# Accuracy of Automated Assessment of Sweep in Standing Hybrid Poplar Trees Using Terrestrial Laser Scanning

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## Abstract

Sweep, in interaction with sawing method, can negatively affect volume and value recovery from logs. Quantitatively assessing sweep in standing trees to determine its impact on product yields, volume recovery, and value recovery can be challenging and time-consuming. Terrestrial laser scanning (TLS) provides an opportunity to measure three-dimensional sweep in standing trees.

A total of 98 trees from three hybrid poplar stands (one 12-y-old stand and two 7-y-old stands) in eastern Oregon were TLS scanned over bark and automatically assessed for sweep to a maximum height of 17 m. The trees from the three stands were then felled, transported to a mill, and scanned after debarking using an industrial scanning system. Trees from one of the stands were scanned four times: twice using TLS in the forest from two scan points, and then mill scanned once over bark and rescanned using the mill scanner after the bark was removed.

The average root mean squared differences (RMSD) between over bark TLS measurements and under bark mill scan measurements were similar to the average RMSDs between over bark and under bark mill scan measurements. Differences were noted between stands. The average RMSD was higher in the 12-year-old stand than in the two 7-year-old stands.

Sweep is defined as a gradual, but pronounced, bend in a standing tree or in a log, pole, or piling (US Department of Agriculture Forest Service 1989). It is caused by the tree responding to environmental stimuli such as light, gravity, wind, snow buildup, soil movement, and animal damage. The tree responds to the mechanical stress by forming reaction wood. From a commercial perspective, reaction wood is undesirable primarily because its mechanical properties are different from nonreaction wood and it can result in twist, cup, or warp during machining. It also responds differently to changes in moisture.

Several studies have illustrated the impact of log sweep, in interaction with sawing method, on volume and value recovery. Ivkovi et al. (2007) found that sweep had a strong negative effect on green volume recovery and showed that a 10 percent increase in log sweep increased sawlog degrade by 17.1 percent and reduced green timber recovery by approximately 0.5 percent in radiata pine. Bond and Araman (2008) noted that traditional straight sawing of curved logs also results in value losses as a result of removing high-quality wood from the outer portions of the log. Hamner et al. (2007) examined the benefits of curve sawing versus straight sawing in eastern US hardwood logs with sweep. Their study indicated that curve sawing increased the volume recovery over the traditional straight sawing method. Bond and Araman (2008), however, reported that lumber from curve sawn cherry (*Prunus avium*) hardwood logs with sweep exhibited significantly more warp after drying than lumber from straight sawn logs. Because of the impacts of sweep on volume and value recovery, logs with sweep may incur a price penalty or, when scaled for volume, a volume penalty.

There are a number of ways for quantifying sweep in logs. In the forest or log yard it can be measured in a two-dimensional (2D) plane by tightening a string or measuring tape from one end of the log to the other on the side of the log in the plane that exhibits the most sweep. The maximum deviation between the string and the centerline of the stem determines the amount of sweep present in each log. In a mill it can be 2D or 3D optically scanned.

Assessment of sweep in standing trees to determine its impact on volume and value recovery is more difficult than assessment of sweep in logs. In some forest regions, timber

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cruisers will estimate an overall percentage reduction in stand volume or value that is due to sweep. The accuracy of such estimates will depend on the skill and experience of the timber cruiser.

MacDonald et al. (2009) describe a 2D system developed in the United Kingdom for allocating stems to one of seven sweep classes based on a visual assessment of the first 6 m of a stem. Stand level sweep class averages are then used to determine the amount of degrade in volume and value recovery due to sweep.

Gordon and Baker (2004) describe a 2D stem quality mapping system used in Australia whereby the cruiser visually identifies for each stem in the sample plot the type of sweep, the start and end points of sweep on the stem, and an estimate of the amount of sweep relative to the stem diameter at the end point of the sweep. The plane containing the greatest amount of sweep is selected as the basis for sweep assessment. Stem centerline information is then used in optimal bucking procedures to determine the combination of log products that would yield maximum value from each individual stem. Individual stem values are summed to obtain sample plot and stand volume and value estimates.

