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Predicting lidar measured forest vertical structure from multi-angle spectral data

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Abstract

A capability to remotely measure the vertical and spatial distribution of forest structure is required for more accurate modeling of energy, carbon, water, and climate over regional, continental, and global scales. We examined the potential of using a multi-angle spectral sensor to predict forest vertical structure as measured by an airborne lidar system. Data were acquired from AirMISR (Airborne Multi-Angle Imaging Spectrometer) and airborne LVIS (Laser Vegetation Imaging Sensor) for a 7000 ha study site near Howland Maine, consisting of small plantations, multi-generation clearings and large natural forest stands. The LVIS data set provided a relatively direct measure of forest vertical structure at a fine scale (20 m diameter footprints). Multivariate linear regression and neural network models were developed to predict the LVIS forest energy height measures from 28 AirMISR multi-angle spectral radiance values. The best model accurately predicted the maximum canopy height (as measured from LVIS) using AirMISR data (rmse = 0.92 m, R^2 = 0.89). The models developed in this study achieved high accuracies over a study site with an elaborate patchwork of forest communities with exceptional diversity in forest structure. We conclude that models using MISR-like data are capable of accurately predicting the vertical structure of forest canopies.
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Keywords: Forest vertical structure; Lidar; Multi-angle; Spectral; AirMISR; LVIS

1. Introduction

Forest structure affects the fluxes of energy and matter across the land–atmosphere interface, and the biodiversity of ecosystems. Forest structure is determined by several factors, including species composition and the three-dimensional distribution of leaves/needles and woody biomass. Many processes, both anthropogenic and non-anthropogenic, alter forest structure including forest management, natural disturbances, and recovery from disturbance (i.e., successional status or age class).

Most remote sensing systems, although providing images of the horizontal extent of canopies, do not provide direct information on the vertical distribution of canopy elements. For example, MODIS (Moderate Resolution Imaging Spectroradiometer) land products provide typical forest parameters at large spatial scales (e.g., forest type, %cover, leaf area index, and net primary production) (Justice & Townshend, 2002), but these products do not provide much insight into the vertical and spatial structure of the forest. Structural information is essential for realistic energy budgeting, and carbon and water cycle modeling at the landscape scale. This requires a capability to remotely measure the vertical and spatial distribution of forest structural parameters that are needed for more accurate models of energy, carbon, and water flux over regional, continental, and global scales. Lidars, multiangle radiometers, radars and imaging spectrometers have been identified as systems that can capture information in the vertical dimension (e.g. Dobson et al., 1996; Lefsky et al., 1999a; Ranson et al., 1994; Treuhaft et al., 2002). In this paper, we consider the use of lidars and multiangle radiometers to estimate forest vertical structure.

The composite return from a lidar footprint is called the lidar waveform signature. The lidar waveform from a large-footprint lidar instrument, such as the Laser Vegetation Imaging Sensor

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(LVIS) (Blair et al., 1999; Drake et al., 2002), has been successfully used to estimate the canopy height, stand volume, basal area, and above-ground biomass (Drake et al., 2002; Lefsky et al., 1999b; Means et al., 1999). The waveform data provides a relatively direct measure of the vertical profile of the canopy components (Blair & Hofton, 1999). In addition, LVIS has a high density of footprints across a wide swath (2 km) that can be used to form an image. LVIS data provide forest structure information and are an excellent data set for developing and testing methods to extract forest structure information using other kinds of sensor data. Ground data of forest structure at such a fine scale and for large regions has not been previously available for developing forest structure algorithms. In addition, lidars in orbit and proposed, do not have a continuous mapping capability, and provide only sample data in a region. A capability to continuously map the vertical structure for large regions would provide fundamental information that would enable more accurate modeling of energy, carbon, water, and climate (Landsberg & Waring, 1997; Cuevas, 2003; Dai et al., 2003; Engel et al., 2002; Hudak et al., 2002; Shugart, 2000).

