Computer Applications in Sustainable Forest Management

Including Perspectives on Collaboration and Integration

Edited by

Guofan Shao
Purdue University, West Lafayette, IN, U.S.A.

and

Keith M. Reynolds
USDA Forest Service, Corvallis, OR, U.S.A.

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Chapter 3

ACTIVE REMOTE SENSING*

Hans-Erik Andersen[1], Stephen E. Reutebuch[2], and Robert J. McGaughey[2]
[1]*College of Forest Resources, University of Washington, Seattle, Washington 98195, USA;*
[2]*U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Seattle, Washington 98195, USA*

Abstract: The development of remote sensing technologies increases the potential to support more precise, efficient, and ecologically-sensitive approaches to forest resource management. One of the primary requirements of precision forest management is accurate and detailed 3D spatial data relating to the type and condition of forest stands and characteristics of the underlying terrain surface. A new generation of high-resolution, active remote sensing technologies, including airborne laser scanning (LIDAR) and interferometric synthetic aperture RADAR (IFSAR) have the capability to provide direct, 3D measurements of forest canopy structure and topography. High resolution LIDAR can be used to measure attributes of individual tree crowns composing the overstory forest canopy. In addition, metrics based upon the lidar height distribution are highly correlated with critical forest structure variables, such as dominant height, basal area, stem volume, and biomass. IFSAR is a microwave remote sensing technology that is also capable of providing 3D positions of backscattering elements within a forest scene. While IFSAR typically provides measurements of lower resolution and accuracy than LIDAR, it has an all-weather capability and is acquired at a much lower cost per unit area. In addition, the use of multiple-frequency RADAR systems allows for the collection of information on different scene components. For example, long-wavelength P-band energy penetrates through the canopy and reflects mainly from the terrain surface, while short-wavelength X-band energy reflects from the first reflective surface. Therefore, the difference between the X-band (canopy) surface measurements and the P-band (terrain) surface will yield vegetation height information. In this chapter, we will describe the basic principles of these active remote sensing technologies in the context of forest canopy inventory and terrain mapping, and present an example of their application within a Pacific Northwest conifer forest.

Key words: Interferometry; laser scanning, RADAR; accuracy; forest; vegetation; survey; lidar; IFSAR; DEM.

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1. INTRODUCTION

Forests are structured as complex systems in three-dimensional or 3D space. The 3D structural organization of the forest canopy and the morphology of the underlying terrain are critical determinants of light regime, micro-climatic variability, and soil characteristics that drive the functional processes of forest ecosystem dynamics (Spies 1998). Effective management of complex forest ecosystems for the provision of a diverse array of outputs, including high-quality habitat, clean water, commercial timber, and recreational opportunities, is dependent upon the ability to quantify and measure critical forest structure attributes and micro-scale terrain characteristics.

Accurate estimation and monitoring of these 3D forest attributes requires collection of 3D data (Andersen 2003). These data are typically collected using traditional stand examination and topographic survey techniques, and are expensive and labor-intensive to acquire. Due to the high costs, the sampling intensity of these field-based inventory programs is typically limited, making the estimates acquired over large, heterogeneous forest areas subject to sampling error. In contrast, remotely sensed data, acquired from either an airborne or spaceborne platform, are potentially cheaper and less labor intensive to acquire, and are spatially extensive, theoretically reducing sampling error. While it is widely recognized that forest structure information is needed over large areas of the United States to meet ecosystem management objectives, the application of remote sensing-based inventories has been limited in scope due the limitations of existing data, processing techniques, and methodology.

The main limitation of remotely sensed data acquired from a passively-sensed technology (such as an aerial camera or satellite-based imaging system) for the acquisition of forest structure and terrain information is related to the fact that the illumination geometry and intensity are not controlled, and that the analysis requires an inference from 2D to 3D. The formation of passive, remotely sensed imagery is dependent upon reflected solar radiation, and is, therefore, subject to the effects of shadowing and bidirectional reflectance, which by virtue of simple geometry severely limit the amount of light reflected back to the sensor from components beneath the canopy surface. Photogrammetric measurement techniques permit the acquisition of 3D information from overlapping 2D imagery (i.e. aerial photographs, high-resolution satellite imagery), but requires that measured points be identified as conjugate points either through manual stereoscopic viewing or application of automated image correlation algorithms. Given the myriad of geometric and illumination effects at play in the formation of a complex forest scene in passive imagery, it is very difficult to train an automated algorithm to correlate (and measure) imaged points on the irregular surface of the canopy, and impossible to measure points underneath the surface that are not imaged. While passively-sensed 2D images are an invaluable source of data on spectral reflectance properties within forest areas, they have limited utility for acquiring accurate information on the 3D properties of the canopy and underlying terrain surface.

2. ACTIVE, HIGH-RESOLUTION AIRBORNE REMOTE SENSING TECHNOLOGIES FOR PRECISION FORESTRY

The emergence of a new generation of active, high-resolution airborne remote sensing technologies in recent years, enabled by the concurrent development of precise geopositioning technologies such as differential global positioning systems (GPS) and inertial navigation systems, has given rise to a source of data that is particularly well-suited to the measurement of 3D forest attributes. Specifically, airborne laser scanning (LIDAR) and interferometric synthetic aperture RADAR (IFSAR) are not subject to the limitations of passively-sensed imagery described above. Small-footprint, discrete-return LIDAR sensing systems emit pulses of laser energy in a narrow beam, and record a coordinate for each laser reflection along a swath beneath the aircraft. LIDAR systems are characterized by actively-pulsed emission of radiation and highly-controlled illumination geometry, enabling the accurate, detailed measurement of reflecting surfaces (i.e. leaves, branches, stems) down through the full depth of the forest canopy. Research in recent years has shown that high-resolution, small-footprint LIDAR data can be used to extract highly detailed information relating to vegetation structure and terrain characteristics (Reutebuch et al. 2005).