Accurate 3D measurement (mean error of 5 to 15 mm) of stem centerlines in standing trees using photogrammetric techniques has been described by tree geneticists Shelbourne and Namkoong (1965). The technique required photos to be taken of single trees and at right angles to each other. Data collection and processing were time-consuming. The method has not been used for conventional forest inventory purposes as far as we are aware.

Terrestrial laser scanning (TLS) provides an alternative opportunity to measure 3D sweep, as opposed to visually assessing 2D sweep, in each stem in standing timber (Thies et al. 2003, Bienert et al. 2007, Keane 2007). Subcentimeter measurement of distances with this technology allows 3D mapping of stem diameters and centerlines in standing trees. Teobaldelli et al. (2008) reported that average TLS diameters were within 1 cm of manually measured diameters for 14-year-old intensively managed poplar plantations in Italy. Antonarakis (2011) compared manual and TLS measured diameters at breast height (DBH) in complex riparian poplar forests in France and found a mean bias of less than a half a centimeter (~1.5%).

Centerline estimates based on 3D mill scans could be considered the standard against which other methods of measuring sweep are assessed. As far as we have been able to determine, the relationships between TLS measurements and actual mill scan measurements have not been investigated. In this article TLS centerline measurements will be compared with centerline measurements obtained with a mill scanner for three hybrid poplar stands harvested and milled in eastern Oregon.

# Methods

## Study location and stand descriptions

GreenWood Resources, Inc., Boardman Tree Farm (BTF) is a hybrid poplar farm located near Boardman, Oregon, just south of the Columbia River in eastern Oregon (45.77°N, 119.54°W). BTF contains approximately 10,000 hectares of hybrid poplar trees of various genetic crosses. Surrounding land is primarily used for agricultural purposes. The area is dry and hot during the summer and dry and cold during the winter. The area is also characterized by windy conditions that result in many trees having lean and sinuosity in the direction of the prevailing winds. The 2D shape of the stems in cross section tends to be elliptical, as opposed to circular, because of wind loading. BTF is separated into various age classes and stocking densities on rectangular parcels representing individual stands. Each stand, approximately 28 hectares, contains hybrid poplar of the same age and same stocking density. BTF grows and harvests trees on a 12-year rotation. Between ages 2 to 5 years, trees are pruned in several lifts to a height of approximately 7.5 m to produce a knot-free sheath surrounding a knotty core. At maturity, trees are harvested mechanically and then transported to a mill that is centrally located at BTF that processes all harvested raw timber. Each tree usually yields appearance grade lumber and pallet wood from the lower part of the stem, and chips from the upper parts of the stem that are too small to produce lumber.

In the summer of 2010, when the poplars were in full foliage, each of three stands—low, medium, and high stocking densities—was sampled systematically with a random starting point for each stand. The low stocked stand contained 7-year-old hybrid poplar trees (*Populus trichocarpa* × *deltoides*) stocked at 360 stems per ha (spha) with an average DBH of 267 mm, the medium stocked stand contained 7-year-old trees (*Populus trichocarpa* × *deltoides*) stocked at 550 spha with an average DBH of 233 mm, and the highly stocked stand contained 12-year-old trees (*Populus deltoides* × *nigra*) stocked at 725 spha with an average DBH of 273 mm. For future reference, the low stocked stand will be referred to as Stand L7, the medium stocked stand will be referred to as Stand M7, and the highly stocked stand will be referred to as Stand H12.

## Plot descriptions, scanning, and preliminary data processing

Twenty equally spaced circular plots each with a 10-m radius—approximately 3 percent of a hectare—were located in each of the three stands. Plots were spaced at every 36th, 31st, and 25th tree in each of four straight lines in Stands H12, M7, and L7, respectively. The perpendicular distance between lines was 36, 31, and 25 trees in Stands H12, M7, and L7, respectively. Each plot center was permanently marked, and all trees in each of the 60 plots were numbered and measured for DBH using a diameter tape. Five standing trees per plot were manually measured for height with an Impulse laser rangefinder. A DBH height function and a taper function were created for each stand from the data collected.

