SIMULATED LIDAR WAVEFORMS FOR THE ANALYSIS OF LIGHT PROPAGATION THROUGH A TREE CANOPY

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ABSTRACT

Full-waveform LiDAR is a technology which enables the analysis of the 3-D structure and arrangement of objects. An in-depth understanding of the factors that affect the shape of the full-waveform signal is required in order to extract as much information as possible form the signal. A simple model of LiDAR propagation has been created which simulates the interaction of LiDAR energy with tree canopy materials, including leaves, bark and air. The model allows for the controlled simulation of a tree canopy, including geometric arrangement of branches and leaves with varying spectral properties. Simulations are presented which demonstrate the interaction of LiDAR energy at the leaf, branch and single-tree canopy scale. Results suggest complex interactions of the LiDAR energy with the tree canopy, including the occurrence of multiple bounces of energy reaching the ground under the canopy.

KEYWORDS: Full-waveform LiDAR, modeling and simulation, waveform shape

INTRODUCTION

Current methods for extracting information from full-waveform LiDAR data depend upon fitting a series of Gaussian peaks to match the full-waveform LIDAR signal. This Gaussian decomposition of the waveform provides a way of quantifying some of the information present in the waveform signal – the peak height, full-width at half maximum, skewness and kurtosis of the fitted Gaussian curves can all be used to quantitatively describe the shape of the waveform. These parameters have been used in land-cover classification schemes, and recently, to extract physical parameters of the land-cover types (Harding et al., 2001, Hofton, et al., 2000, Duncanson et. al., 2010).

Fitting a series of Gaussians to the full-waveform LiDAR signal simplifies the analysis process, but also ignores some of the finer structure present in the waveform. The motivation for the model presented here is to understand the factors that affect waveform shape, with the belief that a better understanding of these factors will allow a greater amount of information to be extracted from the waveform.

There are a variety of factors which affect the waveform shape, independent of the objects being sensed, including sensor artifacts and noise, the instrument response function, the intensity and shape of the transmitted pulse, etc. One of the difficulties in working with real LiDAR waveform data is that many of these factors are considered proprietary information, and their effect on the delivered data is impossible to trace. By working with simulated data, these factors can be held constant while the scene is varied. This enables an understanding to be gained of the theoretical performance and limitations of waveform LiDAR data, even if the modeled signals do not exactly represent the information collected by any specific sensor.

THE LIDAR MODEL

The model allows variation of the LiDAR sensor parameters, including transmitted pulse shape, laser wavelength, beam width and beam spread, and geometric orientation of the sensor in relation to objects in the scene. Table 1 shows some of the settings used in the simulations presented here. Objects in the scene can be removed or rearranged, and material reflectance properties can be adjusted.

Table 1. LiDAR sensor parameters and typical values used in simulations.

LiDAR Sensor Parameters	
Transmitted pulse length	6 ns
Laser wavelength	1064 nm
Sensor altitude above ground	1000 m
Beam spread	0.3 mrad
Energy detection threshold	0.1% of transmitted energy
Laser footprint on ground	30 cm
Laser pointing angle	nadir
Aperture diameter	50 cm
Digitizer rate	1 ns

The simulated full-waveform LiDAR signal is created by repetitively tracking how a single Gaussian-shaped pulse of LiDAR energy interacts with the scene. The Gaussian-shaped pulse of transmitted LiDAR energy is modeled as a series of discrete pulses having an energy equal to a small time-segment of the Gaussian. Each of these time-segment bin pulses is traced through the simulation. When the pulse of energy interacts with a material in the scene, a portion of the energy is absorbed according to the material reflectance properties of the object. The remaining energy may be reflected or transmitted. The type of interaction energy has with an object in the scene is determined according to the material reflectance properties of the object. For example, if a leaf is 60% reflective, with 39% of the energy being absorbed, and the final 1% being transmitted, 60% of the interactions of energy with the leaf will result in the energy being reflected, and 1% of the interactions will result in the energy will being transmitted. Each time a pulse of energy interacts with the leaf, 39% of the energy is absorbed.

The distribution of energy throughout the scene is recorded. The percentages of energy returned to the sensor, scattered out of the scene, or absorbed by objects in the scene is reported along with the number of interactions a pulse underwent before returning to the sensor. This data can be analyzed to gain a better understanding of how LiDAR energy interacts with the scene.

SIMULATED SCENES

The model has been kept as simple as possible to facilitate ease of use, while also enabling investigation of specific factors affecting waveform shape. One of the most significant simplifications is the 2-dimensional nature of the objects in the scene. In order to reduce a 3-D object to a 2-D one, the model treats the 2-D object as a probability map. For example, if the tree shown in Figure 1 is assumed to be a single slice through a 3-D tree, the 3-D object could be reconstructed by spinning the 2-D tree about the trunk. This would create a 3-D tree with solid cones of branches. In reality, branches occur much more infrequently, so the 2-D object is treated as a probability map, with the probability reduced as needed.

