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Reprint from Journal of Forest Planning 13:279-286 (2008)
Japan Society of Forest Planning

Article

Stability of Surface LiDAR Height Estimates on a Point and Polygon Basis

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ABSTRACT

Airborne scanning LiDAR (Light Detection and Ranging) data has significant potential to update, audit, calibrate, and validate operational stand-level forest inventories by providing information on canopy height, vertical structure, and ground elevation. However, using LiDAR data as an operational data source in a sampling context requires repeatable and consistent attribute estimation (i.e. height), from data collected over several acquisition flight lines. We examined the consistency of LiDAR height estimates obtained from the Scanning LiDAR Imager of Canopies by Echo Recovery (SLICER) instrument over Jack pine (*Pinus banksiana*, var. Lamb) and black spruce (*Picea mariana*, var. Mill.) forest stands in central Saskatchewan, Canada. Two analyses were undertaken: first, estimated tree heights derived from pairs of LiDAR returns, acquired from multiple flight lines and within 9m of a single LiDAR footprint, were compared to assess the consistency of height estimates (point stability); secondly, height estimates from multiple flight lines within individual forest inventory polygons were compared to assess the consistency of within-polygon estimates of tree height (polygon stability). The point stability analysis indicated that over all forest classes estimates of height were consistent, with 94% of LiDAR returns (n = 15,896) having a pair-wise height difference within ± 5m. On a polygon basis, both between- and within-flight line standard deviations were considered. Results indicated that the within-polygon variability in estimated tree heights was captured by LiDAR data collected over any portion of a polygon. This result suggests that the inventory polygons are homogenous with regards to height (and related variability) and may be characterized with LiDAR, independent of actual flight path.

Keywords: LiDAR, forest inventory, Landsat, SLICER, BOREAS

INTRODUCTION

Both private forest companies and public forest management agencies require information collected at a range of spatial scales to facilitate short and long term planning. Strategic information is needed to plan for timber production in anticipation of market trends and needs over long time horizons. Since this type of planning is often conducted over a discrete forest management unit, it is possible to rely on information from an objective field sample (Holmgren, 2004). However, the actual allocation of forest operations across a landbase requires estimates of forest variables for each and every forest stand. Given that a full-fledged, field based forest inventory is both operationally and cost prohibitive in most jurisdictions, the ability to estimate forest stand parameters by remote methods is necessary.

For industrial forest management activities the almost universal method used to derive spatial information on forest structure and condition is through the manual interpretation of tree heights from large-scale stereo aerial photography, supported by a sample of field site visits for calibration and quality assurance. Whilst tree height is not the only, or often the primary, driver of forest inventories (often stand volume or diameter at breast height is what is required (Nelson *et al.*, 2003)), there is generally (especially in young to mature forest stands) a strong relationship between height and diameter, volume, stand density and ultimately production. Aerial photography, like most optical remotely sensed imagery, provides only a 2-dimensional representation of forests, which

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requires inference to be applied when estimating vertically distributed parameters (Wulder, 1998). Some examples of factors which affect the accuracy of height estimation in forest inventory include film emulsion, scale, focal length, time of day, shape of tree, character of shadow, character of the forest (e.g., stand density, complexity of stratification), topography, observer skill, and measurement technique (Avery and Burkhart, 2002). Alternatively, airborne scanning LiDAR (Light Detection and Ranging) data provide a 3-dimensional representation of forest structure. Laser altimetry determines the distance from a sensor to a target using a beam of light and recording the time taken for the light to travel to the target object and return. This 3-dimensional view of forest structure allows for estimates of vertically distributed elements of the forest, making LiDAR data well suited to measurement of individual trees (Næsset and Okland, 2002), tree heights (Magnussen and Boudewyn, 1998), and canopy heights (Nelson, 1997).

