Simulation of small-footprint full-waveform LiDAR propagation through a tree canopy in 3D

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ABSTRACT

A Monte Carlo ray tracing simulation of LiDAR propagation has been expanded to 3 dimensions, and makes use of the high-fidelity tree voxel model VoxLAD for realistic simulation of a single tree canopy. The VoxLAD model uses terrestrial LiDAR scanner data to determine Leaf Area Density (LAD) measurements for small volume voxels ($\sim$5 – 20 cm side length). The LAD measurement, along with material surface normal orientation information, is used within the Monte Carlo LiDAR propagation model to determine the probability of LiDAR energy being absorbed, transmitted or reflected at each voxel location, and the direction of scattering should an interaction occur. The high spatial fidelity of the VoxLAD models enables simulation of small-footprint LiDAR systems. Results are presented demonstrating incorporation of the VoxLAD model for realistic tree canopy simulation, and the the full-waveform simulation capability of the Monte Carlo LiDAR code.

Keywords: LiDAR, Monte Carlo, ray tracing, VoxLAD, simulation, small footprint, full-waveform

1. INTRODUCTION

A realistic model of LiDAR propagation enables controlled studies to discover the theoretical limits of the technology without confusion from unknown sensor characteristics, vendor data-processing steps, and scene complexity. Modeling allows control of these factors, and enables absolute knowledge of the conditions in the scene.

In the work presented here, two scans of a Coast Live Oak *(Quercus agrifolia)* with a Riegl VZ-400 terrestrial laser scanner are used as inputs to the VoxLAD model. The resulting tree model, having voxels with 20 cm long sides, provides Leaf Area Density (LAD) estimates for each voxel location. This information, along with estimates of wood density derived from the Riegl VZ-400 data, is used within the Monte Carlo LiDAR model to simulate a full-waveform LiDAR signal. The simulated signal is compared to full-waveform LiDAR signals from an airborne full-waveform AHAB Chiroptera I system.

2. BACKGROUND

Many studies have demonstrated the feasibility of simulating large-footprint LiDAR systems, with results showing excellent correlation between simulated and real LiDAR data.[1–5] Large footprint LiDAR systems, such as the NASA Scanning Lidar Imager of Canopies by Echo Recovery (SLICER) system, Laser Vegetation Imaging Sensor (LVIS), and Geoscience Laser Altimeter System (GLAS) were developed to measure parameters such as canopy structure at the forest scale. These systems have very large footprints (10-25 m for SLICER, 25 m for LVIS, and 70 m for GLAS), and are designed to cover large spatial areas for the purposes of understanding factors affecting global climate.

Small-footprint LiDAR systems, with footprint diameters of a few centimeters, provide much more spatially detailed information than large-footprint systems. These data may be useful for DoD applications, such as

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detection of trails under canopy or other indicators of human activity.[6] In order to extract meaningful information from these signals however, it is critical to understand the factors affecting the collection of data.

The simulation of small footprint LiDAR is in some ways more challenging than the simulation of large footprint LiDAR. Firstly, the model scene inputs must be correspondingly spatially detailed, meaning information is required about the shape and arrangement of trees at the leaf and twig scale. A second challenge in modeling small footprint LiDAR systems is the great amount of variability in collection methods. Survey characteristics (such as flying altitude, pulse repetition frequency, scan angle, etc.) and sensor characteristics (such as laser wavelength and echo detection method) all have a significant effect on the returned signals.[7,8] To model spatially detailed forest scenes, some studies use geometrically defined tree crowns, with statistically distributed clumps of leaves;[9] others use highly detailed tree growth models to simulate trees.[8,10] These studies all show that the tree structure has a significant effect on the measured signal, and is therefore a critical component of any simulation.

The VoxLAD model enables creation of a highly detailed tree model based on terrestrial LiDAR scans of trees. The Monte Carlo LiDAR simulation model has the flexibility to model various collection parameters. Combining VoxLAD with the Monte Carlo LiDAR code enables simulation of small-footprint LiDAR systems.

3. VOXLAD MODEL FOR DERIVING LEAF AREA DENSITY FROM TERRESTRIAL LIDAR DATA

The VoxLAD model enables creation of fine-scale 3-D models of trees based on terrestrial LiDAR scans. Using dense terrestrial LiDAR point clouds as input, the VoxLAD model outputs a 3-D voxel model of the tree, where each voxel contains information about the Leaf Area Density (LAD), defined as the amount (total foliage surface area) of live leaf material per volumetric unit (m^2/m^3).[11–13]

The VoxLAD model follows the contact frequency approach of using a physical probe to measure the amount of material in a given volume by counting the number of leaves contacted by a thin probe inserted into a canopy. In the case of terrestrial laser scanner data, the number of leaves a physical probe would contact is related to the number of laser returns in a voxel. The number of laser returns in a voxel cannot be used as a direct measure of LAD because leaves on the outside of the canopy block laser energy from interaction with the leaves and woody materials further inside the canopy. The VoxLAD model makes use of the Beer-Lambert law, based on the proportion of rays entering a voxel and rays intercepting material inside a voxel, to define parametric equations for calculating LAD estimates at the voxel scale.

For the work presented here, a Coast Live Oak *(Quercus agrifolia)* was scanned from two opposing directions with a Riegl VZ-400 terrestrial laser scanner. The Riegl VZ-400 operates at 1550 nm, and has a $100°(+60°/-40°)$ vertical field of view, 360° horizontal field of view, a reported accuracy of 5 mm and precision of 3 mm, and a beam spread of 0.35 mrad.[14] The Riegl scans were collected on 29 March 2011 with the scanner mounted on a survey tripod approximately 1.7 m above the ground; the first scan was at a distance of approximately 20 m from the center of the tree canopy, while the second scan was collected from a distance of approximately 10 m from the canopy center. The step size between consecutive laser pulses was set at 0.060 degrees in both the vertical and horizontal directions, resulting in a distance between beams of 0.02 m at a distance of 20 m. With a beam diameter of 7 mm at exit from the system, and a beam divergence of 0.35 mrad, the beam diameter at 20 m is 14 mm, and 10.5 mm at a scan range of 10 m. The point clouds from each scan were co-registered using the RiScan Pro software with the help of retro-reflective control points visible within each scan. The resulting point cloud, with points colored according to apparent reflectance, is shown in Figure 1.

