Lidar Remote Sensing for Forestry Applications

Ralph O. Dubayah* and Jason B. Drake**
Department of Geography, University of Maryland, College Park, MD 20742

*rdubayah@geog.umd.edu
**jasdrak@geog.umd.edu

Address correspondence to R. Dubayah, Dept. of Geography, University of Maryland, College Park, MD 20742.

1. Abstract

Lidar remote sensing is a breakthrough technology for forestry applications. Lidar instruments have demonstrated the capability to accurately estimate important forest structural characteristics such as canopy heights, stand volume, basal area and aboveground biomass. This paper provides a brief background on lidar remote sensing, and its current and projected uses in forestry.

2. Lidar Remote Sensing

Lidar (**li**ght **d**etection **a**nd **r**anging) is an active remote sensing technique, analogous to radar, but using laser light. Lidar instruments measure the roundtrip time for a pulse of laser energy to travel between the sensor and a target. This incident pulse of energy (usually with a near-infrared wavelength for vegetation studies) reflects off of canopy (branches, leaves) and ground surfaces and back to the instrument where it is collected by a telescope. The travel time of the pulse, from initiation until it returns to the sensor, provides a distance or range from the instrument to the object (hence the common use of the term "laser altimetry" which is synonymous with lidar).

Lidar systems for forestry applications are classified based on the following characteristics: (1) whether they record the range to the first return and/or last return or fully digitize the return signal; (2) whether they are small footprint (typically on the order of a few centimeters) or large footprint systems (tens of meters); and, (3) based on their sampling rate/scanning pattern. Nearly all commercial lidar systems are low-flying, small-footprint (5-30 cm diameter), high pulse rate (1,000-10,000 Hz) systems recording the range to the highest (and sometimes lowest) reflecting surface within the footprint, and are not fully imaging, using instead many laser returns in close proximity to each other to recreate a surface.

Small-footprint lidar systems may not be optimal for mapping forest structure. First, small diameter beams frequently oversample crown shoulders and miss the tops of trees (see (Nelson 1997) for how this changes with crown geometry), so that unless many shots are taken, the true canopy topography must be reconstructed statistically. Secondly, because of their small beam size, mapping large areas requires extensive flying. Finally, with systems that only record first and/or last returns, it is difficult to determine whether or not a particular shot has penetrated the canopy all the way to ground. If this topography cannot be reconstructed, accurate height determination is impossible because canopy height is measured relative to the ground.

Large-footprint systems (e.g., Blair et al. 1999) have several advantages that help avoid these problems. First, by increasing the footprint size to at least the average crown diameter of a canopy-forming tree (10-25 m), laser energy consistently reaches the ground even in dense forests. The larger footprint size also avoids the biases of small-footprint sensors that may frequently miss the tops of trees. Secondly, large-footprint systems enable a wide image swath, which reduces the expense of mapping large forested areas (Blair et al. 1999). Finally, large-footprint lidar systems also digitize the entire return signal (e.g., in ~30 cm vertical bins) thus providing a vertical distribution of intercepted surfaces (or "waveform") from the top of the canopy to the ground (see Figure 1).

The upcoming Vegetation Canopy Lidar (VCL) satellite (Dubayah et al. 1997) will provide a global data set of canopy heights, vertical distributions of intercepted surfaces and subcanopy topography, all of which have outstanding potential for forestry applications. Recent studies using airborne large-footprint lidar systems have illustrated the effectiveness of this technology in forestry applications. These studies and others using small-footprint systems are discussed below.

3. Applications in Forestry

Lidar remote sensing has vast potential for the direct measurement and estimation of several key forest characteristics (Table 1). The direct measurements of large-footprint lidar are canopy height, subcanopy topography, and the vertical distribution of intercepted surfaces between the canopy top and the ground. Other forest structural characteristics, such as aboveground biomass, are modeled or inferred from these direct measurements (Dubayah et al. 2000).

Canopy Height

Canopy height is calculated by subtracting the elevations of the first and last returns from the lidar signal. With large-footprint systems, the first return above a noise threshold can be used to estimate the top of the canopy, and the midpoint of the last return represents the ground return (Figure 1).

