The impact of plot numbers and plot configuration on the accuracy of pre-harvest stand estimates obtained by terrestrial laser scanning

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Abstract
Estimation of merchantable timber volume in a stand, based on pre-harvest inventories, requires accurate measurements of parameters such as diameter, height, taper and stocking, and appropriate sampling. Data were collected using terrestrial laser scanning with a multi-scan mode, in a stand of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) scheduled for clearfelling. The stand was divided into four blocks. Two to five plots per block were established in the stand and were scanned. For a number of sample trees in each plot, detailed manual measurements of diameter were taken at half-metre intervals along the stem, for comparison with parameters derived from multi-scanning. Pre-sale measurements were also carried out in each block, based on Coillte's (The Irish Forestry Board) Standard Operational Procedures (SOPs), a standard methodology for pre-sale inventories in Ireland, based on the tariff system. The mean diameter at breast height (DBH) values derived from the point cloud data from the three scan positions in each plot were in good agreement with the manually measured DBH values (i.e. root mean square error (RMSE) of 1.72 cm and a bias of 0.3 cm). The volumes derived after adjusting the height values obtained from multi-scan point cloud data with plot-based DBH-height regression models showed the closest match with those produced by the segment method of calculating individual tree volume. The estimated stand volume using data from the three scan positions after correcting for occlusion, and the stand volume estimated based on the use of multi-scan data from the intersecting areas of the scan circles, resulted in volumes within 6.9% and 8.5%, respectively, of the volume of the stand as measured using Coillte's SOPs.

Keywords: *Multi-scanning, forest inventory, occlusion, plot configuration, stand volume, pre-sale measurements.*

Introduction
In Ireland, currently no standard system is in place for the recording or reporting of pre-harvest volume estimates from the private forest sector (Casey and Ryan 2012). At present, this information is mostly obtained by manual, ground-based methods. The use of historic data for volume estimation, forecasting and modelling is constrained because of uncertainties about the inventory methods used and the accuracies achieved. Increased requirements for up-to-date, efficient and reproducible methods for obtaining high quality data make it necessary to investigate new inventory systems. These systems

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should be based on efficient, economic and objective procedures that produce multi-purpose datasets and application software that will transform the data into information relevant to forest planning and sustainable forest management.

International competition has forced commercial timber companies to seek ways to reduce timber production costs. One of the areas where cost can be reduced is in forest inventory. Modern technology has made it possible to maintain measurement accuracy while reducing the cost associated with traditional inventory methods (McRoberts et al. 2010). A promising new technology in multi-purpose forest inventories is terrestrial laser scanning (TLS). This type of scanning is used in a variety of applications where accurate three-dimensional (3D) models are useful, including architectural, industrial and medical measurements, coastal erosion studies and heritage preservation (Alexsson 1999, Hetzel et al. 2001, Henning and Radtke 2006a, van Leeuwen and Nieuwenhuis 2010). The basic principles behind the operation and measurement methods of TLS appear to make the technology suitable for highly automated, multi-purpose forest inventories (Dassot et al. 2011).

Acquiring accurate estimates of forest timber volume from pre-harvesting inventories requires accurate measurements of parameters such as diameter, height and taper. Estimating stand density (number of trees per hectare), basal area, timber volume and total biomass is also important in understanding the overall structure and the dynamics of a forest stand. With recent advances in ground-based terrestrial laser scanning technology, accurate estimation of these forest inventory parameters is becoming possible (Maas et al. 2008, Dassot et al. 2011). Terrestrial laser scanning data have been used to estimate stand densities in different types of forest, ranging from low-density stands (up to 600 stems ha^{-1}) (Watt and Donoghue 2005), to stands with more than 1,000 stems ha^{-1} (Tansey et al. 2009, Liang et al. 2012). They found that stand density is the most difficult forest parameter to estimate using remote sensing technology, including TLS, due to occlusion of stems (Heurich and Thoma 2008).

When acquiring data in forests, TLS data will be lacking from zones that are obscured from the scanner, which means that some trees will be completely hidden and some others will be partially hidden. One possible approach to mitigate this effect is the use of multi-scans (Thies and Spiecker 2004, Thomas et al. 2006, Maas et al. 2008). Multi-scanning is a scanning protocol where at least three positions around the centre of a sample plot are chosen and each is scanned, so that overlapping scanning regions are guaranteed. Compared to the single scan mode, the rate of tree detection in multi-scan mode has been found to be higher (Thies and Spiecker 2004, Maas et al. 2008).

This study investigated the use of TLS single scan and multi-scan modes for a pre-clearfell inventory and analysed the impact of the number of sample plots and the plot configuration on the accuracy and precision of volume estimates, when compared with results based on Coillte's (The Irish Forestry Board) Standard Operational Procedures (SOPs).

Objectives

The objectives of this study were:

- to collect pre-clearfell forest inventory data using TLS and to compare single scan and multiple scan estimates of volume, etc. with those derived using Coillte's standard operating procedures (SOPs);
- to investigate the occurrence of occlusion and to assess the benefits of multiple scanning in reducing it, and;
- to analyse the impact of the number of sample plots and the plot configuration on the accuracy of pre-clearfell TLS inventories.

Materials and Methods

Study site

The forest stand was located in a Coillte-owned forest at Thomastown, Co. Kilkenny, Ireland (52°3'18" N and 7°2'6" W). The stand of Sitka spruce (*Picea sitchensis* Bong. (Carr.)) was planted in 1966. The area of the Sales Proposal (SP) (which is the term used to identify an area scheduled for pre-sale measurements or to advertise timber for sale) was 9.4 ha. The SP was stratified into four blocks for separate volume assessments. Summary statistics for mean diameter at breast height (DBH), stand density, timber volume and area of the blocks, based on an Abbreviated Tariff (see the pre-sale measurement based on Coillte's SOPs), are presented in Table 1.

