Stability of LiDAR-derived raster canopy attributes with changing pulse repetition frequency

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1. Introduction

In this study, we compare LiDAR-derived estimates of canopy height, crown closure and fractional cover collected over a three hour period on July 16, 2005 using variable LiDAR survey configurations. Pulse repetition frequency (PRF) was systematically varied over three regenerating and two mature Acadian mixed-wood forest plots in Nova Scotia, Canada. The objective of this study is to determine if differences in PRF influence typical LiDAR-derived raster representations of canopy structure. The three raster representations of canopy structure that are investigated here are: the canopy height model, crown closure, and fractional cover.

Accurate mapping of vegetation structure has important implications for natural resources management and forest harvesting activities (Dubayah, 2000; Lim *et al.* 2003), assessing the impacts of natural and anthropogenic change on ecosystems (e.g. Weishampel *et al.* 2007), carbon, water, and energy cycling (Lefsky *et al.* 2005; Chasmer *et al.* 2011). In most cases, applications of LiDAR data for monitoring and ecosystem assessment require that: 1) vegetation metrics accurately represent forest attributes so that validation exercises may be limited or no longer required for a range of species types and ages; and 2) temporal datasets can be compared over a period of years to assess ecosystem change. Variations in LiDAR-derived data products due to differences in LiDAR survey configurations, points processing, or rasterisation procedures may vary in magnitude depending on foliage and branching structure of vegetation or vegetation height (e.g. Hopkinson, 2007; Naesset, 2009). When LiDAR data metrics are used within ecosystem or biogeochemical models, slight differences in canopy structural attributes used to parameterize the model could result in compounding errors over time.

Several studies have examined the influence of LiDAR survey configurations on the distribution of laser returns within the canopy (e.g. Holmgren *et al.* 2003; Naesset 2004; Chasmer *et al.* 2006; Hopkinson 2007; Lim *et al.* 2008; Naesset, 2009). In addition to data acquisition settings, the amount of pulse penetration into and through the canopy varies due to the structural characteristics and density of the foliage and ground cover encountered. It has been reported that surveys configured using lower PRFs (typical of older data collections) tend to result in lower laser pulse frequency distributions in the upper quantiles when compared with higher PRF (or more recent) surveys (Hopkinson, 2007; Lim *et al.* 2008). Notwithstanding laser pulse energy plays an important role (e.g. Chasmer et al. 2006; Hopkinson, 2007), increasing point density with PRF also increases the probability of sampling tree tops. However, the influence of PRF-induced shifts in the canopy point cloud on derivative raster canopy attributes are not well understood. The objective of this study is to investigate whether or not raster canopy height, crown closure and fractional cover attributes are stable across four different PRF settings over a forested Acadian mixed wood landscape.