IFSAR systems operate in the microwave portion of the electromagnetic spectrum, and rely upon different sensing principles than optical LIDAR technology. Relatively low-frequency microwave energy used in RADAR systems will physically penetrate the canopy volume, where the degree of penetration is a function of the RADAR frequency. RADAR systems also have the capability to penetrate through cloud cover, which can be a critical factor in acquiring data over areas of the world that are nearly perpetually overcast, such as the tropics. IFSAR data can be characterized as the result of an integrative signal processing procedure, where the 3D location and characteristics of an actively-sensed object or surface point are inferred from the combination of various signal responses associated with this scattering element. The collection of IFSAR at multiple frequencies allows for direct measurement of the geometry of the canopy and terrain surfaces, and can provide a powerful description of forest canopy structure. While the resolution of IFSAR systems cannot, at present, match that of LIDAR, the all-weather capability and lower cost per unit area of IFSAR data indicate that it will emerge as an economically viable option for large area forest survey applications.

The emergence of active, high-resolution, airborne remote sensing technologies has the potential to significantly improve the quality and detail of the spatial data available to the forest manager. In this chapter, we will describe the basic principles of these advanced active remote sensing technologies and discuss their application to forest inventory and terrain mapping.

3. PRINCIPLES OF AIRBORNE LASER SCANNING

Airborne laser scanning, also known by the acronym LIDAR (Light Detection and Ranging), is an operationally mature remote sensing technology that can provide highly-accurate measurements of both forest canopy and ground surface[1]. A LIDAR sensor system essentially works upon the principle of measuring the time interval between the emission and reception of laser pulses. Range measurement is performed by multiplying this time interval by the speed of light ($R = c \times t/2$ (where, R is the range, t is the time interval between emission and receiving the pulse, and c is the speed of light, a known constant: 3×10^8 m/s)).

The leading edge of the returning signal is not a well-defined point, so the time is usually recorded for a point at which the signal exceeds a certain threshold level, which is usually defined as a constant fraction of the signal peak (Baltsavias 1999). If the precise orientation and position of the laser is known from an inertial measurement unit and airborne differential GPS systems, respectively, the 3D vector corresponding to each laser pulse can be reconstructed, and a 3D coordinate assigned to each reflection. The "raw" LIDAR data are then typically provided as an ASCII or binary file

[1] LIDAR systems are classified into two types, depending upon the size of the "footprint" for the laser pulse. "Small footprint" systems typically have footprint diameters of less than 1 meter, while "large-footprint" systems have footprint diameters greater than 10 meters. Given that large footprint, continuous waveform LIDAR systems are neither commercially available nor capable of providing high resolution data, in this chapter we will restrict our discussion to the use of small-footprint, discrete-return LIDAR data. The application of large footprint LIDAR to forestry applications has been discussed in Harding et al. (2001) and Lefsky et al. (2002).

containing X,Y,Z values corresponding to the coordinates of each laser reflection.

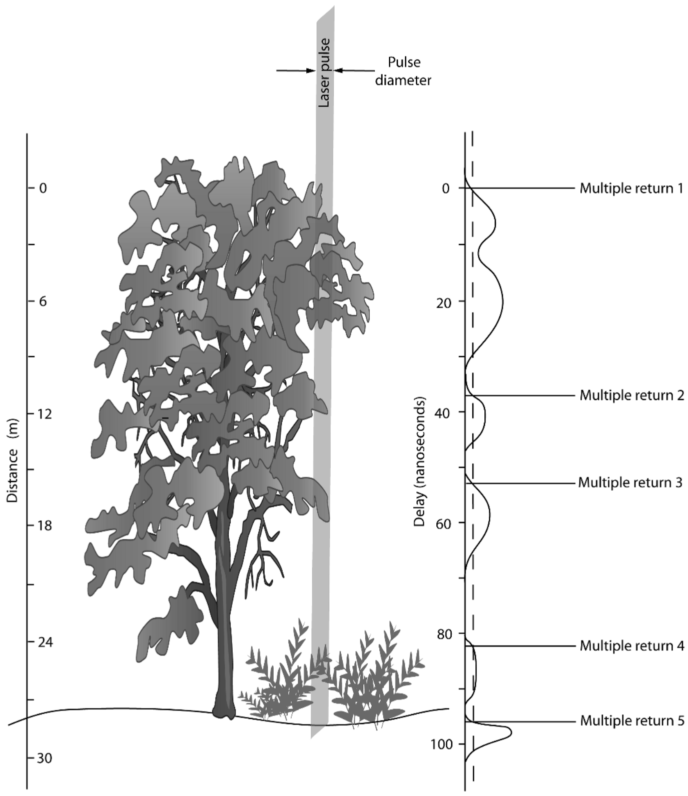

Figure 3-1. LIDAR remote sensing of vegetation. As the laser pulse passes through tree canopy, a signal is returned to the sensor. The leading edges of peaks in the returned signal correspond to multiple returns. Adapted from Lefsky et al. (2002).

The power received by the sensor will depend upon target characteristics, including the physical properties of the target (i.e. diffuse vs. specular reflector) and absolute target, reflectivity. LIDAR systems used for topographic mapping applications usually operate in the near infrared range of the electromagnetic spectrum (800-1100 nm). While specifications vary among systems, current LIDAR systems emit from 5,000-100,000 pulses per second, and vary the scan angle using optical-mechanical devices such as oscillating mirrors. Most systems have the capability of recording multiple reflections from a single laser pulse (i.e. up to 5 per pulse). For example, in a forest area a given pulse may reflect from branches or leaves within the vegetation canopy and the ground below (Figure 3-1). As the scan angle is usually limited to 15-20 degrees off nadir, this system acquires measurements along a “swath” beneath the aircraft (Figure 3-2). For airborne, small-footprint systems, the footprint, or spot size, of the LIDAR pulse when it reaches the ground (or canopy surface) ranges from 0.10-1 meter depending upon flying height. In forested areas, the energy from individual LIDAR pulses can penetrate through gaps, and can therefore provide measurements of the underlying terrain surface.