Plot set-up and data collection

During the summer of 2011, circular plots were located by overlaying the forest area in the SP with a 40 × 40 m grid. From the overlaid grid, 25 potential grid centres were identified as potential sample plot locations. From these 25 potential plot locations, 15 grid centres were selected randomly for the establishment of sample plots for scanning and plot-level DBH and height data collection (Figure 1). Three scan positions, which were separated by 7 m from each other, were included in each plot, as indicated in Figure 1. The spacing of the scan positions was chosen because the accuracy of

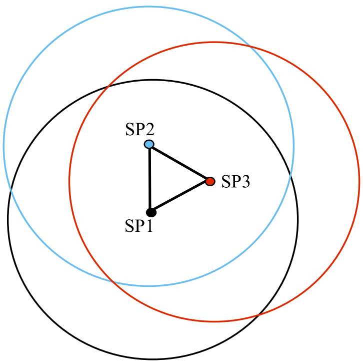
Table 1: *Summary of manually measured pre-sales volume parameters in the study area.*

Block	Area (ha)	Mean DBH (cm)	Mean stocking (stems ha^{-1})	Volume (m^3 ha^{-1})	Volume per tree (m^3 tree^{-1})
1	2.9	31.5	526	479	0.91
2	1.8	27.7	609	311	0.51
3	2.2	27.1	651	365	0.56
4	2.5	28.4	536	332	0.62

diameter estimation decreases as the distance from the scanner increases, due to the effects of the scanner's beam divergence and laser spot size. The centre of the first scan circle was fixed at the centre of the square grid at a position at least 3 m away from any nearby tree. The centres of the second and the third scan positions were fixed at the vertices of the equilateral triangle with 7 m sides, with the second scan position located due north of the first one. If either of the two vertices fell within 3 m of a tree, the new scan centres were determined by moving in a clockwise direction until satisfactory positions were obtained, without changing the first scan position. The radius of each scan circle was 15 m, giving an area of 0.0701 ha. The intersection of the three scan circles covered an area of 0.0414 ha (Figure 1).

Trees in the 15 m radius scan circles in the plots were numbered. A Haglöf Vertex IV Electronic Hypsometer with Sonar Rangefinder (Haglöf, Sweden) was used to determine if trees were inside the 15 m circle. Numbering started in the first scan circle from the north and moved clockwise, using the same method in the second and third scan circles. Any tree in the second or third scan circles not numbered in the previous circles was given a subsequent number. During tree numbering, a dot was put on the tree (under the number) each time it was included in a scan circle (so that it was clear which trees were included in one, two or three scan circles).

At each plot location, six trees in the common area of the three scans (i.e. from trees with three dots) were selected for DBH and height measurements to be used as an input by Autostem™ software for adjusting tree height. Two of these trees were from the top half of the DBH distribution, three from around the mean and one from the bottom half of the distribution. Three of these trees were selected randomly as volume sample trees.



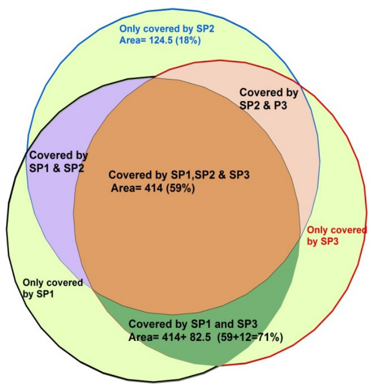


Figure 1: *Plot configurations with multi-scan positions located at the vertices of an equilateral triangle with 7 m long sides (left) and intersections of common areas (m^2) of scan positions (right). The scan circle radius is 15 m.*

(SP1, SP2 and SP3)-Data collection using TLS

The laser-scanning instrument used in this study was a FARO LS 800 HE80. The scanner has a field of view of 360° horizontal and 320° vertical, and a range of up to 80 m, with a distance accuracy of ± 3 mm, and a data collection rate of 120,000 points per second. Point clouds with more than a million accurate measured surface points can be obtained with a wavelength of 785 nm (FARO Technologies, Inc., Lake Mary, FL). The FARO LS 800 HE80 employs range determination technology using the phase-based principle, where a mirror rotates and directs the laser pulses. The FARO scanner's integrated computer is an important advantage in the scanning process. The scanner was mounted on a tripod with a built-in spirit level. The start direction was aligned to magnetic north to calculate azimuths without an offset.

Measurements and analysis based on TLS data

The TLS data acquisition for the estimation of standing timber volume was carried out based on predefined field protocols designed to overcome some of the limitations of this technology. One of the objectives of the study was to investigate the effects of vertical occlusion by branches and horizontal occlusion by stems on volume estimates, and on developing ways to overcome these limitations. The method we examined to reduce the impact of vertical occlusion was to support the TLS derived data by height measurements of trees taken in the blocks and plots where the scanning was carried out. For horizontal occlusion, the use of multiple scan positions was investigated.

Scanning was carried out from the three established scan positions in each of the plots. The height and DBH of individual trees were obtained from the single scan position per plot. The occluded trees in the first scan were, where possible, obtained from the second scan position and, if necessary, from the third scan position. In this way, most of the trees in the plot were included in at least one of the scans from the three scan positions. After estimating the total number of trees per plot using data from the three scan positions, the plot level parameters such as volume and stocking per plot were scaled up to block level and then to stand level estimates. Based on different numbers of scans (i.e. one scan, two scans or three scans per plot), the estimated block volumes were compared to those obtained using Coillte's SOPs.

Trees found in the overlapping scan area were identified in the scan data prior to processing their volume using Autostem™ software (Treemetrics, Ireland). The volumes of trees located in this part of the plot were first derived, where possible, from the single scan data, then from combined data from two scan positions, and finally from combined data from all three scan positions. The volume of the occluded trees in the single scan was determined, where possible, based on the point cloud data from the second scan position. Occluded trees in the first and second scan were identified, and the volume of these trees was obtained, where possible, from the point cloud data from the third scan position.

