

Wetland grass to plantation forest - estimating vegetation height from the standard deviation of lidar frequency distributions

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Abstract:

A vegetation height study was carried out using nine airborne scanning lidar (light detection and ranging) datasets collected over 12 different vegetation types ranging in average height from < 1 m to 24 m at four different sites across Canada between 2000 and 2002. The study tests the hypothesis that average vegetation canopy surface height (Ht) is related to the standard deviation of the topographically detrended vertical sample distribution of all first and last laser pulses (L_{SD}) across a wide variety of vegetation types and heights, and lidar survey configurations. After regressing Ht against L_{SD} for 68 plots and transects, it was found that Ht could be predicted as a simple multiplication (M) of L_{SD} ($M = 2.5$, $r^2 = 0.95$, $RMSE = 1.8$ m, $p < 0.01$). For forest plots only, L_{SD} was found to predict average tree height ($r^2 = 0.86$, $RMSE = 2.0$ m) better than Lorey's height ($r^2 = 0.57$, $RMSE = 3.0$ m). A test of the average height model was performed using stand heights (H_{tFRI}) from an independent forest resource inventory (FRI) for a variety of forest classes. Results from the raw FRI and modeled stand height comparison displayed close to a 1:1 relationship ($H_{tFRI} = 1.05 H_{tLSD}$, $r^2 = 0.41$, $RMSE = 4.5$ m, $p < 0.01$, $n = 297$) but displayed heteroscedacity due to an uneven sample height distribution. After thinning the data to improve the distribution, the regression results improved ($H_{tFRI} = 0.97 H_{tLSD}$, $r^2 = 0.73$, $RMSE = 4.7$ m, $p < 0.01$, $n = 38$). The advantage of using a multiplier of L_{SD} to estimate average vegetation height is thought to be: a) its simple calculation; and b) its applicability to a range of vegetation species and height classes, and survey configurations.

1. INTRODUCTION

Airborne lidar (light detection and ranging) combines: (i) knowledge of the speed of light; (ii) the location of the laser head in space; and (iii) the time from laser pulse transmission to reception to determine three-dimensional co-ordinates over objects at or near the Earth's surface. Utilising scanning technology, laser pulses are swept left and right, perpendicular to the line of flight resulting in a "saw tooth" pattern of points beneath the aircraft. The resultant data can be used to create high-resolution digital elevation models (DEMs) of the ground or vegetation canopy. Current technology can collect multiple returns at pulse repetition frequencies (PRF) of up to 100 kHz, and can cover a ground swath greater than 3000 m depending on flying altitude and scan angle. The resultant laser pulse positional accuracy is typically at the decimetre level. For more information see Baltsavias (1999) and Wehr and Lohr (1999).

Many studies using small footprint discrete return airborne scanning lidar data have demonstrated strong empirical relationships between laser pulse metrics and vegetation height. Although much recent research has focused on individual tree height estimation (e.g. St Onge et al. 2000), most attention has been on comparing plot-level tree heights with some laser pulse derived height metric. For example, Næsset (1997) found that for conifer stands ranging in height from 8 m to 24 m, maximum laser pulse heights above the ground level correlated well with Lorey's mean tree height over a given area. Magnussen and Boudewyn (1998) expanded upon this work by investigating a canopy laser return quantile-based approach for estimating height for conifer plots ranging in height from 15 m to 27 m. Similar laser metrics were tested for the estimation of height and other biometric properties of tolerant hardwood plots of varying treatment and ranging in height from 10 m to 30 m (Lim et al. 2003a). A unique aspect of this study was the evaluation of laser intensity as a potential indicator of biometric properties. Common to these and many other studies is: a) the tendency to focus on forest vegetation with canopy heights several metres above the ground, and b) the derivation of laser height metrics from canopy returns only, with ground level returns typically used only for digital terrain model (DTM) generation. For a summary of research into tree height estimation from lidar data, the reader is referred to Lim et al. (2003b).

Few studies have investigated the estimation of short (near ground surface) vegetation height from small footprint discrete return scanning lidar. The work of Davenport et al. (2000) and Cobby et al. (2001) demonstrated that crop vegetation up to approximately 1.2 m in height could be predicted from the standard deviation of topographically detrended laser pulse returns. Contrary to most studies focusing on forest canopy height estimation, the analysis presented in these studies utilised all laser pulse returns rather than just those identified as having returned from above the ground surface (Raber et al. 2002 provide an overview of laser pulse separation into ground and vegetation classes). The study presented here expands upon previous research by investigating the relationship between the detrended vertical standard deviation of all laser returns (canopy and ground) and average canopy height across a range of vegetation species and heights.