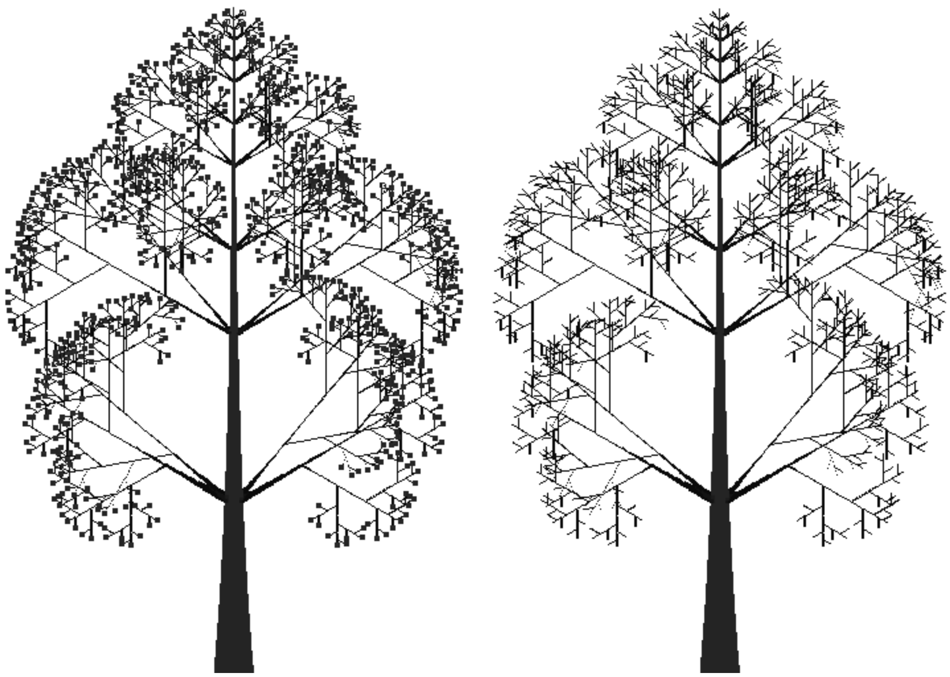

Figure 1. 2-dimensional tree model with and without leaves.

WAVEFORM CREATION

The LiDAR model outputs a raw waveform consisting of all of the points returned to the sensor, and the corresponding intensity of the returned energy. These points represent the composite result of iterating the simulation thousands of time, and there are multiple overlapping points (see Figure 2). The points making up the raw waveform are resampled to a regular time sampling, with the intensity values being averaged at each time sample (see Figure 3). To incorporate the effects of the instrument response function, the raw waveform is convolved with a Gaussian curve representing the Instrument Response Function. The final step in creating the simulated waveform is 'digitizing' the waveform at a particular frequency (see Figure 4). A typical digitizer sampling frequency is 1 ns.

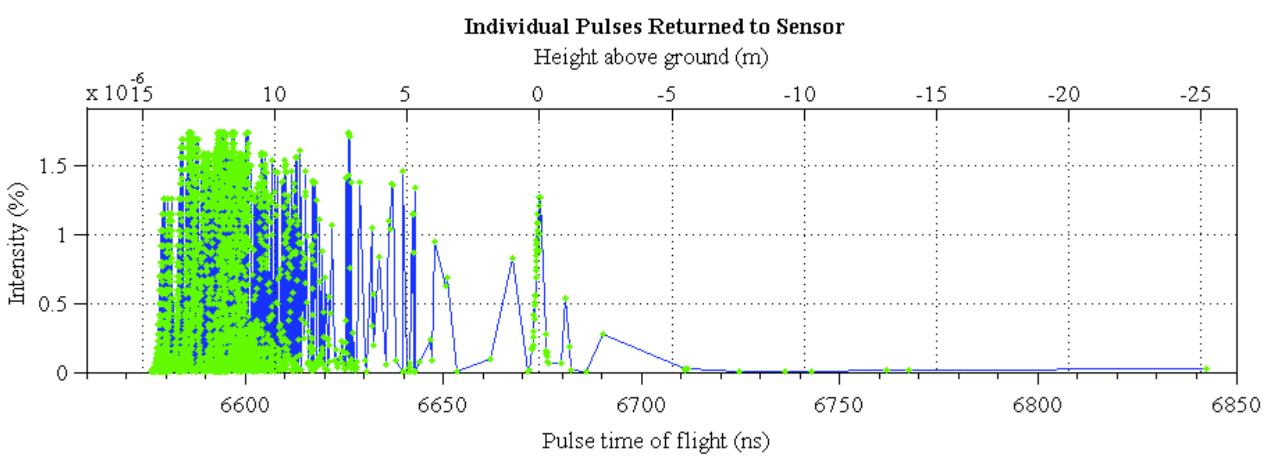

Figure 2. Raw waveform consisting of all points returned to the sensor from multiple model iterations.

