

ASSESSING THE THREE-DIMENSIONAL FREQUENCY DISTRIBUTION OF AIRBORNE AND GROUND-BASED LIDAR DATA FOR RED PINE AND MIXED DECIDUOUS FOREST PLOTS

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ABSTRACT:

The following study reports on the preliminary results of a novel processing technique for characterizing the three-dimensional distribution of airborne and ground-based LiDAR data for conifer and mixed deciduous forest plots. The frequency of laser returns within 1m x 1m x 1m cubes (voxels) and the plotting of percentile distributions within each column (e.g. 1m x 1m x 25m, x, y, z) may benefit radiative transfer modelling for meteorological and carbon flux monitoring purposes. This study examines the voxel column percentile distributions at the 1m and 5m scales and at the plot level (three-dimensional percentile distributions) for both airborne and ground-based LiDAR systems. Here it is demonstrated that for airborne LiDAR, a high percentage of laser pulses intercept the top of the canopy with fewer returns from within the canopy and understory. Similarly, for ground-based LiDAR, a high percentage of laser pulses intercept the understory, stems, and lower canopy, with a lower percentage of pulses intercepting the upper canopy. AL excludes an average of approximately 4.0m from the centre (17m a.g.l.) to the base of the canopy (at 15m a.g.l.), whereas GBL excludes the top 21m to 24.5m of the canopy. This illustrates that substantial parts of the understory and canopy are excluded from airborne and ground-based LiDAR data, respectively. Suggestions are provided to best model the percentile distribution of laser pulses for both airborne and ground-based systems based on the scanner field of view, scan angles, and the distance from the centre of individual voxels.

1. INTRODUCTION

Airborne LiDAR (AL) and ground-based LiDAR (GBL) instruments are currently used to gather information on forest biophysical variables (Magnussen and Boudewyn, 1998; Lim et al. 2003; Hopkinson et al. 2004a). One potential downfall of AL for gaining accurate measures of leafy biomass is the high probability of laser pulses intercepting the top of the canopy with fewer pulse returns from within the canopy. Similarly, for GBL systems, there is a higher probability of laser pulses intercepting the understory, stems and lower canopy with fewer pulse returns in the upper canopy (Figures 1a and b). This will likely result in an underestimation of leafy biomass within the canopy and may influence measures of leaf area index (LAI), clumping within the canopy, canopy closure (for radiation modelling) and tree height (in the case of GBL).

The analysis of the frequencies of laser returns within defined volumes of space (referred to here as voxels) represents one method that can be used to examine the probability of laser pulses intercepting a set volume of space within a forest environment. Voxels are three-dimensional (3-D) cubes with x, y, and z dimensions that can be used to classify laser pulse counts with increasing or decreasing voxel size (Figure 2). The use of voxels in LiDAR data analysis of forest structure is fairly recent (Weishampel et al. 2000; Riaño et al. 2003). Voxels have also been used in radiation, photosynthesis, and transpiration modelling in forested environments through the classification of ray traced 3-D images of individual tree crowns (e.g. Sinoquet et al. 2001).

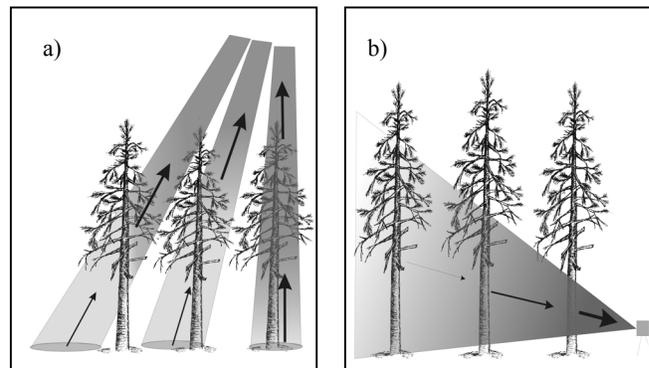


Figure 1. a) Schematic diagram of laser pulses intercepting the top of the canopy for AL. b) Schematic diagram of laser pulses intercepting understory, stems and lower canopy typical of GBL.

Similar attenuation results have been found with spectral remote sensing instruments, which are able to sense the tops of canopies but are unable to account for within canopy shadowing and biomass structure (Chen and Cihlar 1996; Carlson and Ripley 1997; Huemmrich et al. 1999).