A Trimble FX laser scanner, mounted on a surveying tripod, was used to collect standing tree TLS measurements at 1-mm resolution at 28 m. Scans were gathered at either one or two locations within each plot; a second scan was only gathered if tree(s) within the plot radius were occluded by other trees in the primary scan. The primary scan ($TLS_P$) occurred at the center of the plot, and the secondary scan ($TLS_S$) approximately 2 m from the plot center. No attempt was made to accurately align the primary and secondary scans for each plot. The secondary scan was solely used to obtain measurements on trees missed because of occlusion in the primary scan. Time to set up the scanner and take two scans per plot was usually less than half an hour.

The laser scanner scanned a 360° dome sending out millions of laser pulses that struck all objects in a plot, including the ground, and bounced back to the scanner creating a laser point cloud. A maximum of 50 percent of each stem, which is the 50 percent facing the scanner, could be mapped in the point cloud. The number of laser points striking the surface of an object depends both on the distance the object is from the scanner and the scanner's intensity setting. The intensity setting used in this study resulted in about 250 points per $m^2$ striking objects at a distance of 10 m from the scanner.

TLS point cloud data were processed using Autostem software (Treemetrics Ltd., Ireland), which incorporates algorithms developed by Bienert et al. (2007). Point cloud data are used to first develop a digital terrain model (DTM) of the ground. Each object above the DTM, and within the plot radius, is then evaluated using a reliability factor based on a circle adjustment algorithm to determine whether the objects within the point cloud can be considered a tree (Bienert et al. 2007). Once a stem is identified, the DTM surface and the slope of the ground at the base of the stem are used to determine the height to DBH. Once the DBH has been determined from the laser returns, Autostem fits disk segments based on a circle adjustment algorithm above and below the DBH to create a stem profile based on the scanner point cloud measurements of the stem.

The stem profile consists of the diameter over bark and the centerline coordinates for each 10-cm-thick disk segment from the nominal stump (10 cm above the ground) to a 7-cm top. Where there are insufficient point cloud measurements on the stem surface to fit a circle and measure a diameter, Autostem either interpolates between ''good'' measurement points or, where no further measurements can be made, uses a taper function to predict a diameter. A point was considered ''good'' if its reliability factor was greater than 0.8. The reliability factor, as described in Bienert et al. (2007), is the arithmetic mean of five attributes based on measures such as the proportion of the stem section that is visible, diameters of neighboring stem sections, and the number of laser scan points striking the stem section. When a taper function is used, centerline coordinates for the affected disk segment are predicted but could be inaccurate (Fig. 1). Additionally, the assumption that the cross section of the disk segment is circular could lead to inaccuracies in calculated centerline coordinates for elliptical stems.

Not all scanned plots were used in the automated sweep assessment study. Random subsamples of plots were selected for felling and detailed mill measurements. There were 8, 4, and 6 plots randomly chosen from Stands L7, M7, and H12, respectively. Each tree in the randomly selected plots was mechanically felled, delimbed, and then manually tagged on the butt for identification at the mill. The subsampled plots yielded approximately 70 trees from each of Stands L7 and M7, and 160 trees from Stand H12, for a total of 300 trees that were transported to the mill.

## Mill scanning

Ninety-eight of the trees that were scanned and tagged in the forest were also scanned in the mill, allowing a tree-by-tree direct comparison of scanning methods. Trees transported to the mill were first bucked at about 17 m (the maximum length for the mill's log scanner). The bottom 17-m section was sent to the saw mill. The remainder of the tree was chipped. The bottom section was scanned for diameter and sweep using the mill's Nelson Brothers Engineering (NBE) scanner (Trout Lake, Washington). Trees from Stand H12 were scanned first with the bark on ($NBE_{OB}$) and then rescanned after the bark was removed ($NBE_{UB}$). Trees from Stands M7 and L7 were only scanned after the bark was removed. After the trees had been debarked and scanned, they were then optimally bucked to sawlog lengths (8 to 12 ft or 2.6 to 3.8 m).

