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An empirical InSAR-optical fusion approach to mapping vegetation canopy height

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Abstract

Exploiting synergies afforded by a host of recently available national-scale data sets derived from interferometric synthetic aperture radar (InSAR) and passive optical remote sensing, this paper describes the development of a novel empirical approach for the provision of regional- to continental-scale estimates of vegetation canopy height. Supported by data from the 2000 Shuttle Radar Topography Mission (SRTM), the National Elevation Dataset (NED), the LANDFIRE project, and the National Land Cover Database (NLCD) 2001, this paper describes a data fusion and modeling strategy for developing the first-ever high-resolution map of canopy height for the conterminous U.S. The approach was tested as part of a prototype study spanning some 62,000 km^2 in central Utah (NLCD mapping zone 16). A mapping strategy based on object-oriented image analysis and tree-based regression techniques is employed. Empirical model development is driven by a database of height metrics obtained from an extensive field plot network administered by the USDA Forest Service–Forest Inventory and Analysis (FIA) program. Based on data from 508 FIA field plots, an average absolute height error of 2.1 m (r=0.88) was achieved for the prototype mapping zone.

Keywords: Vegetation canopy height; Scattering phase center height; InSAR; Radar; Interferometry; Optical; Multi-spectral; SRTM; Landsat ETM+; Forest inventory; FIA; DEM; Object-oriented; Segmentation; Regression trees

1. Introduction

1.1. Motivation

Spatially extensive and accurate maps of vegetation canopy height are of value not only to ecologists and land managers working in diverse fields such as biodiversity conservation, wildfire risk assessment, and timber production, but also to climate change scientists focused on reducing the uncertainty associated with the carbon cycle component of Earth's climate system. High-resolution maps of canopy height have the potential to significantly improve the accuracy of aboveground biomass and carbon stock baselines upon which models of future climate change necessarily depend. Reliable baseline information is also needed for measuring and monitoring carbon fluxes and for verifying emissions reductions in the context of national and international carbon accounting strategies.

Although the forests of the United States and other mid- to high-latitude nations are covered by extensive inventory plot networks, these data are largely inadequate for the provision of high-resolution estimates of aboveground biomass and carbon stocks. Whereas dry biomass, which contains 45 to 50% carbon by weight (Linder & Axelsson, 1982; Reichle et al., 1973), may be well quantified for the localized areas where measurements exist, extrapolation across larger unsampled regions can contribute to considerable estimate uncertainty (Houghton & Goodale, 2004). Consequently, at regional to continental scales, estimates of multi-dimensional forest structural metrics are necessarily acquired through the use of remote sensing technologies in concert with ground-based measurements derived from national forest inventories. The practice of leveraging the combined strengths of forest inventory and

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satellite image data dates back to the early 1990s in Finland (Tomppo, 1991). More recent examples include applications in northern Europe and the United States (Huang et al., 2002; McRoberts & Liknes, 2005; Reese et al., 2002, 2003; Tomppo et al., 2002).

Numerous approaches have been put forth for the provision of aboveground biomass estimates using the range of available remote sensing technologies including passive optical (e.g., Dong et al., 2003; Myneni et al., 2001), radar (e.g., Dobson et al., 1992; Ranson et al., 1997), and lidar (e.g., Drake et al., 2002; Hyde et al., 2005; Lefsky et al., 1999a,b); however, a technique has yet to be presented that is consistent, reproducible, and applicable across broad geographic extents (Rosenqvist et al., 2003). This is largely due to the fact that biomass is a three-dimensional metric — the accurate estimation of which requires biophysical measures, and therefore remote sensors, that capture both the horizontal (e.g., canopy density/cover) and vertical (e.g., canopy height) structural character of the vegetation (Mette & Hajnsek, 2003; Mette et al., 2004; Treuhaft et al., 2004). While the science of acquiring remotely sensed estimates of horizontal vegetation structure has matured considerably over the past 25 years, only in the last decade have significant advances in instrument development made it possible to obtain consistent and accurate measurements of canopy height and related metrics of vertical vegetation structure (e.g., Lefsky et al., 2002; Treuhaft & Siqueira, 2000). Motivated by these advancements, this research focuses on the three-dimensional structure of forest vegetation in an effort to expand the scientific basis for regional- to continental-scale carbon accounting. Specifically, this research presents an approach to the generation of high-resolution, spatially extensive maps of vegetation canopy height. The approach is the foundation for an ongoing NASA-sponsored project with the ultimate goal of generating the first-ever circa-2000 baseline dataset of vegetation canopy height, aboveground biomass, and carbon stocks for the conterminous U.S. This project is possible, in part, because of the complimentary nature and quasi-synchronous development of several national digital geospatial datasets. The following section provides a brief introduction to these datasets.