2. Method

2.1 Study area

The site is located approximately 5 km south-east of the town of Middleton, within the Annapolis Valley, Nova Scotia, Canada (N 44º 54' 59", W 65º 04' 41") (Figure 1). The area flown is approximately 1 km long by 0.5 km wide, and twenty extraction plot locations equalling approximately 1 hectare in area were defined within this area (Figure 1). The Acadian mixed-wood forest is characteristic of many mixed-wood forests found in Nova Scotia, and comprises of mainly *Acer saccharum* Marsh., *Pinus strobus* L., and *Betula alleghaniensis* Britt.
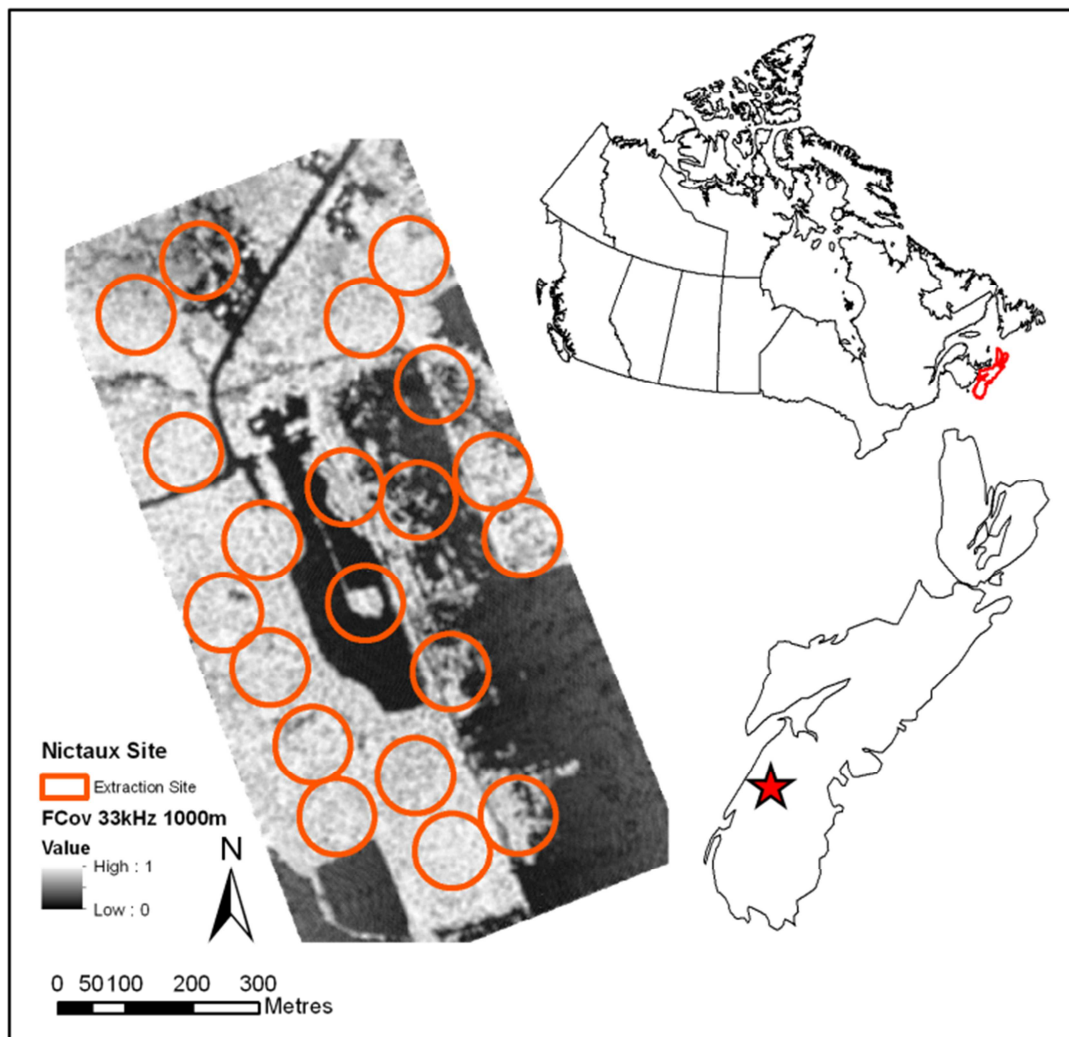

Figure 1: Study area showing fractional cover (33kHz, 1000m altitude, narrow beam) and 20 x 1 hectare LiDAR canopy attribute extraction plot locations.

2.2 Airborne LiDAR data collection and analysis

Airborne LiDAR data were collected during a single flight on July 16, 2005 using an Optech Inc. ALTM 3100, discrete four pulse return system owned and operated by the Applied Geomatics Research Group (AGRG), Nova Scotia. Four LiDAR configurations were flown by varying

PRF (Table 1), and keeping all other data collection parameters equal. All data collections were conducted at 1000 m a.g.l. using a narrow (0.3 mRad) beam divergence (1/e) and a scan angle of ±20 degrees from nadir.

Table 1. Flight configuration parameters for four data collections.