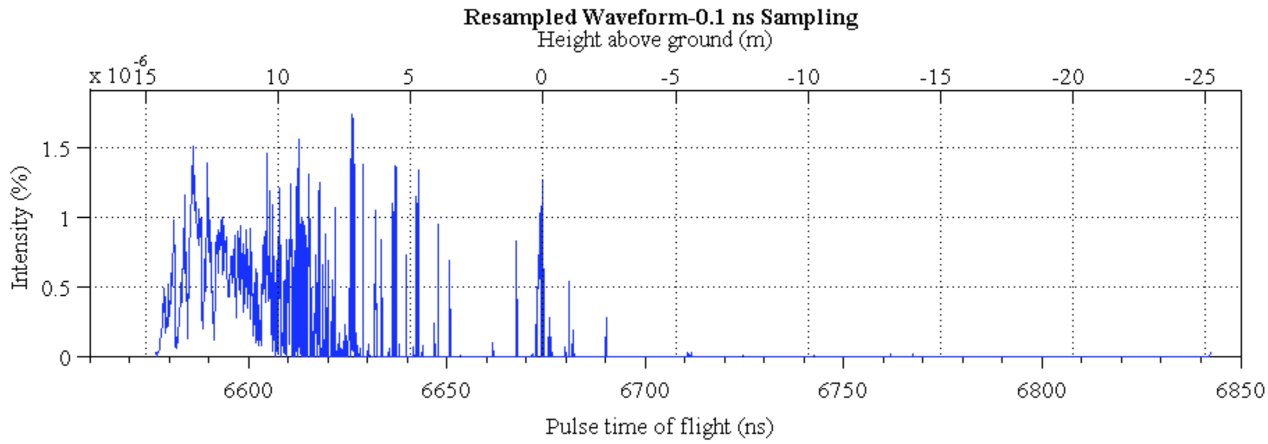

Figure 3. Waveform created by resampling the raw waveform into 0.1 ns time samples.

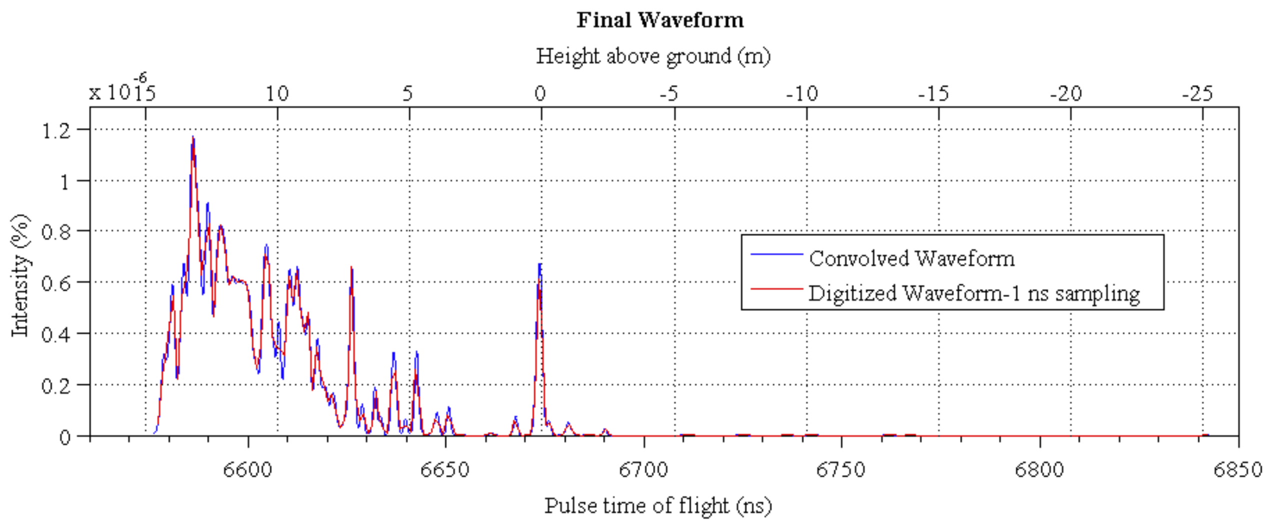

Figure 4. The resampled waveform is convolved with a 3-ns Gaussian Instrument Response Function (blue curve), and then digitized at the digitizer rate (red curve).

SIMULATION RESULTS

A series of simulated LiDAR waveforms are created using the tree model to investigate the number of interactions a pulse of energy undergoes as it propagates through the scene, and the effect this multiple-scattering has on the waveform signal.

The tree model is treated as a probability map by the LiDAR simulation. In the author's experience, LiDAR energy typically reaches the ground under the canopy, and so the probability was adjusted to ensure at least some energy reaches the ground. This is a subjective determination, and results of two simulations with varying probability levels (4% and 7%) are given to illustrate the effect of the material probability setting. The 'low' 4% material probability setting was chosen so that a ground peak is definitely distinguishable in the waveform. The 'high' 7% material probability setting corresponds to a much denser canopy, and was chosen so that the ground is just barely detectable under the canopy. The varying material probability level translates to varying levels of biomass in a real tree.

The model records the number of scattering events each pulse of energy undergoes, and the path the pulses of energy followed throughout the scene. Figure 5 shows the paths taken by pulses of energy which returned to the LiDAR sensor for these two simulations. Pulses of energy scattered out of the scene or completely absorbed by materials in the scene are not shown.

