Calibration of a full-waveform, dual-wavelength terrestrial laser scanner

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Highlights: A model for calibration of a full-waveform, dual-wavelength terrestrial lidar (DWEL) couples a logistic telescope efficiency function with an inverse power function to provide apparent reflectance from intensity with range. Separate models for each laser are fitted together and constrained to provide dual-wavelength spectral fidelity with a normalized difference spectral index.

Key words: Terrestrial lidar calibration; TLS; DWEL; full-waveform; normalized difference

Introduction

A new and important application of terrestrial laser scanning is the quantification of vegetation structure, principally measures of the physical dimensions of trees, amount and location of leaves, and gaps between and within tree canopies. While point clouds of laser returns recording the presence and location of vegetation objects can provide some elements of structure, complete inference of vegetation structure requires using the intensity of the scattered return, which in turn requires calibration. The calibration of terrestrial lidar scanners provides unique challenges, including (1) a very large variation in intensity with range that can induce saturation of the detector system by bright targets in the near field and reduced intensities that merge with the noise field in the far range; and (2) strong telescopic effects, with defocusing producing weak signals at near range. This paper summarizes how these and other challenges have been addressed for a dual-wavelength, full-waveform terrestrial scanner, the Dual-Wavelength Echidna® Lidar (DWEL). The simultaneous calibration of returns from DWEL’s two lasers, pulsing at wavelengths of 1064 and 1548 nm, also demonstrates how calibration can ensure both radiometric and spectral fidelity in a unified process, thus providing a pathway for calibration of other dual and multiple wavelength terrestrial lidars now in various stages of development and application [1-2].

Apparent reflectance

In its most useful form, calibration provides a signal expressed as a property of the scattering event itself, such as the apparent reflectance of the scattering surface. This measure, defined as the reflectance of a perfectly diffuse target orthogonal to the lidar beam and completely filling the field of view that returns the same energy from the same range as an actual target, is directly useful in retrieving vegetation properties such as leaf area index, foliage density with height, and separation of returns of leaves from those of trunks, branches and ground. For terrestrial lidars, it also provides additional value in more consistent measurements of mean tree diameter, canopy height, stem count density, and indirectly, above-ground biomass [3-4].

To further illustrate the properties of apparent reflectance, if we assume a known diffuse reflectance for the target surface (e.g., leaves) and a random orientation of target surfaces (i.e., mean value of \( \cos(\theta) \) of leaves at different orientations equals 0.5), the apparent reflectance is then directly related to the illuminated fraction \( F \) and the gap fraction \( (1 - F) \). Alternatively, we may assume that the target fully intercepts the beam \( (F = 1) \); the apparent reflectance is then directly proportional to the diffuse reflectance of the target [5].

The Dual-Wavelength Echidna Lidar (DWEL)

The primary scientific objective of DWEL instrument is to separate leaves and woody materials in forests readily in three dimensional space using their different spectral reflectances. Based on the design of the Echidna® Validation Instrument (EV1) [3-4], DWEL adds a second coaxial pulsed laser and acquires full-waveform scans at both near-infrared (NIR, 1064 nm) and shortwave infrared (SWIR, 1548 nm) wavelengths with simultaneous laser pulses. At the SWIR wavelength, laser power returned from leaves is much lower than from woody materials, such as trunks and branches, due to absorption by liquid water in leaves. In contrast, returned power from leaves and woody materials is similar at the NIR wavelength. A more complete description of the DWEL is found in [6-7].
Basic processing

Before point cloud generation and radiometric calibration, the raw waveforms from DWEL are preprocessed to remove background noise; convert digitizer time to apparent range by aligning each waveform to the peak of the outgoing pulse using the signals from a scattering wire or internal Spectralon panel [7]; and correct laser power drift, typically due to instrument temperature change, by scaling recorded intensities according to mean intensities observed from the internal Spectralon panel for each mirror rotation. Further processing removes strong, near-range pulses that saturate the instrument’s digitizers and replaces them with unsaturated equivalents. Point clouds of scattering events are then constructed from the preprocessed waveforms. A waveform deconstruction process identifies individual hits found in the waveform and associates each with its peak intensity, creating a cloud of points representing hits and intensities at coordinates determined from range, zenith, and azimuth angles recorded by the instrument.

