University of Southern Queensland

Faculty of Health, Engineering and Sciences

# Comparison of TLS to Total Station Accuracy for Tree Parameter Measurement in Biomass Estimation

A dissertation submitted by

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# Abstract

Biomass estimation is a procedure often used for determining the growth, health, carbon content and contribution a forest has to the environment. For this reason, biomass estimations are an important step in forest decision making and monitoring, requiring accurate measurements.

This project compares the use of terrestrial laser scanners (TLS) and total stations (TS) when measuring the tree parameters of height and diameter at breast height (DBH) for use in biomass estimation.

Allometric equations use accurate height and DBH measurements to estimate the biomass of vegetation. Studies have also shown large differences between TS and TLS measurement of these variables. TS and TLS typically have mm and cm accuracy, however a simple tangent calculation using angle and distance to calculate height causes large errors if the tree is leaning or oddly shaped. Similarly, non-circular tree stems can cause variations in DBH measurement.

This study explores the accuracy of TS and TLS with revised methods of measurement to remove these errors and gain an improved indication of the accuracies of these instruments.

The results of this investigation have shown a dual total station setup method for height measurement achieves an accuracy of 0.052m giving an improved indication of the TLS when compared to this data. Also, a best fit circle approach in DBH measurement using a TLS found greatly improved consistency in measurement compared to other methods and effectively removed the impacts from irregular stem shapes.

Applying the established errors and accuracies to allometric equations, it was found that the TLS methods applied achieve a high level of accuracy for biomass estimation. With continually improving efficiency and visualisation benefits of TLS, this method will continue to grow in popularity.

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# ENG4111 & ENG4112 Research Project

## Limitations of Use

# Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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# Abbreviations

ALS: Airborne laser scanner

DBH: Diameter at breast height

DTM: Digital terrain model

LiDAR: Light detection and ranging

RMSE: Root mean square error

TLS: Terrestrial laser scanner

TS: Total station

# Chapter 1 Introduction

## 1.1 Introduction

Biomass refers to the amount of biological matter in vegetation, customarily given in terms of weight. Tree biomass is a major carbon pool, with forests containing roughly 45% of the global terrestrial carbon (Stovall, Anderson-Teixeria & Shugart 2018). Forests have a major impact on global temperatures due to their carbon sequestration and are critical components of ecosystems. For this reason, biomass measurements are often taken to determine forest condition and value for decision making. These measurements are used by both private owners of forest areas and global level policy making. Tree biomass measurements can also be used for studying the growth of vegetation over time for further use in health monitoring and forest decision making.

There are various methods of determining the biomass of trees and forests. The biomass of trees is calculated using allometric equations, which define the relationship between tree parameters such as the diameter as breast height (DBH) and tree height with the tree mass. These equations are often specie specific and so a single equation can only be applied to a singular tree type. However, there are also generalised allometric equations that can be applied to large tree groups. For example, Williams et al. (2005) analysed 14 woodland species across Australia and created a general equation that was only marginally inferior to the specie specific equations, suggesting that a general predicative equation can be applied to Australian woodland areas.

Traditionally, the DBH and tree height features for use in these equations have been measured with clinometers and tape measures. However, advances in surveying technology have introduced methods such as terrestrial laser scanning, airborne LiDAR, mobile laser scanning and photogrammetry.

Terrestrial laser scanners have been used for many years for their high-resolution mapping ability. The rapid measurement and 3D modelling capabilities has led to many applications such as building modelling, terrain modelling, deformation measurements and cultural heritage monitoring. The advancement of this technology has developed the use of terrestrial laser scanners for forest monitoring purposes.

## 1.2 Project Aims

The aim of this project is to compare the use of a terrestrial laser scanner (TLS) to total station (TS) and tape methods in terms of accuracy and efficiency when measuring tree parameters for biomass estimation.

Total stations are one of the most accurate devices of measurement in the surveying industry, with measurements in the mm level of accuracy. Compared to total stations, TLS are less accurate with measurements usually in the cm level of accuracy. However, these accuracies often represent the measurement of solid, reflective surfaces such as buildings. The accuracy of these measurements may vary greatly when measuring vegetation due to variables such as wind, surface reflectivity, obstructions and general tree shape. For this reason, the investigation should determine the advantages, limitations and accuracy of each of these methods in a forest environment. Due to the nature of allometric equations, errors in DBH and errors in height will influence the calculated biomass by different magnitudes. Therefore, factors such as the varying accuracies of DBH and tree height will also be considered in the investigation.

These recorded and compared accuracies can potentially determine if a TLS would be a worthwhile investment for future applications in this field.

Objectives of this investigation include:

1. Research types and accuracies of terrestrial laser scanners and total stations
2. Research data collection methods for the TLS and TS
3. Collect measurement data of DBH and height in the forest environment (TLS and TS)
4. Analyse and compare accuracies of TS and TLS for;
    - Direct DBH and height measurements (between both methods)
    - When assuming circular tree trunk for DBH and accounting for irregular shapes with TLS
    - Single TS setup compared to a dual setup method

5. Analyse how the established error impacts the relevant allometric equations

6. Analyse tree density impacts on accuracy and obstruction issues

These objectives will establish key differences between the results of TLS and TS methods and how they are impacted by the different tree shapes.

# Chapter 2 Literature Review

## 2.1 Technology

### 2.1.1 Terrestrial Laser Scanners

Modern terrestrial laser scanners collect anywhere from tens of thousands to millions of points every second with accuracies ranging from mm to cm (depending on the scanner and range used). The FARO Focus3D used in this investigation is capable of collecting 976 000 points per second with a ranging accuracy of 2mm in ideal conditions. Each measured point is defined by an X, Y and Z coordinate. This large data collection process enables the creation of accurate 3D models of the immediate environment. This has led to many applications such as building modelling, terrain modelling, deformation measurements and cultural heritage monitoring.

There are two main types of terrestrial laser scanners which use two different methods of point measurement: time-of-flight and phase-shift. These terrestrial laser scanner types mainly differ in their range, data acquisition rate and accuracy. Time-of-flight technology is much more effective at longer ranges as it can still measure accurately at distances above 100m, while phase-shift scanners are more suitable for short range scans (usually <70m) with higher accuracy and increased acquisition rates (San José Alonso et al. 2011).

A study by Wilkes et al. (2017) describes how in forest environments, scanning at intervals of 10m to 30m is ideal for accuracy, and states that the tree canopy of most forest types does not exceed 30m. This suggests that phase-shift type scanners are the suitable choice for data collection in this environment, due to the advantages of short-range accuracy and data acquisition speeds. Furthermore, longer range scans would not be possible in most environments due to tree obstructions leading to incomplete data.

Several factors that will influence the accuracy of TLS include scan geometry, surface geometry, movement, reflectivity and colour. Scan geometry refers to scanner setup positions and considers factors such as distance between scans and overlapping scans for improved accuracy. Colour can be an issue as a dark coloured object may be difficult to scan due to less light is reflected. Other reflectivity issues can include highly reflective surfaces such as road signs, which cannot be measured effectively with TLS. Movement of objects being scanned will be a major impact on TLS accuracy in forests due to wind and branch movement.

Time of flight scanners

The basic principle of the time-of-flight scanner is that a laser is emitted, and the distance is determined through how long it takes for the signal to return. Using the speed of light and the measured time (divided by two to determine the one-way distance) the distance between the laser scanner and target can be calculated. This calculation is shown below:

$$d = \frac{c * t}{2}$$

where d is the distance to target [m]

c is the speed of light [$m.s^{-1}$]

t is the time taken for signal to return [s]

Combining this distance with the horizontal and vertical angles measured by the system, the x, y and z coordinates of each point is determined. This is completed for as many as 100 000 points measured every second to create accurate 3D models of the area. The range of this system type is typically up to 300m.

Phase Shift Laser Scanners

The phase-based method is similar to time-of-flight laser scanners, except the distance is measured using the phase shift of the returning laser signal. A constant laser signal is emitted from the scanner and the waves of various length are measured as it is projected. As the signal returns from the target and to the scanner, the phase shift of the signal is measured to calculate the distance. This system generally has a much higher acquisition speed, with often millions of points being measured every second. Although this type of scanner is more accurate than time-of-flight, the range is usually limited to 100m. However, vegetation data collected in a forest environment will usually be within 50m, meaning the range will be not an issue when used in this project.

### 2.1.2 Total Stations

A total station is a modern surveying instrument that accurately measures angles and distances. Most total stations have an in-built theodolite and an electronic distance meter (EDM) for angular and distance measurement that consist of very high measurement accuracy such as 2mm + 2ppm for distance and an angle accuracy of 3’’ (Specifications of Sokkia Set 3x total station used in this study). This suggests that measurements completed with a total station in this project will be highly reliable. Total stations can generally only measure accurately to prism targets, but as technology progresses, more total stations are being equipped with accurate reflectorless distance measurement capabilities such as the Sokkia total station used in this study.

Although measuring with reflectorless technology would be a much faster process as no target setup is required, there are problems that would occur when measuring forest features. As the accuracy of this technology is dependent on the surface type, this may severely limit the use in this environment. Generally, smooth surfaces of a light colour will achieve a higher accuracy than rough surfaces of a dark colour (Alsalman et al. 2010). A poor surface such as a tree trunk will result in inaccurate measurements, and the dark surfaces may not be able to reflect the signal for measurement.  For these reasons, using a target based total station method would be more appropriate for this investigation.

## 2.2 Measurement Methods

DBH is defined as the distance of a straight line through the centre of the tree, typically at a height of either 1.3m or 1.4m (Maan et al. 2014; Williams et al. 2016; Queensland Aboricultural Association 2018). Various studies and methods have measured this tree attribute differently. This includes excluding bark in measurement or a different defined height such as 1.3m instead of 1.4m.

Using the set height for DBH is not always ideal depending on the state of the tree. Factors such as deformities, slopes and branching will require alternate predetermined methods (shown in figure 2.1).