Measurements of tree parameters (DBH, height and volume)
Three trees per plot were felled for comparison with the stem profiles and individual tree volumes of the scanned trees. The stem profiles and volumes of the felled trees were derived from diameter measurement at 50 cm intervals along the stem. These trees were identified visually and selected in the plots by considering their assumed visibility from all scan positions. However, when analysing the scan data, two out of a total of 45 felled trees could not be detected by the Autostem™ software from all three scan positions due to (partial) occlusion.

Volumes from three individual trees in each plot, derived using four different methods, were compared to each other. The four tree-volume-*per-tree* methods used were:

1. The manual method. Each 50 cm stem section was assumed to have the shape of a frustum:
$$SEG\_V = \frac{\pi h}{12}(D^2 + Dd + d^2) \qquad (1)$$
where *SEG V* is the segment volume (m^3), h is the length (m) of the segment, D is the large-end diameter (m) and d is the small-end diameter (m) of the segment.

2. The automated Autostem™ method. To deal with vertical occlusion in the upper portions of the stem, a generic taper function is incorporated in the Autostem™ software, to automatically estimate diameters for stem sections that were not seen by the TLS. Autostem™ will switch from a circumference fitting process to the taper function if the pre-set (fixed) circumference fitting reliability factor falls beyond a threshold value. In this study, the reliability factor used was set at 70%, which is similar to the one used in Bienert et al. (2007). The taper function used by Autostem™ was a modified Kozak equation for Sitka spruce (Kozak 1988).

Point cloud data from terrestrial laser scanning often do not contain an adequate amount of data points for the top part of the trees, due to occlusion by branches. As a result, heights estimated by Autostem™ using method 2 were, after an initial analysis, corrected using regression models of local DBH-height data obtained from sample trees. The models consisted of two types, resulting in methods 3 and 4.

3. The block regression method. DBH-height regression models were developed using data from all sample trees in each block. The height estimates resulting from this model were used to correct the Autostem™ heights in each block.

4. The plot regression method. DBH-height regression models were developed using data from sample trees in each plot. The height estimates resulting from this model were used to correct the Autostem™ heights in each plot.

Volume estimates from TLS data *per plot* were obtained based on:

a. The single-scan plus occlusion correction method. A horizontal occlusion correction factor for single scan data, calculated for each plot separately.

b. The multi-scan-method. The use of multi-scan data (combined data) in the intersection area of the scan circles.

Forest block volumes were obtained based on the extrapolation of plot volumes to block areas.

Pre-sale measurement using Coillte's SOPs

Estimates of standing volume per block were compiled using Coillte's Pre-Sale Measurement (PSM) Standard Operating Procedures (Purser 1999). These Procedures are based on an adaptation of the Forestry Commission (GB) Abbreviated Tariff system (Matthews et al. 2006).

Coillte's SOPs require locating lines through the stand that are representative of the diameter distribution, and measuring the DBH and height of stems along the lines. The minimum number of DBH and height samples per Sales Proposal is dependent on the extent of the harvest area and the prescribed measurement intensity. A minimum of 110 DBH measurements were taken in each block, and the height measurements in the scan plots were used as the height sample in the abbreviated tariff. Based on Edwards (1983), this results in approximate confidence intervals for the volume estimate of ±12%.

Results

Manual DBH versus Autostem™ DBH obtained from three scan positions

The DBH of the sample trees which were scanned from three different scan positions were analysed. The result (Figure 2) indicated that there are differences in the DBH estimates of some individual trees as a result of measuring from different directions.

The standard deviation of the differences in DBH between the manual measurement and the mean of three scan measurements was 1.7 cm. The range of the differences was -4.9 to 3.2 cm, with a mean of -0.3 cm. There was no clear trend of either overestimation or underestimation, but the mean difference over all felled trees indicated underestimation of DBH as the value was negative. These differences were probably due to the non-cylindrical shape of these trees, and to the presence of small stems and shrubs in the stand, which affected the DBH estimation, either by blocking the laser beam or by confusing the software, which occasionally considered the main tree stem and some of these small stems as a single tree (Figure 3).

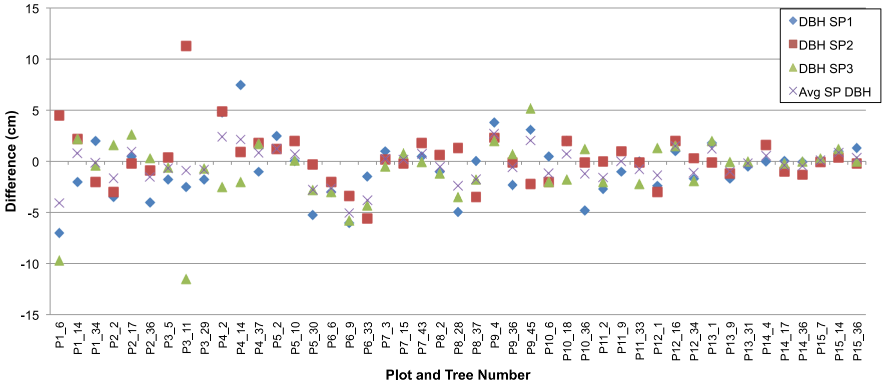


Figure 2: *Differences between manually measured DBH and Autostem™ derived DBH for the three sample trees per plot; DBH SP1, DBH SP2, DBH SP3 and Avg SP DBH refer to DBH derived using data from scan positions 1, 2, 3 and mean DBH derived using data from three scan positions, respectively. P1_6 is used to represent tree number 6 in Plot 1, etc.*

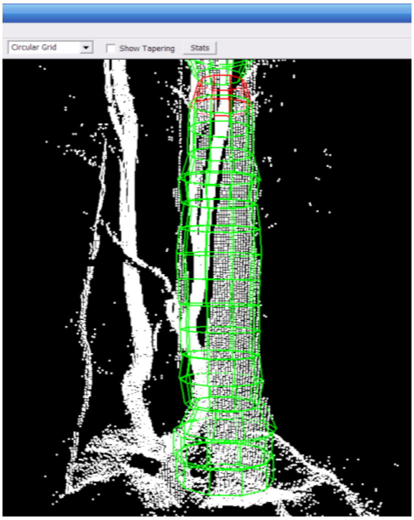


Figure 3: *A tree with overestimated DBH due to the presence of adjacent small stems.*

Mean DBH

The improvement in the DBH estimate as a result of using the mean scan values was substantial, except in a few plots. The root mean square error (RMSE) of mean DBH ranged from 1.2 to 3.0 cm, with bias ranging from -0.1 to +1.9 cm for the sample trees measured in the four blocks (Table 2). The high bias value for block 2 can be attributed to the small number of plots in this block, combined with a number of outliers in the scan data.