It is common knowledge that for a normally distributed sample the range in the data can be approximated by a multiplier (M) of the standard deviation (σ) (at the 95% and 99% confidence levels $M = 4\sigma$ and 6σ , respectively). If we rotate our hypothetical normal distribution 90 degrees and consider the sample range to be analogous to a canopy height level above the ground, then we have some basis for attempting to relate the standard deviation to the canopy surface height. However, vertical laser pulse data within the vegetation canopy are not usually normally distributed. For forest vegetation, the first pulse canopy distributions tend to be skewed towards the upper canopy surface, and near ground last pulse returns skewed towards the actual ground surface often resulting in a bimodal distribution. Short vegetation, however, tends not to display a bimodal distribution (e.g. Hopkinson et al. in press), and this can be attributed to: a) more homogeneous vegetation structure from ground to canopy surface (Cobby et al. 2001); b) limitations in older generation lidar sensors preventing first and last pulse separation for ranges below ~ 4 m (Optech Inc. personal communication, 2003). In bimodal or skewed unimodal cases the sample points are not tightly clustered around the mean and so it is to be expected that the sample σ would be greater than for a normal distribution displaying the same range, and therefore M should be lower.

were circular, covered an area of 400 m², and were georeferenced using GPS to within 5 m. Tree heights for all stems with a diameter at breast height (DBH) > 9 cm were measured using a Vertex sonic clinometer (Haglof, Madison, Miss.) with an approximate measurement error of up to 1 m for some deciduous trees (Lim et al., 2001).

The airborne lidar data collection was carried out in late August 2000 using an ALTM 1225. The survey and sensor configuration are described in detail in Lim et al. (2003a) and a summary is provided in Table 1.

2.2 York Regional Forest (YRF)

Two plots were set up within the North Tract of the YRF area: one a tolerant hardwood (SGL – TH) plot comprised mainly of sugar maple (*Acer saccharum* Marsh) and bitternut hickory (*Carya cordiformis* Wangeh.), similar in character to the NGL – TH plots with no treatment. The second plot was within a mature red pine (*Pinus resinosa* Ait.) plantation (SGL – RP) with uniform upper canopy and no understory. These plots represent end member species in the southern Ontario Great Lakes forest ecozone. The associated data collections are discussed in more detail in Hopkinson, Chasmer et al. (2004), and Lim and Hopkinson (submitted). Field data collection was undertaken in September 2000 and July 2002. The plot sizes were 35 m x 35 m (1225 m²) and the mensuration procedures followed those noted for the NGL plots. In addition, the regional GIS-based forest resource inventory (FRI) for the entire North Tract was provided by Silv-Econ Ltd (Newmarket, Ont.) for the purpose of an independent test of any canopy height models derived from the laser pulse data. The regional FRI was compiled prior to 2000, with stand boundaries delineated by the Ontario Ministry of Natural Resources from aerial photography collected in 1999. Average height was measured using a Suunto optical clinometer from a small selection of trees that were assumed to be representative of each stand. Growth corrections could not be applied to the FRI height data, as the exact dates of measurement for the small selection of stands investigated were not known. It is possible, therefore, that the FRI stand height estimates could be systematically slightly smaller than actual stand heights at the time of the study.

Lidar data collection was carried out five times between September 2000 and July 2002 using various ALTM sensors and survey configurations (Table 1). The tolerant hardwood plot was used in the analysis only for the two summertime leaf-on surveys but the pine plantation plot was kept in the analysis throughout due to expected minimal changes in canopy surface conditions. See Hopkinson, Sitar et al. (2004) for a detailed description of the first two lidar surveys over the YRF.

2.3 Canadian Rockies

Nine plots were set up at 200 m intervals either side of the Icefields Parkway between Banff and Jasper, on steep mountain slopes during early August 2002. The plots traversed an elevational gradient from 1700 m a.s.l. to 2000 m a.s.l. within the montane zone. The plots (RM – PF) were dominated by mature douglas fir (*Pseudotsuga menziesii* Mirb.), subalpine fir (*Abies lasiocarpa* Hook.) and lodgepole pine (*Pinus contorta* Dougl.). The canopies tended to be more open and irregular than those already noted. Mensuration followed the same procedures outlined above and the plots were 20 m x 20 m (400 m²).

