

MODELLING CANOPY GAP FRACTION FROM LIDAR INTENSITY

C. Hopkinson^a and L.E. Chasmer^{ab}

^a Applied Geomatics Research Group, NSCC Annapolis Valley Campus, Lawrencetown, NS, B0S 1P0, CANADA

^b Department of Geography, Queen's University, Kingston, ON, K7L 3M6, CANADA

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ABSTRACT:

We reconstruct the vertical pulse power distribution returned from a commercial small footprint discrete pulse airborne laser terrain mapper within a mixed forest landscape. By modifying a Beer-Lambert approach, we relate the ratio of ground return power / total return power to the canopy gap fraction (P) as derived from digital hemispherical photography (DHP). The results are compared to the commonly cited and utilised ground-to-total returns ratio. Canopy gap fraction data were collected on five separate occasions from April to October of 2006, and analysed using standard DHP procedures. Five airborne lidar datasets were collected during dry conditions coincident with DHP, and all acquisitions were performed using the same sensor and survey configuration. It is found that for the mixed wood environment studied, a lidar intensity-based power distribution ratio provides a higher correlation with DHP gap fraction ($r^2 = 0.92$) than does the often used ground-to-total return ratio approach ($r^2 = 0.86$). Moreover, if the intensity power distribution ratio is modified to account for secondary return two-way pulse transmission losses within the canopy, the model requires no calibration and provides a 1:1 estimate of the overhead (solar zenith) gap fraction.

1. INTRODUCTION

1.1 Rationale

The premise of the study is that the interaction between forest canopy and laser pulses emitted from an airborne lidar (light detection and ranging) mapping system can be considered in some ways analogous to the interaction of direct beam solar radiation with canopy covered environments. We examine the reconstructed vertical pulse power distribution returned from a commercial small footprint discrete pulse airborne laser scanning system and relate properties of the distribution to canopy structural and radiative transfer characteristics. In particular, we compare published gap fraction (P) and plant area index (L_v) algorithms and compare these to new algorithms that utilize the return intensity information. From the algorithms tested we develop a non-parameterized physical model to map the spatiotemporal variation in canopy gap fraction for a mixed forest landscape.

1.2 Gap Fraction, Transmissivity and Leaf Area Index

Leaf area index (LAI) is defined as one half the total leaf area per unit ground surface area ($m^2 m^{-2}$) (Chen *et al.* 2006) and is an important parameter for understanding variability in energy, water and carbon fluxes within an ecosystem. LAI and canopy transmittance (T) are key input parameters in many ecological and hydrological models as they enable the prediction of energy transmission through the canopy to lower layers of biomass or to ground level (e.g. Pomeroy and Dion, 1996). This information is essential in growth (e.g. photosynthesis) and hydrological (e.g. melt and evaporation) process modeling in forested environments. Accurate and consistent LAI measurements are often labour intensive and may also be difficult to collect in remote or difficult to access areas.

FIPAR or the fraction of incoming photosynthetically active radiation absorbed by the canopy can be calculated based on the downwelling PAR at the top of the canopy, and downwelling PAR below the canopy (Gower *et al.* 1999). Chen (1996) states that downwelling PAR above the canopy does not tend to vary spatially during clear conditions, however, downwelling PAR below the canopy varies significantly both in space and time. The ratio of downwelling PAR below the canopy to downwelling PAR above the canopy is closely related to the canopy gap fraction (Gower *et al.* 1999). LAI can be estimated from the canopy transmittance Beer-Lambert's Law (from Gower *et al.* 1999; Leblanc *et al.* 2005):

$$P(\theta) = e^{-k(\theta)O(\theta)LAI / \cos(\theta)} \quad (1)$$

Where $P(\theta)$ is gap fraction along zenith angle (θ), $k(\theta)$ is the extinction coefficient (fraction of foliage area projected onto a perpendicular plane), and $O(\theta)$ is the clumping or non-randomness index (Gower *et al.* 1999; Leblanc *et al.* 2005). Gap fraction can also be difficult to estimate using hemispherical photography and radiation sensors (e.g. Licor LAI-2000) due to photograph over-exposure and variable light conditions.