Lidar instruments have accurately recovered canopy heights in temperate deciduous, pine, Douglas fir and dense tropical wet forests (see references in Dubayah et al. 2000). The ability of lidar instruments to accurately measure canopy heights is important because of the strong link between vegetation height and other biophysical characteristics. These relationships have been used to model many of the forest structural characteristics that are not directly recovered from lidar instruments. In addition, vegetation height is a function of species composition, climate and site quality, and can be used for land cover classification or in conjunction with vegetation indices from passive optical sensors (Dubayah et al. 1997, Dubayah et al. 2000).

<u>Vertical distribution of intercepted surfaces</u>

In addition to the first and last returns, large-footprint systems digitize the complete return signal of the laser pulse between the canopy top and the ground, thus recording a waveform that is related to the vertical distribution of canopy structure. Specifically, a large-footprint lidar waveform records reflections from the nadir-projected vertical distribution of the surface area of canopy components such as foliage, trunk, twigs, and branches (Figure 1). Like canopy height, the vertical distribution of intercepted surfaces provides a new means to classify vegetation, and provides the basis for estimating other important canopy descriptors, such as aboveground biomass. It also functions as a predictor of the successional state of a forest (Dubayah et al. 1997).

As a stand ages and grows, the vertical distribution of canopy components changes relative to younger stands (Dubayah et al. 1997, Lefsky et al. 1999). Older stands characterized by canopy gaps and trees of multiple ages and sizes exhibit a more even vertical distribution of canopy components compared to younger, even-aged stands which have a majority of their canopy materials in the top portion of the canopy. Recent studies have demonstrated that lidar waveforms are sensitive to these structural changes through forest succession (Lefsky et al. 1999).

<u>Aboveground Biomass</u>

Taller trees contain more wood and typically support more foliage and roots than shorter trees of the same species and diameter. Because of the mechanical properties of trees, stem diameter typically increases as trees become taller as well, further increasing wood volume and mass. Remotely-sensed measurements from lidar instruments can exploit these biological constraints to model biomass from height.

Lidar measured heights are highly correlated with aboveground biomass in mixed deciduous-coniferous, pine, Douglas fir/western hemlock, and in dense tropical wet forests (see references in Dubayah et al. 2000). In recent studies, metrics from large-footprint lidar systems were able to explain over 90% of the variation in aboveground biomass in forests with extremely high (up to 1300Mg/ha in Means et al. 1999) biomass and canopy closure (~99% canopy closure in Drake et al. in review) levels.

<u>Other Forest Characteristics</u>

Lidar metrics (e.g., canopy height) have been used to accurately estimate basal area (e.g., Drake et al. in review, Means et al. 1999) and mean stem diameter (Drake et al. in review). The distributions of basal area and mean stem diameter may then be used to infer the density of large trees.

The vertical distribution of intercepted surfaces has been used to model “canopy height profiles” using assumptions from methods developed to estimate vertical foliage profiles from optical point quadrats (Lefsky et al. 1999). In addition, the vertical distribution of intercepted surfaces has also been used to examine the volumetric nature of Douglas fir/western hemlock (Lefsky et al. 1999) and tropical wet (Weishampel et al. 2000) forest canopy structure. These kinds of measurements provide extraordinary new data for forest wildlife management and habitat mapping.

4.0 Limitations and Strengths

It is important to note the overall limitations of lidar remote sensing, in addition to those mentioned earlier for small footprint lidar systems. Lidar, and other optical remote sensing techniques are restricted by clouds and dense atmospheric haze which can attenuate the signal before it reaches the ground. Secondly, there are few lidar data sets available. Commercial airborne (small-footprint) systems are only now becoming available at a cost-effective basis. The third limitation, which relates to the second, is the lack of algorithms and data processing expertise required for operational use of the data. Finally, some forest characteristics (e.g., LAI) cannot be determined either directly, or with modeling from lidar data alone. In these cases, the vertical component provided by lidar should be fused with information from passive optical, thermal and radar remote sensing.

The major strength of lidar remote sensing is that it directly measures vertical forest structure. The direct measurement of canopy heights, subcanopy topography and the vertical distibution of intercepted surfaces provides a wealth of data for forest characterization and management. In addition, the strong relationships between these direct measurements and other biophysical parameters, such as aboveground biomass, provide critical information about the function and productivity of forest ecosystems.