The VoxLAD model takes terrestrial laser scanner (TLS) data as input. Some preprocessing of the TLS data is necessary, including:[11]

1. Characterization of the leaf angle distribution for each layer in the crown
2. Normalization of the TLS return intensities to a common distance
3. Separation of foliage and wood within the TLS data
4. Computation of a correction factor for contact frequency (N) errors due to a non-zero laser-beam size.

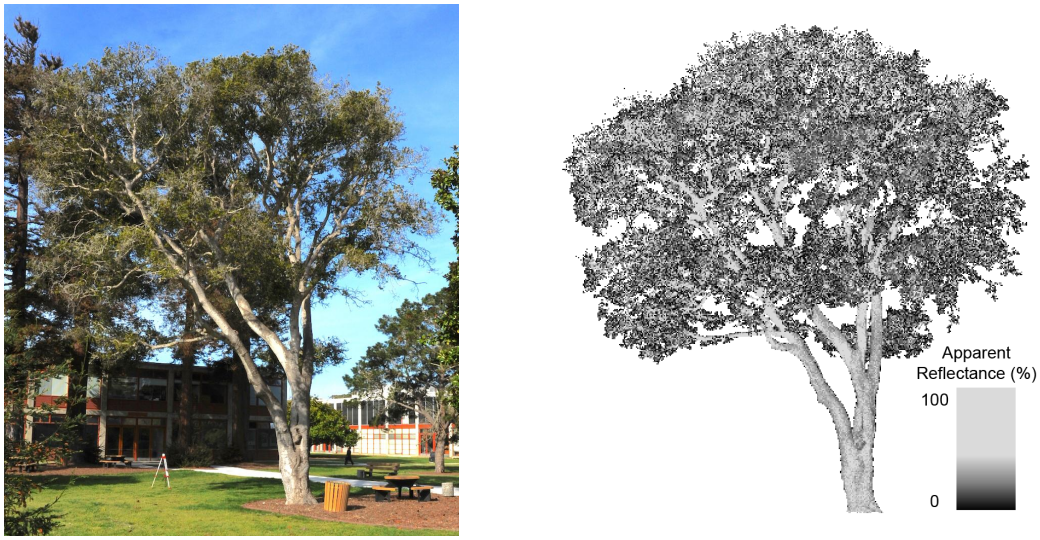

Figure 1: (L) A Coast Live Oak *(Quercus agrifolia)* was scanned from two opposing directions with a Riegl VZ-400 terrestrial laser scanner. (R) The Riegl VZ-400 point clouds colored in gray-scale according to apparent reflectance (%).

An appropriate voxel size must be chosen based on the scanning configuration and the size and shape of leaves in the tree canopy. In the work presented here, voxels have 20 cm long sides. This choice was made based on the size of the Coast Live Oak leaves (typically ~2 inches long x ~1 inch broad), and comparisons to voxel sizes used in Béland 2014.[13]

3.1 Characterization of leaf angle distribution

The Coast Live Oak has relatively small, convex-shaped leaves that appear to be fairly randomly oriented (Figure 2). Therefore, a uniform distribution of leaf angles was chosen to describe the vertical and horizontal orientation of leaves throughout the canopy. It should be noted, however, that the selection of leaf angle distribution function has a significant effect on the LAD values retrieved by the VoxLAD model, and further work is required to determine the most appropriate distribution to use in this particular case. A method for quantifying the leaf angle distribution based on digital camera photographs is presented in Ryu 2010.[15]

Figure 2: Coast Live Oak tree leaves appear randomly oriented in both horizontal and vertical directions.

3.2 Normalization of TLS return intensities to a common distance

The Riegl VZ-400 terrestrial laser scanner has the capability to export a so-called "relative reflectvity" value, given on the logarithmic decibel scale as

$$\text{Relative Reflectivity (dB)} = 10 * log_{10}\left(\frac{\text{Actual Optical Amplitude}}{\text{White Target Optical Amplitude}}\right).$$

The white target is assumed to be larger than the laser footprint, 100% reflecting, flat, and with its surface normal pointing towards the laser scanner.[16,17] For ease of interpretability, these values are converted here from decibels to apparent reflectance (%) values, where apparent reflectance is the ratio (in parentheses above) of actual optical amplitude to the white target optical amplitude.

3.3 Separation of foliage and wood returns and correction for contact frequency errors

The last two pre-processing steps are combined by choosing two apparent reflectance thresholds – the first threshold is used to separate wood and foliage returns, and the second threshold to classify partial beam returns as noise.

The leaves of the Coast Live Oak are generally less reflective than the wood materials at the 1550 nm operating wavelength of the Riegl VZ-400. A threshold to separate leaf and wood returns was chosen as a point approximately midway between the peaks of the histogram representing leaves and wood (see Figure 3). Scans of the tree in leaf-off conditions would be useful for refining the threshold selection, but these data were not available in this case.

Contact frequency errors are caused by the non-zero beam size of the laser scanner. Returns that are generated from pulses only partially hitting a leaf should not be used to calculate LAD values. In Béland 2011, an equation is presented that depends upon the pulse size at a given distance, sensor sensitivity, and size and shape of the leaves to account for contact frequency errors.[11] When using the Riegl VZ-400 however, apparent reflectance values are recorded, and as outlined in Béland 2014, partial returns due to the laser pulse center falling outside the edge of the leaf can be excluded based on a 50% threshold of the nominal (spectrometer measured) leaf reflectance value.[13] At 1550 nm, the nominal reflectance of the Coast Live Oak leaf is approximately 25%, so returns having apparent reflectance values less than 12.5% were classified as noise. The histograms of apparent reflectance values (%) for each of the TLS scans, and the selected thresholds are shown in Figure 3.

