DWEL: A DUAL-WAVELENGTH ECHIDNA LIDAR FOR GROUND-BASED FOREST SCANNING

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ABSTRACT

The Dual-Wavelength Echidna® Lidar (DWEL), a ground-based, full-waveform lidar scanner designed for automated retrieval of forest structure, uses simultaneously-pulsing, 1064 nm and 1548 nm lasers to separate scattering by leaves from scattering by trunks, branches, and ground materials. Leaf hits are separated from others by a reduced response at 1548 nm due to water absorption by leaf cellular contents. By digitizing the full return-pulse waveform (full-width half maximum, 1.5 m) at 7.5 cm intervals, the scanner can identify the type of scattering event, as well as identify and separate multiple scattering events along the pulse path to reconstruct multiple hits at distances of up to 100 m from the scanner. Scanning covers zenith angles of 0-119° and 360 azimuth with pulse centers spaced at 4, 2, and 1 mrad intervals, providing spatial resolutions of 4-40, 2-20, and 1-10 cm respectively at 10 and 100 m distances. The instrument is currently undergoing integration and testing for field deployment in July-August, 2012. ***Index Terms*—Laser radar, Forestry, Vegetation.**

I. INTRODUCTION

A newly-constructed, ground-based lidar scanner designed for automated retrieval of forest structure, the Dual Wavelength Echidna® Lidar (DWEL), emits simultaneous laser pulses at wavelengths of 1064 nm and 1548 nm, providing the capability to separate laser 'hits' of leaves from hits of trunks and branches. The separation principle relies on strong absorption of radiation at 1548 nm by leaf water content, which makes leaves darker than other targets at that wavelength. Building on the design of the Echidna Validation Instrument (EVI), conceived and constructed by Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO), the DWEL uses a rotating mirror scan mechanism, coupled with full digitization of return waveforms, to identify and locate scattering events in the three-dimensional space around the scanner. The scans provide forest structural parameters, including mean tree diameter at breast height (DBH), stem count density (trees per hectare), basal area, canopy height, leaf area index, foliage profile, and above-ground biomass using the approach pioneered by the processing of data from the Echidna Validation Instrument [1–5]. Multiple scans can also be merged to provide 3-D reconstructions of forests that allow virtual measurements of forest structure [6]. This capability opens the door to virtual direct measurement of volumes of trunks, branches, and leaves to estimate both green and woody biomass without allometric equations.

II. RATIONALE FOR DUAL WAVELENGTH CAPABLITY

Many lidar instruments, ground-based as well as airborne, use the wavelength of 1064 nm. This wavelength has an important advantage–forest canopy components, including leaves, needles, fine branches, and bark, have rather similar reflectances at this wavelength, generally around 0.4-0.6 (Figure 1).

Thus, the apparent reflectance associated with a lidar return at a specific range can be taken as a measure of the cross-section of scatterers in the beam. This allows calculation of the gap probability with range as it decreases with each scattering event along the path of the pulse. The mean gap probability with range at a particular zenith angle is a fundamental measurement used to infer the foliage profile and leaf area

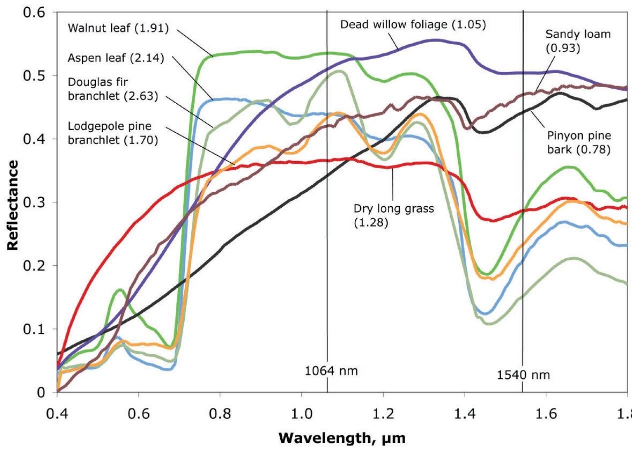

Figure 1. Reflectance spectra for leaves and other typical materials in forest scans (from USGS libraries [7]). The 1064/1540 nm reflectance ratio, shown in parentheses, easily differentiates the leaves.

index, but it includes scattering by canopy elements other than leaves.

With a single wavelength, leaves and trunks can be distinguished by the shape of the return signal as seen in the graph of apparent reflectance with range. If the return fits the output pulse well, the return is likely a trunk. If a return is weaker and less distinctly shaped, it is more likely to be leaves. While this distinction generally works well, larger branches can contribute to the inferred leaf signal at middle and far ranges. Moreover, glancing pulses hitting the edges of trunks are confused with pulses scattered by leaves. Leaves can also partly obscure trunks in the near and middle range, leading to underestimation of stem count density.

However, there is a strong spectral contrast between leaves and other materials in the shortwave infrared, based on leaf water absorption, which is centered at 1450 nm (Figure 1). This contrast extends to 1540 nm, a wavelength near which commercial lasers are readily available. Accordingly, we selected a laser that pulses at 1548 nm for the DWEL instrument, in addition to a 1064 nm laser. Figure 2 demonstrates the principle of spectral separation using two wavelengths. In the bottom image, the reflectance ratio clearly separates trunks and branches.