LiDAR systems applied to forestry applications can be categorized as either 'discrete return' or 'full waveform' systems and differ from one another with respect to how they vertically and horizontally sample a canopy's three-dimensional structure (Lim *et al.*, 2003). Discrete return systems typically allow for two (first and last) or sometimes up to five, returns to be recorded for each pulse. Conversely, a full waveform LiDAR system senses and records the amount of energy returned to the sensor at a series of equal time intervals. In either case, the sensor produces a beam which results in a circular sampling area (i.e., footprint), which increases in size with distance from the sensor. The footprint for most discrete return systems is on the order of 0.2 to 0.9 m. For the full waveform systems, the footprint size may vary from 8m to 70m (Means, 1999; Harding, 2000; Lim *et al.*, 2003). Recently, Hug *et al.* (2004) introduced the LiteMapper-500 capable of waveform digitization over a small footprint (0.4m at flying at 800m above ground level) based on the RIEGL LMS-Q560 laser scanner.

The SLICER (Scanning LiDAR Imager of Canopies by Echo recovery) instrument is an example of a full waveform LiDAR system which can be flown high and fast enabling the characterization of large areas in a short mobilization period (Blair *et al.*, 1994; Harding, 2000). The instrument is also well suited for flying transects enabling sampling and attribute extension. SLICER also provides for an intermediate scale of information (footprint 5-10m) between small-footprint discrete systems and satellite based systems such as the GLAS (Zwally *et al.*, 2002). The SLICER instrument has demonstrated capability to accurately estimate forest canopy heights in both deciduous (Lefsky *et al.*, 1999) and coniferous (Means *et al.*, 1999) dominated stands. LiDAR data has also been shown to accurately estimate biomass and other structural forest attributes, over a wide range of species and structural vegetation types, although most studies have focused on single dataset calibration (Lefsky *et al.*, 2005). More recently, LiDAR technology has gained widespread acceptance for large-scale operational mapping. Recent examples include applications in Norway (Næsset, 2004) and the US state of Delaware (Nelson *et al.*, 2003). Hudak *et al.* (2002) demonstrated an approach for extrapolation of small footprint LiDAR vertical information through the use of auxiliary image data. Wulder and Seemann (2003) used SLICER data and segmented Landsat to update a polygon based forest inventory.

The use of LiDAR data as a sampling tool raises a number of issues related to updating, calibrating, and validating standard forest inventory. To address these issues, we investigate the stability of height estimates on a per point basis comparing multiple LiDAR returns at the same location, and the agreement between multiple LiDAR flight lines through individual forest inventory polygons in a homogenous forest.

METHODS

Study Area

The data used for this analysis was established as part of the Boreal Ecosystem - Atmosphere Study (BOREAS) in central Saskatchewan, Canada (Sellers *et al.*, 1995). For the purposes of this study, a 7,500km^2 study area was defined to represent a variety of boreal forest species types and forest conditions (Fig. 1). The study area is approximately 115km (E-W) and 65 km (N-S) and is located within the Saskatchewan Plains Region of the Great Plains Province of North America. The topography of the study area is gently undulating, with elevations ranging from 400 to 700m (Sellers *et al.*, 1995).

The mixed forest in central Saskatchewan is close to the southern limit of the boreal forest and composed of aspen (*Populus tremuloides* Michx.) and white spruce (*Picea Glauca*) in well drained sites, and Jack pine (*Pinus banksiana*, var.

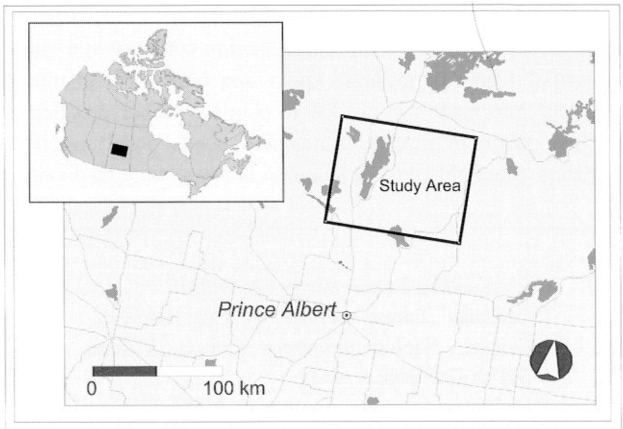

Fig. 1 Study area denoted in black is bounded by the geographic extents 54° 19' N and -106° 0' E (Northwest corner), to 53° 39' N and -104° 15' E (Southeast corner).