The lidar data collection was carried out the week after field mensuration using an ALTM 2050. The general study area and a description of a previous lidar campaign in the area are discussed in Hopkinson et al. (2001). Due to the mountainous nature of the study site, the survey altitude and laser pulse density over the plots varied (see Table 1).

2.3 Utikuma Lake

Utikuma Lake was the only survey site where both short and tall vegetation categories were measured in the field. Four 15 m x 15 m (225 m²) plots each of trembling aspen (*Populus tremuloides* Michx.) (WB – AS) and black spruce (*Picea mariana* Mill.) (WB – BS) were sampled to represent end member species of deciduous and conifer forest within the western boreal forest ecozone. Mensuration of the aspen plots followed the same methods as above. However, applying a > 9 cm DBH rationale to the measurement of tree height in the black spruce plots was impractical, as a high proportion of stems could have a DBH < 9 cm and still comprise a significant part of the canopy surface. Therefore, all stems above 2 m in height were measured, to ensure that all major canopy elements were included in the samples (Hopkinson et al. in press).

Short vegetation heights were measured at intervals of 0.5 m to 2 m along transects of 30 m to 65 m in length. Height of the mean maximum vegetation surface (canopy height) within 0.5 m of every GPS surveyed transect point was visually discerned and measured with a measuring staff (approximate measurement error up to 0.1 m). Vegetation along the transects was classified according to the Duck's Unlimited (2002) land cover classification scheme into aquatic vegetation (WB - AQ), grass and herbs (WB - GH), low shrubs (WB - LS) and tall shrubs. Willow shrub (WB - WS) vegetation (Genus *Salix*) was classified as tall shrub and for the transects travelled, the heights tended to be above 4 m and has therefore been categorised as tall vegetation. Willow canopy surface heights were estimated by extending the survey staff into the canopy (measurement error up to 0.3 m). Given the small area coverage (< 1 m²) of each individual transect canopy height measurement, all height measures were combined and averaged per transect. For the three short vegetation classes (AQ, LS and GH) none of the height measurements exceeded 2 m and so unfortunately no data in the 2 m to 4 m height range were available for this study. The field data collection is discussed in detail in Hopkinson et al. (in press).

An ALTM 2050 lidar survey was carried out coincident to the field data collection in late August 2002. The study area was surveyed with 50% side lap from flight line to flight line, effectively providing 200% data coverage and a very dense laser pulse distribution on the ground of up to five pulse per m² (see Hopkinson et al. in press).

3. ANALYSIS

Airborne GPS trajectory, ground GPS base station, on-board inertial reference system, scan angle and raw laser range data were combined within the Optech *REALM* software to generate UTM co-ordinates for every first and last laser pulse collected over the study areas. The service providers classified the last pulse returns into ground and vegetation using proprietary filtering techniques (e.g. Raber et al. 2002). The ground returns from all surveys were interpolated to a 1 m raster DEM of the ground beneath the vegetation canopy using an inverse distance weighted algorithm (Lloyd and Atkinson, 2002). For more discussion of the classification, DEM interpolation and error assessments of the NGL, SGL and WB lidar data, the reader is referred to Lim et al. (2003), Hopkinson, Sitar, et al. (2004), Hopkinson et al. (in press), respectively. The laser pulse data were then topographically detrended by subtracting from all laser pulse returns the corresponding heights of the interpolated ground DEM. This procedure removed the influence of topography and resulted in laser pulse heights that were now measured relative to ground height; i.e. the same reference plane as the field measured canopy height data. Some interpolation error is expected in the lidar DEMs but this is expected to be at

the cm to decimetre level (e.g. Töyrä et al. 2003; Hodgson et al. 2003), and should not bias the vertical laser pulse distributions other than by the potential introduction of a few negative height values, which will have negligible influence on the calculation of sample standard deviation.

Using the differential GPS plot and transect co-ordinates, the detrended laser pulse data corresponding to the areas covered by each field plot and transect were isolated and L_{SD} calculated. Average plot and transect canopy heights were regressed against the corresponding L_{SD} for short vegetation classes (< 2 m), tall vegetation classes (≥ 4 m) and all vegetation, to test the hypothesis [1] above. For the tall vegetation class, L_{SD} was also compared to plot-level Lorey's tree height, to be consistent with previous studies that have compared laser pulse metrics to tree heights.

