MODELING LIDAR WAVEFORMS USING A RADIATIVE TRANSFER MODEL

B. Peterson[1], W. Ni-Meister[2], J.B. Blair[3], M.A. Hofton[1], P. Hyde[1] and R. Dubayah[1]

[1]Department of Geography
University of Maryland
College Park, MD 20742
USA

[2]Goddard Earth Sciences and Technology Center (GEST)
and Hydrological Branch
NASA/Goddard Space Flight Center
Greenbelt, MD 20771
USA

[3]Laser Remote Sensing Branch
Laboratory for Terrestrial Physics
NASA/Goddard Space Flight Center
Greenbelt, MD 20771
USA

ABSTRACT

In the past, obtaining reliable measurements of key forest canopy metrics has been difficult, even after the development of remote sensing technology. Fortunately, next-generation lidar systems are proving to be useful tools for deriving critical canopy measurements, such as height, structure and biomass. These studies have all focused on empirical comparisons between basic lidar-derived and field-sampled measurements. The results of these studies have shown that lidar remote sensing instruments can successfully measure forest canopy characteristics. However, physically-based remote sensing models are necessary to more fully understand and interpret the interactions of the laser energy with the forest canopy. In this study the Geometric Optical and Radiative Transfer (GORT) model is used to model lidar waveforms. GORT is capable of modeling lidar returns from canopies with clumped multiple layers and multiple species. For this study, GORT was used to model waveforms over the Sierra National Forest in California. Field data input into GORT are a representative sample of the different vegetation types found in the forest. The modeled waveforms are then validated against actual lidar data collected by the Laser Vegetation Imaging Sensor (LVIS) which mapped the area in October 1999. By modeling lidar waveforms based on the physical principles of radiative transfer, GORT fills a missing link between the remotely sensed and actual canopy structure. The results of this study will also aid in future large-scale land surface mapping by developing a link between lidar and other remote sensing data.

1 INTRODUCTION

Forest canopy structure is one of the least studied aspects of the forest ecosystem (Van Pelt and North, 1996; Yang et al. 1999). This lack is often attributed to the difficulty of working in forest canopies (Parker et al. 1992; Weishampel et al. 1996). Remote sensing of forest canopy structure overcomes many of the obstacles inherent in ground-based sampling and has been identified as a valid method for obtaining a variety of canopy data for regions all around the world (Weishampel et al. 1996; Hyyppä et al. 2000). Indeed, remote sensing has been called the only practical way of acquiring quantitative information about the biophysical and biochemical properties of forests (Danson and Curran 1993).

Next-generation, large-footprint lidar systems in particular provide a direct and elegant means to measure the structure of vegetation canopies. These large-footprint, waveform-digitizing systems have been optimized for the measurement of forest vegetation (Blair et al. 1994; Blair et al. 1999). Canopy height, basal area, canopy cover and biomass have all been successfully derived from large-footprint lidar waveform data (Means et al. 1999; Lefsky et al. 1999; Drake et al. in press; Peterson 2000). However, to take full advantage of the wealth of data contained in the lidar waveforms, the interaction between the laser energy and the structural elements of the canopy must be better understood. To this end, this study uses a physically-based remote sensing model to model lidar waveforms in a coniferous forest in the Sierra Nevada.

The model used in this study is the Geometric Optical and Radiative Transfer (GORT) model. It combines the theories of geometric optics and radiative transfer. It was originally developed to study the effects of the canopy architecture of discrete canopies on the radiation environment and to describe the heterogeneous radiation environment in natural vegetation (Li et al. 1995). GORT models the integrated radiation regime within forest canopies at the stand level. The inputs are distribution functions of tree geometry parameters (e.g. mean tree size, shape and density) and the spectral properties of the canopy and the background (Ni-Meister et al. in press). Specifically, GORT calculates the probability of individual photons finding within-crown or between-crown gaps in the canopy. These gaps represent pathways through which the photons can pass through the canopy and reach the ground beneath. GORT models total gap probability as a function of height. A detailed description of the model and how it can be used to model lidar waveforms is provided in Ni-Meister et al. (in press). The GORT model has been validated using field data from the BOREAS study and has also been used to model lidar waveforms from the SLICER instrument that collected data over the BOREAS field sites (Ni-Meister et al. in press).

2 DATA COLLECTION

2.1 LVIS Data

In October 1999 the LVIS instrument mapped a large area of the Sierra National Forest in California. LVIS is a pulsed laser altimeter that records the travel time of a laser pulse to a reflective surface as well as the shape of the output and return waveforms, thereby allowing the heights of the reflecting surfaces within each footprint to be determined (Blair et al. 1999). The system has a vertical precision of approximately 30 cm. The ranging data are combined with airplane roll, pitch and bearing data and GPS data to locate each individual laser footprint on the surface to within 1 m. Flying onboard a NASA C-130 at 8 km above ground level and operating at 320 Hz, LVIS produced 12.5 m-diameter footprints at the surface, overlapping by 50% across track and contiguous along track. In total, an area approximately 180,000 km^2 wide was mapped by LVIS in the Sierra Nevada study area.