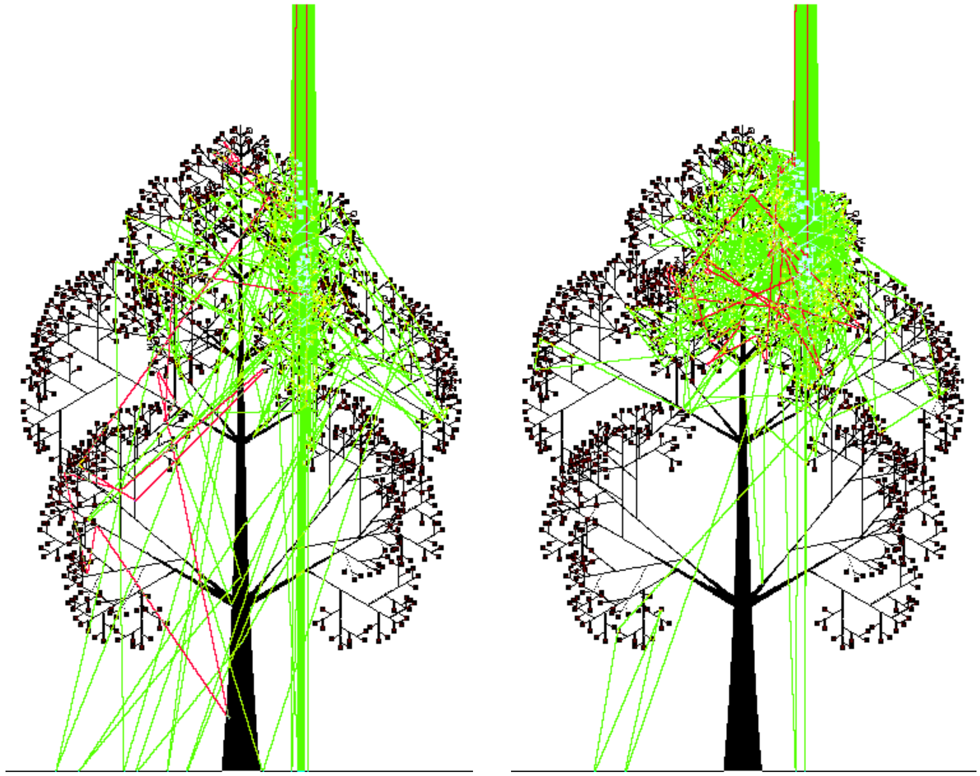

Figure 5. Path taken by LiDAR points which returned to the sensor. The pulse which underwent the highest number of interactions is highlighted in red. The left tree image is the simulation with a lower material probability level; the right tree image has a slightly higher material probability level.

Figure 5 illustrates that due to scattering within the canopy, the waveform signal is influenced by an area much larger than the footprint of the LiDAR beam. The area of influence includes a large portion of the canopy and ground underneath the tree as well.

The left image is the result of a simulation using a slightly lower material probability level than that shown in the right image. Increasing the material probability level restricts the amount of energy that reaches the ground. The number of interactions within the canopy increases as the material probability increases.

For each pulse of energy returned to the sensor, the model records the time of flight, intensity of returned energy and the number of scattering events the energy underwent. An illustration of this data is given in Figures 6 and 7. To gain a better understanding of how multiple-scattering affects the waveform, the number of scattering events is investigated more closely.

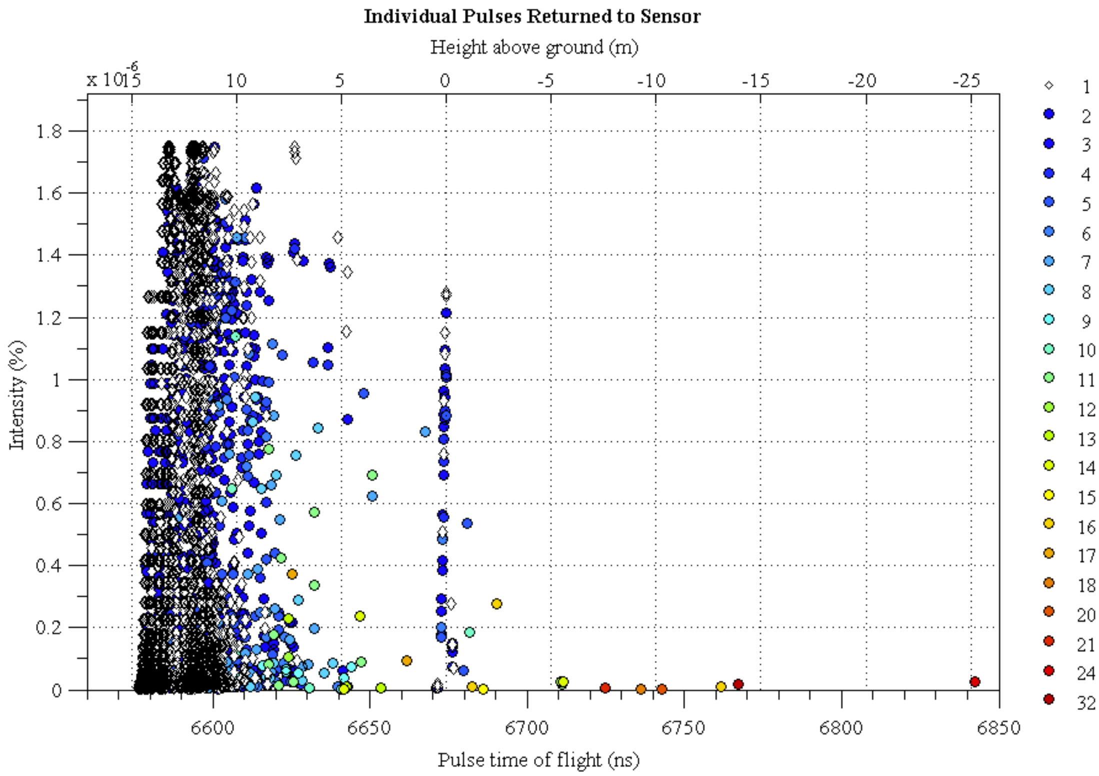

Figure 6. Individual pulses returned to the sensor colored by number of pulse interactions; lower material probability level.