Lamb) and black spruce (*Picea mariana*, var. Mill.) on drier sites with coarse textured soils. In poorly drained areas, bogs support black spruce and small proportions of tamarack (*Larix laricina* var. Du Roi) (ROWE, 1977; LOWE *et al.*, 1996). Also present are fen areas, which are composed mostly of sedge vegetation with discontinuous cover of tree species such as tamarack. Forest disturbance is largely the result of localized logging operations and fire. Recent fires have generally been limited in extent and frequency through a comprehensive forest fire suppression program (SELLERS *et al.*, 1995).

Forest Inventory (GIS) and Landsat-5 TM Imagery

The provincial forest inventory system in Saskatchewan is based on interpretation and digitization of air photos on an approximate 15 year completion cycle (GILLIS and LECKIE, 1993). Inventory validation is undertaken through field visits and the establishment of temporary sample plots. The forest inventory data provided for this study is of variable vintage, with 82.7% of the inventory compiled in 1984; 3.8% compiled before 1984, and 13.5% compiled after 1984. To account for the differing vintage between the LiDAR data and the GIS data, a Landsat Thematic Mapper (TM) scene (Path 37, Row 22) acquired from July 1994, was classified to provide an indication of land cover classes commensurate with the field and LiDAR acquisition programs. The classified image data also provides for an indication of the within polygon land cover characteristics with greater spatial detail than the forest inventory data. The image was geocorrected using a first-order polynomial and a nearest neighbour resampling algorithm, resulting in a root mean square error of approximately 24 metres. The Landsat TM imagery was then classified using a hyperclustering and labeling approach based upon an established protocol (WULDER *et al.*, 2003). Using this approach, 241 initial spectral clusters were generated and subsequently merged down to represent the following general land cover classes: coniferous, deciduous, mixed-wood, shrub, herb, bryoids, wetland (treed), wetland (non-treed), exposed land, and water bodies. These classes were then further generalized using a polygon decomposition process whereby the proportion of land cover classes within each forest inventory polygon was determined (WULDER and FRANKLIN, 2001). The land cover class that represented the greatest amount of area in the inventory polygon was then assigned to the polygon. The forest inventory polygons provide a spatial context for the comparison of the differing LiDAR flight lines. The forest inventory polygons are also the units that are subject to updating in an operational context (e.g., WULDER and SEEMANN (2003)).

SLICER LiDAR Data

The SLICER instrument, developed at the NASA Goddard Space Flight Center, is a scanning modification of a profiling laser altimeter (BLAIR *et al.*, 1994). The SLICER is a LiDAR system that digitizes the backscattered return signal resulting in the capture of a full waveform. The instrument records the vertical distribution of illuminated surfaces within the laser footprint. The SLICER data used in this study was collected as part of the BOREAS project in July of 1996 (HARDING, 1998). Based upon the sensor configuration, the vertical resolution of the SLICER is approximately 1m, with a horizontal resolution of approximately 9m, and with five adjacent footprints resulting in an approximate 45m wide swath. In this study the footprint diameter was approximately 9m, varying by approximately ± 5% (or ± 45cm), due to laser divergence and changes in the distance from the aircraft to the ground.

The BOREAS LiDAR data was processed from the raw data into variables representing key components of the sensed waveform (HARDING, 2000). The height recorded for each LiDAR pulse was determined as difference between the "ground start" variable (i.e., ground inferred from the distribution of energy indicating a terminal location), and the detected laser returns indicative of the canopy top. The geolocation of the height value for each LiDAR footprint was also required in order to compare different height estimates. The location of the footprint is referenced to the first detected reflection (i.e. the canopy top). Accordingly, the absolute geo-location accuracy of footprint locations is limited by the degree of elevation change within the footprint, the differential GPS positioning of the aircraft, information on the laser pointing as established by an Inertial Navigation System (INS), and the encoding of the scanning mirror angle. Tag time errors in the independently recorded data streams, where the range and angle are in one data stream and GPS information in another, may introduce occasional geo-location errors. As a result, the footprint location accuracy can be expected to be at the scale of the laser footprint, in this case about 9m.

