Simulated LIDAR waveforms for understanding factors affecting waveform shape

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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 from the signal. A simple model of LIDAR propagation has been created which simulates the interaction of LIDAR energy with objects in a scene. A 2-dimensional model tree allows controlled manipulation of the geometric arrangement of branches and leaves with varying spectral properties. Results suggest complex interactions of the LIDAR energy with the tree canopy, including the occurrence of multiple bounces for energy reaching the ground under the canopy. Idealized sensor instrument response functions incorporated in the simulation illustrate a large impact on waveform shape. A waveform recording laser rangefinder has been built which will allow validation or model results; preliminary collection results are presented here.

Keywords: Full-waveform LIDAR, waveform shape, simulation

1. INTRODUCTION

A variety of metrics for extracting forest structure information from full-waveform LiDAR data have been introduced. The 2010 paper by L.I. Duncanson et. al. provides a summary of techniques, including Gaussian decomposition and methods which make use of the fact that a LiDAR waveform signal is a record of laser energy returned over time. While there are many different waveform processing methods which have been developed, it is difficult to validate or compare them due to the complexity of LiDAR data. A waveform has a 3-dimensional arrangement in space, but in order to compare with ground based measurements, a 2-D lat/long coordinate is assigned to the waveform. If the laser is pointing off nadir at time of collection, this becomes a complicated issue. For spaceborne systems such as the GLAS system aboard ICEsat, an assumption of a nadir pointing laser can be made, but there is a great deal of complexity due to the large area of the footprint, which may cover multiple landcover types and variable terrain. Variability in ground based measurements is another factor which complicates comparison (and is also a motivating factor for the use of full-waveform data). Due to the complicated nature of waveform data, determining exactly what is being measured by the LiDAR system and what information can be extracted from the signal, is a difficult problem. Models such as the one presented in this paper will allow a better understanding of the factors affecting waveform shape, and with this, the ability to extract more information from the data.

2. PREVIOUS WORK

Results of this modeling effort presented previously outlined the basic operation of the model, and demonstrated a variety of test cases designed to illuminate various aspects of the model. The most significant recent work includes porting the code from the IDL programming language to MATLAB, and the incorporation of the sensor’s instrument response function. The change in programming languages was merely personal preference. The incorporation of the instrument response function has a significant impact on the final waveform shape, creating waveforms which look much more realistic. A utility to analyze the number of pulse interactions has been developed, and is used to investigate the effects of multiple-scattering.

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3. THE SIMULATED SCENE

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.](image)

4. 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.

<table>
<thead>
<tr>
<th>Lidar Sensor Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitted pulse length</td>
<td>6 ns</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>1064 nm</td>
</tr>
<tr>
<td>Sensor altitude above ground</td>
<td>1000 m</td>
</tr>
<tr>
<td>Beam spread</td>
<td>0.3 mrad</td>
</tr>
<tr>
<td>Energy detection threshold</td>
<td>0.1% of transmitted energy</td>
</tr>
<tr>
<td>Laser footprint on ground</td>
<td>30 cm</td>
</tr>
<tr>
<td>Laser pointing angle</td>
<td>nadir</td>
</tr>
<tr>
<td>Aperture diameter</td>
<td>50 cm</td>
</tr>
<tr>
<td>Digitizer rate</td>
<td>1 ns</td>
</tr>
</tbody>
</table>
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 energy interacts with a material in the scene, the type of interaction (reflection or transmission) is determined according to the material reflectance properties of the object. The material reflectance properties also define how much energy is absorbed with each interaction. Any energy remaining after absorption may be reflected or transmitted.

5. 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 curve representing the Instrument Response Function. The Instrument Response Function can have a significant impact on the shape of the final recorded waveform; this is explored further in Section 6.

![Figure 2](image1.png)

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

![Figure 3](image2.png)

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

The final step in creating the simulated waveform is convolution with the simulated Instrument Response Function, and digitizing the waveform at a particular frequency. A typical digitizer sampling frequency is 1 ns.
6. INSTRUMENT RESPONSE FUNCTION

The Instrument Response Function (IRF) is simulated by convolving the resampled raw waveform with a Gaussian (or Gaussian-like) curve. This convolution operation simulates the effect of factors specific to the electronics of the sensor. To illustrate the effect of the sensor IRF, a comparison is made between waveforms with created using different instrument response functions.