Height estimates

Heights of sample trees derived automatically by Autostem™ without the use of DBH-height regression models displayed large differences depending on the scan position, and resulted in large discrepancies when compared with the manually measured heights. Using the mean value of the two or three Autostem™ measurements did not resolve this issue, which led to the use of height data from the DBH-height models. Tree heights derived by Autostem™ using plot-based DBH-height regression models showed smaller differences with manually measured tree heights than those derived by Autostem™ using the block-based DBH-height regression model (Figure 4). The mean heights from the three scan positions were in good agreement with the manually measured heights, except for three trees whose heights were less than those obtained using the DBH-height model.

Volume of individual trees determined from three scans positions

The volumes of the individual trees, determined by the four methods, displayed considerable differences. The volumes estimated using method 2 showed the largest deviations for individual sample trees compared to the volumes derived by method 1. Method 3 resulted in reduced volume differences with method 1 compared to the volume differences between methods 2 and 1. The volumes derived using method 4 showed the closest match to those produced by method 1. The mean volumes calculated based on the tree parameter values from the three scan positions showed reduced differences with the method 1 volumes, compared to the variation in the volume estimates from the individual scan positions with method 1 (Figure 5).

Table 2: *DBH, root mean square error (RMSE) and bias per block, based on sample tree measurements.*

Block	No. of plots	Mean manual DBH (cm)	Mean multi-scan DBH (cm)	RMSE (cm)	bias (cm)
1	5	36.1	36.2	1.6	0.1
2	2	33.3	35.1	3.0	1.8
3	3	31.8	31.7	1.5	-0.1
4	5	29.9	30.0	1.2	0.1

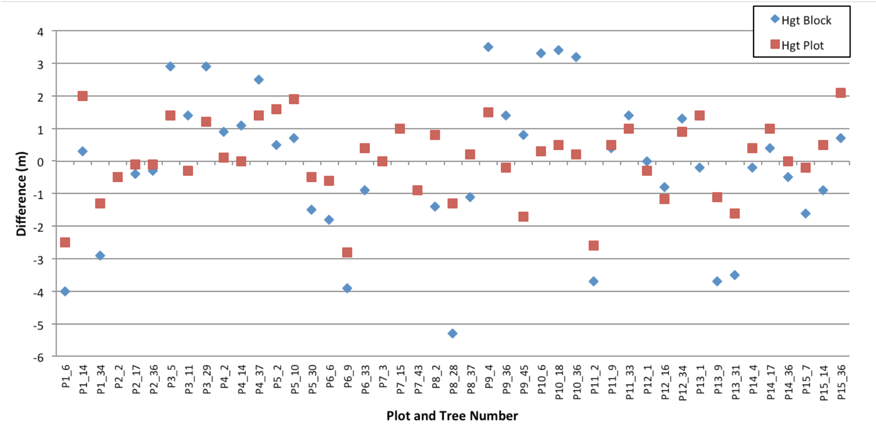


Figure 4: *Differences between tree heights measured using the manual method and tree heights derived using plot- and block–based DBH-regression models, for the three sample trees per plot. Hgt Block refers to height data derived by Autostem™ using block-based DBH-height regression models, and Hgt Plot refers to height data derived by Autostem™ using plot-based DBH-height regression models. P1_6 is used to represent tree number 6 in Plot 1, etc.*

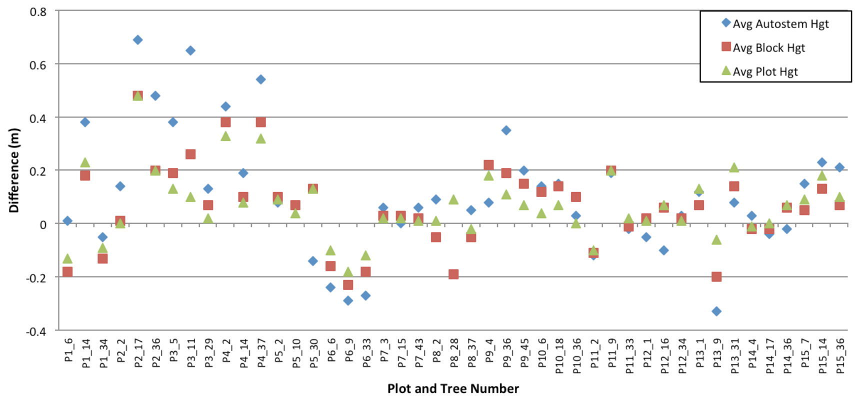


Figure 5: *Differences between tree volume measured using the segment method and tree volumes based on default Autostem height, adjusted height using block and plot-based DBH-height regression models, for the three sample trees per plot. Avg Autostem Hgt, Avg Block Hgt and Avg Plot Hgt represent volume data derived using average default heights of Autostem™, volume derived from heights obtained from block-based DBH-height regression models and plot-based DBH-height regression models, respectively. P1_6 is used to represent tree number 6 in Plot 1, etc.*

Volume per plot – based on single multi-scan

One of the objectives of this study was to investigate if there was an improvement in the accuracy of volume estimation derived using the three scan positions (multi-scan mode) compared to the single-scan mode, and to investigate the combining of scans and its possible advantage in volume estimation compared to single-scan modes. Data derived from the three scan positions were therefore processed in two different ways. The first method was based on occlusion correction factors and the second method was based on the use of combined scans.

