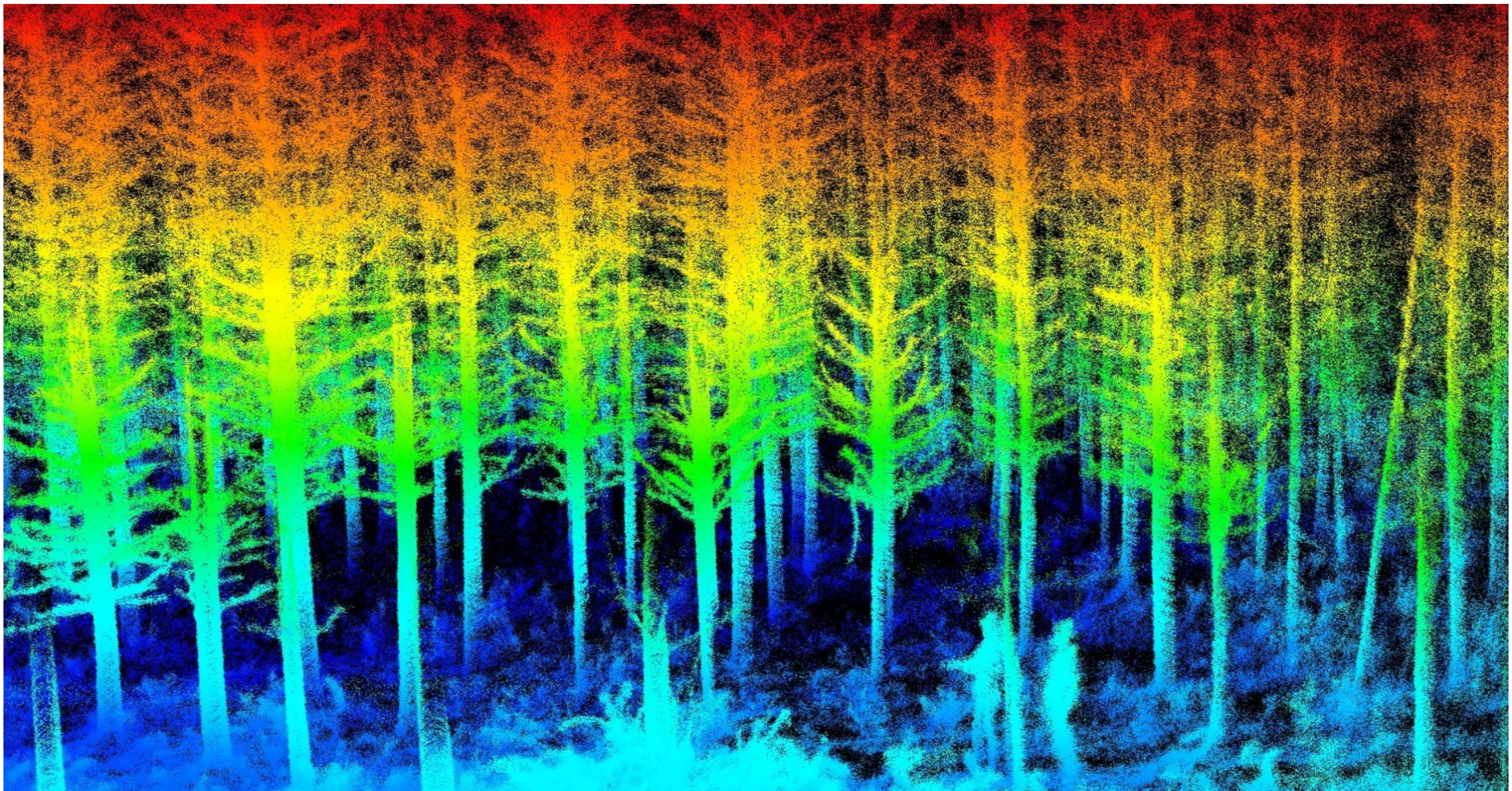

Stem and Stand Characterization using Mobile Terrestrial LiDAR in Plantation and Complex Multi-Cohort Stands

Technical report no. 38 - March, 2018

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Technical report no. 38

Abstract

The study investigated the impact of various data acquisition settings of a mobile LiDAR system on stem attributes such as DBH. Our trials in plantation and complex stands provided best LiDAR acquisition settings for future operational implementation in a context of real time 'vision' for forestry machines.

Acknowledgements

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Introduction

Increased mechanization within the forest sector over the last century has yielded tremendous returns in terms of productivity; however, current and projected workforce shortages within the sector have given rise to a need for reducing the dependence on machine operators and field staff. Traditionally labor intensive tasks such as forest inventory and compliance monitoring could be accomplished, or facilitated through the use of advanced sensor and modelling technologies. Eventually, this technology will serve as the starting point for providing real time ‘vision’ for autonomous or semi-autonomous machines capable of operating with minimal human assistance.

Point cloud data generated by terrestrial laser scanners can provide detailed and accurate 3-dimensional information and has the potential to reconstruct terrain, tree, and stand conditions. Reconstruction algorithms for individual trees recently developed from terrestrial LiDAR data have shown some potential for implementation in an operational setting but occlusion is still the major challenge over larger areas due to the line of sight limitations of static positioning. Mobile LiDAR remains challenging but provides the opportunity to broaden the application of this technology to forest machines and to speed up data acquisition in addition to minimizing the occlusion effect by acquiring returns of the target from multiple angles. Recent research on the utilization of mobile LiDAR systems in forestry has focused on developing algorithms to extract single tree or plot information (e.g., Huang et al., 2011; Pierzchała et al., 2018; Bauwen et al., 2016) while few studies have addressed how the information could impact forestry operations.

Field trials conducted by FPInnovations in the fall of 2016 have proven the capability of mobile terrestrial LiDAR (MTL) to accurately detect the position of individual stems as well as extract basic stem and stand characteristics such as diameter at breast height (DBH) and basal area (BA) over short distances (Thiel and Li, 2017). Over longer distances the occlusion effect became more pronounced as the angle between the sensor and ground became shallower and therefore more likely to be blocked by undulating terrain or debris in the sensor’s line of sight. The occlusion of the forest floor prohibited the algorithm from correctly classifying the stems despite having adequate returns on the stem. This limited the ability to adequately test the capability of the sensor as a result of the geometric limitations of the setup. Additionally, the system was tested during leaf-off conditions in a hardwood stand to minimize the occlusion effect that would be encountered under leaf-on conditions or under mixedwood conditions when encountering coniferous trees.

Trials using the same LiDAR system were conducted in the summer of 2017 at the Petawawa Research Forest in Chalk River, Ontario to test the true range of the LiDAR system in a forest condition by elevating the sensor as well as by using a mount that permitted the sensor to capture data along the same transect at 3 different scanning angles. The overlapping scan angles could be used to detect more complex stem attributes such as crown base height as well as defects that may not be visible to an operator from a given viewpoint. The system was tested in a complex multi-cohort mixedwood stand to assess the system capabilities in a typical stand, in addition to in a spruce plantation designed to test the theoretical range limits of the sensor/algorithm as point clouds become more diffuse at range.

Methodology

Mobile LiDAR System

The LiDAR unit selected for this test was a Velodyne HDL-32E[1] equipped to a lightweight computer by CGQ (Centre de Géomatique du Québec). The unit has a rotating 360º horizontal field of view and a 40º vertical field of view (+10º and -30º), returns 700,000 points per second and has an advertised return range of 80-100m. The setup was modified for the trials in 2017 to include a mounting plate with 3 fixed positions spaced 35° apart (-35°, 0°, +35°) to allow researchers to gather crown and ground returns for trees close to the transect line (Figure 1). A cable system tethered between trees and elevated about 2.5m above ground level was used to reduce erratic sensor movements during data acquisition. A self-levelling trolley (Figure 1) with a large counterweight allowed the unit to sit above the cable and be pulled along manually by researchers positioned at either end of the cable.

