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Jennifer S. Barnett for the degree of Master of Science in Forest Engineering presented on May 25, 2012.
Title: Estimating Volume and Value on Standing Timber in Hybrid Poplar Plantations Using Terrestrial Laser Scanning: A Case Study

Abstract approved:

Glen E. Murphy

Terrestrial laser scanning (TLS) may provide a way to increase timber value recovery by replacing manual timber cruising with a simple-to-use, cost-effective alternative. TLS has been studied in several trials worldwide. Past studies have not compared TLS based estimates with mill estimates of stem value and volume.

Three differently stocked stands of hybrid poplar were selected for diameter, stem sinuosity and height measurement using manual cruising and TLS. Selected trees were harvested and transported to a mill where they were scanned and then processed into lumber and chips. Data gathered using both manual and TLS methods were used to obtain stem volume and value estimates to compare with mill estimates.

Results indicated that TLS diameter measurements were more accurately matched to mill and manual measurements up to about 7.5 meters on the stem than above 7.5 meters on the stem in all three stands. Stem curvature comparisons indicated that the variation between TLS and mill centerline measurements was similar to the variation between repeat mill scan measurements of the same stems.

Using TLS as a pre-harvest inventory tool showed that additional revenue could be obtained from the reallocation of saw-log and chip log volume to veneer logs of various sizes in all three stands. It was also shown that the sampling error required to estimate stand value was greater than was required to estimate stand volume within the same error limits.

Estimating Volume and Value on Standing Timber in Hybrid Poplar Plantations Using Terrestrial Laser Scanning: A Case Study

by
Jennifer S. Barnett

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APPROVED:

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Dean of the Graduate School

I understand that my thesis will become part of permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Jennifer S. Barnett, Author

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CONTRIBUTION OF AUTHORS

Dr. Glen Murphy co-authored parts of the Introduction and Materials and Methods sections of Chapters 2, 3 and 4.

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Chapter 1 – Project Overview

1.1 The Evolution of Timber Inventory Since 1900

Since the development of a world timber market, standing timber volume has been measured by humans. This method of tree measurement, called timber cruising, recognizes the talent of foresters to measure standing timber with precision and accuracy. The same methods have been employed by timber cruisers to estimate timber value for about the past one hundred years. McClure et al. (1979) indicated that an assessment of forestland began about 1933 in the Southeast region of the United States and was based on inventory methods used in Sweden and Finland at that time. According to McClure et al. (1979) the Forest Survey used compass lines spaced ten miles apart and sampled plots of one-hundred and fourteen acres at six-hundred and sixty foot intervals along the compass lines. They indicated that within each plot trees were tallied by species and size to determine volume, and bored to determine the rate of diameter growth. By 1946 McClure et al. (1979) indicated that inventory methods of the Forest Survey advanced tremendously with the use of aerial photographs to classify land use and locate one-hundred and fourteen acre randomly selected ground plots on a systematic grid. For the surveys in this time period, McClure et al. (1979) indicated that crews marked the sampled plots and added a stump tally in order to estimate the amount of timber harvested in previous years. In the mid 1950's the Forest Survey incorporated variable radius plot sampling using an angle gauge in order to better assess growth and mortality rates, as well as timber removals, and between 1966 and 1977 variable radius plots were clustered and used to obtain volume estimates (McClure et al. 1979). By the mid-1950's the Forest Service also began to use composite volume tables to estimate standing timber volume. According to Gevorkiantz and Olsen (1955), volume tables could be used to estimate standing timber volume for forest surveys or timber valuation, among other uses. They claim that past volume tables did not take into account variable stem form, bark and taper across regions, so corrections needed to be made to account for such variation. In 1956, the Forest Service published "Tables for estimating board-foot volume of timber" written by Clement Mesavage and James W. Girard. These volume tables incorporated the Girard form class to account for variability in stem form. According to Avery and Burkhart (2002), the Girard form class quotient is the ratio between diameter under bark at the top of the first 16-foot log and the diameter at breast height (DBH) over bark. Just as the Forest Survey refined inventory methods over time others have sought to develop new and innovative ways to estimate standing volume with increased timeliness at the lowest cost. Tallant (2003) performed 1/5th acre plot inventory studies on the difference in the time required for measuring diameters with a logger's diameter tape or calipers, as well as the difference in the times required for measuring heights with a clinometer or a sonar-based hypsometer. He found that it was faster to measure diameters with calipers and heights with a sonar-based hypsometer.

According to Nieuwenhuis (2002) the main objectives of timber harvesting and production are volume and value maximization while minimizing costs. Nieuwenhuis (2002) explains that the importance of increasing value recovery is not given the consideration it should in pre-harvest inventory. The identification of stem defects is an important part of determining value associated with a stand because the volume and value estimation on an individual stem decreases with the existence of stem defects. According to Bell and Dilworth (2007) stem attributes such as scarring, knots, sweep, crotch and breakage require that a deduction in volume and value of a stem be made. In New Zealand the Atlas Cruiser system utilizes tree feature mapping to measure and describe the form and quality attributes of each tree within the inventory plot (Gordon and Baker, 2004). The cruiser records, for the entire length of a stem, the beginning and ending points of the defect. Then a code is applied to the particular defect and the Atlas Cruiser software determines the potential log product yields. That information is then coupled with market prices, and volume and value estimates to the user, along with a breakdown of products, the percentage of each product and the error limits associated with the estimates.

1.2 Costs Associated with Timber Inventory

Manual timber cruising has been assumed to be the best way to determine the volume and value that will be recovered at the mill from standing timber, but manual cruising is costly. Over time trends in the global timber market have changed which have made it imperative to find ways to minimize timber production costs. In 1979, Dr. James E. Moak began investigating the costs of timber production in the United States South. In his study, timber cruising was one of five increasing costs of timber production. He indicated that timber cruising costs increased by three times over the previous 24 years (Moak, 1979). Today, the costs of estimating standing timber inventory range from 7.2% of total harvesting costs in Ireland, to 5% of harvest costs in the Pacific Northwest (Murphy, 2008).

In recent times, the world economy has forced commercial timber companies to seek ways to minimize timber production costs. One of the areas where expenses can be reduced is in forest inventory. Modern technology has made it possible to maintain cruise measurement accuracy while minimizing the cost of traditional inventory methods. According to Bortolot (2006), conventional inventory methods can be disadvantageous because they are time consuming and labor intensive. Furthermore, Bortolot (2006) indicated that conventional inventory methods do not always produce sufficiently accurate results. A combination of remote sensing data collection (Aerial LiDAR) and ground collected information could produce a sufficiently accurate forest inventory estimate (Bortolot, 2006).

Good metrics of the quantity, quality and location of timber resources within each stand are essential for ensuring that wastage is minimized, harvest and volume growth increments are balanced, log products are optimally matched to markets, and the value of the forest is maximized at the time of harvest. Forest owners around the world are evaluating new approaches for obtaining these metrics with the goals of increasing their accuracy and reducing their data gathering costs. Emerging technologies include satellite imagery (Tomppo et al. 1999), harvester data collection and data mining (Murphy et al. 2006), airborne laser scanning (Reutebuch et al. 2005), and terrestrial laser scanning (TLS) (Bienert et al. 2007, Keane 2007).

1.3 A Cost Minimizing Alternative to Traditional Inventory Methods

TLS is a laser scanning system which mounts on a surveying tripod and can be used to measure tree attributes directly in the forest (See Figure 1.3.1). The TLS system, coupled with traditional methods of locating fixed radius plots, measures all trees in the plot either from the center of the plot (single scan setup) or at various positions outside of the plot (multiple scan setup). The fixed radius plot setup is shown in Figure 1.3.2 (Bienert et al. 2006). According to Bienert et al. (2006), the single scan setup is the least time consuming alternative.

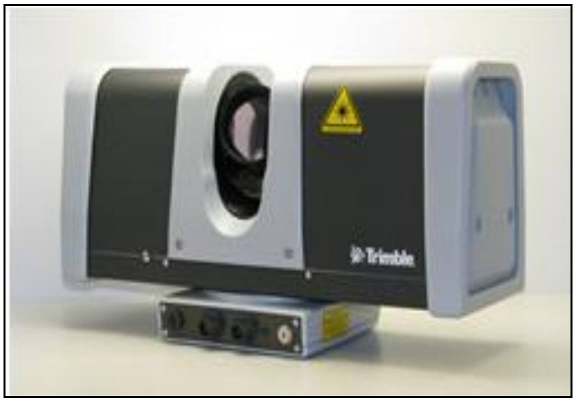


Figure 1.3.1 Trimble laser scanner

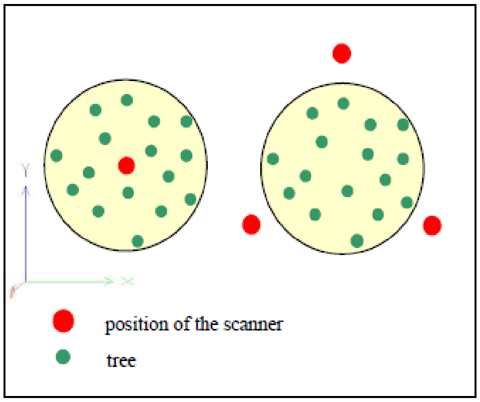


Figure 1.3.2 Image of scanner setup (Bienert et al. 2006)

The laser scanner scans a 360 degree dome sending out laser pulses which strike all objects in a plot, including the ground. According to Bienert et al. 2006, once a scan is obtained the data is processed resulting in a digital terrain model (DTM) used to determine the topography below the objects it scans and the profiles of the objects scanned in the plot. A circularity filter based on a circle adjustment algorithm determines which objects can be considered a tree (Bienert et al., 2006). Figure 1.3.3 shows laser returns of the outline of a stem. During processing the user defines the level of circularity that defines a stem. Bienert et al. (2006) indicate that once a stem is identified the DTM surface (Σ) and the slope of the ground (g) at the base of the stem are used to determine the height to DBH, as shown in Figure 1.3.4.

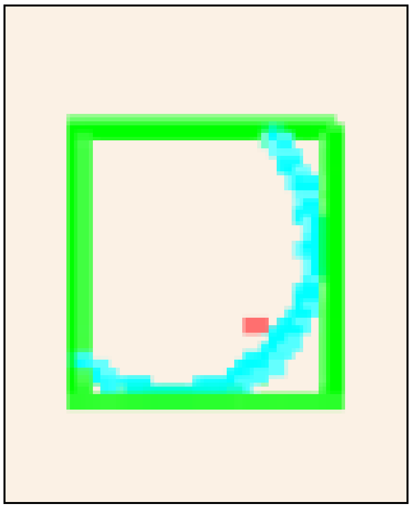


Figure 1.3.3 Object identified by TLS as a tree (Bienert et al. 2006)

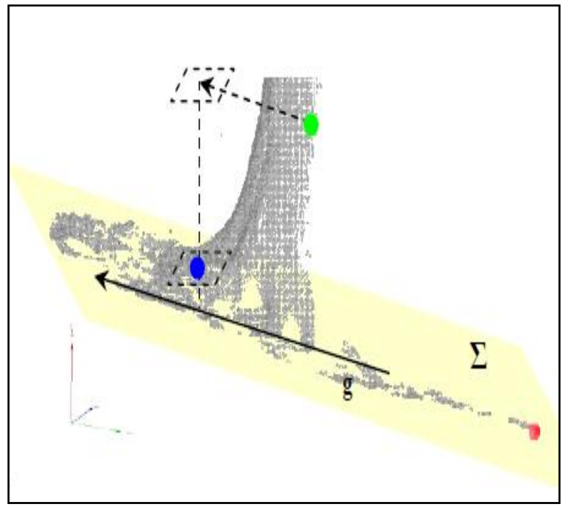


Figure 1.3.4 Calculation of height to DBH based on DTM surface (Σ) and ground slope angle (g) (Bienert et al. 2006)

Once the DBH has been determined from the laser returns the software fits disk segments based on a circle adjustment algorithm above and below DBH to create a stem profile (See Figure 1.3.5) based on the scanner measurements of the stem. From the stem profile the height of the tree is predicted to the top, as shown in Figure 1.3.6.

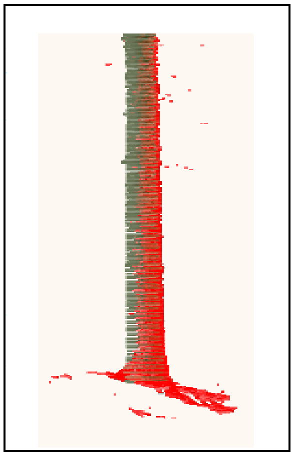


Figure 1.3.5 Stem profile generated from TLS diameter measurements (Bienert et al. 2006)

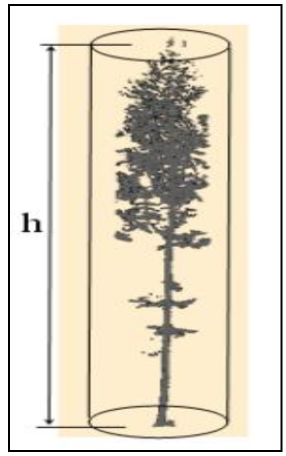


Figure 1.3.6 Height prediction from stem profile (Bienert et al. 2006)

TLS is being used operationally in Ireland to assess stand value and estimate log product yields. It has been studied in a number of trials worldwide. In Sitka spruce in Ireland, in Douglas-fir in Oregon, USA, and in radiata pine in Australia (e.g. Keane 2007, Murphy 2008, Murphy and Acuna 2010, Murphy et al. 2010) timber was measured with TLS, manually, and with a mechanical harvester. The stem diameters, volume and value recovery estimates resulting from each method were compared. These trials highlighted the potential utility of TLS technology and the conditions under which it might work best. Teobaldelli et al. (2008) have used TLS to measure stem diameters at a height of 1.37 meters or breast height (DBH), (sample of 21 trees) and upper stem diameters (sample of 3 trees) in 14-year old intensively managed poplar plantations in Italy. Average TLS diameters were reported to be within one centimeter of manually measured diameters. Antonarakis (2011) compared manual and TLS measured DBH's in complex riparian poplar forests in France and found a mean bias of less than a half a centimeter (~1.5%). Siefert et al. (2010) have simulated lumber recovery based on TLS scans of pine stems in South Africa.

As far as we have been able to determine, the relationships between TLS measurements and actual mill scan measurements, with respect to volume and value recovery estimation, have not been investigated for poplar stands. Nor has the ability of TLS to accurately scale logs based on log sweep been assessed. This TLS trial investigated the similarities and differences in volume and value recovery between TLS, mill and manual measurements in order to examine the accuracy that TLS measurements has in comparison to mill and manual measurements.

1.4 Project Area Description

GreenWood Resources, Inc. Boardman Tree Farm (BTF) is a hybrid poplar tree farm located near Boardman, Oregon just south of the Columbia River in eastern Oregon. BTF was interested in utilizing TLS as a tool for inventory and product allocation on standing timber. To facilitate this interest they agreed to allow a TLS trial to take place in the summer of 2010.

BTF contains approximately 10,000 hectares of hybrid poplar trees. Surrounding land is primarily utilized 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 which result in many trees having lean and sinuosity in the direction of the prevailing winds. The two-dimensional shape of the stems in cross section tends to be elliptical, as opposed to circular, due to wind loading. BTF is separated into various age classes and stocking densities on rectangular parcels representing individual stands. Each stand, approximately 28 hectares in area, contains hybrid poplar of the same age and at a particular stocking density. BTF grows and harvests trees on a 12 year rotation. Between ages two to five years trees are pruned in several lifts to a height of approximately 7.5 meters to produce a knot free sheath surrounding a knotty core. At maturity trees are harvested mechanically by a feller buncher. A grapple skidder is then used for tree length extraction to the roadside where trees are usually bucked to approximately 17 meters and delimbed by a static delimber/slasher (or processor/delimber). The 17 meter logs are then transported to a mill that is centrally located at BTF which 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.

1.5 Data Collection and Processing

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 seven year old trees stocked at 360 stems per hectare (spha), the medium stocked stand contained seven year old trees stocked at 550 spha and the highly stocked stand contained twelve year old trees stocked at 725 spha. For future reference the low stocked stand will be referred to as Stand L-7, the medium stocked stand will be referred to as Stand M-7 and the highly stocked stand will be referred to as Stand H-12.

Twenty equally spaced circular plots each of 10 meter radius - approximately three percent of a hectare - were located in each of the three stands. Plots were spaced at every 36^{th}, 31^{st} and 25^{th} tree in each of four straight lines in Stands H-12, M-7 and L-7, respectively. The perpendicular distance between lines was 36, 31 and 25 trees in Stands H-12, M-7 and L-7, 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 was created for each stand from the data collected.

A Trimble FX laser scanner was used to collect standing tree TLS measurements at 1 millimeter at 28 meters resolution. Scans were gathered at either one or two locations within each plot, the second scan only being gathered if tree(s) within the plot radius were occluded by other trees in the primary scan. The primary scan occurred at the center of the plot and the secondary scan approximately two meters from the plot center. Time to set up the scanner and take two scans per plot was usually less than half an hour.

Random subsamples of plots were selected for felling and detailed manual and mill measurements. There were 8, 4 and 6 plots randomly chosen from Stands L-7, M-7 and H-12, 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 L-7 and M-7, and 160 trees from Stand H-12, for a total of 300 trees that were transported to the mill.

From the 300 trees to be transported to the mill, 50 trees from each stand were manually measured using calipers for diameter over and under bark (bark was removed with an axe) to determine bark thickness at zero meters, 1.3 meters (DBH), 3 meters, 6 meters, and then at three meter intervals up to a 70 millimeter top (over bark). The diameter measurements obtained were used for the accuracy comparison. They were also used to develop over bark taper functions and bark thickness functions for each of the three stands.

Trees from the sub-sampled plots were then transported to the mill and bucked at about 17 meters (the maximum length for the mill's log scanner). The bottom 17 meter stem section was scanned using the mill's Nelson Brothers Engineering (NBE) scanner for diameter and sweep with the bark on (See Figure 1.5.1 for an example of the display screen). The trees were then rescanned after debarking and optimally bucked to saw log lengths (8 to 12 feet or 2.6 to 3.8 m). The bucked logs were then sawn in the mill and lumber recovery recorded. Lumber recovery and grade data were combined with lumber prices, chip prices and mill operating costs to determine return-to-log mill-door values for logs of different lengths, dimensions and sweep classes.