2.2 Field Data

Field data for this study were collected in the summer of 2000 in the Sierra National Forest as part of a larger, on-going research study conducted by the U.S. Forest Service, the University of Michigan and the University of Maryland and are a representative sample of the different vegetation types found in this area. Circular plots centered on lidar footprints measured 15 m in diameter. Within these plots all trees over 10 cm dbh were sampled. Measurements included: total tree height, height to partial crown, partial crown wedge angle, height to full crown, four crown radius measurements and distance and azimuth relative to the plot center. Tree crown shape and species were also recorded.

Leaf Area Index (LAI) measurements were also taken in these plots. These measurements were taken at 61 points located every 3 m up to 15 m on transects radiating from the plot center at every 30 degrees and at the plots center. The LAI measurements were taken with two LICOR LAI-2000 instruments - one in the plot taking below-canopy measurements at the 61 points (four measurements at each point) and one located a short distance away logging clear sky data. The data from the two sensors were merged using the LICOR C2000 software and used to calculate LAI for each of the 61 points.

3 METHODS

Because each field plot was centered on the location of one footprint, there was one LVIS waveform to which to compare the data from the field. A total of 16 plots were included in this analysis. For each plot, the associated waveform was normalized and the canopy portion of the waveform was identified by removing the last peak in the waveform, which corresponds to the ground portion of the return signal. This method is comparable to that described by Means et al. (1999), although nothing was done to compensate for any difference in reflectance for the ground versus the canopy. Because the ground returns for this data set were relatively strong, this method of obtaining the canopy portion of the return was considered robust. The canopy return of the normalized waveform was then compared to the GORT output and a crown volume profile constructed from the field data.

The field data were used to calculate parameters to initialize the GORT model. The model requires the following tree geometry parameters: upper crown center height boundary (h2), lower crown center height (h1), average crown radius (R), and crown depth/crown radius ratio (e) and crown count density (ë). Values for these tree geometry parameters are provided for one example plot in Table 1. The tree geometry parameters and their derivation are described in Ni-Meister et al. (in press). Foliage area volume density (favd) was derived from the LAI data. The favd was calculated through the following equation:

$$favd * 4/3 * ë * ð * R^2 * b = LAI, \qquad (1)$$

where b is vertical crown radius (all variables were obtained for each plot from the field data).

Table 1: Input tree geometry parameters for the GORT model for a single plot in the study area

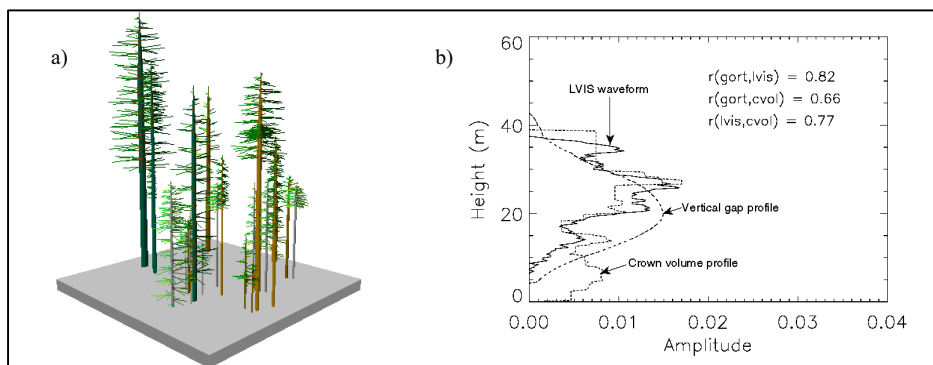| ë	h1	h2	R	e	favd
0.13	4.36 m	27.15 m	1.89 m	2.47	0.3

Figure 1. a) Profile view of a sample plot in the study area. The tree geometry parameters for the GORT model are given in Table 1. (This image was created with the Stand Visualization System developed by the U.S. Forest Service.) b) The lidar canopy return for this same plot is shown along with the GORT-generated vertical gap profile and the vertical crown volume profile. (All profiles normalized). The correlation coefficients are shown in the top right corner.

All the input parameters for the GORT model were calculated from the field data for each individual plot. The model was run separately for each plot. Each model run produced between-crown and within-crown gap probabilities for each height interval (set at 30 cm to correspond with the vertical resolution of LVIS) in the canopy. Total gap probability was calculated by adding between-canopy and within-canopy gap probabilities. A vertical profile of total gap probability was constructed by calculating total gap probability as a function of height. The normalized vertical profile was compared to the normalized LVIS canopy waveform for each plot.

Crown volume profiles were also calculated from the field data. Crown cross-sectional area was calculated at 30 cm height intervals for the entire canopy down to the ground. The individual crowns were assumed to be cylindrical in shape, however partial crown height, full crown height and partial crown wedge measurements were used to adjust for cases in which the crown cross-sectional area would not be adequately modeled as a circular disk. In this way the crown volume profile adjusted for anomalies in crown shape. The normalized crown volume profiles were also compared to the normalized GORT gap probability profile and the normalized lidar canopy waveform.