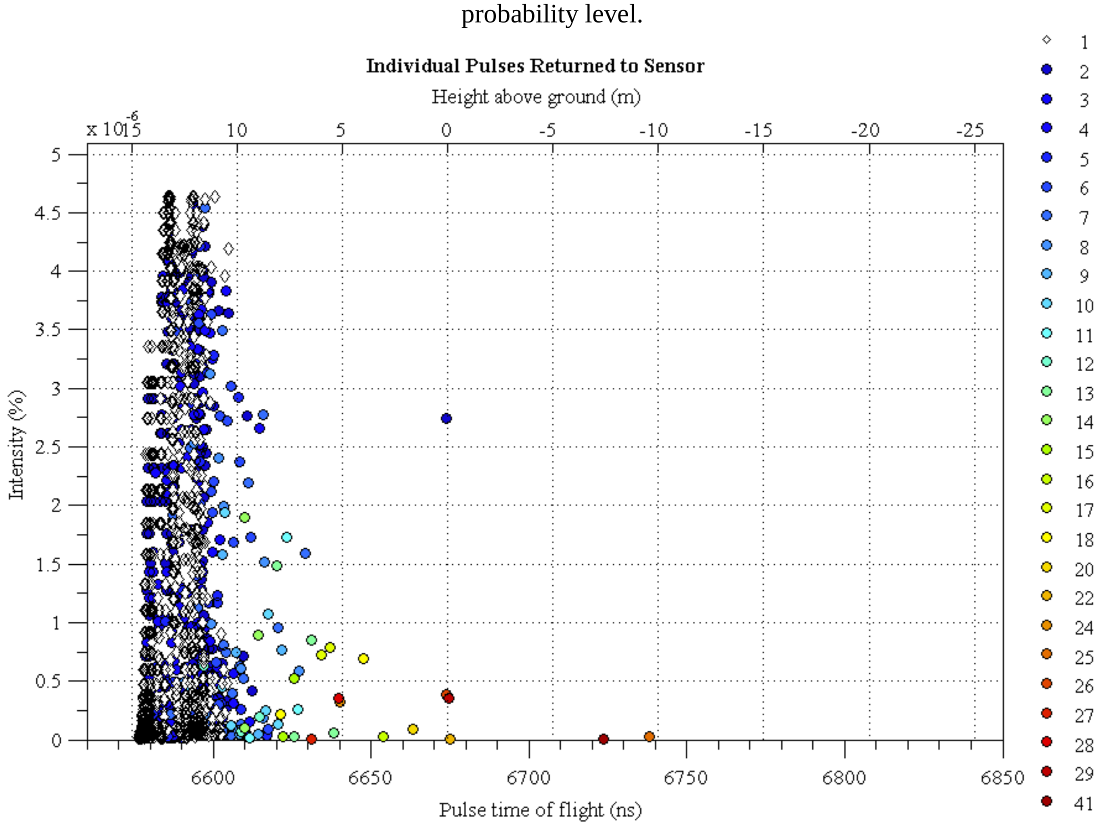

Figure 7. Individual pulses returned to the sensor colored by number of pulse interactions; higher material probability level.

Figures 6 and 7 show that multiple-scattering tends to increase the width of the peak of the waveform, and contributes to secondary peaks. Using a higher material-probability level means interactions with materials in the scene are more likely. At the lower material-probability level, some of the returns from the ground are singly-scattered returns. At the higher material-probability level, the energy that reaches the ground undergoes multiple scattering events. Because of multiple-scattering, there appears to be energy returning from below ground level. The intensity level of these returns is so reduced however, there is very little contribution to the waveform (see Figures 2-4).

Although some of the energy returned to the sensor undergoes significant scattering, it appears that most of the contribution to the waveform comes from singly-scattered energy. The distribution of numbers of scattering events is illustrated in Figures 8 and 9. These figures highlight the fact that most of the energy contribution to the waveform is from singly-scattered energy.