Stand volume estimation based on correction factors (Method a)

This work showed that on average 18% of stems were occluded in all plots, based on the analysis of data from single scan positions (Table 3). The occlusion was corrected at every scan position, and the mean volumes, estimated from data from the three scan positions, were used to estimate the volumes per block (Table 4). The stand volume estimate, based on weighted block values and using method a, was 3,780.4 m^3, while the volume based on Coillte's SOPs was 3,581.9 m^3.

Table 3: *Number (#) of trees and occlusion (occl.) percent, per scan position (SP1, SP2 and SP3). B1P2 refers to Plot 2 in Block 1, etc.*

Plot	# trees in SP1	# trees in SP2	# trees in SP3	# occl. trees in SP1	# occl. trees in SP2	# occl. trees in SP3	Occl. % SP1	Occl. % SP2	Occl. % SP3
B1P1	36	35	34	7	2	6	19	6	18
B1P2	37	37	35	3	5	7	8	14	20
B1P3	37	35	35	4	3	5	11	9	14
B1P4	42	42	37	12	7	6	29	17	16
B1P5	41	40	37	6	4	5	15	10	14
B2P6	42	41	42	8	5	9	19	12	21
B2P7	41	43	43	10	10	4	24	23	9
B3P8	50	51	47	8	16	14	16	31	30
B3P9	45	48	43	14	8	9	31	17	21
B3P10	46	45	44	3	9	6	7	20	14
B4P11	42	39	36	7	3	6	17	8	17
B4P12	41	35	40	9	4	3	22	11	8
B4P13	38	37	39	9	6	6	24	16	15
B4P14	36	33	36	9	7	6	25	21	17
B4P15	38	39	42	4	8	15	11	21	36

Table 4: *Estimates of volume (m^3) before and after occlusion correction per plot (P), hectare (ha), and block (B), using three scan positions (SP). The confidence intervals (CI) for the SOPs-volumes are based on Edwards (1983). B1P2 refers to Plot 2 in Block 1, etc.*

Plot	Volume before occlusion correction (m^3)			Volume after occlusion correction								SOPs Volume (95% CI)
				Per Plot			Per ha				*Block mean* (95% CI)	
	SP1	SP2	SP3	SP1	SP2	SP3	SP1	SP2	SP3	Mean	(m^3 ha^{-1})	(m^3 ha^{-1})
B1P1	28.10	33.25	27.07	34.88	35.27	32.87	498	503	469	490	516 (456-576)	479 (428-537)
B1P2	34.63	32.89	28.79	37.69	38.03	35.98	538	543	513	531		
B1P3	37.63	36.44	31.39	42.19	39.85	36.62	602	568	522	564		
B1P4	29.03	38.14	31.02	40.64	45.77	37.02	580	653	528	587		
B1P5	26.12	26.61	22.53	30.59	29.56	26.05	436	422	372	410		
B2P6	20.14	21.58	23.10	24.88	24.58	29.39	355	351	419	375	327 (249-405)	311 (278-348)
B2P7	13.06	16.05	18.44	17.28	20.92	20.33	246	298	290	278		
B3P8	25.61	16.45	20.81	30.49	23.97	29.64	435	342	423	400	402 (331-473)	365 (325-409)
B3P9	15.87	19.64	19.42	23.04	23.56	24.56	329	336	350	338		
B3P10	29.08	25.49	30.64	31.11	31.86	35.48	444	454	506	468		
B4P11	23.23	25.01	22.23	27.87	27.09	26.67	398	387	380	388	317 (275-359)	332 (296-372)
B4P12	18.80	15.38	18.17	24.08	17.36	19.64	344	248	280	290		
B4P13	16.49	18.94	20.36	21.61	22.61	24.06	308	323	343	325		
B4P14	13.48	15.49	14.25	17.97	19.66	17.10	256	280	244	260		
B4P15	18.99	17.19	16.01	21.22	21.63	24.90	303	308	355	322		

Volume estimation using different numbers of plots and scan positions

Different combinations of plots and scan positions were used to investigate the best scenario for obtaining accurate volume estimates from TLS. As the number of plots increases, the precision of the volume estimate increases. In addition, as the number of combined scan positions increased, more precise volume estimates were produced (Figure 6).

<u>Stand volume based on data from combined scans (method b)</u>

The use of multi-scanning plots to account for occlusion was investigated and the results have shown the benefit of having more than one scan in the plot. The maximum increase in volume, as a result of using multi-scan mode compared with a single scan, was recorded in Block 2 (Table 5), with a mean value of 18.9% of the volume in the scan intersection area collected from the second scan position. On average, the mean volume added as the result of using multi-scanning in the stand was 13.6% going from single-scan to double-scan, and a further increase of 1.15% was obtained when a third scan position was added.