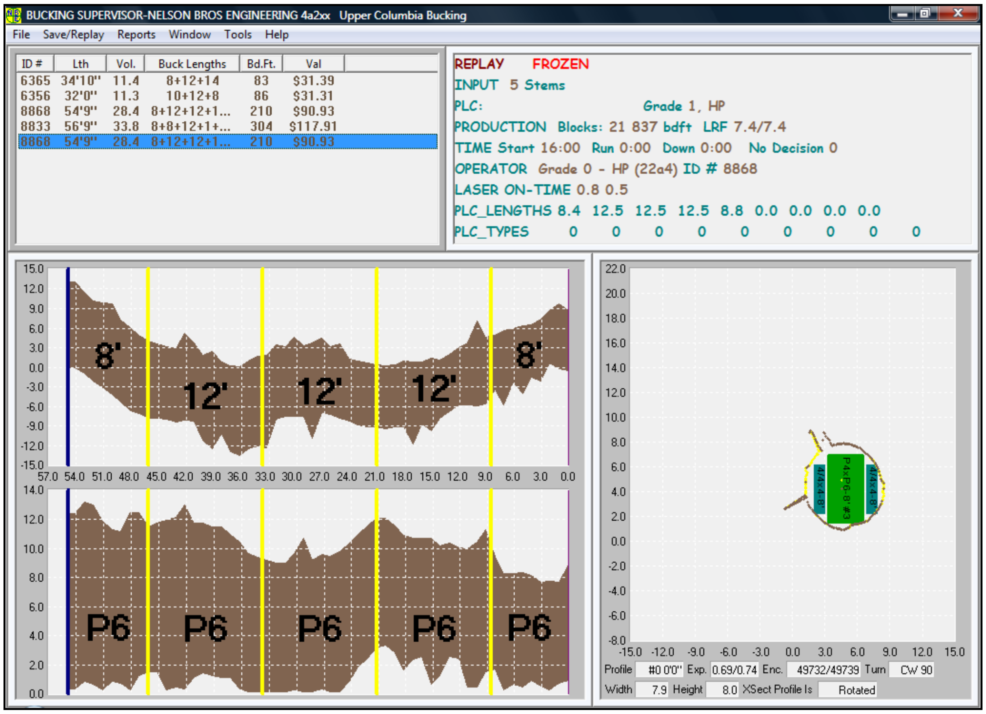


Figure 1.5.1 Log specifications (upper left), bucking lengths (lower left) and boards to be cut (lower right) output on the Nelson Brothers Engineering display screen

To generate mill scans, each stem was laid on a conveyer belt at the mill and then run through the NBE scanner. 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 down the stem. NBE modified their software so that a text file of the three dimensional profile of each stem was available. 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.

After the TLS and NBE scans were processed value from the TLS scanned trees had to be determined for the volume and value analyses. TLS with optimal bucking (TLSOB) was used to obtain estimates of value on each individual stem. TLSOB differs from TLS in that TLS data in the form of a text file is read into VALMAX optimal bucking software developed by Glen Murphy. VALMAX combines market prices and product specifications with the TLS scan data to optimally allocate log products from the standing timber based on the maximum value from each stem. This process is illustrated in Figure 1.5.2.

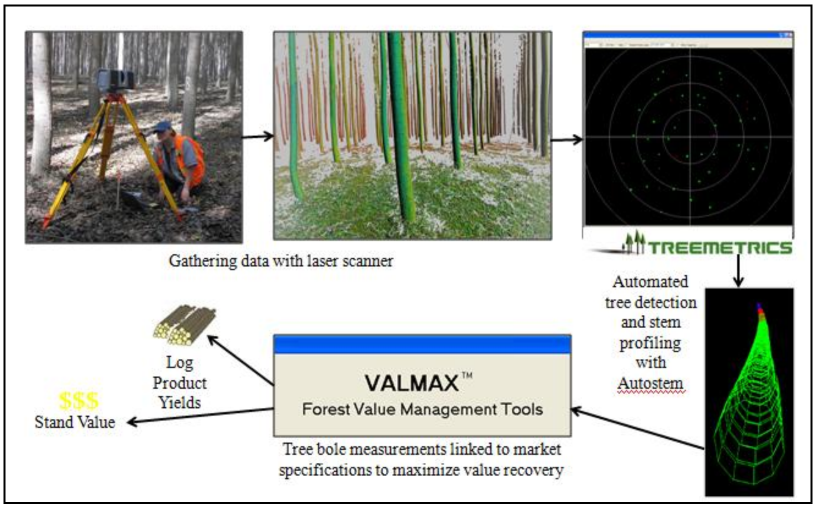


Figure 1.5.2 Process of turning TLS data gathered in the forest (upper left) into TLSOB results by processing plot data into detailed stem profiles (right) and using VALMAX optimization software (bottom center) to generate optimal log product yields and stand values (bottom right)

1.6 Research Objectives

There were two main objectives to this research; to determine the capacity of TLS to produce accurate diameter and sweep measurements and to demonstrate some of the uses of TLS.

One of the most important aspects of commercial timber production is the ability to assess the volume of merchantable timber in a stand. We sought to determine TLS's ability to estimate the hybrid poplar volume in each of three stands by comparing the volume estimated by manual cruising to the TLS volume estimate. The objective of this comparison was to compare TLS volume estimates in standing hybrid poplar against traditional cruising methods. Results will indicate whether TLS has the ability to produce volume estimates that reflect the volume estimated from traditional cruising.

A major component of volume estimation by any method is accurate diameter measurement. We were able to collect diameter measurements using manual, TLS and NBE mill scan methods with the goal of comparing the average difference in diameter measurement between all three methods at various intervals (see Chapter 2 Methods) on each stem. An assessment of the average difference in diameter measurement will demonstrate TLS's ability to measure diameters at various intervals on a stem in comparison to manual and NBE diameter measurements.

We remarked previously on the high level of sinuosity present in the hybrid poplar stands at BTF. According to BTF, the high level of sinuosity present in their hybrid poplar stands results in loss of saw log volume recovery at the mill. One of the objectives of this trial was to compare the accuracy of TLS's stem and log centerline measurements on standing hybrid poplar against NBE stem centerline measurements taken at the mill. The results of this comparison will demonstrate TLS's ability to accurately assess the level of sinuosity present in each stem and log by comparing the level of error between TLS and NBE centerline measurements.

The ability of TLSOB to generate various product allocation schemes on standing timber was evaluated. The objective was to determine the potential value gained from allocating some saw log timber to veneer production, which BTF currently does not do. We demonstrate how the results can then be applied to evaluation of changes in markets and mill design.

In addition to product allocation we wanted to demonstrate the utility of TLSOB for determining the sample size required for estimating stand volume or value for a given error level. There were two objectives; firstly to compare desired sample size based on manual measurements using traditional simple random sampling (SRS) methods with desired sample size obtained by SRS with TLSOB for estimating stand volume, and secondly to compare desired sample size for value estimates with desired sample size for volume estimates.

In the following chapters we will compare the accuracy of TLS measurements with measurements gathered from mill scanners and a traditional timber cruise. We will also demonstrate the use of TLSOB to determine desired sample size and allocate products in standing timber with the goal of maximizing value. In Chapter 2 we compare TLS diameter measurements to manual and NBE diameter measurements, and compare TLS volume estimates to volume estimates calculated from the NBE diameter measurements. In Chapter 3 TLS centerline measurements will be compared to centerline measurements obtained with NBE scanners for all three stands. Chapter 4 demonstrates the use of TLSOB to allocate log products in standing timber in all three stands. Chapter 5 demonstrates the use of TLSOB to determine desired sample size in standing timber and compares the results obtained by traditional methods in all three stands.

Chapter 2 – Diameter Measurement and Calculated Volume Comparison

2.1 Introduction

Volume estimation in standing timber has long been the work of timber cruisers in forestry. Manual methods of estimating volume have virtually remained unchanged since forestry was in its infancy. In the early 1900's forest surveys and reconnaissance became an important part of British Columbia's growing economy. Parminter (2000) indicated that early in the development of timber cruising in British Columbia timber volume calculation was more an estimation, or "rule of thumb" process than an accurate assessment of the amount of merchantable wood in a stand. The Royal Commission decided that it was imperative for British Columbia to produce an accurate estimate of the merchantable timber contained on their land, so timber cruisers performed forest reconnaissance all over British Columbia and determined that the timberland contained 50% more saw timber volume than the Royal Commission's previous estimates (Parminter, 2000). The Royal Commission's findings illustrate the importance of generating accurate cruise data for timber production.

Though a basic measurement, diameter is one of the most important measurements which can be made in the process of taking timber inventory because both volume and value of standing timber is often estimated based on this parameter. In order to obtain a reliable estimate of volume it is important to acquire accurate measurements of diameter and height.

Accuracy of measurement is defined by West (2009) as "the difference between a measurement or estimate of something and its true value". Accuracy is typically scaled in terms of bias and precision. According to West (2009), bias illustrates the difference between the average of a group of measurements and the true value of the item being measured and precision illustrates the differences in repeated measurements of the same point. Different measurement tools produce different levels of accuracy. When measuring a tree the diameter tape is most commonly used, according to West (2009). A metric diameter tape measures the diameter of a tree to the nearest millimeter because it is calibrated to 1 millimeter increments (West, 2009). With a diameter tape measurement we say that the measurement is accurate to the nearest millimeter. Another tool used to measure tree diameters are calipers. According to West (2009), the measurement acquired by a diameter tape differs from the measurement acquired using calipers in that calipers measure one diameter of the tree and a diameter tape acquires the average diameter at a particular measurement point. Mechanical harvesters are often used in timber harvests in order to measure diameters and heights. Marshall et al. (2006) indicated that mechanical bucking systems typically lose 18% of possible value, as compared to an 11% loss in potential value with motor manual systems. They claim that possible sources of potential value loss include errors in diameter and length measurements made by the mechanical harvester.

It is difficult to measure the level of accuracy that TLS produces in diameter measurements because studies vary as to the most accurate method of diameter measurement. In other words, there is no way to determine which diameter measurement is the accurate one. We can perform a meaningful comparison between TLS and NBE and TLS and manual diameter measurements that will indicate the level of accuracy that TLS possesses in relation to traditional standing timber diameter measurement methods such as manual.

2.2 Methods

In addition to field data collection on the seventy trees from each of Stands L-7 and M-7, and one-hundred and sixty trees from Stand H-12, the raw TLS and NBE measurement data were required to be converted into a useable form for comparison purposes. As noted in Chapter 1 only the bottom 17 meters (approximately) of each stem was scanned by the NBE scanner at the mill. It was therefore necessary to "crop" the manual measurements and the TLS measurements so that all comparisons were made on the same stem segments for each stem. The following is a description of the additional methods used to convert the data for comparison purposes.

2.2.1 Extraction of the TLS Measurements

The Trimble laser scanner generated a scan file in C3D format. These files were then converted to a *.pts file format using the Trimble FX Controller computer program. The *.pts files were then converted by Treemetrics Ltd. to *.dat file format. The *.dat files were then imported into Treemetrics' Autostem software which identified tree locations within each plot, produced profiles of each tree and then exported the plot data as a *.tre file format. The *.tre files contained the actual individual stem measurements needed for analyses. The *.tre files were read in Microsoft Notepad and each contained the diameter and abscissa and ordinate coordinates of the centerline at 1 decimeter intervals up the entire length of each stem to a 7 centimeter top.

TLS cannot "see" through stems, branches or leafy vegetation. In the upper portions of the stem, one of the three taper functions, developed using multiple linear regression for the three stands was used by the Autostem software to automatically estimate diameters for stem sections that could not be seen. The taper function used by Autostem was a modified Kozak equation. The equation used was:

$$\ln\left(\frac{d}{D}\right) = f\left(\begin{array}{l} \ln(X)X^6,\ \ln(X)X^2\left(\frac{D}{H_S}\right),\ \ln(X)X^3\left(\frac{D}{H_S}\right),\ \ln(X)X\left(\frac{D}{H_S}\right), \\ \ln(X)X^2\left(\frac{D}{H_S}\right)^2,\ \ln(X)\left(\frac{1}{h}\right),\ \ln(X)\left(\frac{H_S}{\sqrt{h}}\right),\ \ln(X)\left(\frac{H_S{}^2}{\sqrt{h}}\right) \end{array}\right)$$

Where D is DBH, d is the diameter at the specified height, H_S is the felled stem height, h is the height of the measurement above ground and X = $\frac{(H_S - h)}{(H_S - H_{bh})}$, where H_{bh} is the distance from the diameter measurement to breast height.

Stand specific taper functions were developed using multiple linear regression and based on the over bark diameter measurements gathered using calipers of the 50 felled trees in each stand. For Stand H-12 the root mean squared error (RMSE) was 14.0 millimeters and for Stands M-7 and L-7 the RMSE was 10.3 millimeters.

Autostem also predicted the heights of the stems in each of the three stands. The DBH/height equation used to predict heights was developed from manual field measurements of DBH and height from each plot and was estimated using simple linear regression. The following equations describe the relationship used to predict the heights:

For Stand H-12:

$$\ln(H_S) = 3.954 - 140.58\left(\frac{1}{D}\right) \quad (R^2 = 0.83,\ MSE_{Reg} = 1.47,\ MSE_{Res} = 0.007)$$

For Stands M-7 and L-7:

$$\ln(H_S) = 3.520 - 110.56\left(\frac{1}{D}\right) \quad (R^2 = 0.70,\ MSE_{Reg} = 2.05,\ MSE_{Res} = 0.010)$$

The bark thickness ratio, defined as the diameter under bark divided by the diameter over bark, was used to simulate the removal of bark on each stem in all three plots. The bark thickness ratio used in Stand H-12 was 0.944 and in Stands M-7 and L-7 it was 0.948.

2.2.2 Extraction of the NBE Measurements

The mill scans were read into NBE’s modified New Buck 4 software which generated a log profile at 3 decimeter increments for the scanned length of each stem. The log profile included the centerline and radii (to the closest 1/10th of an inch) in 1 degree increments for each measurement point. Software, provided by Glen Murphy, converted these log profiles so that they contained a centerline and average diameter (in millimeters) for each decimeter of scanned stem length. The diameter measurements obtained were used for the accuracy comparison.

2.2.3 Chi Square Test for Difference in Diameter

Using diameter measurements obtained by the TLS, NBE and manual data collection methods we compared the average difference in diameter measurement on a plot and stand level for each of the three stands. For each stem, the manual diameter measurement was subtracted from the TLS diameter measurement at the butt, DBH, 3 meters, 6 meters and every 6 meters thereafter up the stem. The comparison was made on stems with the over bark for plots 1 to 6 in Stand H-12, plots 1, 6, 11 and 16 in Stand M-7 and plots 1 to 8 in Stand L-7 and with the under bark for plots 1 to 6 in Stand H-12. The average difference in diameter measurement at each interval was then obtained for each plot and for the three stands using a Microsoft Excel spreadsheet.

A Chi Square Test was used to determine if the average differences in diameter measurement at each interval on the stem were statistically significant. For all three stands the test was performed on each plot and for the entire stand. The Chi Square test was a modified version of the traditional Chi Square test in order to determine what percent of the true NBE and manual measurement the TLS measurement fell within. The equations used for the Chi Square test were:

$$\chi^2_{(n-1)} = \frac{\sum_{i=1}^{n}(x_i - \mu_i)^2}{\sigma^2}$$

$$\sigma^2 = \frac{E^2}{1.96^2}$$

$$E_i = \frac{P\mu_i}{100}$$

$$\sigma_i^2 = \frac{E_i^{\ 2}}{1.96^2} = \frac{P^2\mu_i^{\ 2}}{196^2}$$

$$\chi^2_{(n-1)} = \sum_{i=1}^{n}[\frac{(x_i - \mu_i)^2}{\sigma_i^{\ 2}}] = \sum_{i=1}^{n}[\frac{196^2(x_i - \mu_i)^2}{P^2\mu_i^{\ 2}}] = \frac{196^2}{P^2}\sum_{i=1}^{n}(\frac{x_i}{\mu_i} - 1)^2 ,$$

where P is the percent error from the true value, x_i is the observed TLS diameter measurement and μ_i is the true NBE or manual diameter measurement. A Microsoft Excel spreadsheet was used to determine the percent error of the observed diameter measurement from the true diameter measurement.

2.2.4 Chi Square Test for Difference in Volume

A comparison was also made between TLS and NBE volume estimates in Stand H-12. Diameter data from all plots in Stand H-12 was used in calculating the volume. The *.tre files contained the TLS volume for each decimeter segment up the stem in liters. The volume was obtained in cubic meters using the following conversion:

1 liter = 0.000001 cubic meters

The *.txt files contained the NBE radius measurements for each 3 decimeter segment up the stem in millimeters. The volume was obtained in cubic meters using the following equation:

$$\text{Volume} = 0.000000001(\Pi r^2 h),$$

where r is the average in millimeters of the diameters at each end of the 3 decimeter segment and h is the 3 decimeter segment (300 millimeters). The comparison was made between the TLS and NBE volumes obtained from each stem. To obtain the entire stem volume the segment volumes were summed.

A Chi Square test was used to determine if there were statistically significant differences between the whole stem volumes generated by TLS data and those generated by NBE data. The same Chi Square test used to determine statistically significant differences in diameter measurement was used to determine statistically significant differences in volume.

2.3 Results

2.3.1 Diameter Measurement Comparison

We first examined the performance of TLS on over bark diameter measurements in Stand H-12. Except at the butt and at DBH, where TLS overestimated the diameter by a small amount, TLS underestimated the diameter at every segment when compared to the NBE diameter at the same segment. It is evident from Figure 2.3.1.1 that diameter measurements collected by TLS at lower segments on the stem were, on average, more accurately matched to the NBE diameter measurements than diameter measurements collected at higher segments on the stem. Similar results were found for the comparison between TLS and manual methods shown in Figure 2.3.1.1. Overall, for over bark diameter measurements obtained in Stand H-12 TLS performed well up to the six meter height on the stem when compared to NBE and manual diameter measurement methods.