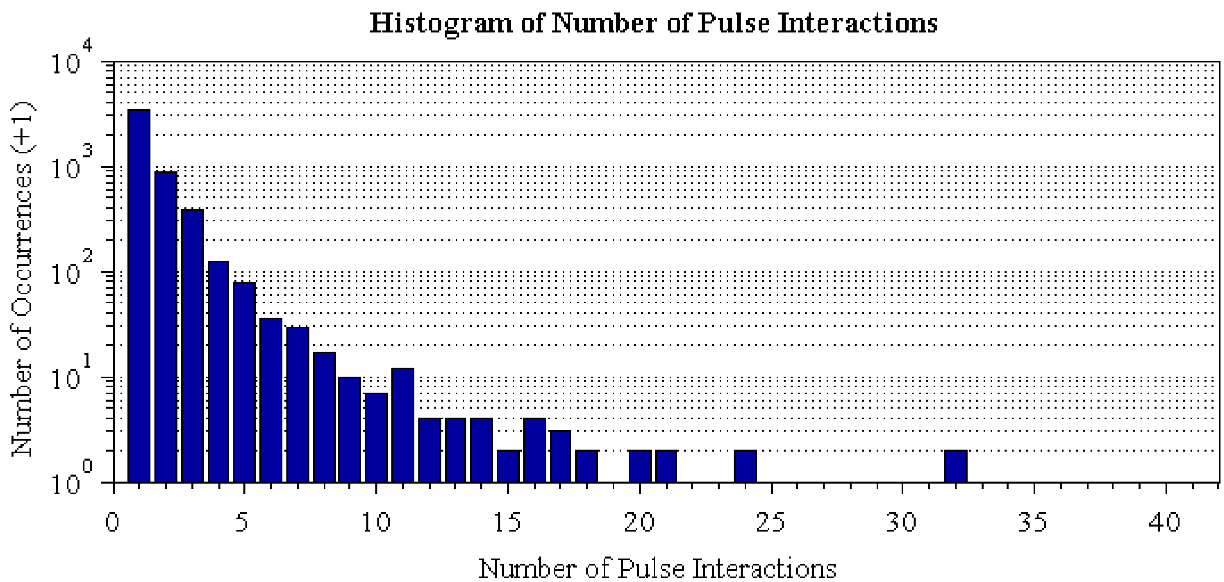

Figure 8. Histogram of number of pulse interactions; lower material probability level (Note: Number of interactions was increased by 1 to ensure visibility on log-scale plot).

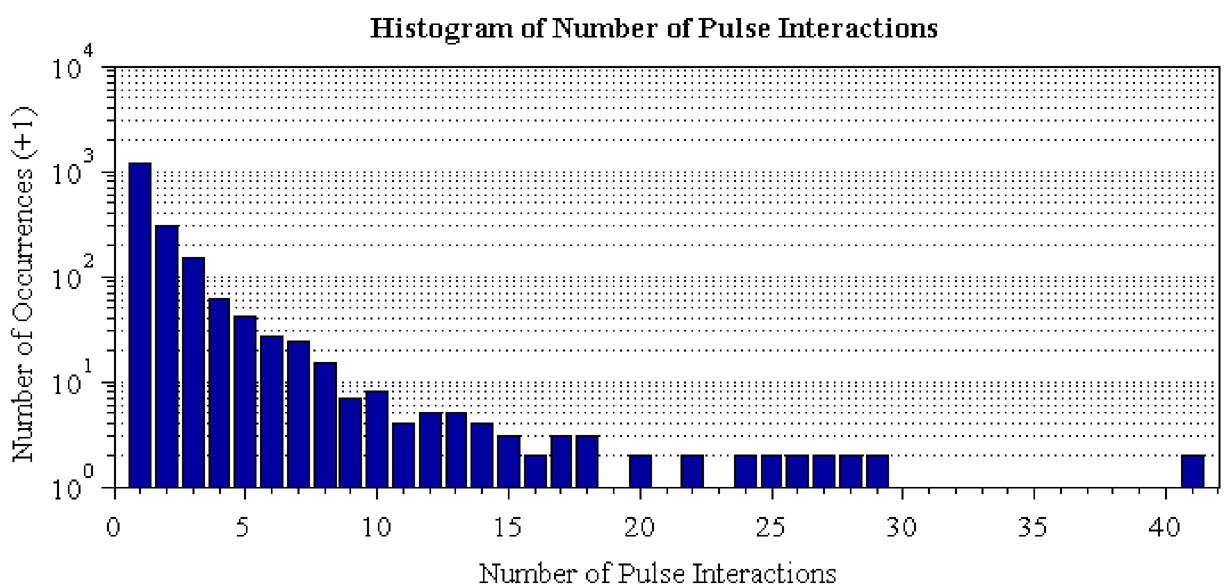

Figure 9. Histogram of number of pulse interactions; higher material probability level (Note: Number of interactions was increased by 1 to ensure visibility on log-scale plot).

Finally, in Figures 10 and 11, a comparison is made between the waveforms created using the LiDAR pulses which underwent multiple interactions in the scene, and the pulses which only had single interactions. It appears that the major peaks in the waveform are captured by the singly-scattered energy. This has implications for algorithms which rely on assumptions of single-scattering dominance, and also for future modeling efforts. The speed of simulation can be increased if interactions are restricted to single-scattering events. The multiple-scattering energy does affect the waveform however; the width of the waveform peak is widened by the multiple-scattering energy, and smaller secondary peaks are more pronounced. These factors are important when measuring biomass.