Figure 1. Mobile LiDAR system setup with 0° and 35° scan angles

Plot location and setup

The first component of the study was conducted in September 2017 in a genetic spruce trial with a tree-spacing of 6 feet (1.83 m) (Figure 2, left) which was established in the 1980s at the Petawawa Research Forest (PRF). The plantation condition was chosen to test the range of the LiDAR system under optimal conditions with minimal understory obstructions. The second component of the study was done in a complex, multi-cohort mixedwood permanent sample plot (PSP2) located in PRF (Figure 2, right). All trees larger than 20 cm DBH in PSP2 were re-measured in 2016 along with their positions.

[1] http://velodynelidar.com/hdl-32e.html

Figure 2. Spruce plantation (left) and PSP2 (right) in Petawawa Research Forest, Chalk River, Ontario, Canada.

Data capture

The plot setup consisted of 4 parallel 20m long transects spaced 10m, 30m, 20m apart respectively. These transects were designated as A, B, C and D with A1, B1, C1, D1 denoting the start positions and A2, B2, C2, D2 denoting the end positions. This allowed us to combine transects in different combinations to test the spacing at 10m increments from 10m to 60m. LiDAR data was collected at three different scanning angles for each transect. During data acquisition for each angle, the LiDAR system was moved from the start positions (A1, B1, etc.) to the end points (A2, B2, etc.) where the sensor was left for about 5 seconds before being returned back to the initial position at the same speed. This created two scans of the same line which were later merged together for analysis. A total of 6 scans (3 angles, two scans per angle) were acquired for each transect. The multi-angle approach was used to explore to what extent the crown base height and total tree height could be extracted from the data with the help of the increased data point coverage in the canopy and on the forest floor due to the steeper acquisition angles.

Validation of the data captured in the spruce plantation was done with the help of re-measurements that had been conducted in 2002 and again in 2014. The re-measurement data included the position of the trees in their relative rows/columns as well as vigor, height, and DBH measurements. A linear equation was built using the 2002 and 2014 DBH to estimate the DBH increase between 2014 and 2017.

The XY positions (in UTM projection coordinate system) of the 8 trees serving as anchor points for the 4 transects were recorded using an SXBlue II GPS unit. More accurate DGPS coordinates of the 8 trees used in PSP2 were recorded again in November 2017 using a Trimble DGPS unit. In PSP2, 10 sample trees were measured for DBH, crown base height and total tree height using diameter tapes and a Vertex that was calibrated in the morning and again at lunch to account for temperature variations throughout the day. The position of these reference trees was taken using a compass and Vertex to record their position relative to any of the already GPSed anchor trees.

Data processing and analysis

The acquired LiDAR data was post-processed by an external service provider[2], including the point cloud extraction, data format conversion (from original .pcap to the commonly used .las format), and to manually merge the point cloud from different transect lines and angles. The post-processed data includes:

1. Point cloud for a single transect with individual scan angles.
2. Point cloud for a single transect with three of the scan angles merged.
3. Point cloud of two separate transects with the three scan angles merged for each transect. The point density was thinned to reduce the data volume of this data set.

In the spruce plantation, polygons for the three chosen plots (S.2472, S.2603, and S.2604) were delineated in ArcMap and spatially adjusted to overlap with the LiDAR data. Stem detection and DBH extraction of trees from the post-processed LiDAR data was completed in the open source Computree software (version 4.0). The algorithm in the software took the raw LiDAR point cloud, generated the digital terrain model (DTM) and removed points from non-stem elements. It then sliced the stem horizontally and fit cylinders to the slices to calculate the optimized circle diameter at 1.3m to return the final DBH output (Figure 3). The scripts for processing the data in Computree were created and optimized based on FPI researcher's experience combined with experts' recommendations from the University of Sherbrooke. The data from PSP2 was processed in a similar manner to obtain DBH values.

For the spruce plantation, the obtained stem locations were spatially mapped and matched with the field measurement data from 2014. DBH results from the individual LiDAR data were re-entered in a spreadsheet and compared with the field DBHs on a tree-by-tree basis. A subset of sample trees in the three plots were used to analyze the effect of distance relative to the transect lines on the error in DBH estimation. Analysis to assess the most effective DTM coverage that could be derived from different data scans and their various combinations was done in addition to assessing the differences between single scan line, double scan line, and the effects of multiple scan angles on DTM coverage.

[2] Kaarta, Inc.(http://www.kaarta.com)

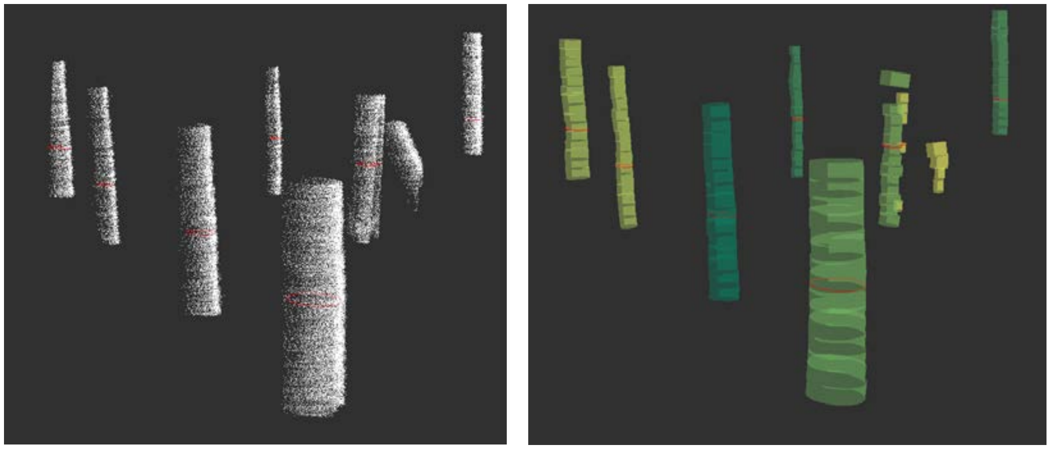


Figure 3. Extracted stem point cloud (left) and fitted stem cylinders (right) with the calculated DBHs (red circles)

In addition, to assess the feasibility of extracting tree height and lowest branch height information, points from the LiDAR data were visually identified for a few sample trees that were visible from the LiDAR data. Tree height was estimated as the elevation difference between the highest point return in the upper canopy and lowest point on the ground. The elevation difference between the lowest point returned from the lowest branch and the lowest point on the ground were used to calculate the height to the lowest branch.

Similar analysis was done in PSP2 to assess the effects of a complex understory and forest floor on the ability of the algorithm to extract important stem and stand characteristics over various distances.

Results and Discussion

DTM Coverage

The Digital Terrain Model (DTM) is used by Computree to estimate the position of the forest floor around any given stem as a reference point for DBH calculations. As the distance between the sensor and return point (tree, ground, etc.) increases, the number of LiDAR points returned from the ground tends to decrease due to physical obstructions as well as a shallower angle between the sensor and ground. Because of this, the DTM becomes less accurate or incorrect beyond a certain distance due to the lack of ground points.

In the spruce plantation, the DTMs for all post processed LiDAR data was analyzed and we found that the maximum range at which a reliable DTM could be extracted from a single scan line was about 50m (Figure 4). Spikes around the periphery indicate incorrect raster values of the ground elevation since the terrain should be very flat based on field observations. Consequently, detection and DBH calculation of trees more than 50m away from the transect line would not be reliable due to the low quality of the DTM at this range.