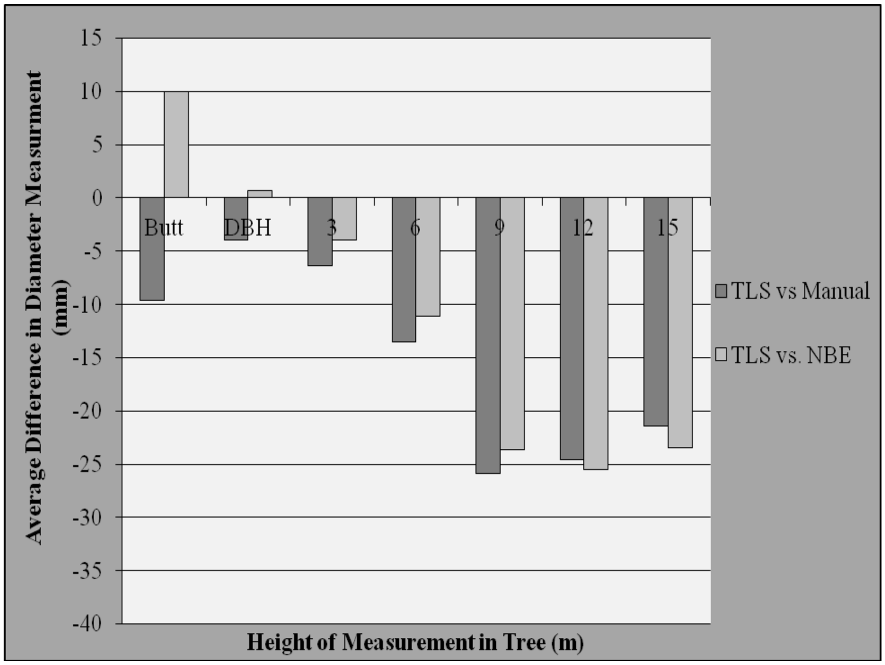


Figure 2.3.1.1 Average difference in over bark diameter measurement between TLS and manual measurement methods and TLS and NBE measurement methods for plots 1 to 6 in Stand H-12.

The trend for the under bark comparison for Stand H-12 shown in Figure 2.3.1.2 resembled the trend for the over bark comparison for Stand H-12 in that smaller average differences were found at lower segments than at higher segments on the stem. The differences in average under bark diameter measurement for the comparison between TLS and manual methods were small from the butt to 3 meters (under 10 millimeters deviation). From the 6 to 9 meter height on the stem the deviation of the TLS average from the manual average increased steadily and then decreased slightly at the 12 and 15 meter heights. The comparison between TLS and NBE average difference in under bark diameter measurement followed the same trend as the TLS and manual comparison. Overall, for both the TLS and manual and TLS and NBE comparisons, the average differences in under bark diameter measurement were larger from the three to fifteen meter height than the average differences in over bark diameter measurement, but from butt to DBH the average difference in under bark diameter measurement improved over the over bark comparison.

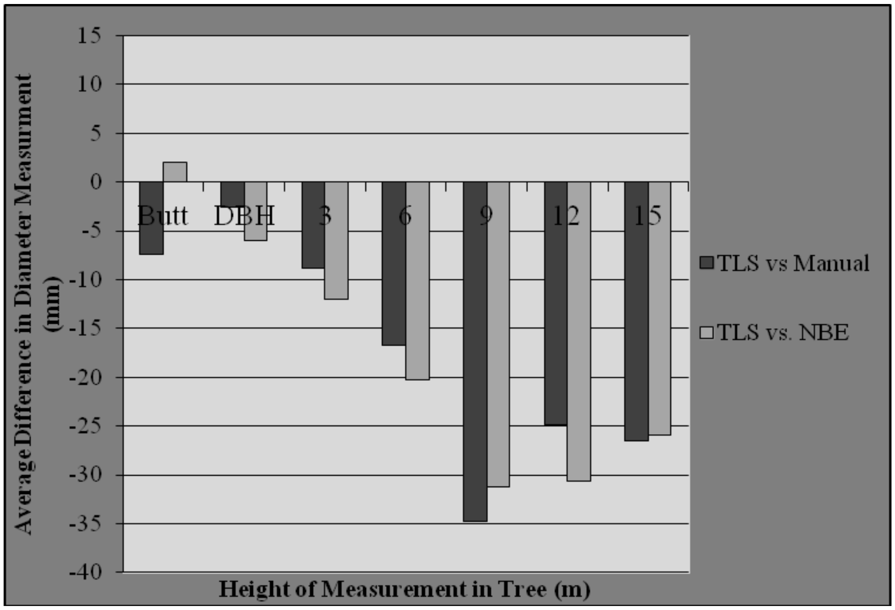


Figure 2.3.1.2 Average difference in under bark diameter measurement between TLS and manual measurement methods and TLS and NBE measurement methods for plots 1 to 6 in Stand H-12.

The trees in Stand M-7 and Stand L-7 were not as tall as the trees in Stand H-12, so we were only able to complete the diameter measurement comparison on the bottom nine meters of stem for the comparison between TLS and NBE average diameter measurements. Results indicated much better accuracy for Stand M-7 than for Stand H-12. Figure 2.3.1.3 indicates that TLS overestimated the average NBE diameter measurement from the butt to 3 meters and then underestimated the NBE diameter measurements from 6 to 9 meters. The discrepancies in average diameter measurement between TLS and NBE were small (from 11 millimeters over to 16 millimeters under the average NBE measurement). Results indicated that TLS underestimated the manual diameter measurement from the butt to 9 meters; however, as with the comparison between TLS and NBE measurement methods the discrepancies are small (from 7 to 16 millimeters under the manual measurement).

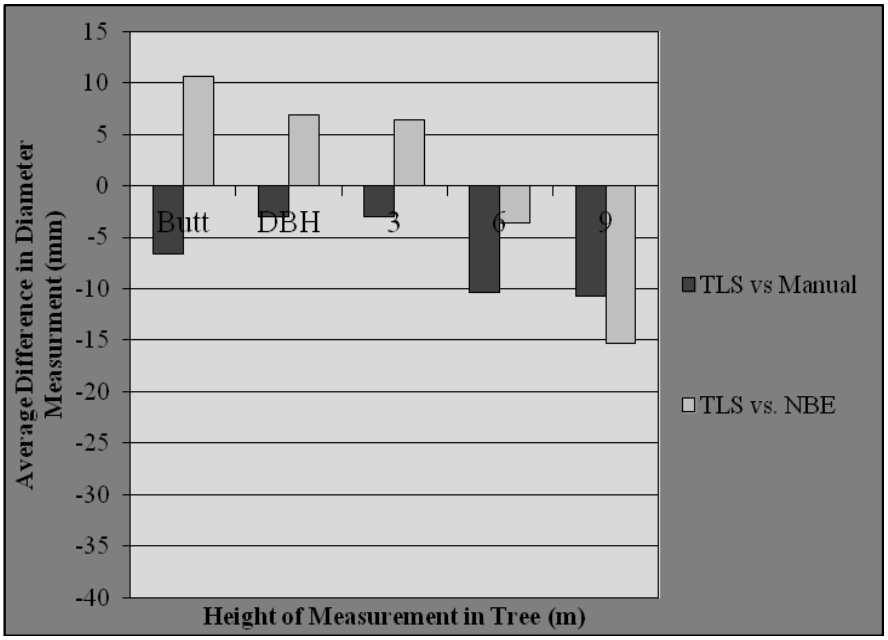


Figure 2.3.1.3 Average difference in over bark diameter measurement between TLS and manual measurement methods and TLS and NBE measurement methods for plots 1, 6, 11 and 16 in Stand M-7.

TLS performed well in Stand L-7, although it overestimated the average NBE diameter measurement and underestimated the average manual diameter measurement. Figure 2.3.1.4 shows the average difference in over bark diameter measurement between TLS and manual and TLS and NBE methods. There were no average differences in diameter measurement over 10 millimeters for either the manual or NBE comparison. The largest deviation of the TLS measurement from both the manual and NBE measurement was at the butt. All other deviations, with the exception of the TLS versus manual comparison at the 6 meter height, were less than 5 millimeters.

Figure 2.3.1.4 Average difference in over bark diameter measurement between TLS and manual measurement methods and TLS and NBE measurement methods for plots 1 to 8 in Stand L-7.

2.3.2 Chi Square Test for Difference in Diameter Measurement

We tested the hypothesis that there were no statistically significant differences outside of 10% between TLS and manual and NBE over bark diameter measurements obtained from all three stands. In Stand H-12 there was strong evidence of a difference between average TLS diameter measurements and average manual and NBE diameter measurements at every height segment on the stem when testing the differences at 10% accuracy (See Tables A-1 and A-2 in the Appendix). Less accuracy was required at the bottom portion of the stem than at the top in order for the differences in average diameter measurement not to be statistically significant in Stand H-12. At the top the allowable error between TLS and manual methods was almost 50% in Stand H-12 which translates to about a 100 millimeter difference in average diameter measurement (See Table A-2 in the Appendix). The allowable error at the top of the stem between TLS and NBE methods was smaller (about 35%) than the allowable error between TLS and manual methods (See Table A-1 in the Appendix).

At all heights on the stem there was strong evidence of a difference between the average under bark TLS diameter measurements and average under bark manual and NBE diameter measurements at 10% allowable error for Stand H-12. As height on the stem increased the allowable percent error for little to no difference in diameter measurement increased (See Tables A-3 and A-4 in the Appendix).

For Stand M-7 the Chi Square test indicated that there was no evidence of a difference between average TLS and manual diameter measurements obtained at DBH (See Table A-6 in the Appendix). At all other heights on the stem results of the Chi Square test indicated that there was evidence of a difference between average TLS and manual diameter measurements and an allowable error of 21 to 26% would be required for there to be little to no difference in TLS and manual average diameter measurement. Results of the comparison between average TLS and NBE diameter measurements indicated that there was strong evidence of a difference at every height segment on the stem when testing the differences within 10% accuracy (See Table A-5 in the Appendix). The allowable error for little to no difference in average TLS and NBE diameter measurements was 24.5 to 33.5% depending on the height segment, which was higher than for the TLS and manual comparison.

The comparison between average TLS diameter measurements and average manual and NBE diameter measurements for Stand L-7 indicated significant differences in diameter measurement. There was strong evidence of a difference within 10% of the average manual and NBE diameter measurements at all measurement intervals except DBH (TLS vs. manual and NBE) and 3 meters (TLS vs. manual) (See Tables A-7 and A-8 in the Appendix). At DBH and 3 meters the allowable error was 10 to 11.5%, respectively. At the upper segments of the stem, depending on the height segment, the allowable percent error to achieve little to no difference between average TLS and NBE diameter measurement was 12 to 16.5% compared to 13 to 28.5% for little to no difference between average TLS and manual diameter measurements.

2.3.3 Interval for Little to No Evidence of Significant Diameter Difference

Just because the percent allowable error increased as height increased on the stem it did not necessarily mean that the actual allowable error increased. Figure 2.3.2.1 indicates the interval of allowable error between average TLS and manual diameter measurements in Stand H-12 in order for there to be no statistically significant difference in average diameter measurement. Even though the percent allowable error increased as the height on the stem increased, it was evident that the actual allowable error in millimeters stayed the same, with some exception around the 9 and 12 meter height on the stem. This translates to diameter measurement discrepancies of about 40 to 50 millimeters between TLS and manual measurement methods up the entire stem. This finding was consistent with the comparison between average over bark TLS and NBE diameter measurements, as well as for the under bark diameter measurement comparison.

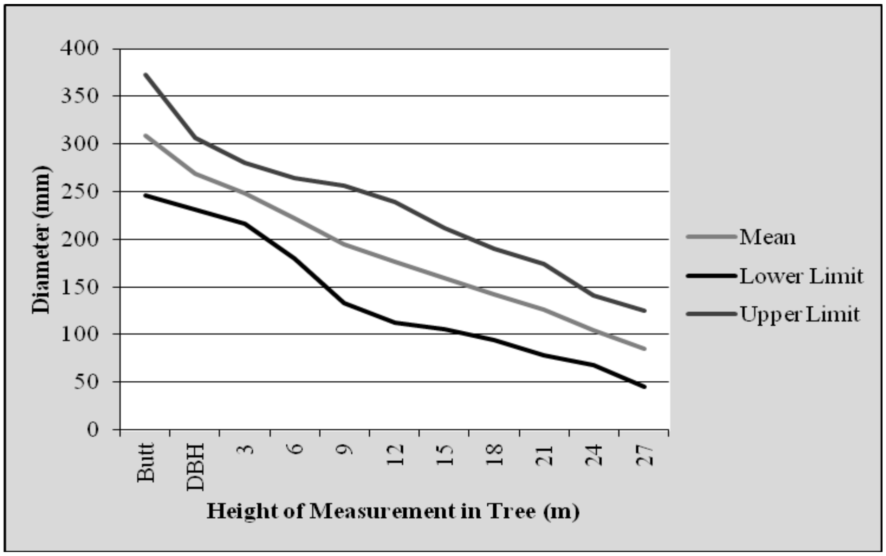


Figure 2.3.3.1 Actual interval of allowable error for a conclusion of little to no difference in over bark diameter measurement between TLS and manual measurement methods for plots 1 to 6 in Stand H-12.

Figures 2.3.3.2 and 2.3.3.3 show the average differences in actual allowable error between TLS and manual and TLS and NBE, respectively, for Stand M-7. We found that the actual allowable error for little to no difference in average diameter measurement was larger for the comparison between TLS and NBE methods than for the comparison between TLS and manual methods. This indicates that the error in diameter measurement was consistent up the entire stem for both TLS and manual and TLS and NBE comparisons; however, TLS did not perform as well against NBE diameter measurements as it did against manual diameter measurements.

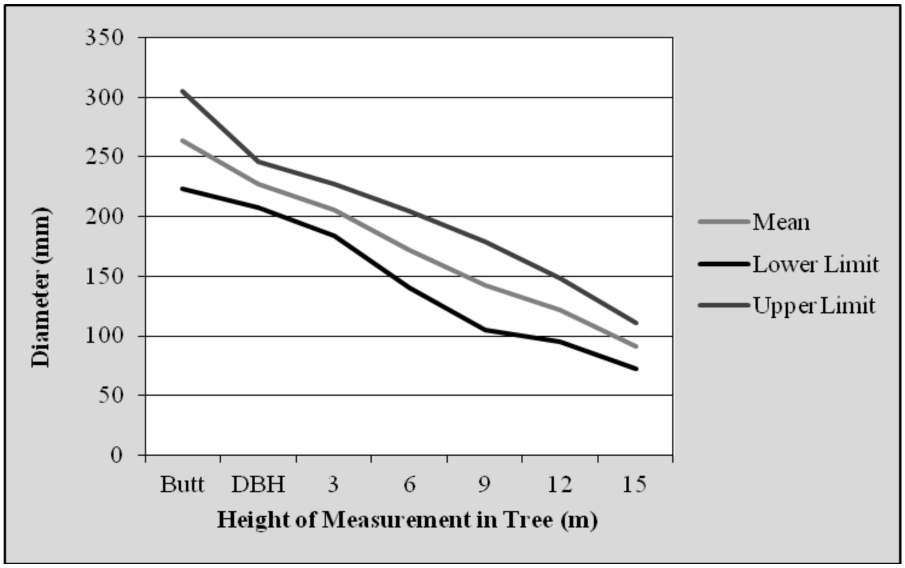


Figure 2.3.3.2 Actual interval of allowable error for a conclusion of little to no difference in over bark diameter measurement between TLS and manual measurement methods for plots 1, 6, 11 and 16 in Stand M-7.

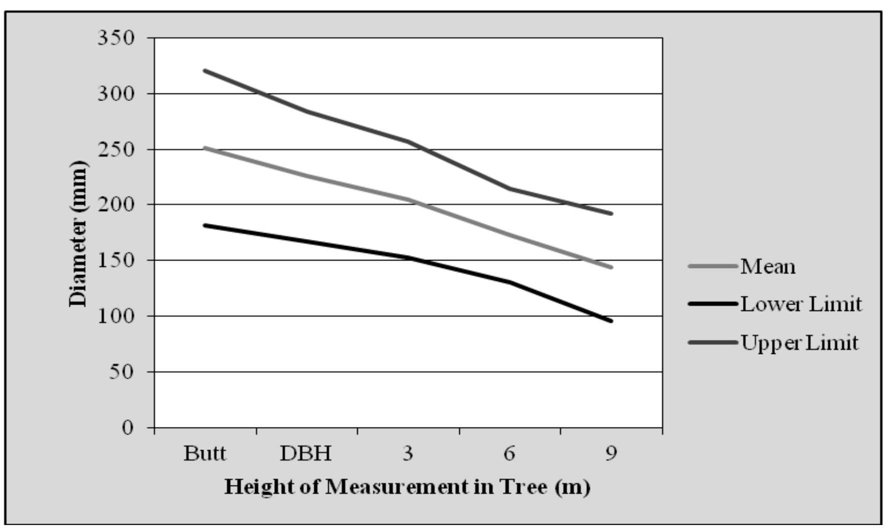


Figure 2.3.3.3 Actual interval of allowable error for a conclusion of little to no difference in over bark diameter measurement between TLS and NBE measurement methods for plots 1, 6, 11 and 16 in Stand M-7.

It is clear in Figure 2.3.3.4 that the allowable diameter error to achieve little to no difference in over bark diameter measurement was consistent from DBH to 18 meters for the comparison between TLS and manual measurement methods in Stand L-7. The exception was at the butt where the allowable measurement error was much larger. This indicated that the actual error in diameter measurement was the same for each height position on the tree. This was the most consistent measurement error of all three of the stands and indicated that TLS had the same level of difficulty measuring diameter at all measurement heights on the tree except at the butt. At the butt the allowable error for little to no evidence of a difference in diameter measurement was close to 100 millimeters. TLS had about the same error as compared to manual diameter measurements when compared to NBE diameter measurements, except at the butt where the error was lower for the TLS versus NBE comparison. The minimum deviation from the NBE average for there to be little to no evidence of difference in diameter measurement was consistent at all measurement points up the stem, including at the butt. The comparison between TLS and NBE at the butt fit the trend for the rest of the stem much more closely in Stand L-7 than in stands H-12 and M-7. Overall, the allowable deviation from the NBE average for there to be little to no evidence of a difference in diameter measurement was between about 25 to 40 millimeters.

