Examining the Influence of Changing Laser Pulse Repetition Frequencies on Conifer Forest Canopy Returns

Laura Chasmer, Chris Hopkinson, Brent Smith, and Paul Treitz

Abstract

The distribution of laser pulses within conifer forest trees and canopies are examined by varying the rate of laser pulse emission and the inherent laser pulse properties (laser pulse energy, pulse width, pulse length, and roll-over or trigger time). In this study, an Optech, Inc. ALTM 3100 airborne lidar is used, emitting pulses at 50 kHz and 100 kHz, allowing for changes in laser pulse characteristics while also keeping all other survey parameters equal. We found that:

1. *Pulses and associated characteristics emitted at 50 kHz penetrated further into the canopy than 100 kHz for a significant number of individual trees.*
2. *At tall tree plots with no understory, pulses emitted at 50 kHz penetrated further into the canopy than 100 kHz for a significant number of plots.*
3. *For plots with significant understory and shorter trees, pulses emitted at 100 kHz penetrated further into the canopy than 50 kHz. We suspect that this may be due, in part, to canopy openness.*

Laser pulse energy and character differences associated with different laser pulse emission frequencies are likely a contributing factor in laser pulse penetration through the canopy to the ground surface. Efforts to understand laser pulse character influences on canopy returns are important as biomass and vegetation structure models derived from lidar are increasingly adopted.

Introduction

The need for accurate estimates of forest biomass has led to the use of airborne laser scanners or light detection and ranging (lidar) for biomass estimation from vegetation height metrics in vegetated/forested environments. Lidar data have been used extensively for estimating vegetation characteristics since the early 1980's (e.g., Maclean and Krabill, 1986; Nelson *et al*., 1988; Lefsky *et al*., 1999; Zimble *et al*., 2003; Hopkinson, *et al*., 2005). Airborne and terrestrial (ground-based) lidars are able to detect some vegetation structure by converting time measurements from laser pulse emission to reception into distances as the laser pulse reflects from leaves, stems, and branches before encountering the ground surface. Multiple reflections can be recorded from a single emitted laser pulse using small-footprint, discrete return systems. The development of these active sensors has led to a wealth of studies on the application of lidar for measuring structural components (e.g., height, connectivity, quantity, type, extent, and position (Parker, 1995)) of vegetation, which are difficult using standard remote sensing techniques. Tree height is of particular interest within the forestry literature because it can be directly sampled using airborne lidar. Height samples from lidar have also been shown to correspond reasonably with allometric equations and field sampled biomass and leaf area index studies, important for both ecological processes and economic and social growth (e.g., Parker *et al*., 2001; Lefsky *et al*., 2005). Laser scanners may also be of benefit for validating larger-scale process models and lower resolution remote sensing algorithms (Chen *et al*., 2004; Lefsky *et al*., 2005).

The increasing interest in lidar for forestry applications has led to recent studies that are repeating old surveys to obtain multi-temporal data that may quantify forest growth and change observed at time of survey (e.g., St-Onge and Vepakomma, 2004; Gobakken and Naesset, 2004; Lefsky *et al*., 2005). Frequently, studies that use lidar data examine the distribution of laser pulses as they penetrate through the canopy (e.g., Magnussen and Boudewyn, 1998; Lovell *et al*., 2003; Chasmer *et al*., 2004). A change in the vertical frequency and distribution of laser pulse returns within the canopy from one survey to the next may be related to a change in the structural attributes of that canopy, for example, growth in height, change in leaf area/canopy closure, random versus non-random (clumping) leaves, seasonality, and so on. However, these may not be solely influenced by the vegetation structure and biomass for which the laser is sampling. Differences in scanner settings (e.g., Holmgren *et al*., 2003), flying heights (e.g., Naesset, *et al*., 2004; Yu *et al*., 2004), survey line configurations (e.g., Holmgren *et al*., 2003), and ground topography (e.g., Naesset and Bjerknes, 2001) have been found to alter the distribution and frequency at which laser pulses reflect from the top and within tree canopies. Further, the laser pulse properties (e.g., energy and length of the laser pulse, the beam width, and the amount of energy required to trigger a receivable laser pulse reflection) vary as a function of the rapidity of laser

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Table 1. Optech, Inc. Specified Laser Pulse Energy and Peak Power for Recent Airborne Lidars

Lidar System	1210	1225	2033	2050	3100	3100	3100	3100
PRF (kHz)	10	25	33	50	33	50	71	100
Pulse Energy (μJ)	170	140	86	118	164	112	83	59
Peak Power (kW)	24.1	15.9	14.8	11.2	21.8	13	7.2	3.7

pulse emission or "pulse repetition frequency" (Naesset, 2005). Typically, as laser pulse emission frequency increases, laser pulse energy decreases, yielding increased laser pulse width and greater standard deviation in z (Optech, Inc., unpublished). For example, the Optech, Inc. ALTMs have laser pulse properties that vary depending on the type of sensor used (Table 1).

"Systematic" differences in laser pulse properties emitted by different types of sensors may be large enough to be confused with temporal variations in vegetation structure that is observed from one survey to the next. Because we are using lidar data for increasingly sophisticated assessment of vegetation structural properties, we must also continue to advance our understanding of laser pulse characteristics within different forest types and from different sensors.

