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LIDAR REMOTE SENSING OF FOREST CANOPY STRUCTURE AND  
RELATED BIOPHYSICAL PARAMETERS AT THE H.J. ANDREWS  
EXPERIMENTAL FOREST, OREGON, USA

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## ABSTRACT

Scanning lidar remote sensing systems have recently become generally available for use in ecological applications. Unlike microwave and conventional optical sensors, lidar sensors directly measure the distribution of vegetation material along a vertical axis and can be used to provide three-dimensional characterizations of vegetation structure. Ecological applications of scanning lidar have previously used uni-dimensional indices of canopy height. A new three-dimensional approach to interpreting lidar waveforms was developed to characterize the total volume of vegetation and empty space within the forest canopy, and their spatial organization. These aspects of the physical structure of canopies have been infrequently measured, either from field or remote methods. We applied this approach to 21 plots in Douglas-fir / Western Hemlock stands on the west side of the Cascade range in Oregon, which had coincident lidar measurements and field surveys. We were able to predict both biomass and leaf area index from the volumes of four classes of canopy structure. These predictions were non-asymptotic over a wide range, up to 1200 Mg ha<sup>-1</sup> of biomass and an LAI of 12, with 90 % and 88 % of variance explained, respectively. Furthermore, we were able to make accurate estimates of other stand structure attributes, including the mean and standard deviation of diameter at breast height, the number of stems greater than 100 cm in diameter, and independent estimates of the basal area of Douglas-fir and Western hemlock.

These measurements are directly related to indices of forest stand structural complexity, such as those developed for old-growth forest characterization.

## INTRODUCTION

Characterization of forest structure in moderate to high biomass systems is one of the key challenges in remote sensing. The need for wide-scale inventory of the amount and complexity of forest structure is especially pressing in the Pacific-Northwest where Douglas-fir [*Pseudotsuga menziesii*] forests are of particular interest. These forests are among the most productive in the world, with primary old-growth stands having a total of as much as  $650 \times 10^6$  g C/ha in aboveground and belowground pools (Harmon et al. 1986). Furthermore, differences in the physical structure of these forests at progressive stages in their development have been the focus of intense scientific and management attention due to the dependence of at least two endangered species on the physical structure of old-growth stands. The ability to remotely sense both the total biomass and physical structure of these forests would provide one way to meet the need for forest inventory in support of research and management of both carbon balance and habitat conditions.

The SLICER (Scanning Lidar Imager Of Canopies By Echo Recovery) instrument is one of a new generation of lidar remote sensing systems that augment traditional first-return laser altimetry with a surface lidar capability (Aldred and Bonnor 1985, Nilsson 1996). Laser altimeters measure the distance between the sensor and a target through the precise measurement of the time between the emission of a pulse of laser light from the sensor, and the time of detection of light reflected from the target. In surface lidar, the power of the entire returning laser signal is digitized, resulting in a waveform that records the vertical distribution of the backscatter of laser illumination from all canopy elements (foliar and woody) and the ground reflection, at the wavelength of the transmitted pulse (1064 nm, in the near-infrared). The use of relatively large footprints (5-25 m) is optimized to recover returns from the top of the canopy and the ground in the same waveform, yet be small enough to be sensitive to the contribution of individual crowns. Details of the technical aspects of SLICER can be found in (Blair et al. 1994, Harding et al. 1994). Motivation for work relating forest attributes to lidar sensed canopy structure has been enhanced by the announcement that VCL, the Vegetation Canopy Lidar mission, has been funded by NASA's Earth System Science Pathfinder (ESSP) program (Dubayah 1997). Scheduled to be launched in mid 2000, VCL will provide global coverage of surface LIDAR data similar to that used in this study, with transects of contiguous 25 meter footprints spaced every 2 km along the earth's surface.