Stability Analysis

To undertake the point stability analysis, the following procedure was used (as illustrated in Fig. 2):

- For every LiDAR return, the height was computed from the SLICER data stream;
- A 9m radius buffer was then placed around each LiDAR return;
- LiDAR returns from adjacent SLICER flight lines were then overlaid on the buffered returns;
- Any pair of LiDAR hits which fell within the 9m buffer were tagged, the difference in height calculated, and the horizontal distance between the LiDAR returns recorded. The pair-wise selection of points was done on a flight line-by-flight line basis.

For the polygon stability analysis (as illustrated in Fig. 2):

- The forest inventory polygons were buffered by 9m to reduce any edge effect and geo-location issues.

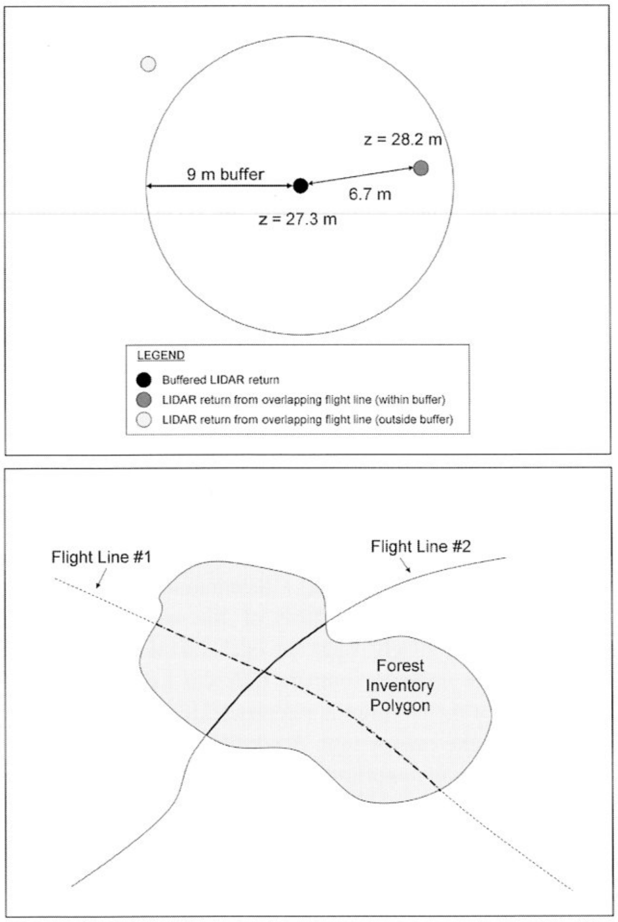

Fig. 2 For the point stability analysis (top panel) a 9m buffer was applied to each LiDAR return. The height of LiDAR returns from adjacent SLICER flight lines that fell within the 9m buffer were recorded, as was the horizontal distance between the two returns. For the polygon stability analysis (bottom panel), the within- and between- flight line standard deviations were compared to assess the pattern of variation in LiDAR heights.

- The SLICER flight lines were overlaid on the buffered forest inventory polygons.
- An analysis of variance (ANOVA) was then applied to the LiDAR height observations, stratified by polygon, to assess polygon height stability.
- Within polygon standard deviation of the hits between flight lines and within flight lines was compared to assess the pattern of variation in the LiDAR heights. The within line standard deviation is a measure of the variability of height values that may be expected for an individual flight line within a polygon. Low values indicate little variability in height values, likely cover type related, such as for water or wetlands, while a high value indicates that the height values may represent a mixture of tree tops, canopy openings and within crown hits, with the mixture and the values determined by the forest cover type.
- The between line standard deviation indicates the agreement of mean canopy height values of individual flight lines passing through a polygon. A low value indicates a high accuracy of the mean LiDAR canopy height of a flight line and that a single flight line across a polygon can provide a reliable estimate of the average canopy height in the polygon.

RESULTS

Point Stability Analysis

Analysis of the adjacent SLICER flight lines indicates that 18,507 individual LiDAR hits fell within the 9m footprint of a second hit. The height differences for measurements taken within the same footprint zone were then stratified by the nominal distance between paired measurements. By overlaying the lidar returns on the Landsat derived land cover classification, the relationship between the two height estimates used in the pairwise comparison of (purportedly) the same cover type, and the degree to which their footprints overlap, can be examined.