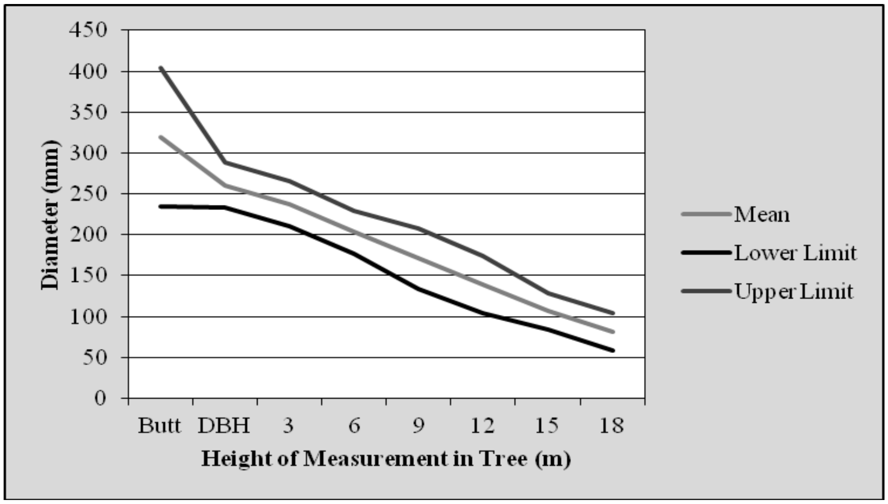


Figure 2.3.3.4 Actual interval of allowable error for a conclusion of little to no difference in over bark diameter measurement between TLS and manual measurement methods for plots 1 to 8 in Stand L-7.

2.3.4 Volume Comparison (TLS versus NBE)

A comparison between the volume in Stand H-12 plots 1 to 6 obtained from the TLS measurements on standing timber and NBE diameter measurements was made in order to determine to what degree the error in diameter measurement between the two methods affected the calculated volume. Table 2.4.5.1 shows the total TLS and NBE volume per plot and the difference between the volumes obtained by the two methods. TLS underestimated the volume in all plots measured by TLS and NBE methods. The range of underestimation of volume by TLS across plots was between 0.08 cubic meters (0.5%) and 2.59 cubic meters (18.1%). The average TLS volume underestimation for Stand H-12 was 1.58 cubic meters per plot (11.7%).

Table 2.3.4.1 Stand H-12 comparison between merchantable volumes estimated from TLS and NBE diameter measurements.

Stand 1 Plots 1 to 6						
Plot	**TLS Volume (m^3)**	**NBE Volume (m^3)**	**Difference (m^3)**	**Tree Count**	**Weight**	**Weighted Diff.**
1	10.70	13.11	-2.41	20	0.183	-0.443
2	11.74	14.33	-2.59	22	0.202	-0.523
3	15.35	15.42	-0.08	21	0.193	-0.015
4	13.20	14.77	-1.57	21	0.193	-0.303
5	9.19	10.90	-1.71	17	0.156	-0.267
6	4.70	5.05	-0.35	8	0.073	-0.026
Total	64.87	73.59	-8.71	109	-	-
					Average	-1.58

The results of the Chi Square test for difference in volume measurement by plot were not surprising. Table 2.4.5.2 shows the results of the Chi Square test for differences between TLS and NBE volumes for plots 1 to 6 in Stand H-12 at 10% allowable error. There is strong evidence of a difference between the average TLS volume and average NBE volume for plots 1 to 6 at 10% allowable error (p-value < 0.001). The allowable percent error for there to be little to no difference in average volume between TLS and NBE measurement methods ranged from 27 to 57.5%. The allowable percent error for there to be little to no difference in average volume between TLS and NBE measurements for plots 1 to 6 combined was 58.5%.

Table 2.3.4.2 Stand H-12 Chi Square test results for merchantable volume comparison between TLS and NBE diameter measurements

Chi Square Test Results for Volume Comparison					
		10% accuracy			
Plot	**df**	$\chi^2_{(n-1)}$	**p-value**	**% Accuracy**	**new p-value**
1	19	495.48	< 0.001	41.0	.01 < p < .05
2	21	1495.87	< 0.001	68.0	.01 < p < .05
3	20	975.15	< 0.001	57.0	.01 < p < .05
4	20	319.81	< 0.001	32.0	.01 < p < .05
5	16	863.50	< 0.001	57.5	.01 < p < .05
6	7	101.42	< 0.001	27.0	.01 < p < .05
All	108	4515.96	< 0.001	58.5	.01 < p < .05

2.4 Discussion

2.4.1 Diameter Measurement Comparison

Previous studies of TLS systems have indicated similar results for the accuracy of rounded objects. Mechelke et al. (2007) indicated that when testing several models of TLS systems (Leica, FARO, Trimble and Z+F IMAGER 5006) fitting a sphere, discrepancies in fitting measurement ranged from 41 to 76 millimeters for all four scanners. These results are not unlike the results obtained for average difference in diameter measurement for upper parts of the stem in Stand H-12. Melkas et al. (2008) found that accuracy of diameter measurement at DBH and below with a Canon EOS 400D Laser-camera was within 5 millimeters for spruce, 6.4 millimeters for birch and 7.6 millimeters for pine when compared to manual caliper diameter measurements. As noted in Chapter 1 Teobaldelli et al. (2008) reported errors within 1 centimeter and Antonarakis (2011) reported errors within a half centimeter for TLS measurements of DBH compared with manual measurements. The results from Melkas et al. (2008), Teobaldelli et al. (2008), and Antonarakis (2011) indicate similar levels of accuracy to this TLS trial. There is little research on the accuracy of TLS diameter measurements at heights above DBH. Schilling et al. (2011) studied the accuracy of TLS DBH measurements on birch trees and they claim that TLS measurement accuracy is affected by the strength of the reflected laser pulse, which depends on the incident angle of the scanner and the properties of the materials that the object being scanned is made of. In light of this, the fact that the scanner is "looking up" into the tree when it takes a diameter measurement means that the incident angle could be the cause of the measurement discrepancies we obtained.

The homogeneity of the poplar in each stand at BTF allowed us to identify the height locations of strengths and weaknesses of the TLS scanner by examining patterns between plots for which certain heights on the stem showed minimal and maximal deviations in average diameter differences. The results for the accuracy comparison revealed that the height position of the minimum and maximum average diameter difference was consistently similar between plots in all stands for all three measurement method comparisons. With a couple of exceptions, TLS performed better, on average, at lower heights on the stem than at higher heights when compared to manual and NBE diameter measurements. This occurred where the taper function was engaged on the stem because the top portion of the stem could not be seen by the scanner.

Some of the most surprising results in this chapter were the inaccuracy of both the under bark and over bark diameter measurements in the upper portion of the stems in Stand H-12. The trends among individual plots were similar for both the manual and NBE comparisons in that if TLS underestimated the average manual diameter measurement then it also underestimated the average NBE diameter measurement by almost the same amount, with the exception of plot 6 (See Figures A-1 to A-12 in the Appendix). The large underestimation of the average over bark diameter shown by TLS in comparison to both the manual and NBE average diameter measurements from 6 meters to the top of the stem in plots 1 to 3 in Stand H-12 certainly affected the overall average diameter differences for the stand (See Figures A-1 to A-3 in the Appendix). Plots 4 to 6 in Stand H-12 followed the same trend of underestimation but the differences were not as extreme (See Figures A-4 to A-6 in the Appendix). Stand H-12 was the first stand scanned in this trial and it is interesting to note that as TLS and manual sampling moved from plot 1 to plot 6 the average differences in diameter measurement became lower for the upper portions of the stem, but it appears that there was more going on than just scanner operator error or poor manual measurement technique, especially since the average diameter difference was so low at DBH and 3 meters. It is clear that there is more error where the taper function begins to predict upper stem diameters, so it is possible that the taper function used for the TLS measurements in this analysis did not fit the trees we were sampling, although the taper function was developed based on a sample of the trees from Stand H-12.

With the exception of plots 2 and 6 in Stand H-12 TLS misestimated the average diameter measurement by less than 10 millimeters from butt to DBH (See Figures A-1 to A-6 in the Appendix), indicating that the overall trend was that TLS performed better at lower portions of the stem when compared to manual and NBE measurement methods. This is consistent with findings from other TLS trials on curved objects. Since Stand H-12 was a dense stand pruned up to about 7.5 meters there was more of an opportunity for foliage interference affecting the scanner at the top of the stem than at the bottom. A combination of foliage interference and dense growing conditions could account for the lack of accuracy shown in the results of the average difference in diameter measurement comparison in Stand H-12.

We were not surprised at the level of accuracy shown by TLS with the comparison of average under bark diameter measurements to average manual and NBE under bark diameter measurements in Stand H-12. We knew that there was some level of error in the measurements before the bark was removed, so that error would be passed down to the under bark measurements. We know that the bark thickness function for Stand H-12 created from manual measurements was correct because it fit an average line to the set of data, so it is unclear where this additional error above and beyond the over bark measurements on the same trees comes from.

The results of the average diameter difference comparison for Stand M-7 painted TLS in a much better light for measurement accuracy than the results for Stand H-12. The results of the over bark average diameter difference comparison for Stand M-7 indicated that TLS performed very well across all plots at all heights on the stem. With the exception of plot 6 at the 9 meter height there were no average diameter differences greater than 20 millimeters in any plots and at any heights on the stem (See Figures A-13 to A-16 in the Appendix). TLS tended to underestimate the average manual diameter measurement and overestimate the average NBE diameter measurement at almost all heights up the stem in Stand M-7, but again, these differences were small when compared to Stand H-12. The main differences between Stand H-12 and Stand M-7 were the age and density of the stems. When TLS data was collected on Stand M-7 the trees were at mid-rotation age and planted less densely than in Stand H-12. In Stand H-12 the trees were at rotation age so they tended to have larger diameters and more crown closure. Stand M-7 appeared to have less crown closure than Stand H-12, so less foliage interference at higher stem heights.

The results for Stand L-7 were similar to Stand M-7 in that TLS underestimated the average manual diameter measurement and overestimated the average NBE diameter measurement. With the exception of plots 1, 3 and 7 in Stand L-7 there were no average diameter differences over 20 millimeters for either the TLS and manual or TLS and NBE comparison, and the differences greater than or equal to 20 millimeters were at the butt.

2.4.2 Volume Estimation Comparison

It was not surprising to find that TLS underestimated the NBE volume per plot in Stand H-12 by a fairly large amount (average of about 12%) considering the differences in average diameter measurement between TLS and NBE. TLS volume measured in plots 1 and 2 certainly increased the overall error from NBE measurements taken on the stems in plots 1 to 6 in Stand H-12. The Chi Square test results indicate that one would have to be willing to accept a range of 32 to 68%t error in volume, depending on the plot, in order to accept TLS as an accurate measure of volume in Stand H-12. For plots 1 to 6 combined in Stand H-12 error of 58% or more can be expected from TLS volume estimation. One issue with this comparison is that we assumed the NBE estimate of volume to be the accuracy standard to measure TLS against. Of course, there is a possibility that the volume obtained from NBE measurements was incorrect, but it is impossible to check this. With volume recovery, the mill has the final word as to how much volume is truly contained in each stem so for this project we chose to assume that the NBE volume estimate was accurate. In reality, this may not be the case.

Chapter 3 – Using TLS to Determine Sweep on Standing Timber

3.1 Introduction

Research objectives for this project included the appraisal of TLS as a tool which can be used to estimate volume and value recovery on standing timber. Volume and value degradation based on the amount of sweep in saw logs is a problem for timber production, especially in stands which are characterized by high levels of sweep in mature standing timber. The hybrid poplar stands at BTF exhibit high levels of sweep due to the almost constant high winds which occur there. From the time they are planted the hybrid poplar in this area are subjected to high winds causing bending of the stem. In addition animal browsing in this region can result in stem deformities. Part of the BTF TLS trial was devoted to developing TLS as a tool to measure sweep characteristics in standing hybrid poplar.

Several studies have illustrated the impact of stem sweep on volume recovery and how the sawing method can determine volume and value recovery. Hamner et al. (2007) examined the benefits of curve sawing vs. straight sawing logs in order to maximize value recovery in logs with sweep. Sweep was measured on various hardwoods grown in the eastern US by tightening a string from one end of the log to the other on the side of the log on the surface side that exhibited the most sweep. The maximum deviation between the string and the centerline of the stem determined the amount of sweep present in each log. Results of the Hamner et al. (2007) study indicated that curve sawing logs characterized by sweep increased the volume recovery over the traditional straight sawing method. Using TLS to estimate sweep in standing timber prior to cutting and transport has implications for eliminating the need to cut timber to measure sweep, for determining the bucking pattern that would improve volume and value recovery at the mill, and for determining the sawing method which would maximize volume recovery.

Ivkovi et al. (2007) found that log sweep in radiata pine is among the biological traits affecting value recovery in Australia. They indicate that log shape affects volume recovery through processing. The Ivkovi et al. (2007) study produced a bio-economic model of the areas where value recovery based on log characteristics could be improved. Results of this study indicate that sweep had a strong negative effect on green volume recovery and a 10% decrease in log sweep in radiata pine reduced saw log degrade by 17.1%, improving green timber recovery by approximately 0.5%.

According to Ivkovi et al. (2007), the sweep data used to create the model was collected from optical scanners used at an industry mill. Ivkovi et al. (2007) acknowledge that the stems used to create the saw logs used in the production of this model were previously selected for their lack of sweep which means that the data collected for the model does not include the most severely swept stems.

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 meters of a stem. Stand level 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 the type of sweep, the start and end points of sweep on the stem, and an estimate of the amount of sweep. Stem centerline information is then used in optimal bucking procedures to determine the combination of log products that would yield maximum value.

The current methods of log scaling and accounting for sweep in the United States are complicated and some believe that this task should be made easier. Wengert (2001) points out, that most scalers are set in their ways and reluctant to change in order to make scaling for sweep easier and more efficient.

TLS provides an opportunity to measure 3D sweep, as opposed to visually assessing 2D sweep, in each stem in standing timber. This has implications in predicting the growth form of different hybrid poplar clone varieties. The detailed stem profile generated by TLS data can indicate which varieties of hybrid poplar clones grow the straightest. In addition to form characteristics, TLS data can, with some precision, predict log product yields that maximize volume recovery in hybrid poplar. This is important to an operation such as the BTF hybrid poplar plantation because of the high level of sinuosity in the hybrid poplar stands there.

3.2 Methods

The mill output files used in the diameter and calculated volume comparison in Chapter 2 were used to extract the position of the centerline measurement obtained by the NBE method. The *.tre files used in the diameter and calculated volume comparison were also used to extract the TLS centerline position for the same stem segment scanned in the mill. We remind the reader that only the bottom 17 meters (approximately) of each stem was scanned in the mill; hereafter referred to as stem segment.

We determined the average root mean squared deviation (RMSD) between NBE centerline measurements for stem segments with the bark left on and NBE centerline measurements with the bark removed. This comparison was only performed for 6 plots (1 to 6) in Stand H-12 due to time limitations at the mill permitted.

We determined the average RMSD between TLS and NBE for all three stands using the over bark diameter measurements obtained. Results were examined for stem segments from the butt to where the taper function began (pre-taper function) and from the butt to top of the stem segment. Pre-taper function analysis was performed where the laser returns from TLS came into direct contact with the bole in that section of the stem segment (i.e., where the scanner could “see” the stem). Autostem software assumes from this point up the stem that there is no change in sweep and that the stem continues to point in whatever direction was the last direction it was pointing. Full stem segment analysis was performed to determine how the taper function fit to the section of the stem segment where the scanner could not "see" affected the accuracy of the TLS centerline measurement. Full stem segment lengths varied, as tree heights in Stand H-12 varied, and not all stems were tall enough to meet the 17 meter bucking standard used by BTF.

Next we looked at the average RMSD between NBE centerline measurements for stem segments with bark left on and TLS centerline measurements on stem segments with bark left on. All trees from all stands measured both at the mill and in the forest were included in the calculation of the average RMSD. Results for the average RMSD were examined for stem segments from the butt to where the taper function began to predict diameters for upper portions of the stem and butt to top of the stem segment for all stands. As with the NBE comparison between over bark and under bark centerline measurements, full stem segment lengths varied, as tree heights in all stands varied, and not all stems were tall enough to meet the 17 meter bucking standard used by BTF. The sum of squared differences, a component of the average RMSD calculation, was calculated using the following equations:

For NBE over bark versus NBE underbark:

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

For TLS versus NBE:

$$\text{Sum of squared differences} = \sum_{i=1}^{n}\left[\left(\text{TLS}_{x} - \text{NBE}_{x}\right)^2 + \left(\text{TLS}_{y} - \text{NBE}_{y}\right)^2\right]$$

where NBEOBx and NBEOBy were the x and y centerline coordinates for the NBE over bark centerline measurement for one segment, NBEUBx and NBEUBy were the x and y centerline coordinates for the NBE over bark centerline measurement for one segment, TLSx and TLSy were the x and y centerline coordinates for the TLS centerline measurement for one segment and n was the number of segments. The RMSD for an individual stem was calculated using the following equation:

$$\text{RMSD} = \sqrt{\frac{\text{Sum of squared differences}}{\text{\# of segments in a stem}}}$$

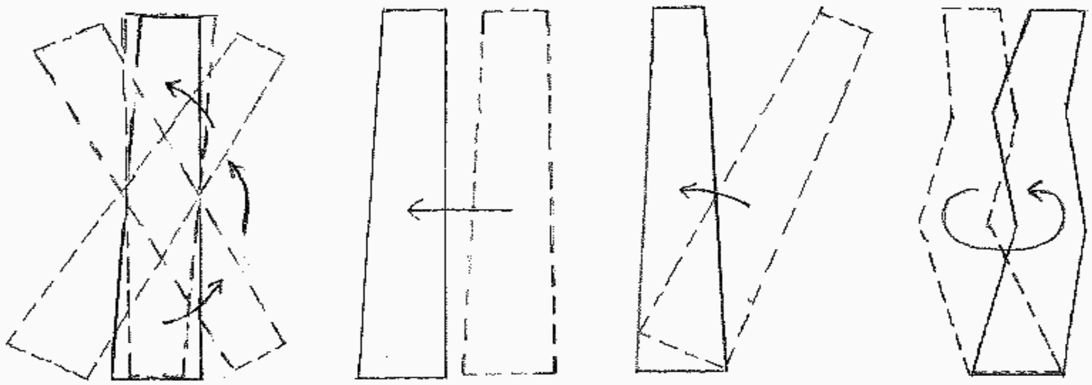
and the average RMSD for a stand was calculated using the following equation:

$$\text{Average RMSD} = \frac{\sum_{i=1}^{n} \text{RMSDs}}{\text{\# of measured stems in a stand}}$$

where n was the number of measured stems in a stand.