Canopy structure, "the organization in space and time, including the position, extent, quantity, type and connectivity, of the aboveground components of vegetation" (Parker 1995), should be expected to reveal a great deal about the

state of development of forests in general and Douglas-fir/Western Hemlock forests in particular. At the most basic level, differences in stand development should be reflected in the mean and maximum height of the dominant individuals in these stands (Lefsky 1997, Means et al. Submitted). However, even within the context of stand development, the structure of these forests shows considerable variance, as a result of differences in the local importance of various mechanisms of forest succession and disturbance, and environmental factors (Spies and Franklin 1991). The effect of these processes may be discernible using subtler features of canopy structure. Young and mature Douglas-fir forests have a high percent cover of uniformly distributed and sized trees, and as a result their canopies are usually a densely packed mono-layer. The size and number of small gaps in these forests are an indicator of the direction and speed of their future development (Spies et al. 1990). These features should be observable by the type of scanning lidar instrument used in this study.

Defining characteristics of old-growth forests include the existence of large individual trees, high diversity of tree heights and DBH, relatively high species richness, as well as the presence of large standing snags and felled logs. Multiple canopy layers, or more specifically the continuous distribution of foliar surfaces from the top of the crown to the ground, are a key physical feature of old-growth forests distinguishing them from the simpler canopies of young and mature stands (Spies and Franklin 1991). These physical characteristics are both the cause of the old-growth forest's unique compositional and functional attributes, and the most powerful class of measurements for discriminating young, mature and old-growth conditions (Spies and Franklin 1991). Most of these characteristics either have a direct effect on the vertical distribution of biomass in the forest (e.g. large individual trees, multiple canopy layers), or have an identifiable vertical signature (e.g. high diversity of DBH). Therefore, information about the total amount and complexity of forest structure is likely to be closely related to the forest's three dimensional physical distribution, and most clearly represented in the vertical dimension.

Most work in remote sensing of forested systems has been analysis in the spectral domain, specifically the analysis of multi-spectral images. The spectral qualities of forest stands are due both to the electromagnetic properties of the elements that are present in each pixel (foliage, soil, woody debris, etc.) and to their three-dimensional organization (Li 1986), which determines the total cover of each element in the pixel and the distribution of illumination and shadow on those elements. While these type of images have been extremely valuable for general vegetation mapping, it has not been possible to derive from them detailed biophysical information for moderately-high to high-biomass systems (e.g., Fassnacht et al. 1994, Spanner 1990). A second approach to the use of multi-spectral images is analysis in the spatial domain. This approach uses the two-dimensional spatial pattern of spectral variability to infer aspects of the physical organization of forests, and has had considerable success in predicting

forest structure (Cohen 1990, Woodcock 1994, Woodcock 1988). However, these approaches have been constrained by the requirement that they infer three dimensional structure from its two-dimensional projection, in the form of a remotely sensed image.

The failure of optical sensors to adequately measure the structural properties of forests is not incidental; it is a consequence of the imaging process itself. These sensors integrate energy and matter fluxes along the axis between the sensor and scene. Integration along this dimension, roughly corresponding to the "z-axis" or height of vegetation, combines the overstory, understory, and soil measurements into a single measurement per pixel. This results in a two-dimensional remotely-sensed image, with the spectral data for each pixel most influenced by cover of canopy structure. More detailed structural information from closed canopies is only possible when there are associated changes in the horizontal dimension (both within and among pixels), such as varying proportions of tree and shadow with changing tree density (Woodcock 1994, Cohen et al. 1990), or by the increased presence of new scene components (such as lichen) in the forest canopy (Cohen 1995). Lidar does not suffer from this limitation, because it directly measures the vertical distribution of aboveground plant biomass.

Lidar is an established technology used to obtain accurate high resolution measurements of surface elevations from airborne and Space Shuttle platforms (Krabill et al. 1984, Bufton et al. 1991). The first generation lidar sensors for vegetation studies were designed to record distance to the first reflective surface intercepted by a laser pulse over a relatively small sampling area, or footprint, approximately 1 m in diameter (Arp et al. 1982, Ritchie et al. 1992). Returns from the top surface of a forest canopy were combined with subsequent measurements of distance to the forest floor, obtained through gaps in the forest canopy, to infer the height of the dominant trees. A later, more sophisticated technique involved recording the distance to the first and last reflective surface for each footprint, giving a direct height measurement for each observation. Such techniques have proven useful for predicting canopy height, timber volume and forest biomass (Maclean and Krabill 1986, Naesset 1997, Nelson et al. 1988), and percent canopy cover (Ritchie et al. 1993). However, the relatively small geographic area covered in these data sets, challenges in analyzing the data, and the lack of standardized methods for their geolocation have limited the use of conventional lidar sensors within the ecological community.