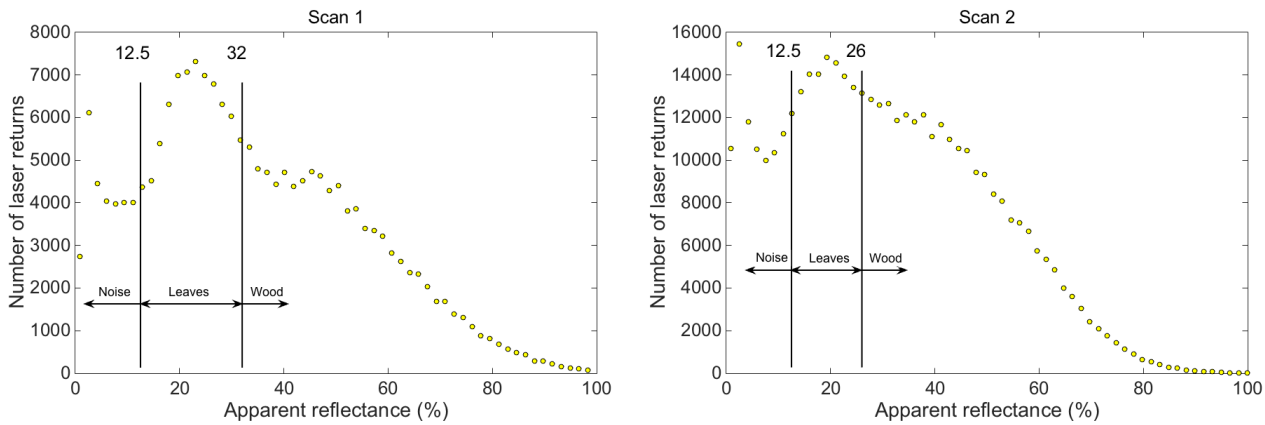

Figure 3: Histograms of apparent reflectance values from the Riegl VZ-400 terrestrial laser scans of the Coast Live Oak, with thresholds used to classify the points as wood, leaf or noise returns shown as vertical black lines. (L) Scan 1 was collected from a distance of approximately 20 m, while (R) Scan 2, was collected from a distance of approximately 10 m from the tree center.

Spectral measurements of the Coast Live Oak show the variability in reflectivity of the leaf and bark materials (Figure 4). The overall apparent reflectance reported by the Riegl VZ-400 is expected to be lower than the spectrometer measured leaf reflectance due partial beam returns – a laser beam which is only partially reflected will appear darker than a one that is fully reflected from a surface. The differences in apparent reflectance values between the two Riegl VZ-400 scans may be due to the difference in laser beam sizes caused by the use of different scanning ranges (20 m from canopy center for Scan 1 (~14 mm beam size); 10 m from canopy center (~10.5 mm beam size) for Scan 2).

The resulting wood, leaf, and noise classified point clouds are shown in Figure 5a-5c. Because of overlap in the reflectance values for wood and leaf returns, it is not possible to choose a threshold that precisely separates the materials. As can be seen in Figure 5b, there are returns from the edges of the trunk and branches that are misclassified as leaves. These points, to the greatest degree possible, were manually removed from the leaf point cloud and reclassified as wood returns (see Figure 5d). The final classified point cloud, with bark points in brown and leaf points in green, is shown in Figure 5e.

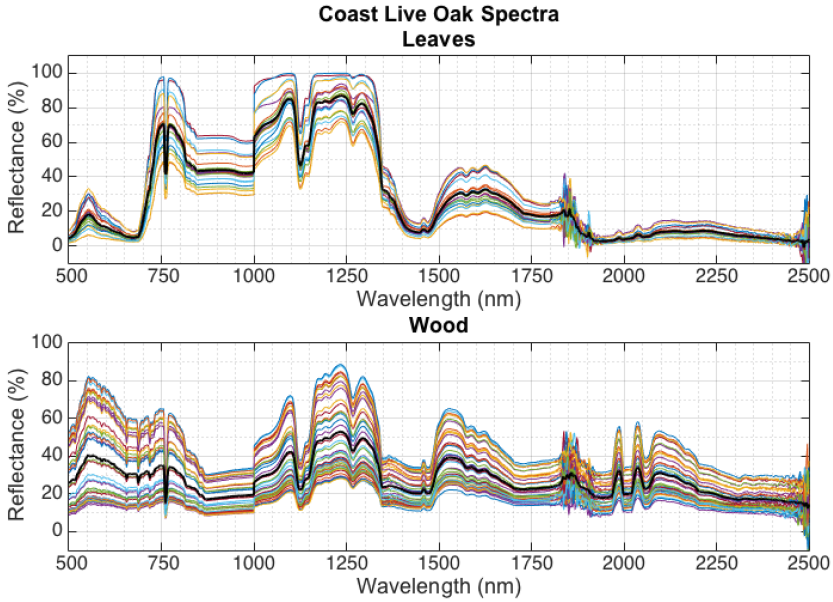

Figure 4: ASD Spectrometer spectra of Coast Live Oak leaf and wood materials.