The purpose of this study is to determine if differing laser pulse characteristics (peak power and laser pulse energy) associated with changing pulse repetition frequencies (PRFs) affect the shape of laser pulse return frequency distributions within individual tree crowns of red pine (*Pinus resinosa*), keeping all other survey parameters the same. The experiment is then tested at the plot level for 100 plots of red and white pine (*Pinus strobes*) of differing ages, treatments, and understory vegetation. It is understood that the frequency at which laser pulses are emitted are invariably tied to a variety of laser pulse properties and characteristics associated with the common PRF description, for example, pulses emitted at 50 kHz as opposed to 33 kHz or 100 kHz. It is these combined properties that may affect the physical ability of laser pulses to penetrate into and reflect from within vegetation canopies. The following null hypothesis is examined using the Kolmogorov-Smirnov (K-S) test: H_0 = laser pulse frequency distributions within conifer tree crowns for pulses emitted at 50 kHz and 100 kHz display no significant differences. H_a = laser pulse frequency distributions within conifer tree crowns for pulses emitted at 50 kHz and 100 kHz do display significant differences.

Methods

Study Area

The study area, known as the North Tract of the York Regional Forest (YRF), is located approximately 50 km north of Toronto, Ontario Canada. The study area (approximately 2 km × 1.5 km) consists of a variety of localized red (*Pinus resinosa*) and white pine (*Pinus strobes*) plantations and patches of mixed deciduous stands on slightly undulating topography with elevation changes of less than 20 m. Forest patches also vary in age and treatment type, altering growth and structural characteristics throughout the forest. Past treatment procedures within the YRF also vary, but are typical of both managed and previously harvested forests in southern Ontario (Figure 1). Tree heights for conifer patches vary from 1 m to 30 m and dominate approximately 73 percent of the YRF North Tract (Hopkinson *et al.*, 2004a).

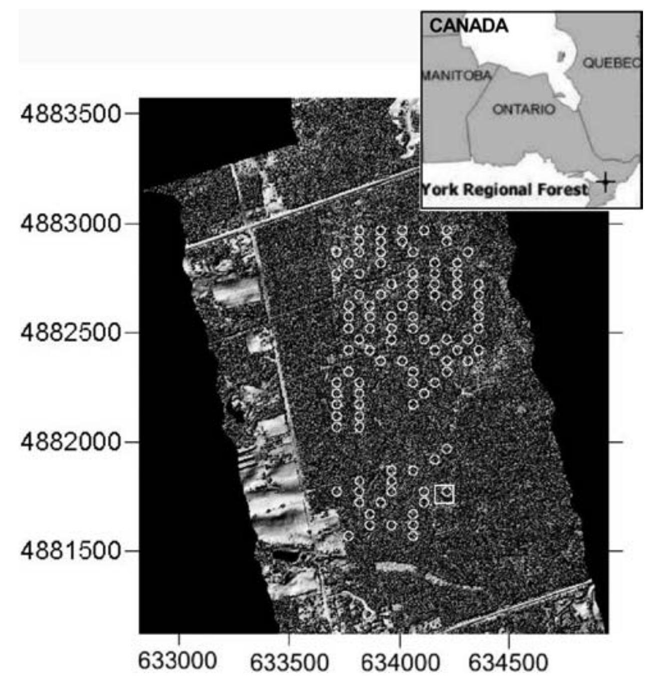


Figure 1. Rasterised shaded relief image obtained from airborne lidar flown in November 2004 at the YRF study area. One hundred 11.3 m radius red and white pine conifer plots of varying ages and structures (represented by white circles) and the 30 m × 30 m red pine plantation used for individual tree analysis (white square) are shown.

Airborne Lidar Data Collection Procedures

Since 2000, one terrestrial lidar survey and nine airborne lidar surveys have been organized for the YRF (Hopkinson *et al.*, 2004a; Hopkinson *et al.*, 2004b; Chasmer *et al.*, 2004) using generations of Optech, Inc. discrete return small-footprint Airborne Laser Terrain Mappers (ALTMs 1210 to 3100). Airborne lidar data used in this study were collected over a 2-hour period in November 2004 using an Optech, Inc. ALTM 3100. Care was taken to vary only the laser pulse repetition frequency to separate out the physical influences of laser pulse characteristics on within canopy frequency distributions. Two flight passes consisting of two pre-specified survey lines at 50 percent overlap were conducted at 1000 m AGL using PRFs of 50 kHz and 100 kHz. Table 2 provides information on input and output parameters for the two coincident surveys as well as the accuracy estimated following calibration of the sensor.

Table 2. ALTM 3100 Scanner Settings for Airborne Lidar Data Collections at Varying PRFs at the YRF on 16 November 2004

Parameter	50 kHz	100 kHz
Flying Height (m AGL)	1000	1000
Flying Speed (knots)	110	110
Scan Angle (±) degrees	18	18
Scan Overlap (%)	50	50
Scan Frequency (kHz)	33	44
Cross-Track Resolution (m)	0.858	0.572
Down-Track Resolution (m)	0.857	0.643
Resolution (m) with overlap	~0.428	~0.30
Vertical Accuracy (m)	±0.087	±0.153
Horizontal Accuracy (m)	±0.5	±0.5

Field Sampling

Field mensuration data were collected for a managed, homogeneous, mature 35 m × 35 m red pine plantation from 04–17 July 2002. All trees were uniquely numbered with aluminium tags prior to measuring individual tree position, height, depth of canopy, crown diameter, and stem diameter at breast height (DBH). Adjustment for growth has been performed according to Plonski (1960). Detailed discussion of field sampling and data collection are discussed in Hopkinson *et al.* (2004b).