The new generation of lidar instruments developed at NASA's Goddard Space Flight Center (Blair et al. 1994, Dubayah et al. 1997) and elsewhere (Hyypä and Hallikainen 1996, Nilsson 1996) have minimized these barriers to a wider application of the technology (Weishampel et al. 1996). Whereas earlier devices used a small footprint and most often measured the distance to the first reflective surface, the newer devices send out a laser pulse over an approximately 5-25 m diameter footprint, and record the timing and power of backscattered light over

the full height profile (Harding et al. 1994). Although the power of the return signal falls as the signal is intercepted by canopy structure, return energy from the ground is recorded in nearly all waveforms, which allows an estimate of the total height of the stand, and indicates that some energy is available for the detection of understory foliage, where present. Using an algorithm developed by Drs. D. Harding and M. Lefsky (Lefsky 1997), the lidar waveform can be transformed to estimate the bulk canopy transmittance and the vertical distribution of reflective canopy surfaces. Two recent studies have demonstrated that these new lidar devices can make accurate measurements of stand height, aboveground biomass, and basal area in deciduous forests of the eastern United States (Lefsky 1997) and Douglas-fir/western hemlock forests in the Pacific Northwest (Means et al., submitted). In both of these studies, only uni-dimensional measurements of average height were used, thus the full three dimensional aspects of canopy structure was not exploited.

## METHODOLOGY

Lidar waveforms were collected by the SLICER instrument in September, 1995. SLICER was configured to measure five waveforms cross-track, with each waveform covering a footprint 10 m in diameter. Geo-referencing of laser footprints is performed by combining laser ranging data with aircraft position, obtained via kinematic GPS methods, and laser pointing, obtained with a laser-ringing gyro Inertial Navigation System mounted on the SLICER instrument (Blair 1994). During the period in which these measurements were taken, the vertical resolution of the waveforms collected by SLICER was set at 11 cm, which when combined with the 600 sample-wide waveform, limited the waveform to a maximum height of 66 m. Waveforms with this problem were hand corrected by J. Means (Means et al. Submitted) based on independent estimates of topography and field data, to eliminate the truncation error.

Field data for this study were collected from the vicinity of the H.J. Andrews Experimental forest, located on the west side of the Cascade Range in Oregon, USA. Twenty-one 0.25 ha field plots have been established under the existing SLICER transects, with each plot associated with a 5 by 5 array of waveforms. In each plot, trees with height greater than 1.37 m were identified by species, measured for diameter at breast height (DBH) to the nearest cm, and evaluated for crown ratio (the proportion of tree height which is canopy) to the nearest 10 %. Total aboveground biomass was estimated from DBH using allometric equations (Means et al. 1994). Leaf area index values were calculated using allometric equations relating stem DBH to sapwood cross-sectional area as found in (Urban 1993). Sapwood area was converted to all sided leaf area using the species-specific coefficients in (Waring et al 1982).