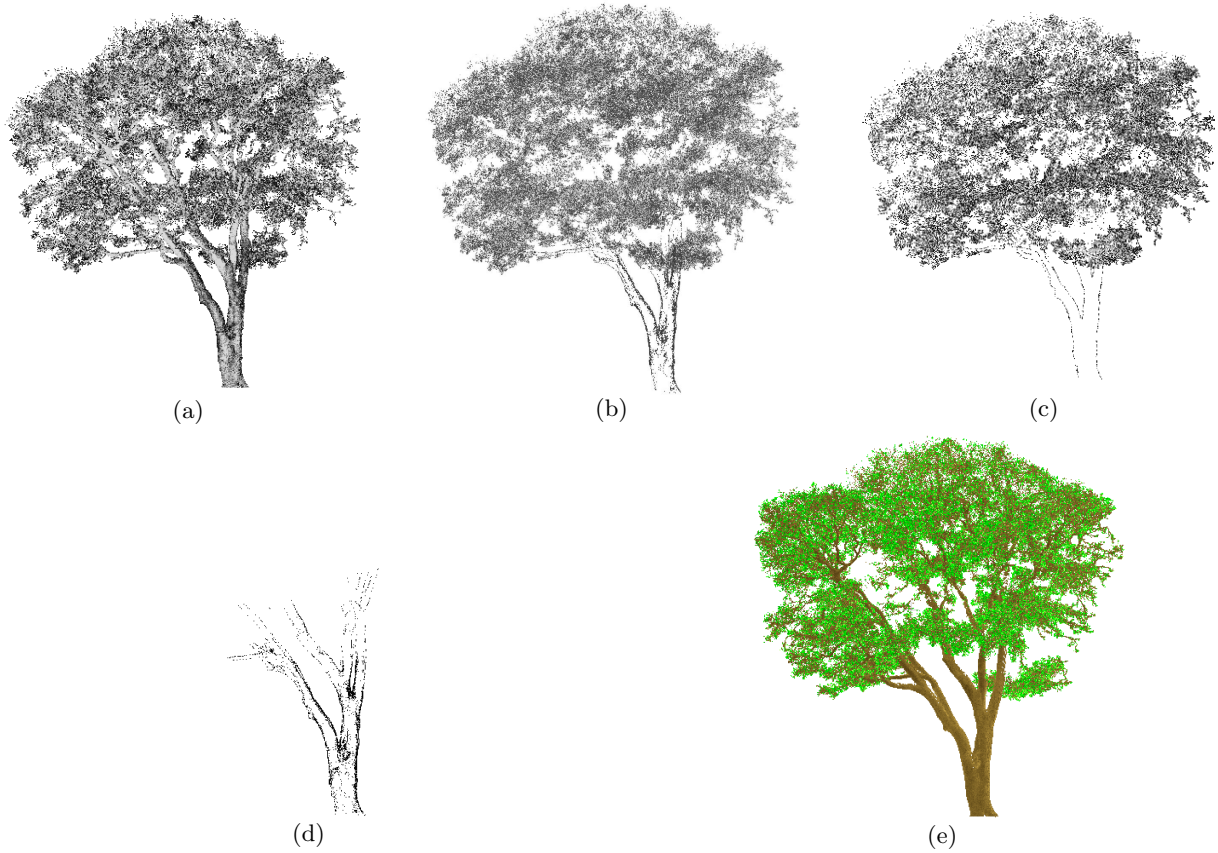

Figure 5: (a)-(c) Wood, leaf and noise returns from the initial classification of Riegl VZ-400 TLS point cloud based on threshold of apparent reflectance values. (d) Points that were misclassified as leaves based on apparent reflectance threshold were manually reclassified as wood returns. (e) Final classified point cloud, with bark returns in brown, and leaf returns in green.

3.4 Post-processing of VoxLAD results

3.4.1 Occlusion of voxels

If the tree canopy being examined is sufficiently dense, occluded voxels may cause a bias in reported LAD values. The VoxLAD model checks for occlusion on the basis of percent of voxel volume explored. Additional details and correction methods are presented in Béland 2014 to make this adjustment.[13] In the work presented here, no occluded voxels were detected, so no adjustment was needed.

3.4.2 Voxel size

The choice of voxel size can have a significant impact on the reported LAD values. In Béland 2014, it is suggested that the voxel size should be roughly 10 times the leaf size (defined as the mean secant through the leaf). This ensures the voxel is appropriately sized to satisfy the assumption of random distribution of materials (i.e., no clumping) within the voxel, and enables the detection of occluded voxels. However, this choice of relatively small voxel size may cause a slight overestimation of LAD values (on the order of ~5%).[13] In this case, a voxel side length of 20 cm was used, and the VoxLAD reported LAD values were multiplied by a correction factor of 0.95 to adjust for overestimation.

The resulting voxel model of the tree canopy, with leaf voxels colored according to LAD, is shown in Figure 6.

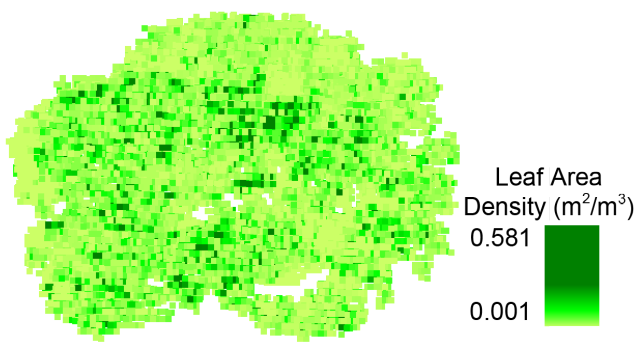

Figure 6: Voxel model of leaf canopy from VoxLAD model; points colored according to Leaf Area Density (LAD) in units of leaf area per unit volume (m^2/m^3). Voxel side length is 20 cm.

4. REFINEMENT OF SCENE MODEL FOR INCORPORATION INTO LIDAR SIMULATION

To incorporate the VoxLAD model results into the Monte Carlo LiDAR simulation code, a minimal amount of refinement was required. The LiDAR simulation code requires a measure of the probability of each type of material being present in a given location. The LAD measurement provides this information about the leaf materials in the tree canopy. For the wood material, a simple correlation was defined between the number of LiDAR returns in a given voxel and the probability of wood material existing at that location. The histogram of numbers of LiDAR returns in each wood voxel was calculated, and a linear stretch between 0 and 100% was applied to values falling below the 90% threshold of the cumulative distribution function. This results in a wood voxel model where the trunk and other thick branches are assigned a probability of 100%, while voxels with smaller branches have a lower probability. The resulting wood "probability" voxel model is shown in Figure 7 (L). This probability measure is used within the simulation to determine the likelihood of LiDAR energy interacting with wood material at a given voxel location.

The ground surface is modeled as being a flat surface. Voxels are assigned spectroradiometric and surface normal orientation properties. There is currently limited flexibility in modifying the ground surface.

The final voxel model, combining wood "probability" voxels, VoxLAD derived leaf voxels, and the ground surface is shown in Figure 7 (R).