Stem Map

An inertial survey instrument known as the POS-LS (Position Orientation System – Land Survey), manufactured by Applanix, Inc. (Toronto, Ontario) was used to locate trees within the plot (see Hopkinson *et al.*, 2004b). Locational errors in POS-LS were less than 5 cm, but were measured at the side of the tree stem and were not corrected for location at the center of the stem.

Tree Measurements

Tree heights and depths of canopies for individual trees in the red pine conifer plot were measured from the ground to the top of the live canopy and then to the base of the live canopy using a Vertex sonic clinometer (Haglof; Madison, Mississippi). The base of live crown was measured based on the live branches nearest to the ground surface. Individual tree stem DBH measurements were made at a height of 1.3 m above the ground using a DBH tape measure. Tree crown diameter was measured along the four cardinal directions (N-S and E-W) using a measuring tape and a compass at the average recorded.

Airborne Lidar Data Processing

Although up to four pulse returns can be received by the ALTM 3100, only first and last pulses have been examined for consistency with the majority of studies involving small footprint laser scanners for biomass change. First and last pulses were combined for 50 kHz and 100 kHz datasets, respectively. Although separation and analysis of first and last pulse returns would have been interesting, it was beyond the scope of the current study. A ground classification of the laser pulse returns was performed in Terrascan (Bentley, Inc.) for the purpose of vegetation removal. Due to the date of acquisition (November), there was reduced foliage within the understory, and this allowed for better penetration to the ground surface. The influence of topography on the pulse return distribution was removed by calculating the residuals from the digital elevation model (DEM) of ground-classified returns and vegetation point cloud data within Surfer (Golden Software, Inc.). The DEM was created using an inverse distance weighting algorithm (IDW) with a search radius of 1.5 m. The purpose of topography removal was to make field and lidar data comparable. Because the centers of the tops of trees are frequently shifted from the location of stems on the ground (Popescu *et al.*, 2003), individual trees were shifted from the POS-LS locations by creating a canopy height model (CHM) from the 50 kHz and 100 kHz data. The highest elevation laser pulses at the top of the tree canopy were identified using the IDW algorithm. Tops of tree canopies were compared both in height and location to field sampled tree heights and locations obtained from the POS-LS data. New tree coordinates were established based on the gridded maximum height and proximity to the nearest POS-LS tree location. Each tree has been further checked for correspondence in height, base of canopy, and crown diameter using a terrestrial laser scanner (Hopkinson *et al.*, 2004b). Individual tree laser point clouds were then extracted by selecting points within a specified

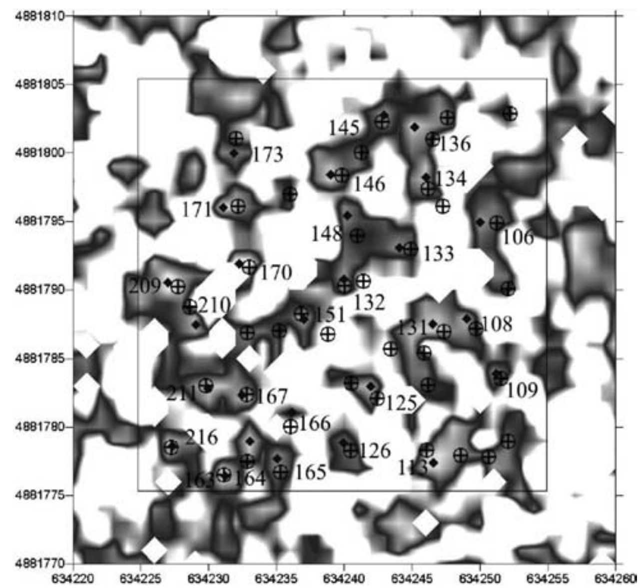


Figure 2. Registration of airborne lidar and POS-LS tree locations. Airborne lidar data have been combined (first pulse only 50 kHz and 100 kHz), detrended to remove topography influences and gridded using an inverse distance weighting algorithm with a search radius of 50 cm. Light grey areas illustrate the highest tree crown elevations, whereas darker grey and black represent lower elevations (all above 15 m AGL). White areas are below 15 m AGL Circle and cross hairs are POS-LS locations of tree stems (after correction, see Hopkinson *et al.*, 2004a). Black diamonds are "new" tree locations based on the highest elevation laser pulse distributions and closest nearby POS-LS tree locations. Tree numbers are also indicated. Locations were further checked for individual 50 and 100 kHz PRFs and registration to same trees digitised using the terrestrial laser scanner (not shown).

radius from center (based on the average crown diameter) (Figure 2). Plots used for the second part of the analysis have been extracted based on timber cruises and classified patches of forest types and treatments (Silv-Econ, Inc.). One hundred classified red and white pine conifer plots, systematically spaced at 100 m and 200 m in the north-south and east-west directions, respectively, were selected and lidar data from all two PRFs were output for each of these plots (Figure 1). Airborne laser point clouds have been extracted for each plot and examined for average and maximum tree heights and understory vegetation, and then classified according to a maximum number of laser pulse returns below the dominant canopy.