Therefore, a maximum spacing of 100m between scan lines would be able to create a continuous DTM under flat terrain condition. This distance would need to be shortened as terrain and understory conditions deviate from this ideal condition.

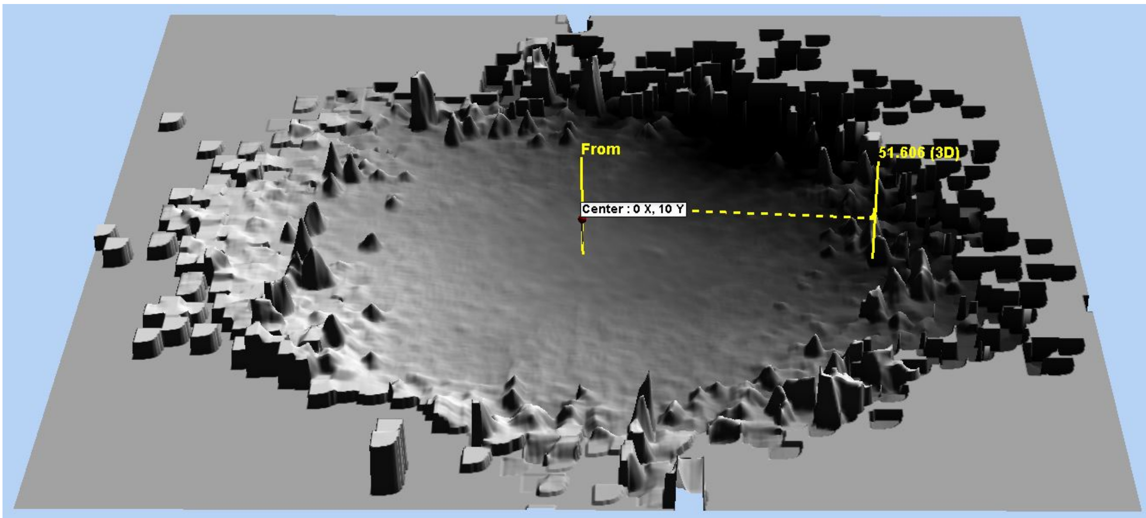


Figure 4. DTM derived from Computree software using the single angle LiDAR data in a spruce plantation. The maximum distance at which the sensor can generate a reliable DTM is approximately 50m on flat terrain.

In a more complex understory with undulating terrain that would be representative of a typical harvest block, the effective DTM range for a single scan with 0 degree angle was about 30 m (Figure 5, left). This is about 20 m less than what was observed in the spruce plantation. Merging two scans for a single line did not improve the DTM range due to the effect terrain slope, understory debris, and vegetation tend to play in limiting the forest floor return range of the laser returns at greater distances, despite a greater number of total points being captured.

The combination of A and D lines using multi-angle (Figure 5, center) data produced a seemingly smooth DTM without obvious gaps (Figure 5, right) over 60 m which supports our findings from the spruce plantation which suggest that merging two scan lines doubles the effective DTM coverage between scan lines. Based on our observations, at spacings beyond 60m the risk of producing a DTM gap where not enough points on the ground are returned increases. As a result, 60m is likely the maximum distance to have the DTM coverage necessary for DBH estimation in a natural stand, with 50m being a more conservative spacing.

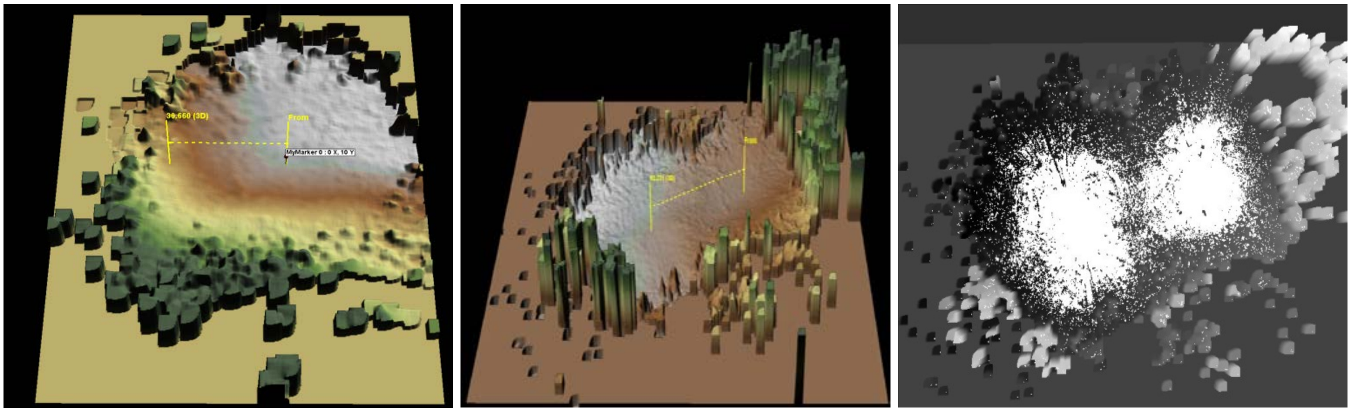


Figure 5. DTM coverage of the single scan data (left), combination of two scan lines (center), and the point cloud of the combination lines A and D shows that the middle between the two lines is more or less fully covered (right).

Single scan vs. double scan

The results from single scan line data (A1->A2) and that from two merged scan lines (A1->A2 and A2->A1) were compared in the spruce plantation to assess the ability to detect a greater number of stems with extra passes along the same transect. The LiDAR was found to have similar raw horizontal coverage since the returns were detected from the same scan line. Combining the data from multiple scan lines increased the range at which Computree could detect individual stems; however, this was as a result of the increased point density when using two scans. Computree's algorithm filters out objects with low densities to reduce the number of false stem detections, so using a double scan helped to avoid these stems being filtered out by essentially doubling the number of returns on a given stem. However, the concentration of the extra points around those already captured from the single scan did not increase the reliability of DBH estimations with results varying between 5 and 15cm relative to the field data.

Results from PSP2 showed a similar result, albeit at a shorter distance; the reliable stem detection range was found to be about 20m for the single scan data with reliability decreasing noticeably over the 20-30m range. Combining multiple scans was again found to increase the stem detection rate although DBH estimation was not improved by adding the second scan.

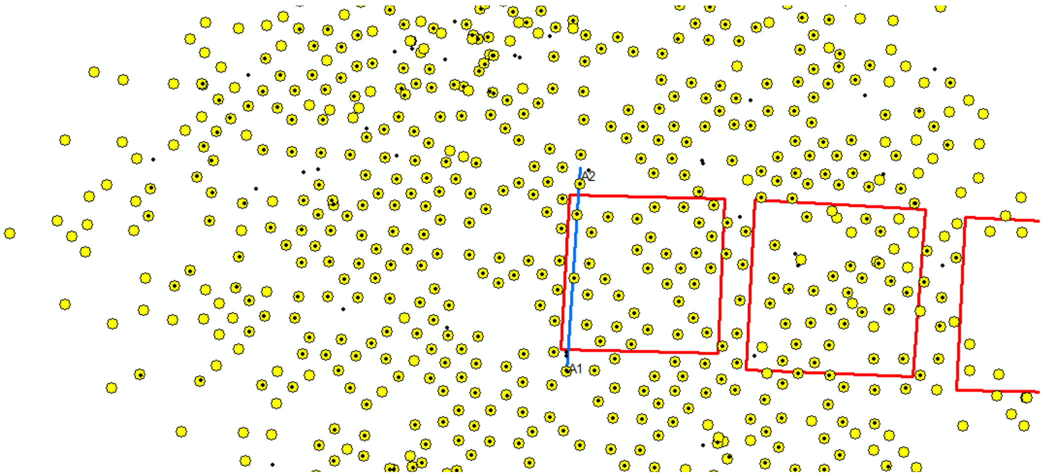


Figure 6. Automated stem detection from single scan (small black markers) and two scan LiDAR data (larger yellow markers).