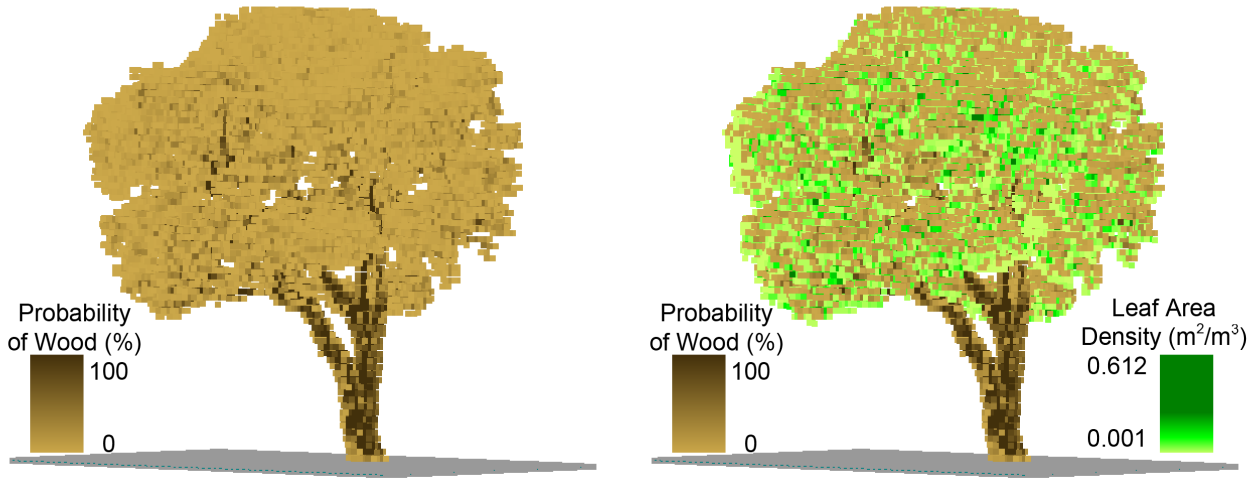

Figure 7: (L) Wood "probability" voxels colored in brown-scale according to the probability of wood material being present in a given voxel. (R) The final voxel model of the Coast Live Oak with the ground surface in grey, wood "probability" voxels in brown scale, and leaf voxels in shades of green according to LAD as derived by the VoxLAD model.

5. LIDAR SIMULATION

The LiDAR model is a Monte-Carlo ray tracing simulation of laser energy propagation through a scene. At each point in the scene, the interaction of LiDAR energy is determined probabilistically according to the presence of materials at the location, the reflective properties of the material, and the surface normal orientations. Energy is absorbed according to the spectral properties of the material. The remaining energy may be reflected or transmitted. Reflection causes the energy to change its direction of propagation, with the outgoing pulse direction determined according to the scattering properties of the material (Lambertian or specular), and the surface normal orientation of the material. The model has recently been improved to allow the simulation of interactions in 3-D.

The results presented here have been designed to simulate an airborne collect from May 2014 by an AHAB Chiroptera I system over the Monterey Bay peninsula area (see Table 1). Waveforms from the AHAB system were recorded for the scene, including the Coast Live Oak tree as modeled by VoxLAD, enabling qualitative comparisons between the simulated and real-world data (see Section 6). Unfortunately, lack of information about the pointing angle of the laser for each firing of the AHAB laser, as well as the lack of georegistration information for the Riegl VZ-400 TLS scans, prevented a precise simulation of any specfic AHAB waveform.

5.1 LiDAR model material interactions

The likelihood of laser energy interacting with a given material at each voxel is determined probabilistically. As explained in Section 4, the probability of wood materials being present, and therefore the likelihood of energy interacting with wood materials in a given voxel, is directly related to the number of TLS returns in the voxel volume. In the case of the ground surface, if the energy encounters a voxel defined as "ground", an interaction will occur.

For leaf materials, the LAD value reported by VoxLAD defines the amount of leaf material within a voxel. The likelihood of energy interacting with the leaves, however, depends not only on the amount of material present, but also on the orientation of the leaves with respect to the direction of laser propagation. The Monte Carlo LiDAR model incorporates the leaf orientation probabilistically by defining statistical distributions for the azimuthal and zenith angles of leaf surface normals. In this case, leaf azimuth angles were described as being symmetric about the center of the canopy, meaning all leaves face out from the center of the canopy. The zenith angles were described according to a uniform distribution, meaning all orientations from horizontal to vertical were equally likely. A scaling factor, S, to account for leaf orientation is defined as the dot product between

Table 1: Parameters used in the LiDAR model to simulate an airborne collect by an AHAB Chiroptera I system.

LiDAR Model Simulation Parameters			
Sensor			
Wavelength	1064 nm		
Laser off-nadir angle	15.135º		
Collection Altitude	360 m		
Beam Divergence (half angle)	0.5 mrad		
Waveform Sampling Frequency	1.8 GHz		
Laser pulse	4 ns long, Gaussian shaped		
Aperture diameter	0.5 m		
Scene			
Material Spectral Properties @ 1064 nm	Reflectance	Transmittance	Absorbance
Leaf	0.75	0.20	0.05
Bark/Wood	0.33	0	0.67
Ground (Wood Chips)	0.85	0	0.15
Scattering properties	Lambertian		
Tree height	13.6 m		
Leaf zenith angles	Uniformly distributed between 0 (vertical) and $\pi/2$ rad (horizontal)		
Leaf azimuth angles	Azimuthally symmetric around center of tree		
Ground zenith angles	$\pi/2$ (horizontal)		
Ground azimuth angles	Uniformly distributed between 0 and 2π rad		
Simulation			
Number of iterations	20 million		
Iteration step size	Time step (ns): 0.667128 Distance step (cm): 20		
Multiple scattering	Allowed		

the unit vectors describing leaf surface normal orientation and laser propagation direction. This scaling factor ranges between 0 and 1, where 1 is representative of the leaf surface being orthogonal to the direction of laser propagation (leaf surface normal is parallel to the direction of laser propagation). A value of 0 occurs when a leaf is hit "edge-on" by the laser beam. The probability of energy interacting with leaf material within a given voxel is the product of the LAD value and the scaling factor S. This formulation is inferior to a leaf projection function defining the projection coefficient of unit foliage area on a plane perpendicular to the view direction, but was necessary here for speed of processing considerations.[11,12,15] Further work is needed to quantify the effect of this choice, which may be significant.