The following study has three objectives:

1. To examine the 3-D frequency distribution of AL and GBL returns for mixed deciduous and red pine plots using a methodology that employs voxels processed at one resolution (i.e., 1m x 1m x 1m).

- To examine the laser pulse return frequency distributions with height through the canopy as percentiles for quantifying canopy and understory transmissivity for both AL and GBL systems.
- Calculate and map 3-D percentiles for each plot and discuss relevance to tree location, canopy clumping, and the radiation extinction coefficient.

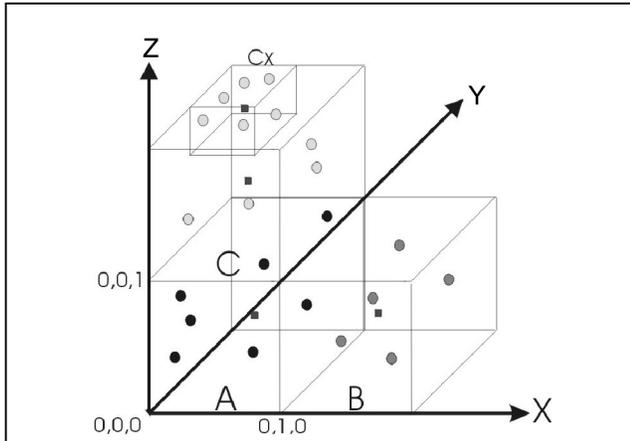


Figure 2. Schematic diagram of the voxel procedure of LiDAR data. Voxels are represented by 3-D cubes with co-ordinates represented by x, y, and z, and numbers at the corners of each voxel (A to C). Voxel centroids are represented by squares in the centre of each voxel and laser points are shown as circles in different shades of grey. Voxel A has a count of 7 laser pulses (black), B has a count of 5 laser pulses (dark grey), and C has a count of 10 laser pulses (light grey). Counts represent within-voxel laser pulse frequency. Where laser pulses are clumped, smaller voxels can be used to classify dense clusters (e.g. Cx).

2. DATA COLLECTION

2.1 Study Area

The first plot consists of tolerant hardwood sugar maple (*Acer saccharum* Marsh), bitternut hickory (*Carya cordiformis* Wengen.) and other mixed deciduous species. The mixed deciduous plot contains substantial understory and is untreated. The second plot is a mature red pine (*Pinus resinosa* Ait.) plantation with no understory. Both plots are 25m by 25m in area. Approximate maximum height of trees in both plots is 25m. Forest mensuration data were collected at both plots coincident to the times of survey. These included tree height, diameter at breast height, species type, leaf area index, canopy diameter in two directions, and tree locations. Details on field and LiDAR data collection can be found in Hopkinson et al. (2004a) and Hopkinson et al. (2004b).

2.2 Airborne and Ground-based LiDAR Data Collection

Airborne LiDAR data were collected on July 5th 2002 using the Optech Inc. Airborne Laser Terrain Mapper (ALTM) 2050 sensor (Optech Inc. Toronto, Ontario) at 50 kHz utilising discrete, first and last pulse technology. The sensor altitude was 850 m.a.g.l. with a scan rate of 44 Hz and a scan angle of $\pm 15^\circ$ for the mixed deciduous plot and $\pm 20^\circ$ for the red pine plantation.

The ground-based LiDAR data were collected using the ILRIS-3D system (Optech Inc. Toronto, Ontario) coincident to the AL survey. ILRIS-3D records the x, y, z and intensity of laser pulse returns (either first or last return) in the same manner as the ALTM. ILRIS-3D has a 40° field of view in the x and y directions, and a pulse rate of 2 kHz. The ILRIS-3D resolution used for this study is ~ 1 cm in x, y, and z directions and increases in size as scanner distance increases.

ILRIS-3D was set up at five locations surrounding a 25 m x 25 m homogeneous sub-area of the red pine (RP) and mixed deciduous (MD) plots and pointed towards a central point for co-registration between scans (Figure 3). Co-registration of scan lines with referenced control point 'target' markers were performed by Optech, Inc. using the PolyWorks software package. 73% of trees in the RP plot, targets, and ILRIS-3D set up locations were located using an Applanix Inc. Position Orientation System – Land Survey (POS-LS) backpack. Positional accuracy of the POS backpack is within 0.05 m (Applanix Inc.). Trees in the MD plot were located using distance and bearings to triangulate tree positions to known locations. Planimetric errors may exceed 2 m at the edge of the plot. Sensor set up, georeferencing, and data processing is detailed in Hopkinson et al. (2004a).

