# Using a Full-Waveform, Ground-Based, Scanning Lidar (Echidna®) to Retrieve Forest Vegetation Structural Parameters in American Hardwood and Conifer Stands

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**Abstract – A ground-based, scanning, near-infrared (1064 nm) lidar, the Echidna® validation instrument (EVI), built by CSIRO Australia, retrieves structural parameters of forest stands rapidly and accurately, and by merging multiple scans into a single point cloud also provides 3-D stand reconstructions. Scans and field work in the USA (New England in 2007 and the Sierra Nevada of California in 2008) show that retrievals of mean tree diameter, stem count density (stems/ha), basal area, above-ground woody biomass, and leaf area index for 1-ha plots match conventional field measurements very well. Three-D forest reconstructions provide the ability to make virtual structural measurements that also match field measurements very well.**

Keywords: ground-based lidar, forest structure, 3-D reconstruction

## 1. Introduction

Many studies have explored the use of remote sensing, from both aircraft and spacecraft, to monitor and map the above-ground biomass of forests. Measuring forest biomass and mapping forest structure have been challenging due to limitations with existing optical and radar sensors, because forest structure contains not only horizontal but also vertical information. Passive optical systems can provide vertical information based on multiangle data, but without resolving individual tree crowns, it is difficult to retrieve and separate height and cover.

Lidar (light detection and ranging) has the potential to provide more detailed information on canopy structure because it effectively adds a third dimension—range—to the data. This allows lidar to provide both a useful map of the position of the ground surface along with returns that indicate how the foliage and stems are arranged vertically above the ground (Jupp et al., 2005).

Many studies have successfully derived biomass and timber volume using regression methods that relate some properties of airborne lidar signals to on-the-ground measurements of biomass (Dubayah and Drake, 2000). However, stem diameter (DBH) and stem count density are the parameters most directly related to biomass, and these parameters are more easily estimated by ground-based, rather than airborne scanning.

Leaf area index (LAI), foliage profile (leaf area with height), and stand height are critical vegetation structural parameters for carbon balance modeling and in the surface radiation balance modules of regional and global climate models. A number of previous studies have utilized lidar for retrieval of leaf area index. Most of these have utilized small-footprint (footprint<1 m) first-and-last return airborne lidar systems that return the distance to the first or first and last scattering events, and acquire counts of scattering events by height above the ground to determine the fraction of leaf area with depth However, this approach is limited by the inability to differentiate canopy returns from ground returns. A strength of the airborne approach is its ability to cover and map large areas.

### 1.1 About the Echidna® Lidar

The Echidna validation instrument (EVI), built by CSIRO Australia, is based on a concept for an under-canopy, multiple-view-angle, scanning lidar, with variable beam size and waveform digitizing termed Echidna®. The Echidna has been patented in Australia, the United States, New Zealand, China and Japan, with patents in other countries pending. The EVI, which is the first realization of the Echidna concept, utilizes a horizontally-positioned laser that emits pulses of near-infrared light at a wavelength of 1064 nm. The pulse is sharply peaked so that most of the energy is emitted in the middle of the pulse. The time length of the pulse, measured as the time at which the pulse is at or above half of its maximum intensity, is 14.9 ns, which corresponds to about 2.4 m in distance. Pulses are emitted at a rate of 2 kHz. The pulses are directed toward a rotating mirror that is inclined at a 45-degree angle to the beam. As the mirror rotates, the beam is directed in a vertical circle, producing a scanning motion that starts below the horizontal plane of the instrument, rises to the zenith, and then descends to below the horizontal plane on the other side of the instrument. Coupled with the motion of the mirror is the motion of the instrument on its vertical axis, rotating the scanning circle through 180° of azimuth. In this way, the entire upper hemisphere and a portion of the lower hemisphere of the instrument is scanned.

Although the laser beam is a parallel ray only 29 mm in width, it passes through an optical assembly that causes the beam to diverge into a fixed solid angle. This expansion of the beam with distance allows the laser pulses to census the entire hemisphere. The size of the solid angle can be varied from 2–15 mrad. The rotation speeds of the mirror and the instrument on its mount are also varied so that the hemisphere can be covered slowly by many fine pulses or rapidly by fewer coarser pulses.

As the light pulse passes through the forest, it may hit an object and be scattered. The light returning to the instrument is focused on a detector that measures the intensity of the light it receives as rapidly as 2 gigasamples per second. Since the pulse is traveling at a known speed, the time between emission of the pulse and its receipt at the detector indicates the distance to the object. At 2 GS/sec the sampling distance is close to 7.5 cm. However, because the pulse shape is consistent and stable, it is possible to estimate the range to the peak of the pulse by interpolation. The accuracy is a function of signal relative to the noise level but is normally less than half the sample spacing (i.e., 3.75 cm) with highest accuracy being in the near field where peak return signal power is high. The output of the detector is digitized electronically and stored by computer to provide a full-waveform return that records the scattering of the pulse from within a meter or less of the instrument to as much as 150 m away. More information on the EVI and its early trials can be found in Jupp et al. (2005; 2009).