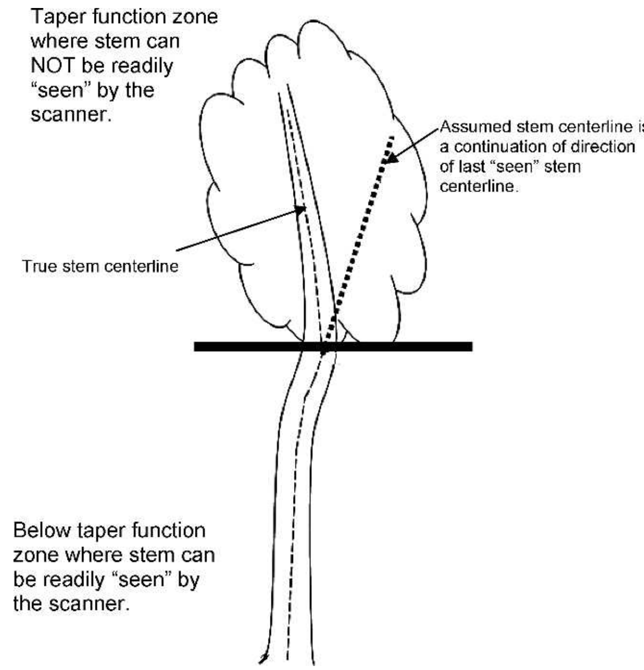


*Figure 1.—When insufficient laser points are available to accurately measure stem diameter, for example, when a portion of the stem is hidden by the crown, a taper function is used to predict diameter. Within the taper function zone an assumption is made that the stem centerline is a continuation of the last seen centerline in the below taper function zone. This may or may not be a correct assumption.*

To generate mill scans, each stem was laid on a conveyer belt at the mill and then run through the NBE scanner. The NBE scanner is a linear scanner fitted with two opposing JoeScan JS-20 scanning heads that each capture cross-sectional measurements, across a 145° arc, to the nearest tenth of an inch (~2.5 mm). Each stem was fed into the NBE scanner so that the small end of the stem was scanned first to obtain the scaling cylinder, and then measurements were scanned successively at 1-inch (25-mm) intervals down the stem. Stems were not clamped when passing through the scanner. NBE modified their software so that a text file of the 3D profile (centerline and 360 cross-sectional radii at 1° intervals) at 1-foot intervals (~30 cm) of each stem was available for analysis. The cross-sectional data were not filtered for outlier removal. Outliers would have been caused by pieces of bark or branch stubs on the log surface. While outliers would certainly have had some effect on the calculated position of the stem centerline, it is likely that the effect would have been small since the centerline location was based on 360 radial measurements per stem cross section.

There was no way to control the angle at which each stem was laid on the conveyer belt, so the position of a tree in relation to the NBE scanner differed from the position of the same tree in relation to the TLS scanner. TLS scans were generated on standing trees at a fixed azimuth from the plot center to the tree, and standing stems were scanned from the butt to the top.

## Evaluation of repeatability of measurements

Twenty-five trees from stand H12 were specifically chosen for analysis purposes since they had been TLS scanned twice ($TLS_P$ and $TLS_S$) and had also been NBE scanned twice ($NBE_{OB}$ and $NBE_{UB}$). Selecting these stems allowed us to assess the repeatability of both TLS centerline measurements and NBE centerline measurements on the same trees. These assessments are in addition to comparing the accuracy of TLS measurements in relation to NBE measurements.

## Data preprocessing

The measurement positions for the NBE scans were inverted in relation to the measurement positions for the TLS scans (stem sections were scanned tip first by the NBE scanner and butt first by the TLS scanner), and so the NBE data points had to be inverted, then translated, and finally vertically rotated to match the vertical positions of the TLS data points. In addition, the position of a tree in relation to the horizontal angle at which the NBE scanner contacted the stem differed from the position of the same tree in relation to the azimuth at which the TLS scanner contacted the stem. Hence, the centerline measurements generated by the TLS scans needed to be horizontally rotated (around the $z$ axis) in order to match the horizontal angle at which centerline measurements were taken by the NBE scanner. Figure 2 shows an example of inversion, translation, and rotation.

Inversion, translation, and rotation of the centerline of each stem were accomplished using a computer program written in Microsoft Visual Basic by the second author. Because there was no mark on either the standing tree or the felled stems that would allow an exact line up of the mill scan with the standing tree scan, the best horizontal rotation angle for the TLS centerline measurement was considered to be the one that produced the smallest root mean squared deviation (RMSD) between the NBE and TLS centerline measurements.