3.2.1 Inversion, Translation and Rotation of TLS and NBE Centerline Measurements

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 3.2.1.1 below shows an example of inversion, translation and rotation.



a. Inversion

b. Translation

c. Vertical Rotation

d. Horizontal Rotation

Figure 3.2.1.1 Methods used to invert, translate and rotate the TLS centerline and translate and rotate the NBE centerline

Inversion, translation and rotation of the centerline of each stem were accomplished using a computer program written in Microsoft Visual Basic by Glen Murphy. Since 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 rotation angle for the TLS centerline measurement was considered to be the one that produced the smallest RMSD between the NBE and TLS centerline measurements.

3.2.2 Translation and Rotation of the NBE Centerline Measurements

To perform the centerline accuracy analysis on the over bark and under bark NBE centerline measurements the NBE 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 and NBE. This was accomplished using the same Microsoft Visual Basic program written by Glen Murphy. As with the translation and rotation of TLS and NBE centerline measurements, since there was no mark on either the standing tree or the felled stems that would allow an exact line up of the over bark mill scan with the under bark mill scan, the best horizontal rotation angle for the NBE centerline measurement was considered to be the one that produced the smallest RMSD between the over bark and under bark NBE centerline measurements.

3.3 Results

3.3.1 NBE Over Bark versus NBE Under Bark Centerline Measurement Accuracy

Table 3.3.1.1 shows the results of the NBE over bark versus NBE under bark comparison. The difference between average RMSD below the taper function zone and the full stem RMSD was 13 millimeters higher for the full stem segment than the RMSD below the taper function zone. Also, the spread of the means at the 99% confidence level was higher for the full stem segment than for the portion of the stem below the taper function zone, which indicates more variation in the taper function zone than in the zone "seen" by the scanner.

Table 3.3.1.1 Mean RMSD and the variation of the RMSD from the actual estimated measure of the centerline at the 99% confidence level for NBE under bark and over bark measurements in plots 1 to 6 in Stand H-12

	Mean RMSD (mm)	SD	SE	Count	99% LCL	99% UCL
Below Taper Function Zone	56	39	7	31	37	75
Full Stem Segment	69	44	8	31	47	91

3.3.2 NBE Over Bark versus TLS Over Bark Centerline Measurement Comparison

Table 3.3.2.1 indicates the results of the TLS and NBE centerline measurement comparison for Stand H-12. The average RMSD was 21 millimeters higher for the full stem segment than the portion of the stem below the taper function zone. The spread of the mean squared deviations was higher for the full stem segment than below the taper function zone suggesting more variation in the mean of the squared deviations for the whole stem measurements.

The average RMSD between TLS and NBE centerline measurements was 1 millimeter higher than the average RMSD between NBE over bark and NBE under bark centerline measurements below the taper function zone. The spread of the mean squared deviations for the NBE over bark versus NBE under bark centerline measurements was larger than the spread of the mean squared deviations for the NBE versus TLS centerline measurements, indicating more variability in the NBE over bark and NBE under bark mean squared deviations from the actual centerline below the taper function zone.

The average RMSD of the centerline measurements was 9 millimeters higher for the full stem segment comparison between TLS and NBE than for the full stem segment comparison between NBE over bark and NBE under bark. The spread of the average RMSD suggested that there was more variability in the full stem segment centerline measurements for the NBE versus NBE comparison than for the NBE versus TLS comparison.

Table 3.3.2.1 Mean RMSD and the variation of the RMSD from the actual estimated measure of the centerline at the 99% confidence level for NBE and TLS measurements in plots 1 to 6 in Stand H-12

	Mean RMSD (mm)	SD	SE	Count	99% LCL	99% UCL
Below Taper Function Zone	57	24	5	28	45	70
Full Stem Segment	78	30	6	28	62	94

The results of the centerline measurement comparison between TLS and NBE over bark centerline measurements for Stand M-7 were very different from the previous comparisons for Stand H-12. Below the taper function zone the average RMSD was 24 millimeters lower for the comparison between TLS and NBE centerline measurements in Stand M-7 than for the comparison between TLS and NBE over bark centerline measurements in Stand H-12. The spread of the mean squared deviations was lower for the comparison between the TLS and NBE over bark centerline measurement in Stand M-7 than for the comparison between TLS and NBE over bark centerline measurement in Stand H-12, which indicated that the centerline measurements in Stand M-7 more closely matched the NBE measured centerline of the stems.

The average RMSD for the portion of the stem below the taper function zone was 30 millimeters lower than the whole stem average RMSD for the comparison between the TLS and NBE centerline measurements for Stand M-7. The spread of the mean squared deviations for the full stem segment was much larger than the spread of the mean squared deviations for the portion of the stem below the taper function zone, indicating more variation in the full stem segment centerline measurements for Stand M-7.

Table 3.3.2.2 Mean RMSD and the variation of the RMSD from the actual estimated measure of the centerline at the 99% confidence level for NBE and TLS measurements in plots 1, 6, 11 and 16 in Stand M-7

	Mean RMSD (mm)	SD	SE	Count	99% LCL	99% UCL
Below Taper Function Zone	33	19	3	35	25	42
Full Stem Segment	63	76	13	35	28	98

The results for the comparison between TLS and NBE over bark centerline measurements in Stand L-7 were very similar to those in Stand M-7 for the section of the stem below the taper function zone. Table 3.4.2.3 shows the results of the NBE and TLS centerline measurement comparison for Stand L-7. All trees from Stand L-7 measured both at the mill and in the forest were included in the calculation of the average RMSD. The comparison between TLS and NBE over bark centerline measurements in Stand L-7 had the lowest average RMSD of any of the previous comparisons. The average RMSD for the TLS and NBE over bark centerline measurement comparison was 26 and 2 millimeters lower than the average RMSD for the TLS and NBE over bark centerline measurements for Stands H-12 and M-7, respectively. The spread of the mean squared deviations below the taper function zone was the lowest of the spread of the mean squared deviations of all comparisons. The average RMSD for the full stem segment in Stand L-7 was significantly lower than the average RMSD for any of the other comparisons presented previously, as well as the spread of the mean squared deviations.

Table 3.3.2.3 Mean RMSD and the variation of the RMSD from the actual estimated measure of the centerline at the 99% confidence level for NBE and TLS measurements in plots 1 to 8 in Stand L-7

	Mean RMSD (mm)	SD	SE	Count	99% LCL	99% UCL
Below Taper Function Zone	32	15	2	38	25	38
Full Stem Segment	46	28	5	38	34	59

3.4 Discussion

The average RMSD of the centerline measurement in all stands was larger for the full stem segment than for the portion of the stem below the taper function zone. The taper function assumes a constant direction of the stem. If the stem leans to a certain angle at the portion of the stem where the scanner can “see”, and then changes direction in the upper portion of the stem where the scanner cannot “see”, the result is a continuation of the centerline pattern that was present just as the taper function engaged. This could be the reason for the average RMSD of the full stem segment always being larger than the average RMSD of the bottom portion of the stem.

The NBE centerline measurement comparison between stems with bark left on and bark removed was performed to show repeatability. The same tree was measured once with the bark on and once with the bark removed. Average RMSDs for centerline measurement of 56 millimeters for the stem segment below the taper function zone and for the full stem segment, 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 included in the centerline measurement. The error could also be due to the stem conforming to the mill scanner belt.

The fact that the average RMSD for the comparison between the NBE and TLS over bark centerline measurements for Stand H-12 was only 2 millimeters higher than the repeatability measure found by the comparison between NBE over bark and NBE under bark centerline measurements suggests that the TLS estimate of the centerline measurement was no different than the NBE centerline measurement for the partial stem analysis. The full stem segment analysis for the same comparisons showed an increase in average RMSD of 9 millimeters with TLS. This is not a bad result, though not as accurate as the measurements on the portion of the stem below the taper function zone. Based on the TLS and NBE comparisons and the NBE repeatability comparisons that were performed on the same stems, we were able to say with some certainty that TLS had the same capacity as NBE to measure the centerline of a stem accurately. This allowed us to compare the differences in average RMSD between TLS and NBE centerline measurements for each stand.

In Stand H-12 the NBE and TLS centerline measurement comparison for partial stem resulted in an average RMSD of 57 millimeters. This is similar to the average RMSD we found in the NBE over bark versus under bark comparison for the bottom portion of the stem. The full stem segment comparison between NBE and TLS resulted in an average RMSD of 78 millimeters. Considering the error inherent in the NBE measurement technique a 57 millimeter and a 78 millimeter average RMSD does not seem like a large error on the side of TLS, but there is no way to determine which centerline measurement method is most accurate because there is no correct centerline measurement to compare each average RMSD to. We can perform a meaningful comparison of both NBE and TLS estimates of the centerline coordinates of a stem by taking into account the error inherent in the NBE centerline measurement method.

The spread of the average RMSD for the comparison between TLS and NBE centerline measurements can be used to determine which method measures the centerline of a stem more precisely. The difference in centerline measurements only varies by a little over one centimeter in Stand H-12 in the portion of the stem where the scanner could “see”. In the portion of the stem where the TLS scanner could not “see” the spread of the average RMSD was not much larger than that found by the NBE scanner for the same portion of the stem. In Stand M-7 for the portion of the stem where TLS could “see” the over bark centerline measurement was more accurately matched to the NBE centerline measurement in Stand M-7 than in Stand H-12. It is also clear from the comparison in Stand M-7 between point estimates and confidence intervals that the scanner did not perform as well for measuring the centerline in parts of the stem where the scanner could not “see” in Stand M-7 as it did in Stand H-12. In Stand L-7, however, the difference in TLS and NBE centerline measurements was smaller than for both Stands H-12 and M-7. The spread of the average RMSD in Stand L-7 was also the smallest of all stands in this trial, both for the full stem segments and for the portions of the stem below the taper function zone.

The accuracy indicated by the ability of TLS to match the centerline measurements to the NBE centerline measurements shows some promise for the future of sweep determination, particularly in the more highly valuable bottom portions of stems where saw log material is found. In the case of the methods where sweep is visually assessed in standing trees (e.g. used by the Atlas Cruiser), there would no longer be a requirement to take the time to categorize sweep and record the beginning and ending points of the sweep on each stem, which could be a time-consuming process. TLS does that automatically in minutes, on all trees within a plot. With some other sweep determination methods (Hamner et al. 2007, Ivkovi et al. 2007 and Wengert 2001), destructive sampling was necessary to acquire the measurements associated with sweep determination. Implications on heterogeneous stands would be disastrous using these methods because so much timber would be required to be destroyed in order to obtain the measurements needed to build models and apply a species specific estimate of volume loss due to sweep.

Chapter 4 – TLS Product Re-allocation Based on Mill Door Values

4.1 Introduction

The comparison between the TLS and NBE centerline measurements in Chapter 3 demonstrated that TLS can be used to determine the amount of sweep in standing hybrid poplar by measuring the centerline of the stems in Stands H-12, M-7 and L-7. The level of accuracy found in the average RMSD between TLS and NBE centerline measurements indicated that TLS centerline measurements were comparable to centerline measurements made by the mill scanner. In this chapter, we will show how TLS centerline measurements can be used to allocate a variety of wood products to standing timber. Specifically, TLS will be used to allocate existing chip and saw log products in standing timber. Saw log allocation will be based on small end diameter (SED) and length of the log, as well as the amount of sweep contained in each log. In addition to saw and chip log product allocation this chapter will demonstrate the use of TLS to determine the potential value gain by the allocation of veneer in standing timber.

One of the ongoing challenges for timberland owners is the goal of maximizing production to maximize profit. Civilization has utilized wood in all aspects of developed society for centuries, so there are many different types of products that can be obtained from wood. Production of veneer, either as a covering on reconstituted wood or as laminated veneer lumber (LVL) can be an alternative to production of saw timber.

Hybrid poplar boards produced from saw logs are extremely weak by themselves. According to Balatinecz and Kretschmann (2001), wood produced from all species of poplar has low density and consists of a porous structure, although the bending strength and stiffness of poplar wood is comparable to that of spruce, pine and fir. According to Balatinecz and Kretschmann (2001) Canadian experiments performed on hybrid poplar indicated that veneer produced from industrial-grade poplar possessed nearly the same strength and stiffness properties as veneer produced from Douglas-fir. This is of great importance for hybrid poplar because it opens up a new market for hybrid poplar in the face of its historically negative image when it comes to strength and durability. This is where the veneer market becomes important because of the low strength and stiffness requirements for its utilization as a market item. Balatinecz and Kretschmann (2001) further explain that poplar wood is extremely fibrous and can be melded with other materials to create a composite material more efficiently than saw logs can. Inclusion in the veneer market could open doors for new production and profit maximization for hybrid poplar plantation owners.

The production of veneer can be more costly than saw log production, depending on the percentage of veneer that is allocated from the raw wood. In his thesis comparing saw log to veneer production costs, Leatherman (2007) indicated that under Scribner scaling rules allocating 25% saw log and 75% veneer resulted in a lower production cost of veneer than for saw log when looking at the physical allocation method. By contrast, allocating 50% saw log and 50% veneer resulted in a lower production cost for veneer than for saw log, according to Leatherman (2007). It is important to predict the combination of veneer and saw log that produces the highest value at the lowest production cost before manufacturing the products because, as was shown by Leatherman (2007), costs of production can increase or decrease, depending on product allocation.

Traditional cruisers do not cruise timber for veneer allocation. Their interest is in saw log production and they cruise for the highest grade of saw logs they can possibly find. Hybrid poplars are bred for homogeneous properties, so it would be relatively simple to predict the sapwood and heartwood strength and stiffness properties for hybrid poplar veneer production. TLS provides a way to predict the amount of veneer grade wood contained in standing timber without destructive sampling of stems. This has important applications in pre-allocating veneer products to optimize value and lower costs while the timber is still standing.

Forest owners who are seeking to supply new products from their forests (such as veneer) could benefit from predicting value recovery from these new products on standing timber. From the point of view of forest owners who process their own forest products predicting the percentage of various products on standing timber could give them an indication of the costs associated with production of these products. From the point of view of a forest owner who seeks to sell timber to outside mills predicting value recovery could give them an idea of the minimum or maximum bid they should accept for purchase of their timber. In light of the desire of forest owners to predict the optimal product yield from their stands the development of technology to do so is important. TLS acquires actual stem measurements from the standing timber. Coupled with timber production optimization software, TLS with optimal bucking (TLSOB) could be used to evaluate value and volume recovery that could be obtained from different stands for current production schemes and alternative production schemes that include new log-types, such as veneer logs. The following sections outline the methods used and the results obtained to demonstrate the capability of TLSOB to predict the value of standing timber based on three different production scenarios.

4.2 Methods

All three stands were included in the analysis of value based on log product yields. Each stem in each plot was optimally bucked using VALMAX Optimizer simulation software (developed by Dr Glen Murphy). VALMAX Optimizer determines which log products could feasibly be cut from a stem and then selects the combination of log products, using a dynamic programming optimal bucking algorithm which maximizes overall stem value. Feasibility depends on the specifications (lengths, small and large end diameters, maximum allowable sweep [defined as a fraction of the SED] and allowable stem qualities) for each potential log-type.

Stem profiles were obtained from the TLS derived under bark *.tre files. A total of 22 products, including waste segments of logs, were included in the analyses. Four types of veneer logs, 16 types of saw logs, and chip logs of varying lengths were included. Figure 4.2.2 shows the breakdown of all products considered in this analysis and their 2010 return-to-log prices ($\$/m^3$). Veneer logs could be two lengths (1.3 and 2.5 meters) and four diameter classes ranging down to a minimum SED of 200 millimeters. Very little sweep was allowed in veneer logs. Sawlogs could be three lengths (2.5, 2.8 and 3.1 meters), four diameter classes (ranging down to 150 millimeter SED), and four sweep categories. For instance, a large saw log with minimal sweep would be defined as a log with minimum SED larger than 300 millimeters and sweep no larger than minimum SED divided by eight (S300_x8). A large saw log with maximal sweep would be defined as log with minimum SED larger than 300 millimeters and sweep no larger than minimum SED divided by one (S300_x1). Chiplogs could be random lengths ranging between 2.5 and 4.0 meters with a minimum SED of 70 millimeters.

Return-to-log prices were calculated based on lumber and chip prices that were current in summer of 2010 and estimated mill operating costs. Lumber and chip yields were based on mill records for grade recovery and NBE scans from 300 stems extracted from Stands H-12, M-7 and L-7.

Figure 4.2.1 shows one type of VALMAX output for two stems, indicating the log types which, if cut, would maximize value from the stem. The tops of the logs are relative to the stump; e.g. the first log for Stem 12 would be a Veneer-VS log that started at zero decimeters above the stump and finished at 26 decimeters.

Log-type	Height (dm) above stump
Stem Number	12
waste	252
chiplogs	247
chiplogs	186
chiplogs	137
S150_X4	124
S150_X8	98
chiplogs	72
Veneer_VS	62
chiplogs	49
Veneer_VS	39
Veneer_VS	26
Veneer_VS	13
Stem Number	13
waste	293
chiplogs	289
chiplogs	234
S150_X8	224
Veneer_VS	198
Veneer_VS	173
Veneer_VS	148
Veneer_VS	123
S200_X4	98
Veneer_S	72
S300_X8	59
waste	27
S300_X8	26

Figure 4.2.1 Height of each log product above the stump for two sample stems

Log-type	Best Value
Veneer_L	73
Veneer_M	67
Veneer_S	60
Veneer_VS	53
S300_X8	75
S300_X4	72
S300_X2	70
S300_X1	68
S250_X8	56
S250_X4	53
S250_X2	51
S250_X1	49
S200_X8	41
S200_X4	38
S200_X2	35
S200_X1	33
S150_X8	28
S150_X4	25
S150_X2	23
S150_X1	21
Chiplogs	21
Waste	0

Figure 4.2.2 Return-to-log prices by product used by VALMAX

Three product scenarios were used to determine the value gain from adding a veneer production line to the existing saw log and pulp production line at The Collins Company mill. The control scenario predicts the percent breakdown of saw log and pulp volume in each plot and per hectare estimated by TLSOB. The first veneer scenario predicts the percent breakdown of saw log, pulp and veneer logs with SED greater than or equal to 250 millimeters (Veneer_L, Veneer_M, Veneer_S). The second veneer scenario includes the same log types as the first veneer scenario with the addition of veneer logs greater than or equal to 200 millimeter SED (Veneer_VS). These three scenarios were executed on a plot level first and then a multiplication factor of 31.85 hectares was used to determine the yield from each production scenario on a per hectare level. Both product yields and per hectare values were calculated.