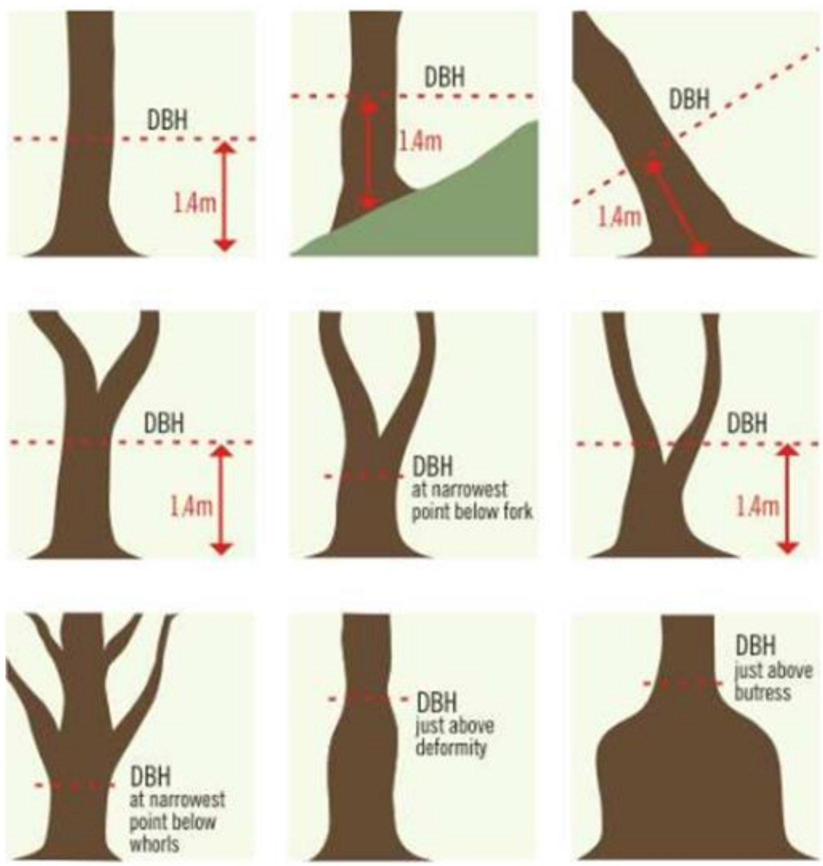


*Figure 2.1: Measuring DBH considerations (Queensland Aboricultural Association 2018)*

### 2.2.1 Total Station Method

The most common total station method of measuring tree parameters is simply measuring the distance to the tree and using the vertical and horizontal angles to find the different values. There have been studies that investigate the ability to estimate the height of the tree by measuring the diameter at different points of the tree. This is beneficial in areas with a thick canopy, where the top of the trees cannot be observed. Zhao et al. (2014) measured the DBH, the diameter at the highest visible point and the middle point's diameter. This achieved a reasonable accuracy of 70-80% when using a tree growth equation and 70-90% using a stem curve method.

### 2.2.2 Terrestrial Laser Scanner Method

Wilkes et al. (2017) investigated data acquisition considerations for terrestrial laser scanning in forest areas. It was suggested that a minimum of three scan locations are required to capture a single tree, but in thick canopies when measuring a large tree, around six scans would be necessary to obtain a high level of detail in the canopy.

When scanning a larger area, for practical and repeatable purposes it was recommended to use a grid method. For dense areas requiring a higher resolution, setups every 10 metres were needed. For open areas, setups only every 20 metres needed to be use for accurate results. This should enable each tree to get multiple perspectives from TLS setups.

A common method of obtaining the tree height from the point cloud data is to record the change in height between the lowest and highest point of the tree. A digital terrain model (DTM) is also often created and the distance from the highest tree point to the DTM defines the height.

The DBH is defined as a direct line between the edges through the centre of the tree (usually at a height of 1.3m or 1.4m). Investigations have sometimes found this value by creating a layer consisting of the coordinates at a height of 1.25m to 1.35m above the terrain. By implementing a search for circles model and implementing using the Randomised Hough transformation (which detects curves such as circles and ellipses), the DBH is calculated. Other studies have measured distances between two points on opposite sides of the trunk, although this could result in inconsistencies if the trees are a non-circular shape (Stanley, 2013).

## 2.3 Allometric Equations

Allometric equations are required to estimate the biomass of measured trees. By imputing the measured tree attributes, the equations often give the biomass in terms of kg. These allometric equations are created with two different methods; one destructive and the other non-destructive. The first and most common method is explained by Vashum and Jayakumar (2012) and Ximenes et al. (2018), where trees are harvested and weighed to find biomass relationship to measured tree parameters. With the introduction and advancement of remote sensing technology, authors have investigated another, non-destructive, method (ie: Stovall, Anderson-Teixeria & Shugart 2018; Kankare et al. 2018). This method uses TLS to create 3D models of trees and determine volumes to define relationships between biomass and the tree parameters. The results have shown that overall there is a lower root mean square error (RMSE) with this method, and that sample sizes of 100-200 are required for suitable prediction accuracy.

These reviewed papers have shown large amounts of allometric equations, varying for tree groups and specific species. The different tree densities and shape are what cause the equations to differ and why multiple are needed for improved accuracy. Equations investigated in a study by Daba and Soromessa (2019) utilised tree density as a third parameter input enabling application to similar species with varying densities. Other studies by Ximenes et al. (2018) and McPherson and Van Doorn (2016) automatically incorporate these densities in the equations which is one cause of the equations varying. However, the tree shape is a main cause in the changing equations with different ratios being found between DBH and AGB depending on the specie, in addition to limited applications of equations through specified DBH ranges for specific species (McPherson & Van Doorn 2016). This means that if a tree is too small or large, the equation would not be able to be accurately applied. The range, and therefore equation, will change to cover the typical size of the relevant tree species. Ximenes et al. (2018) has provided various allometric equations for common tree types in Australia shown in table 2.1, with references to allometric equations for tree groups that will be considered in this project.

*Table 2.1: Allometric equations for some Australian tree types (Ximenes et al. 2018)*

| Species | Equation | Source |
|---|---|---|
| **Blackbutt** | ln M (kg) = −2.3267 + 2.485 × ln DBH (cm)<br>ln M (kg) = −2.642 + 2.551 × ln DBH (cm) × 1.109<br>M (kg) = (0.000527127 × DBH (cm)^2.19699) × 710<br>log M (kg) = −1.3326 + 2.6934 × log DBH (cm) | Keith et al. [22]<br>Montagu et al. [23] [1]<br>Mackowski [24] [2]<br>Applegate [25] |
| | ln M (kg) = 0.0580 × DBH$^{2.673}$<br>ln M (kg) = 0.0311 × DBH$^{2.405}$Ht$^{0.465}$ | This study<br>This study |
| **Mountain ash** | log M (kg) = −2.43 + 2.58 log Girth (cm) | Ashton [26] |
| | M (kg) = −45.6 + 248.9 DBH(m)^2 HGT (m) (Stem); M (kg) = −42.2 + 25.7 DBH (m)^2 HGT (m) (Branches); M (kg) = −16.9 + 6.4 × ln DBH (cm) (Leaves) | Feller [27] |
| | M (kg) = 0.8721 × DBH^2 − 9.4009 × DBH (cm) | Sillett et al. (derived); [28] |
| | ln M (kg) = 0.7555 × DBH$^{2.038}$<br>ln M (kg) = 0.0392 × DBH$^{1.814}$Ht$^{0.955}$ | This study<br>This study |
| **Silvertop ash** | log M (kg) = −2.43 + 2.58 log Girth (cm) | Ashton [26] |
| | log M (kg) = −1.0373 + 2.3867 log DBH (cm) (Stem-wood); log M (kg) = −2.1434 + 2.7344 log DBH (cm) (Stem-bark); M (kg) = 4.7424 + 0.01026 DBH^2 (cm) (Leaves); M (kg) = −246.9228 + 0.2254 DBH^2 (cm) (Branches-wood); M (kg) = −69.5361 + 0.059 DBH^2 (cm) (Branch-bark); M (kg) = 3.4289 + 0.0133 DBH^2 (cm) (twigs) | Stewart et al. [29] |
| | ln M (kg) = −2.3267 + 2.485 × ln DBH (cm)<br>log M (kg) = −2.43 + 2.58 log Girth (cm) | Keith et al. [22]<br>Ashton [26] |
| | ln M (kg) = 0.0564 × DBH$^{2.579}$<br>ln M (kg) = 0.0375 × DBH$^{2.390}$Ht$^{0.352}$ | This study<br>This study |

It is also worth noting that accuracy in DBH and accuracy in height will not influence each equation by the same proportion. Generally, DBH is the most important value used for biomass estimation, with the tree height often not being used in an equation.

## 2.4 Previous Accuracy Studies

A there have been various studies exploring the use of airborne LiDAR, terrestrial LiDAR, total stations and even photogrammetry for the use of biomass estimation.

### 2.4.1 TLS and ALS Comparisons

TLS is not the only use of LiDAR in this environment. In recent years, the use of airborne laser scanning (ALS) in this field has increased, and so there have been several investigations with the intention of comparing the ALS method to TLS in respect to several parameters.

Sadadi et al. (2016) and Brede et al. (2017) compared tree height measurement using ALS and TLS for biomass and carbon stock estimation. These studies established methods that enabled relatively accurate measurement of tree height using both ALS and TLS. There have also been studies comparing the accuracy of DBH measurement between ALS and TLS (ie: Weiser et al. 2017; Brede et al. 2017). These results show slightly higher accuracy when using TLS, with differences ranging from 1.8% to 9% depending on the tree thickness. As these papers have shown a higher accuracy in DBH measurement when using terrestrial LiDAR compared to airborne LiDAR, this report will further investigate the accuracy of the TLS when compared to a TS.

### 2.4.2 TLS and TS Studies and Justification

Yu et al. (2016) investigated the measuring accuracy of a total station for DBH, tree height and volume in a forest environment. These results showed a low relative error of 0.108% for DBH and 0.051% for tree height. Applying the methods of DBH and height measurement with total station, the study used the variance and covariance of the measurements to deduce the accuracy.

Although the measurements were accurate, it does not mean the determined DBH and height values were accurate. This is due to the tree geometry. To measure the tree height with a total station, the horizontal distance to the tree and the vertical angle to the top of the tree are both measured. This calculated height can therefore be inaccurate due to the tree geometry where if the top of the tree is not directly above the trunk, a false height will be calculated when using the measured values. This error is amplified when measuring directly adjacent to the tree and minimised by measuring further away. However, in a forest environment, vegetation blockage and visibility issues may limit the separation between the TS and the tree. Therefore, this study should also attempt to negate this impact by measuring the tree height from two total station setup positions.

Studies conducted by Maan et al. (2014) and Stanley (2013), compared the gathered data between TLS and field measurements and demonstrated that the DBH and height measurements were relatively precise. Maan et al. (2014) determined a ratio between the two measurement methods for DBH and height of 0.96 and 0.79. The report stated the average height and DBH was 9.44m and 0.433m respectively. Stanley (2013), found that the difference in height between field and TLS measurement was anywhere from a few centimetres to half a metre. DBH was also measured more accurately in this study, with the difference in measurement between the two methods typically being less than 2cm.

These two studies observed the measurement value differences between a TLS and TS but did not directly establish an accuracy of either instrument. There was a large difference in height measurement found and this is likely due to tree movement and failure to pick up points; but could also be partly from the tree geometry error that occurs when using the TS. It will be beneficial to investigate the individual accuracies of these methods and provide further information of the suitability of each method for future use in biomass estimation. Comparing the differences in measurements between TLS and TS in this report also may not present the same findings as previous studies. These results may vary depending on the equipment used and its specifications and measuring capabilities. Further differences in results between the studies may occur due to canopy thickness differences, meaning the issue of density should also be examined with potentially multiple project sites.