1.3 Lidar estimates of P and LAI

Numerous studies have examined the use of lidar for obtaining gap fraction (P), leaf area index (LAI), the fraction of incoming photosynthetically active radiation absorbed by the canopy (FIPAR) and extinction coefficients (k) from lidar (e.g. Magnussen and Boudewyn, 1998; Parker *et al.* 2001; Todd *et al.* 2003; Morsdorf *et al.* 2006; Thomas *et al.* 2006).

For every emitted laser pulse, there can be several reflecting surfaces along the travel path. Those backscatter elements that are strong enough to register a sufficiently large energy spike at the sensor are known as 'returns'. For a discrete pulse return system such as the airborne laser terrain mapper (ALTM, Optech Inc., Toronto, Canada), the recorded ranges can be separated into single, first, intermediate and last returns. Single returns are those for which there is only one dominant backscattering surface encountered (e.g. a highway surface). For the ALTM, it is possible to also record two intermediate returns making a total of four possible returns from a single emitted pulse. While there is some slight loss of detection capability between adjacent returns (known as "dead time"), this multiple return capability means that there is a reasonable probability of sampling the dominant canopy and ground elements along the pulse travel path.

Laser pulses that are returned from within the canopy have intercepted enough foliage or branch material to be recorded by the receiving optics within the lidar system, while some of the remaining laser pulse energy continues until it intercepts lower canopy vegetation, the low-lying understory and the ground surface. Laser pulse returns from the ground surface have inevitably passed through canopy gaps both into and out of the canopy. Increasing numbers of gaps within the canopy will result in gap fractions approaching 100%, whereas fewer gaps within the canopy will result in a gap fraction closer to zero. Lidar estimates of canopy P and LAI are often based on the assumption that gap fraction is equivalent to canopy transmittance (T) and from Beer-Lambert's Law:

$$P = T = \frac{I_l}{I_o} = e^{-kLAI} \quad (2)$$

Where I_o is open sky light intensity above canopy, I_l is the light intensity after travelling a path length (l) through the canopy and k is the extinction coefficient, which can be approximated to a value of 0.5 in a canopy of spherical leaf distribution (Martens *et al.* 1993) but generally varies between about 0.25 and 0.75 for natural needle- and broad-leaf canopies (Jarvis and Leverenz, 1983). The main geometric difference between the canopy interaction of solar and airborne lidar laser pulse radiation is that solar radiation is incident at all zenith angles while laser pulses are typically incident only at overhead ($\theta = 0$ to 30 degrees) angles. Therefore, any direct lidar estimate of P will be for approximately overhead gap fraction only and for a path length close to the height of the canopy. However, by assuming randomly dispersed foliage elements, an isotropic canopy radiation environment (i.e. equal transmittance in all directions) and ignoring the division of woody and leafy foliage, it is possible to derive a first approximation of LAI as a function of the overhead gap fraction:

$$LAI = -\frac{\ln(P)}{k} \quad (3)$$

Several studies have used this or a similar approach to estimate P and LAI from lidar data. In particular, Solberg *et al.* (2006) used this approach and assumed that P could be approximated by the ratio of below canopy returns to total returns. A similar but simpler approach was taken by Barilotti *et al.* (2006) where the same ratio was found to linearly correlate with LAI. The assumptions of the two previous studies were corroborated by Riaño *et al.* (2004) and Morsdorf *et al.* (2006) where the ratio of lidar canopy returns to all returns was found to be a

reasonable indicator of the inverse of gap fraction; i.e. fractional canopy cover. Morsdorf *et al.* (2006) compared canopy lidar fractional cover estimates with field-based DHP fractional cover and found the best correlation was returned when using first return data only ($r^2 = 0.73$). A method for estimating LAI that utilised laser profiling techniques was presented by Kusakabe *et al.* (2000), where field plot data were compared to the cross-sectional area contained within the lidar surface profile across the plots. The rationale underlying this approach was that LAI would increase with tree height and stem density, and both of these physical attributes would act to increase the cross sectional area of a lidar profile across a plot.