To perform the NBE and TLS centerline repeatability analyses, the data points were required to be translated and rotated (horizontally and vertically), but not inverted, as they were for the centerline measurement comparison between $TLS_P$ and $NBE_{UB}$. As with the translation and rotation of TLS and NBE centerline measurements, because there was no mark on either the standing trees or the felled stems that would allow an exact line up of the repeated scans, the best horizontal rotation angle for the centerline measurement comparison was considered to be the one that produced the smallest RMSD between repeat scan centerline measurements.

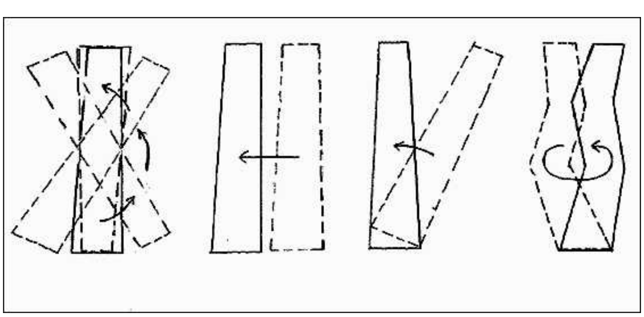

*Figure 2.—Methods used to invert, translate, and rotate the terrestrial laser scan centerline and translate and rotate the Nelson Brothers Engineering centerline.*

## Data analysis

We determined the following:

- The average RMSD between $NBE_{OB}$ and $NBE_{UB}$ centerline measurements for the lower stem sections for Stand H12
- The average RMSD between $TLS_P$ and $TLS_S$ centerline measurements for the identical lower stem sections that had been NBE scanned on the same stems from Stand H12
- The average RMSD between $TLS_P$ and $NBE_{UB}$ centerline measurements for the same stem segment scanned in the mill for Stands H12, M7, and L7

As already stated, only the bottom 17 m (approximately) of each stem (hereafter referred to as the lower stem section) was scanned in the mill.

Results were examined for two portions of the lower stem section; from the butt to where the taper function began (pretaper function) and from the butt to the top of the lower stem section (full stem section). Full stem section analysis was performed to determine how the taper function fit to the portion of the stem section where the scanner could not ''see'' affected the accuracy of the TLS centerline measurement. Full stem section lengths varied because tree heights varied, and not all stems were tall enough to meet the 17-m bucking standard used by BTF.

The sum of squared differences, a component of the average RMSD calculation, was calculated for each stem section using the following equations:

For $TLS_P$ versus $TLS_S$ scans:

$$\text{Sum of squared differences} = \sum_{i=1}^{n}\left[(TLS_{Px} - TLS_{Sx})^2 + (TLS_{Py} - TLS_{Sy})^2\right]$$

For $NBE_{OB}$ versus $NBE_{UB}$ scans:

$$\text{Sum of squared differences} = \sum_{i=1}^{n}\left[(NBE_{OBx} - NBE_{UBx})^2 + (NBE_{OBy} - NBE_{UBy})^2\right]$$

For $TLS_P$ versus $NBE_{UB}$ scans:

$$\text{Sum of squared differences} = \sum_{i=1}^{n}\left[(TLS_{Px} - NBE_{UBx})^2 + (TLS_{Py} - NBE_{UBy})^2\right]$$

where $x$ and $y$ are the centerline coordinates for each type of scan, and $n$ is the number of segments in the stem section. In these calculations a segment was 1 foot (3 dm) in length. The number of segments depended on the length of the stem section included in the comparison, the maximum number being about 57 (the length prebucked to fit within the mill's log scanning system). The RMSD for an individual stem section was calculated using the following equation:

$$\text{RMSD} = \sqrt{\frac{\text{Sum of squared differences}}{n}}$$

and the average RMSD for a stand was calculated using the following equation:

$$\text{Average RMSD} = \sum_{j=1}^{k} \text{RMSD}_j \div k$$

where $k$ is the number of measured stems in a stand.