4 RESULTS

The similarities between the LVIS waveform, vertical profile of gap probability and crown volume profile for each plot were assessed by calculating correlation coefficients (Pearson's r) between these different profiles (Figure 1). Histograms showing the distribution of correlation coefficients for all the plots are shown in Figure 2. The mean values of the correlation coefficients were 0.61, 0.54, and 0.67 for the LVIS waveform/vertical gap profile, LVIS waveform/crown volume profile and vertical gap profile/crown volume profile pairs respectively. The best overall correlation was between the crown volume profiles and the gap probability profiles.

5 DISCUSSION AND CONCLUSION

The results show that GORT was able to model the LVIS waveforms for the Sierra Nevada field sties. This model validation demonstrates that GORT was able to characterize lidar waveforms using a few tree geometry parameters and the spectral properties of the canopy leaves as derived from LAI measurements in the field. The current tree geometry calculations are based on observations that are characteristic of the boreal forest in central Canada rather than the forests of the Sierra Nevada. Revisions to the equations used to derive the tree geometry for the plots in this study could improve the relationship between the vertical gap profiles, LVIS waveforms and the crown volume profiles. These results are also based on a relatively small sample size. Once further data are included in the study the overall results may improve.

In general, the lidar waveforms tend to show a concentration of material near the top of the canopy, whereas the vertical gap profiles indicate a more evenly spread out canopy (Figure 2). This discrepancy should be
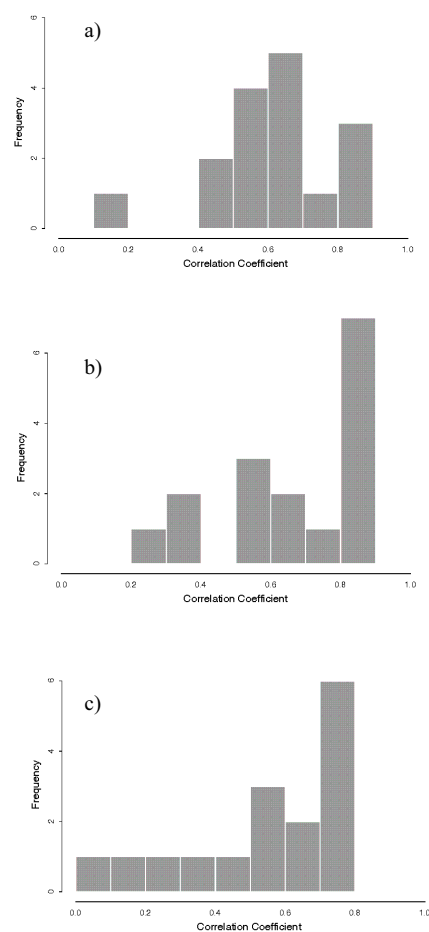

Figure 2. Histograms showing the distribution of the correlation coefficients for the LVIS waveform/vertical gap profile (a), vertical gap profile/crown volume profile (b) and the LVIS waveform/crown volume profile (c) relationships.

examined in greater detail. There are two approaches to this: 1. The GORT model should be rerun several times for each plot using different input parameters to test the sensitivity of the shape of the gap profile to factors that influence tree geometry (e.g. presence or absence of a layer of dominant and co-dominant trees or tree species). 2. Previous research has shown that upper layers in the canopy may obscure lower layers, thereby reducing the amount of energy reflected back by the lower portions of the canopy and resulting in erroneously weak lower canopy returns (Means et al. 1999; Lefsky et al. 1999). Methods to address for this have been developed (Means et al. 1999; Lefsky et al. 1999) and should be applied to the lidar waveforms in this study to see if this would improve the correlation between them and vertical gap profiles. This may then lead to the development of a 'correction factor' that could be applied to the vertical gap profile to create more realistic waveforms. Establishing whether or not these approaches improve the relationship between the lidar waveforms and the vertical gap profiles will greatly aid in the understanding of how the energy interacts with the elements of a natural vegetation canopy. The

comparisons of the vertical gap profiles and lidar waveforms to the crown volume profiles can also aid in determining which elements of the canopy influence their shape. These comparisons also demonstrate that traditional canopy volume profiles may not adequately capture the heterogeneity of natural canopies in terms of the vertical distribution of reflecting surfaces in the canopy and light penetration.

The results of this study will help develop a better understanding of the interactions between the energy of a lidar laser beam and the forest canopy. By modeling lidar waveforms based on the physical principles of radiative transfer, GORT fills a missing link between the remotely sensed and actual canopy structure. The results of this study will also aid in future large-scale land surface mapping by developing a link between lidar and other remote sensing data. If lidar waveforms can be modeled from field data or other remote sensing data then it will be possible to derive a better three-dimensional picture of the structure of the Earth's vegetated surface, even in areas that have not been mapped by a lidar instrument.

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