Configuration	PRF (kHz)	Point Density/m^2
1	33	0.92
2	50	1.30
3	70	1.83
4	100	2.32

Laser returns were classified into ground, below canopy (1.5m threshold) and all hits files within the Terrascan software package (Terrasolid, Finland). Ground returns were used to derive a 1 m resolution digital elevation model (DEM), using an inverse distance weighting approach. A digital surface model (DSM) was created based on a localized maxima algorithm, which uses returns at the maximum height within a specified search radius (in this case 2.5 m search radius was adopted for all datasets to ensure no data voids). Canopy height surfaces were determined by subtracting the DEM from the DSM to create a canopy height model (CHM) at 1 m resolution for each configuration. Canopy fractional cover was determined as the ratio of the canopy points above 1.5 m to all hits (throughout the canopy to ground). Hopkinson and Chasmer (2009) investigate four LiDAR-based models of canopy fractional cover, and the simple ratio method was adopted in this case as it is widely used and straightforward. Additionally, the CHM was thresholded at 5 m and reclassified into crown (>5 m) and non-crown (<5 m) to develop a binary mask of crown closure. The choice of 5 m was arbitrary and a priori not optimal for all canopy conditions but it was chosen by trial and error as a median canopy height and is used for the sake of illustration. A more in depth analysis is needed to identify an optimal threshold selection based on local canopy conditions but this approach was adequate for the purpose of identifying any systematic PRF dependence.

3. Results and Discussion

Comparisons were performed on plot-level means and maxima of the CHM, fractional cover and crown closure. The 33 kHz data were selected as the baseline datasets, and all observed PRF-dependent differences in the raster canopy attributes were tested for significance using a paired t-Test. In all comparisons the differences were significantly different at the 99% level of confidence (Table 2). Table 2 illustrates the progression of mean height determined by the CHM's, increasing with an increase in PRF. The 33 kHz setting gives the lowest height, and 100 kHz the highest, confirming the anticipated result that to detect higher elements of the canopy, a higher density of pulses is required. Deviations of canopy height per PRF, compared with data collected at 33 kHz are shown in Figure 2.

Table 2 illustrates the percentage of change in mean crown closure, determined above a canopy height threshold of 5 m, from 33 kHz to 50, 70 and 100 kHz, respectively. In general, crown closure increases slightly with an increase in PRF. Where complete crown closure exists, an increase in PRF deviations in crown closure are often less than 1 percent (Figure 4). However, as canopy openness increases, increases in PRF shows increased variability of crown closure up to 7% (Figure 4).

Table 2. Statistical descriptions of canopy height and fractional cover derived using different PRFs