Common to the studies mentioned is that they all used laser pulse return height attributes but not the intensity. Intensity has implicitly been used in estimates of canopy gap fraction in the full waveform lidar literature where the strength of the returned signal from within or below the canopy is considered to be directly related to the transmissivity of the canopy. For example, in Lefsky *et al.* (1999), it was suggested that canopy fractional cover can be estimated as a function of the ratio of the power reflected from the ground surface divided by the total returned power of the entire waveform. It was further suggested that this power ratio needed to be adjusted as a function of different reflectance properties at ground and canopy level.

For airborne laser pulses encountering and returning from a forested canopy at near-nadir scan angles, we cannot observe the incident pulse intensity as it enters the canopy; neither can we measure the transmitted intensity after it has passed through the canopy. However, by considering the total reflected energy from the canopy to ground profile as being some proportion of the total available laser pulse intensity, and the reflected energy from ground level as a similar proportion of the transmitted pulse energy, we have a means of estimating total canopy transmissivity at near-nadir angles. Further we can assume that atmospheric transmission losses for all outgoing and returning laser pulses are similar and small in magnitude relative to canopy losses. By building on the work of Lefsky *et al.* (1999), Parker *et al.* (2001) and adapting equation (2), a general pulse return power relationship can be described for gap fraction by:

$$P = f \frac{\sum I_b}{\sum I_t} \quad (4)$$

Where $\sum I_b$ is below canopy power (the sum of all ground return intensity) and $\sum I_t$ is the total power (sum of all intensity) for the entire canopy to ground profile. However, this model does not explicitly account for potentially different probabilities associated with receiving a return signal from the ground or canopy level; i.e. the ground and lower level canopy return signals might incur two-way transmission losses due to travelling both into and out of the canopy, while those return signals at the outer envelope of the canopy do not incur any canopy transmission losses. For discrete return data, it is fair to assume that first and single returns generally have not incurred appreciable transmission losses prior to being reflected back towards the sensor. However, intermediate or last returns are, by definition, a reflected component of the residual energy left over after a previous return was reflected from a surface encountered earlier in the travel path of the emitted pulse. From Beer-Lambert's Law and assuming uniform transmission losses per unit path length travelled, it can be assumed that a below canopy (ground level) return incurs a similar proportion of transmission loss during its exit from the canopy as it did on the

way into the canopy. This leads to a variation of equation (4) such that for secondary returns within or below the canopy:

$$P = f \sqrt{\frac{\sum I_b}{\sum I_t}} \quad (5)$$

The analysis presented in this paper builds on previous research in a number of ways: 1) to sample a range of canopy LAI and light conditions, data are collected from multiple sites across an entire growing season; 2) the previously published discrete return ratio method of computing gap fraction is compared to plot-level field DHP data; and 3) new discrete return gap fraction methods are developed and tested based on equations (4) and (5) utilizing the pulse intensity information as an indicator of transmission losses within the canopy.

2. STUDY AREA

The study was conducted over a flat to rolling valley site (< 50 m total elevation variation) near Nictaux in the Acadian forest ecozone of Nova Scotia. The study area was less than 1 km wide by approximately 2 km long and comprised a number of common land cover types for this region: predominantly Acadian mixed woodland (mostly yellow birch - *Betula alleghaniensis* Britton, with some mixed pine - *Pinus* and mixed spruce - *Picea* trees). The site is the subject of ongoing lidar and agro-forestry experiments, for which supplemental ground control, plot mensuration and DHP data exist (e.g. Hopkinson *et al.* 2006).