The two main error impacts that will be investigated in this study are the height geometry (highest point not above tree trunk) and DBH geometry (non-circular trees trunks leading to misrepresentation of DBH when measured with girth tape). Exploring these factors may provide further details of the differences in measurement discovered by Maan et al. (2014) and Stanley (2013).

This investigation will highlight specific equipment, density and method impacts to accuracy when comparing these results to previous studies; providing further information in the topic of biomass estimation when using TLS and TS.

# Chapter 3 Methodology

## 3.1 Introduction

The aim of this project is to compare the use of a terrestrial laser scanner (TLS) to total station and tape methods in terms of accuracy and efficiency when measuring tree parameters for biomass estimation.

Previous studies on this topic have determined considerable differences between the results from TS and TLS measurement methods, particularly for when measuring tree height. This methodology section outlines the equipment and processes used to take DBH and Height measurements and determine the accuracy of these as well as the tree geometric errors that may be present.

## 3.2 Project Site

The project site to be used is Black Gully Reserve. This site is located in Toowoomba and largely consists of eucalyptus tree species, blackbutt, spotted gum and ironbark which were measured in this investigation. The site was chosen to be used due to the common Australian tree species found there which can be applied to the existing allometric equations and offer accuracy information relevant to many Australian tree types. Black Gully Reserve can be seen in figure 4.1 below.

*Figure 3.1: Black Gully Reserve project site*

## 3.3 Equipment

### 3.3.1 FARO Focus 3D

The terrestrial laser scanner used was the FARO Focus 3D shown in figure 4.2, owned by the University of Southern Queensland. This scanner produces detailed 3D models of any environment made up of millions of points with defined x, y and z values. Twelve spherical targets were used for scan registration which enables multiple scan setups to be joined together for a better representation of the environment. Four targets are the minimum requirement to align two scans and so the extra two spheres should be used for redundancy and in case targets get knocked over or blocked from view.


*Figure 3.2: FARO Focus 3D (Faro 2018)*

### 3.3.2 Sokkia Set 3x

The total station used is the Sokkia Set 3x shown in figure 4.3. This total station can measure precise vertical and horizontal angles with an accuracy of 3 seconds. The EDM measures distances with an accuracy of 2mm + 2ppm.

*Figure 3.3: Sokkia Set 3x (Sokkia 2011)*

## 3.4 Field Procedures

The TLS will use the grid geometry between setups (20m intervals with variations where appropriate). It should be ensured that each tree will have all sides scanned when the measurement data is combined. The same trees will be measured as with when the TS was used for direct comparison between measurements and the results of previous studies.

### 3.4.1 Target Setup for Registration for TLS

Key factors that needed to be considered for the target setup and registration:

- Six targets used for scan alignment and redundancy
- Place targets in high and low positions and in irregular configurations to remove multiple possible scan solutions
- Short distances between the scan setup positions and targets for accurate measurement and target recognition. Scan intervals used were roughly 20m, and so this led to no issues in this regard.
- Targets need to be visible from both scan positions

### 3.4.2 Diameter at Breast Height

The DBH is not measured with the total station, but with girth tape due to the simplistic, accurate and efficient measurement speed. The circumference of the stem at 1.4m is measured and divided by pi to calculate the diameter for comparison to the TLS measurements.

The process of finding the DBH using the TLS is much more complex. Instead of measuring the distance between two points on opposite sides of the trunk in the point cloud, a best fit circle approach was used. This was to investigate the impacts that a non-circular shape tree would have on tape and compare to other TLS methods used in other studies.

After registering each of the scans using the FARO Scene software, the points of on single trees stem of height between 1.35 and 1.45 were selected (figure 4.4) and the coordinates of each of these points were exported.

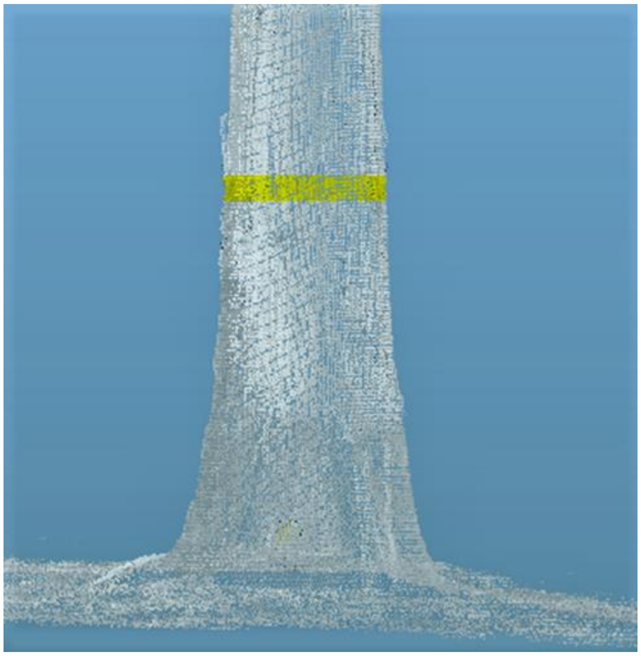

*Figure 3.4: Selection of points on tree stem of height 1.35-1.45m*

Using horizontal components of these points, a best fit circle approach was used to offer the best representation of the tree's DBH. The calculations for this were completed in excel.

The basic process for this involved firstly estimating the centre position of the circle with an X and Y coordinate. This enables automatic calculation of the average radius (average distance between coordinates of exported points and centre coordinates), followed by the square error of the radius for each point (error between individual point radius distance and average radius distance). Using the excel function of solve for minimum value, the document could alter the predicted centre position until the sum of square error reached the minimum value. This gave a centre point position and radius of a circle that best represented the tree stem. An example of these results is shown in figure 4.5.

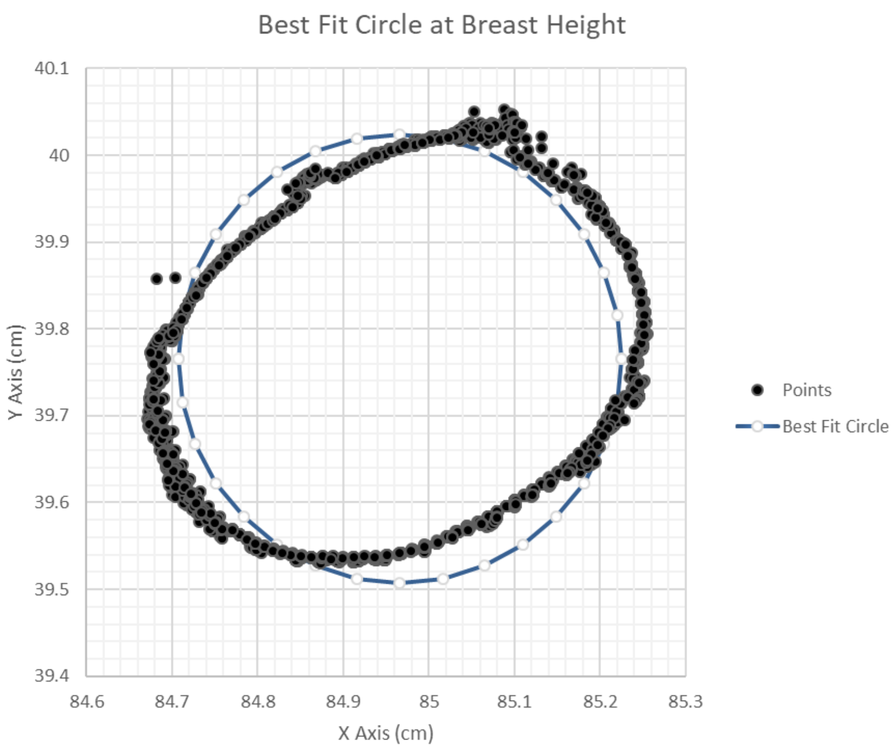


*Figure 3.5: Best fit circle of tree stem*

It is known that if a circle and ellipse have the same circumference, the circle will contain a larger area. The common field measurement technique of DBH uses tape to measure the circumference of a tree. As the tree is often truly more of an ellipse shape, but assumed to be a circle, this could indicate that DBH values found could indicate a larger volume than what really exists. Therefore, exploring the application of a best fit ellipse could help replicate the results made using a tape if the tree exhibits this shape.

To solve this, a best fit ellipse was also applied to the same points as the best fit circle. This would enable the circumference of the ellipse to be found and compared to those values found with tape measurement. The best fit ellipses were automatically computed using NLREG software, and an example of the results are shown in figure 3.6:

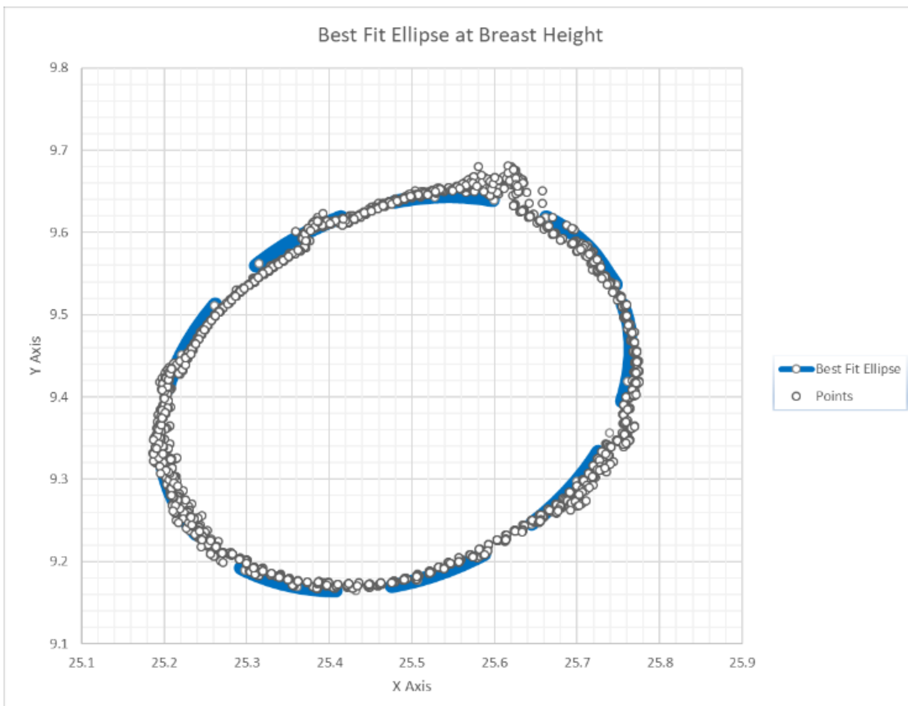


*Figure 3.6: Best fit ellipse of tree stem*

### 3.4.3 Height

Using the scan data from the TLS, the height of a tree was determined from the vertical offset between the highest and lowest point of the tree.

When measuring the height of a tree using a total station, if a single angle to the top of a tree and measurement to the base of the tree is used (known as the tangent method), there will be a geometric error that results from the top of the tree not being directly above the stem. This error is shown in figure 3.6 and will be further analysed using the TLS point cloud by measuring the horizontal offset between the top and bottom of the tree in the point cloud.