5. Online Access and Sources

An online directory of commercial small footprint systems can be found at: http://www.airbornelasermapping.com. VCL data will be available online through EROS Data Center approximately 6 months after the anticipated launch in 2001. The data products (e.g., canopy heights) will be available at the geolocated footprint-level, and in 1 degree and 2km gridded products (see Dubayah et al. 1997 for more details). To learn more about the VCL mission and for related links on large-footprint lidar systems visit: http://www.inform.umd.edu/geog/vcl/.

6. References

Blair, J. B., D. L. Rabine, and M. A. Hofton. 1999. The Laser Vegetation Imaging Sensor (LVIS): A medium-altitude, digitization-only, airborne laser altimeter for mapping vegetation and topography. *ISPRS Journal of Photogrammetry and Remote Sensing* 54: 115-122.

Drake, J., D. Clark, R. Dubayah, R. Knox, J. B. Blair, and R. L. Chazdon. in review. Estimation of Tropical Forest Structural Characteristics Using Large-footprint Lidar. *Remote Sensing of Environment* .

Dubayah, R., J. B. Blair, J. L. Bufton, D. B. Clark, J. JaJa, R. G. Knox, S. B. Luthcke, S. Prince, and J. F. Weishampel. 1997. The Vegetation Canopy Lidar mission. Pages 100-112. *Land Satellite Information in the Next*

Decade II: Sources and Applications. American Society for Photogrammetry and Remote Sensing, Bethesda, MD.

Dubayah, R. O., R. G. Knox, M. A. Hofton, J. B. Blair, and J. B. Drake. 2000. Land surface characterization using lidar remote sensing. in M. Hill and R. Aspinall, eds. *Spatial Information for Land Use Management*. International Publishers Direct, Singapore.

Lefsky, M. A., W. B. Cohen, S. A. Acker, G. G. Parker, T. A. Spies, and D. Harding. 1999. Lidar remote sensing of the canopy structure and biophysical properties of Douglas-fir western hemlock forests. *Remote Sensing of Environment* 70: 339-361.

Means, J. E., S. A. Acker, D. J. Harding, J. B. Blair, M. A. Lefsky, W. B. Cohen, M. E. Harmon, and W. A. McKee. 1999. Use of large-footprint scanning airborne lidar to estimate forest stand characteristics in the Western Cascades of Oregon. *Remote Sensing of Environment* 67: 298-308.