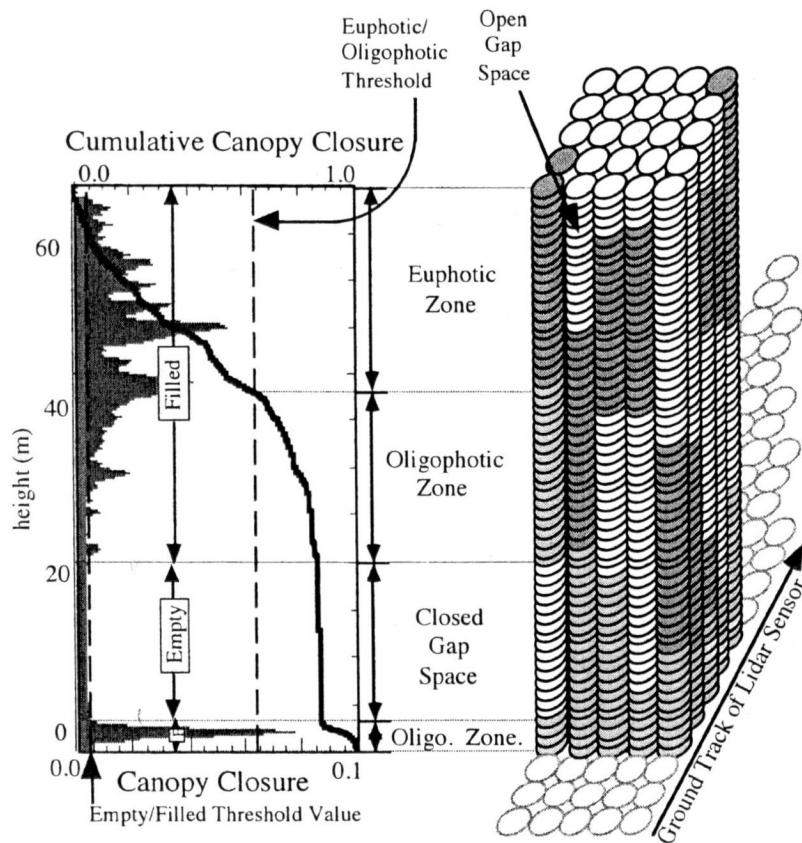


Figure 1: Canopy Volume Method

Waveforms were processed using the canopy volume profile algorithm (Figure 1). Following the procedures in (Lefsky 1997) the waveform was transformed into an estimate of the canopy height profile (CHP), the relative distribution of the canopy as a function of height. A threshold value was then used to classify each element of the CHP into either "filled" or "empty" volume, depending on the presence or absence (in the profile) of canopy material. A second step classified the filled elements of the matrix into an "euphotic" zone (Richards 1983) which contains all filled elements of the profile that are within the uppermost 65 % of canopy closure, and an "oligophotic" zone, consisting of the balance of the filled elements of the profile. These two classifications were then combined to form three classes; empty volume beneath the canopy- (ie. closed gap space), filled volume within the euphotic zone, and filled volume within the oligophotic zone. These same classes were then computed for each of the twenty five SLICER waveforms in a 5 by 5 array. The waveforms are then compared,

and a fourth class is added, "open" gap volume is defined as the empty space between the top of each of the waveforms and the maximum height in the array. At this point, the total volume of each of the four classes of canopy structure can be tabulated for each 5 by 5 array of waveforms.

To determine the ability of SLICER measured canopy structure indices to predict a series of stand structure attributes (See Table 1), stepwise multiple regression were performed using as independent variables the total volume of each of the four canopy structure classes and the total volume occupied by vegetative material, as measured by the combined volume of the euphotic and oligophotic zones. In addition, the mean canopy surface height, the number of waveforms greater than 55m tall, the mean CHP height, as well as the maximum stand height, canopy surface range, quadratic mean canopy height and average number of canopy structure classes per unit height were included as independent variables.

## RESULTS

Figure 2 presents canopy volume profile diagrams for representative young mature and old-growth plots. These diagrams indicate, for each 1 meter vertical interval, the percent of each plot's 25 waveforms that belong to each of the four canopy structure classes. Young stands are characterized by short stature, uniform canopy surface (as indicated by the height distribution of the interface between the euphotic zone and open gap space), and an absence of empty space within the canopy (ie. closed gap space). Mature stands are taller, but still characterized by a uniform upper canopy surface. In contrast to young stand mature stands have a large volume of closed gap space. Mature stands Douglas-fir often have a high density of large trees with uniform DBH. The uniformity of size leads to the uniform canopy surface height, and the interception of light and other resources by these trees results in the absence of canopy structure at lower levels. Old-growth stands are distinguished from mature stands by their uneven canopy surface, and the wide vertical distribution of each of the four canopy structure classes. Whereas stands from earlier stages of stand development have canopy structure classes in distinct vertical layers, in the old-growth stands each canopy structure class occurs throughout the height range of the stands. The continuous distribution of canopy surfaces from the top of the crown to the ground has been cited as a key physical feature of old-growth forests distinguishing them from the simpler canopies of young and mature stands (Spies and Franklin, 1991)

Scatterplots of predicted vs observed stand structure attributes are presented in Figure 3, and results of the stepwise multiple regression are presented in Table 1. The strength of the relationships developed here are very strong in comparison to other remote sensing techniques, and compare favorably with allometric equations relating complementary aspects of individual tree geometry.