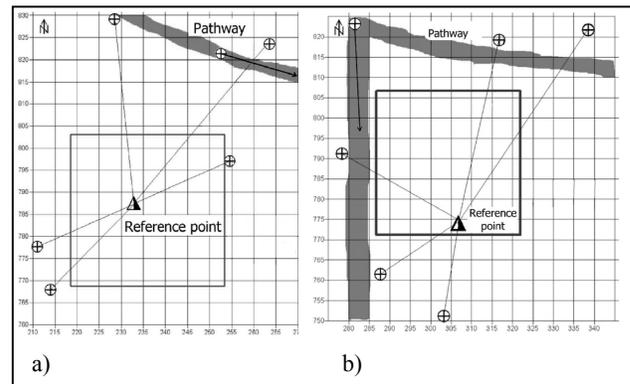


Figure 3. a) ILRIS-3D instrument locations in x and y co-ordinates (depicted by cross-hairs and circle) and centre of scan lines into the red pine conifer plantation. b) Similar ILRIS-3D instrument set up for the mixed deciduous plot.

3. METHODOLOGY

AL data, airborne GPS trajectory, ground GPS base station data, on-board inertial reference system, scan angle and raw laser range data were combined and processed using the Optech Inc. REALM software package. GBL, POS backpack sensor and target location data and individual scan lines were combined and processed using the PolyWorks software package (IMALIGN). Both AL and GBL have been processed by Optech Inc. to obtain UTM co-ordinates for every first and last pulse recorded using the AL and for every first or last pulse recorded using the GBL. For AL, last pulse returns have been classified into ground and vegetation using proprietary filtering techniques developed by Optech Inc. (e.g. Raber et al. 2002). Ground returns from AL were interpolated to a 1m raster DEM of the ground beneath the vegetation canopy using an inverse distance weighting (IDW) algorithm (Lloyd and Atkinson, 2002). Laser pulse data were then topographically

detrended by subtracting the corresponding heights of the interpolated ground DEM from the laser pulse returns. The detrending procedure removed the influence of topography and resulted in laser pulse heights that could be measured relative to the ground height. GBL data were also detrended in a similar manner, but by subtracting the interpolated AL ground DEM from the GBL laser points. Interpolation error is expected in the LiDAR DEM's at the centimetre to decimetre level (e.g. Töyrä et al. 2003).

AL and GBL were then process (into voxels) using the Integrated Matrix Language (IML) of SAS (SAS Inc.). Laser pulses have been classified according to x, y, and z locations within a 25m x 25m x 25m plot and subset into separate 1m x 1m x 1m voxels (Figure 2). The corners and centroid co-ordinates of each voxel were recorded along with the frequency of laser pulses within each voxel. Voxel tabulations have been further processed by combining 1m 'columns' through the canopy (e.g. 1m x 1m x 25m) in x, y, and z. Voxel column laser pulse frequencies from the ground through to the top of the canopy have been presented as percentiles. Percentile distributions of laser pulses allow for comparison between AL and GBL, regardless of vegetation height or the number of pulses individually and throughout the plot (3-dimensionally).

4. RESULTS AND DISCUSSION

4.1 Laser Pulse Frequency Distributions of AL and GBL

Average, plot-level laser pulse frequency distributions for the MD and RP plots are presented in Figures 4 and 5. Frequency distributions are presented as percentiles in increments of five percent.