Laser pulse return frequency distributions were generated for individual trees and plots to test the hypothesis that frequency distributions associated with varying laser pulse characteristics at two PRFs were not significantly different. A Kolmorogov-Smirnov (K-S) test was then used to determine if the differences between laser pulse characteristics emitted at 50 kHz and 100 kHz were statistically significant at 95 percent confidence levels (Ebdon, 1985). To perform a K-S test, one would expect that the cumulative frequency distributions of laser pulses emitted at the different PRFs should be similar if they are random samples drawn from the same population (H_0). If they are significantly different, then H_0 is rejected and the alternative hypothesis is accepted. Top of canopy and base of canopy were considered to be the height of the maximum laser pulse within the individual tree crown (tree height), and minimum laser pulse at the base of the canopy that occurred within an inflection point of ten percent or greater within the cumulative frequency distribution (beyond the tree stem).

Integration of Airborne Lidar with Terrestrial Lidar for Individual Trees

The tripod-mounted ILRIS-3D terrestrial scanning lidar (Optech, Inc.) was used for illustrative purposes to identify individual tree crown structural components that may be missed in the airborne laser pulse frequency distribution. Individual trees (N = 29) have been extracted using the Polyworks software suite (InnovMetrics Software, Inc.) and registered to POS-LS tree locations and to the nearest top of canopy airborne lidar data (Chasmer *et al. in press*).

Results

The following sections discuss how changing the laser pulse characteristics associated with PRFs at 50 kHz and 100 kHz using an Optech, Inc. ALTM 3100 affects top of canopy and base of canopy sampling at both the individual tree and plot levels for red and white pine.

Laser Pulse Return Frequency Distributions at the Individual Tree Level

At the individual tree level, it was found that for many trees, changing laser pulse characteristics associated with pulses emitted at 50 kHz and 100 kHz had an influence on the ability of laser pulses to penetrate the tree canopy, thereby slightly altering the vertical laser pulse return frequency distributions. For each tree, the K-S test was used to determine if significant differences existed between vertical frequency distributions for pulses emitted at 50 kHz and 100 kHz. The results in Table 3 indicate that laser pulses emitted at 50 kHz (and their associated characteristics) penetrate further into the canopy than those emitted at 100 kHz for a statistically significant number of trees (N = 29, p = 0.05). Therefore, the null hypothesis that no significant differences between the vertical distributions is rejected.

The greatest differences between laser pulse return cumulative frequency distributions at 50 kHz and 100 kHz tended to occur within the canopy and near the base of the live crown (Table 3). These differences indicate that a greater proportion of laser pulses at 50 kHz penetrated into, and reflected from within tree crowns, whereas proportionally fewer pulses emitted at 100 kHz penetrated as deeply into the canopy for first and last pulses only. This indicates that pulses emitted at 50 kHz, and containing greater laser pulse energy, are potentially better able to describe within canopy structural characteristics at the individual tree level for pure conifer trees. Significant differences between laser pulse frequency distributions at 50 kHz and 100 kHz also occurred near, or at the top of the tree crown, illustrating that pulses emitted at 100 kHz did not penetrate as deeply into the canopy on first pulse reflection as did those emitted at 50 kHz. Therefore, laser pulses emitted at 100 kHz may be more appropriate for top of tree crown mapping than those emitted at the lower PRF (discussed later), at least for pure conifer stands. The laser pulse return frequency distribution for pulses emitted at 50 kHz and 100 kHz are illustrated in Figure 3 for an individual tree example where laser pulses emitted at 50 kHz penetrate further into the canopy than those emitted at 100 kHz. The distribution of laser pulses are also compared with the more realistic structural elements mapped using the terrestrial laser scanner for the same tree to visually illustrate how both sensors map the same tree. The point cloud image in Figure 3 illustrates that much of the centre and lower parts of the tree do not receive equal proportions of laser pulses as the upper canopy (Chasmer *et al., in press*). This is especially the case with laser pulses emitted at higher 100 kHz. These can also be compared with cumulative and percent laser pulse frequency distributions (Figure 3). In this case, the base of the canopy for this particular tree has been measured at a height of 16.6 m AGL, although the TLS maps lower dead branches that must not be confused with the live crown.

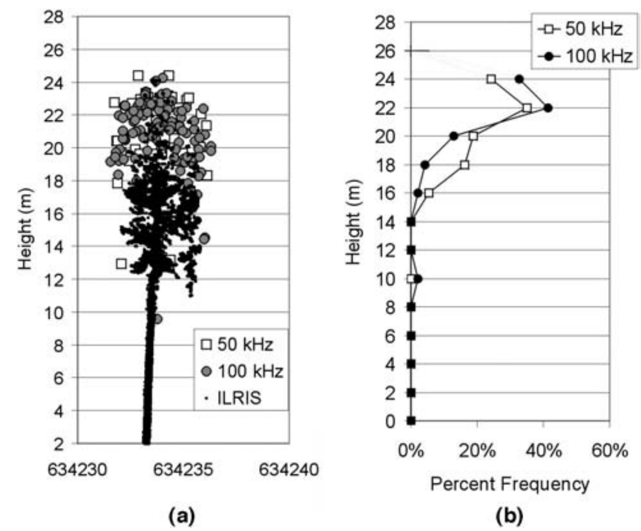


Figure 3. Laser pulse frequency distribution within the canopy (a), and percent distribution (b) of airborne lidar and terrestrial lidar laser pulse returns for a sample tree. Laser pulse characteristics associated with different laser pulse frequency distributions overestimate canopy base in conifer trees. Field measured base of live crown is 16.6 m AGL.