Paired $t$ tests of RMSDs were undertaken to determine whether there were any statistically significant differences ($P = 0.05$) in repeatability of TLS and NBE centerline measurements for stems from Stand H12. Confidence intervals ($P = 0.01$) around the average RMSDs for TLS versus NBE centerline measurements were constructed to determine whether there were any differences in the accuracy of TLS measurements between stands.

# Results

## Repeatability of measurements

The results of the repeatability assessments for the TLS scans and the NBE scans can be seen in Table 1.

The average RMSD between repeated TLS centerline measurements below the taper function zone was 43 mm compared with 55 mm for the full stem section for stems in Stand H12. The average RMSDs between repeated NBE centerline measurements were 55 and 70 mm for the below the taper function zone and full stem section, respectively, for the same 25 stems from Stand H12. Paired $t$ tests indicated that the average RMSDs for TLS and NBE scans were not significantly different ($P = 0.05$) from each other for either the below taper function zone or the full stem section.

## Accuracy assessment of TLS scans in relation to NBE scans

The results of the $TLS_P$ versus $NBE_{UB}$ comparisons can be seen in Table 2. The average RMSD for Stand H12 for the portion of the stem below the taper function zone was 55 mm, which was 23 mm lower than for the full stem section (78 mm). The confidence limit range was also lower for the below taper function zone than for the full stem section.

The results of the centerline measurement comparison between $TLS_P$ and $NBE_{UB}$ centerline measurements for Stand M7 were very different from the comparisons for Stand H12. Below the taper function zone, the average RMSD was 22 mm lower for Stand M7 (33 mm) than for Stand H12 (55 mm). The confidence limit range was also lower for Stand M7 than for Stand H12, which indicated that the centerline measurements in Stand M7 more closely matched the NBE measured centerline of the stems. For the full stem section, comparison average RMSDs were 30 mm higher than for the below taper zone comparisons.

The results for the comparison between $TLS_P$ and $NBE_{UB}$ centerline measurements in Stand L7 were similar to those in Stand M7 for the section of the stem below the taper function zone. The average RMSD for the $TLS_P$ and $NBE_{UB}$ centerline measurement comparison was 23 and 1 mm lower than the average RMSD for the $TLS_P$ and $NBE_{UB}$ centerline measurements for Stands H12 and M7, respectively. The variability in RMSDs below the taper function zone was the lowest of all comparisons. The average RMSD for the full stem section in Stand L7 was lower than the average RMSD for either of the other two full stem section comparisons.

The average RMSD between $TLS_P$ and $NBE_{UB}$ centerline measurements was the same as the average RMSD between repeated NBE centerline measurements below the taper function zone; i.e., 55 mm. However, a comparison made between the average RMSD between $TLS_P$ and $NBE_{UB}$ measurements and the average RMSD between repeated TLS centerline measurements below the taper function zone showed a statistically significant difference ($P = 0.05$) of 12 mm.

Similar results were found for the full stem section comparisons. The difference between the $TLS_P$ versus $NBE_{UB}$ average RMSD (78 mm) and the average RMSD of repeated NBE measurements (70 mm) was not significantly

*Table 1.—Root mean squared differences (RMSD) between repeated centerline measurements using Nelson Brothers Engineering (NBE) mill scans and terrestrial laser scans (TLS) on the same 25 stems from Stand H12.*

| | Below taper function zone | | Full stem section | |
|---|---|---|---|---|
| | TLS | NBE | TLS | NBE |
| Average RMSD (mm) | 43 | 55 | 55 | 70 |
| SE (mm) | 6 | 7 | 5 | 8 |
| Lower confidence limit (99%) (mm) | 26 | 35 | 42 | 47 |
| Upper confidence limit (99%) (mm) | 60 | 74 | 69 | 92 |
| No. of stems | 25 | 25 | 25 | 25 |

*Table 2.—Root mean squared differences (RMSD) between Nelson Brothers Engineering mill scanner under bark and terrestrial laser scan centerline measurements in Stands H12, M7, and L7.*

| | Below taper function zone | | | Full stem section | | |
|---|---|---|---|---|---|---|
| | H12 | M7 | L7 | H12 | M7 | L7 |
| Average RMSD (mm) | 55 | 33 | 32 | 78 | 63 | 46 |
| SE (mm) | 5 | 3 | 2 | 6 | 13 | 5 |
| Lower confidence limit (99%) (mm) | 41 | 24 | 25 | 62 | 27 | 34 |
| Upper confidence limit (99%) (mm) | 68 | 42 | 39 | 95 | 99 | 58 |
| No. of stems | 25 | 35 | 38 | 25 | 35 | 38 |

different. The difference (23 mm) was statistically significant, however, between the $TLS_P$ versus $NBE_{UB}$ average RMSD and the average RMSD of repeated TLS measurements.