1.2. Confluence of national mapping efforts

The last several years have been marked by an unprecedented confluence of high-resolution geospatial data sources and derived products for the conterminous U.S. The first of these datasets was acquired early in 2000 when the NASA-JPL Shuttle Radar Topography Mission (SRTM) used C-band (5.6 cm, 5.3 GHz) interferometric synthetic aperture radar technology (InSAR) to obtain high-resolution (one arc-second) elevation data on a near-global scale for the purpose of generating the most complete digital topographic database of Earth. Rather than reflecting the "bald-earth" surface, an SRTM-derived digital elevation model (DEM) is unique in that it more closely reflects the elevation surface formed by vegetation (e.g., tree canopies) and anthropogenic features (e.g., buildings, towers, etc.). Assuming the elevation of the bald-earth surface is known, an estimate of the interferometric "scattering phase center height" (h_{spc}) can be computed (Brown, 2003; Brown & Sarabandi, 2003; Kellndorfer et al., 2004; Kobayashi et al., 2000; Saich et al., 2001). It follows that the value of h_{spc} is correlated with both the amount and height of vegetation present. Recent research has confirmed the feasibility of using SRTM DEMs together with bald-earth topography data to estimate the height of vegetation canopies (Brown, 2003; Brown & Sarabandi, 2003; Kellndorfer et al., 2004; Walker et al., 2007).

A second dataset with considerable potential to provide information on the horizontal structure of forests is the 2001 National Land Cover Dataset (NLCD; Homer et al., 2004). This multi-layer dataset, currently being developed by the Multi-Resolution Land Characteristics (MRLC) Consortium, uses an ecoregional mapping approach and consists of 1) normalized Tasseled Cap (TC) transformations of Landsat 7 ETM+ imagery from three time periods (early, peak, and late growing season), 2) classified land cover data derived from TC imagery, 3) independent image derivatives of imperviousness and tree canopy density, and 4) independent ancillary data layers including DEM derivatives of slope, aspect and elevation derived from the National Elevation Dataset (NED), which was seamlessly compiled for the entire United Sates for the first time in 1999. All data layers are being released at a grid spacing of 30 m.

A third and final dataset, also under active development, is the multi-partner Landscape Fire and Resource Management Planning Tools Project (LANDFIRE). LANDFIRE is an ecosystem, wildland fire, and wildland fuels mapping project designed to generate a comprehensive suite of spatial data layers describing wildland fuel, existing vegetation composition and structure, historical vegetation conditions, and historical fire regimes. A set of more than 20 national map products is being produced by LANDFIRE using the NLCD ecoregional mapping approach. Specific deliverables include maps of mean fire return interval, percent fire severity, and successional class, as well as existing vegetation type, canopy cover, and canopy height. The canopy height product is currently in development and is slated to be released as a discrete (i.e., five forested height classes) data layer. Aboveground biomass and carbon stocks are not being mapped as part of the LANDFIRE project. Consistent with the NLCD, all LANDFIRE data layers are being released at a grid spacing of 30 m.

The success of a mapping project such as the one proposed here depends largely on the availability of a suitable ground reference database. Complimenting the aforementioned assemblage of national spatial datasets is a national ground reference database available as part of the Forest Inventory and Analysis (FIA) program administered by the USDA Forest Service. In continuous operation since 1930, the FIA program is the only nationwide source of timely, consistent, and reliable forest inventory and monitoring information. The FIA Database (FIADB) contains plot-level forest biometric information collected repeatedly at more than 125,000 locations throughout the United States.

Given the highly complementary nature and quasi-synchronous development of the SRTM, NLCD, and LANDFIRE data sources, an exceptional opportunity exists for exploiting

InSAR/optical synergies. Whereas the SRTM InSAR data provide information pertaining to the vertical structure, i.e., primarily vegetation height, several optically-derived layers provided as part of the NLCD and LANDFIRE projects are suitable for characterizing key aspects of horizontal structure (i.e., vegetation type, canopy cover/density, etc.).

1.3. Objectives

Building on knowledge gained in the context of research conducted by Kellndorfer et al. (2004), Pierce et al. (2006), and Walker et al. (2007), the general objective of this article is to present the results of a proof-of-concept study focused on development of a robust empirical approach for generating a high-resolution, year-2000 baseline estimate of vegetation canopy height for the conterminous U.S. The approach utilizes data fusion, knowledge-based image segmentation, and regression-tree techniques to synergistically exploit the information content of the SRTM interferometric data together with that of data layers obtained from the NED, NLCD and LANDFIRE datasets.