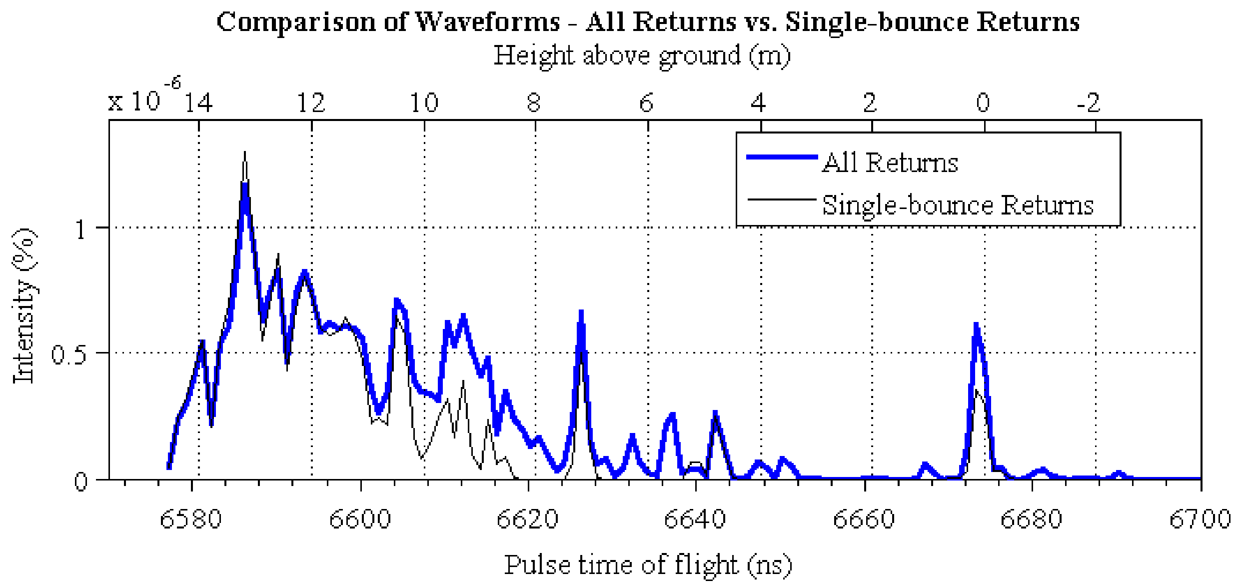

Figure 10. Individual pulses returned to the sensor colored by number of pulse interactions; lower material probability level.

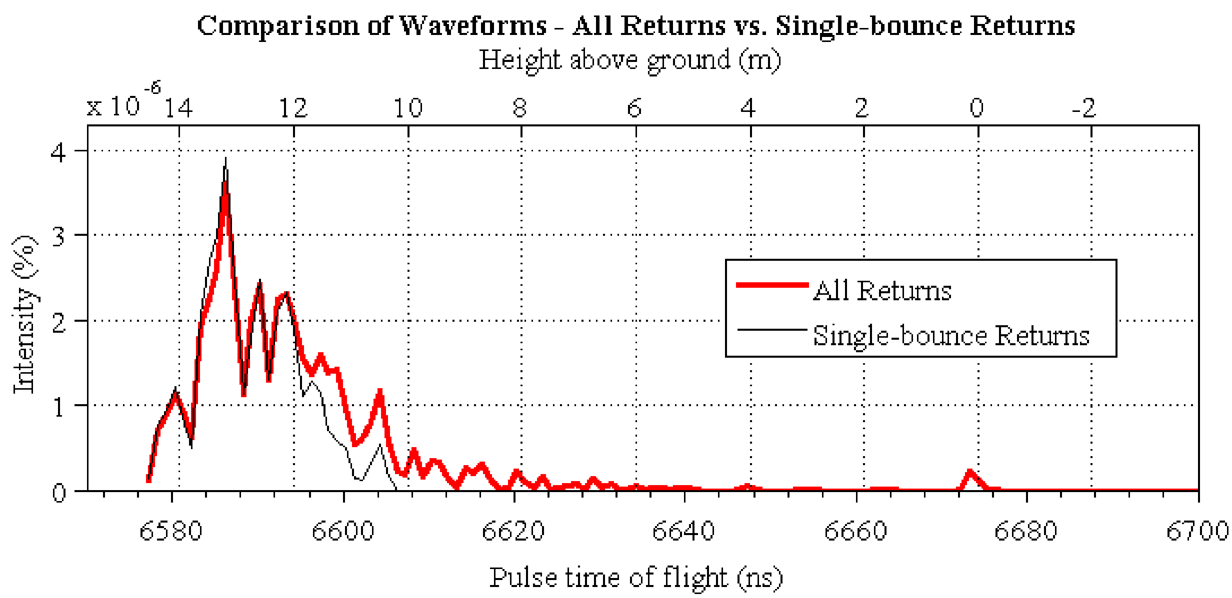

Figure 11. Individual pulses returned to the sensor colored by number of pulse interactions; higher material probability level.

For ease of comparison, waveforms created using the two material probability levels are shown in a single graph. Figure 12 shows the comparison between waveforms created using all of the returns to the sensor (including multiple-scattering events), and Figure 13 shows the waveforms created from only the singly-scattered energy.