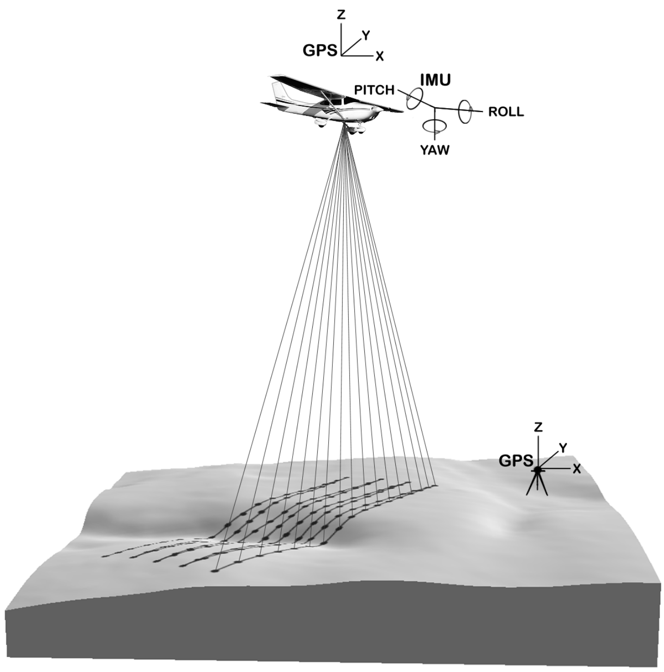

Figure 3-2. An illustration of airborne laser scanning.

4. LIDAR TERRAIN MAPPING IN FORESTED AREAS

The application of LIDAR for mapping of forested terrain has been a prominent research theme in recent years. The main challenge in using LIDAR to develop terrain models lies in the development of filtering algorithms that effectively separate the LIDAR returns reflecting from the ground surface from those reflecting from the vegetation. These algorithms typically employ an iterative approach where "spikes" in the last return LIDAR data set are systematically removed based upon a measure of local curvature (Sithole and Vosselman 2003). While several of these algorithms are documented in the open literature, for the most part the development of these techniques has remained a proprietary activity (Elmqvist 2002, Haugerud and Harding 2001, Kraus and Pfeifer 1998). In several studies, the accuracy of digital terrain models derived from LIDAR was found to be significantly higher than that obtained from conventional aerial photogrammetric methods. For example, in several studies conducted in a Pacific Northwest conifer forest in western Washington State (USA) that evaluated the accuracy of LIDAR-derived and USGS DTMs through comparison to surveyed check point elevations, the root mean square error (RMSE) of the LIDAR DTM was found to be 0.32 meter, while the RMSE of the standard USGS 10-meter DTM was 8.8 meters (Andersen et al. 2005b, Reutebuch et al. 2003). Visual assessment of these DTMs in this forested area confirms the quantitative findings – the high level of detail contained in the LIDAR DTM, including small-scale drainage features, road prisms, and microtopography, is quite evident when compared to the coarser resolution of the USGS 10-meter DTM (Figures 3-3 and 3-4) (Plates 3-3 and 3-4). The accuracy of the LIDAR-derived DTM generated from high-density LIDAR data (e.g. 4 returns/m^2) was not found to be highly correlated with any measure of canopy density, indicating that LIDAR can be effectively used to generate highly accurate DTMs even in areas with very dense forest cover (Reutebuch et al. 2003).

5. LIDAR FOR FOREST INVENTORY APPLICATIONS

Methodologies for extracting forest measurement information from LIDAR data have been carried out at two different scales - individual tree-level and plot-level - depending upon the type of data used and the type of application. When data are acquired at a high enough density (resolution), the dimensions of individual trees composing the overstory canopy can be measured using the LIDAR-derived canopy surface model (Figure 3-5) (Plate 3-1). In one approach, computer vision algorithms are implemented to automatically recognize and measure various attributes of individual trees, including total height, crown height and crown diameter.

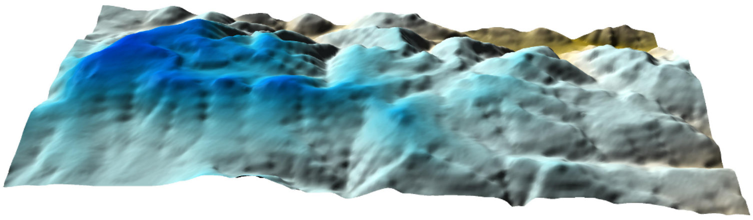

Figure 3-3. Shaded relief of the USGS 10-meter DTM for Capitol Forest study area, Washington, USA. (See also color plate 3-3 on p. CP2)

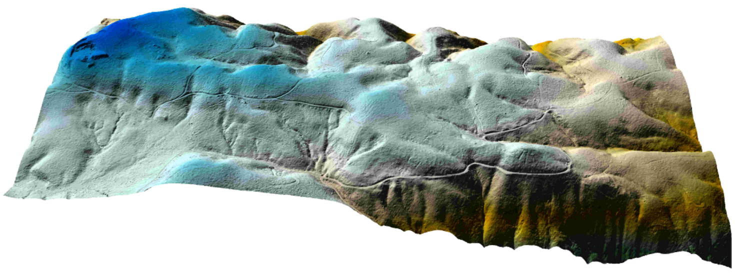

Figure 3-4. Shaded relief of the LIDAR-derived digital terrain model for Capitol Forest study area, Washington, USA. (See also color plate 3-4 on p. CP3)

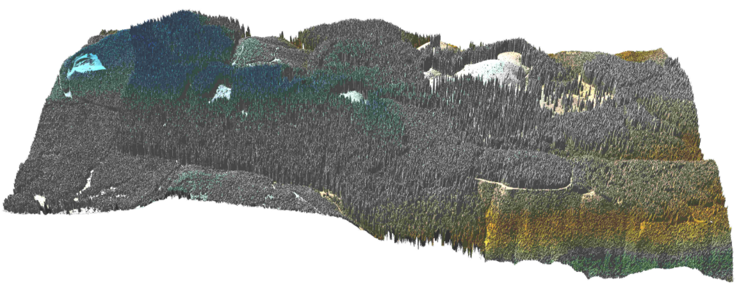

Figure 3-5. Shaded relief of the LIDAR-derived canopy surface model for Capitol Forest study area, Washington, USA. (See also color plate 3-5 on p. CP3)

Probably the most widely used computer vision algorithm for extraction of individual tree-level information from high density LIDAR is the morphological watershed algorithm (Soille 1999). In this algorithm, the (inverted) canopy surface model is considered to be a collection of small "watersheds" associated with the inverted shapes of individual tree crowns. The morphological watershed algorithm then segments the canopy height model into areas associated with each tree crown composing the surface (Figures 3-6a and 3-6b) (Plates 3-6 and 3-7). Several studies have shown that morphological computer vision techniques (such as the watershed algorithm) can be effectively used to identify tree crown structures and measure individual tree attributes (Persson et al. 2002, Schardt et al. 2002, Straub 2003, Ziegler et al. 2000). When LIDAR data from different years are acquired, this approach can be used to analyze height growth and crown expansion at the individual-tree level (Andersen et al. 2005c, Yu et al. 2004).