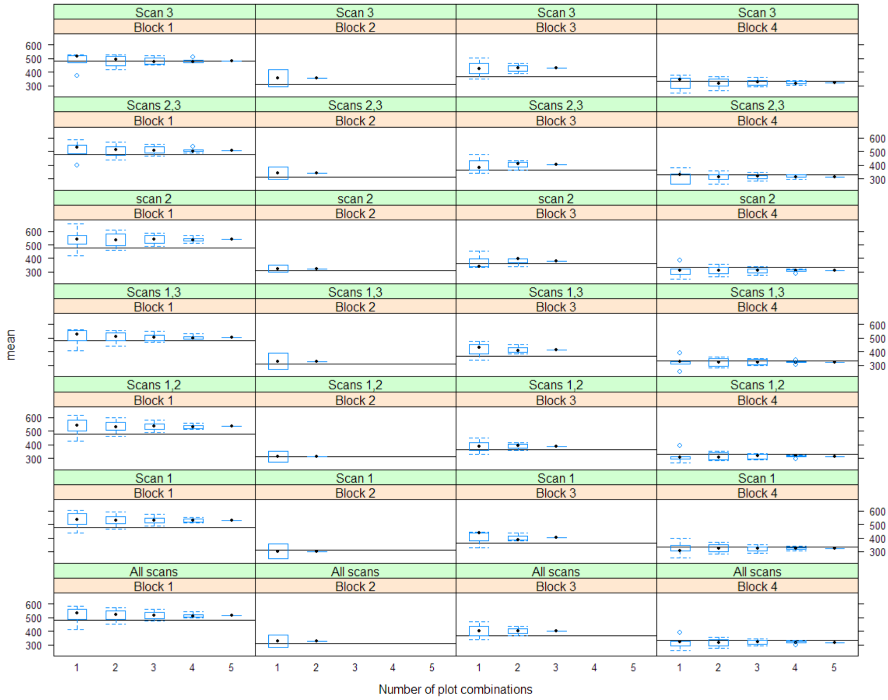


Figure 6: *The effect of different combinations of numbers of plots and scan positions, per block, on volume (m^3) estimation, after correcting for occlusion. The black horizontal lines are estimates of volume obtained using Coillte's SOPs.*

The expansion of the volume of the trees in the intersection area (414 m^2), based on three scan positions (method b), to block level resulted in an estimate of 518 m^3 ha^{-1} for block 1 (Table 5). The stand volume estimate using method b, based on the weighted block values, was 3,761.2 m^3, while the SOPs' stand volume estimate was 3,581.9 m^3.

Discussion

Diameter

The comparison of the manually measured DBH of the felled trees with the laser scanning estimates indicated that the variation in the scan estimates might be due to three factors. First, the angle from which the trees are scanned will affect the diameter values. Even though the stem sections of Sitka spruce tend to be circular, some trees and tree sections are non-circular, possibly due to lean, reaction wood and wind loading. Second, some trees were occluded from the TLS at one or more of the scan positions, due to the presence of branches and shrubs at breast height. Third, some trees were partially occluded from the TLS at breast height by being partly hidden behind other trees. In addition to the factors mentioned, the over-estimation or under-estimation

Table 5: *Stand volume in the intersection area of the three scan positions and percentage of volume gained using method b. B1P1 stands for block 1, Plot 1, etc.*

Plot	Volume (m^3) SP1	Volume (m^3) SP1+2	Volume (m^3) SP1,2+3	Volume added by SP2 (%)	Volume added by SP3 (%)	Mean volume added by SP2 (%)	Volume (m^3 ha^{-1}) SP1,2+3
B1P1	18.0	20.0	20.0	9.7	0.0		
B1P2	21.1	21.5	22.0	1.9	2.3		
B1P3	20.2	22.3	22.3	9.4	0.0	10.8	518
B1P4	16.8	22.5	22.5	25.2	0.0		
B1P5	19.0	20.6	20.6	7.6	0.0		
B2P6	15.1	16.9	17.2	10.5	1.8	18.9	341
B2P7	7.6	10.4	11.1	27.2	5.8		
B3P8	16.1	17.1	17.8	5.8	3.8		
B3P9	10.3	14.0	14.5	26.4	3.6	16.0	402
B3P10	14.9	17.7	17.7	15.8	0.0		
B4P11	13.9	14.9	14.9	6.4	0.0		
B4P12	9.7	10.8	10.8	10.3	0.0		
B4P13	10.9	13.7	13.7	21.0	0.0	12.9	312
B4P14	8.7	10.7	10.7	18.9	0.0		
B4P15	13.2	14.4	14.4	8.0	0.0		

ofthe DBH of a given tree scanned from different scan positions could also have been related to the incident angle and distance from the scanner (Lovell et al. 2011). The reflectance of a target varies according to the angle it subtends the illuminating beam. Maximum reflectance occurs from a perpendicular target and decreases according to the cosine of the angle of incidence. The reason for achieving more accurate and precise DBH estimates from the mean of the estimates from the three scan positions results from compensating for one or more of the factors mentioned above.

The finding of this study resulted in a root mean square error (RMSE) of 2.9 cm (8.8%) for the DBH estimate from single scan mode data. The multi-scan mode produced a RMSE of 1.7 cm (5.2%) for the whole stand area, while biases ranging from -0.6 to 3.0 cm and from 0.0 to 1.9 cm were obtained from the analysis of DBH measurements using single scan and multi-scan modes, respectively. A TLS-study by Lindberg et al. (2012), in Norway spruce (*Picea abies* (L.) Karst) dominated stand with 600 stems ha^{-1} and 26.8 cm mean DBH, resulted in an estimation of DBH with RMSE of 3.80 cm (13.1%), and a bias of 0.16 cm (0.5%). Watt and Donoghue (2005) derived 12 DBH measurements using a Reigl LPM-300VHS scanner in a stand of mature Sitka spruce with 600 stems ha^{-1} in northern England and, compared to manual measurements, reported an average difference of 1.5 cm and an R^2 of 0.92 with RMSE of 2.3 cm, based on data collected using two scan positions. Henning and Radtke (2006b) derived 28 DBH measurements using TLS with a mean difference of ~5 cm compared to standard inventory methods. Tansey et al. (2009) determined DBHs of Corsican pine (*Pinus nigra* var *maritama* (Ait.) Melv.) in a stand with 1,031 stems ha^{-1}, with mean errors between 1.9 and 3.7 cm. The estimates of bias found in the studies quoted are similar or larger than those found in the present study. Results from the analysis of upper-stem diameters (not presented here) indicated large differences between manual measurements and those obtained using Autostem™, especially when the taper equation was used due to occlusion.

Height

Height was the most difficult parameter to derive from the TLS data. Other studies have also reported that height is difficult to be accurately determined using TLS point cloud data (Tansey et al. 2009, Liang et al. 2012). Antonarakis (2011) attributed the difficulty of deriving tree heights from ground scanners to pulse reflection; because the scanner is on the ground shooting upwards, there can be obstruction from foliage intervening in the LiDAR's view of the tree stem. This results in more points being returned from below the canopy, with less retuning from the top part of the tree. Therefore, taller trees and denser canopies will lower the probability of determining the height to the crown tip. Hopkinson et al. (2004) reported an underestimation of tree heights of 7–8% using ground laser scanning.