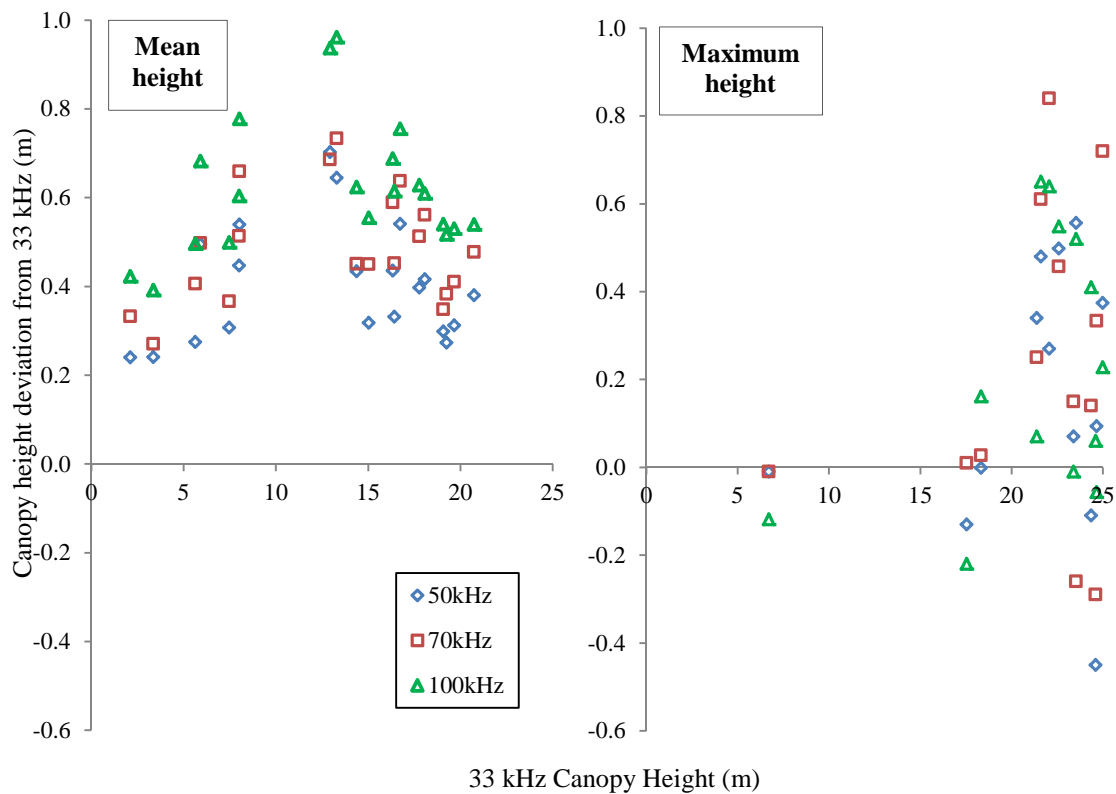|	CHM mean plot height statistics		Fractional Cover Percentage	Crown Closure plot statistics		
PRF	Mean (stdev)	Max	Mean cover % (stdev)	Mean % cover (stdev)	Mean difference from 33 kHz % (stdev)	Maximum mean difference from 33 kHz
33	13.01m (5.93)	22.74m	71 (18)	79.7 (28.2)	-	-
50	13.41m (5.94)	22.79m	82 (11)	81.1 (27.3)	1.4 (1.5)	4.6
70	13.50m (5.96)	22.86m	78 (12)	81.3 (27.2)	1.6 (1.8)	5.6
100	13.63m (5.96)	22.93m	82 (10)	81.7 (26.8)	2.0 (2.2)	6.6

Figure 2. Plot-level mean and maximum canopy height model residuals by PRF (50, 70, 100) from 33 kHz.

Figure 3 illustrates canopy height derived from the 33 kHz data and the grid-level height residual between canopy heights derived from 33 kHz and 100 kHz. Differences between the PRFs are emphasized at the edges of crowns, and 99% of the change falls in the range of -3.8 m to +3.8 m. This also illustrates the PRF sampling influence on crown morphology in that the lower sampling density associated with 33 kHz completely fails to sample many smaller individual crown elements in some of the more open areas of the study area.

Increases in PRF do not systematically cause increases in canopy fractional cover. For example