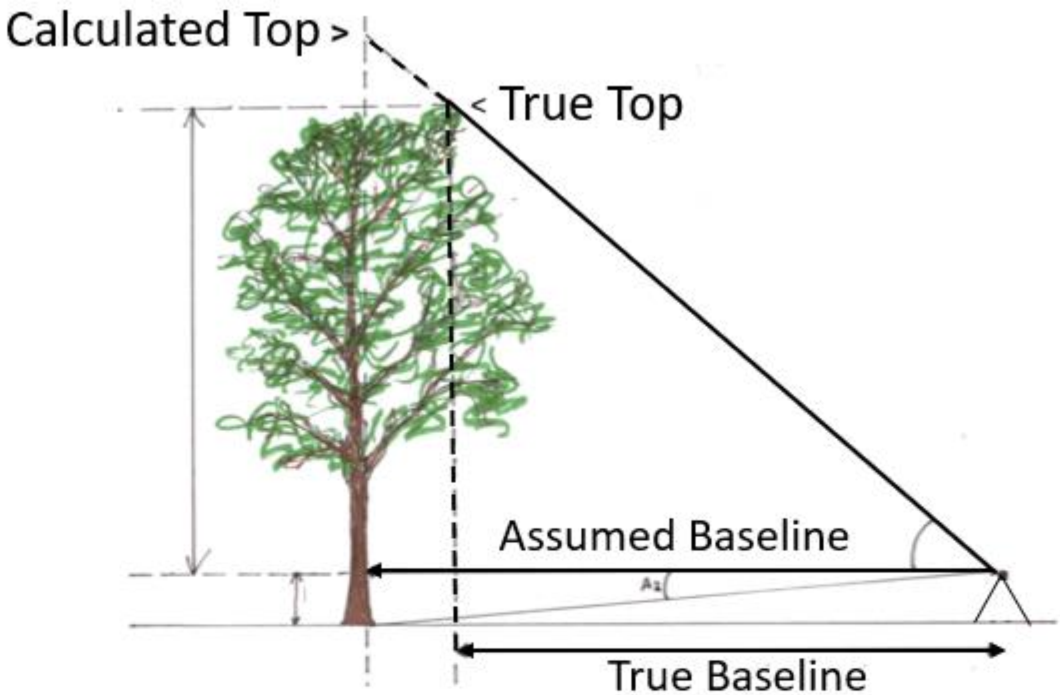


*Figure 3.7: Height error with single TS setup (Koutar, Philippona & Spraggon 2018)*

For this error to be negated when using the TS, the initial method used involved setting up twice in a straight line to the tree. Using the distance between the setup points, the change in angle to the top of the tree and a measurement to the base of the tree, the tree height could be calculated. This method proved ineffective as there were large errors in the angular measurement due to tree movement (such as 5-minute angular differences between face left and face right values). The two setups were often very close together for the top of the tree to be visible in both positions (roughly 5m) and this amplified the initial angle error resulting in around 0.5m height errors.

The height measurement method then changed so that the two total station setups were roughly perpendicular with the tree (the distance to the tree remained roughly the same but the distance between setups was usually above 50m). This required both horizontal and vertical angles to be measured between the setup points and the tree to create an intersection point and new horizontal to the top of the tree. This dual total station setup method is shown in figure 3.7. The large distance between the setups meant the angular errors to the tree had much less influence on the height accuracy.

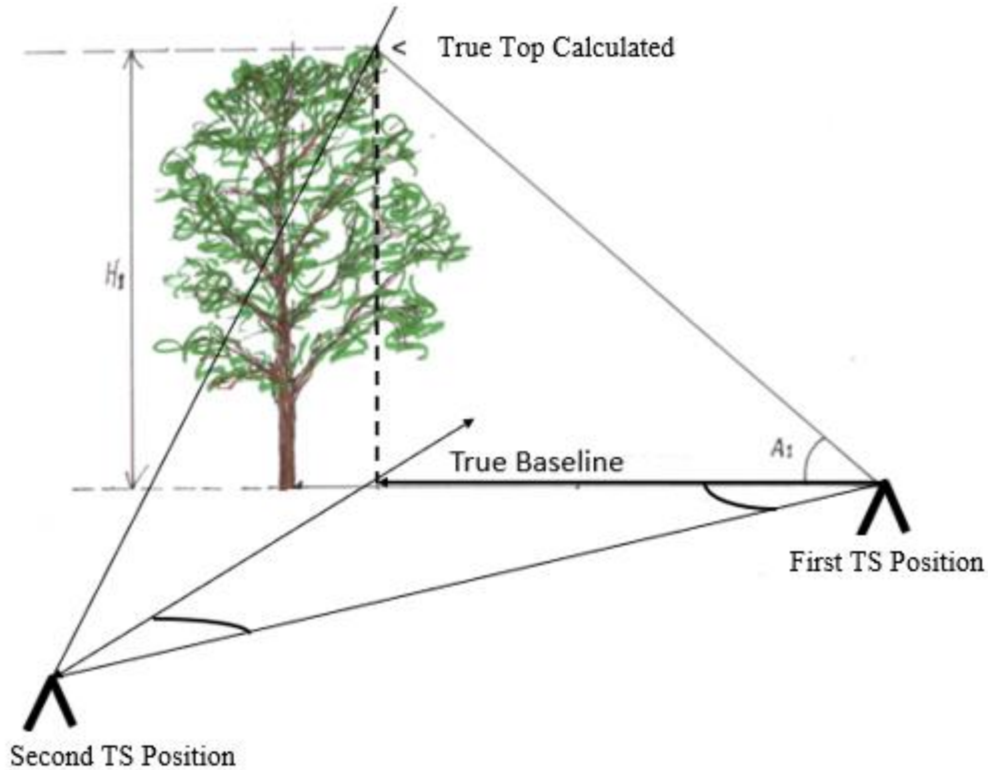


*Figure 3.8: Measuring true height with two total stations, adapted from Koutar, Philippona & Spraggon (2018)*

This dual total station method creates an intersection point at the treetop's horizontal position using the horizontal angles. This enables the horizontal distance between the TS setup points and the treetop to be found. The measurement can then be checked by measuring the vertical angles from the two total station positions and using the previously found horizontal distances. This should calculate two heights of ideally the same value. The change in level between the total station setups and the base of the tree is measured with a prism set on a bipod.

## 3.5 Conclusion

The field measurements enable direct comparison between the results of both TS and TLS measurement methods, with repeated TS measurements for accuracy determination. The tree geometry impacts to DBH and height can also be accurately determined using the listed methods. Using the relevant allometric equations, the influences of DBH and height errors to biomass estimation can be determined.

# Chapter 4 Results and Discussion

## 4.1 Introduction

The data collection was carried out in black gully reserve. Different sections of the reserved were measured to identify if there were any impacts to accuracy when measuring different tree species. The three species measured were believed to be blackbutt, spotted gum and ironbark. These species are very common in Australia and were thought to give a good representation of typical trees that would be measured in biomass estimation processes, as eucalypt forest types make up roughly 75% of Australia's native forest area according to the Australian Government Department of Agriculture (2019).

The scan measurements were generally taken either on the same day, or within a few days of the total station measurements to maintain consistency of what is being measured for comparison.

## 4.2 Scan Registration

The number of scans setups per area varied from six to nine to ensure all sides and points on the trees were measured. When setting out the targets the following positioning was used to ensure accurate registration:

- Six targets used between any two scans for redundancy in registration
- Targets place in high and low positions and in irregular configurations to remove multiple possible scan solutions
- There was roughly 20m between scan setups to ensure all tree components were measured and so this was also adequate for maintaining short distances to targets for target recognition and accurate measurement
- Targets were visible from both scan positions

Scanning was undertaken at ¼ resolution and 4x quality as test runs suggested this was suitable for accurate measurement and tree definition without wasting time through long scan durations. Scanning for one position took roughly 10 minutes excluding setup times.

Conducting the registration in the Scene software found that the spherical targets gave a fit tolerance under 3mm suggesting that the accuracy of measurement was of a high standard.

## 4.3 DBH Measurements

The DBH of 25 trees was measured using the best fit circle approach from scan data and calculated after measuring the circumference using tape. This consisted of ironbark, blackbutt and spotted gum species with height of 1.4m was used to define the position of breast height.

### 4.3.1 Ironbark

The first lot of data shows the results from ten ironbark trees. The typical surface of one of these trees is shown in figure 4.1:

*Figure 4.1: Breast height of ironbark*

As previously seen in figure 4.1, the surface of this tree type is very rough with many extrusions. This was expected to cause larger differences than normal when comparing the TLS and Tape methods which was the reasoning for choosing to measure this tree type. It was expected that the tape would follow the extruded parts of the tree and therefore find a larger DBH. The best fit circle approach with the TLS data averaged out these intrusions and extrusions to create a circle that best represents the tree stem. An example of this data is shown in figure 4.2:

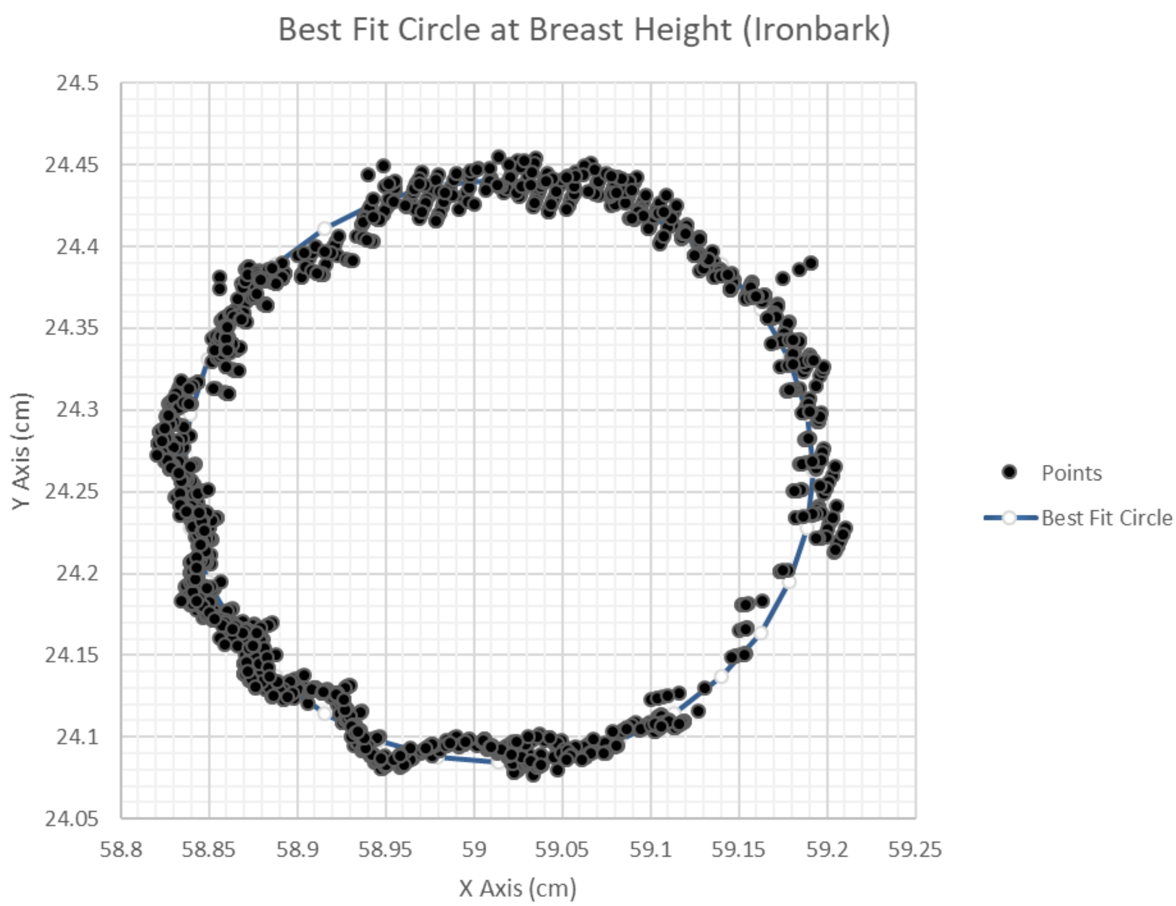


*Figure 4.2: Best fit circle of ironbark tree stem*

The DBH was calculated using both the TLS and tape with the results shown in table 4.1:

*Table 4.1: DBH measurements of ironbark*

| | **DBH of Ironbark (m)** | | |
|---|---|---|---|
| | **TLS** | **Tape** | **Difference** |
| | 0.291 | 0.318 | 0.027 |
| | 0.361 | 0.387 | 0.026 |
| | 0.387 | 0.413 | 0.026 |
| | 0.331 | 0.359 | 0.028 |
| | 0.356 | 0.383 | 0.027 |
| | 0.334 | 0.362 | 0.028 |
| | 0.353 | 0.378 | 0.025 |
| | 0.329 | 0.354 | 0.025 |
| | 0.409 | 0.436 | 0.027 |
| | 0.367 | 0.396 | 0.029 |
| **Average** | **0.3518** | **0.3786** | **0.0268** |
| **Standard Deviation** | **0.0330** | **0.0330** | **0.0013** |

These results found that there was a small spread in the diameter sizes of the trees measured, with a range of roughly 0.1m. The comparison found that the tape consistently found larger DBH values and was on average 0.27m larger. This was very consistent with a standard deviation of the difference being 0.0013m

4.3.2 Blackbutt

The second lot of data shows the results of ten blackbutt trees. The typical surface of one of these trees is shown in figure 4.2:

*Figure 4.3: Breast height of blackbutt*

The surface of this tree type is very smooth in comparison to the ironbark, with only occasional strips of extruding bark. It was therefore expected that the results from the TLS and Tape methods would be similar as the tape would provide a better representation of the outer surface. An example of the results from the scan data is shown in figure 4.4:

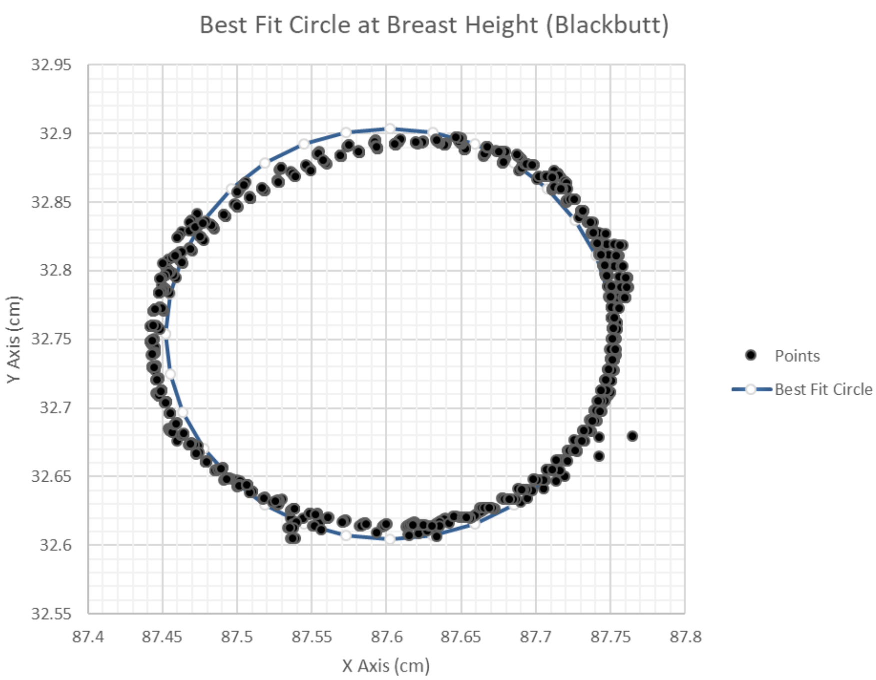


*Figure 4.4: Best fit circle of blackbutt tree stem*

The results of the TLS and tape measurements are shown in table 4.2:

*Table 4.2: DBH measurements of blackbutt*

| | **DBH of Blackbutt (m)** | | |
|---|---|---|---|
| | **TLS** | **Tape** | **Difference** |
| | 0.243 | 0.255 | 0.012 |
| | 0.276 | 0.290 | 0.014 |
| | 0.299 | 0.312 | 0.013 |
| | 0.517 | 0.538 | 0.021 |
| | 0.477 | 0.496 | 0.019 |
| | 0.429 | 0.446 | 0.017 |
| | 0.311 | 0.326 | 0.015 |
| | 0.254 | 0.265 | 0.011 |
| | 0.263 | 0.276 | 0.013 |
| | 0.312 | 0.324 | 0.012 |
| **Average** | **0.3381** | **0.3528** | **0.0147** |
| **Standard Deviation** | **0.0989** | **0.1021** | **0.0033** |

These results found a larger spread in the diameter sizes of the trees measured than that of the ironbark trees, with a range of roughly 0.3m. The comparison also found consistently larger values of TLS measurement compared to tape with DBH on average 0.15m larger. This was also a relatively consistent difference with a standard deviation of the difference being 0.0033m.

### 4.3.3 Spotted Gum

There were less spotted gum species within the site. However, five could still be measured in one scan setup location which can be used to verify the expected differences between the tape and TLS methods. Figure 4.5 shows the surface of a spotted gum at breast height.

*Figure 4.5: Breast height of spotted gum*

The results of the DBH measurements of the Spotted Gum are shown below in table 4.3:

*Table 4.3: DBH measurements of spotted gum*

| | **DBH of Spotted Gum (m)** | | |
|---|---|---|---|
| | **TLS** | **Tape** | **Difference** |
| | 0.311 | 0.323 | 0.012 |
| | 0.449 | 0.465 | 0.016 |
| | 0.428 | 0.443 | 0.015 |
| | 0.358 | 0.376 | 0.018 |
| | 0.375 | 0.390 | 0.015 |
| **Average** | **0.3842** | **0.3994** | **0.0152** |
| **Standard Deviation** | **0.0553** | **0.0563** | **0.0022** |

These results show similar results to the blackbutt species, with a similar average difference, also smaller than that of the ironbark trees. This was expected as like the blackbutt trees, the surface is generally smooth with no major extrusions.

### 4.3.4 Discussion

The small standard deviations of differences between the TLS and tape measurements (0.001m to 0.003m) show that both methods are consistent and capable of measuring at a high accuracy. This section explores further conclusions that can be drawn from this data and how this information can be beneficial.

The DBH measurements found that there was a moderate, consistent difference between the TLS and tape methods. The blackbutt DBH measurements found an average difference of 0.015m between the two measurement types, while ironbark found an average difference of 0.027m. This is likely because of the different types of bark the two trees have. When measuring the circumference of the ironbark, the tape will follow only the extruded parts of the bark while the scanner also considers the intruded sections creating a smaller circle that better represents the tree. This which explains why the difference would be larger with the ironbark trees compared to the other eucalyptus species.

Another consideration is that the ironbark had a much smaller standard deviation of measurement difference. The difference between the TLS and tape measurement values were almost always the same compared to the blackbutt and spotted gum which, although were small, still varied more. The results showed that this is likely due to the varying tree stem sizes. The standard deviation of diameter sizes for the ironbark, blackbutt and spotted gum were roughly 0.03m, 0.1m and 0.05m respectively. The blackbutt trees had the greatest range and standard deviation of stem sizes with the specific values showing that the largest values had the largest differences between the TLS and tape measurements. Figure 4.6 shows that it is likely that there is some relationship between stem size and the difference between measurements taken with tape and a TLS. Extensive measurements will need to be taken to draw solid conclusions.

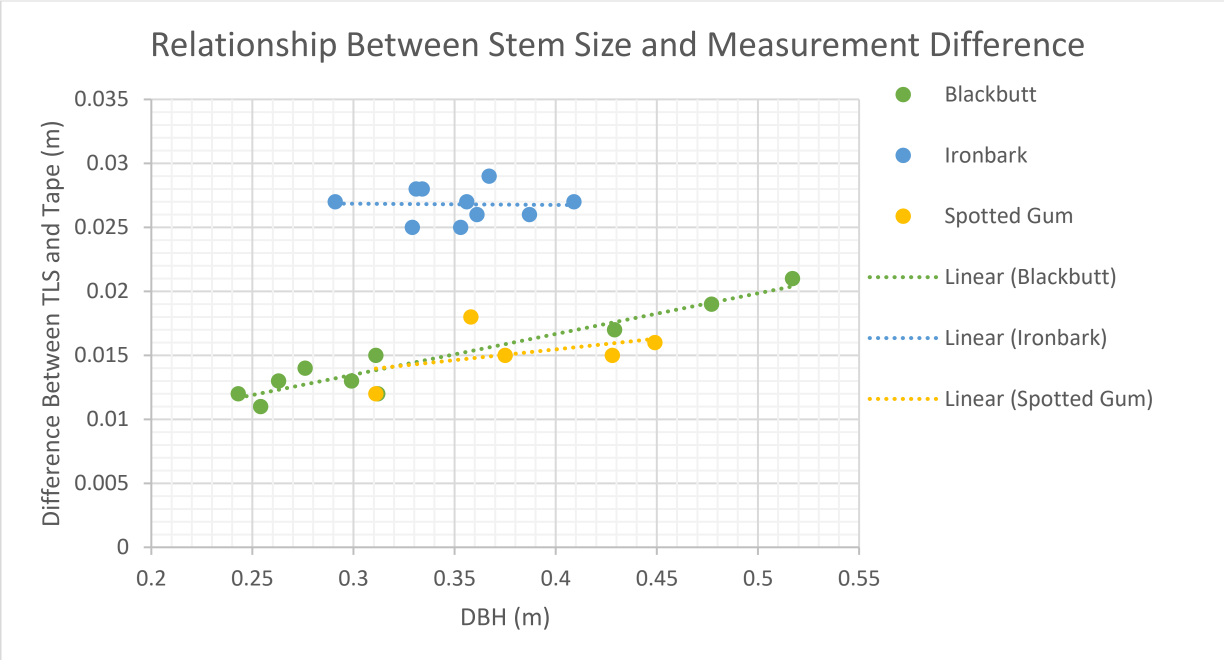


*Figure 4.6: Relationship between stem size and measurement difference*

The reason that the best fit circle TLS method and the tape method obtain different values, but with relatively consistent differences, is that they are technically measuring two different things. The TLS and tape methods both measure the circumference of a shape that is close to the same area. However, the tape measures an irregular shape, assumes it is a circle and uses the circumference to calculate the radius. The TLS uses an actual circle that best represents the cross-sectional area of the tree stem. This shows that the tape obtaining consistently larger values then the TLS should be expected. Although this suggests that the TLS method gives a better representation of the true DBH, which method is correct in biomass estimation is not clear.