4.3 Results

From the TLS data we were able to generate values for all three stands on both a plot and hectare level for three different product allocation scenarios. Results indicate the value increase per hectare.

In Stand H-12 the potential value increase per hectare from adding veneer production was significant. Table 4.3.1.1 shows the average value increase per hectare predicted by TLSOB from adding veneer production and very small veneer production, and a 95% confidence interval for the average values from all three allocation scenarios. Adding veneer production produced an average value increase of $759 per hectare, which translates to an average value increase of 4% over producing saw logs and chip only. Adding very small veneer production would increase the average value by $2852 per hectare over producing saw logs and chip only, and by $2093 per hectare over producing saw logs, chip and veneer. This translates to a 14 and 10% increase in value recovery, respectively, on average, per hectare. The spread of the means in average value per hectare was similar for all three scenarios, indicating that the variation in product allocation value between plots was low. Figure 4.3.1.1 shows the log product breakdown for Stand H-12. Potential veneer production would borrow from saw log production to increase potential value recovery in Stand H-12, and as minimum SED for veneer production decreased the amount of saw log production decreased. For value gain from potential very small veneer production the majority of the stem would be allocated to veneer production.

Table 4.3.1.1 Predicted value and volume recovery and 95% confidence interval for all three product scenarios in Stand H-12

Stand H-12				
	Value of Saw log & Chip per hectare	**Value of Saw log, Chip and Veneer to 250 mm per hectare**	**Value of Saw log, Chip and Veneer to 200 mm per hectare**	**Volume per hectare (m^3)**
Average	$20,790	$21,549	$23,642	538.09
SD	$2,779	$2,881	$3,029	46.99
Standard Error	$621	$644	$677	10.51
95% CI Upper Bound	$22,090	$22,897	$25,059	560.09
95% CI Lower Bound	$19,489	$20,200	$22,224	516.09

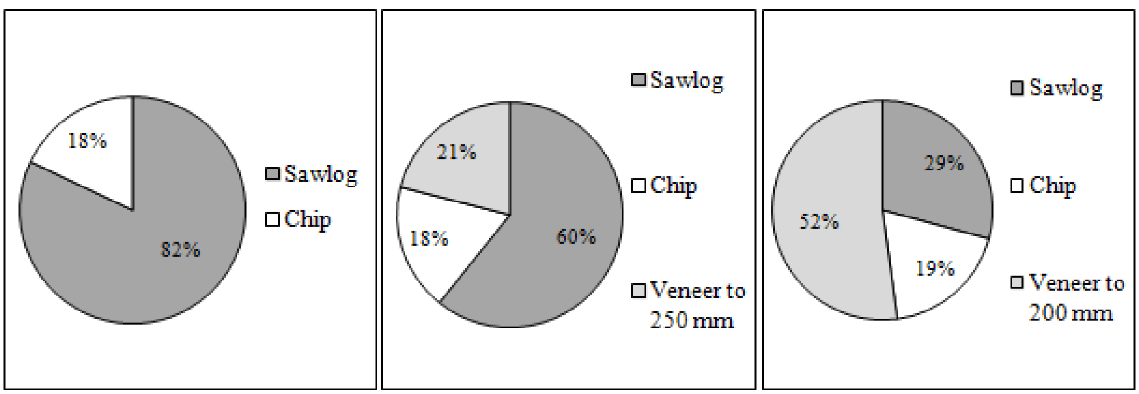


Figure 4.3.1.1 Optimal TLSOB product allocation for Stand H-12

Stand M-7 was at mid-rotation when the scans used in this analysis were acquired, so the average value per hectare for the stand was much lower than the average value predicted in full rotation Stand H-12. Table 4.3.1.2 indicates that TLSOB predicted an average value gain of $509 per hectare in Stand M-7 by adding veneer production to saw log and chip production. This translated to a potential 13% increase in average value per hectare. The difference in potential average value between allocations of veneer and very small veneer was $450, or 11% over saw log and chip only, indicating that the average value gain would be much higher from allocating very small veneer production than veneer production. There was almost no difference in the spread of the means between all three scenarios, indicating that the variation in product allocation values between plots was low. The percent breakdown of allocation from the three different log product scenarios is shown in Figure 4.3.1.2. There is very little small veneer allocated from saw logs in Stand M-7. When very small veneer production is considered the allocation between saw log, chip and veneer is almost equal and the potential average value is increased significantly.

Table 4.3.1.2 Predicted value and volume recovery and 95% confidence interval for all three product scenarios in Stand M-7

Stand M-7				
	Value of Saw log & Chip per hectare	**Value of Saw log, Chip and Veneer to 250 mm per hectare**	**Value of Saw log, Chip and Veneer to 200 mm per hectare**	**Volume per hectare (m^3)**
Average	$4157	$4,217	$4,675	140.46
SD	$1,282	$1,291	$1,340	28.42
Standard Error	$287	$289	$300	6.36
95% CI Upper Bound	$4,781	$4,795	$5,275	153.18
95% CI Lower Bound	$3,583	$3,639	$4075	127.74

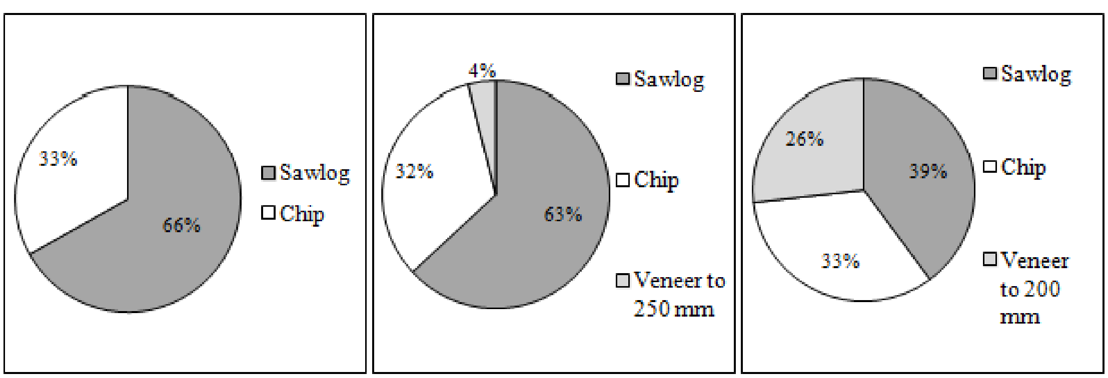


Figure 4.3.1.2 Optimal TLSOB product allocation for Stand M-7

Stand L-7 was at mid-rotation, as well, so like Stand M-7 there was not as much potential value realized from either of the three allocation scenarios as was realized in Stand H-12. Table 4.3.1.3 indicates that allocating veneer created a potential value gain of $108 per hectare, resulting in a 4% value gain per hectare over saw log and chip only. Adding very small veneer yielded a predicted value increase of $452 and $343 per hectare over potential value from saw log and chip, and saw log, chip and veneer, respectively. It was possible to increase the average value per hectare by 15% over saw log and chip production by allocating part of Stand L-7 to very small veneer production. As with Stands H-12 and M-7 the spread of the means was similar across allocation scenarios, indicating that the value increases for each product allocation were similar between plots. The product allocation breakdown for Stand L-7 is shown in Figure 4.3.1.3. The product breakdown for optimal value potential from Stand L-7 is similar to Stand M-7. To optimize value per hectare in Stand L-7 there is a small amount of small veneer allocated over saw log and chip; however, when very small veneer is considered the percentage of veneer produced over saw log and chip rises to increase value recovery significantly.

Table 4.3.1.3 Predicted value and volume recovery and 95% confidence interval for all three product scenarios in Stand L-7

Stand L-7				
	Value of Saw log & Chip per hectare	**Value of Saw log, Chip and Veneer to 250 mm per hectare**	**Value of Saw log, Chip and Veneer to 200 mm per hectare**	**Volume per hectare (m^3)**
Average	$3,023	$3,131	$3,474	93.69
SD	$572	$592	$643	15.74
Standard Error	$128	$132	$143	3.52
95% CI Upper Bound	$3,279	$3,395	$3,762	100.73
95% CI Lower Bound	$2,767	$2,866	$3,186	86.65

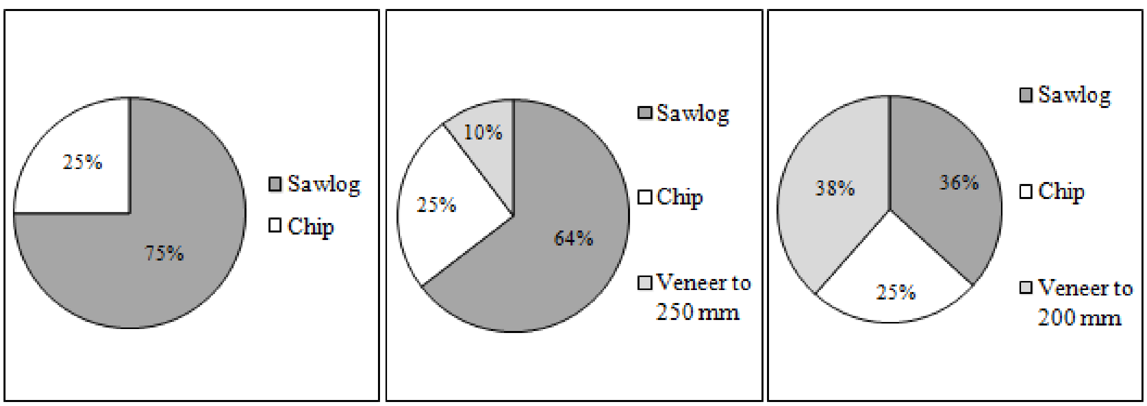


Figure 4.3.1.3 Optimal TLSOB product allocation for Stand L-7.

4.4 Discussion

One of the goals of this project was to demonstrate the use of TLS technology on standing timber as a tool to predict potential volume and value gain from reallocating timber production. To do this it was necessary to determine the amount of sweep in a stem while the tree was standing. We were able to use TLS to measure sweep found in individual stems in all three stands for the purpose of estimating the volume and value gain from incorporating a veneer production line into a mill for supplying veneer markets.

Other applications for obtaining detailed log product information on standing timber have coupled traditional methods of recording defect in standing timber with optimal product allocation to mills. At the Fourth Forest Engineering Conference in 2011, Shorthouse et al. (2011) established the importance of enhancing traditional forest inventory to better predict log product yields. They claim that using simulated optimal bucking can enhance traditional inventory estimates to better match the value that is actually recovered at the mill by coupling regression models created from mill scan data with recorded tree characteristics from a traditional cruise. Though Shorthouse et al. (2011) illustrate promising advances in traditional inventory methods of predicting value recovery, the Forestry Commission in Scotland (2003) claims that traditional mensuration techniques do not account for factors that affect product recovery, such as knots and sweep, because they simply estimate volume and value based on measured tree dimensions and an "assumed rate of taper". They further explain that traditional techniques used to predict recoverable volume do not indicate what log products will actually come from the standing timber once it is harvested. Ultimately, the Forestry Commission of Scotland (2003) claim that the earlier in the supply chain logs can be divided into products the more appropriate the allocation of products will be in relation to the market requirements. It seems that the ability to allocate log products from standing timber to appropriate markets is the key to optimal value recovery at the mill.

Optimal bucking coupled with other inventory methods does hold promise in determining log product yield and accurate value recovery estimates from standing timber to the mill. The Forestry Commission of Scotland (2003) indicated that a "stem straightness scoring system" that was developed by MacDonald (2009) has been used to determine the stem form in Sitka spruce. According to Hubert et al. (2002-2003), stem straightness surveys were used to gather information on sweep in Sitka spruce to create the “stem straightness scoring system”. They indicate that a model was developed based on the relationship between stem form and a variety of variables including planting year, yield class, thinning history, stocking density and wind exposure, to create a stem scoring system. This system, according to the Forestry Commission in Scotland (2003), can be used to predict the recovery of high value saw logs on the bottom 6 meters of a stem.

It seems that with the advent of these new technologies the importance of predicting recoverable timber value at the stand level has become the innovation that traditional inventory was lacking. One of the advantages of using TLS over other methods of value recovery assessment is that detailed stem measurements are used to predict product value within a stem, whereas other methods use a “blanket” score or code which may not be applicable to all species in all stands. With TLS the value of each stem is assessed from measurements obtained from that stem, and no others. The Forestry Commission of Scotland (2003) concluded by saying that “innovative laser techniques offer the opportunity for strategic level assessments of timber volumes and quality (using airborne LIDAR) and more detailed stand level pre-harvest assessments (using terrestrial laser scanners)”.

Chapter 5 - Determining Sampling Error and Desired Sample Size Using TLS

5.1 Introduction

When a forest inventory is conducted it is widely accepted that for industrial forestry the goal is to determine the total amount of volume and value that is contained in a stand. For timeliness and cost-efficiency, we typically do this by sampling a fraction of a stand to obtain an average and then relate that average to the total volume contained in a given area. The fact that the average is an estimate of volume warrants a measure of the precision of the sample in order to assess the level of error that might be inherent in the estimate. Precision is based on the estimate of the average and the standard error of the mean of the variable of interest. Bell and Dilworth (2007) define the standard error of the mean as "the mathematical range from the sample mean within which the true but unknown population is likely to fall….." The variability of the attribute of interest can affect the precision of a sample. If a stand of trees is unmanaged the variability in age, volume and height can be significant.

In order to determine the level of variability in a stand forest inventory typically requires that an assessment of the type, density and size of timber in a stand is performed before the main cruise in order to determine the level of precision needed to accurately assess a desired attribute and the number of sample plots needed to obtain a desired precision. A pre-cruise assessment can be performed either onsite or through remote sensing data from the area of interest in order to establish the sampling error and sample size required to meet a certain precision. The United States Forest Service (2005) uses multi-phase sampling at a sampling intensity of 10% in the Western United States. Phase 1 involves using remote sensing data (aerial photographs, digital orthoquads and satellite imagery) to locate fixed radius sample plots prior to entering a stand. In Phase 2 the United States Forest Service (2005) collects data on tree species, tree size and tree condition, among other attributes of the plot. Other phases include sampling for forest health.

Current inventory methods are based on total volume calculations; however, volume may not be the objective of the inventory. At the University of the South Office of the Domain Management (2003), forest inventory has the objective of valuing the timber on their land for revenue to support various educational and community programs, in addition to determining forest health and tree volume. The University of Florida (2006) indicates that the desired sample size depends on the value of the timber on the land, among other variables. Because of the variation in value between plots of the same volume, plot sampling based on total stand volume will, in general, contain different error than if the sample were based on stand value.

An estimate of total stand volume is far more useful to a timber cruiser than to a forest industry accountant. The cruiser estimates stand volume for a variety of reasons. For short term planning on an operational level total stand volume estimates may be desired to plan for trucking and transport, as well as equipment limitations. Total volume and basal area estimates provide information for habitat evaluation in standing timber. Long term tactical applications for total volume estimates include road building and maintenance planning, and successive total volume estimates can be used to track volume growth over time.

From the point of view of the forest industry accountant an estimate of stand value is more useful than an estimate of total stand volume. Investment decisions must be based on the most accurate available estimates of net worth. Long term forecasting depends on the value of the land, which includes standing timber. More importantly, estimating timber value accurately on a stand level is pivotal in organizing timber sales.

TLSOB can be used to determine precision on existing inventory plots, or to determine the number of plots needed to meet a desired precision. Depending on the particular goals of forestry personnel, sampling to determine total stand volume will require a different number of plots than sampling to determine total stand value. Two plots in a stand may contain the same volume but certain growth characteristics such as amount of sweep in each stem may vary the value and product allocation possibilities between the same two plots.

The following sections demonstrate the use of TLSOB as a tool to establish sampling precision and desired sample size from the perspectives of volume and value determination objectives. The following sections also compare the sampling precision and desired sample size at various errors derived from TLSOB with those obtained from a manual volume cruise.

5.2 Methods

5.2.1 TLSOB Derived Sampling Error and Desired Sample Size

To obtain the precisions of the samples in each of the three stands the data obtained in Chapter 4 was utilized. Once the optimal log products determined from TLSOB were allocated in each stand (See Chapter 4) we were able to determine the percent error of our sample, as well as the number of plots needed to meet 5 and 10% sampling error (at the 95% confidence level) for each stand, based on value and volume recovery management initiatives. Percent error of the TLSOB samples was calculated using the following equation:

$$\text{Percent error} = \frac{t * s_{\bar{y}_n}}{\bar{y}_n}$$

where $s_{\bar{y}_n}$ was the standard error of the volume or value in stand n, $\bar{y}_n$ was the mean of the volume or value in stand n, and t was the Student's t value for the confidence interval of interest. The desired sample size for the 5 and 10% sampling error level was determined using a similar calculation to the one used in the calculation of percent sampling error. The equation used was:

$$n = \frac{t^2 * s_y^{\,2}}{(AE*\bar{y})^2}$$

where s_y^2 was the standard error of the plots sampled for a particular stand, AE is the allowable error in decimal form (5 or 10%, for our purposes), $\bar{y}$ was the average value or volume for the stand and t was the t-distribution multiplier to determine the variance of the samples. To determine t the equation was iterated until the value of t was determined that matched the desired sample size minus one degrees of freedom associated with that particular t value.

5.2.2 Manually Derived Sampling Error and Desired Sample Size

In order to compare the TLS derived and manually derived estimates of sampling error and desired sample sizes at 5 and 10% sampling error, the volume contained in each of the twenty plots in Stands H-12, M-7 and L-7 was calculated from the manually gathered data. The modified Kozak equation and the predicted height from the DBH/height equations defined in Chapter 2 were used to predict the diameter of the stems in each plot at various heights on the stem. The quadratic mean diameter (QMD) of each plot in each stand was used in place of the DBH in the modified Kozak equation. QMD was calculated using the following equation:

$$QMD = \sqrt{\frac{\overline{BA}}{\frac{\pi}{40000}}}\text{, where}$$

$$BA = \text{Basal area} = DBH^2 * \frac{\pi}{40000} \text{ and}$$

average BA was the average of the basal area calculated for each tree in the plot. DBH was measured by metric diameter tape. Then, the bark was removed from the predicted diameter at each 3 decimeter height on the stem using the bark thickness ratio defined in Chapter 2. The predicted radius was obtained by dividing the predicted diameter with the bark removed by two. The cubic meter volume of each 3 decimeter height segment was then calculated using the following equation:

$$\text{Volume} = \sum_{i=1}^{n} \pi r^2 h \text{ , where}$$

r was the predicted under bark radius, n was the number of segments and h was 3 decimeters. The volume obtained was considered the volume of the "average" tree in a plot and was multiplied by the tree count in the plot to obtain a total plot volume.