3. METHODS

3.1 DHP data collection and analysis

Canopy gap fraction data were collected and analysed using the DHP procedures outlined in Leblanc, *et al.* (2005). DHP data collection took place on five separate occasions: April 8th, May 12th, May 28th, August 18th and October 8th. The first collection was during early spring leaf off conditions, while the second was at the commencement of leaf flush. The May 28th dataset was at intermediate seasonal leaf area levels, while August 18th was close to maximum leaf area. The final dataset was collected during the autumn senescence and leaf drop period. These five datasets, therefore, represented the full seasonal growth cycle, capturing variable leaf area and transmittance conditions.

Six Acadian mixed wood plots were established and the centre of each located using Leica SR530 global positioning system (GPS) receivers differentially corrected to the same base coordinate that was used for the airborne lidar survey. (In total we set up nine plots but the data for plots 5, 6 and 7 were not collected). Each of the six plots contained five photograph stations: one at the plot centre and one at an 11.3 m radius out from the centre at each of the four cardinal compass directions. Each station (30 in total) was marked with a stake to allow each location to be revisited. The camera was always set up level at 1.3 m above ground level to ensure consistent data collection. In total, 150 individual photographs were collected during the growing season of 2006.

All photographs were collected late in the evening on each day, immediately prior to dusk, to minimize direct sunlight and ensure even background sky illumination conditions. Photographs were collected using a Nikon Coolpix E8800 camera with a 180° fisheye (FC-E9) lens set at 8 mega pixels with an exposure setting one f stop smaller than the automatic

exposure reading to slightly under-expose the image and increase contrast between vegetation and sky. Each photograph was processed using DHP and TracWin software (S. Leblanc, Canada Centre for Remote Sensing provided to L. Chasmer through the Fluxnet-Canada Research Network).

3.2 Lidar data collection and preparation

The lidar sensor used was an Optech Incorporated (Toronto, Ontario) airborne laser terrain mapper (ALTM) 3100 owned by the Applied Geomatics Research Group (AGRG) operating at a wavelength of 1064 nm. All data were collected and processed by the authors. Five datasets were collected in 2006 coincident (within two days) of the DHP field data collections. All airborne lidar acquisitions were collected during dry conditions and using the same sensor and platform configuration. The surveys were flown at 1000 m a.g.l., 70 kHz pulse repetition frequency, peak pulse power of 7.2 kW, 0.3 mrad beam divergence (1/e) producing a footprint diameter on the ground of approximately 0.3 m, ±15 degree from nadir scan angle (30 degree field of view), 50% swath overlap with roll compensation to keep survey swaths uniform. These settings provided a sampling density of approximately 3 points per m² and ensured that every point on the ground was observed from two directions at a mean viewing angle of 7.5 degrees.

The airborne GPS trajectories were differentially corrected to the AGRG GPS base station receiver less than 5 km from the centre of the survey site. Raw lidar ranges and scan angles were integrated with aircraft trajectory and orientation data using *PosPAC* (Applanix, Toronto) and *REALM* (Optech, Toronto) software tools. The outputs from these procedures were a series of flight line data files containing las binary xyz (easting, northing, elevation, intensity) information for each laser pulse return collected.

Following lidar point position computation, the xyz data files were imported into the *Terrascan* (Terrasolid, Finland) software package for plot subsetting and to separate canopy and below canopy returns. The data acquired for the leaf-off April 8th data collection were classified using the Terrascan morphological ground classification filter to provide a digital elevation model (DEM) to which all datasets could be normalised. After normalization, all elevations for all datasets were relative to the same ground level datum; i.e. possessed heights ranging from 0 m to approximately 25 m. This allowed all returns to be divided into canopy and below canopy returns using a height threshold of 1.3 m to coincide with the height of the DHP field data.

For each of the 30 DHP stations, all laser pulse return data were extracted within a circular radius of 11.3 m. This radius was chosen as it was: a) consistent with field mensuration practices; b) was the distance between adjacent photo stations and thus provided complete plot lidar coverage; and c) was close to the optimal radius of approximately 15 m observed in Mosdorf *et al.* (2006). In addition to the canopy and below canopy classes, the return data were further subdivided into four sub-classes related to the nature of the return itself; i.e. single, first, intermediate and last returns. For the canopy class, it is possible for a return to belong to any one of the four sub classes (provided the canopy is deep enough), however, ground returns can only belong to either the last or single return sub class. This subdivision was carried out as the return number and its position in the sequence indicates whether or not the pulse has been split and incurred any energy transmission losses on its way into and out of the canopy.