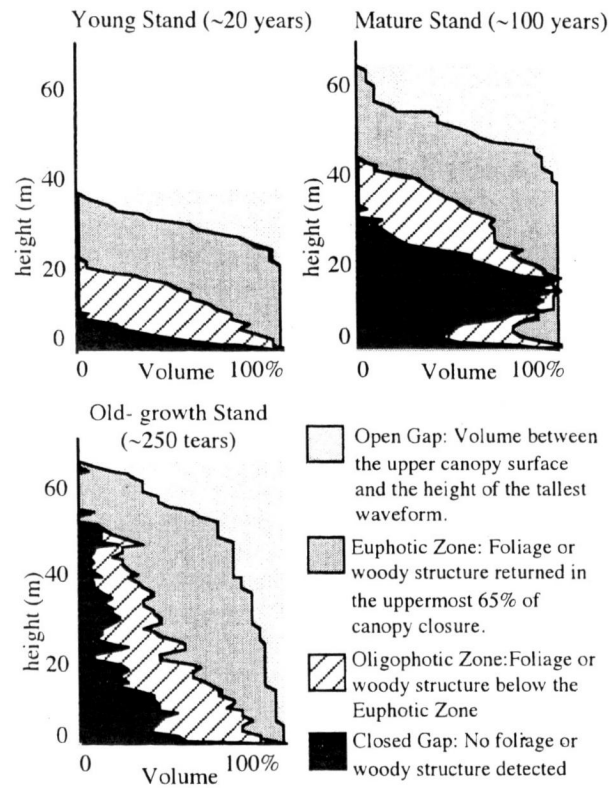


Figure 2: Canopy Profile Diagrams

Examination of the scatterplots indicates that the predicted values of aboveground biomass and LAI show no asymptotic tendency, even at the largest values (1200 Mg/ha Biomass, LAI of 12). The equation predicting biomass involved positive correlations with the total filled volume, and the number of waveforms taller than 55m. The equation predicting LAI involved a positive correlation with the total filled volume and the open gap volume, and a negative correlation with the closed gap volume. This indicates that the surface area of leaves is proportional to the volume they are distributed in, that increases in the vertical range of the upper canopy surface increases LAI, and the presence of empty spaces within the canopy decreases LAI. Although both LAI and aboveground biomass use the total filled volume variable in their equations, scatterplots and regressions have shown that the predicted values of each variable are no more highly correlated with each other than the original data.

Mean DBH is predicted from the mean height of the canopy height profile. The condition of high mean DBH is associated with the same characteristics as found