A test of the height model from [1] was performed using independent FRI data from a 1.5 km x 1 km area in the centre of YRF North Tract. This area was selected, as it contained 19 stands of distinct conifer and deciduous species and height characteristics (12 of these having at least 90% of their area fully within the study area). Within the area selected there were also hay fields that had not been included in the FRI but were noted on the ground at the time of the September 2000 survey, to be up to 1 m in height. The GIS FRI height data were converted from stand-level polygons to a raster grid. Grid cells of 50 m x 50 m were chosen, as the stand boundaries are known to be off by at least 20 m in places, and this resolution provides enough grid cells per height and vegetation class for meaningful results (n = 297). This approach inevitably leads to mixed cells at stand boundaries but it was considered that a higher resolution would not improve the analysis, as it could lead to a greater number of misclassified cells. Most grid cells were located over mature forest stands, biasing the sample distribution towards high vegetation heights and therefore introducing heteroscedacity. To remove heteroscedacity, the sample data were systematically thinned to provide an even distribution of FRI heights (n = 38) and the regression analysis performed again.

4. RESULTS AND DISCUSSION

4.1 Establishing M

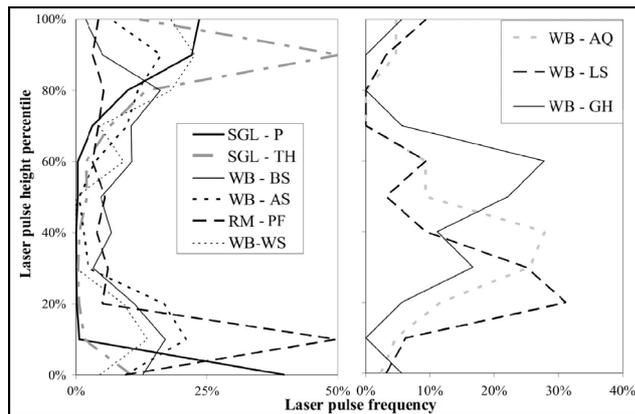


Figure 1. Vertical laser pulse distributions for each vegetation class. A) tall vegetation (≥ 4 m) with possibility of dual pulse returns; B) short vegetation (< 2 m) with only single pulse returns. (Acronyms explained in text.)

Examples of ALTM first and last laser pulse frequency distributions from canopy to ground level for each vegetation class studied is presented in Figure 1. The height and frequency axes are presented as percentiles (10% increments), to enable direct comparison of each vegetation class laser pulse distribution, regardless of height or number of pulses. For tall

vegetation classes (Figure 1A), it is apparent that the sample distributions tend to be bimodal with modes at canopy and ground level. The relative magnitude of each of these modes, will somewhat depend on canopy openness and laser pulse penetration through the canopy. Of note, however, is that one tall vegetation class, Rockies montane (RM - PF)), does not display a distinct bimodal distribution in the example provided. This is likely because there was no distinct upper canopy but rather a sparse grouping of mature trees of various heights with foliage exposed to the sky on all sides. For the short vegetation transects sampled (Figure 1B), the laser pulse distributions from ground to canopy tend to display a single strong mode with an otherwise irregular distribution. All vegetation classes display at least one major mode with a frequency ranging between 15% and 50% of all laser pulse data within the vertical distribution.

For the short vegetation transect data (Figure 2), the null hypothesis of no relationship between mean maximum canopy height and L_{SD} can be rejected at the 99% confidence level. The M factor relating L_{SD} to short vegetation canopy height is 2.7 with 77% of the variance explained by the linear regression model. This result is comparable with that of Cobby et al. (2001), in that their r^2 of 0.8 and RMSE of 0.14 m are almost identical to the findings here. However, the relationship established between Ht and L_{SD} by Cobby et al. (2001) was logarithmic, predicted Ht to be less than L_{SD} at around 4 m above the ground, and therefore has a range of application that is limited to Ht < ~ 2 m. For the results presented in Figure 2, logarithmic regression returned an r^2 of 0.70 with an RMSE greater than 0.2 m and was considered unsatisfactory compared to the linear model. A linear model was also favoured here because it has the potential to be useful for a wide range of Ht values; i.e. for both short and tall vegetation.