For all materials and surfaces in the scene, the type of interaction – reflection, transmission, or absorption – is determined by a weighted random selection according to the material's defined spectral properties at the laser operating wavelength (see Table 1).

5.2 LiDAR model simulation results

The Monte Carlo LiDAR code was used to simulate the scene in "leaf on" and "leaf off" conditions. Figure 8 shows the traces of simulated energy scattered back towards the sensor and recorded as part of the waveform signal in both scenarios. The simulated waveforms are compared to the airborne full-waveform signals from the AHAB Chiroptera I system in Section 6. Figure 9 shows the simulated waveforms and the corresponding AHAB Chiroptera I waveforms.

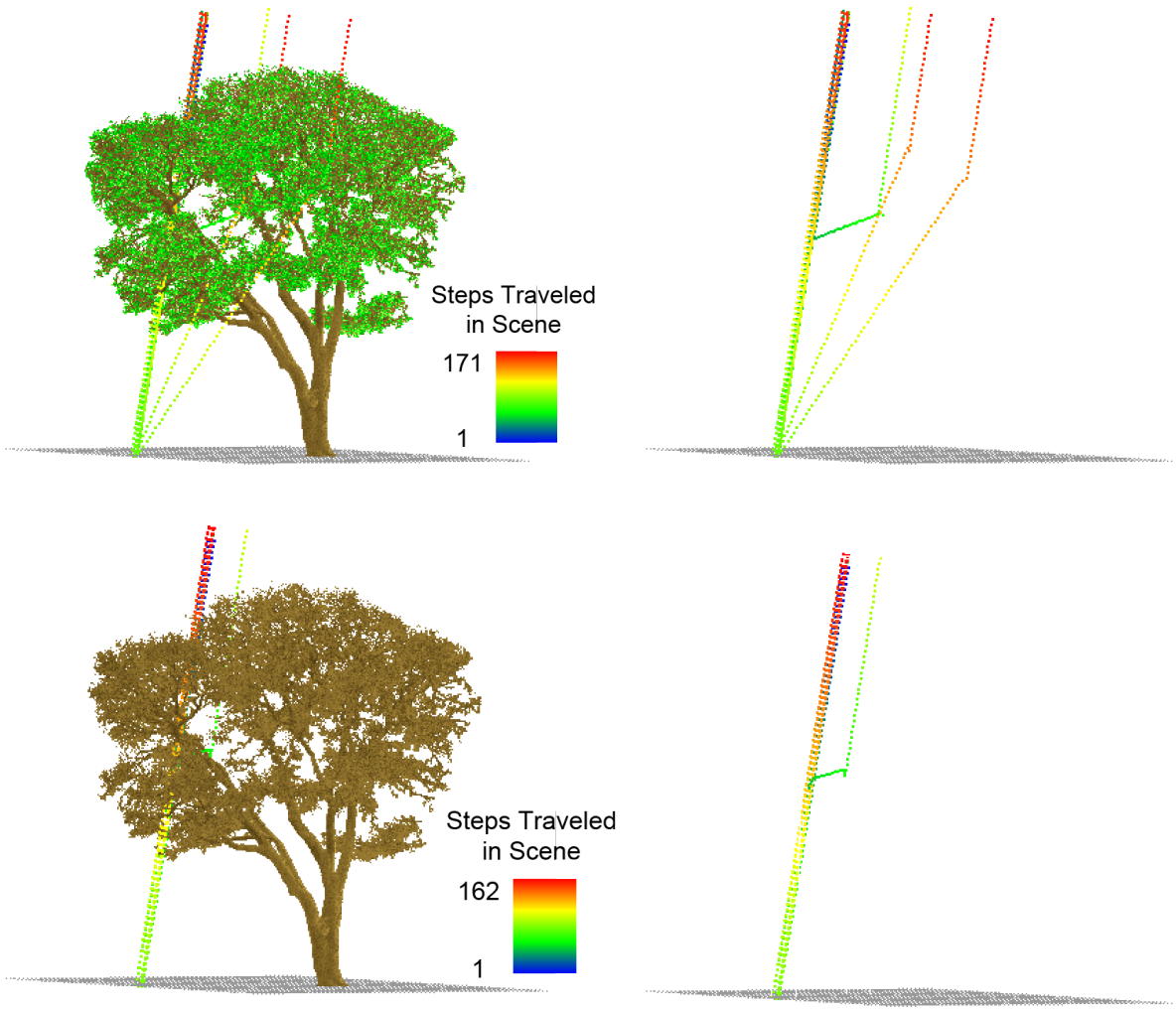

Figure 8: (Left) Trace of energy that was scattered back towards the sensor and recorded as part of the simulated waveform signal overlaid on the Riegl VZ-400 TLS point clouds, and (Right) with TLS point cloud data removed to enable viewing of scattering within the canopy. Traces of energy are colored according to number of steps traveled within the simulated scene. The Riegl VZ-400 point cloud data is colored according to the leaf (green) or wood (brown) classification of the points. The top row shows the simulation of "leaf-on" conditions, and the bottom row shows "leaf-off" conditions. The reader is referred to the online version of this paper for a corresponding video file: http://dx.doi.org/10.1117/12.2177158

6. COMPARISON TO AIRBORNE WAVEFORMS

Full-waveform LiDAR data were collected with an AHAB Chiroptera I system in May 2014. Two sources of uncertainty made replicating a specific waveform difficult. The first source of uncertainty was caused by the lack of laser pointing information for the AHAB Chiroptera I system. This made an exact replication of the collection geometry challenging. Since the point cloud data extracted from the waveforms has geographic information associated with each point, the approximate laser pointing vector for waveforms with multiple returns can be determined by fitting a vector to the extracted points.

A second source of uncertainty was caused by the lack of georegistration information for the Riegl VZ-400 TLS data. These data were manually aligned to match the AHAB Chiroptera I point clouds.