As a control, LiDAR returns occurring over water were investigated separately. For LiDAR returns over water, the height difference between pairs of LiDAR hits, spaced at 0 to 1m through to 8 to 9m, was always less than 1 meter, indicating that multiple measures of height, even when separated by a horizontal distance of up to 9m, were accurate. Observed differences are likely the results of errors in of GPS and INS adjustments, and possibly in some cases, shoreline encroachment.

An example from a Landsat TM-classified coniferous forest cover type is presented in Fig. 3; a large majority of pairs of hits were within ± 5m of each other. This figure also indicates a number of pairs of LiDAR hits increases as a function of distance, with approximately 200 pairs of LiDAR hits occurring within 1m of each cell, increasing to over 1600 for pairs within 9m of each other. By comparison, the observations for a deciduous forest cover type (Fig. 4) show less uniform and less consistent differences. Adjacent pairs have height differences ranging from 0 to over 10m for nominal distances between returns of 3m to 9m. Results for a mixed forest cover type (Fig. 5) were, as expected, intermediate relative to results for areas dominated by coniferous and deciduous species.

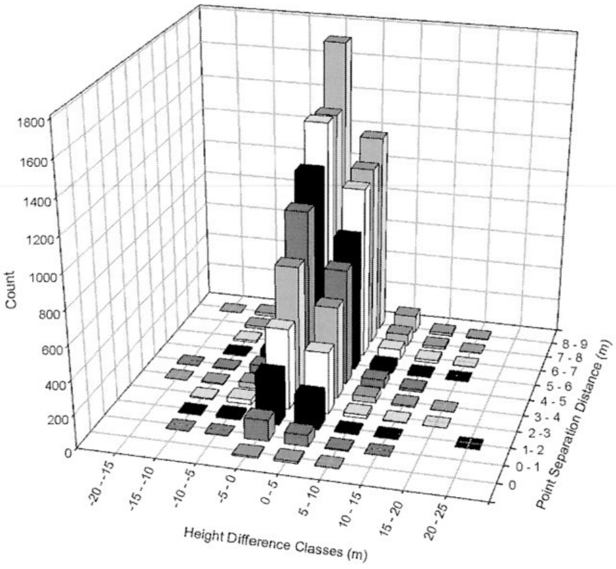

Fig. 3 Bar graph illustrating variability of SLICER height estimates as a function of multiple measures of the same location and area, stratified as coniferous land cover class.

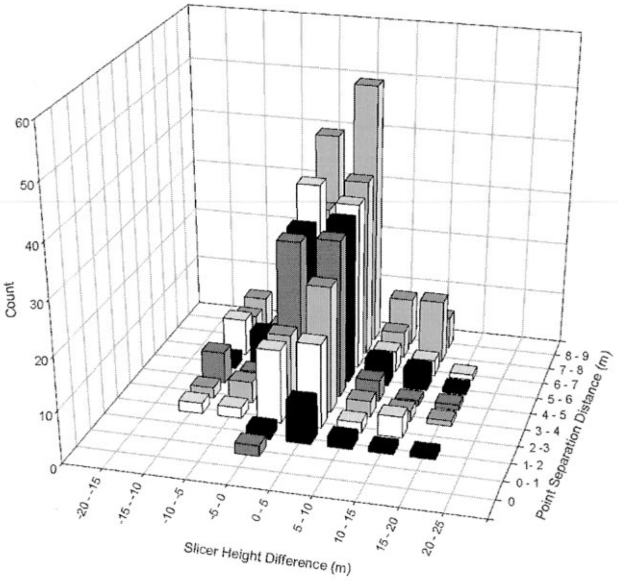

Fig. 5 Bar graph illustrating variability of SLICER height estimates as a function of multiple measures of the same location and area, stratified as mixed-wood land cover class.