Three types of information are provided by a full-waveform digitizing lidar: range; peak intensity (or amplitude); and the shape of the reflected waveform (Jupp et al., 2005). These depend on the range, geometry, and reflectance properties of the scattering surface. In the case of waveform returns from a lidar scanning a forest canopy from below, there are at least two classes of waveforms: (1) hard targets, such as tree trunks and branches; and (2) soft targets, such as clusters of leaves that do not individually obstruct the entire lidar beam and are positioned at slightly different distances from the instrument. These can be separated by the ratio of the height of the peak to its width, with sharper peaks returned by hard targets.

## 2. Retrieval of Structural Parameters

Retrieval of mean tree diameter, stem count density, basal area, and biomass rely on the processing of EVI scans using the "Find Trunks" algorithm (Lovell et al., 2011). In this algorithm, pulses lying in a horizontal plane at or near the height of the instrument are used to identify trunks and output their diameter and location. The algorithm first selects the returns that are likely to be from trees, using a threshold of apparent reflectance. Moving

by azimuth angle, the algorithm identifies trunks by their hard returns, circular shape, change in reflectance strength from center to edges, and, by consulting adjacent horizontal slices, their vertical continuity.

Diameter is obtained by observing the angular distance between the trunk's edges. Where one side of the trunk is obscured by leaves or another trunk, the algorithm determines the trunk center (closest point with greatest reflectance) and doubles the span between the clear edge and the center. If both sides are obscured, it outputs the visible span along with a flag. In this case, the tree adds to the tree count, but does not contribute to the mean DBH computation. Range is measured as the distance to the center of the tree, computed by adding half the retrieved DBH to the distance of the nearest point on the tree stem. As output, the algorithm provides a file of center locations and diameters of trunks located.

Biomass is estimated using allometric equations. Since the EVI does not identify species, we used a pooled allometric equation based on the first- or first- and second-most abundant species at the site. We applied the equation to the effective mean diameter of the stand, where the effective mean diameter is the geometric mean of the retrieved diameters raised to the power of the exponent in the allometric equation. Biomass is than estimated by multiplying by the stem count density (trees/ha).

Leaf area index (LAI), foliage profile (leaf area with height), and stand height are critical vegetation structural parameters for biogeoscience applications. This is especially true of leaf area index, which is used in carbon balance modeling and in the surface radiation balance modules of regional and global climate models. Retrieval of effective LAI using the EVI relies on estimation of the gap fractions measured in azimuth rings from the zenith to 60°. Gap fraction is determined by cumulative apparent reflectance in any angular direction encountered as each laser pulse exits the top of the canopy. The process of retrieving effective LAI and the foliage profile is described more fully in Jupp et al. (2005, 2009). Mean canopy top height is also estimated using gap fraction data.

## 3. Results

Deployments in New England in 2007 (Table A) and the southern Sierra Nevada of California in 2008 (Table B) tested the ability of the instrument to retrieve mean tree diameter, stem count density (stems/ha), basal area, and above-ground woody biomass from single scans at points beneath the forest canopy. Parameters retrieved from five-scan averages in six 1-ha stand sites matched manually-measured parameters, $R^2$ = 0.94–0.99 (New England) and 0.92–0.95 (Sierra Nevada).

Table A. Comparison of Field Measurements and EVI Retrievals, New England, 2007[1]