In this study, large differences were observed between the height values derived from Autostem™ and the actual heights of trees felled and measured manually. The mean tree height obtained by TLS was 1.4 m less than that manually measured, with an RMSE of 4.9 m. These results are similar to those found by Maas et al. (2008) who reported an underestimation of tree height by TLS of 0.64 m, with a RMSE of 4.55 m. The use of TLS height data to estimate volume is unlikely to provide sufficiently accurate estimates for sale purposes where there is upper stem occlusion due to branches. However, when used in conjunction with locally derived DBH-height regression models, TLS can provide sufficiently accurate estimates.

The study showed that plot-based height sample trees provided a more accurate method to correct Austostem™ heights than using all sample trees amalgamated at block level. Using fewer than six height sample trees per plot resulted in less precise DBH-height models.

Volume

<u>Volume based on individual trees</u>

Analysis of the errors of the method 2 TLS volume estimates for individual trees showed that they were due to errors in both DBH and height estimation. For one tree, the error in volume estimation from Autostem™ software was as large as 0.99 m^3, compared with the manually derived estimate. In particular, the propagation of height estimation errors led to errors in the volume estimation, and it was necessary to provide the Autostem™ software with more accurate height information. As has been shown, the best estimate of tree volume, based on individual scan position data, was achieved when height was adjusted using plot-based DBH-height regression models (method 4).

All of the estimated individual tree volumes in four of the plots in block 1, derived using Methods 2, 3 and 4, were less than the corresponding method 1 volumes. This indicates that the Autostem™ method underestimated the volumes of the trees in block 1, which contained bigger trees than the rest of the blocks (Table 2 and Fig. 5). In the other blocks, Autostem™ produced both under- and over-estimates. These findings indicate that Autostem™ may underestimate the volume of large trees. A possible explanation is that for taller trees Autostem™ relies to a greater extent on the taper equation to estimate upper stem diameters, as a larger part of such stems will be vertically occluded.

Dassot et al. (2012) conducted a study on 42 trees of various species and size classes to evaluate the potential of multi-scan mode TLS to assess their main stem volume. They found the relative difference between TLS and manually measured volume estimates to be within ± 10%. Tansey et al. (2009) attempted to extract stem volume from TLS data but without success. They attributed this to the uncertainty of stem height estimation from TLS data.

Stand volume based on the use of an occlusion correction factor (method a)

Block 1 contained the highest volume per hectare. Based on data from the first scan position, the smallest estimated volume per plot in block 1 was in Plot 1: 16.8 m^3 (Table 5), which was due to the large number of trees occluded from the first scan position in the plot. The single scan volume for the whole stand, using weighted block volumes adjusted with occlusion correction factors, differed from the SOPs volume by +13.3%.

Autostem™ was also used by Murphy (2008) to determine the volume and value of three stands (comprising large, medium and small DBH trees) of Douglas fir (*Pseudotsuga manziesii* (Mirb.) Franco) in Oregon, USA. He processed point clouds provided by a FARO LS800 HE80 scanner with Autostem™ with the fully automated profiling procedure. Total and merchantable wood volumes were underestimated by 22% compared with standard inventory methods. The semi-automated procedure, when tree heights were obtained separately and entered into the Autostem™ software, resulted in the underestimation of 5% of total volume. Murphy et al. (2010) carried out a study at two locations in plantations of radiata pine (*Pinus radiata* D. Don) plantations in Australia with average stockings of 400 and 250 stems ha^{-1}, respectively. Mean tree volume estimates based on TLS measurements were within 3% of estimates based on manual measurements for four of the six stands. On large area plots with a high stocking, up to half of the trees were occluded.

Volume based on scan intersection area (combined area) (method b)

The result of the analysis of the combined scans in the intersection area showed that the use of the second scan position added significantly to the accuracy of the volume estimates. Furthermore, these combined-scan estimates of volume per hectare were very close to those based on the mean volume estimates from the three separate scan positions corrected for occlusion. The largest difference was observed in block 2 at 14 m^3 ha^{-1}. As there were just two sample plots in block 2, this may be the reason for the relatively larger difference in volume estimates between these two methods.

Limitations on volume comparisons

The only data used to compare the block and stand volumes derived from the laser scanner data in our study were the data collected based on Coillte's SOPs. Only approximate error estimation is provided for this method (Edwards 1983). However, as it represents an industry approach, comparison of the scan results with those from the SOPs make sense, to identify areas where differences may occur if TLS is used more widely for stand volume estimation. The need exists, however, to compare the scanning results with data from (calibrated) harvester heads or sawmill in-feed scanners.

Conclusions and recommendations

Terrestrial laser scanning can provide an accurate volume estimate for an entire stand based on plot-level scan data, using two or more intersecting scanning circles (method b), and after the height measurement estimation is adjusted (methods 3 and 4). Without height estimation adjustment and the use of overlapping scanning circles, TLS standing volume estimation should be used with caution. In relation to the number of intersecting scans needed, even after most of the occluded trees in the intersecting area of the scan circles were identified from the second scan, the use of a third intersecting scan further improved the accuracy of the volume estimate, albeit by a proportionately far smaller amount (1.15%) than the addition by a second scan (13.6%). The increase in accuracy as a result of using the second and third scan positions is likely to be less in plots with smaller radii, as occlusion in smaller areas tends to decrease due to reduced interference by the smaller number of trees between the scanner and the targets. Therefore, it could be beneficial to use smaller scan circles; however, in order to capture the same overall sample area, more scans would be required, adding to cost.

The estimation of stand volume using the multi-scan method (b) showed that it resulted in comparable accuracy as the volumes obtained from single scans after adjusting for occlusion using correction factors (method a), that were obtained by counting the trees in the plot. The multi-scan method is therefore a reliable and quick method, which avoids the need for tree counting and for the establishment and marking of plot boundaries, while significantly increasing the accuracy compared to single scan results.