Scan Angle

The visualization of the LiDAR data (Figure 7) shows the added points (colored points) generated by merging multiple scan angles into one dataset. This increases the close range point density in the upper and lower canopy as well as increasing ground point density compared to the single 0 degree angle (Figure 7, grey points) scanning approach at close range. The modified acquisition geometry was especially useful for trees in the 10 to 20 m range that could not otherwise be captured by the single (0 degree) scan angle.

Figure 8 shows a perpendicular view of the data captured over a 10 second period from the +35 degree scan. The result clearly shows that the angled data capture actually increased the point coverage and density, although the density increment varied with respect to the distance. The effect of increased density from additional scanning angles resulted in increased stem detection occurrences as described in the previous section although the multi-angle scan data did not improve the accuracy of DBH estimations due to occlusion limiting the proportion of the bole that can be seen from any point along the scan transect. The effect of occlusion is mostly affected by the position of the sensor whereas changing the angle simply increases the proximity at which returns in the canopy and on the forest floor can be captured, essentially eliminating blind spots at close proximity to the scan line. Reducing occlusion caused by understory debris and vegetation is largely addressed by moving the sensor along a horizontal plane to capture from multiple vantage points. To increase the range at which a reliable DTM can be produced the sensor would need to move along a vertical plane to increase the likelihood of capturing ground returns at greater distances.

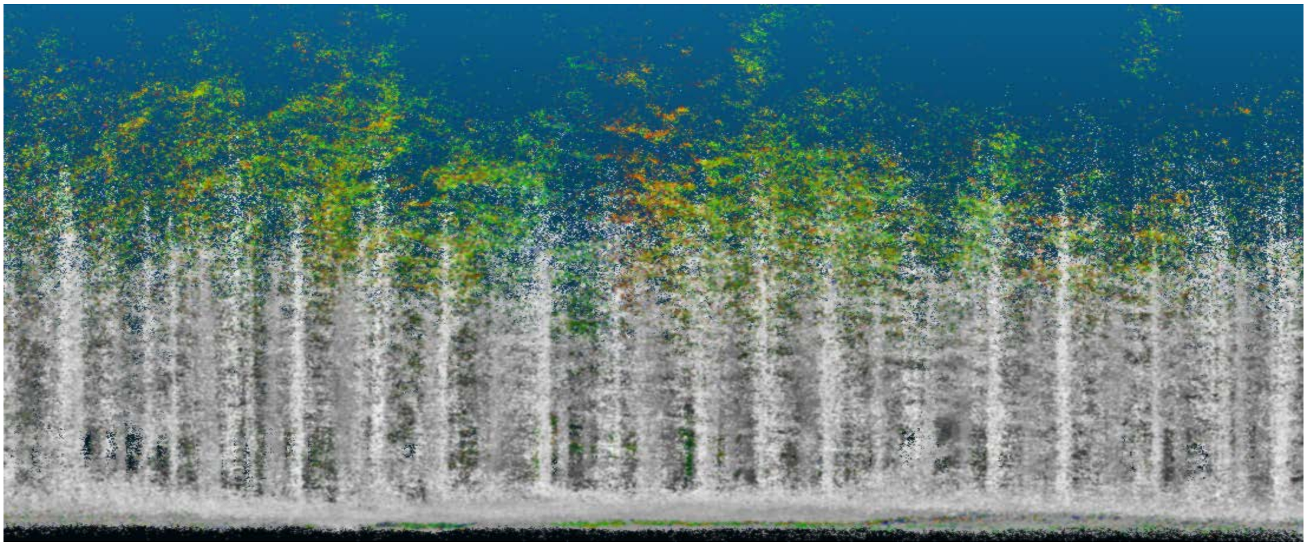


Figure 7. Side view (parallel to the scan line) of the point cloud captured from the multi-angle LiDAR data.

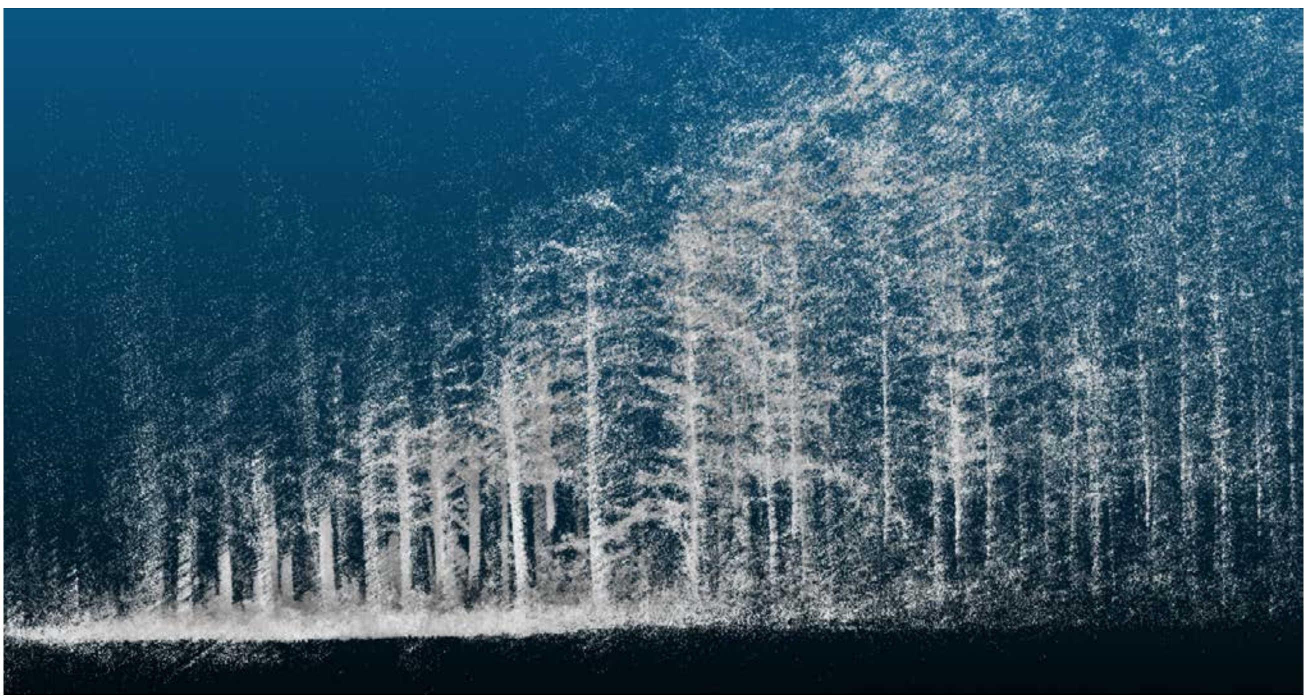


Figure 8. Profile view (perpendicular to the scan line) of the point cloud from the +35 degree scanning angle.

DBH calculation

Results from the single scan line in the spruce plantation showed that the average DBH differences between the calculated LiDAR values and the field data (converted to 2017 DBH as mentioned previously) is generally less than 2cm for those trees within 20m of the transect (Figure 9). Beyond that distance, the single angle scan resulted in relatively large errors that were typically higher than 2cm with a maximum of 6.5cm, meaning that the single angle scanning cannot provide reliable DBH estimation at distances beyond 20m although the position of the stems could be accurately recovered.