The simulated waveforms from the Monte Carlo LiDAR simulation code and a series of time-sequential

AHAB Chiroptera I waveforms extracted from the canopy of the Coast Live Oak tree canopy, are plotted in Figure 9. The AHAB waveforms were plotted so that ground peaks aligned with the elevation value reported in the extracted point cloud data. These waveforms all have very similar footprint locations and laser pointing angles.

While the uncertainties in georegistration prohibit a quantitative comparison, the simulated waveform appears to underestimate the canopy material. Possible explanations for the differences in the simulated and real AHAB Chiroptera I waveforms are given in the following section.

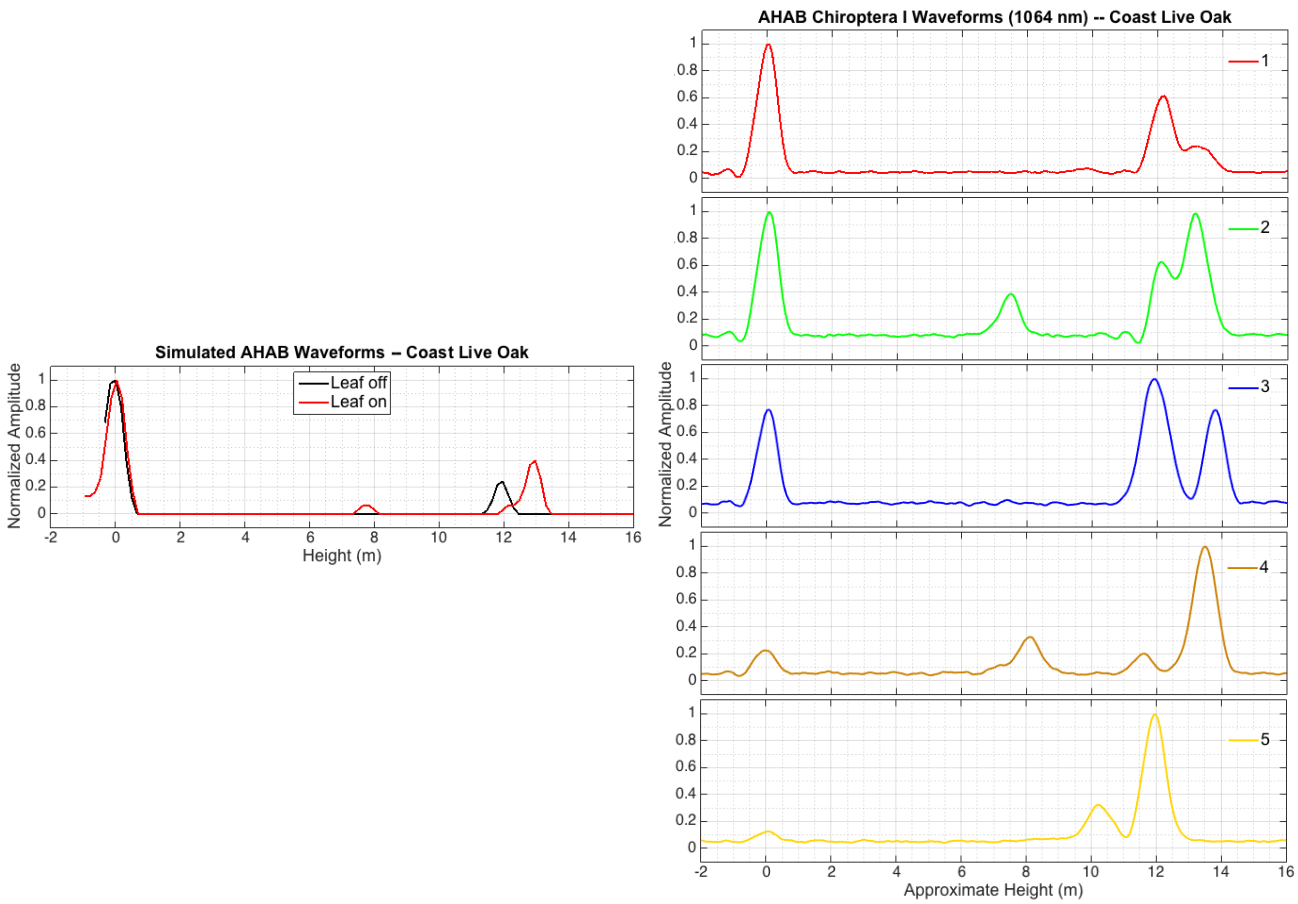

Figure 9: (L) The simulated waveforms, and (R) a series of AHAB Chiroptera I 1064 nm laser waveforms from the Coast Live Oak tree.

7. DISCUSSION

There are several potential sources of error in the simulation process that require further investigation.

7.1 Inputs to the VoxLAD model

The separation of wood and leaf returns in the terrestrial laser scanner point cloud can have a significant effect on the final LAD estimates from VoxLAD. As shown in Figure 4, ASD spectrometer measurements of the Coast Live Oak show a large amount of variability for both wood and leaf materials, with reflectance values at the 1550 nm operating wavelength of the Riegl VZ-400 TLS ranging from 20 to 60% for the wood materials, and 15 t0 45% for the leaf materials. While the leaves are generally less reflective than the wood materials at 1550 nm, there is a significant amount of overlap with the range of wood reflectance values. A simple apparent reflectance threshold was used to classify returns as being either wood or leaf – a more sophisticated method of classifying the points may be necessary here. Similarly, the points classified as "noise" were based on a threshold set at

50% of the nominal leaf reflectance value. This choice is appropriate for leaves having "little indentation" and "not excessive anisotropic properties" – the Coast Live Oak may not fit this description.[13]

7.2 Monte-Carlo LiDAR Simulation

The probability of wood material being present in a given voxel was determined based on the number of LiDAR returns from within each voxel. Because leaf and wood material at the outer edge of the canopy may block laser energy from reaching the center for the canopy, this approach may be underestimating the amount of wood material present. The effect of changes in pulse density with distance are currently not accounted for. A better wood model may be possible by using the VoxLAD model to calculate the normalized wood density, following the same process used to determine LAD.