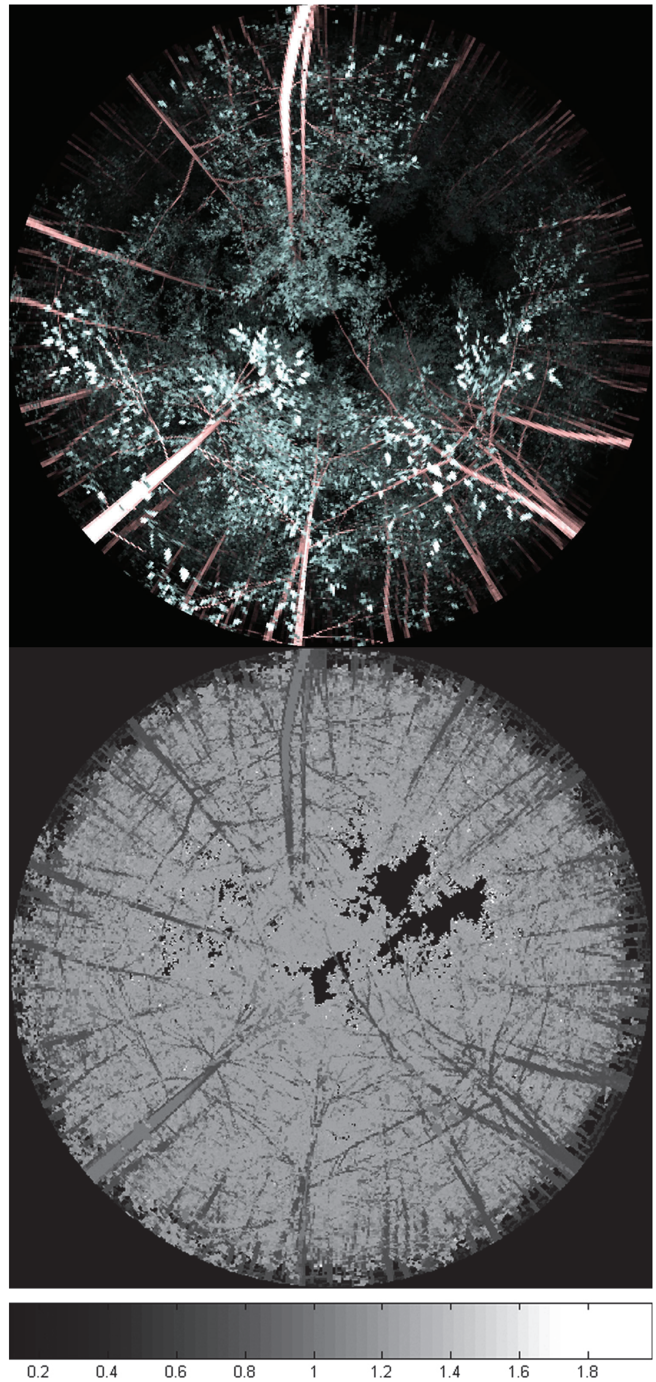

Figure 2. A simulated silver birch (Betula pendula) canopy as imaged at 1064 and 1530 nm. On the top (1064 nm–green; 1530 nm–red), leaves and trunks are clearly distinguished. On the bottom, the ratio of 1064 nm to 1530 nm easily separates leaves (light) from trunks and branches (dark). Gaps are black. (Image courtesy of Philip Lewis, University College London.)

III. Instrument Design and Specifications

The DWEL instrument design is based on a concept for an under-canopy, multiple-view-angle, scanning lidar with full-waveform digitizing, termed Echidna, which was developed and patented by CSIRO. (US patent 7,187,452, Australian Patent 2002227768, New Zealand Patent 527547, Japanese Patent 4108478. Echidna is a registered trademark of CSIRO). The DWEL is being built by the Boston University Centers for Space Physics and Remote Sensing, under the US National Science Foundation grant MRI-0923389.

Figure 3 provides a design view of the DWEL instrument. Two lasers are triggered simultaneously, one each at 1064 nm and 1548 nm. A green continous-wave laser allows the operator to visualize the beam direction. The measurement–laser pulses are expanded and collimated to an approximately 6-mm beam diameter ($1/e^2$). Each beam is then reshaped in cross–section from Gaussian to a flat (or ‘top hat’) profile using a diffraction apparatus (PiShaper), and an a interchangeable lens pair can be selected to allow beam divergences of 1.25-, 2.5-, or 5-mrad.