An alternative approach to the analysis of LIDAR for extraction of forest measurements uses regression to model the relationship between a collection of metrics describing the spatial distribution of LIDAR returns within a plot area (e.g. 0.1 ha) and stand measures derived from field measurements collected at this plot (e.g. basal area, stem volume, dominant height). This approach is particularly useful when LIDAR data are collected at a lower density, or the vertical structure of the forest is complex (i.e. composed of multiple canopy strata). Typically, the metrics used to describe the spatial distribution of LIDAR returns in a plot area include several height quantile measures (e.g. 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentile heights), as well as other metrics such as the mean height, maximum height, and coefficient of variation of height, and a LIDAR-derived measure of canopy cover, e.g. the percentage of LIDAR first returns that reflect from the canopy (e.g. higher than 2 meters above the terrain). This plot-level approach has been used by researchers in the United States and Europe to estimate stand inventory parameters in several different forest types, where predictive regression models were shown to explain from 80 to 99 percent of the variation (i.e. R^2) in field-measured values (Means et al. 2000, Næsset 2002, Næsset and Okland 2002). In a study carried out using 99 field plots measured at the Capitol Forest study area in Washington State (described previously), strong regression relationships between LIDAR-derived predictors and field-measured values were found for several critical inventory parameters, including basal area ($R^2 = 0.91$), stem volume ($R^2 = 0.92$), dominant height ($R^2 = 0.96$), and biomass ($R^2 = 0.91$) (Figures 3-7a, 3-7b, -37c and 3-7d) (Andersen et al. 2005c). This approach has also been used to estimate several important canopy fuel parameters using LIDAR data (Andersen et al. 2005a). Although the results are somewhat preliminary, recent research has also indicated that the intensity of the near-infrared reflection from LIDAR data acquired in leaf-off conditions can be used to determine species type (Brandtberg et al. 2003).

6. PRINCIPLES OF INTERFEROMETRIC SYNTHETIC APERTURE RADAR

Side-looking airborne RADAR (SLAR) is an active imaging technology that operates in the microwave portion of the electromagnetic spectrum[2]. SLAR operates on the principle of emitting short pulses of microwave energy and recording the reflection from a given area on the ground. The resolution of a side-looking RADAR imaging system in the cross-track direction (i.e. perpendicular to the flight path) is determined by the pulse duration (shorter pulse = higher across-track resolution), while the resolution of the RADAR in the azimuth direction (parallel to flight direction) is determined by the length of the antenna aperture (i.e. longer aperture = higher azimuth resolution) (Figure 3-8).

Because practical considerations will limit the length of a real aperture, in synthetic aperture RADAR (SAR) imaging a very long aperture is synthesized through integration of the magnitude and phase information of the returned echoes from a feature over the entire time it is in view of the RADAR (Waring et al. 1995). Because relatively long-wavelength RADAR energy penetrates through (even dense) water vapor, RADAR imaging is often possible in situations where optical sensing is severely limited or even impossible due to persistent cloud cover. The strength of the signal received by RADAR antenna for a given ground resolution cell (represented by *RADAR backscatter coefficient* σ^o) is mainly a function of the wavelength of the microwave energy, the characteristics of the imaged feature, and the geometry of the image acquisition (Jensen, 2000).

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[2] Imaging RADAR systems are operated from both airborne and spaceborne platforms. Spaceborne systems typically have spatial resolutions ranging from 10 - 30 m, while airborne RADAR systems have resolutions from 1-10 meters.

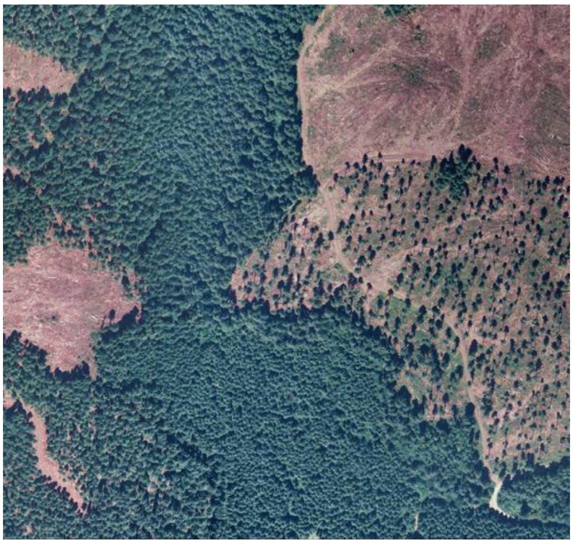

Figure 3-6a. Orthophoto of selected area, Capitol Forest study area, Washington, USA. (See also color plate 3-6a on p. CP4)