This test was also applied to laser pulses emitted at 100 kHz that had been resampled (thinned) to match the sample point density of laser pulses emitted at 50 kHz. Laser pulses emitted at 100 kHz were resampled following systematic

TABLE 3. SUMMARY STATISTICS OF LASER PULSE FREQUENCY DISTRIBUTIONS FOR INDIVIDUAL TREES (N = 29, SIGNIFICANCE, p = 0.05) AND RESAMPLED (THINNED) LASER PULSES EMITTED AT 100 KHZ

	50 kHz	100 kHz	50 kHz	100 kHz resampled
Sample Point Density (m^2)	4	9	4	~4
Percent Penetration	45% penetrated more than 100 kHz	14% penetrated more than 50 kHz	48% penetrated more than 100 kHz	22% penetrated more than 50 kHz
Average Height of Greatest Difference (m)	20.4	24.2	20.1	23.7

removal of laser pulse returns throughout the canopy at two-pulse or three-pulse intervals, relative to the *surplus* number of pulses. The results of the resampling demonstrate that greater numbers of laser pulses emitted at 50 kHz penetrate further into the canopy than those emitted at 100 kHz (Table 3), although a larger percentage of resampled pulses emitted at 100 kHz penetrate further into the canopy than those emitted at 50 kHz for non-resampled datasets, however, the differences remain significant at 95 percent confidence levels.

The results found require further testing and sensitivity analysis for forests containing different tree species, canopy openness, tree heights, leaf area index, canopy clumping, and flight parameters. Because conifer needles scatter light differently than randomly distributed deciduous leaves, the results shown here may not be representative of all types of vegetation. Despite required sensitivity testing, results do indicate that different laser pulse characteristics have an influence on how laser pulses are reflected from the top and within vegetation canopies. In conifer tree examples, it is apparent that pulses emitted at a slower rate, and with higher energy may be more appropriate for estimating volume or surrogates for biomass *if* pulses are able to penetrate to the base of the live crown. However, care must be taken when considering volumetric change detection using different sensors because the differences in sensor configuration and pulse characteristics affecting the distribution of laser pulses within the canopy may be confused with apparent tree differences at coincident survey times. Similarly, the measurement of tree growth over short time intervals will be highly sensitive to survey and sensor configuration. Table 4 compares the average base of live crown and average tree height at the plot level from pulses emitted at 50 kHz and 100 kHz with measured. The height of the average base of the live crown (important for directly estimating volume) was determined using the height of the lowest laser pulse reflected from within the tree canopy. In conifer species studied here, the base of the live crown is best approximated by laser pulses emitted at 50 kHz, although the height of the base is overestimated in comparison to field measured.

The average top of canopy yielded greater similarities between pulse characteristics at 50 kHz and 100 kHz and field measurements, as is to be expected (because lidar is able to directly sample the top of the tree). However, pulses emitted at 50 kHz penetrated further into the canopy (and therefore underestimated average tree height) in comparison with average measured top of canopy and that mapped using pulses emitted at 100 kHz. Thus, we may infer that (all else being equal) if previous surveys utilised pulses emitted at higher energies and lower laser pulse emission frequency are then re-surveyed using newer technology with higher pulse emission frequency, point density, and associated pulse characteristics, differences in the return distribution due to data collection technology and methodology might be assumed to be growth. In the example provided here, although the surveys were flown on the same day, average differences in the maximum height of pulse returns between 50 kHz and 100 kHz are between 30 cm and 40 cm, typical of two years of growth in red pine conifer plantations (Plonski, 1960). Therefore, care should be taken to compare datasets with similar laser pulse configurations and similar flight configurations that also may act to lower laser pulse energy (e.g., significantly changing flying height).

Laser Pulse Frequency Distributions at the Plot Level

The second part of this study compared the effects of different laser pulse emission frequency and associated characteristics at the plot level for red and white pine trees that have different structural and understory characteristics. It was anticipated that differences in structural characteristics of the different plots would yield different relationships between the laser pulse repetition frequency (50 kHz and 100 kHz) and associated pulse characteristics. Mensuration data for one hundred sample plots (11.3 m radius) of red and white pine were provided by the managing silvicultural firm, Silv-Econ, Inc. (Newmarket, Ontario). Forest-wide measurements and classification of management procedures were recorded within a geographic information system. These data were used for forest type classification only, with further characterization based on lidar data. Plots have been further classified according to the specifications in Table 5.