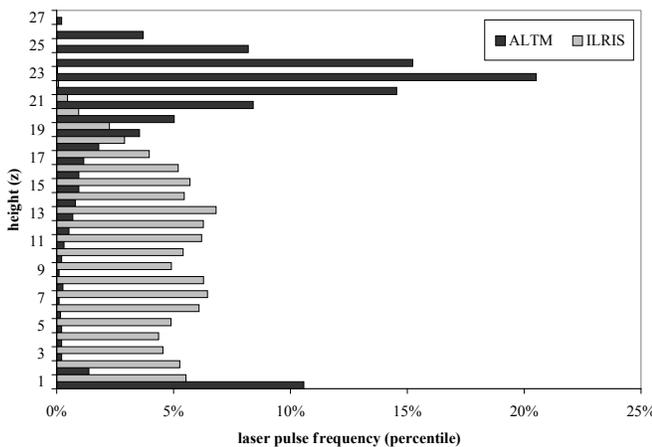


Figure 4. Average laser pulse frequency (percentile) distributions for AL (ALTM) and GBL (ILRIS) obtained for the mixed deciduous forest plot. Voxels (1m) have been horizontally averaged at each height from ground level to the top of the canopy to obtain average frequency distributions of laser pulses.

For both the MD and RP forest plots, it is evident that the AL collects the greatest percentage of laser pulses within the upper part of the canopy whilst GBL collects the greatest percentage of laser pulses within the lower part of the canopy and in the

understory. This is logical given the laser pulse will become increasingly attenuated the further it travels from the sensor, and will also be subject to pulse returns from foliage and woody material directly visible from the sensor. This process can be described as analogous to an 'extinction coefficient' in meteorological applications (Monteith and Unsworth, 1990). Tree height and canopy base height have been measured using a Vertex Hypsometer for all trees above a diameter at breast height (DBH) of 9cm. Average in situ measured tree heights for the RP and MD plots are 24.5m and 23m respectively. Average canopy base height for the RP is approximately 15m. The MD plot includes dense understory and upper canopy, and therefore average canopy base is not determined. In both plots, AL approximates the average heights of the trees (Figure 4 and 5) but is not able to account for differences in the understory. The RP plot exhibits the greatest differences between the AL and GBL in approximation of average tree and canopy base heights. AL excludes an average of approximately 4m from the centre (17m a.g.l.) to the base of the canopy (at 15m a.g.l.), whereas GBL excludes the top 21m to 24.5m of the canopy. This illustrates that substantial parts of the understory and canopy are excluded from airborne and ground-based LiDAR data, respectively.

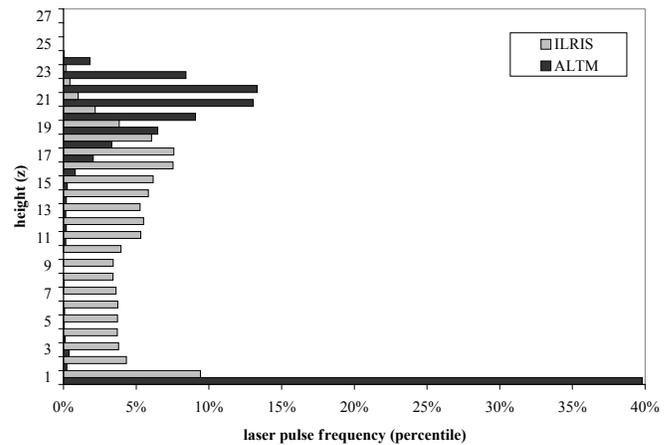


Figure 5. Average laser pulse (percentile) frequency distributions for AL (ALTM) and GBL (ILRIS) obtained for the red pine plantation. Voxels (1m) have been horizontally averaged at each height from ground level to the top of the canopy to obtain average frequency distributions of laser pulses.

4.2 3-D Percentiles of Voxel Columns from AL

To understand the attenuation of laser pulses through the canopy and the canopy transmissivity or opaqueness to AL, in particular, 1m voxel columns (1m x 1m x 25m) of laser pulse frequencies have been plotted as 3-D percentile distributions for both the RP and MD (Figures 6 and 7). 3-D percentile distributions are similar to average plot level percentile distributions, except that they are calculated at 1m increments (x, y, and z) for the entire plot and viewed from the top, down. 3-D percentile distributions may also be an adequate tool for individual tree counting and location, canopy clumping (voxel resolutions may be increased - Sinoquet et al. 2001), and for understanding diminished laser pulse frequencies at the edges of the scan, as in the case of GBL.