This is due to how biomass equations are created and so this needs to be considered. It was previously mentioned in section 2.3 of this paper, that there are two methods of creating allometric equations; one destructive and the other non-destructive. The destructive method would likely involve manual measurement of tree parameters before they are harvested and weighed to find biomass relationships. Therefore, the results from tape measurement would be of better use for finding DBH as the equations were formed with this supposed error. However, if a non-destructive method was used through applying 3D modelling and the existing tree densities, it can be assumed that the method of DBH measurement with TLS discussed here more accurately represents the DBH that would be used in these equations.

Best fit ellipse methods were explored to determine if the tape results could be replicated with the TLS. By inserting the tree stem point coordinates into the NLREG software, the semimajor axis, semiminor axis, rotation and other information could automatically be computed. Using the circumference of the ellipse and dividing by pi, the resultant DBH should be similar to when measured by tape. However, it was found that in most circumstances the results would be almost identical to those measured by the best fit circle. This is because the tree stems were often irregularly shaped with random extrusions, but still more closely represented a circle than an ellipse. There were only two situations where the results varied greatly between the circle and ellipse representations. This occurred in the larger size trees where the shape was visibly like an ellipse (figure 4.7).

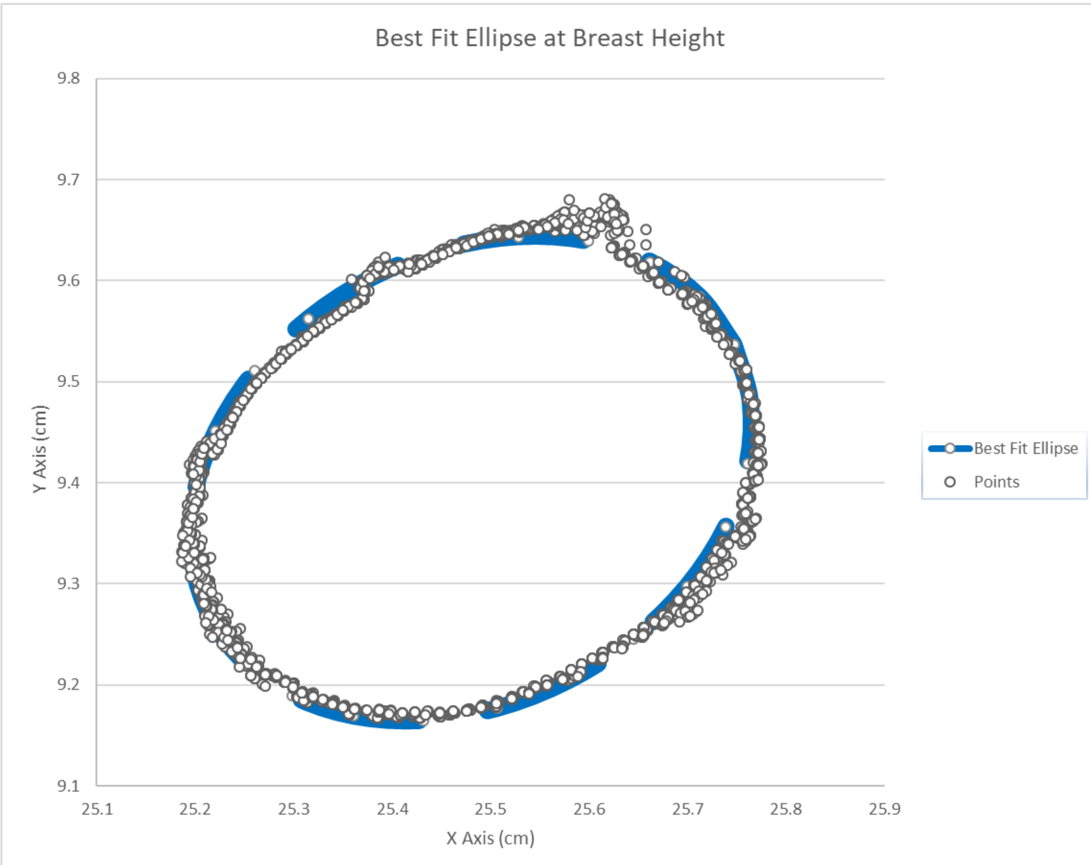


*Figure 4.7: Best fit ellipse at breast height*

However, these results still found differences of 0.014m and 0.015m instead of 0.021m and 0.019m respectively. This suggests that surface irregularities such as lumps, bark and imperfect looping of tape around the stem are a main cause of differences in tape and TLS measurement.

Figure 4.8 below shows several trees that illustrate the common shape of the stems. They were generally circular, but with bark or extrusions that would extend the tape measurements.

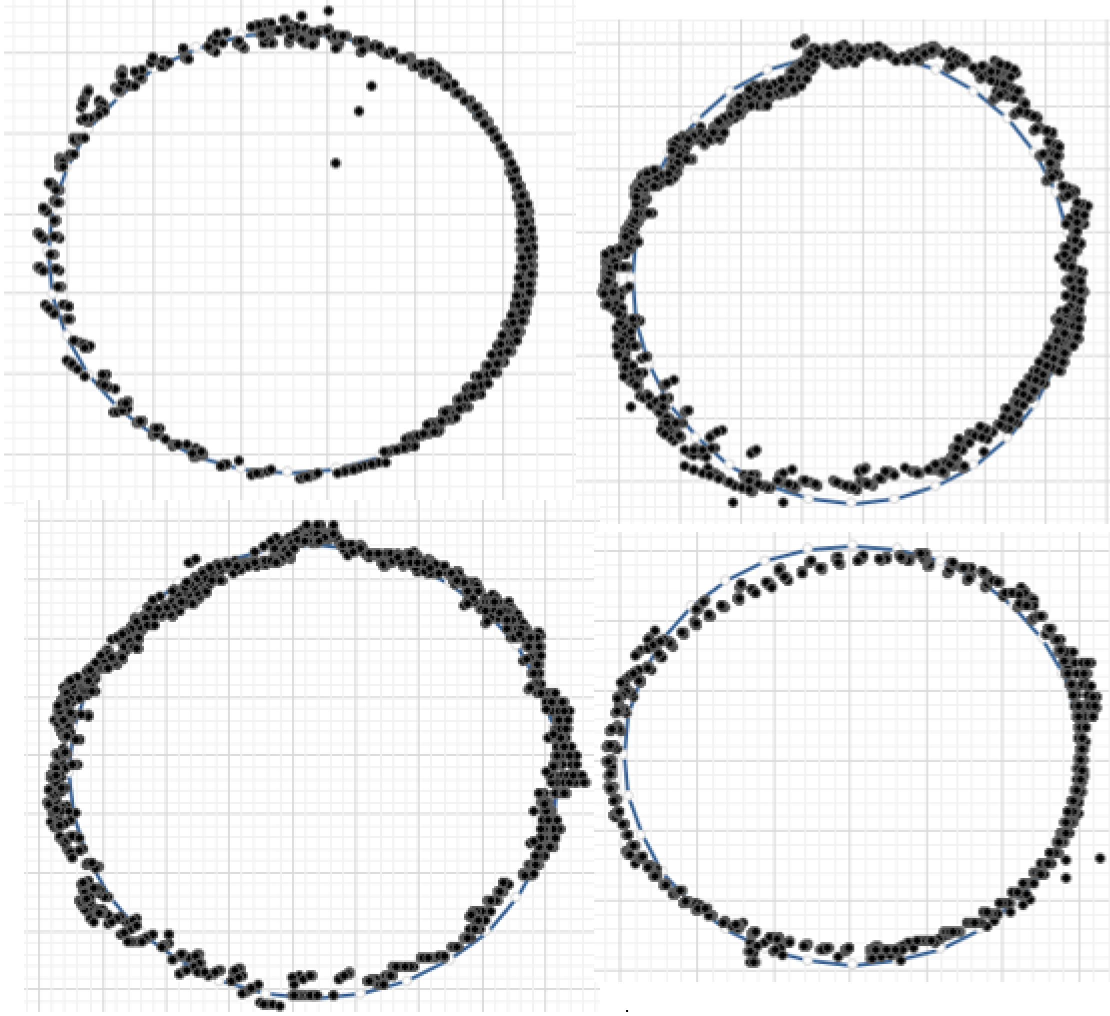

*Figure 4.8: General shape of tree stems*

There were other stems measured that were very irregular, neither circular nor ellipsoidal in nature. The best example of this is shown in figure 4.9:

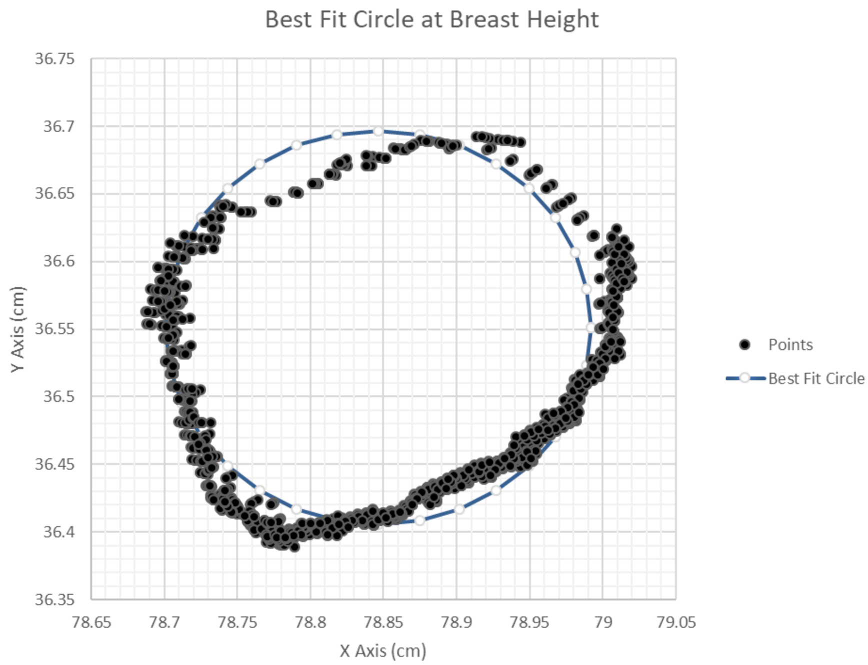


*Figure 4.9: Irregular stem shape example*

For the most part, these results would remain consistent with the other tape differences showing that the best fit circle remains effective no matter the stem shape.