at 70 kHz, estimates of fractional cover are lower than that derived from data collected at 50 kHz. However, when compared with 33 kHz, fractional cover derived using higher PRFs are greater and all differences are significant at the 99% level of confidence. The largest difference is at 100 kHz, where canopy fractional cover is 11% greater than at 33 kHz. The deviations of fractional cover per PRF, compared with data collected at 33 kHz are shown in Figure 5.The variation in the type of plots sampled (varying age and openness, amount of understory) and the presence of mid-canopy returns representing canopy cover all influence depth of penetration of pulses into the canopy. Moreover, it has earlier been demonstrated that pulse power plays a critical role in controlling the level of pulse penetration and detection with canopies (Chasmer et al. 2006; Hopkinson, 2007), so it is important to emphasise that canopy representation is not a simple function of sampling point density. The observations here of a variable simple ratio-based fractional cover appear to be indicative of behaviour that is influenced both by pulse power and sampling density. For example, while it is known that increased pulse power increases the chances of ground level returns in continuous canopy cover (Hopkinson, 2007), increased sampling density will increase ground level representation in regions of more open canopy.
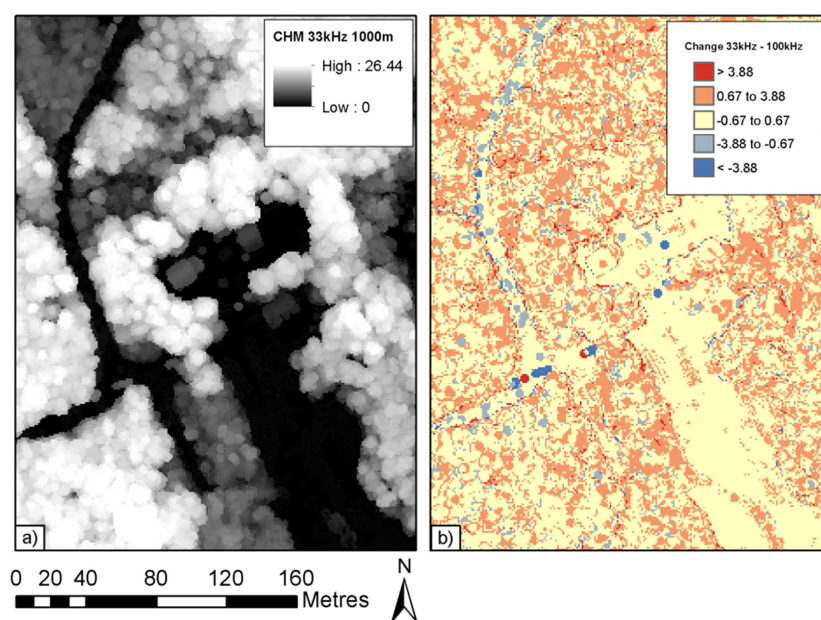

Figure 3: a) Subset of CHM for a mixture of Acadian mixed wood regeneration and mature stands generated from the 33 kHz LiDAR data; b) CHM difference image (100kHz - 33kHz)
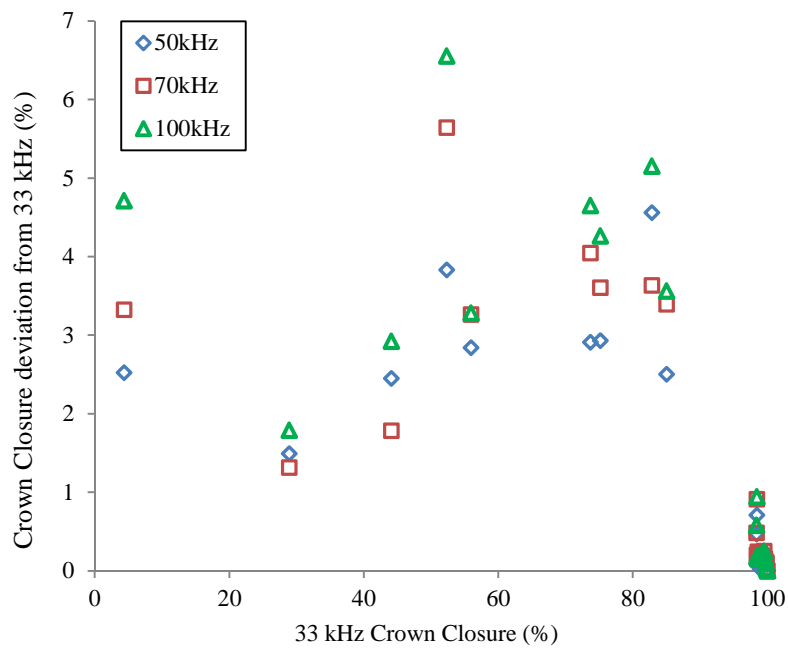
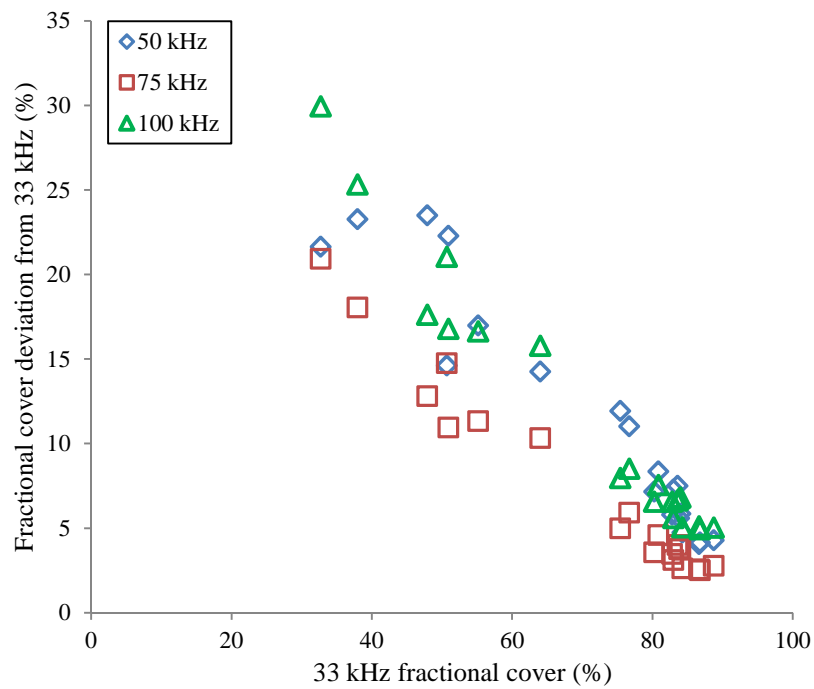Figure 4.   Percent deviation of crown closure from 33 kHz.