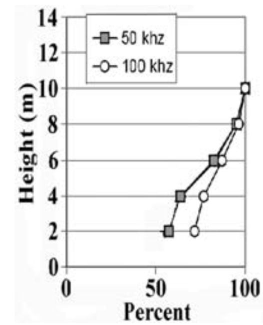
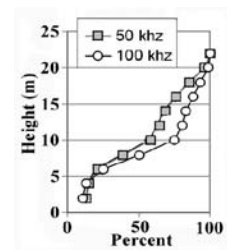
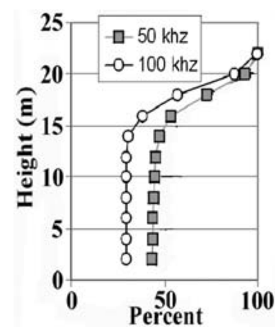
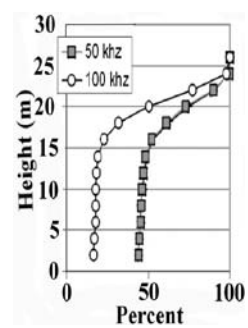
The results of the analysis, summarised in Table 6, demonstrate that for forest plots with tall trees and no significant understory (Classes 3 and 4), laser pulses emitted at 50 kHz frequently penetrate further into the canopy than those emitted at 100 kHz. However, for shorter vegetation with significant understory (Classes 1 and 2), it is apparent that laser pulses emitted at 100 kHz often penetrated further into the canopy than those emitted at 50 kHz, although the relationship is not as strong as that for taller trees. These results are unexpected according to our stated hypothesis and further analysis is required to examine why laser pulses emitted at a higher PRF and with lower energy would penetrate further into a shorter canopy with understory vegetation. This might be because plots with multiple canopy levels or significant understory may have reduced upper canopy coverage (i.e., increased canopy openness) and therefore, at 100 kHz, pulses passing through *this* upper canopy may not backscatter enough energy to trigger a first return until the lower canopy is reached. It is expected that the differences in penetration of laser pulses with differing laser pulse characteristics may also be influenced by canopy structure, leaf area index, and canopy clumping (affecting within canopy light distribution) as well as the complex properties of the laser pulse, rarely examined within the forestry literature.

Variability in laser pulse penetration to the ground surface with different PRF may be an indicator of some of the physical characteristics of pulses emitted at 50 kHz and 100 kHz. This is also of utmost importance for those who require accurate digital elevation models of the ground surface. According to our hypothesis, we would expect that the greatest proportion of pulses to reach the ground surface would occur at a lower PRF (e.g., 50 kHz), while 100 kHz should see a lower proportion of laser pulses reflecting from

TABLE 4. AVERAGE BASE OF LIVE CROWN AND TOP OF LIVE CROWN AS MEASURED USING AIRBORNE LIDAR WITH VARYING PRF AND TERRESTRIAL LIDAR, COMPARED WITH FIELD MEASURED. POSITIVE DIFFERENCES REPRESENT OVERESTIMATION OF HEIGHT (TALLER THAN FIELD MEASURED) AND NEGATIVE DIFFERENCES REPRESENT UNDERESTIMATION OF HEIGHT (SHORTER THAN FIELD MEASURED)

PRF	Average Base of Live Crown	Difference from Measured	Standard Deviation	Average Top of Live Crown	Difference from Measured	Standard Deviation
50 kHz	17.3 m	2.4 m	2.0 m	23.7 m	−0.5 m	0.7 m
100 kHz	19.0 m	4.1 m	1.5 m	24.0 m	−0.1 m	0.5 m
Field Measured	14.9 m		1.0 m	24.2 m		0.7 m

Table 5. Examples and Frequency of Laser Pulse Distributions for Four Classified Structural Red Pine Conifer Types

<table>
<tr><th>Classification</th><th>Schematic Drawing</th><th>Percent Distribution</th></tr>
<tr><td>Class 1: Young succession following clearcut. Significant understory. Tree height ≤14 m. N = 32</td><td></td><td>
</td></tr>
<tr><td>Class 2: Middle aged trees previously clearcut. Significant understory. Tree height >14 m, <24 m. N = 33</td><td></td><td>
</td></tr>
<tr><td>Class 3: Middle aged trees previously clearcut. No significant understory. Tree height >14 m, <24 m. N = 17</td><td></td><td>
</td></tr>
<tr><td>Class 4: Older trees previously clearcut and planted. No significant understory. Tree height >24 m. N = 16</td><td></td><td>
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the ground. Laser pulses at ground level (±0.5 m) were examined for each of the 100 pine plots for the two PRFs, and divided into proportions on a plot-by-plot basis. Results are summarised in Table 7. For both PRFs, approximately 50 percent of all laser pulses reached the ground surface. Pulses emitted at 50 kHz had the greatest proportion of laser pulses reaching the ground. Proportion of penetration to the ground by 100 kHz, averaged slightly less than 50 kHz, overall. Variation in percent penetration to the ground surface is likely the result of less vegetation at the ground surface, and therefore more laser pulse energy being backscattered from the ground. Significant differences between pulses were examined for all average pulses at the 90 percent significance levels using a paired two sample for means t-test. There are significant differences between pulses emitted at 50 kHz and 100 kHz ($p = 0.1$). Results indicated that as vegetation height decreases, penetration of laser pulses through the canopy to the ground increased, corroborating the results of Naesset and Bjerknes (2001).