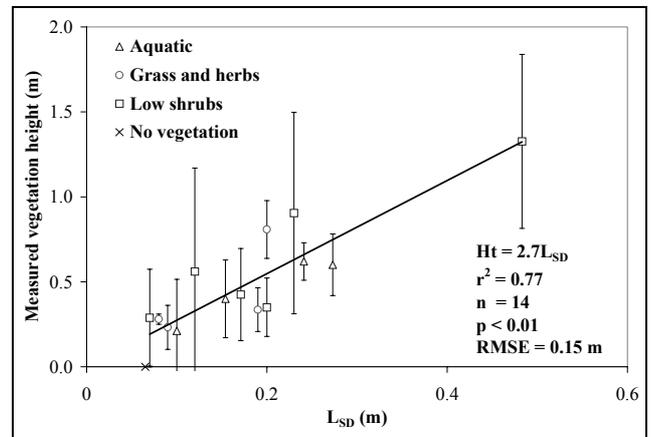


Figure 2. Mean maximum canopy heights for short vegetation classes plotted against laser pulse distribution standard deviation (L_{SD}). Error bars = standard deviation in transect height measurements.

A problem with the application of a simple linear M factor, is that for small values of L_{SD} , there will always be a positive value for Ht due to the inherent noise in the LiDAR data. From Hopkinson et al. (in press) it was found that for LiDAR data collected over flat unvegetated ground, L_{SD} was approximately 0.07 m. This would therefore lead to a minimum Ht value of ~ 0.19 m, if the M factor of 2.7 were applied to areas of very short or no vegetation. Another potential problem with the application of a simple M factor to areas of short vegetation is that L_{SD} will tend to increase in areas of steep slope, regardless of vegetation height, as a result of LiDAR positional inaccuracy (Hodgson et al. 2003). For such sloping areas it might be possible to adjust M downwards based on the angle of slope in the ground DEM. Unfortunately, the influence of slope on M was not quantified

due to the methodological necessity for flat areas to enable controlled L_{SD} and Ht measurements for the short vegetation classes. Fortunately, however, the influence of noise and slope to L_{SD} diminish as vegetation height increases, and are likely insignificant components of L_{SD} for the tall vegetation classes.

For the 54 tall vegetation plots (Figure 3), the null hypothesis of no relationship between average height and L_{SD} can be rejected at the 99% confidence level. The M factor relating L_{SD} to Ht was slightly lower (2.5) than for short vegetation (2.7) with 86% of the variance explained by the linear regression model. However, this difference in M was not statistically significant. After plotting all short and tall vegetation together, it was found that $M = 2.5$ ($r^2 = 0.95$, $n = 68$, $RMSE = 1.8$ m). It is worth noting that most of the data plot close to the regression line, with the exception of NGL - TH. If the NGL - TH data are removed from the analysis, the RMSE reduces to 1.4 m.

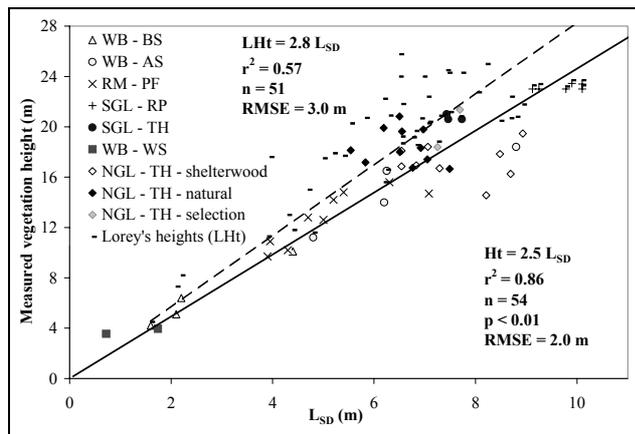


Figure 3. Plot-level average and Lorey's heights for tall (≥ 4 m) willow and forest classes plotted against the laser pulse distribution standard deviation (L_{SD}). Legend labels explained in the text.