To facilitate development, implementation, and evaluation of the proof-of-concept study, as well as enable future nationwide implementation of the approach, the ecoregional "mapping-zone" concept developed as part of the NLCD 2001 project was adopted for use. The concept, which has also been implemented by the LANDFIRE project, was developed in order to simplify the process of large-scale land cover mapping by stratifying the nation into 66 sub-regions that represent relative homogeneity in terms of biophysical (landform, soil, and vegetation) and spectral characteristics (Homer & Gallant, 2001; Homer et al., 2004). For the purposes of this proof-of-concept study mapping zone 16 (MZ16) was chosen. The zone, which spans over 62,000 km^2 including portions of central Utah, southeastern Idaho, and southwestern Wyoming, was selected because it was the first zone for which all data layers relevant to this research, particularly those currently under production as part of the NLCD and LANDFIRE projects, were available.

2. Mapping zone 16 description

The boundary of MZ16 largely follows that of Ecoregion 19 (Wasatch and Uinta Mountains) of the United States Environmental Protection Agency's Level III Ecoregions of the Conterminous United States (Woods et al., 2001). The zone is composed of a core area of high-elevation, steep, rugged mountains with narrow crests and valleys. This core is flanked in some areas by dissected plateaus and open high mountains (Woods et al., 2001). Elevations within the zone range from 1450 to 4100 m. Over half of the zone is forested, with both vegetation and underlying soils following a pattern of elevational zonation. Low elevations are typically characterized by grasses and a variety of shrubs (often heavily grazed) including sagebrush, chaparral, and mahogany. Low to middle elevations (also grazed) are covered by a range of vegetation types, which include oak and pinyon–juniper woodlands, as well as areas of chaparral, aspen (*Populus tremuloides*), ponderosa pine (*Pinus ponderosa*), and Douglas-fir (*Pseudotsuga menziesii*). Middle to high elevations tend to be covered by large continuous tracts of coniferous forest that include Engelmann spruce (*Picea engelmannii*), subalpine (*Abies lasiocarpa*) and white fir (*Abies concolor*), as well as bristlecone (*Pinus longaeva*), limber (*Pinus flexillis*), and lodgepole pine (*Pinus contorta*). The highest peaks rise well above tree-line and are characterized by alpine vegetation.

3. Model development database

A prerequisite to the construction of multivariate tree-based regression models relating observed canopy height to SRTM and other remote sensing and ancillary data is the compilation of a model development database (MDDB). The MDDB consists of multiple records corresponding to the number of reference observations (i.e., FIA field plots) available within the mapping zone. Each record contains multiple fields, which correspond to the specific response (derived from the FIADB) and predictor (derived from remote sensing and ancillary data sources) variables on which modeling is to be based. The following section describes the various data acquisition, image processing, and computational steps involved in compilation of the MDDB. A diagrammatic summary of these steps is presented in Fig. 1.

3.1. Data acquisition and preprocessing

3.1.1. SRTM and NED data

For a complete description of both the SRTM and NED digital elevation data, the reader is directed to Kellndorfer et al. (2004). The SRTM C-band and NED DEMs for MZ16 were acquired from the United States Geological Survey (USGS) EROS Data Center (Dean Gesch, *pers. comm.*) in the form of 17 individual raster image tiles each covering an area of one degree by one degree. Tiles from each dataset were mosaiced and an SRTM minus NED difference (SRTMDIFF) image was calculated based on the rationale put forth by Kellndorfer et al. (2004). A topographic slope (SLP) layer was also generated from the NED DEM.

3.1.2. NLCD 2001 data

A detailed summary of the NLCD 2001 data-layer production methods is presented by Huang et al. (2001) and Homer et al. (2004). NLCD 2001 data were acquired from the USGS EROS Data Center (Dean Gesch, *pers. comm.*) and included layers of land cover (LC) and canopy density (CD). The LC layer, acquired primarily for reference purposes, consists of 17 classes that generally approximate the thematic detail represented in the Level II classification of Anderson et al. (1976). Developed independently of the LC layer, the CD layer depicts the spatial distribution of tree canopy density (trees ≥ 5 m tall) as a continuous variable with values ranging from 1 to 100% (Huang et al., 2001).