Discussion

The results presented illustrate significant differences in the ability of laser pulses to penetrate through the canopies of pure conifer species for pulses emitted at two different PRFs. Such differences slightly affect the accuracy of measuring forest metrics using airborne laser scanners and also improve metrics (e.g., height) when certain PRFs are used

Table 6. Laser Pulse Characteristic Differences with PRF at the Plot Level for Four Structural Classes of Red Pine Conifer Plots. Bold Lettering Indicates Significant Differences at 95 percent (Numbers Within Brackets are Significant at 80 percent). Negative Values Indicate Penetration Opposite to What is Expected. For Example, where 50 kHz Penetrates Further into the Canopy than 100 kHz, the Result is Positive. Where 100 kHz Penetrates Further into the Canopy Than 50 kHz, the Result is Negative

PRF Penetration	Class 1	Average Height of Greatest Difference	Class 2	Average Height of Greatest Difference	Class 3	Average Height of Greatest Fifference	Class 4	Average Height of Greatest Difference
50 kHz > 100 kHz	−6% (9%)	0 to 2 m (4 to 8 m)	−12% (0%)	8 to 12 m	29% (11%, −5%)	10 to 14 m (16 to 18 m)	18% (18%)	16 to 18 m (16 to 20 m)
Total combined:	Plots with significant understory ($p = 0.05$)		50 kHz > 100 kHz −18%		Plots with no significant understory ($p = 0.05$)		50 kHz > 100 kHz 47%	

Table 7. Average Percent Penetration of Laser Pulses to the Ground Surface Within All Plots and Those with Varying Understory and Canopy Structure

PRF	Average Number of Pulses per Plot at Ground (std. dev.)	Average % Penetration Understory	Average % Penetration – Short Trees with Little Understory	Average % Penetration – Tall Trees with Little Understory
50 kHz	513 (±195)	46%	50%	42%
100 kHz	695 (±367)	39%	46%	33%

(e.g., 100 kHz). Thus, it is important to understand some of the physical differences between laser pulses emitted at varying PRFs in order to explain these observations (Table 1).

It is likely that variability in laser pulse penetration with specified PRFs and laser pulse characteristics can be explained, in part, by the properties of the emitted laser pulse specific to the sensor used. It is understood that pulses emitted at higher frequencies (used as an indicator for a range of pulse characteristics) have lower amounts of energy stored within laser diodes between the firing of each laser pulse than for pulses emitted at lower frequencies, simply because of the repetition at which pulses are emitted from the laser diodes. Therefore, the amount of energy available for each laser pulse will decrease with increasing PRF, altering the amount of energy that is reflected from biomass within the canopy and received as a detectable amount of backscatter by the sensor electronics. This will slightly alter the distribution of laser pulses within the canopy for pulses emitted with varying PRFs. Consider actual laser pulse energy per PRF: for this particular sensor (ALTM 3100), at 50 kHz, laser pulse energy is 112 μJ and peak power is 13 kW, while at 100 kHz, the laser pulse energy is 59 μJ, and the peak power is 3.7 kW (Table 1; Optech, Inc., unpublished). As a result, pulses emitted at lower frequencies have higher sensitivity and *reflectability* than pulses emitted at higher frequencies for an opaque surface because there is greater peak power yielding a more stable pulse reflection at the center of the pulse. Stability in laser pulse reflection is also related to the laser pulse width. As pulse frequency increases, laser pulse width also increases from 8.6 ns at 50 kHz to 16 ns at 100 kHz, creating a noisier signal as PRF increases, typical standard deviations in z are 4 cm to 5 cm for 50 kHz and 9 cm to 11 cm for 100 kHz (Optech, Inc., unpublished). This means that a laser pulse at 50 kHz can lose a significant amount of energy in the upper parts of the tree but may still have enough energy to trigger an additional response(s) within the canopy and at the ground surface if enough biomass is present for the fraction of reflection to be received by the sensor. This may partly explain why deeper penetration into the canopy is observed at the individual tree level and within mature forest plots with little understory by laser pulses emitted at 50 kHz as opposed to 100 kHz. At 100 kHz, significant laser pulse energy is likely to return from within the top parts of the tree because of minimal interruption of the pulse by foliage. However, as the pulse continues through the canopy, it will lose energy, and may not encounter enough opaque biomass within the canopy to backscatter enough energy to trigger a response by the sensor. Therefore, laser pulses emitted at 100 kHz are less likely to reflect from deeper within the canopy than those emitted at 50 kHz, but do tend to better estimate tree height because of increased pulses reflecting from the top parts of pure conifer canopies. This may also be explained by examining the backscatter response for individual pulses encountering a forest canopy. The amplitude of the reflected pulse energy increases as it interacts with more biomass at the top of the canopy. However, as the pulse penetrates deeper into the canopy, the pulse backscatter amplitude decreases. This is illustrated schematically in Figure 4. Despite this explanation, we continue to see confounding results, opposite to what we expect, in forest canopies with mixed deciduous understory. This leads us to believe that the penetration of laser pulses at higher PRFs may be the result of multi-tiered vegetation, upper canopy openness and therefore further penetration by pulses emitted at 100 kHz. Organization and clumping of foliage within the canopy may also have an influence on laser pulse penetration, as it does on the light regime within random versus clumped canopies (Leblanc, *et al*., 2005; Hardy, *et al*., 2004).