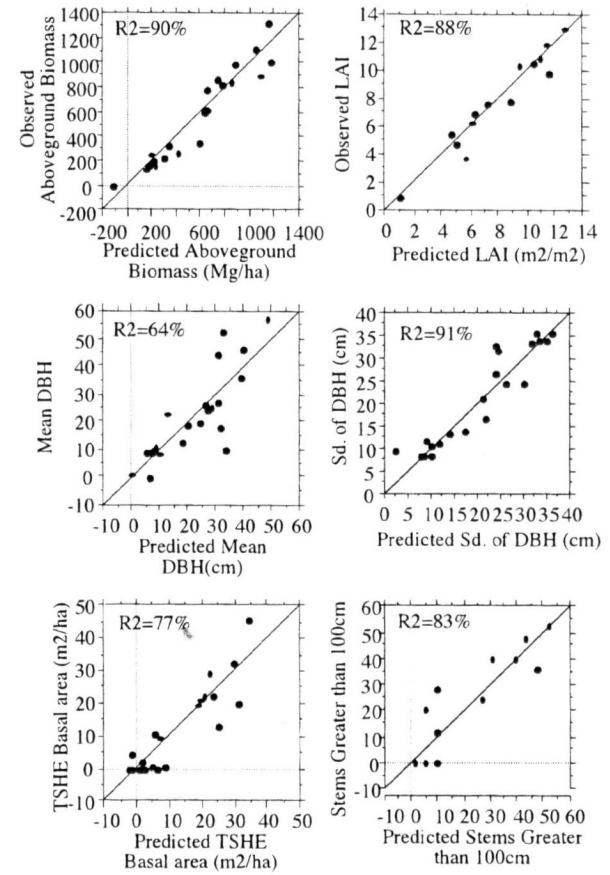


Figure 3. Observed vs. Predicted Stand Structure Attributes

in mature stands. High mean DBH occurs when there is a high density of large trees with uniform DBH, which suppress smaller individuals. These same conditions lead to the concentration of foliage near the top of the stand. In contrast, the standard deviation of DBH is proportional to the number of waveforms taller than 55m, the filled canopy volume and the open gap volume because the combination of a few very large trees and the absence of moderately sized trees (indicated by the open gap space) that results in high variability of DBH. The number of stems greater than 100cm is most highly correlated with the number of individual lidar waveforms in each stands 5 x 5 array that exceed 55m in height.

A positive correlation between open gap space and the density and basal area of shade tolerant species such as Western Hemlock [*Tsuga heterophylla* - Abbreviated TSHE], is used to predict Western Hemlock basal area. While the basal area of western hemlock and the main shade intolerant species (Douglas-fir) both increase with the maximum height of the stand, Western hemlock basal area increases with the open gap space, while Douglas-fir basal area decreases. This is due to the shade tolerant's dependence on shaded gaps for regeneration. When the canopy is tall, but has many open gaps, the open gap space increases along with the regeneration potential of Western Hemlock.

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Table 1. Results of stepwise multiple regression of stand attributes<sup>1</sup> against canopy structure volumes, and associated indices.

	Adjusted R <sup>2</sup>	Inter-cept	Mean Canopy Surface Height (m)	Number of Waveforms taller than 55m	Mean CHP <sup>2</sup> Height (m)	Filled		Closed		Open			
						Canopy Volume (m <sup>3</sup> m <sup>-2</sup> )	Gap Volume (m <sup>3</sup> m <sup>-2</sup> )	Canopy Volume (m <sup>3</sup> m <sup>-2</sup> )	Gap Volume (m <sup>3</sup> m <sup>-2</sup> )	Canopy Volume (m <sup>3</sup> m <sup>-2</sup> )	Gap Volume (m <sup>3</sup> m <sup>-2</sup> )		
Total Biomass (Mg*ha <sup>-1</sup> )	90%	-295.88		26.75 <sup>B</sup>		27.98 <sup>A</sup>							
Total Basal Area (m <sup>2</sup> *ha <sup>-1</sup> )	80%	-22.82				2.97 <sup>A</sup>							
PSME Basal Area	78%	-1.236	1.915 <sup>A</sup>										-1.906 <sup>B</sup>
TSHE Basal Area	77%	-2.44		1.11 <sup>C</sup>									-1.57 <sup>B</sup>
Shade Tolerant Stems >40cm	48%	-18.41											2.23 <sup>A</sup>
Mean DBH (m)	64%	-5.198			1.588 <sup>A</sup>								5.39 <sup>A</sup>
Stdev DBH (m)	91%	-3.11		0.80 <sup>B</sup>		0.58 <sup>A</sup>							0.47 <sup>C</sup>
Stems >100cm LAI	83%	1.36		4.18 <sup>A</sup>									0.19 <sup>C</sup>
	88%	-0.22				0.33 <sup>A</sup>							-0.44 <sup>B</sup>

Superscripted letters indicate rank of each variable

1) Additional independent variables used in these stepwise multiple regressions, but not used in any equation include maximum height, canopy surface range, quadratic mean canopy height, and average number of canopy structure classes per unit height.  
2) CHP = Canopy Height Profile (Lefsky 1997)