| Parameter | Source | Harvard Forest | | Howland Forest | | Bartlett Forest | | Site $R^2$ or Power |
|---|---|---|---|---|---|---|---|---|
| | | Hemlock | Hardwood | Tower† | Shelterwood | B2 | C2 | |
| Mean DBH (m) | Field | 0.198±0.006 | 0.168±0.008 | 0.127±0.009[2] | 0.156±0.015 | 0.166±0.007 | 0.148±0.007 | $R^2$ = 0.936 |
| | EVI | 0.200±0.002 | 0.170±0.016 | 0.118±0.009[2] | 0.165±0.011 | 0.161±0.014 | 0.134±0.011 | |
| Stem count density (trees/ha) | Field | 1284±98 | 1020±72 | 3281±353[2] | 1017±179 | 1432±67 | 1485±27 | $R^2$ = 0.999 |
| | EVI | 1331±130 | 1105±71 | 3341±494[2] | 1042±179 | 1467±73 | 1549±84 | |
| Basal area (m²/ha) | Field | 55.5±1.96 | 37.5±1.7 | 55.4±3.1[2] | 26.5±0.9 | 45.0±1.6 | 40.7±3.2 | $R^2$ = 0.938 |
| | EVI | 55.4±3.65 | 38.8±3.3 | 49.8±4.5[2] | 29.4±4.0 | 45.5±2.41 | 38.1±5.2 | |
| Aboveground woody bio-mass (t/ha) | Field | 234±7.0 | 249±9 | 162±12[2] | 94.4±3.3 | 254±14 | 216±14 | $R^2$ = 0.975 |
| | EVI | 233±9.7 | 264±26 | 161±6[2] | 101±6 | 240±9 | 211±9. | |
| Stand height (m) | LVIS | 25.1±0.36 | 24.9±0.30 | 22.8±0.56 | 25.8±0.23 | 20.7±0.93 | 22.8±0.56 | Power = 0.992 |
| | EVI | 23.0±0.40 | 22.4±0.86 | 23.6±0.62 | 25.4±0.30 | 21.0±1.44 | 19.2±0.71 | |
| Leaf area index | LAI-2000 BU | 4.70±0.04 | 4.37±0.14 | 4.07±0.51 | 3.42+0.41 | 4.76±0.96 | 4.34±1.04 | Power = 0.915 |
| | EVI | 4.47±0.46 | 4.16±0.11 | 4.80±0.69 | 3.74±0.87 | 4.60±0.27 | 4.23±0.24 | |
| | LAI-2000 Others | 4.4[3] | 5.0±0.67[4] | 4.18±0.45[5] | — | 5.03±0.36[6] | 4.55±0.29[6] | Power= 0.993 |
| Dominant species | | Hemlock, white pine | Red oak, red maple | White spruce | Hemlock, white spruce | Red maple, yellow birch | Beech, red maple | |

[1]Data are averages for 5 scans or plots at each site arranged at the corners and center of a square 50 m × 50 m. Standard deviations are based on values for these 5 scans. All correlation coefficients are significant at the 1-percent level. [2]Exception: Howland Tower, 5 scans, 3 plots. [3]Destructive sampling (Catovsky and Bazzaz, 2000). [4]Cohen et al., 2006. [5]J. T. Lee, University of Maine. [6]A. Richardson, University of New Hampshire.

In New England, retrieved leaf area index (LAI) values were not significantly different from those of LAI-2000 and hemispherical photography (ANOVA β <= 0.16); and in the Sierra, $R^2$ = 0.81 and 0.96. New England stand heights, obtained from foliage profiles, were not significantly different (β= 0.91) from LVIS RH100 values in 2003.

Table B. Comparison of Field Measurements and EVI Retrievals, Sierra Nevada, 2008

| Parameter* | Source | Site 23 | Site 99 | Site 168 | Site 301 | Site 305 | Site 338 | Site 406 | Site 801 | Site $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Mean of DBH (m) | Field | 0.41 ± 0.02 | 0.30 ± 0.01 | 0.37 ± 0.01 | 0.37 ± 0.02 | 0.58 ± 0.02 | 0.44 ± 0.03 | 0.60 ± 0.02 | 0.87 ± 0.09 | 0.9 |
| | EVI | 0.41 ± 0.05 | 0.31 ± 0.03 | 0.39 ± 0.04 | 0.42 ± 0.04 | 0.62 ± 0.04 | 0.52 ± 0.08 | 0.59 ± 0.05 | 1.00 ± 0.07 | |
| Stem count Density (trees/ha) | Field | 110 ± 29 | 421 ± 79 | 570 ± 86 | 231 ± 64 | 284 ± 40 | 347 ± 65 | 256 ± 27 | 125 ± 12 | 0.95 |
| | EVI | 127 ± 18 | 515 ± 57 | 634 ± 93 | 198 ± 59 | 288 ± 61 | 338 ± 46 | 260 ± 28 | 144 ± 21 | |
| Above-ground Biomass (t/ha) | Field | 115 ± 64 | 221 ± 34 | 1088 ± 92 | 361 ± 60 | 1214 ± 150 | 647 ± 28 | 833 ± 80 | 2664 ± 250 | 0.96 |
| | EVI | 97 ± 59 | 215 ± 58 | 1128 ± 102 | 221 ± 34 | 1115 ± 173 | 600 ± 65 | 714 ± 118 | 2006 ± 196 | |
| LAI | LAI-2000 | 0.73 ± 0.23 | NA | 2.22 ± 0.46 | 0.76 ± 0.17 | 1.35 ± 0.47 | NA | 2.43 ± 0.28 | 2.18 ± 0.44 | 0.91 |
| | EVI | 0.65 ±0.24 | NA | 2.46 ±0.3 | 0.58 ±0.14 | 2.03 ±0.5 | NA | 2.59 ±0.26 | 2.42 ±0.47 | |
| | Hemi | 0.64 ± 0.25 | NA | 2.14 ±0.19 | 0.61 ±0.16 | 1.82 ±0.3 | NA | 2.39 ±0.08 | 2.28 ±0.19 | 0.99 |
| Dominant species | | Jeffrey pine | White fir, incense cedar | Red fir | Red fir | Red fir | Red fir | White fir, sugar pine | Red fir, giant sequoia | |

*Standard errors based on values of plots, n=5.