Further work is needed to verify the validity of the method for determining the probability of interaction with leaf materials, which currently depends upon taking the dot product between the leaf surface normal orientation and the laser beam propagation direction. The use of a leaf projection function, defining the unit area of the leaf with respect to the laser propagation direction, would be a more valid choice, but speed of processing issues currently make this infeasible. The effect of the 3D shape of leaves needs to be accounted for.

7.3 Comparison to AHAB Chiroptera I waveforms

While the laser pointing information for the AHAB sensor was not available, making an exact replication of operating parameters impossible, the geolocation information from extracted points was used to estimate the laser pointing direction. This method only works in the case of waveforms having multiple extracted returns. Other unknown sensor characteristics, such as the system impulse response function, may also contribute to differences in the simulated waveforms.

A GPS system was not used when the Riegl VZ-400 data were collected, and so the data were geo-registered; accuracy of the geo-registration has not be verified.

Finally, The scans from the Riegl VZ-400 system were collected in March 2011, and the AHAB Chiroptera I full-waveform data were collected in May 2014. Drought conditions existed during the three years between collects, and the canopy of the Coast Live Oak has suffered. Differences most certainly exist between the VoxLAD modeled canopy (derived from the 2011 Riegl VZ-400 data), and the real canopy as measured by the AHAB Chiroptera I in May 2014. An updated scan with the Riegl VZ-400 terrestrial LiDAR system could be used to verify the differences.

8. CONCLUSION

The VoxLAD model was used to derive a 3D model of a Coast Live Oak (*Quercus agrifolia*) tree canopy from Riegl VZ-400 terrestrial LiDAR scans. The VoxLAD model provides an estimate of Leaf Area Density at each voxel location within the scene. A voxel model of the wood material in the scene was created by equating the number of Riegl VZ-400 LiDAR returns from wood materials with the likelihood of wood material being present in a given voxel. The ground was modeled as a flat surface with homogeneous spectroradiometric properties. A simulation of the scene was designed to replicate an airborne collect with an AHAB Chiroptera I full-waveform system. Due to lack of information about the AHAB system and lack of georegistration information in the terrestrial laser scanner data, an exact simulation of the airborne collect was impossible, but a qualitative comparison of simulated and real waveforms shows a general correspondence.

9. ACKNOWLEDGEMENTS

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REFERENCES

1. J. B. Blair and M. A. Hofton, "Modeling laser altimeter return waveforms over complex vegetation using high-resolution elevation data," *Geophysical Research Letters* **26**(16), pp. 2509–2512, 1999.
2. G. Sun and J. K. Ranson, "Modeling lidar returns from forest canopies," *IEEE Transaction on Geoscience and Remote Sensing* **38**(6), pp. 2617–2626, 2000.
3. W. Ni-Meister, D. L. B. Jupp, and R. Dubayah, "Modeling LiDAR waveforms in heterogeneous and discrete canopies," *IEEE Transaction on Geoscience and Remote Sensing* **39**(9), pp. 1943–1958, 2001.
4. S. Kotchenova, N. V. Shabanov, Y. Knyazikhin, A. B. Davis, R. Dubayah, and R. B. Myneni, "Modeling lidar waveforms with time-dependent stochastic radiative transfer theory for remote estimations of forest structure," *Journal of Geophysical Research* **108**(D15), 2003.
5. H. Huang and R. H. Wynne, "Simulation of lidar waveforms with a time-dependent radiosity algorithm," *Canadian Journal of Remote Sensing* **39**(S1), pp. S126–S128, 2013.
6. A. M. Kim and R. C. Olsen, "Detecting trails in LiDAR point cloud data," *Proceedings of SPIE Defense, Security, and Sensing* **8379**, 2012.
7. C. Hopkinson, "The influence of flying altitude, beam divergence, and pulse repetion frequency on laser pulse return intensity and canopy frequency distribution," *Canadian Journal of Remote Sensing* **33**(4), pp. 312–324, 2007.
8. M. I. Disney, V. Kalogirou, P. Lewis, A. Prieto-Blanc, S. Hancock, and M. Pfeifer, "Simulating the impact of discrete-return lidar system and survey characteristics over young conifer and broadleaf foresets," *Remote Sensing of Environment* **114**, pp. 1546–1560, 2010.
9. N. R. Goodwin, N. C. Coops, and D. S. Culvenor, "Development of a simulation model to predict lidar interception in forested environments," *Remote Sensing of Environment* **111**, pp. 481–492, 2007.
10. F. Morsdorf, C. Nichol, T. Malthus, and I. H. Woodhouse, "Assessing forest structural and physiological information content of multi-spectral lidar waveforms by radiative transfer modeling," *Remote Sensing of Environment* **113**, pp. 2152–2163, 2009.
11. M. Béland, J.-L. Widlowski, R. A. Fournier, J.-F. Côté, and M. M. Verstraete, "Estimating leaf area distribution in savanna trees from terrestrial lidar measurements," *Agricultural and Forest Meteorology* **151**(9), pp. 1252–1266, 2011.
12. M. Béland, J.-L. Widlowski, and R. A. Fournier, "A model for deriving voxel-level leaf area density estimates from ground-based lidar," *Environmental Modelling & Software* **51**, pp. 184–189, 2014.
13. M. Béland, D. D. Baldocchi, J.-L. Widlowski, R. A. Fournier, and M. M. Verstraete, "On seeing the wood from the leaves and the role of voxel size in determining leaf area distribution of forests with terrestrial lidar," *Agricultural and Forest Meteorology* **184**, pp. 82–97, 2014.
14. RIEGL Laser Measurement Systems, "RIEGL VZ-400 Specifications." Datasheet.
15. Y. Ryu, O. Sonnentag, T. Nilson, R. Vargas, and H. Kobayashi, "How to quantify tree leaf area index in an open savanna ecosystem: A multi-instrument and multi-model approach," *Agricultural and Forest Meteorology* **150**, pp. 63–76, 2010.
16. RIEGL Laser Measurement Systems, "Latest News, March 2009." News bulletin, March 2009.
17. M. Pfennigbauer and A. Ullrich, "Improving quality of laser scanning data acquisition through calibrated amplitude and pulse deviation measurement," *Proceedings of SPIE Defense, Security, and Sensing* **7684**, 2010.