Increased spread around the regression line in the NGL - TH data is possibly related to imprecise (relative to the other study sites) field GPS data leading to poor co-location of field and LiDAR plots. However, of note is that different TH treatments scatter either side of the regression line, with the height of natural plots underestimated and shelterwood treatments overestimated. This difference in L_{SD} height estimation could be due to: a) slightly different laser pulse distributions in each of the treatment types leading to a change in M; or b) an overestimation of the plot-level average height due to not measuring the smaller trees in the plots. Certainly, the > 9 cm DBH measurement method for the NGL plots would ignore the influence of smaller trees in the plot and result in an overestimation of average plot-level height. This problem would be minimal in natural plots where the canopy is comprised almost exclusively of mature trees, but enhanced in the shelterwood treated plots where mature trees have been removed. The possibility of a vegetation type dependent M factor must also be considered, as 11 of the 14 natural TH plot heights from both the NGL and SGL locations plot above the Ht / L_{SD} regression line (Figure 3). However, the data available for this study are insufficient to enable quantification of the subtle differences in M due to tree type and canopy structure. In this study L_{SD} has been compared to average canopy height, whereas various other studies have concentrated on the relationship between LiDAR derived metrics and plot-level Lorey's height (e.g. Naesset, 1997; Magnussen and Boudewyn, 1998). From the lower RMSE (2.0 m compared to 3.0 m) and increased explanation of the variance ($r^2 = 0.86$ compared to 0.57) in Figure 3, it appears that for the data used in this study L_{SD} is a better estimator of average rather than Lorey's height.

This is probably because L_{SD} is related to the entire vegetation column and is influenced by the ground and canopy frequency distribution modes, whereas Lorey's height is related to dominant trees in the canopy and therefore the upper tail of the laser pulse distribution.

4.1 Testing M

Grids of independent FRI Ht and L_{SD} derived Ht for the North Tract of the YRF area are illustrated in Figure 4. The most obvious difference between the two grids is that the L_{SD} heights are more spatially variable. This is to be expected, as the FRI stand polygons are colour coded to average stand height and provide no information on within stand variation, whereas the L_{SD} heights are calculated on an individual grid cell basis. There are some similarities in the two grids; namely some of the shorter vegetation polygons are clearly discernible in both, and the overall average heights are similar. However, the heights of the tallest FRI stands have been underestimated in the L_{SD} height grid. Of note is that the tallest stands are of the tolerant hardwood (TH) class, and are similar in canopy characteristics to the NGL and SGL TH plots investigated. From Figure 3, it is apparent that the TH natural plot data lie slightly above the regression line suggesting that a slightly higher M factor would be more appropriate for this class.

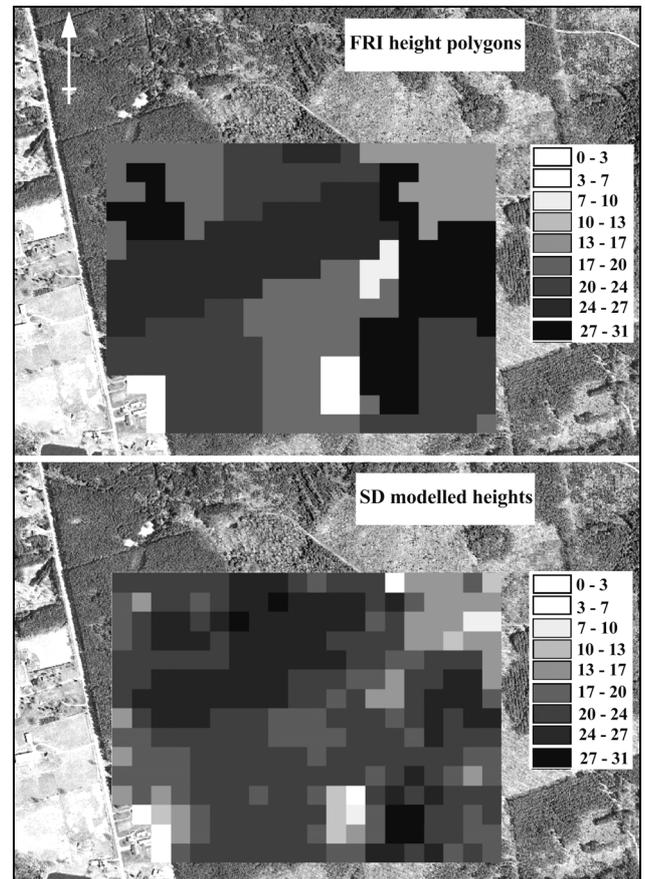


Figure 4. FRI Ht grid compared to L_{SD} Ht model grid. Grid cell average heights in m.