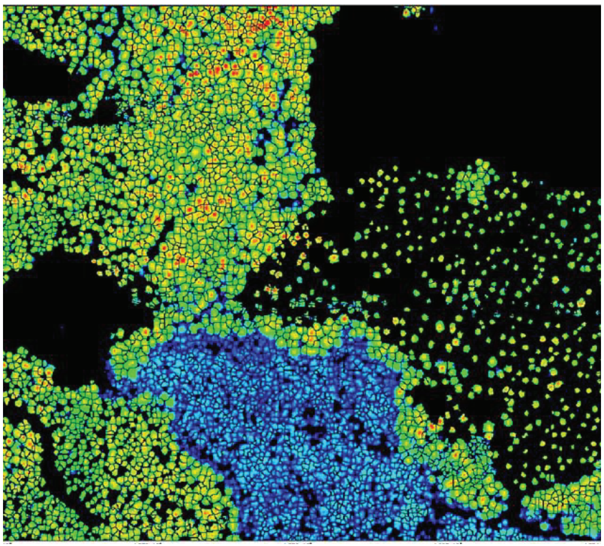

Figure 3-6b. Individual tree-level segmentation of LIDAR canopy height model via morphological watershed algorithm (color-coded by height: blue = 20 m, green = 30 m, yellow = 40 m, red = 50 m; black lines indicate boundaries of segments; black areas indicate areas with no tree cover). (See also color plate 3-6b on p. CP4)

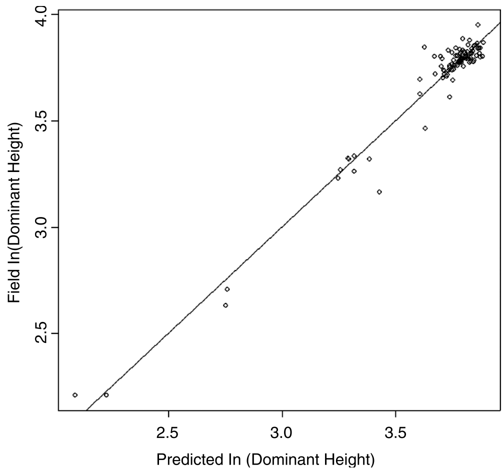

Figure 3-7a. Results of plot-level LIDAR-based estimation of forest inventory parameters at Capitol Forest study site. Scatterplot represents relationship between predicted (x) and field-based (y) estimates of dominant height at the individual plots. Line represents 1:1 relationship.

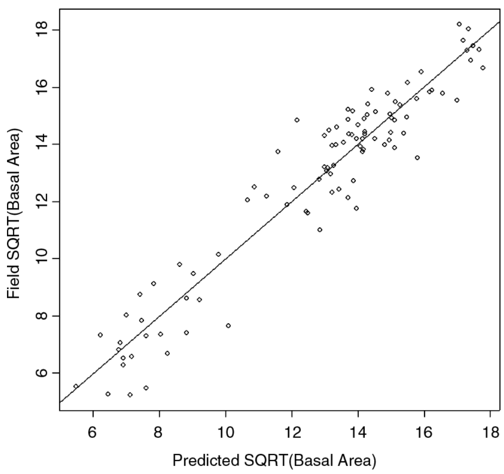

Figure 3-7b. Scatterplot representing relationship between predicted (x) and field-based (y) estimates of basal area at the individual plots.

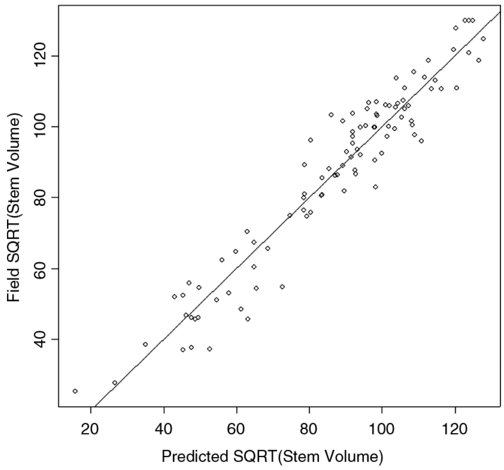

Figure 3-7c. Scatterplot representing relationship between predicted (x) and field-based (y) estimates of stem volume at the individual plots.

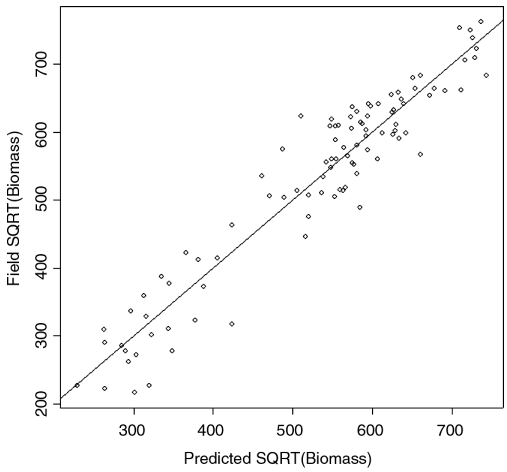

Figure 3-7d. Scatterplot representing relationship between predicted (x) and field-based (y) estimates of biomass at the individual plots.

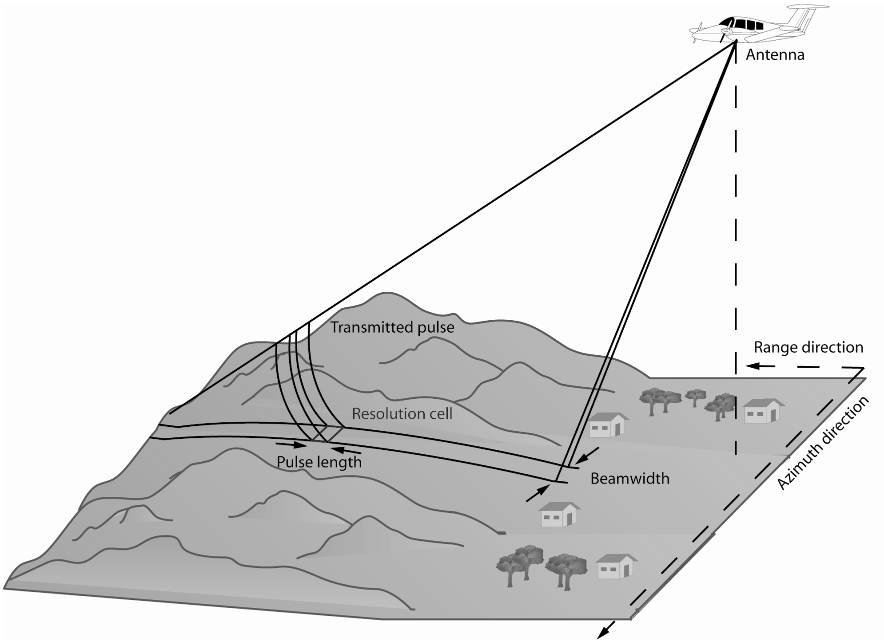

Figure 3-8. Geometry of a side-looking airborne RADAR system. Adapted from Lillesand and Kiefer (1987).