3.3 Lidar gap fraction analysis

For this analysis, gap fraction was estimated from the extracted photo station and plot-level lidar data using three methods. These lidar estimates of gap fraction were then compared with the photo and plot-level DHP estimates calculated from both the single overhead annulus ring (0 - 10 degrees) and nine ring hemispherical (0 - 80 degree) data. The first was using the ratio of ground level (below canopy) returns to total returns and was known as the pulse return ratio method (P_{pr}). This method is similar to that of Solberg *et al.* (2006) and has parallels to the fractional cover methods presented by Riaño *et al.* (2004) and Morsdorf *et al.* (2006). Further, laser pulse return power ratio methods were generated using return intensity data. Two variations were tested: 1) The simple pulse intensity power ratio is based on equation (4) with no modification; i.e. Gap fraction (P_{ipr}) is estimated as the ratio of the sum of all ground level return intensities divided by the sum of total return intensity; 2) The square root power ratio (P_{sqr}) is modified from equation (5) to account for the likelihood of two-way transmission losses for intermediate or last returns as follows:

$$P_{sqr} = \frac{\left(\frac{\sum I_{GroundSingle}}{\sum I_{Total}} \right) + \sqrt{\frac{\sum I_{GroundLast}}{\sum I_{Total}}}}{\left(\frac{\sum I_{First} + \sum I_{Single}}{\sum I_{Total}} \right) + \sqrt{\frac{\sum I_{Intermediate} + \sum I_{Last}}{\sum I_{Total}}}} \quad (6)$$

Where each subscript refers to the class and/or sub-class of pulse return. In this model, first and single returns incur no reverse transmission loss through canopy and so are not square rooted, while intermediate and last returns should lose similar proportions of energy due to interception on both incoming and outgoing transmission; i.e. a power function loss. It is possible that differences in ground and canopy reflectance could influence these results. However, an adjustment of equation (6) based on reflectance is not presented here, as ground level vegetation, canopy level woody material and spatio-temporal variations in both make most assumptions about systematic reflectance variations invalid.

4. RESULTS

The seasonal variation in DHP gap fraction (P_{DHP}) is clearly visible in Figure 1. The mean overhead (0 to 10 degrees zenith) and hemispherical (0 to 80 degrees zenith) P_{DHP} statistics, lidar ground-to-total return ratio (P_{pr}), the simple intensity power ratio (P_{ipr}) and the square root intensity power ratio (P_{sqr}), along with the coefficients of determination (r^2) are presented in Table 1. All results illustrate high correlations suggesting that any one of these methods can be used to estimate gap fraction (or fractional cover). While there are high correlations for all three lidar gap fraction methods, we see that the best correlation for both the 80 and 10 degree P_{DHP} results, however, is using the simple intensity power distribution ratio.

	Summary		r^2	
	Mean	SD	P_{DHP} 10 deg	P_{DHP} 80 deg
P_{DHP} (10 degree)	0.46	0.24		
P_{DHP} (80 degree)	0.36	0.17	0.92	
Ground return ratio (P_{pr})	0.62	0.18	0.81	0.86
Intensity power ratio (P_{ipr})	0.43	0.31	0.89	0.92
Square root Power ratio (P_{sqr})	0.46	0.25	0.86	0.92

Table 1. Gap fraction summary statistics (n = 150)

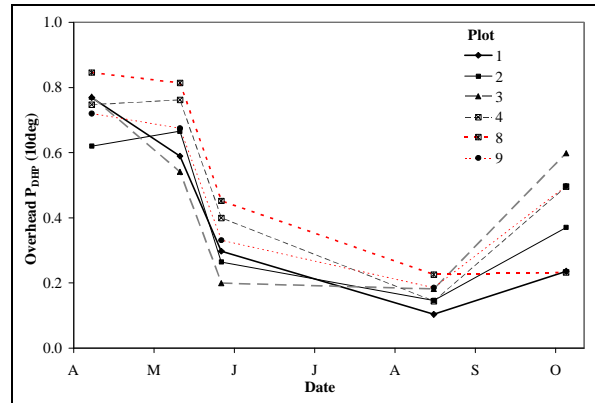


Figure 1. Plot-level seasonal DHP overhead gap fraction.