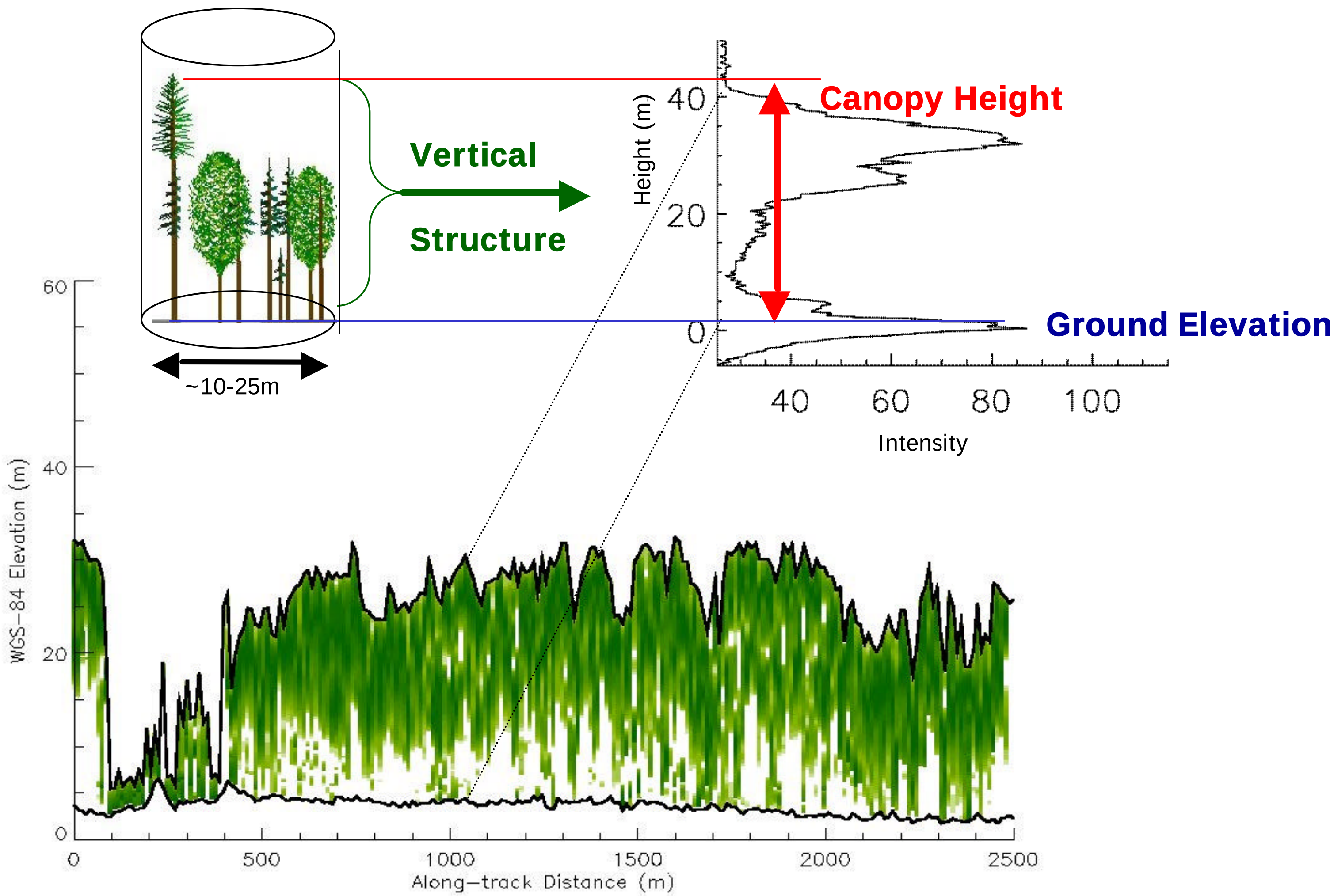
Nelson, R. 1997. Modeling forest canopy heights: The effects of canopy shape. *Remote Sensing of Environment* 60: 327-334.

Weishampel, J. F., J. B. Blair, R. G. Knox, R. Dubayah, and D. B. Clark. 2000. Volumetric lidar return patterns from an old-growth tropical rainforest canopy. *International Journal of Remote Sensing* 21: 409-415.

Table 1. Potential contributions of lidar remote sensing for forestry applications (see text for details).

Forest Characteristic	Lidar Derivation
Canopy Height	Direct retrieval
Subcanopy Topography	Direct retrieval
Vertical distribution of intercepted Surfaces	Direct retrieval
Aboveground Biomass	Modeled
Basal Area	Modeled
Mean Stem Diameter	Modeled
Vertical Foliar Profiles	Modeled
Canopy Volume	Modeled
Large Tree Density	Inferred
Canopy Cover, LAI	Fusion with other sensors
Life Form Diversity	Fusion with other sensors

Figure 1. Conceptual basis of large-footprint lidar remote sensing. Pulses of laser energy reflect off canopy (e.g., leaves and branches) and ground surfaces, resulting in a waveform, shown in the upper right. The amplitude of individual peaks in the waveform are a function of the number of reflecting surfaces (e,g,. leaves and branches) at that height. The canopy height is determined by subtracting the range to the ground (the midpoint of the last peak) from that to the first detectable canopy return or some threshold above that return. The profile in the lower portion of the figure is from data collected by a scanning airborne lidar instrument (e.g., Blair et al. 1999) flown over Maryland. The darker shades represent areas where more canopy materials are located.



Canopy Height
Vertical
Structure
Ground Elevation
~10-25m
Height (m)
40
20
0
40 60 80 100
Intensity
WGS-84 Elevation (m)
60
40
20
0
0 500 1000 1500 2000 2500
Along-track Distance (m)