In the context of forest vegetation mapping, the wavelength of the RADAR system will determine whether the SAR backscatter is dominated by surface scattering or volume scattering. When relatively short-wavelength (i.e. 3 cm for X-band) microwave energy interacts with the surface of the forest canopy, the energy is scattered by small-scale components of the canopy, such as the foliage and small branches. Therefore at these wavelengths the RADAR energy reflects mainly from the surface of the canopy (Figure 3-9). In contrast, RADAR energy with relatively long wavelengths (i.e. 74 cm for P-band) will penetrate into the canopy and reflect from large scale components composing the canopy, including large branches, stems, and the terrain surface. Therefore for long wavelength RADAR systems the reflectance is dominated by volume scattering from large-scale canopy features and surface scattering from the terrain surface (Figure 3-9). The magnitude of RADAR backscatter (i.e. reflection) from a feature is also dependent upon a variety of surface characteristics, including structure, surface roughness, and water content. In addition, some SAR systems have the capability to send and receive energy with different polarizations. Because RADAR energy can be depolarized upon interaction with various surface features, independently recording the reflection of like-polarized energy (e.g. vertical send – vertical receive (VV) or horizontal send – horizontal receive (HH)) and cross-polarized energy (e.g. vertical send – horizontal receive (VH) or horizontal send – vertical receive (HV)) can yield valuable information regarding the characteristics of imaged features, and can be particularly useful in the analysis of vegetation type and structure. For example, if the RADAR energy interacts mainly with single scatterers at the surface of the canopy, the energy is not depolarized and there is a strong reflection of like-polarized energy. In contrast, if the RADAR energy is reflected from multiple scatterers within the canopy structure, it is often depolarized and there is a strong reflection of cross-polarized energy (Jensen 2000). A RADAR image acquired from a system with a particular frequency, polarization, and incidence angle can therefore provide information related to canopy water content, vegetation type, biomass components (foliage, branches, stems), and canopy structure (leaf orientation, leaf area index, main stem geometry and spatial distribution) (Jensen 2000, Carver 1988).

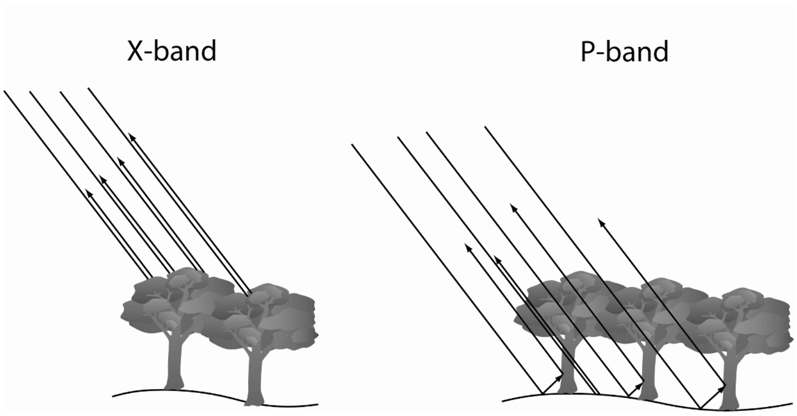

Figure 3-9. Short wavelength X-band RADAR energy reflects from canopy surface while long wavelength P-band energy penetrates through canopy and reflects from stems and terrain surface Adapted from Moreira et al. (2001).

While SAR images can provide important information relating to vegetation properties, the inherently 2D format of the data only allows for indirect estimation of 3D structural attributes within a forested scene. The development IFSAR in recent years has enabled the direct measurement of the elevation of scattering elements within a ground resolution cell. Determining the 3D coordinates of reflecting surfaces using IFSAR involves quantitative analysis of the phase shift between two complex-valued RADAR images obtained with slightly different imaging geometries. The interferometric phase difference at each image point is related to the difference in path length between each antenna and the point, which is a function of surface elevation. This interferometric phase information can be combined with knowledge of the sensing geometry for each antenna to obtain an elevation for each image point (Rosen et al. 2000) (Figure 3-10). Because the penetration of microwave energy into a forest canopy is a function of RADAR wavelength, the interferometric surface elevation obtained in a forested setting will also be a function of wavelength. For example, the interferometric measurements obtained from an X-band RADAR with a relatively short wavelength will represent the “first-return” surface of the canopy (Figure 3-11) (Plate 3-11), while the interferometric elevation measurements from a long-wavelength P-band system will generate a surface corresponding to the underlying terrain and understory vegetation (Figure 3-12) (Plate 3-12).