The almost 1:1 relationship between independent grid cell FRI data and L_{SD} modeled vegetation heights in Figure 5 suggests that the M factor of 2.5 established from the training data sets is appropriate when dealing with several different vegetation heights and classes. It can be argued that with an RMSE of 4.7 m and only a 73% explanation of the variance that this simple model is of limited value. However, it also needs to be noted that the FRI data used for this test was collected over an unknown period of time prior to the LiDAR data, was imprecisely

collected compared to the training data used, and the 50 m cell size probably introduced errors due to stand edge effects. Bearing these factors in mind, the high RMSE and intermediate r^2 are to be expected.

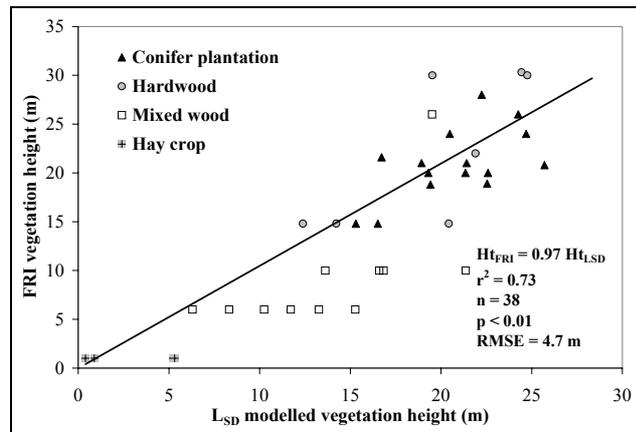


Figure 5. Vivian forest grid cell FRI / L_{SD} modeled heights for the September 2000 low altitude survey (FRI data > 14 m height thinned to remove heteroscedacity).

5. CONCLUSIONS

The analysis has demonstrated that the mean maximum vegetation height for aquatic, grass/herb and low shrub classes of short vegetation (all < 2 m in height) can be estimated using a simple multiplier (M factor) of the vertical laser pulse distribution standard deviation (L_{SD}). For tall vegetation classes (> 4 m) the average canopy height calculated from all individual stem height measurements, was also related to L_{SD} . M varied for short and tall vegetation, 2.7 and 2.5, respectively but when all data were combined M was found to be 2.5 ($r^2 = 0.95$, $n = 68$, $RMSE = 0.18$ m, $p < 0.01$). For tall vegetation, L_{SD} and Lorey's height were not well correlated. This was considered due to Lorey's height being a function of dominant canopy elements, which should be represented in the upper tail of the canopy distribution, whereas L_{SD} is sensitive to the high frequency modes within the entire distribution from canopy to ground.

Although there are various other laser pulse distribution estimators of vegetation height, L_{SD} is thought to be useful in that it is a function of the overall distribution shape from ground to canopy and, provided there is a sufficient number of laser pulses in the area of interest, is insensitive to laser pulse density. Grid based maximum laser pulse height (e.g. Naesset, 1997) or canopy quantile based (e.g. Magnussen and Boudewyn, 1998) estimators, although probably better than L_{SD} on an individual data collection basis, should theoretically vary with sample density because they are more sensitive to the upper tail of the distribution.

The average M factor of 2.5 does slightly underestimate the heights of TH species in both the training data and the model, and so there probably is some vegetation class dependence to the M factor; i.e. a larger value for M seems appropriate for vegetation with canopy characteristics similar to the TH class. However, as a robust first approximation to mapping vegetation height over large areas of varying height and class, an M factor of 2.5 provides reasonable results. The advantage of using a multiplier of L_{SD} to estimate average vegetation height is thought to be: a) its relatively simple calculation (i.e. no need to filter the data or sort into quantiles); and b) its wide application to a range of vegetation species and height classes, and survey configurations. This needs to be investigated more thoroughly by conducting a comparison of L_{SD} with other vegetation height predicting laser pulse metrics. To make the L_{SD} M factor of

practical use in vegetation height mapping applications, further study is needed to quantify the subtle variations in M for certain categories of vegetation, terrain slope and different types of lidar sensor.