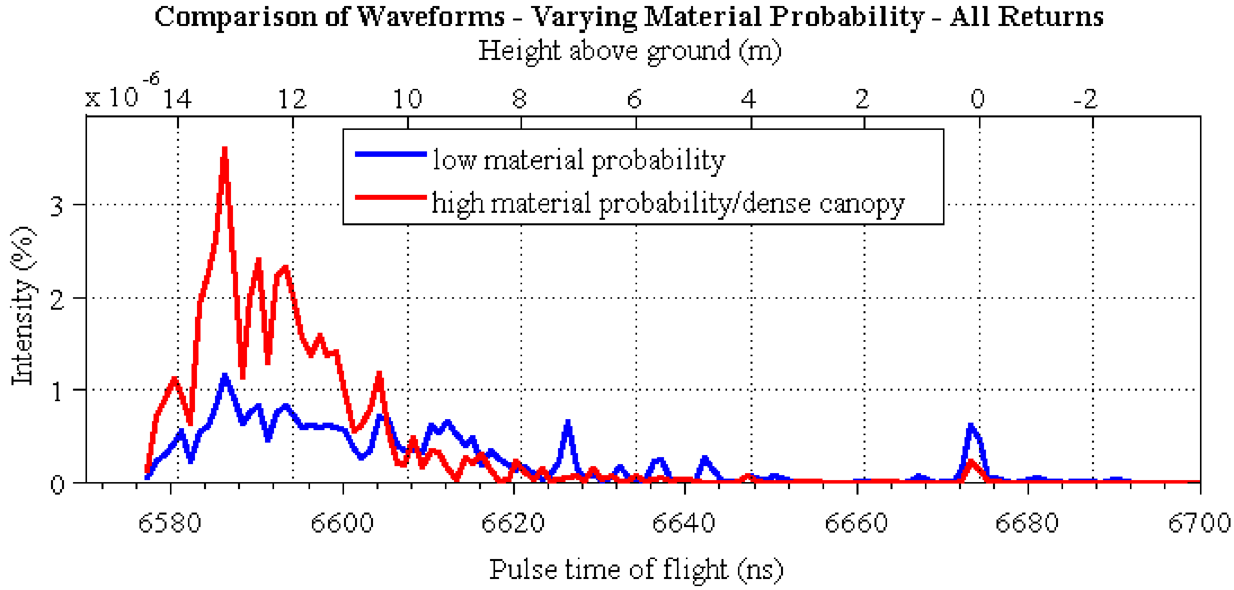

Figure 12. Comparison of waveforms created using all returns from simulations with different material probability levels; the higher probability level corresponds to a tree having a denser canopy.

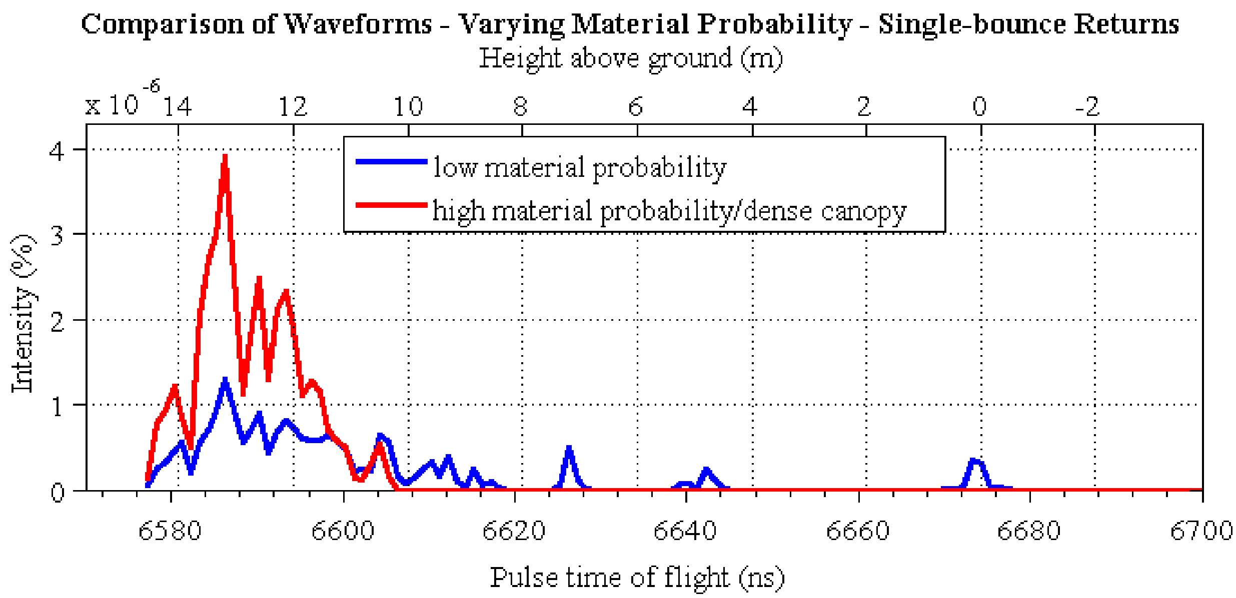

Figure 13. A comparison of the simulated waveforms created using only single-bounce returns from simulations using different material probability levels; the higher probability level corresponds to a tree having a denser canopy.

Note that at the higher material probability level (denser tree canopy), the ground is not detected by singly-scattered energy (see Figure 13). As shown in Figure 12, energy is returned from the ground, but the energy has undergone multiple-scattering events. Figures 12 and 13 illustrate how the waveform peak widens with increasing canopy density.

CONCLUSIONS AND FUTURE WORK

The simulations presented here demonstrate some of the complexity of full-waveform LiDAR data, and the effect multiple-scattering has on the full-waveform LiDAR signal.

One area of interest is the level of detail which can be extraced by a waveform signal. As waveform LiDAR technology advances, higher fidelity data will become available, and smaller details in the waveform signal will be separable from the noise. Further research is needed to understand how to capture and utilize this information.

REFERENCES

Duncanson, L.I., Niemann, K.O., and Wulder, M.A., 2010. Estimating forest canopy height and terrain relief from GLAS waveform metrics, *Remote Sensing of Environment, 114*:138-154.

Harding, D.J., Lefsky, M.A., Parker, G.G. Blair, J.B., 2001. Laser altimeter canopy height profiles: methods and validation for closed-canopy, broadleaf forest, *Remote Sensing of Environment, 76(3)*, 283-297.

Hofton, M.A., Minster, J.B., Blair, J.B., 2000. Decomposition of laser altimeter waveforms, *IEEE Transactions on Geoscience and Remote Sensing, 38(4)*, 1989-1996.

Kim, A.M., Olsen, R.C., and Borges, C.F., 2009. Simulation full-waveform LiDAR, *Master's Thesis, Naval Postgraduate School, Monterey, CA.*