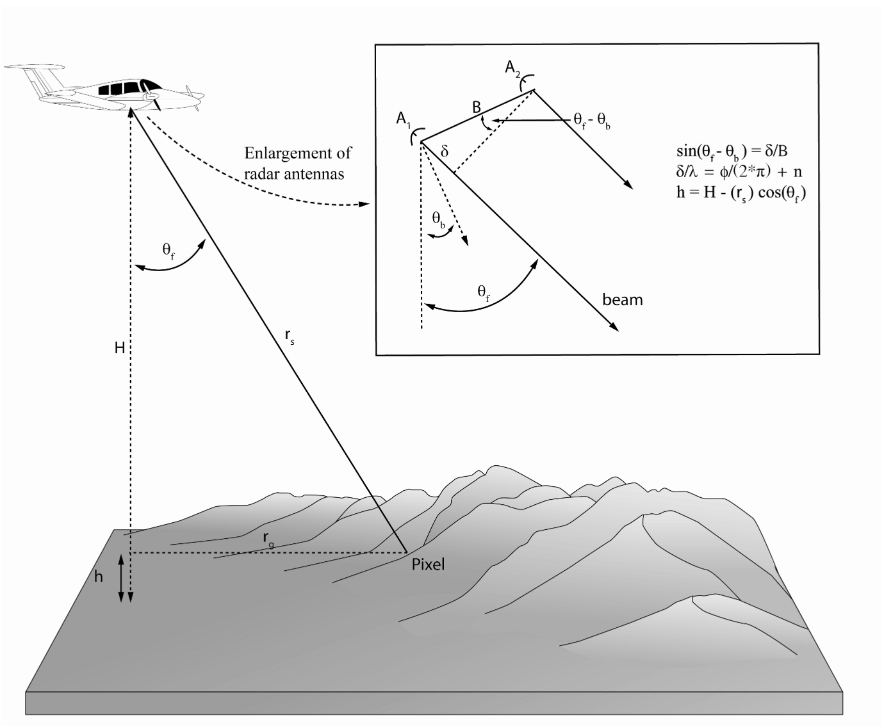

Figure 3-10. Geometry of RADAR interferometry. Adapted from Mercer (2004).

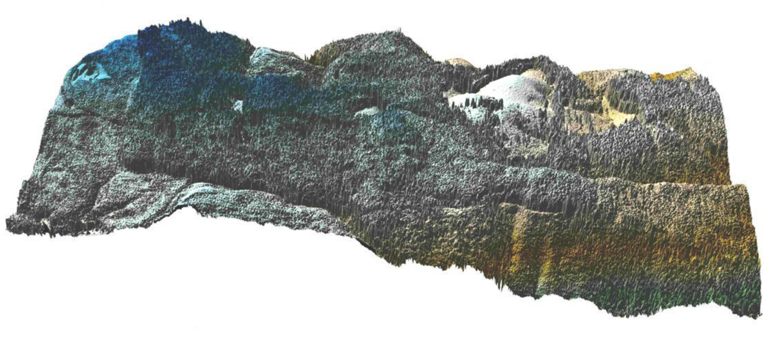

Figure 3-11. Shaded relief of the canopy surface model generated from X-band IFSAR data at Capitol Forest study area, Washington, USA. (See also color plate 3-11 on p. CP5)

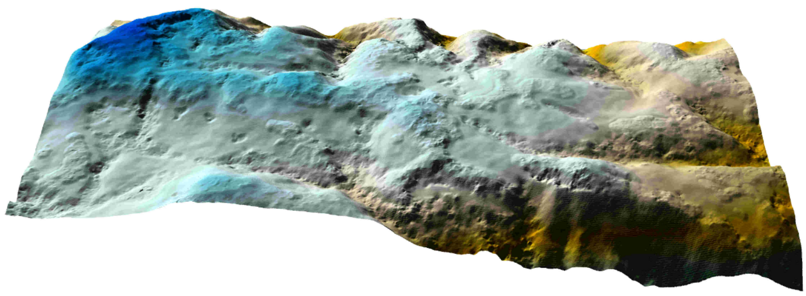

Figure 3-12. Shaded relief of the digital terrain model generated from P-band IFSAR data at Capitol Forest study area, Washington, USA. (See also color plate 3-12 on p. CP5)

7. IFSAR TERRAIN MAPPING IN FORESTED AREAS

Several very-large scale mapping campaigns in recent years have established the cost-effectiveness of the IFSAR technology for terrain mapping. For example, the commercial vendor Intermap Technologies Corporation has embarked on an ambitious campaign to acquire topographic data at national scales using their Star-3i X-band IFSAR system. Intermap has already acquired IFSAR-derived topographic data for all of Great Britain, through the NextMap Britain program. Because the accuracy of interferometric measurement is also a function of wavelength, in areas within little vegetation the X-band IFSAR-derived surface can be highly accurate. For example, in a study carried out in Germany, the accuracy of an X-band IFSAR-derived DTM was reported at 20 cm (Schwäbisch and Moreira 1999). Validation of the topographic data acquired in the NextMap Britain project also reflects this level of accuracy. An accuracy assessment of the NextMap Britain project, carried out via comparison to LIDAR, GPS, and photogrammetric checkpoints, resulted in RMSE values ranging from 0.5-1.1 m in various conditions (Mercer 2004). While the topographic data acquired from X-band IFSAR systems are quite accurate in areas with little or no vegetation cover, the accuracy of these data declines in areas with dense forest cover, due to the fact that it is essentially a "first return" surface. For example, Hodgson and others (2003) evaluated the accuracy of X-band IFSAR-derived DTMs in a mixed deciduous forest in North Carolina and reported an overall RMSE of 10.7 meters.

The inherent limitations of X-band systems for topographic mapping in forested areas has led to increased interest in the development and application of airborne IFSAR systems that utilize RADAR energy at longer wavelengths (i.e. P-band) that will penetrate through the forest canopy and reflect from the underlying terrain surface. For example, a recent study reported an RMSE of 2.6 meters for a P-band IFSAR-derived DTM acquired for a conifer forest with varying levels of forest density in the Pacific Northwest (via comparison to 347 high-accuracy topographic check points acquired with a total station survey) (Andersen et al. 2005b). An earlier study of P-band accuracy carried out in a forested area of Germany showed an accuracy of 5 meters (Hofmann et al. 1999). While these recent results have indicated the potential of P-band IFSAR for topographic mapping over large areas, to date the application of these systems has been limited to the research domain, mainly due to constraints upon the available bandwidth and interference with communication systems.

8. MULTI-FREQUENCY IFSAR FOR FOREST INVENTORY APPLICATIONS

The use of multi-frequency IFSAR data allows for independent measurement of both the canopy and terrain surfaces, where canopy level measurements are generated from X-band and terrain-level information is obtained from the P-band IFSAR data (Figure 3-13) (Plate 3-13). An IFSAR-derived canopy height model can be generated easily as the difference between the X-band canopy surface model and the P-band terrain model.