![Waveform created by convolution with a 3ns IRF.](image)

Figure 4. Waveform created by convolution with a 3ns IRF. On the left, the IRF is a Gaussian curve; on the right, the IRF is modeled with a short “rise time”, and a longer “fall time”. This 3ns IRF curve represents a fairly high fidelity in waveform recording capability, and fine detail in the waveform structure is maintained.

![Waveform created by convolution with a 10ns IRF.](image)

Figure 5. Waveform created by convolution with a 10ns IRF. On the left, the IRF is a Gaussian curve; on the right, the IRF is modeled with a short “rise time”, and a longer “fall time”. This 10ns IRF curve represents a lower fidelity waveform recording capability, with a loss of finer waveform structural details.

7. MULTIPLE-SCATTERING

One of the more interesting results from this modeling effort has been the surprising number of interactions a pulse of energy undergoes within the scene. 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 6 shows the interaction of energy which contributed to the simulated waveforms for two separate simulations.
As mentioned previously, the tree model is treated as a probability map by the LiDAR simulation. Here two simulations with varying probability levels (4% and 7%) are used to illustrate the effect of the material probability setting. In the author’s experience, LiDAR energy typically reaches the ground under the canopy, and so the high 7% material probability setting was chosen so that the ground is just barely detectable under the canopy. The low 4% material probability setting corresponds to a less dense canopy, and was chosen so that a ground peak is definitely distinguishable in the waveform. The varying material probability level translates to varying levels of biomass in a real tree.

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. Figure 7 shows the ‘raw’ waveform data consisting of all points which returned to the sensor, with points colored according to the number of interactions the pulse underwent before returning to the sensor.
These plots 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.
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.

![Histogram of Number of Pulse Interactions](image1)

Figure 8. Histogram of number of pulse interactions for a simulation using a 4% material probability level.

![Histogram of Number of Pulse Interactions](image2)

Figure 9. Histogram of number of pulse interactions for a simulation using a 7% material probability level.

In Figures 10 and 11, the simulated waveforms are shown. At the higher material probability level (denser tree canopy), the ground is not detected by singly-scattered energy (see Figure 11). Energy is returned from the ground, but the energy has undergone multiple-scattering events. These figures illustrate how the waveform peak widens with increasing canopy density.
8. LEAF-ON VS. LEAF-OFF TREE CANOPY

As illustrated in Figure 1, the tree can be modeled with or without leaves. The following figures allow comparison of results for simulations using a tree modeled with and without leaves. Figure 12 shows how LiDAR energy interacts with the tree canopy for the two simulations. When the tree is missing leaves, more energy reaches the ground under the canopy. A 7% material probability level was used in both simulations.
Figure 12. 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 the tree having leaves; the right tree image shows the simulated tree without leaves.

Figure 13 illustrates the waveforms created from these two simulations. It is interesting to note the shift in location of the main peak, the change in width of the main peak, and the presence of peaks due to branch returns in the leaf-off simulation.

**Comparison of Waveforms - Leaf-on vs Leaf-off - All Returns**

![Comparison of Waveforms - Leaf-on vs Leaf-off - All Returns](image)

Figure 13. Waveform created from simulation of tree with and without leaves.
9. COMPARISON TO LASER RANGEFINDER DATA

A waveform recording laser rangefinder has been built which will allow validation of modeled waveforms (see Figure 14). First results are given here, and illustrate some of the significant complexity present in real LiDAR data. The laser, photomultiplier tube and oscilloscope combine for a nominal temporal (range) resolution of 1-2 ns.

Waveform signatures were created by shining a 532 nm laser horizontally at pine tree branches at a distance of approximately 30 m. Individual branch clumps were spaced at about 2 m. Channel 2, illustrated in cyan in the top plot of Figure 15, is the “trigger” signal used to determine time-of-flight of the transmitted LiDAR signal. There are actually two peaks being transmitted. This secondary peak tends to go away as the instrument warms up, but this itself represents a challenge as the shape of the transmitted pulse changes over time. The bottom plot of Figure 15 shows the output voltage from the photomultiplier tube (CH1). In order to convert the measured voltages to power or intensity, the instrument must be calibrated, with the gain and efficiency of the various electronic components being quantified.
10. CONCLUSIONS

A simple model for full-waveform LiDAR propagation has been presented which allows variation of basic parameters affecting waveform shape. Illustrations of the effects of multiple-scattering on the LiDAR signal, as well as a comparison of tree leaf-off vs leaf-on conditions have been given. While a model can be used as an aid to understanding, some of the complexity of real LiDAR data is a factor of the specific instrument characteristics with which the data was collected. These factors will complicate data processing efforts, and will be sensor specific.

REFERENCES