The same simple random sampling methods used to obtain the TLSOB derived sampling error and desired sample size were used to obtain the manually derived sampling error and desired sample size.

5.3 Results

5.3.1 TLSOB Derived Sampling Error and Desired Sample Size

The sampling error obtained by our TLSOB sample in Stand H-12 is shown in Table 5.3.1 to be about 6% for the value objective cruise. The volume objective cruise yielded a lower sampling error for our TLSOB sample than the value objective cruise, indicating that there was more variation in product value than product volume. This is reflected in the coefficients of variation (CVs) shown in Table 5.3.1 in that the CV decreased from 19% for the value objective cruise to 9% for the volume objective cruise. As a result the predicted sample size required to achieve a 5% sampling error in the volume objective cruise was half that of the value prediction cruise. There was also a slight difference in the sampling errors between the three allocation scenarios, indicating a slight per plot variation in the value potential of the products allocated.

Table 5.3.1.1 Sampling error and desired sample size for 5 and 10% sampling errors based on value for each allocation scenario and volume

Stand H-12				
	Saw log & Chip per hectare	**Saw log, Chip and Veneer to 250 mm per hectare**	**Saw log, Chip and Veneer to 200 mm per hectare**	**Volume per hectare**
CV	13%	13%	13%	9%
Sampling Error	6.3%	6.3%	6.0%	4.1%
# Plots at 5% Sampling Error	30	30	28	12
# Plots at 10% Sampling Error	9	9	9	4

According to Table 5.3.2, in Stand M-7 the value cruise CVs were large compared to Stand H-12, indicating large amounts of variation in product values between plots. This large variation was consistent across all allocation scenarios in Stand M-7. The variation was also reflected in the precision of our sample, as well as the required sample size to reach 5 and 10% sampling error. The variation in volume between plots was not as large as the variation in value of products between plots in Stand M-7. Compared to the sampling error and desired sample sizes with the value recovery objective in Stand M-7, the sampling error and desired sample sizes with the volume recovery objective were much smaller. Table 5.3.2 indicates that the number of required sample plots to reach both a 5 and 10% sampling error with the value prediction objective doubled over the volume prediction objective desired sample size. Results also indicated that there was more variation in both volume and value recovery potential in Stand M-7 than in Stand H-12. Not only did the values of individual products vary more in Stand M-7 than in Stand H-12, they varied more than the volume between plots in both stands.

Table 5.3.1.2 Sampling error and desired sample size for 5 and 10% sampling errors based on value for each allocation scenario and volume

Stand M-7				
	Saw log & Chip per hectare	**Saw log, Chip and Veneer to 250 mm per hectare**	**Saw log, Chip and Veneer to 200 mm per hectare**	**Volume per hectare**
CV	31%	31%	29%	20%
Sampling Error	14.4%	14.3%	13.4%	9.5%
# Plots at 5% Sampling Error	148	147	129	66
# Plots at 10% Sampling Error	39	39	34	18

According to the results shown in Table 5.3.3, there was more variation between volume and value recovery prediction in Stand L-7 than in Stand H-12, and less than in Stand M-7. The CVs for all three allocation scenarios were the same in Stand L-7 and this was reflected in the sampling errors and desired sample sizes for the value objective cruise. There was little difference in CVs between the value and volume objective samples, although the CV and corresponding sampling error and desired sample sizes were slightly lower for the volume objective cruise than for the value objective cruise. About 10 more plots were required for the value objective cruise than the volume objective cruise to reach a 5% sampling error, and only three more plots were required for the value objective over the volume objective in order to reach the 10% sampling error.

Table 5.3.1.3 Sampling error and desired sample size for 5 and 10% sampling errors based on value for each allocation scheme and volume

Stand L-7				
	Saw log & Chip per hectare	**Saw log, Chip and Veneer to 200 mm per hectare**	**Saw log, Chip and Veneer to 150 mm per hectare**	**Volume per hectare**
CV	19%	19%	19%	17%
Sampling Error	9.0%	9.0%	8.8%	7.9%
# Plots at 5% Sampling Error	58	58	55	45
# Plots at 10% Sampling Error	16	16	16	13

5.3.2 Manually Derived Sampling Error and Desired Sample Size

Since we did not cruise manually for a value objective we were only able to make a comparison between TLS and manual volume recovery objective cruises of the CV, sampling error and desired sample size. TLS underestimated the volume per hectare acquired from the sample of 20 plots in all three stands. In Stand M-7 the CV calculated from the volume cruise estimated from the manually gathered data was very similar to the CV calculated from the TLS volume cruise, indicating that TLS was accurate to manual cruise standards in that stand. This was reflected in the sampling error and desired sample sizes obtained for both cruising methods, as well, as they were identical. Stand L-7 showed almost the same results as Stand M-7, with the CV, sampling error and desired sample sizes for 5 and 10% errors from the TLS cruise being slightly lower than for the manual cruise. This indicates that TLS was a little more precise in volume estimation than manual cruising methods in Stand L-7. In Stand H-12 the opposite occurred. The manual cruise was slightly more precise than the TLS cruise, and since both precisions were so low this made a significant difference in the desired sample size for a 5% sample.

Eleven more plots were required by TLS over the manual cruise in order to reach a sampling error of 5%.

Table 5.3.2.1 Volumes, sampling errors and desired sample sizes at 5 and 10% sampling errors for all three stands based on volume estimates calculated from manually and TLS gathered data

	Stand H-12	**Stand M-7**	**Stand L-7**
Average Volume Manual (m^3/ha)	581.08	168.74	118.62
CV (Manual)	4.3%	20.5%	17.8%
Sampling Error (Manual)	2.0%	9.6%	9.2%
Desired n (5%) (Manual)	5	67	51
Desired n (10%) (Manual)	3	19	15
Average Volume TLS (m^3/ha)	538.09	140.46	93.69
CV (TLS)	9.0%	20.0%	17.0%
Sampling Error (TLS)	4.1%	9.6%	7.9%
Desired n (5%) (TLS)	14	68	46
Desired n (10%) (TLS)	5	19	13

5.4 Discussion

Results of the value gain from adding production scenarios were examined on a volume and value basis separately in order to demonstrate the application of TLSOB technology to multiple aspects of planning in the timber industry. The differences in sampling error generated by TLS sampling methods between cruising for value and cruising for volume illustrated the need for value recovery prediction in addition to volume recovery prediction in forest sampling. This was illustrated in all three stands; however, the differences were more profound in Stand M-7 than in Stands H-12 and L-7, as the variation in log product value between plots was significant over the variation in stem volume between plots. It is evident from CVs obtained from the comparison between TLS and manual sampling errors and desired sample sizes in Section 5.3.2 that volume variation exists within Stand M-7, and not the TLS measurements, so this certainly could have been reflected in the value variation between plots, as well, and it appears that is the case. It is probable that this occurs because the volume contained in each plot may be similar between plots but the value contained in each plot may differ significantly between plots due to variation in the quality of products in each of the stems.

Results for all three stands indicated that when the recoverable value increased significantly from allocation of very small veneer over veneer the sampling error and required sample size for a particular sampling error decreased. This was presumably due to the fact that with the allocation of very small veneer the values obtainable in each plot increased significantly, thus increasing the average recoverable value significantly in each stand. The standard deviation increased slightly as more products were considered for allocation, but not enough to offset the significant increase in average recoverable value. This resulted in a decrease in the CV, sampling error and desired sample size for a particular sampling error when significant increases in value recovery were possible in all three stands. The conclusion to be made here is that significant increases in value recovery changed the sampling error and desired sample sizes at 5 and 10% error levels; however, small increases in value recovery from adding veneer did not.

The forestry accountant would find that TLS is the preferred method to use as a pre-harvest inventory tool to predict the recoverable value within a stand. The sampling error of the TLS cruise reflects the true precision needed to obtain a more accurate estimate of the recoverable value in a stand, as opposed to the traditional method of obtaining the sampling error and desired sample size from a volume cruise and predicting the value contained in a stand from that total volume minus a certain percentage for defect. With respect to predicting value recovery increases from adding products such as veneer it would be difficult to manually cruise a stand for veneer product breakdown the way it has been accomplished with TLS, unless a product allocation scenario specifically designed for manual cruising has been utilized, and the stand is cruised multiple times. In that case, manual cruising for optimal product allocation would be very time consuming and potentially more costly than the increase in value recovery the cruiser would be attempting to predict. A timber inventory report from Sartain-Williams (2007) indicated that value information obtained from forest sampling makes drastic “jumps” that are a result of differences in products contained in the volume of the trees being sampled. They claim that these “jumps” are somewhat remedied by the specification of log product requirements by mills, but “blended” valuation of timber is more applicable from an inventory perspective. Blended valuation of timber is presumably more applicable for traditional inventory because it is difficult to obtain detailed estimates of the products contained in a stand. Inventory performed with TLS could provide a better estimate of log products required by a mill than traditional inventory methods, such as those used by Sartain-Williams.

Chapter 6 - Conclusions

TLS holds definite promise as a tool that can be used for forest inventory. With the world economy growing increasingly inflationary TLS could provide an inexpensive and time saving method by which forest inventory can be acquired. This is a new use for this kind of technology so more research is needed in order to put the use of this technology into regular practice.

The results for the diameter measurement comparison indicate that there is more study and comparison needed for TLS to meet the accuracy standards that industry needs to put this technology into practice for forest inventory. The accuracy realized for DBH measurements at BTF with uniformly grown, uniformly planted genetically cloned hybrid poplar trees can no doubt be translated to a variety of other species that might not be so evenly planted and grown. The inaccuracies arise when the scanner looks up into the crowns of the stems. The software that finds the stem in the point cloud data seems to be "confused" by branching on the upper portion of the stem. In light of the statistically significant average diameter differences between TLS and NBE found in Stand H-12 it was no wonder that the volume comparison for plots 1 to 6 in Stand H-12 indicated statistically significant differences in volume recovery between TLS and NBE for each plot, as well. In chapter 5 we demonstrated the ability of TLS to determine volume for an entire stand but until diameter accuracy is improved, particularly in the upper portion of the stem TLS volume estimation on standing timber should be looked at with caution.

Another possible explanation for the diameter inaccuracy found between average TLS diameter measurements and average NBE and manual diameter measurements is the presence of occluded contours. As explained by Vaillant and Faugeras (1992), occluded contours occur when a three dimensional image is created by some projection method, in their case a camera. An occluded contour is the curvature on the backside of the edge of a three dimensional object that cannot be observed by the camera, or laser. For a tree, this means that the front diameter may be cylindrical up to either edge of the stem but beyond the edges of the stem where the laser cannot see the stem may be some other shape than cylindrical. If the back side of the tree is, say, elliptical or oddly shaped then the laser will underestimate the diameter because it assumes that the back side of the stem is cylindrical. On the other hand, if the back side of the stem is “sunken in” or if there is a defect that cannot be observed by the scanner then the diameter of the stem will be overestimated. This suggests that diameter accuracy may be improved by utilizing multiple scans of trees within a plot, albeit at an additional cost. It also suggests that elliptical or other models of stem shape should be considered.

TLS seemed to perform very well in measuring the centerline of the stems when compared to NBE. It was beneficial to have performed the comparison between NBE over bark and under bark centerline measurements on Stand H-12 because then we were able to get an idea of the variation inherent in the centerline position between different points on the stem. Since the same measurement method was used for this comparison we knew that any TLS measured variation in the comparison between TLS and NBE centerline measurements would show up beyond the variation inherent between the different points on the stem. For Stand H-12 the fact that the RMSD was about the same for the comparison between TLS and NBE as the comparison between NBE over bark and NBE under bark meant that the TLS measurement of the centerline was as good as the mill scan accuracy in this case. Unfortunately, we were unable to repeat the NBE over bark versus NBE under bark centerline measurement comparison in stands M-7 and L-7 due to time constraints from the mill, but with that comparison from Stand H-12 and the accuracy level obtained from the sweep comparison in Stand H-12 we can carry that accuracy assumption over to stands M-7 and L-7 because the measurement processes were exactly the same.

With the centerline measurement comparisons we again see the influence of the “seen zone versus the “unseen” zone on accuracy. The RMSD after the taper function was engaged was higher than below the taper function zone suggesting that the TLS algorithms were unable to take into account the variation in stem position at different heights within the “unseen” zones. With both the centerline and the average diameter comparisons the points on the stem where actual laser measurements were used had high accuracy compared to measurements taken higher in the stem. Diameter accuracy may be able to be improved by fitting a better taper function where the scanner cannot see or by using multiple scans that may allow more of the stem to be seen will be more difficult to deal with. Multiple scans may be required. However, improving centerline accuracy should be weighed against the likelihood that upper portions of the stem are likely to yield less valuable products, anyway..

One of the most beneficial uses of TLS we have demonstrated with this project is the ability to determine potential value gains from product reallocation. We can do this on standing timber so there is no need for destructive sampling in order to get an idea of extra value potential within a stand. With the accuracy shown in sweep comparison it is likely that the increases in value we saw from the possible addition of a veneer production line at the Collins Company mill may be close to what could actually be realized from all three stands. Considering the state of the world economy and the need for companies such as BTF to find ways to reallocate wood products for potential value recovery gains from existing inventories TLS provides a way to determine the best product reallocation scenarios without destructive sampling.

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Appendix

Table A-1 Chi Square test for difference in average over bark diameter results for the comparison between TLS and NBE methods in Stand H-12, plots 1 to 6

TLS vs. NBE Over Bark Diameter Measurement - Stand H-12 Plots 1 to 6					
		10% accuracy			
Height of Measurement (m)	df	$\chi^2_{(n-1)}$	p-value	% accuracy	new p-value
Butt	33	133.08	p < 0.001	17.0	0.05 < p < 0.10
DBH	36	130.78	p < 0.001	16.5	0.05 < p < 0.10
3	36	116.35	p < 0.001	15.0	0.05 < p < 0.10
6	36	254.83	p < 0.001	22.5	0.05 < p < 0.10
9	36	626.34	p < 0.001	35.5	0.05 < p < 0.10
12	33	583.62	p < 0.001	35.5	0.05 < p < 0.10
15	31	463.65	p < 0.001	32.5	0.05 < p < 0.10

Table A-2 Chi Square test for difference in average over bark diameter results for the comparison between TLS and manual methods in Stand H-12, plots 1 to 6

TLS vs. Manual Over Bark Diameter Measurement - Stand H-12 Plots 1 to 6					
		10% accuracy			
Height of Measurement (m)	df	$\chi^2_{(n-1)}$	p-value	% accuracy	new p-value
Butt	47	267.90	p < 0.001	20.5	0.05 < p < 0.10
DBH	48	125.00	p < 0.001	14.0	0.05 < p < 0.10
3	48	104.20	p < 0.001	13.0	0.05 < p < 0.10
6	48	224.60	p < 0.001	19.0	0.05 < p < 0.10
9	47	631.30	p < 0.001	31.5	0.05 < p < 0.10
12	46	798.80	p < 0.001	36.0	0.05 < p < 0.10
15	45	676.60	p < 0.001	33.5	0.05 < p < 0.10
18	43	672.10	p < 0.001	34.0	0.05 < p < 0.10
21	40	799.80	p < 0.001	38.0	0.05 < p < 0.10
24	36	612.10	p < 0.001	35.0	0.05 < p < 0.10
27	23	751.80	p < 0.001	46.5	0.05 < p < 0.10

Appendix (continued)

Table A-3 Chi Square test for difference in average under bark diameter results for the comparison between TLS and NBE methods in Stand H-12, plots 1 to 6

TLS vs. NBE Under Bark Diameter Measurement - Stand H-12 Plots 1 to 6					
		10% accuracy			
Height of Measurement (m)	df	$\chi2_{(n-1)}$	p-value	% accuracy	new p-value
Butt	33	297.60	p < 0.001	25.5	0.05 < p < 0.10
DBH	33	129.20	p < 0.001	16.5	0.05 < p < 0.10
3	33	175.700	p < 0.001	19.5	0.05 < p < 0.10
6	33	265.90	p < 0.001	24.0	0.05 < p < 0.10
9	33	610.60	p < 0.001	36.0	0.05 < p < 0.10
12	30	764.80	p < 0.001	42.0	0.05 < p < 0.10
15	27	700.60	p < 0.001	42.0	0.05 < p < 0.10

Table A-4 Chi Square test for difference in average under bark diameter results for the comparison between TLS and manual methods in Stand H-12, plots 1 to 6

TLS vs. NBE Under Bark Diameter Measurement - Stand H-12 Plots 1 to 6					
		10% accuracy			
Height of Measurement (m)	df	$\chi2(n-1)$	p-value	% accuracy	new p-value
Butt	33	297.60	p < 0.001	25.5	0.05 < p < 0.10
DBH	33	129.20	p < 0.001	16.5	0.05 < p < 0.10
3	33	175.70	p < 0.001	19.5	0.05 < p < 0.10
6	33	265.90	p < 0.001	24.0	0.05 < p < 0.10
9	33	610.60	p < 0.001	36.0	0.05 < p < 0.10
12	30	764.80	p < 0.001	42.0	0.05 < p < 0.10
15	27	700.60	p < 0.001	42.0	0.05 < p < 0.10

Appendix (continued)

Table A-5 Chi Square test for difference in average over bark diameter results for the comparison between TLS and NBE methods in Stand M-7, plots 1, 6, 11 & 16

TLS vs. NBE Over Bark Diameter Measurement Stand M-7 Plots 1, 6, 11 and 16					
		10% accuracy			
Height of Measurement (m)	df	$\chi^2_{(n-1)}$	p-value	% accuracy	new p-value
Butt	42	432.70	p < 0.001	27.5	0.05 < p < 0.10
DBH	42	379.50	p < 0.001	26.0	0.05 < p < 0.10
3	42	375.40	p < 0.001	25.5	0.05 < p < 0.10
6	40	331.00	p < 0.001	24.5	0.05 < p < 0.10
9	25	415.30	p < 0.001	33.5	0.05 < p < 0.10