The r^2 values for the DHP 9 ring (0 to 80 degree) hemispheric gap fraction results are higher than those for the single overhead annulus ring (0 to 10 degree) due to the larger area sampled and subsequent increased stability in the data (Table 1). For the overhead DHP gap fraction, the small field of view (radius of ~ 3.5 m at a canopy height of 20 m), leads to an increased likelihood of localised variations in canopy gaps that are not representative of the overall canopy conditions. Regarding the absolute magnitude of P , we see that the intensity-based methods produce values (0.43 and 0.46 for P_{ipr} and P_{sqr} , respectively) that are within 6% of the overhead DHP value (0.46), while the pulse return ratio value (0.62) is over-estimated by 35%. In fact, the square root intensity-based method (P_{sqr}) provided the closest estimate both in magnitude and in variance (expressed as the standard deviation), despite a negligibly lower explanation of the variance ($r^2 = 0.86$) than for P_{ipr} ($r^2 = 0.89$).

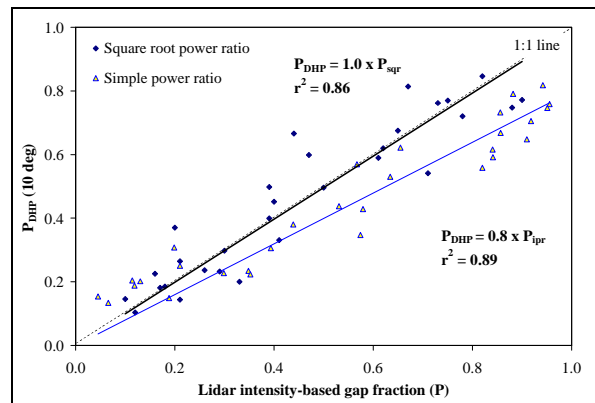


Figure 2. DHP overhead gap fraction (P_{DHP}) with lidar intensity power ratio (P_{ipr} and P_{sqr})

The high correlation and close match in absolute values is further illustrated in Figure 2, where we clearly see a 1:1 relationship between P_{DHP} and P_{sqr} . This result suggests that by applying a two-way Beer-Lambert Law transmission loss to the intermediate and last return intensity values, we are more accurately recreating the laser pulse power distribution. These results also demonstrate that by including the intensity data, we achieve both a better correlation with, and more accurate estimates of, canopy gap fraction. Of most significance here is that the lidar intensity based estimate of gap fraction appears to require no calibration.

5. CONCLUSION

While lidar ground-to-total return ratios have been demonstrated in the published literature to show strong correlation to canopy gap fraction and fractional coverage, it is shown here that for the mixed wood environment studied, the model can be improved slightly (r^2 increase from 0.86 to 0.92) by considering the lidar power distribution ratio as reconstructed from the laser pulse intensity data. Moreover, if the intensity power distribution is modified to account for secondary return two-way pulse transmission losses within the canopy, the resultant gap fraction model requires no calibration and provides a 1:1 direct estimate of overhead gap fraction. This is an improvement over the ground-to-total pulse return ratio where it was found that despite a good correlation with DHP gap fraction, the actual value predicted was over-estimated by approximately 35%. The implications of these observations are that: a) canopy transmissivity in overhead zenith directions can be directly quantified from lidar data without the need for ground calibration; and b) if the canopy extinction coefficient is *a priori* known or can be estimated from look up tables, the plant area index can also be mapped. If canopy clumping, woody-to-total and needle-to-shoot ratios are known, then such estimates of plant area index can be converted to leaf area index.

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