phi_0 - \phi) + \cos\theta_0 \cos\theta. \quad (1)$$

Fig. 1A illustrates the complexity of combining these effects. The local incidence angle is the angle between the off-nadir beam and a line normal to the terrain surface, which can be thought of as the effective slope as observed relative to the laser beam. The x-axis indicates the difference between the sensor azimuth and terrain aspect (Fig. 1B). When the terrain slope is zero, the effect is from off-nadir pointing only, i.e. the local incidence angle is equal to the off-nadir pointing angle. Similarly, when the off-nadir angle is zero, the local incidence angle is set by terrain slope alone. When both off-nadir

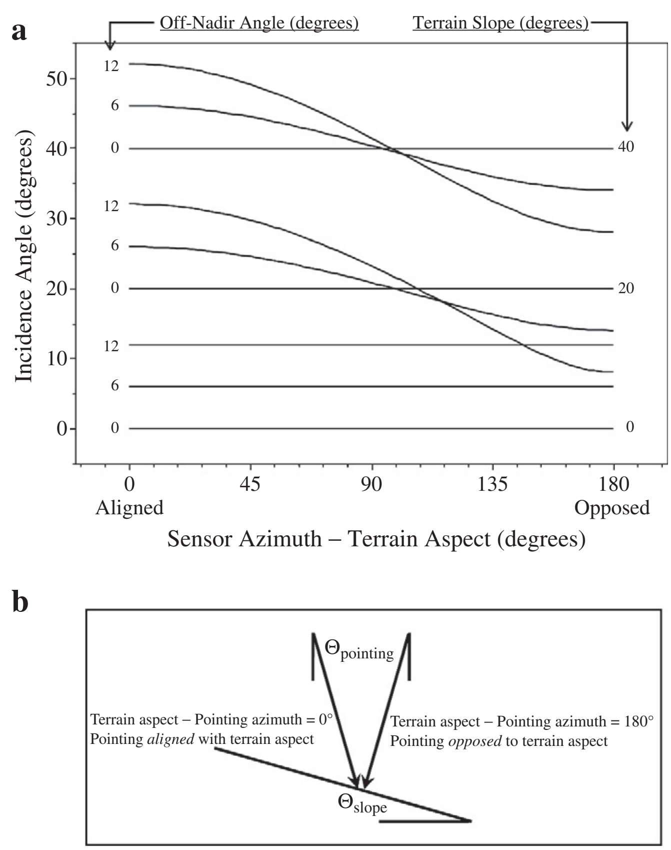

Fig. 1. A) Evaluation of the local incidence angle equation to illustrate the combined effects of terrain slope, off-nadir pointing and the angle between terrain aspect and sensor point angle. B) Illustration of the angle between terrain aspect and sensor point angle.