However, there are circumstances where this approach has limitations. This is when there is incomplete data from blocked views or inadequate setup amounts. If only one side is measured the best fit circle will predict the shape of the second side to remain consistent. This will be fine in most circumstances, however, if the shape varies from the typical circular nature, the prediction will be wrong.

There were some exclusions from the presented data for this reason. One example is shown in figure 4.10, where a branch blocked the view of the stem at one scan location.

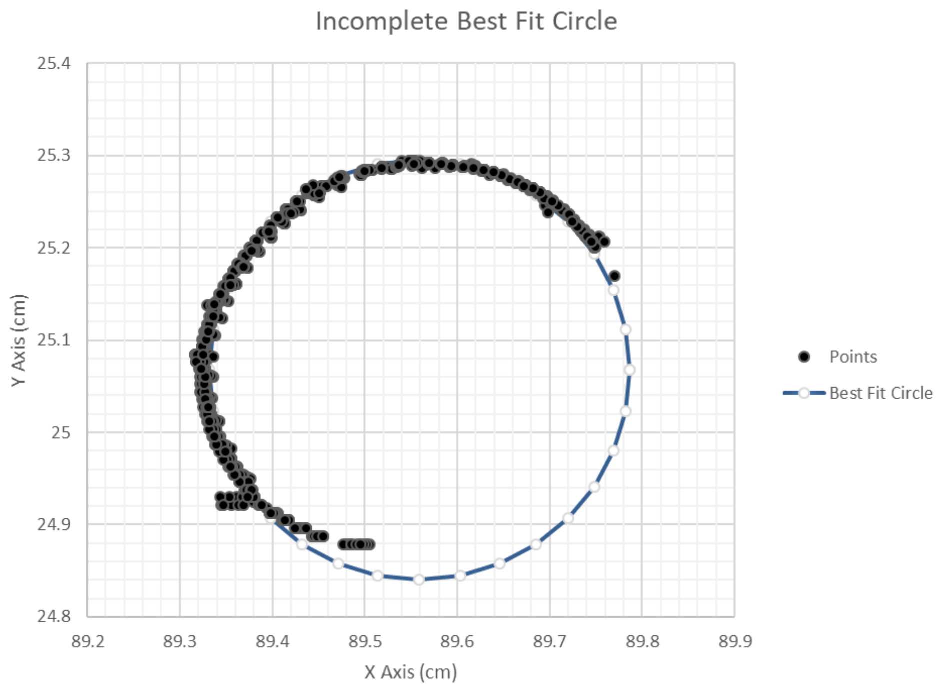


*Figure 4.10: Incomplete best fit circle*

This example shows how the stem began to curve in more, but the circle provided an estimation using only the visible portion. The DBH of this tree was found to be 0.455m, 0.003m smaller than the tape measurement. Although this is accurate, it is inconsistent with the other results showing that full visibility is important for the best representation on DBH with scan data. It is just as likely that partial visibility could cause great overestimations.

## Comparison to Previous Studies and Conclusions

This paper compares results found to studies by Maan et al. (2014) and Stanley (2013) who also explored the use of TLS for forest applications. With regards to the DBH, the study by Stanley was highly focused on as a FARO Focus scanner with the same specifications was used, but with a different method of application and results.

The site Stanley used consisted of various Australian rainforest species that had similarly smooth surfaces and thickness to that of the blackbutt and spotted gum in this investigation. Therefore, comparisons made between the two methods should be reasonable.

Where this study applied a best fit circle method, the compared study directly extracted the DBH from the scene point cloud, likely from distance offset between two opposite points on the tree stem. This would therefore expose the method to errors resulting from the non-circular stems or extrusions and find different DBH values depending on what side measured.

These results found that although the TLS didn't underestimate the DBH relative to the tape measurement, the error between the two varied greatly. Where the circle fit method found standard deviations of the difference between TLS and tape to range from 0.001m to 0.003m. Stanley found these same standard deviations to range from 0.012m to 0.021m.

This suggests that a much higher level of accuracy can be achieved with the best fit circle approach used in this study. However, as previously mentioned, a correction may need to be applied to either the tape or TLS method to minimise the expected difference that occurs. If enough data is collected for this correction, the results suggest that the TLS can measured DBH with an accuracy of at least ±3mm. This could be variable depending the nature of the tree stem, such as size and bark type.

## 4.4 Height Measurements

The three measured tree types all had similar canopy structure, with the only real difference being that the ironbark trees averaged 19m in height and the blackbutt and spotted gum averaged roughly 27m. There were approximately 20 trees measured, each using two total station setups to remove tree geometry errors and give a check shot. This process was also repeated to determine the accuracy of measurement for the TS for use in comparison to the height measurements taken from the TLS scans.

Table 4.4 shows the results of the TLS and derived total station height measurements. However, many measurements were removed for various accuracy reasons discussed later, leaving only 11 trees with reliable measurements for comparison (6 ironbark and 5 blackbutt trees).

*Table 4.4: Height measurements with TLS and TS*

| Terrestrial Laser Scanner | Total Station | Difference |
|---|---|---|
| 19.836 | 20.155 | 0.319 |
| 12.616 | 12.759 | 0.143 |
| 21.727 | 21.636 | -0.091 |
| 19.995 | 20.423 | 0.428 |
| 18.753 | 18.488 | -0.265 |
| 17.944 | 17.631 | -0.313 |
| 24.730 | 24.426 | -0.304 |
| 23.383 | 23.517 | 0.134 |
| 28.440 | 27.897 | -0.543 |
| 26.224 | 26.341 | 0.117 |
| 32.952 | 33.399 | 0.447 |

The standard deviation of the TLS error was found to be 0.331m, with the assumption that all the TS measurements could represent the true height. The TS measurements had an accuracy of 0.052m, found through repeated observations of the same tree. Therefore, there is still some uncertainty of the accuracy of the TLS.

Dual total station setups were used as to method to calculate the true height value, without impact from the errors that would result from the top of the tree being offset from the stem. However, the method was found to be inconsistent, with some major errors still being present. One main concern, and why many of the tree height measurements were not included in the data analysis, is that the same treetop point was not being measured at both total station setups. If the horizontal angle to two different points are being measured, this will create incorrect baseline distances for height calculation (the intersection of the horizontal angles is used to find the horizontal distance to the top of the tree from both setups). This error is found when using the vertical angle from both stations to calculate height, as they should find the same height. Although a considerable amount of care was taken to measure the same highest tree point, the check often found differences up to the size of metres, and so these results had to be removed. If the same point is measured, the accuracy should ideally be on the level of millimetres. However even slight breezes and tree sway made measurement inconsistent which is why the accuracy was found to be 0.052m after redundant measurements, much larger than the specified accuracy of the instrument.

The accuracy was found through completing the TS measurement process twice, with the setup locations varying only slightly. As the setup locations were not changed to measure the tree height from a different perspective, there is a chance that although the same point was measured each time, the point measured could only appear highest. However, this is unlikely as full circling of each tree was completed before each measurement to scout the highest point. Possible errors in this regard should still be considered with regards to the TLS and TS comparison and could explain why there are some large differences between the measurement techniques.

While the dual total station measurement had many incorrect measurements that needed to be removed, there were some circumstances where comparison could not be made due to TLS error. This occurred when sections of the tree canopy were not collected. Figure 4.11 illustrates this error:

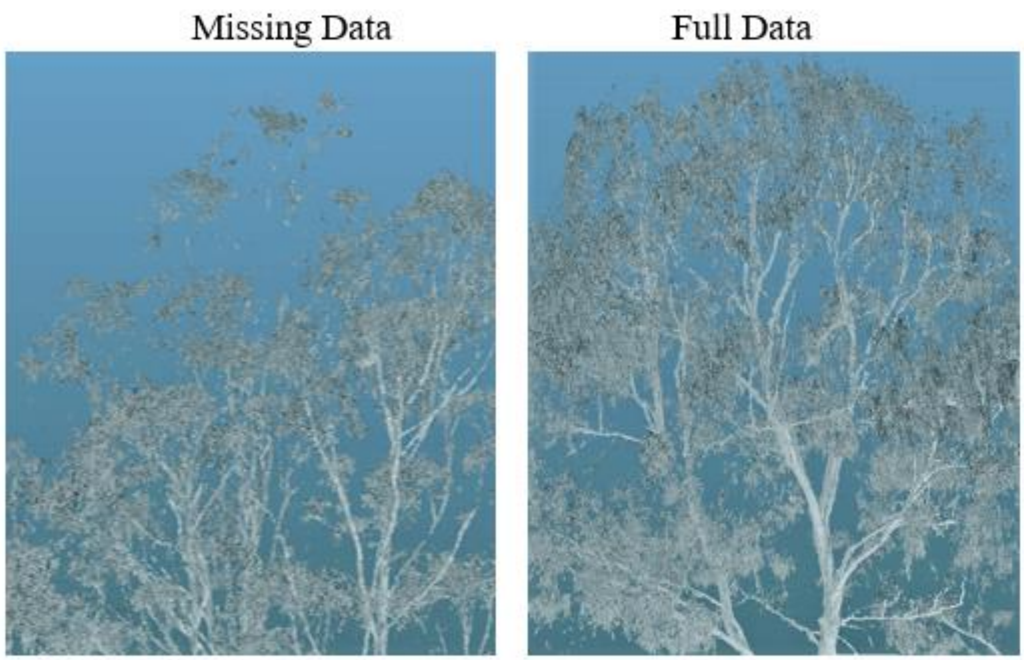


*Figure 4.11: Missing data in TLS scans*

There were some circumstances in which this same error occurred in the DBH measurements. The missing data error is impacted by the forest density, as blocked views will restrict the coverage a scan will have. This study has demonstrated that the density of a forest does not have a major impact on the accuracy but could make some tree measurements inconclusive. A higher density would simply require more TLS scan positions for full scan details. Further investigation into sites with undergrowth and thicker canopies could gain further knowledge on the data collection requirements. However, in eucalypt forests such as this site, three scan positions are easily enough to obtain an accurate 3D model of a tree.