Table A-6 Chi Square test for difference in average over bark diameter results for the comparison between TLS and manual methods in Stand M-7, plots 1, 6, 11 & 16

Overbark TLS vs. Manual Diameter Measurement Stand M-7 Plots 1, 6, 11 and 16					
		10% accuracy			
Height of Measurement (m)	df	$\chi^2_{(n-1)}$	p-value	% accuracy	new p-value
Butt	45	147.20	p < 0.001	15.5	0.05 < p < 0.10
DBH	46	44.13	0.20 < p < 0.975	8.5	0.05 < p < 0.10
3	46	66.96	0.02 < p < 0.025	10.5	0.05 < p < 0.10
6	46	213.90	p < 0.001	18.5	0.05 < p < 0.10
9	46	416.80	p < 0.001	26.0	0.05 < p < 0.10
12	43	284.70	p < 0.001	22.0	0.05 < p < 0.10
15	42	248.60	p < 0.001	21.0	0.05 < p < 0.10

Appendix (continued)

Table A-7 Chi Square test for difference in average over bark diameter results for the comparison between TLS and NBE methods in Stand L-7, plots 1 to 8

TLS vs. NBE Over Bark Diameter Measurement - Stand L-7 Plots 1 to 8					
		10% accuracy			
Height of Measurement (m)	df	$\chi^2_{(n-1)}$	p-value	% accuracy	new p-value
Butt	47	102.90	p < 0.001	13.0	0.05 < p < 0.10
DBH	47	60.82	0.05 < p < 0.10	10.0	0.05 < p < 0.10
3	47	85.83	p < 0.001	12.0	0.05 < p < 0.10
6	46	121.20	p < 0.001	14.0	0.05 < p < 0.10
9	37	141.30	p < 0.001	16.5	0.05 < p < 0.10

Table A-8 Chi Square test for difference in average over bark diameter results for the comparison between TLS and manual methods in Stand L-7, plots 1 to 8

TLS vs. Manual Over Bark Diameter Measurement - Stand L-7 Plots 1 to 8					
		10% accuracy			
Height of Measurement (m)	df	$\chi^2_{(n-1)}$	p-value	% accuracy	new p-value
Butt	40	389.80	p < 0.001	26.5	0.05 < p < 0.10
DBH	41	61.36	0.02 < p < 0.025	10.5	0.05 < p < 0.10
3	41	74.68	0.001 < p < 0.002	11.5	0.05 < p < 0.10
6	41	93.49	p < 0.001	13.0	0.05 < p < 0.10
9	41	251.90	p < 0.001	21.5	0.05 < p < 0.10
12	40	362.80	p < 0.001	25.5	0.05 < p < 0.10
15	38	218.00	p < 0.001	20.5	0.05 < p < 0.10
18	24	294.80	p < 0.001	28.5	0.05 < p < 0.10

Appendix (continued)

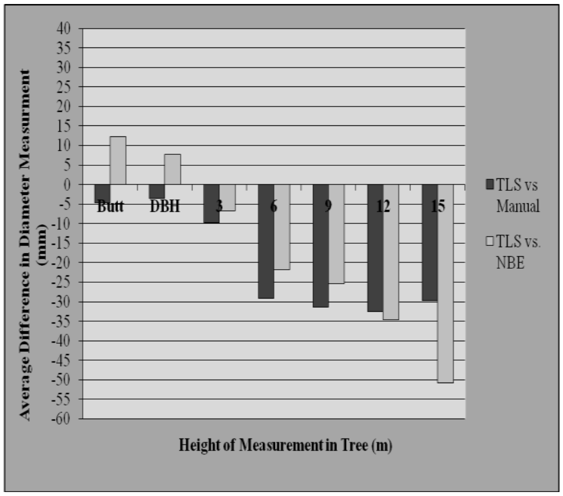

Figure A-1 Average over bark difference in diameter measurement for plot 1 in Stand H-12.

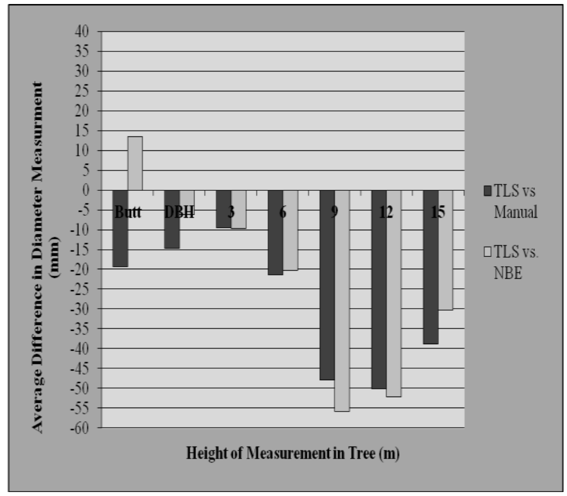

Figure A-2 Average over bark difference in diameter measurement for plot 2 in Stand H-12.

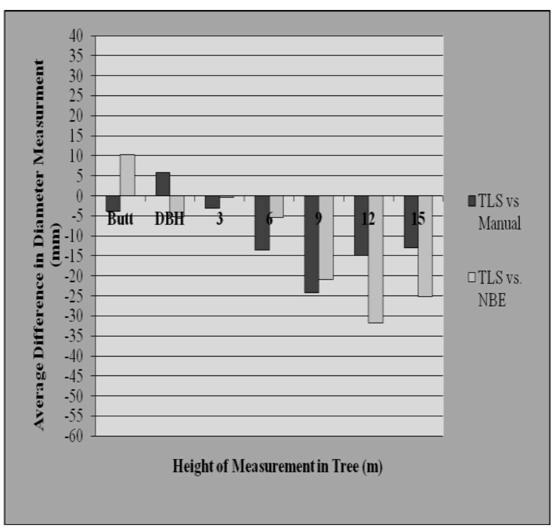

Figure A-3 Average over bark difference in diameter measurement for plot 3 in Stand H-12.

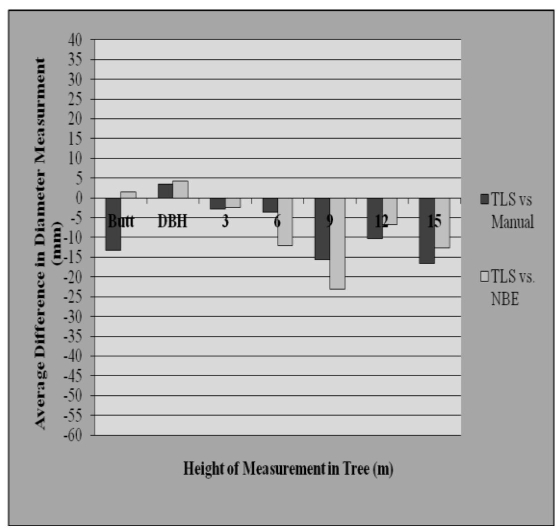

Figure A-4 Average over bark difference in diameter measurement for plot 4 in Stand H-12.

Appendix (continued)

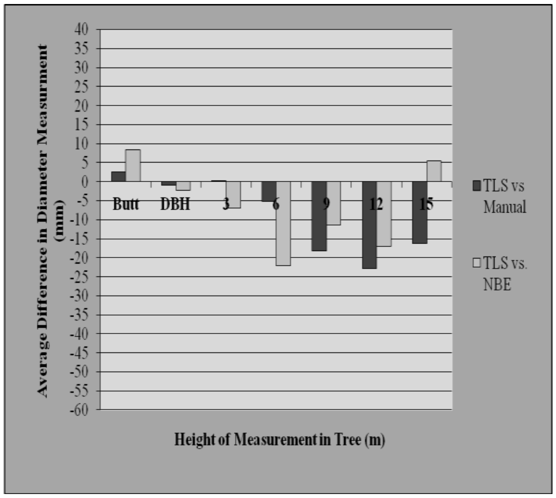

Figure A-5 Average over bark difference in diameter measurement for plot 5 in Stand H-12.

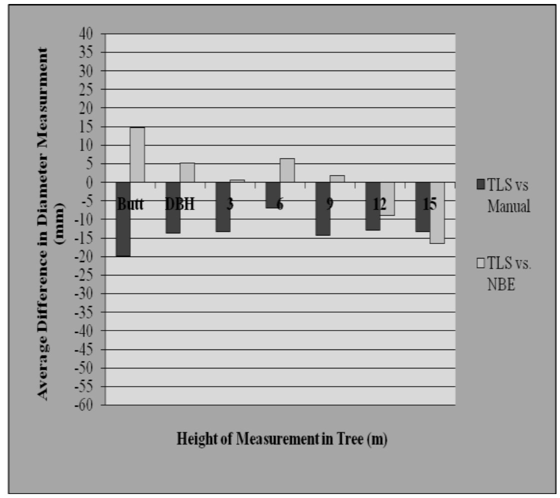

Figure A-6 Average over bark difference in diameter measurement for plot 6 in Stand H-12.

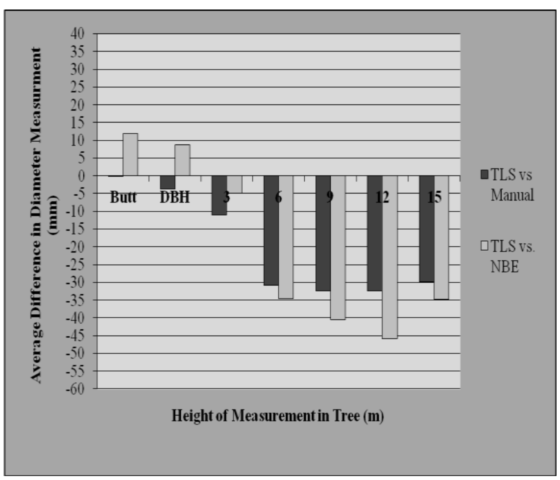

Figure A-7 Average under bark difference in diameter measurement for plot 1 in Stand H-12.

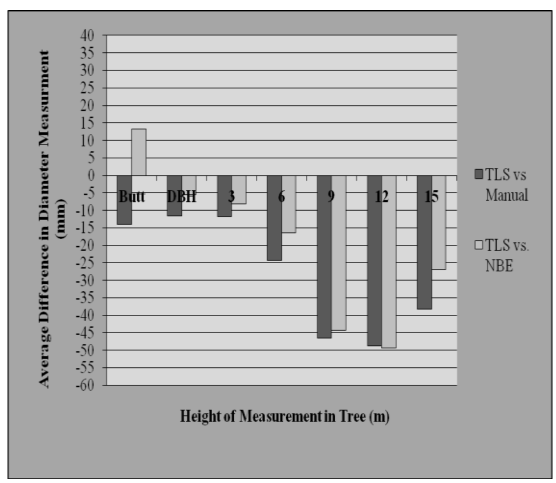

Figure A-8 Average under bark difference in diameter measurement for plot 2 in Stand H-12.

Appendix (continued)

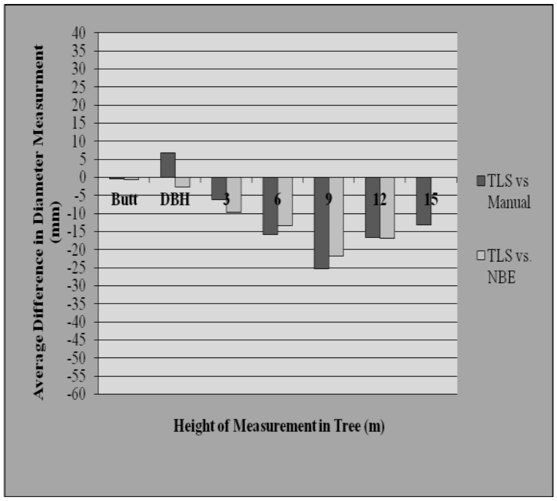

Figure A-9 Average under bark difference in diameter measurement for plot 3 in Stand H-12.

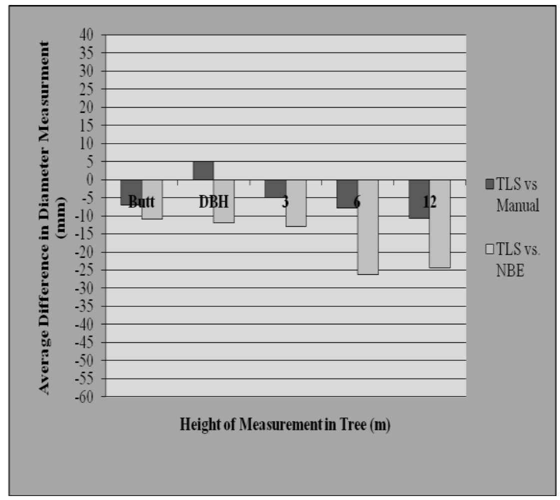

Figure A-10 Average under bark difference in diameter measurement for plot 4 in Stand H-12.

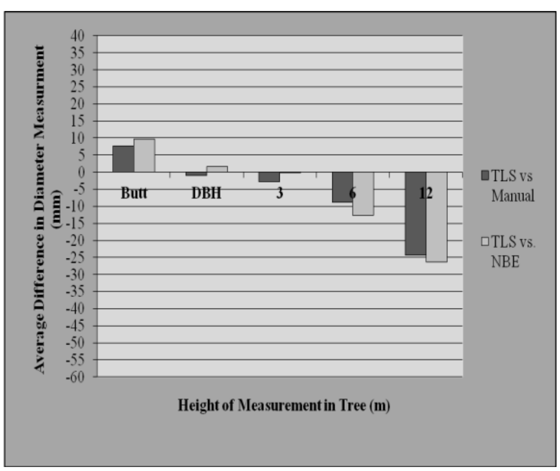

Figure A-11 Average under bark difference in diameter measurement for plot 5 in Stand H-12.

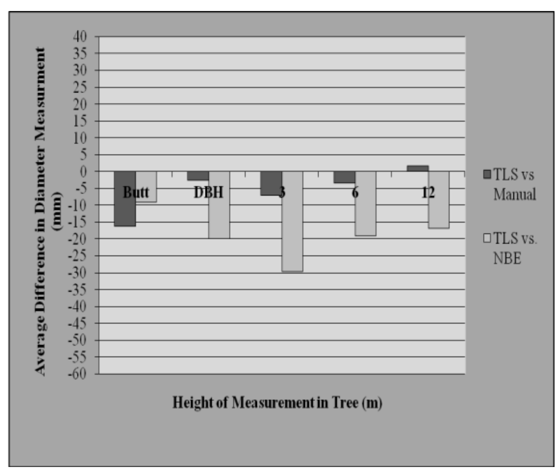

Figure A-12 Average under bark difference in diameter measurement for plot 6 in Stand H-12.

Appendix (continued)

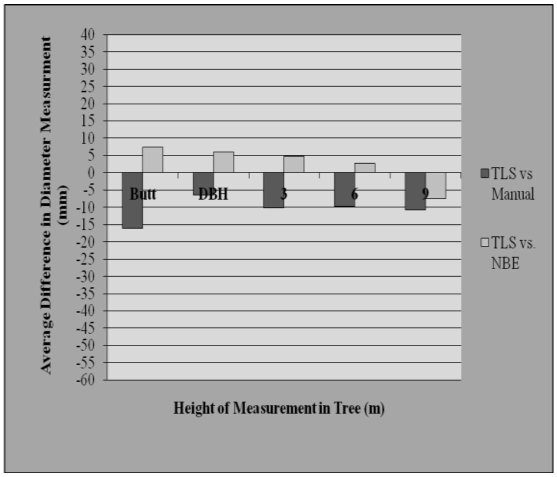

Figure A-13 Average over bark difference in diameter measurement for plot 1 in Stand M-7.

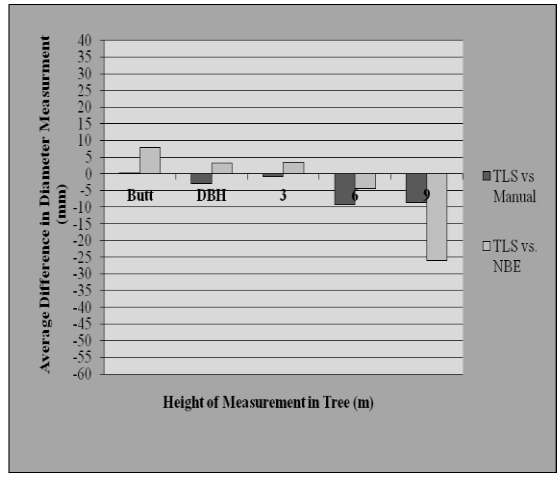

Figure A-14 Average over bark difference in diameter measurement for plot 6 in Stand M-7.

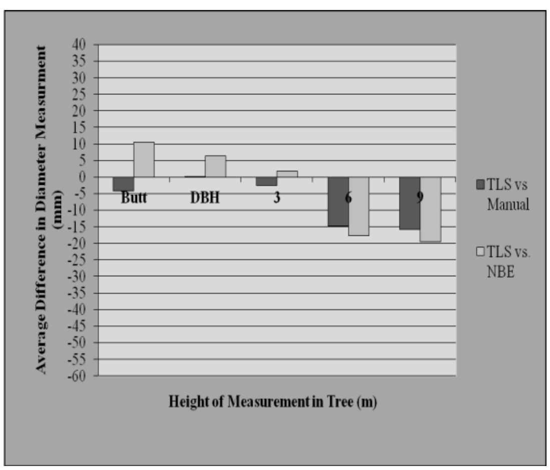

Figure A-15 Average over bark difference in diameter measurement for plot 11 in Stand M-7.

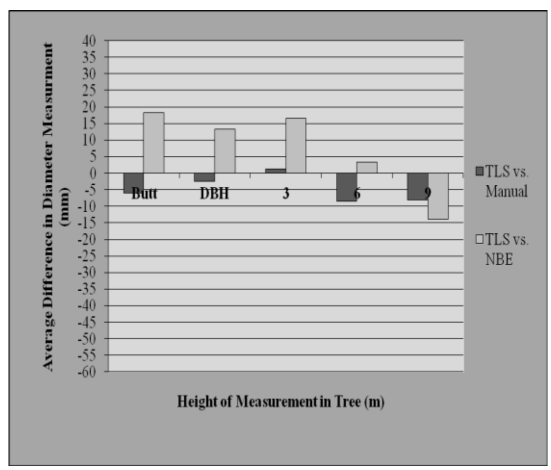

Figure A-16 Average over bark difference in diameter measurement for plot 16 in Stand M-7.