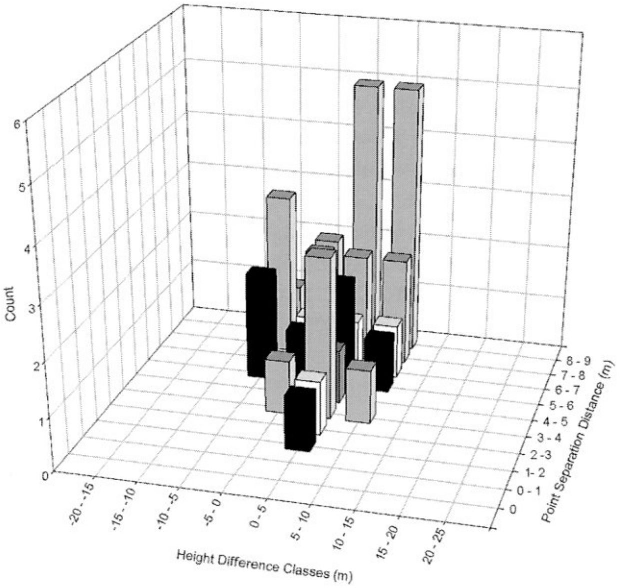

Fig. 4 Bar graph illustrating variability of SLICER height estimates as a function of multiple measures of the same location and area, stratified as deciduous land cover class.

Within Polygon Stability Analysis

In total, 360 polygons were intersected with 2 or more flight lines, representing 152,292 LiDAR returns. Most polygons had only two flight lines, with only 5% of polygons having more than 5 flight lines (Table 1). Only polygons with 2, 3, or 4 flight lines were included in the analysis. The within polygon stability analysis is undertaken through an analysis of variance (ANOVA) generating the within flight line and among flight line height variability of the forest inventory polygons. As a comparison, 5,919 LiDAR heights from multiple flight lines over three water polygons were used with a between line mean standard deviation of 0.15m and a within line mean standard deviation of 0.69m. The low values for both the between and within flight line variation, indicate, as expected both a high precision [variation within a flight line] and accuracy [variation between flight lines] of LiDAR data taken over flat surfaces. Corresponding results for vegetated surfaces reflects the variation sensed in the surface cover and its spatial distribution.

Of the 360 forested inventory polygons with multiple flight lines, the majority (275) were classed as coniferous from the Landsat imagery. The remaining forested polygons were either deciduous or mixed forest classes. Due to a lack of variation between cover types, the forest cover types were pooled and the tables illustrating within and between polygon standard deviation results are combined for all forest cover-types.

Over all classes, the between line results indicate, for example, that when 2 flight lines are flown over a polygon the estimates of mean polygon canopy height are within ± 1 meter of agreement in 73% of the examined polygons and within ± 2 meters in 89% of cases (Table 2). As the number of flight lines per inventory polygon increases, the agreement between the heights decreases, with only 53% of polygons having height estimates within ± 1m.

Within polygon, similar trends are noted in the within line variability which indicates that along the flight line, height varies considerably with variation up to ± 5m in nearly 90% of cases (Table 3). As more flight lines are added into the polygon this variation actually increases with approximately 80% of the polygons having ± 5m of height variation. The results indicate that each flight line is in close agreement in the variation detected; however, each flight line encounters different height structures within the polygon. This confirms that the polygons are in reality, not entirely homogenous and there is height variability within each stand; yet, each overpass is capturing the heterogeneity within the stand as a whole, in a similar manner. A caveat to this interpretation is a requirement that the inventory polygons used for context are not too old, with age as an indicator of the possibility of disturbance (e.g., fire, blow-down, or harvest) having occurred, potentially in a variable manner within the polygon, and subsequently captured with the lidar.

Table 1 Frequency of occurrence of flight lines collecting data on the same polygon.

# flight lines	# polygons
2	264
3	56
4	22
5	5
6	6
7	2
8	3
9	1
10	1
Total polygons	360

DISCUSSION

The provincial forest inventory program in Saskatchewan requires the measurement of tree heights to the nearest 5 m class (GILLIS and LECKIE, 1993, p. 53). The results from the SLICER LiDAR data indicates that the precision of single point-based measurements are well within the jurisdictional requirement in coniferous forests stands, with 93% of all paired LiDAR hits within 9m distance of each other being within ± 5m in height. This result increases to 95% of all paired hits being within ± 5m in height at distances less than 2m apart. In the case of deciduous forest stands, 82% of all paired LiDAR hits within 9m of each other are within ± 5m in height, which increases to 96% of all paired hits being within ± 5m at distances less than 5m apart.