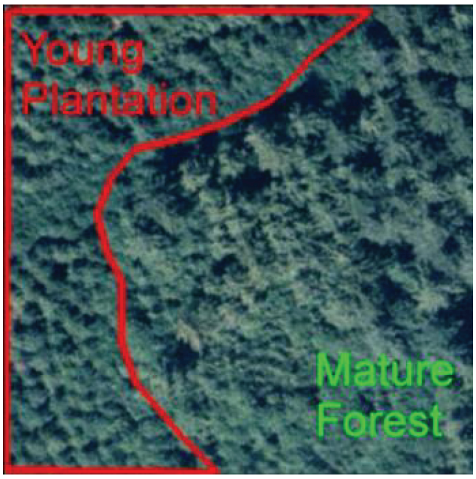

Figure 3-13a. Orthophoto of area with young plantation and mature forest in Capitol Forest study area, Washington, USA. (See also color plate 3-13a on p. CP6)

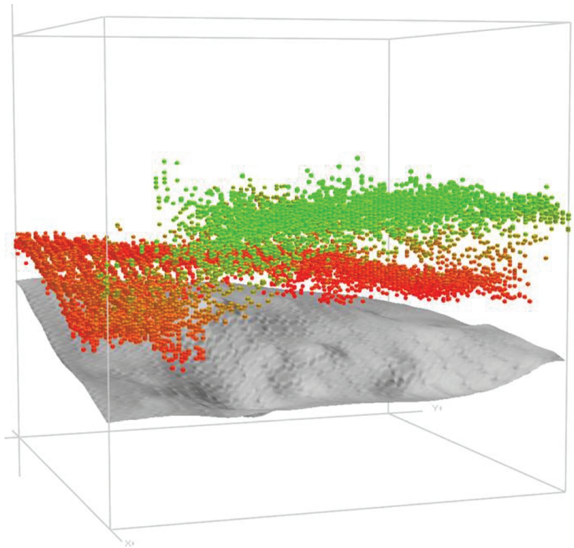

Figure 3-13b. 3D graphical visualization of above area showing X-band IFSAR elevation measurements (color-coded by height) overlaid on P-band digital terrain model. (See also color plate 3-13b on p. CP6)

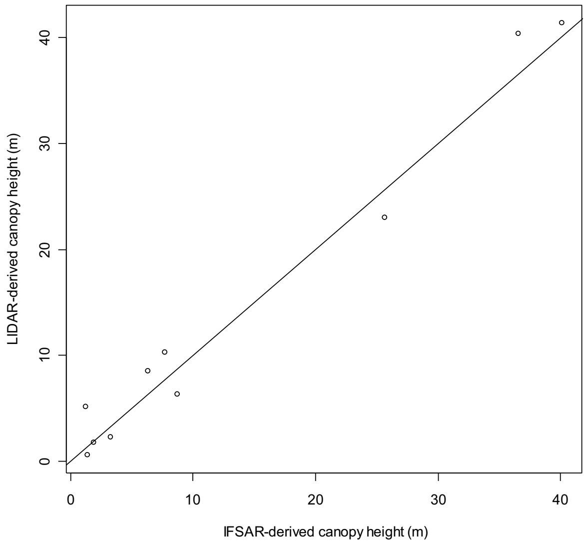

Figure 3-14. Relationship between LIDAR-derived stand heights and IFSAR-derived stand heights. Stand height is calculated as the median value of the canopy height model within a stand. Line represents 1:1 relationship.

In a study carried out at a conifer forest within the Pacific Northwest, using a multi-frequency X-band/P-band system, a high correlation was found between the IFSAR-derived canopy height and LIDAR-derived canopy height at the stand level (r = 0.99) (Figure 3-14). The geometric (height) information provided by SAR interferometry has the potential to dramatically increase the utility of RADAR data for forest inventory applications. Because even long-wavelength P-band RADAR backscatter tends to be less and less sensitive to changing biomass levels beyond 100 tons per hectare due to saturation, the utility of SAR for forest inventory in highly productive temperate forests and tropical rainforests can be limited (Imhoff 1995). Recent studies have shown that interferometric observables, such as coherence and phase, are more sensitive than RADAR backscatter to changes in forest structure parameters at higher biomass levels (Treuhaft and Siqueira 2004). The use of IFSAR therefore reduces the effect of RADAR saturation and provides for more accurate estimation of forest inventory variables across a broad range of forest types. In a study investigating the utility of X-band/P-band IFSAR data for tropical forest mapping in a region of the Brazilian Amazon with biomass levels reaching 350 tons/ha, high correlations were reported between interferometric height (X-band – P-band)

and forest height from ground measurements ($R^2 = 0.87$) (Santos et al. 2004). In the same study, a predictive linear model for biomass was developed using P-band backscatter (HH polarization) and interferometric height as independent variables ($R^2 = 0.89$). Therefore, the results of this study indicate that the inclusion of interferometric variables can successfully alleviate the problem of RADAR saturation in tropical forest biomass estimation. It should be mentioned that recent theoretical developments in the electrical engineering community have indicated the potential for incorporating the polarimetric information into the interferometric analysis of forest structure and terrain (Cloude et al. 2002). Recent research has also proposed using IFSAR data acquired at multiple baselines in order to infer the vertical distribution of canopy materials (Reigber et al. 2000).

9. CONCLUSIONS

The quality and quantity of spatial information now becoming available to the resource management community due to the emergence of high-resolution active remote sensing technologies is truly remarkable. In the near future, a forest manager can expect to have accurate, and highly-detailed, digital information relating to terrain morphology and forest stand structure provided as standard remote sensing deliverables. Although the concurrent development of high-resolution passive remote sensing technologies, including hyperspectral airborne sensors such as the Compact Airborne Spectrometer Instrument (CASI), also promises to provide a tremendous amount of information relating to species class and condition, it can be argued that the emergence of active airborne remote sensing technologies, such as LIDAR and IFSAR, will represent a truly revolutionary advance in how we measure and inventory natural resources. The demonstrated capability of these systems to provide a direct measurement of 3D structure and terrain, enabled through the application of precise geopositioning technologies such as GPS and inertial measurement systems, will allow foresters to implement a site-specific approach to environment management, optimizing use and therefore increasing the value of the forest resource.

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