Calibration model

The purpose of our calibration is to convert the intensity associated with each pulse peak to apparent reflectance, a measure that removes the effects of telescope efficiency and fall-off with range. The calibration model is:

$$\rho_{app}(R_j) = I_j \frac{R_j^b}{C_0 \cdot K(R_j)}$$

$$K(r) = \frac{1}{1 + C_1 \cdot e^{-C_2 \cdot r}}$$

where $\rho_{app}(R_j)$, $I_j$, and $R_j$ are the apparent reflectance, intensity, and range of the $j$th peak; $C_0$ is a constant scaling intensity to apparent reflectance; $C_1$, $C_2$, and $C_3$ are constants of the telescope efficiency function $K(r)$ with range $r$; and $b$ is the exponent of range. The efficiency function has a logistic shape rising from 0 to 1; parameters $C_1$ and $C_3$ together determine the range at which the function approaches its asymptote of one, while $C_2$ controls the rate at which telescope efficiency rises from 0 to 1 in the near range. For DWEL, the functions rise rapidly from 0 m range to 0.5 at about 3-4 m (NIR, SWIR) and reach 1 asymptotically at about 10-15 m.

To provide data to fit the model, we scanned three panels of different reflectance values from a nearly perpendicular direction at 33 range locations from 0.5 m to 70 m. The three panels included a white Spectralon panel and two foam boards painted with flat interior wall paint in light and dark gray tones. We used the manufacturer’s specification for the Spectralon panel and determined the reflectances of the gray panels by the average ratio of each gray panel to the Spectralon panel at all ranges. All panels were sufficiently large to intercept the whole laser beam at 70 m.

To fit the model, we estimated the calibration parameters of the two wavelengths together in a joint calibration model using an objective error function that minimized relative errors in $\rho_{app}$ from both wavelengths and a spectral constraint that minimized the differences in a normalized difference index from both wavelengths ($NDI = (\rho_{1064} - \rho_{1548})/(\rho_{1064} + \rho_{1548})$). The constraint optimized the calibration for vegetation study and also improved the stability of parameter fitting. To assess the goodness of fit of the model, we randomly divided the intensities (about 24,000 samples for each range) into a training set (80 percent) and a validation set (20 percent). In the training set, return intensities were normalized by the corresponding panel reflectance to provide equivalent target reflectances of 1.0 and then averaged together for each range to reduce noise in the data. Table 1 documents the fit of the model to both training and validation datasets; $R^2$ values are high and RMSE values are quite low. More definitive studies are needed to confirm these results. It should be noted, however, that no instrument is perfectly stable and recalibration will most likely produce slightly different values.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>1064 nm</th>
<th>1548 nm</th>
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<tbody>
<tr>
<td>Training</td>
<td>0.954</td>
<td>0.983</td>
</tr>
<tr>
<td>Validation</td>
<td>0.948</td>
<td>0.964</td>
</tr>
</tbody>
</table>

Example of apparent reflectance processing

Figure 1 provides two images of a scan of a deciduous hardwood forest stand in the northeastern United States, acquired in September, 2014. The site, located within the Harvard Forest, Petersham, Massachusetts, is a 1-ha plot dominated by red maple (Acer rubrum), red oak (Quercus rubra), and white birch (Betula papyrifera) with an understory of these species accompanied by American beech (Fagus grandifolia), American chestnut (Castanea dentata) and others. Several large white pines (Pinus strobus) also occur in the stand. The images are color composites, with 1548 nm values in red, 1064 nm values in green, and blue as dark constant. Values displayed are the sums of intensity or apparent reflectance returns, averaged for all waveforms in the bins of an equal-angle projection. In the upper image, intensity clearly decreases with range and colors are inconsistent. In the lower image, trunks are visible at far range and colors are more uniform.
Conclusion

In summary, our work addresses the challenges posed in calibrating multiple-wavelength, full-waveform terrestrial laser scanners by formulating a flexible calibration model, acquiring appropriate calibration data, fitting the model with a constraint providing spectral consistency, and testing the results. The next step is to use calibrated data to retrieve forest structural parameters with the new dual-wavelength data of the DWEL. This is the subject of additional papers now in preparation. This work was supported by the US National Science Foundation, under grant number MRI-0923389.

References