The errors can be largely explained by the field of view limitation along the transect; when trees are further away from the scan line, half or more of the bole cannot be scanned from any position along the 20m transect whereas trees that are close to the transect can have a larger proportion of the bole scanned due to a shallower acquisition angle. Since the DBH estimation is based on a fitting of cylinders around 1.3m height, fewer LiDAR points returned from around the stem (between 0.5 and 2.5m as specified by the software algorithm) hinders the ability of the algorithm to calculate the true form of the stem despite being able to identify it's position. A longer transect would overcome some of these limitations, assuming the maximum range of the sensor was not exceeded and visual obstructions did not limit the number of returns. Additionally, the applied software algorithm has very few filtering steps that are sensitive to the change of point density around an identified tree. Data with fewer points spaced evenly across the bole could produce a worse DBH estimation than those with more points when the same parameters were applied in the algorithm.

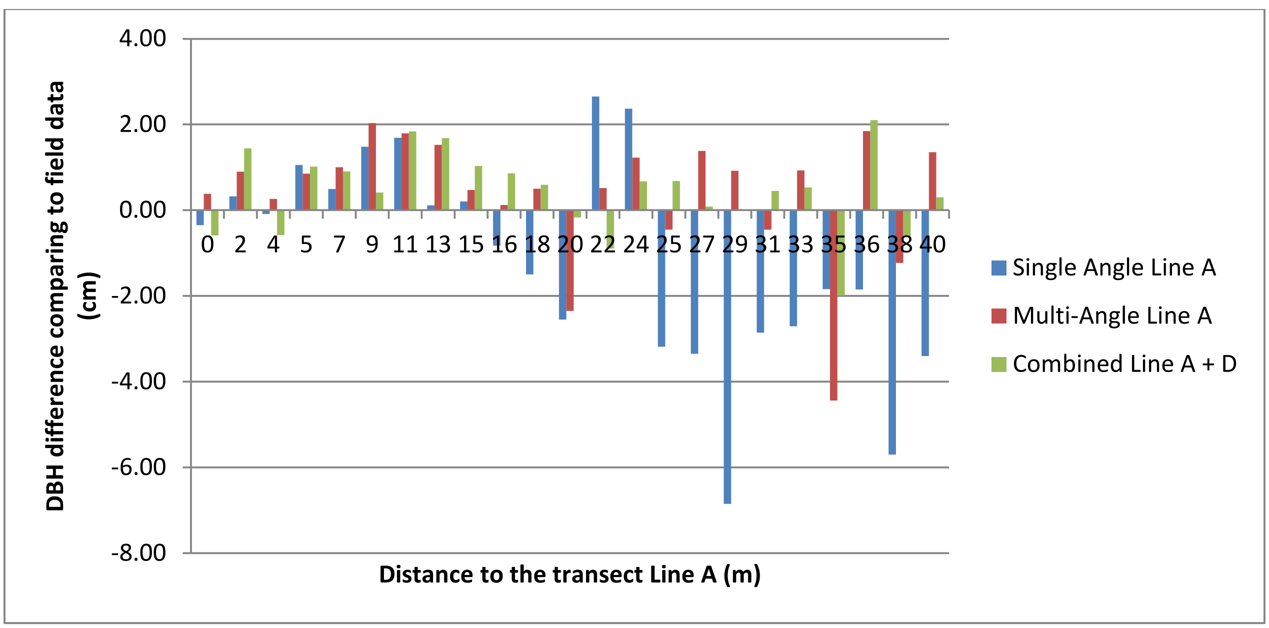


Figure 9. Average DBH errors relative to the distance from line A. Negative values represent underestimated DBHs and positive values represent an overestimation.

Combining point clouds generated along different transects helped to produce a more accurate DTM by reducing the occlusion effect as well as providing a 360° view of the trees located towards the center of the stand (30m from each scan line) which helped to improve DBH estimation for these trees. Scans from Line A and Line D were combined together and the DBH results were verified against the field data on a tree-by-tree basis. The combined data overestimated DBH by 2-2.5 cm on average. This error is likely because the noise created by manually merging point clouds using CloudCompare software. When the points are not aligned together perfectly, a thicker bole is projected by the Computree software due to the slight shift of one data set relative to the other. This effect would be eliminated if all scan lines were conducted on the same uninterrupted scan (one file) rather than attempting to merge and align the point cloud after the trial.

To account for this, the DBHs from the combination data of Line A and D were simply adjusted by subtracting 2 cm from the field data during the merging process (Appendix 1). After the adjustment, the average DBH error for the combined A+ D line was below 2cm in most cases (Figure 9).

The combination of scan lines (A+D) also increased the reliable detection range versus that of two independent single scan lines (Figure 10). The combination of lines A+D creates a buffer zone beyond the 20m that was deemed to be the reliable range detection for DBH estimation. By using the partial point cloud data from the two lines, two 'partial' point clouds can be combined to create a more complete point cloud from which to generate a DTM as well as calculate the DBH of these trees in the 20-40m zones for which a stem can usually be detected, but not reliably estimated in DBH. Figure 10 shows the stems which could be detected from one or both of the transects, however, DBH estimation is greatly improved for the stems between the two scan lines due to the combination of point clouds captured from different sensor positions. The lower point cloud density for these trees is compensated by the second data source providing a perspective not visible from the first scan line. A few trees were missed in the stem detection using the combined data (Figure 10) possibly due to point cloud alignment issues or noise from smaller vegetation.

The results from PSP2 were similar to those observed in the spruce plantation. The effective single scan distance was about 20m with DBH estimation errors increasing in the 20-30 m range where stems could still be detected but not have their DBH reliably calculated (Figure 11). Adding a second scan line increased the stem detection rate due to greater number of point returns but again did little to improve DBH estimation. The use of multi-angle data increased the detection and DBH estimation in the 10-20m range as well as detecting more trees in the 20-40m range due to increased point coverage and density. It is also noted that although the results would indicate higher gross DBH errors in PSP2, the increased size of the trees increases the net error (in cm) despite seemly the error as a proportion of DBH being similar to those seen in the spruce plantation.