The instrument specifications are similar, but improve upon the single-wavelength Echidna Validation Instrument (EVI). Full-width half-max pulse length of the lasers is 5.1 ns, corresponding to 1.5 m in distance. Pulses fit a Rayleigh shape that is sharply peaked, such that most of the energy is emitted in the middle of the pulse. Pulse rates are 20 kHz, but only every tenth pulse is digitized. The designed signal-to-noise ratio is 10:1 (8:1) at 100 m with 0.1 reflectance at 1064 nm (1548 nm). Scan resolution has three settings: 1, 2, and 4-mrad. Dichroic filters combine the two pulses before the rotating scan mirror. The 10 cm minor axis–elliptical scan mirror rotates at 0.318 to 1.27 Hz, depending on the angular scan resolution selected. Scan time varies with resolution: 11 min at 4 mrad; 41 min at 2 mrad; and 2.7 hr at 1 mrad. Absolute value optical encoders in the zenith and azimuth directions resolve instrument pointing to better than 2^{14} bits per revolution. Zenith angles of 0-119° and azimuth angles of 0-360° are scanned by mirror rotation and instrument revolution. A dark Lambertian target inside the instrument housing is also scanned for calibration with each rotation.

A 10-cm diameter Newton-Nasmyth telescope receives the return signal from the scan mirror and at the receiver a dichroic beamsplitter separates the 1548 nm and 1064 nm signals which are sensed by InGaAs photodiodes, protected by narrow-band filters. Photodiode signals are digitized with 10-bit precision at two gigasamples per second. This provides 7.5 cm sampling of the 1.5 meter pulse, allowing reconstruction of the return waveform. A compactPCI computer collects the digital and housekeeping data, which is offloaded in real time via a local network to a separate field computer. Estimated instrument weight is 21 kg, including 230 watt-hours of lithium-ion battery energy. The estimated power consumption is 115 W. The laser system attains a 3R safety classification, and is eye-safe unless viewed directly within 30 m using optical magnification.

IV. Instrument Status

At the time of preparation of this paper, the DWEL instrument was in the final stages of assembly and integration. The receiving optical train has measured the full laser pulse waveforms at both wavelengths in the laboratory. We anticipate field data acquisition during July-August, 2012.

V. Conclusion

The full-waveform Dual Wavelength Echidna Lidar (DWEL) ground-based lidar scanner extends and improves the ability of the Echidna Validation Instrument (EVI) to retrieve forest structural parameters. By recording the full-waveform

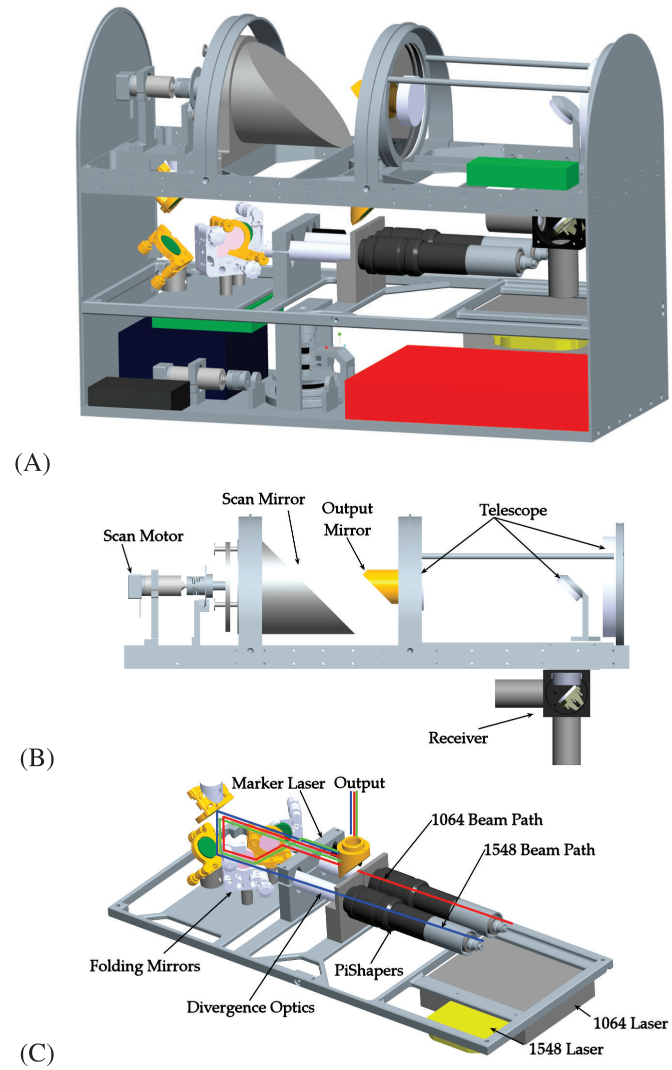

Figure 3. DWEL design. A, cut-away view of the instrument without cover. Electronics and batteries are on the lower left and the computer is the lower right box. B, side-view of telescope. C, output optical bench and path of laser beams.

return over 360° azimuth and 119° zenith, the DWEL can characterize a full canopy out to ranges of 100 m and capture leaves, leaf clusters, branches and trunks at resolutions of 4, 2, and 1 mrad (4-40, 2-20, and 1-10 cm at 10 and 100 m). By scanning simultaneously with two wavelengths, DWEL data can separate leaf ‘hits’ from hits of trees, branches and ground. This will provide better characterization of leaf area, branch area, foliage profile, and trunks, as well as derived structural parameters of mean stem diameter, stem count density, basal area, biomass, and canopy height.

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