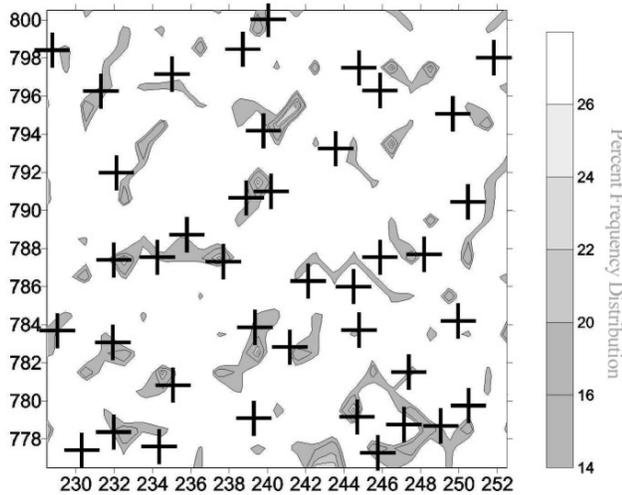


Figure 6. Plot of 3-D laser pulse frequency distributions for the RP plot. Maximum laser pulse frequency distributions shown here ($> 14\%$) indicate areas where laser pulses are greatest and is expected where the upper canopy, visible to the AL, is densest (likely where trees are located). Voxels 0 to 1m a.g.l. have been removed due to tendency of laser pulses to accumulate at the ground surface. Black cross-hairs are tree stem locations as obtained from the Applanix POS system. X- and y-axes are truncated UTM co-ordinates.

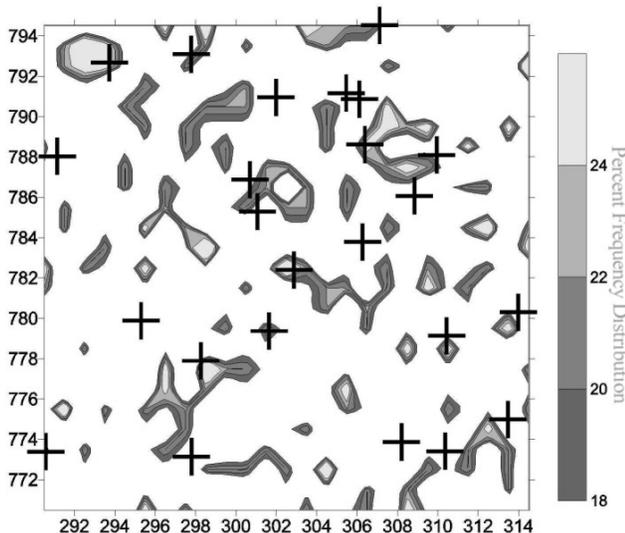


Figure 7. Laser pulse frequency distributions for the MD plot. Maximum laser pulse frequency distributions shown are $> 18\%$. In this plot, openings in the forest canopy (lower extinction coefficient) will allow laser pulses to penetrate to the understory. This creates difficulty when using laser pulse frequency to count trees and find stem locations. As per Figure 6, voxels 0 to 1m a.g.l. have been removed. Black cross-hairs are tree stem locations as obtained from triangulation methods and may be subject to errors of 2m or greater at the edge of the plot.

5. CONCLUSIONS

The following preliminary study has used 3-D voxel and voxel columns through the canopy to examine the attenuation of laser pulses from both AL and GBL. It has been found that AL excludes an average of 4m from the base of the live canopy due to a reduction of laser pulses reaching this part of the canopy. Further, GBL tends to exclude the top 3.5m of the tree canopy. In both cases, laser pulses are reduced, but may not be completely removed as this will depend on vegetation structure and leaf area. For example, Hopkinson et al. (2004a) found that GBL is still able to accurately characterise tree height, despite laser pulse attenuation. Laser pulse attenuation for the AL is further examined by plotting the 3-D percentile distribution columns using 1m voxels. Clumping of leaves within the canopy will affect the ability of the AL to penetrate into the canopy. This may also improve the counting and locating of trees. This study illustrates that substantial parts of the understory and canopy will be excluded and may have affect leaf area index and biomass estimations from both AL and GBL.

5. FUTURE RESEARCH

Quantification of the frequency of laser pulses through both AL and GBL is planned with respect to the voxel centroid distance from the scanner and scan/sensor geometries. The probability of laser pulse return, despite attenuation, will be modelled for voxels that are prone to a lack of laser pulses due to vegetation obstruction.

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