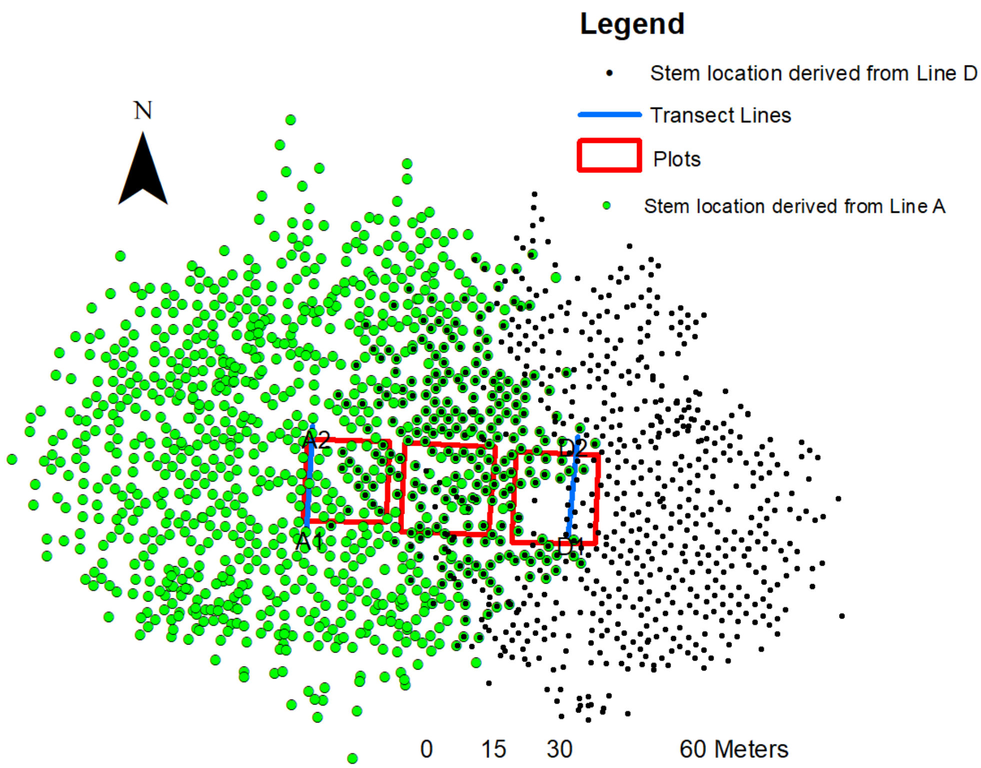


Figure 10. Solid green circles represent the trees detected from the LiDAR data along transect line A; black dots indicate those from the LiDAR data along transect line D; red boxes indicate the three plots; the blue lines represent the positions of transect line A and D. Plot ID (from left to right): 2472, 2603, and 2604.

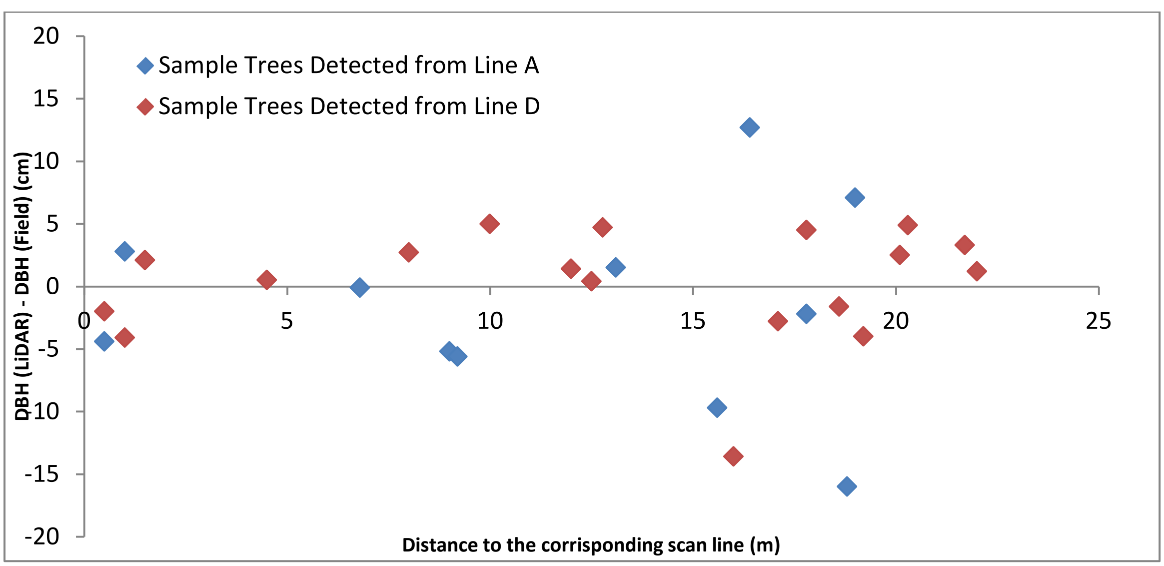


Figure 11. DBH estimation accuracy related to the scan line which the data are accounted for.

Introduction of two scan lines (A + D) in PSP2 (Figure 12) resulted in greater net coverage between the two scan lines which were spaced 60m apart. Figure 12 shows the detection from each of the lines and P1 and P2 were small plots manually designed for evaluation based on inventory data. The results showed that the combination of the two lines did increase the detection and DBH estimation rates compared to each individual scan lines; however, many stems were still missed. This can partially be explained due to the increased understory complexity compared with the spruce plantation. Upon further investigation it was also determined that the manual merge of the two scan lines again introduced noise due to the point clouds not being properly aligned and therefore filtered out or miscalculated by Computree despite having adequate point densities on the stem (Figure 13). Based on this we concluded that the maximum spacing for reliable stem and DBH estimation in a complex stand is about 50m when using a multi-angle approach. Reducing this spacing would improve DBH estimation by increasing overlap between the two point clouds.

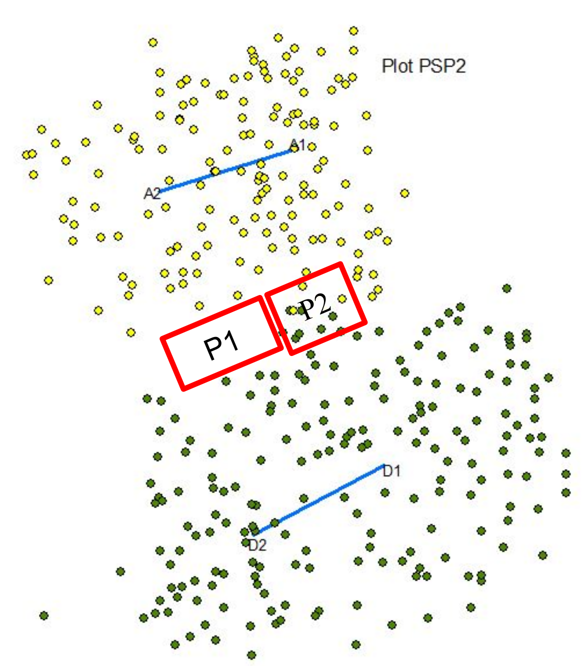


Figure 12. Stem detection from lines A (yellow) and D (green) in PSP2.

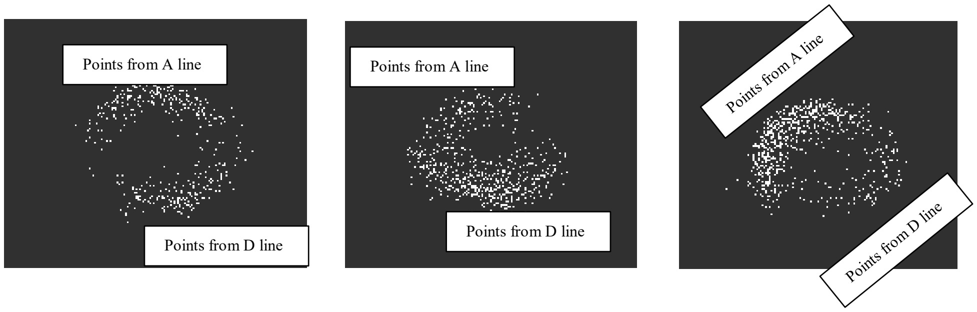


Figure 13. Three examples of the stem point clouds from the trees in P1 and P2 between scan lines A and D in PSP2 showing a misalignment issues caused by manually merging two scan lines.