## 4. Three-Dimensional Reconstruction

Acquiring multiple overlapping scans of a forest site provides the possibility of merging the scans into a single 3-D reconstruction (Figure 1). To test this idea, we reconstruct two conifer stands of 50 m by 50 m size from the Sierra Nevada field campaign of 2008 using point clouds of "hits." In our procedure, we processed each lidar pulse return to identify one or multiple hits and their associated peak return power; converted peak power to apparent reflectance; located the hits in Cartesian coordinate space and stored them as points in a point cloud with associated attributes; registered and merged five overlapping scans into a single point cloud; identified the ground plane and classified ground hits; classified non-ground hits as trunk/branch or foliage hits using apparent reflectance values; and used commercial software tools to display, manipulate, and interact with the point cloud to make direct measurements of trees in the virtual space of the reconstruction. Early trials show very good to excellent virtual measurement of tree diameter, height, and crown size with $R^2$ values ranging from 0.81 to 0.99 for the two stands.
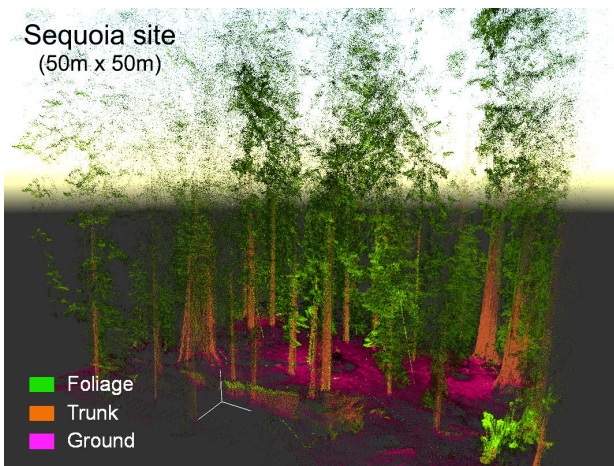


Figure 1. A 3-D reconstruction of a high-elevation conifer forest site in the Sierra National Forest. The large trees in the left and right sides of the image are giant sequoias. A 50 m by 50 m area is shown in this perspective view.

## 5. Conclusions

The Echidna lidar provides a major advance in our ability to make automated measurements of forest structure that can replace tedious and time-consuming manual measurements. It has proven its worth in both deciduous hardwood and evergreen conifer stands over a range of stand conditions typical of the American northeast. The properties of the Echidna lidar system, which include a near-infrared wavelength for strong scattering and beam penetration; a full census of the upper hemisphere that extends below the horizontal as well; and the digitizing of the full waveform of the return pulse; all contribute to provide an instrument with the ability to make fast and highly accurate measurements of forest structure, including DBH, stem count density, basal area, biomass, leaf area index, and foliage profile (not shown here).

With 3-D reconstructions prepared for two Sierra Nevada high-elevation conifer sites, we have demonstrated how merging point clouds from multiple scans can be used to reconstruct both individual trees and entire stand segments. The reconstructions can provide accurate, virtual measurements of crown dimensions. The reconstructions also open the door to retrieving true leaf area index and foliage profile, and we are currently working on these applications.

## References

Dubayah, R. and J. Drake, "Lidar remote sensing for forestry," Journal of Forestry, vol. 98, pp. 44–46, 2000.

Jupp, D., D. Culvenor, J. Lovell and G. Newnham, "Evaluation and validation of canopy laser radar (LIDAR) systems for native and plantation forest inventory," Final Report prepared for the Forest and Wood Products Research and Development Corporation (FWPRDC: PN 02.2902) by CSIRO, 150 pp., 2005.

Jupp, D., D. Culvenor, J. Lovell, G. Newnham, A. Strahler and C. Woodcock, "Estimating forest LAI profiles and structural parameters using a ground-based laser called 'Echidna®'," Tree Physiology, vol. 29, pp. 171–181, 2009.

Lovell, J., D. Jupp, G. Newnham and D. Culvenor, "Measuring tree stem diameters using intensity profiles from ground-based scanning lidar from a fixed viewpoint," ISPRS Journal of Photogrammetry and Remote Sensing, vol. 66, pp. 46-55, 2011.

Strahler, A., D. Jupp, C. Woodcock, C. Schaaf, T. Yao, F. Zhao, X. Yang, J. Lovell, D. Culvenor, G. Newnham, W. Ni-miester and W. Boykin-morris, "Retrieval of forest structural parameters using a ground-based lidar instrument (Echidna®)," Canadian Journal of Remote Sensing, vol. 34, pp. 5426–5440, 2008.