## Discussion

One of the difficulties with assessing the accuracy of 3D sweep measurements is selecting a standard against which new measurements can be compared. Accurate 3D measurements are very difficult to obtain by felling a tree and manually measuring a stem profile. We selected an industrial mill scanner to be the standard against which TLS-derived sweep measurements could be compared.

The NBE centerline measurement comparison between stems with bark left on and bark removed was performed to show repeatability of the mill scan measurements. The same tree was measured once with the bark on and once with the bark removed. Average RMSDs for centerline measurements of 55 and 70 mm for the stem section below the taper function zone and for the full stem section, respectively, indicate there is some variation in repeat measurements. This error could be due to the presence of small bits of bark or other organic matter attached to the stem that were picked up by the NBE scanner and resulted in an offset in the centerline measurement. The error could also be due to the ~17-m-long stem section bending and conforming to the mill scanner belt.

The TLS centerline measurement comparison between stems scanned from two locations (a primary and secondary scan point) was performed to show repeatability of the TLS scan measurements. Average RMSDs between repeat TLS measurements were 12 to 15 mm lower than those found for the repeat NBE measurements, but these differences were not statistically significant.

Average RMSD comparisons between the $NBE_{UB}$ and $TLS_P$ centerline measurements and repeat NBE measurements showed no statistically significant difference for either the below taper zone or the full stem section. Based on the $TLS_P$ and $NBE_{UB}$ comparisons and the NBE repeatability comparisons that were performed on the same stems from Stand H12, we were able to say with some certainty that TLS had the same capacity as the NBE industrial mill scanner to measure the centerline of a stem accurately.

The average RMSD of the centerline measurement in all stands was larger for the full stem section than for the portion of the stem below the taper function zone. As shown in Figure 1, the automated stem profile extraction procedures assume that the stem centerline in the taper function zone is a continuation of the centerline last ''seen'' by the scanner in the below taper function zone. This assumption could be the reason for the average RMSD of the full stem section always being larger than the average RMSD of the bottom portion of the stem. We note, however, that the average RMSD between over bark and under bark NBE measurements was also higher for full stem sections than for below taper zone stem sections, despite there being no assumption of centerline continuation into the taper function zone in this comparison.

Differences were noted between stands. The average RMSD was higher in Stand H12, the older stand with larger diameter trees, than in Stands M7 and L7 for both the below taper function zone and the full stem section. We have no explanation for this difference.

As noted in the ''Methods'' section, the algorithms used in the Autostem software were based on an assumption that stem cross sections were circular. However, ellipticity of stem cross sections was evident, particularly in the bottom few meters of stems. It is possible that fitting an ellipse to stem cross sections, instead of a circle, could have resulted in improved accuracy of centerline and sweep measurements for the poplar stands studied.

There are a number of limitations related to this study. First, measurements were made on a single species, albeit in three stands. Second, only one mill scanner and one TLS scanner were used in the comparisons. Results may differ with different mill scanners and TLS scanners. Third, no reference point was marked on each stem scanned. This meant that exact RMSDs could not be calculated, only minimum RMSDs for each tree. Differences between repeat mill scans could therefore be higher than reported. Similarly, differences between mill and TLS scans could be higher than reported.

Despite these limitations we can say that, based on the work carried out to date, the accuracy indicated by the ability of TLS to match the centerline measurements to mill scan centerline measurements shows some promise for the future of sweep determination in standing trees, particularly in the more highly valuable bottom portions of stems where sawlog material is often found. The TLS method benefits from being quick to capture data, is quantitatively rather than qualitatively based, and does not require destructive sampling of stems. Further research is required, however, to determine whether these conclusions extend beyond the mill scanner, TLS scanner, and poplar species evaluated.

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