As indicated in this study, in addition to horizontal occlusion, the other limitation of TLS was a weakness of providing accurate measurements of tree height and upper stem diameters (i.e. vertical occlusion). Providing manually measured height data to improve the tree height estimation of TLS (methods 3 and 4) can be time consuming and costly, especially for large-scale (national or global) forest inventory purposes. The combination of TLS with airborne laser scanning, for tree height (and tree number) estimates, is one possible way to address this limitation.

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References

Antonarakis, A.S. 2011. Evaluating forest biometrics obtained from ground lidar in complex riparian forests. *Remote Sensing Letters* 2: 61-70.

Axelsson, P. 1999. Processing of laser scanner data Algorithms and applications. *Isprs Journal of Photogrammetry and Remote Sensing* 54: 138-147.

Bienert, A., Scheller, S., Keane, E., Mohan, F. and Nugent, C. 2007. Tree detection and diameter estimations by analysis of forest terrestrial laserscanner point clouds. ISPRS workshop on Laser Scanning 2007 and SilviLaser 2007, Espoo, Finland, pp 50-55.

Casey, J. and Ryan, M. 2012. *Situation and Outlook for Forestry 2011/2012*. Forestry Development Department, Teagasc, Athenry, Galway.

Dassot, M., Constant, T. and Fournier, M. 2011. The use of terrestrial LiDAR technology in forest science: application fields, benefits and challenges. *Annals of Forest Science* 68: 959-974.

Edwards, P. 1983. Timber measurement – a field guide. *Forestry Commission Booklet,* 49. Her Majesty's Stationery Office, London.

Henning, J.G. and Radtke, P.J. 2006a. Detailed stem measurements of standing trees from ground-based scanning lidar. *Forest Science* 52: 67-80.

Henning, J.G. and Radtke, P.J. 2006b. Ground-based laser imaging for assessing three-dimensional forest canopy structure. *Photogrammetric Engineering and Remote Sensing* 72: 1349-1358.

Hetzel, G., Leibe, B., Levi, P. and Schiele, B. 2001. 3D object recognition from range images using local feature histograms, Computer Vision and Pattern Recognition, 2001. CVPR 2001. In *Proceedings of the 2001 IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, vol. 2: II-394-II-399.

Heurich, M. and Thoma, F. 2008. Estimation of forestry stand parameters using laser scanning data in temperate, structurally rich natural European beech (Fagus sylvatica) and Norway spruce (*Picea abies*) forests. *Forestry* 81: 645-661.

Hopkinson, C., Chasmer, L., Young-Pow, C. and Treitz, P. 2004. Assessing forest metrics with a ground-based scanning lidar. *Canadian Journal of Forest Research* 34: 573-583.

Kozak, A. 1988. Avariable-exponent taper equation. *Canadian Journal of Forest Research* 18: 1363-1368.

Liang, X.L., Litkey, P., Hyyppä, J., Kaartinen, H., Vastaranta, M. and Holopainen, M. 2012. Automatic stem mapping using single-scan terrestrial laser scanning. *IEEE Transactions on Geoscience and Remote Sensing* 50: 661-670.

Lindberg, E., Holmgren, J., Olofsson, K. and Olsson, H. 2012. Estimation of stem attributes using a combination of terrestrial and airborne laser scanning. *European Journal of Forest Research* 131: 1917-1931.

Lovell, J.L., Jupp, D.L.B., Newnham, G.J. and Culvenor, D.S. 2011. Measuring tree stem diameters using intensity profiles from ground-based scanning lidar from a fixed viewpoint. *Isprs Journal of Photogrammetry and Remote Sensing* 66: 46-55.

Maas, H.-G., Bienert, A., Scheller, S. and Keane, E. 2008. Automatic forest inventory parameter determination from terrestrial laser scanner data. *International Journal of Remote Sensing* 29: 1579-1593.

Matthews, R.W. and Mackie, E.D. 2006. *Forest Mensuration: A Handbook for Practitioners*. Forestry Commission, Edinburgh.

McRoberts, R.E., Cohen, W.B., Næsset, E., Stehman, S.V. and Tomppo, E.O. 2010. Using remotely sensed data to construct and assess forest attribute maps and related spatial products. *Scandinavian Journal of Forest Research* 25: 340-367.

Murphy, G. 2008. Determining stand value and log product yields using terrestrial lidar and optimal bucking: a case study. *Journal of Forestry* 106: 317-324.

Murphy, G.E., Acuna, M.A. and Dumbrell, I. 2010. Tree value and log product yield determination in radiata pine (*Pinus radiata*) plantations in Australia: comparisons of terrestrial laser scanning with a forest inventory system and manual measurements. *Canadian Journal of Forest Research* 40: 2223-2233.

Purser, P. 1999. *Timber Measurement Manual: Standard Procedures for the Measurement of Round Timber for Sale Purposes in Ireland*. COFORD, Dublin.

Tansey, K., Selmes, N., Anstee, A., Tate, N.J. and Denniss, A. 2009. Estimating tree and stand variables in a Corsican Pine woodland from terrestrial laser scanner data. *International Journal of Remote Sensing* 30: 5195-5209.

Thies, M. and Spiecker, H. 2004. Evaluation and future prospects of terrestrial laser scanning for standardized forest inventories. *International Archive of Photogrammetry, Remote Sensing and Spatial Information Sciences* 192-197.

Thomas, V., Treitz, P., McCaughey, J.H. and Morrison, I. 2006. Mapping stand-level forest biophysical variables for a mixedwood boreal forest using lidar: an examination of scanning density. *Canadian Journal of Forest Research* 36: 34-47.

van Leeuwen, M. and Nieuwenhuis, M. 2010. Retrieval of forest structural parameters using LiDAR remote sensing. *European Journal of Forest Research* 129: 749-770.

Watt, P.J. and Donoghue, D.N.M. 2005. Measuring forest structure with terrestrial laser scanning. *International Journal of Remote Sensing* 26: 1437-1446.