As previously discussed, the SLICER LiDAR is a full waveform LiDAR instrument covering a moderate spatial footprint area (9m). The instrument detects "ground start" which is triggered by a return of the laser pulse above a preset threshold. Given a 9m footprint, in most cases the top of a tree canopy is likely to be within the footprint (assuming a tree crown size approximately commensurate with the footprint) making the "ground start" indicator a robust and significant predictor of tree height. The precision of these measures as demonstrated in this paper supports this view. Caution should be taken however when applying these results to small footprint LiDAR surfaces. In these cases, the footprint is much less (< 50cm) with a discrete sampling distance such as 1.5 - 5m. Thus the probability of a hit at the very apex of the crown is also less likely. As a result, small footprint LiDAR estimates

Table 2 Relative frequencies of between line standard deviations of canopy heights in GIS polygons.

		Between line standard deviation (m)							
		0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	> 5	count	mean
Number of lines per polygon	2	73.7%	16.1%	5.7%	2.4%	1.8%	0.3%	334	0.705m
	3	65.2%	23.6%	6.8%	2.2%	1.1%	1.1%	89	0.892m
	4	53.1%	28.1%	9.4%	0.0%	6.3%	3.1%	32	1.372m

Table 3 Relative frequencies of within line standard deviations of canopy heights in GIS polygons.

		Within line standard deviation (m)							
		0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	> 5	count	mean
Number of lines per polygon	2	4.5%	14.4%	33.5%	24.0%	12.0%	11.7%	334	3.16m
	3	3.4%	13.5%	25.8%	24.7%	21.3%	11.2%	89	3.36m
	4	3.1%	18.7%	25.0%	28.1%	6.8%	18.8%	32	3.25m

of tree height whilst highly precise (i.e. repeat measurements are similar, tightly scattered around a mean that may be biased) are often significantly negatively biased. The stability of small footprint LiDAR estimates of height would be expected to be similar to the findings made here, with the variation found at the scale of the smaller footprint.

The results of this study also have implications for broad scale LiDAR applications, and possibly to space-borne LiDAR design. Forest stands are highly variable. The process of defining forest stand boundaries for inventory and management attempts to delineate stands of common structure, condition and species composition, however considerable variation still exists within each stand. This variability is well captured by LiDAR hits through the stand; however, these results also indicate that multiple hits along a scan line can capture this variation adequately. These findings may aid in the design of future space borne LiDAR instruments - the concentration of measurements along a single line may be preferable to a dispersion of returns across a larger number of flight lines.

CONCLUSIONS

In previous studies, the estimation of canopy height from LiDAR observations has proven effective and is becoming an accepted methodology for forest inventories. The consistency of LiDAR height estimates is critical for forest managers considering the application of LiDAR data into existing and new forest inventory data collection exercises. The consistency of the SLICER height data, on both a point and polygon basis, illustrate the utility of LiDAR in forest inventory surveys, for sampling of forest structural conditions (including transects), and studies requiring scaling of LiDAR measures.

Recording and evaluating multiple LiDAR hits within the footprint threshold around the same location indicates that variability in LiDAR heights is limited when the separation between observations is small. In consideration of the boreal forest cover of this central Saskatchewan study area; estimates of canopy height from multiple flight lines through individual polygons indicate an acceptable level of variability related to the path taken over the polygon. The between line standard deviations indicate, in the case of 2 flight lines through a polygon, that height estimates are within 1m in over 70% of cases. The within line standard deviations indicate that there is considerable variability of height values collected within each line. Considering both between and within line standard deviation results, we conclude that within each polygon there is variability in LiDAR heights and that this variability is well captured by collecting data over any portion of a polygon. These results, on a point and polygon basis, indicate the utility of LiDAR data as a sampling tool in a forest inventory context.

ACKNOWLEDGEMENTS

Xilin Fang, of the Forestry Branch of the Saskatchewan Parks and Renewable Resources, is thanked for provision of the forest inventory data. Joanne White, of the Canadian Forest Service, is thanked for assistance in drafting of the figures and editorial insights.

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(Received 22 January 2007)
(Accepted 28 September 2007)