3.1.3. LANDFIRE data

A single data layer, existing vegetation type (EVT), was acquired from the LANDFIRE project website (www.landfire.gov), which is the primary source for additional information on the LANDFIRE project and individual data-layer production methods. The EVT classification scheme is based on the terrestrial ecological systems classification developed by NatureServe for the Western Hemisphere (Comer et al., 2003). The scheme was developed to provide a practical, mid-scale classification unit that could be readily mapped from remotely sensed imagery and readily identified by managers in the field. Of the 599 ecological systems (hereafter referred to as classes) identified within the U.S., 60 were observed to occur within MZ16. Of these, 53 were characterized by some form of woody or herbaceous vegetation while the remaining seven were non-vegetated, e.g., water, permanent snow/ice, barren, developed, etc. Of the vegetated classes, 23 were forested.

3.1.4. FIA data

The monitoring component of the FIA program consists of a systematic sample across all public and private lands in the U.S. In the late 1990s, the FIA program adopted a common field plot design consisting of four 1/24th acre fixed-radius (24.0 ft/7.3 m) subplots (FIA, 2004). Field plots are distributed across the landscape with approximately one sample (FIA plot) every

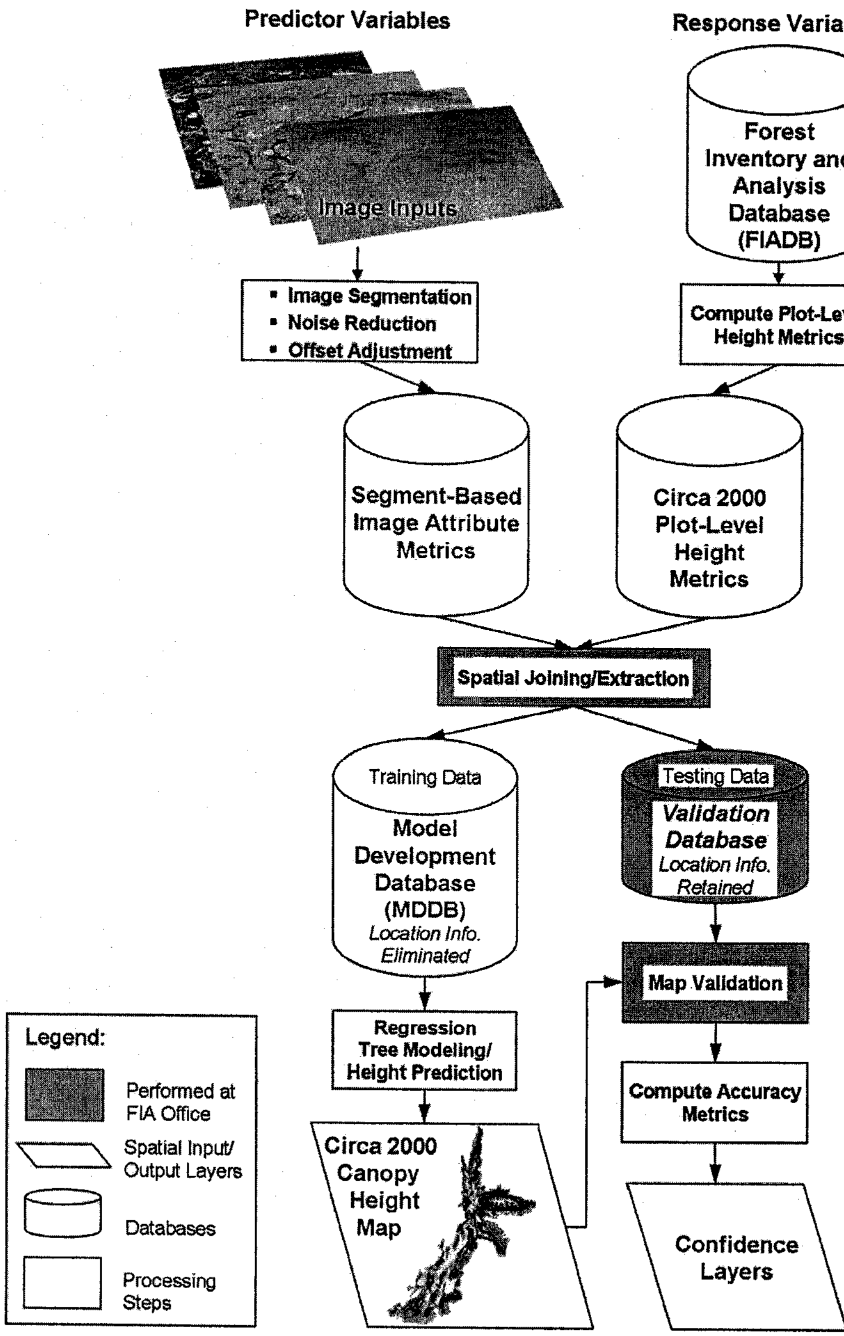

Fig. 1. Process flow diagram depicting the principal steps in the height mapping approach.