Stand attributes

Stem detection and accurate DBH estimation are essential to extract stand characteristics and produce reliable inventory. Table 1 shows the stem density, DBH, and basal area numbers for each plot in the spruce plantation. The values of SA and MA in plot 2604 are low, due to that the plot was the furthest one referring to the scan line A (see Figure 10 for the plot position) and not many trees were detected. All 3 point clouds (SA, MA, CD) underestimated stem density as consequence of algorithm filtering issues caused by noise introduced during manual merging. At larger distances, the CD point cloud was the most reliable and detected 83% of the actual stems across the 3 plots. DBH estimates were also most reliable using the CD point cloud data with the average for all 3 plots being off by only 1%. Basal area was the least accurate as a result of the underestimation of tree counts in the 3 plots; however, the CD point cloud underestimated BA by only 14% which is within a reasonable range for operational inventory. Given that the comparison was based on a modelled DBH growth rather than actual measurements, the errors could be possibly reduced if more data were available to validate the growth model. Additionally, the results suggest that combining multiple scan lines (CD) resulted in worse stem density, DBH, and BA estimates compared to the single angle (SA) data at close ranges (2472) despite the same point cloud data being used. This further supports our theory that combining multiple data sets resulted in 'noise' that affected the software's ability to accurately identify and measure the stems. By collecting the data as one continuous file, this error could be eliminated and likely result in the combined point cloud treatment yielding the most reliable results. Finally, with further testing, correction factors could be developed to account for omissions in relation to forest type and/or season during which the data is collected.

Table 1. Stand characteristics from the spruce plantation. SA – single angle data from line A; MA – multi-angle data from line A; CD – combination data from line A and line D. "Adjust" indicates that the DBH was reduced by 2cm as shown in Figure 9 due to errors caused by noise created during the merging process.

	Plot 2472	Plot 2603	Plot 2604	Average
Average Tree density_Field (#/ha)	**1000**	**875**	**950**	**942**
Average Tree density_SA	925	725	50	567
Average Tree density_MA	900	850	400	717
Average Tree density_CD (adjust)	850	725	775	783
Average DBH_Field (cm)	**23.04**	**21.41**	**22.17**	**22.21**
Average DBH_SA	23.75	18.31	18.75	20.27
Average DBH_MA	24.73	20.91	16.17	20.6
Average DBH_CD (adjust)	24.26	20.92	22.15	22.44
Basal Area_Field (sq. m/ha)	**40.93**	**33.95**	**38.05**	**37.64**
Basal_Area_SA	40.19	20.64	1.38	20.74
Basal_Area _MA	41.84	31.27	8.4	27.17
Basal_Area _CD (adjust)	38.45	28.18	30.61	32.42

Tree height and crown base height

Due to the time limitations of the project, we were unable to develop an automated approach to extract height and crown base height attributes from the LiDAR data. However, a sample of individual trees was manually processed to assess the quality of the point cloud data generated using the revised acquisition methodology that was used. Table 2 shows the tree height of 3 trees in plot 2472 from the spruce plantation using the multi-angle data. The LiDAR unit captured the majority of the top crown from the 35 degree scanning (i.e., +45 degree Field Of View), however, height was underestimated by 2-3 m. The pointed tip of spruce trees are not easily scanned by the laser pulse to create sufficient returns back to the receiver. The lowest branch could be clearly interpreted from the data but we were unable to assess the accuracy of this measure due to lack of field measurement data. In theory, the height of the lowest branch can be estimated from the LiDAR vertical profile which could be obtained from the LiDAR point cloud. Crown base height can serve as an indicator of wood quality as well as an important measure for wildfire fuel loads if a fire were to break out.

Table 2. Tree height from field and LiDAR data. RowID and TreeID refer to the position of the individual tree in plantation plot 2472.

RowID	TreeID	Maximum Height (m)	Ground Position (m)	Tree Height LiDAR (m)	Tree Height 2014 (m)	Tree Height 2017 (m)
5	5	13.91	-3.19	17.1	20.2	N/A
9	9	14.68	-2.6	17.28	19	19.3
7	3	16.02	-2.2	18.22	20.6	N/A

In PSP2 tree number 292 was chosen to validate the height estimation potential of mobile LiDAR in a complex stand. The tree was positioned 33 m from end point D2 and 43m from endpoint A2. The height that was manually calculated based on the highest point return was 31.2m compared to our field measurement of 31m (Figure 14). The more accurate height calculation in PSP2 compared to those observed in the spruce plantation (~2m) can be partially explained due to the crown form of tree 292 (white pine) which has a flatter top compared with the pointed tip spruce scanned in the plantation setting. Another reason is possibly that the three sample trees in the spruce stand were not spatially in the middle of the two scan lines such that the upper canopy points from them were less than the points from the tree 292 in PSP2. The combination of scan lines A and D also helped to increase the point density in the upper crown despite the majority of returns coming from scan line A (Figure 15), even though it was physically further away than scan line D. This highlights the value of data acquisition from multiple angles in a complex forest setting where data capture is mostly limited by visual obstructions rather than sensor range.

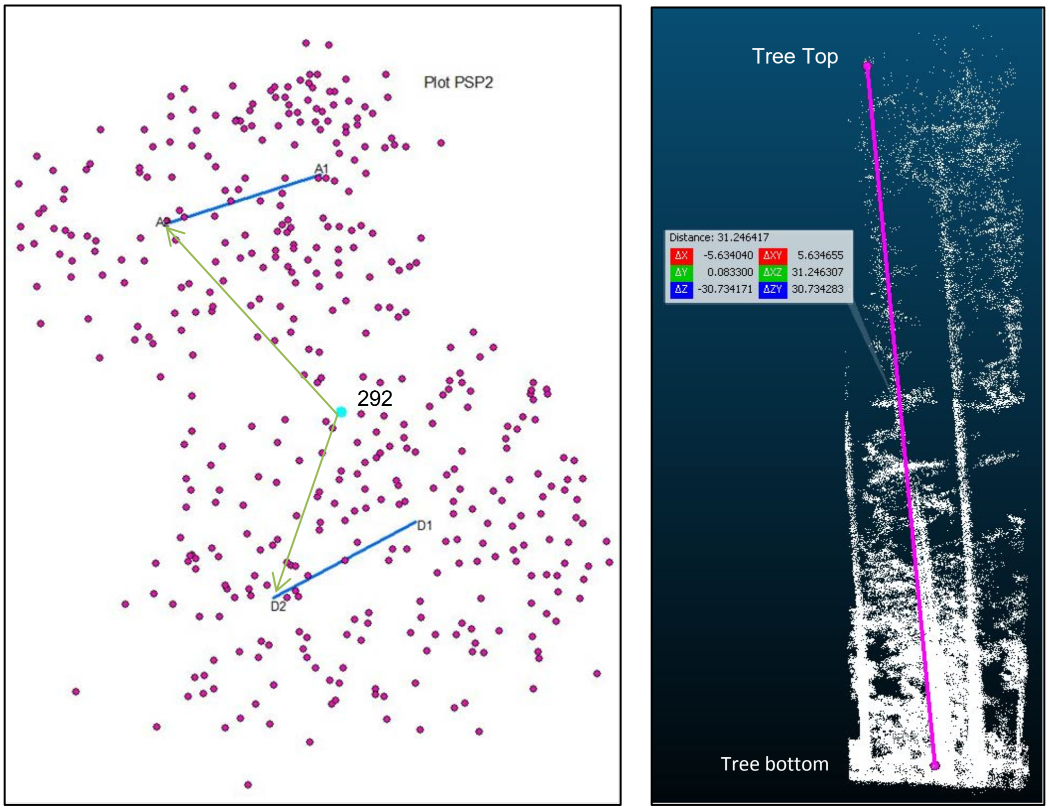


Figure 14. Left: Detected stems from the combination line data A and D with the tree 292 being selected to demonstrate the height calculation potential from the data. Right: Profile view of a 3m circular plot with the point cloud around tree 292 showing the point densities throughout the canopy.