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References

- Baltsavias, E.P. 1999. Airborne laser scanning: basic relations and formulas. *ISPRS J. Phot. and Rem. Sen.*, 54, pp. 199-214.
- Cobby, D.M., Mason, D.C., Davenport, I.J. 2001. Image processing of airborne scanning laser altimetry data for improved river flood modelling. *ISPRS J. Phot. and Rem. Sen.*, 56, pp. 121-138.
- Davenport, I.J., Bradbury, R.B., Anderson, G.Q.A., Hayman, G.R.F., Krebs, J.R., Mason, D.C., Wilson, J.D. and Veck, N.J. 2000. Improving bird population models using airborne remote sensing. *Int. J. Rem. Sens.*, 21, pp. 2705-2717.
- Ducks Unlimited Canada. 2002. Utikuma Lake, Alberta Earth Cover Classification User's Guide. 63pp. Ducks Unlimited Canada, Edmonton, Alberta and Ducks Unlimited, Inc., Rancho Cordova, California.
- Hodgson, M.E. and Bresnahan, P., 2004. Accuracy of Airborne Lidar-Derived Elevation: Empirical Assessment and Error Budget. *PERS*, 70, pp. 331 - 340.
- Hopkinson, C., Demuth, M.N., Sitar, M. and Chasmer, L.E., 2001. Applications of Airborne LiDAR Mapping in Glacierised Mountainous Terrain. *Proc. Intl. Geoscience and Remote Sensing Symposium*. Sydney, Australia, July 9-14, 2001.
- Hopkinson, C., Chasmer, L.E., Young-Pow, C., Treitz, P., 2004a, Assessing Plot-level Forest Metrics with a Ground-based Scanning LiDAR. *Can. J.For. Res.* 34, pp573-583
- Hopkinson, C., Sitar, M., Chasmer, L.E., Treitz, P., 2004b, Mapping Snowpack Depth Beneath Forest Canopies Using Airborne LiDAR. *PERS*, 70 (3), pp323-330
- Hopkinson, C., Chasmer, L.E., Zsigovics, G., Creed, I., Sitar, M., Kalbfleisch, W., Treitz, P., Vegetation class dependent errors in LiDAR ground elevation and canopy height estimates in a Boreal wetland environment. *Can J. Rem. Sens.* (accepted pending revisions).
- Lim, K., Treitz, P., Groot, A., St-Onge, B., 2001. Estimation of individual tree heights using LiDAR remote sensing, *Proc. of the 23rd Canadian Symposium on Remote sensing*, Sainte-Foy Quebec, 251-258.
- Lim, K., Treitz, P., Baldwin, K., Morrison, I., Green, J., 2003a. Lidar remote sensing of biophysical properties of tolerant northern hardwood forests. *Can. J. Rem. Sens.* 29, pp. 658-678.
- Lim, K., Treitz, P. Wulder, M. St-Onge, B. and Flood, M., 2003b, LiDAR Remote Sensing of Forest Structure, *Prog. Phys. Geog.* 27, pp. 88-106.
- Lim, K., Hopkinson, C., Comparing Empirical Distribution Functions of Laser Height Derived from Two Airborne Lidar Surveys of a Forest, *PERS*, (submitted)
- Lindsey, J., and Creed, I., Sensitivity of Digital Landscapes to Artifact Depressions in

- Remotely-Sensed DEMs. *Photogrammetric Engineering and Remote Sensing* (in press).
- Lloyd, C.D., and Atkinson, P.M. 2002. Deriving DSMs from LiDAR data with kriging. *Int. J. Rem Sens* 23, pp. 2519–2524.
- Magnussen, S., and Boudewyn, P. 1998. Derivations of stand heights from airborne laser scanner data with canopy-based quantile estimators. *Can. J.For. Res.* 28, pp. 1016-1031.
- Næsset, E. 1997. Determination of mean tree height of forest stands using airborne laser scanner data. *ISPRS J. Phot. and Rem. Sen.* 52, pp. 49-56.
- Raber, G.T., Jensen, J.R., Schill, S.R. and Schuckman, K. 2002. Creation of digital terrain models using an adaptive lidar vegetation point removal process. *PERS* 68, pp. 1307-1315.
- St-Onge, B., Dufort, J., and Lepage, R., 2000. Measuring tree height using scanning laser altimetry. *Proc. of the 22nd Annual Canadian Remote Sensing Symposium*, Victoria, BC, Canada. August 21 – 25, 2000.
- Töyrä, J., Pietroniro, A., Hopkinson, C. and Kalbfleisch, W. 2003. Assessment of airborne scanning laser altimetry (LiDAR) in a deltaic wetland environment. *Can. J. Rem. Sens.* 29, pp. 679-690.
- Wehr, A. and U. Lohr, 1999b. Airborne laser scanning - an introduction and overview, *ISPRS J. Phot. and Rem. Sen.* 54, pp. 68-82.