Another consideration is the distance that must be covered between laser pulse reflections sensed by the receiving optics, also partly explaining variation in penetration by laser pulse characteristics associated with different PRFs in discrete return lidar systems. The ALTM 3100 receiving optics are unable to sense a laser pulse reflection within 2 to 2.5 m of a prior return received by the sensor. The *blind zone* for an ALTM 3100 is 2.1 m between first and second pulse returns, and 3.8 m between second and third pulse returns and third and fourth pulse returns (Optech, Inc., unpublished). This may partly explain why the proportion of laser pulse reflections at the ground surface vary with respect to laser pulse characteristics and canopy structure, especially

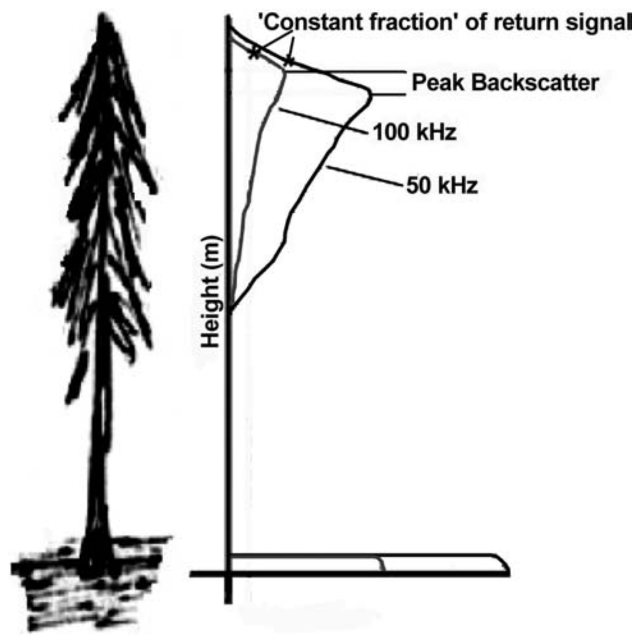

Figure 4. Simplified, conceptual diagram of laser pulse backscatter energy distribution through the canopy (not to be confused with laser pulse return frequency distribution). The point of peak laser pulse backscatter occurs after a certain amount of energy interacts with biomass. Energy increases until a constant fraction of the return signal is reached and a laser pulse return is triggered.

for differences in 50 kHz and 100 kHz. In forests with younger trees and a complex understory, a more powerful 50 kHz laser pulse may have the energy to reflect returns at 2 m steps through the canopy and into the understory, resulting in a *brighter* signal than those emitted at 100 kHz within the understory. Therefore, laser pulses emitted at 50 kHz should still have proportionally more energy reflecting from the ground than those emitted at 100 kHz that travel the same path. Variations in this trend may occur if laser pulses emitted at 50 kHz reflect detectable energy within branches of up to 4 m from the ground surface.

Many of the observations that have been made here require further experimentation with variations in scanner and flight parameters as well as different tree species, understory characteristics, and associated canopy clumping and LAI properties. Variation in average laser pulse intensities may also provide insight into the distribution of energy through the canopy, especially if examined at specified height percentiles. Examination of vegetation structural attributes, leaf area, canopy clumping, and tree type will also have an influence on small variations in the distribution of laser pulses throughout the canopy and may have a greater influence in mixed and deciduous canopies. Such experiments are the basis of further analyses following on from this study.

Conclusions

In this paper, we examined some of the physical elements of laser pulse distribution using two different PRFs within red and white pine forest environments. Significant differences in laser pulse frequency distributions have been found to occur at the individual tree level, within classified plots, and in relation to laser pulse penetration to the ground surface for red and white pine conifer trees. These differences appear to be related to both canopy characteristics and the physical properties of laser pulses emitted. The results of this study demonstrate that:

1. Significant differences in laser pulse frequency distributions occur between laser pulses emitted at 50 kHz and those emitted at 100 kHz, and their associated characteristics. These differences can, at least partly, be explained through an understanding of the physical properties of laser pulses emitted at different energy levels.
2. Laser pulses emitted at 50 kHz penetrated through the canopy to a greater degree than those emitted at 100 kHz, and therefore, most closely mapped the base of the canopy when compared to field measurements.
3. Laser pulses emitted at 100 kHz did not penetrate as deeply into individual tree canopies, and hence these data were most comparable to measured tree heights.
4. A significant number of plots (47 percent) experienced greater penetration by laser pulses emitted at 50 kHz than those emitted at 100 kHz in mature red and white pine forest plots with little understory.
5. In multi-tiered plots with significant deciduous/coniferous understory, the opposite was found to occur within 18 percent of plots, whereby pulses emitted at higher frequencies penetrated further into the canopy than those emitted at lower frequencies. It is possible that this is due, in part to canopy openness, foliage clumping, and the diffusion of light as it passes through the canopy. However this has yet to be tested.
6. Larger proportions of laser pulses emitted at 50 kHz reflected from the ground surface than those emitted at 100 kHz in forest plots that contained tall trees and little understory as well as within plots containing dense understory.

This study has demonstrated that the distribution of laser pulses through the canopy do vary with laser pulse characteristics associated with a particular pulse repetition frequency which may be of importance when examining conifer vegetation structure and changes near the noise level of the data.

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