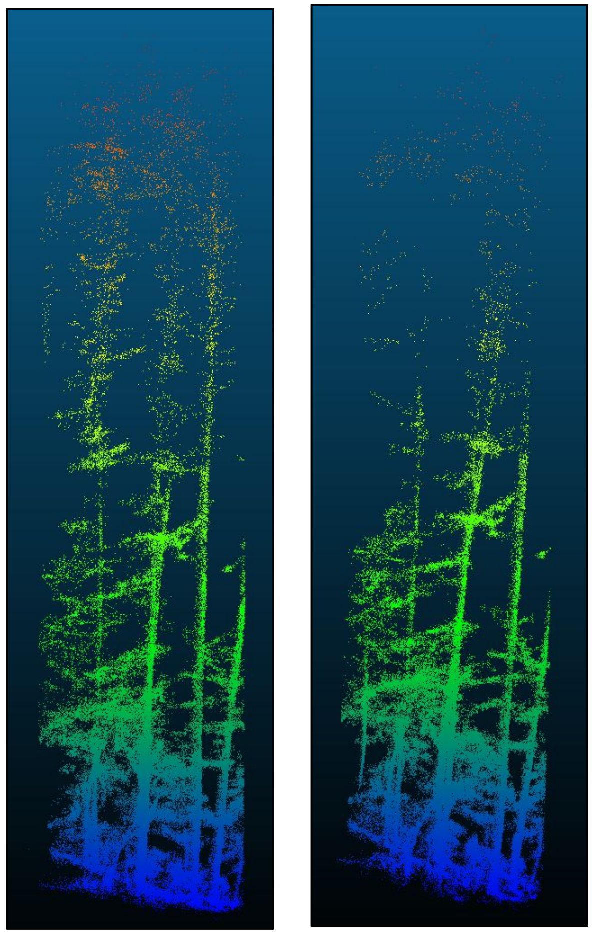


Figure 15. Left: point could of the combined A and D dataset (multi-angle); Right: point cloud of the scan line D data (multi-angle). The majority of top crown points were captured from scan line A despite being further away from the target tree.

Conclusion

The use of mobile terrestrial LiDAR data has the potential to reduce the need for traditionally labor intensive tasks such as inventory and compliance monitoring by providing accurate stem and stand data. Our results have shown that in a simple stand with minimal understory obstructions, a single scan line with one scanning angle can reliably estimate DBH and stem position up to 20m away. The use of multiple scan angles was useful in capturing crown data in the point cloud, particularly at close ranges, however, the combination of multiple scan lines was shown to have the greatest benefit in terms of increasing distance between transects up to 60 m in a plantation setting. The experimental design limited our ability to test spacings beyond 60m in the plantation setting, however results suggest that the spacing could be increased based on point overlap at 60m. In a complex stand, a reliable DTM could be extracted from a single scan line at 30m and trees could be reliably detected at 20m. Combining multiple scan angles increased the stem detection range to 60m although DBH error increased significantly between 50 and 60m.

DBH estimation error was generally found to increase with distance from the scan line. Additionally, comparison between the spruce plantation and PSP2 found that DBH error also tended to increase proportionally with the size of the stem being scanned at greater ranges, most likely as a result of the algorithm’s cylinder fitting process.

The combination of the two scan lines resulted in a consistent DBH bias that needed to be accounted for and which was most likely caused by the noise created by manually merging two data sets without a clear way of aligning them. The results of the mobile LiDAR data would likely have been improved by gathering the data in one continuous file. Additionally, where omissions are more common at greater distances, a correction factor could likely be developed to reduce error when working in more complex stands.

Tree heights and height to lowest branch could be reliably extracted from the multiple angle point cloud and was mostly found to be limited by the acquisition geometry rather than point cloud density in the upper canopy. Automated height calculations remain to be tested.

The new generation mobile sensors/systems have been emerging such as GeoSLAM Zeb-Revo, providing a wider FOV and internal co-registration process during the acquisition, despite of the shorter laser range. They could potentially mitigate some of the aforementioned limitations with the Velodyne sensor which could be considered in the future. In addition, future testing of mobile terrestrial LiDAR systems should revolve around data acquisition on a moving forest machine as a first step to test the feasibility in relation to movement, vibrations, and geometry. Automated algorithms currently exist for DBH and other stem attributes, however, tree height, lowest branch and taper could be quickly collected and offer value to planners looking to maximize the value of their product stream through better inventory, or by providing operators with a decision support tool based on stem quality as well as silvicultural objectives. In the long term, mobile terrestrial LiDAR has the potential to serve as the 'eyes' needed to achieve autonomous or semi-autonomous navigation of forest machines.

References

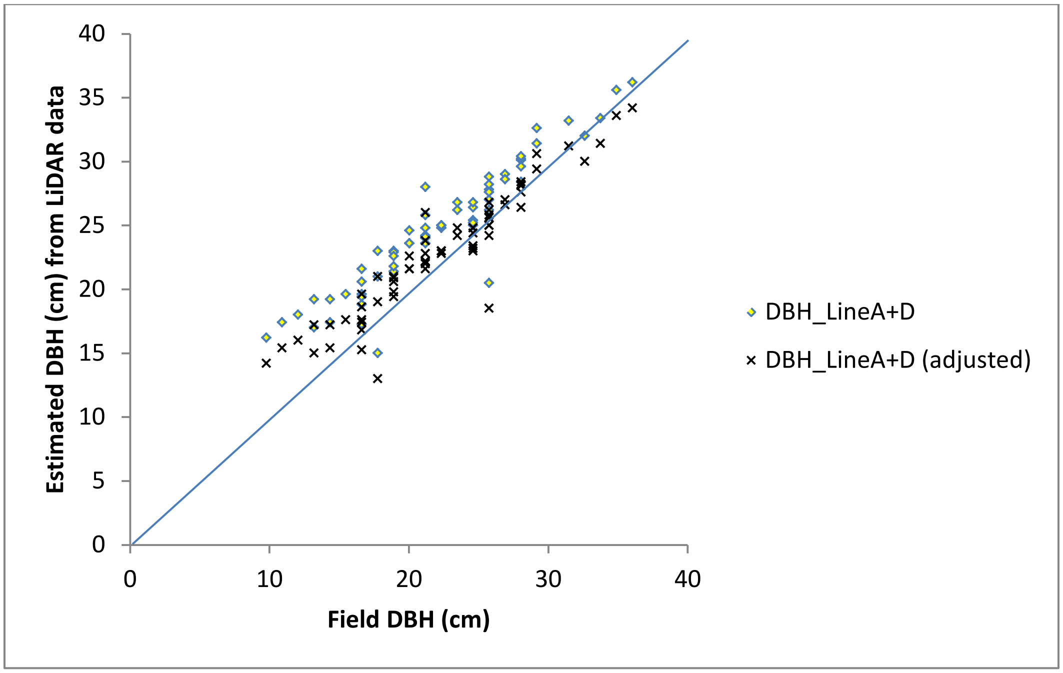
Bauwen, S., Bartholomeus, H., Calders, K., and Lejeune, P. (2016) Forest Inventory with Terrestrial LiDAR: A comparison of Static and Hand-Held Mobile Laser Scanning. Forests, 7, 127.

Huang, Huabing & Li, Zhan & Gong, Peng & Cheng, Xiao & Clinton, Nick & X. Cao, C & Ni, Wenjian & Wang, Lei. (2011). Automated Methods for Measuring DBH and Tree Heights with a Commercial Scanning Lidar. Photogrammetric Engineering and Remote Sensing. 77: 219-227.

Pierzchała, M., Giguère, P., Astrup, R. Mapping forests using an unmanned ground vehicle with 3D LiDAR and graph-SLAM. (2018) Computers and Electronics in Agriculture. 145:217-225.

Thiel, M., and Li, J. (2017) Preliminary testing of mobile terrestrial LiDAR unit and future application considerations. Technical Report, FPInnovations.

Appendix



Appendix 1. Adjustment of the calculated DBH from the combination data of line A and D.

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