Figure 5.   Percent deviation of fractional cover from 33 kHz.

Crown closure can be compared to fractional cover in that crown closure considers the gaps between individual tree crowns, whereas fractional cover is an index of all canopy gaps whether inside or between tree crowns. In theory, then, fractional cover should illustrate a smaller value than crown closure for an equivalent height threshold. In this study, different height thresholds were used (1.5 for fractional cover and 5 m for crown closure) for practical reasons, so the results are not directly comparable. Nonetheless, crown closure does illustrate a slightly higher cover at both 33 kHz (80% as opposed to 71%) and 70 kHz (81% as opposed to 78%). However

differences between crown closure and fractional cover at 50 kHz and 100 kHz are not significant. These observations suggest that fractional cover results are less systematically influenced by changes in PRF (and sampling density) than crown closure derived from thresholded CHMs.

4. Conclusion

The results of this study show that LiDAR-derivative raster canopy attributes are not stable with PRF. Higher canopy elements (such as tree tops) are more frequently sampled at higher PRF due to the increased sampling density, which also causes an upward shift of the CHM. This is important to verify because it is also known that increased PRF coincides with reduced pulse power and weaker detection capability within and below the canopy (Hopkinson, 2007). Average differences in mean canopy height per plot between 33 kHz and 50 kHz, 70 kHz, and 100 kHz are 0.40 m, 0.49 m, and 0.62 m, respectively, and for max plot-level heights are 0.05 m, 0.12 m and 0.19 m, respectively. Differences in the distribution of laser returns through the canopy also affect canopy fractional cover, whereby higher PRFs display some tendency to lead to higher fractional cover estimates by up to 11% on average compared with lower PRFs (e.g. 33 kHz). It is speculated that this increase in the simple ratio fractional cover is more associated with reduced return representation at ground level than it is due to increased detection within the canopy (e.g. Hopkinson, 2007).

Vertical shifts in laser returns throughout the canopy combined with variable sampling coverage of the outer canopy surface caused by varying PRF will result in significant systematic differences in gridded canopy height and CHM thresholded crown closure but equally significant but less systematic differences in canopy fractional cover. Therefore, we conclude that LiDAR derived raster canopy attributes are not stable with PRF and such settings must be considered and accounted for when conducting multi-temporal change detection or site to site comparison studies. Furthermore, these settings should be accounted for (or error margins calculated) if developing and applying LiDAR-based models of vegetation structure, growth or biomass across many different datasets.

Acknowledgements

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