Imaging the Earth's surface through various angles by the Multiangle Imaging Spectrometer (MISR) instrument on-board the Terra Spacecraft (Diner et al., 1998) could provide a capability to continuously map forest vertical structure by using directional reflectance information. Early studies showed the promise of directional reflectance data for distinguishing forest types (e.g., Ranson et al., 1994; Russell et al., 1997). Multiangle data significantly improved the accuracy of recovering forest parameters when inverting 3-D optical models (Kimes et al., 2002). More recently, studies by the MISR science team members indicate the usefulness of off-nadir data for surface heterogeneity and vegetation structure (e.g., Chopping et al., 2003; Gobron et al., 2002; Jin et al., 2002; Pinty et al., 2002).

MISR's 375 km swath and 275–1100 m spatial resolutions may provide a capability of mapping forest structure parameters at regional, even global scales. Coincident data acquired from the MISR airborne simulator instrument (AirMISR web site) and LVIS provide an opportunity for examining the potential of using multi-angle spectral sensors to map forest vertical structure measures. In this study we explore the potential of accurately predicting forest vertical structure as measured from LVIS using AirMISR spectral and angular data. We developed and compared a number of prediction methods including linear and neural network models.

2. Methods

2.1. Study area

LVIS and AirMISR data were acquired in the summer of 2003 as part of a NASA Terrestrial Ecology Program aircraft campaign. Our study site is located at approximately 45° 15′N latitude and 68° 45′ W longitude at International Paper's Northern Experimental Forest near Howland, Maine, USA (Fig. 1). This site was also the location of the NASA Forest Ecosystem Dynamics Multi-sensor Aircraft Campaign in 1990 (Ranson et al., 1994; Ranson & Sun, 1994) and intensive SIR-C/XSAR (Spaceborne Imaging Radar-C/X-Band Synthetic Aperture Radar) experiments in 1994 (Ranson & Sun, 1997). The area comprises approximately 7000 ha containing several intensive experimental sites, where detailed ecological measurements have been obtained. The study area contains an assortment of small plantations, multi-generation clearings, and large natural forest stands. A variety of forest ecosystem studies are currently in progress at this site (e.g., Xiao et al., 2004).

4. Conclusions and implications

The models developed in this study achieved high accuracies over a study site with an elaborate patchwork of forest communities with exceptional diversity in forest structure. Models using the 17 × 17 window had high accuracies when predicting the H100 value (rmse = 0.92 m, R^2 = 0.89) using 15 inputs (all view angles and all spectral bands). The accuracies for predicting the H75, H50, and H25 values had similar accuracies.

Relatively high accuracies were obtained with models using a minimum number of inputs. For example, Models using the 17 × 17 window data with only 5 inputs (4 view angles and 4 spectral bands) had accuracies of rmse = 1.11 m, R^2 = 0.84. At the satellite level, the blue band is not appropriate for retrieving canopy parameters due to the large atmospheric scattering component; however, high accuracies were obtained without this band. In this study, forest vertical structure can not be captured accurately using only the 4 spectral bands in the nadir view or all view angles with a single spectral band.

These methods seem to be relatively accurate even at the highest canopy density experienced in this study that was estimated at 300 t/ha. In addition, these models are relatively sensitive to noise with the rmse value approximately doubling with each 2% increase in noise. The authors are currently exploring the potential of using MISR data for predicting forest structure measures.

The data products from LVIS available at the time of this study were limited to the H100, H75, H50, and H25 quartile height values. We believe, however, that many other forest structure measures could be accurately estimated using multi-angle-spectral data. For example, these forest structure measures could provide additional information to accurately retrieve other key parameters such as biomass, leaf area index, fraction of photosynthetically active radiation, and albedo. In addition, forest structure information could be utilized as additional constraints for current retrieval/inversion algorithms (e.g. look-up-table approaches) for vegetation parameters.

It has been shown that the directional radiances in or near the principal plane of the sun provides information that leads to more accurate prediction of canopy structure parameters than from other azimuth planes (e.g., Gobron et al., 2000). For satellite data (e.g., MISR) the directional views deviate from the principal plane of the sun. Consequently, the authors believe that the accuracies for predicting forest structure measures may decrease as the deviation from the solar plane increases.

In conclusion, models similar to the ones developed in this study using MISR-like data are capable of accurately predicting the vertical structure of forest canopies. A continuous capability to remotely measure the vertical and spatial distribution of forest structure is required for more accurate modeling of energy, carbon, water, and climate over large regional, continental, and global scales. The findings also provide information for future satellite and aircraft mission design.