When obtaining the heights of trees in the point clouds, the horizontal offset between to top of the tree and the stem was also recorded. These results are shown in table 4.5:

*Table 4.5: Horizontal offset of treetops*

| **Tree Height** | **Horizontal Offset** |
|---|---|
| 19.836 | 0.656 |
| 12.616 | 0.842 |
| 21.727 | 0.309 |
| 19.995 | 1.602 |
| 18.753 | 1.432 |
| 17.944 | 1.591 |
| 24.730 | 0.640 |
| 23.383 | 2.351 |
| 28.440 | 2.385 |
| 26.224 | 0.540 |
| 32.952 | 0.401 |
| **Average:** | **1.159m** |

Using this data, the results that could be obtained with a single total station method can be replicated. This data shows that on average, the horizontal offset in the direction of measurement would be approximately 0.58m (half average horizontal offset) and an average tree height is roughly 23m. The horizontal distance to tree stem for measurement was aimed to be at least 50m for adequate treetop visibility. Using this knowledge, the expected error that would occur using a new distance of 50.58m instead of 50m is 0.267m. This is an estimate of the expected average error assuming perfect measurement accuracy, thus showing that the dual total station method successfully obtains higher accuracy.

The accuracy of the TLS found should therefore be more reliable as the values it was compared to were closely replicated the true tree height. However, more data needs to be collected for conclusive results due to the inconsistency of successful measurement. The current established accuracy of TLS in this study was compared to the results found by Stanley (2013), who found the accuracy assuming a single TS measurement can represent the true height. It was found that in this study, the TLS had a more realistic improved accuracy of 0.331m compared to 0.468m (standard deviation of errors) found by Stanley.

Regardless of the height method used for biomass estimation, it was found that height has limited influence when applying these measurements to allometric equations. Any of the listed methods can be used depending on the required efficiency, reliability or whether the advantages of 3D modelling are desired.

## 4.5 Allometric Equation Application

The errors of the different measurement techniques could be applied to an allometric equation to determine the impacts to biomass estimation. The allometric equation used was obtained from Williams et al. (2005) and is as follows:

$$\ln(AGB) = -2.0596 + 2.1561 * \ln(DBH) + 0.1362 * (\ln(H))^2$$

where AGB is the above ground biomass (kg)

DBH is the diameter at breast height (cm)

H is the tree height (m)

This equation was used as it is a generalised allometric equation that can be applied to eucalyptus tree types in Australia.

Using the average tree height and DBH of this study (23m and 34cm respectively), the impacts of measurement errors are explored.

The results from the combined DBH data found that on average the TLS underestimated the values obtained from tape by 0.020m on average. This obtains a conversion factor of 0.88 between the measurement methods which is a considerably large error (975kg to 1103kg). However, if a correction can applied, only an error of 3mm (from standard deviation) would result. An error of 3mm shows highly precise biomass estimation, difference of 975kg to 993kg would occur (0.98 ratio).

The maximum difference between TLS and TS height measurement found was 0.543m. The error that this would cause in the biomass estimation is a difference of 975kg to 995kg (0.98

ratio). This shows that the current accuracy of the TLS is of an adequate standard for use in biomass estimation, with the DBH being the major influencing factor that requires accurate measurement. As a single TS setup appeared to have a similar accuracy and so if TS is applied for biomass estimation it is not recommended to use multiple setups. This because using multiple stations requires an approximate measurement time of 30min, mostly from scouting the tree for visibility from both positions. Although this method is accurate, there are also many circumstances of unusable data due to measuring different treetop points at each position. A single total station measurement can be completed in 5 minutes while maintaining suitable accuracy, and so this is recommended for efficiency.

# Chapter 5 Conclusions

## 5.1 Introduction

This study has shown that a terrestrial laser scanner is a highly effective tool for biomass estimation with an accuracy that rivals the total station for tree parameter measurement. The focus of this study was on the measurement capabilities of these two technologies and the limitations they may have in a forest environment for biomass estimation.

Overall, the results have found that the TLS has the required accuracy for effective biomass estimation, with the benefit of being more reliable, efficient and the advantage of a 3D representation of the site for further analysis and visual representation at any time.

## 5.2 Discussion and Recommendations

The TLS was able to accurately measure DBH with a best fit circle approach. This greatly improved reliability of measurement as the random extrusions and irregular shaped were averaged out to obtain a realistic representation of the DBH. The standard deviation of differences between the TS and TLS ranged from 0.001m to 0.003m showing both methods had high precision and reliability for DBH measurement. The TLS would measure the DBH to be 0.020m smaller on average and offers the possibility to apply a correction for either method. This gap resulted from the extended distance the tape measures through random extrusions on the stem. The impact was demonstrated when a rough barked tree type would consistently obtain a higher difference, extended by 0.012m on average.

As the DBH accuracy was found to have a major impact on the biomass, it is recommended that TLS is used for biomass with a best fit circle approach for the improved reliability. This is assuming that care is taken to measure each stem from at least three different perspectives. Without using a best fit circle in either TLS data or tape measurement, results can be subject to the random shapes and forms the tree takes.

Multiple total station setups were found to have greatly increased accuracy, except the measurement process would take a long period of time and be prone to large errors through incorrect measurements. Although high accuracy could be achieved, it was found to be unreliable due to errors in measuring different treetop points at each position. Trees that were accurately measured did however allow an improved indication to what the TLS height accuracy was.

Although extensive data could not be obtained due to many failures of measurement, the data did conclude that both TLS and a single total station setup method could obtain height accuracies that were suitable for biomass estimation. If was found that there were no major density or obstruction issues in the eucalyptus type forest. The TLS could clearly define the thin canopy with only some circumstances of obstruction; as long as care is taken in checking the setup positions, the collected data should be conclusive.

In summary, the highest accuracy of height could be achieved with two total stations setups. However, from a practical viewpoint, both the TLS and single total station setup would offer greatly improved efficiency with adequate accuracy for biomass estimation. The TLS method is recommended as it is less prone to large errors in both height and DBH from inconsistent tree geometry in addition to the many advantages of 3D modelling. The collection of any 3D environment will enable further data analysis at any time without being on field, in addition to a visual representation and identification that is not possible with collected TS data. This enables easier comparison if remeasurement is needed for a task such as growth estimation.

## 5.3 Further Research

Further research can be conducted as the technology continues to improve. With the introduction of new TLS technology, it should be expected that the accuracy will continue to improve and provide improved results for biomass estimation.

Further investigation into the impacts and suitability of TLS into thick canopy conditions and undergrowth could be conducted. This may find that the TLS is not capable of suitable data capture in these environments.

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# Appendix A

Project Specifications

ENG4111/4112 Research Project

**Project Specification**

For: Nathan Krautz

Title: Comparison of TLS to total station accuracy for tree parameter measurement in biomass estimation

Major: Surveying

Supervisors: Chris McAlister

Enrolment: ENG4111 – ONC S1, 2019

ENG4112 – ONC S2, 2019

Project Aim: To compare the use of a terrestrial laser scanner (TLS) to total station and tape methods in terms of accuracy and efficiency when measuring tree parameters for biomass estimation.

Programme: Version 2, 17$^{th}$ March 2019

1. Research current methods of measuring tree parameters.
2. Collect measurement data of DBH and height in the forest environment (TLS and TS) with methods that aim to remove error impacts
3. Analyse and directly compare accuracies of height between TLS and TS methods
4. Compare DBH accuracies between tape and TLS. Investigate the differing accuracies of biomass estimation when assuming circular tree shape for DBH with tape and accounting for irregular shapes with TLS.
5. Analyse how the established error impacts the relevant allometric equations
6. Analyse tree density impacts on accuracy and obstruction issues

# Appendix B

## Risk Assessment

UNIVERSITY OF SOUTHERN QUEENSLAND

University of Southern Queensland **Offline Version**

USQ Safety Risk Management System

**Note:** This is the offline version of the Safety Risk Management System (SRMS) Risk Management Plan (RMP) and is only to be used for planning and drafting sessions, and when working in remote areas or on field activities. It must be transferred to the online SRMS at the first opportunity.

| **Safety Risk Management Plan – Offline Version** | | | |
|---|---|---|---|
| Assessment Title: | Laser Scanning of Vegetation | Assessment Date: | 20/07/2019 |
| Workplace (Division/Faculty/Section): | Surveying | Review Date:(5 Years Max) | 20/07/2024 |
| **Context** | | | |
| **Description:** | | | |
| What is the task/event/purchase/project/procedure? | Using a terrestrial laser scanner for tree measurement in bushland reserve | | |
| Why is it being conducted? | Research Project | | |
| Where is it being conducted? | Toowoomba, Black Gully Reserve | | |
| Course code (if applicable) | ENG4111 | Chemical name (if applicable) | |
| **What other nominal conditions?** | | | |
| Personnel involved | Nathan Krautz, William White | | |
| Equipment | TLS | | |
| Environment | Stable terrain and weather | | |
| Other | | | |
| Briefly explain the procedure/process | Setting up the TLS and targets in various positions within the reserve to capture tree positional data | | |
| **Assessment Team - who is conducting the assessment?** | | | |
| Assessor(s) | | | |
| Others consulted: | | | |

Eg 1. Enter Consequence

Eg 2. Enter Probability

Eg 3. Find Action

| | Consequence | | | | |
|---|---|---|---|---|---|
| **Probability** | **Insignificant** No Injury 0-$5K | **Minor** First Aid $5K-$50K | **Moderate** Med Treatment $50K-$100K | **Major** Serious Injuries $100K-$250K | **Catastrophic** Death More than $250K |
| Almost Certain 1 in 2 | M | H | E | E | E |
| Likely 1 in 100 | M | H | H | E | E |
| Possible 1 in 1000 | L | M | H | H | H |
| Unlikely 1 in 10 000 | L | L | M | M | M |
| Rare 1 in 1 000 000 | L | L | L | L | L |

**Recommended Action Guide**

**E**=Extreme Risk – Task ***MUST NOT*** proceed

**H**=High Risk – Special Procedures Required (See USQSafe)

**M**=Moderate Risk – Risk Management Plan/Work Method Statement Required

**L**=Low Risk – Use Routine Procedures

| Step 1 (cont) | Step 2 | Step 2a | Step 2b | Step 3 | | |
|---|---|---|---|---|---|---|
| ***Hazards***: From step 1 or more if identified | ***The Risk:*** What can happen if exposed to the hazard without existing controls in place? | ***Consequence:*** What is the harm that can be caused by the hazard without existing controls in place? | ***Existing Controls:*** What are the existing controls that are already in place? | ***Risk Assessment:*** Consequence x Probability = Risk Level | | |
| | | | | **Probability** | **Risk Level** | **ALARP? Yes/no** |
| **Example** | | | | | | |
| Working in temperatures over 35° C | Heat stress/heat stroke/exhaustion leading to serious personal injury/death | catastrophic | Regular breaks, chilled water available, loose clothing, fatigue management policy. | possible | high | No |
| Injury from TLS | Laceration, eye damage from laser beam | Minor | Appropriate shoes, clothing, protective glasses and 7m away from the scanner during use, cones and signs for pedestrians with no use if people adjacent to scanner | Unlikely | Low | Yes or No |
| Manual Handling | Lifting and carrying injuries | Minor | Use proper handling techniques | Unlikely | Low | Yes or No |
| UV | Sunburn | Minor | Appropriate clothing, sunscreen, hat, utilise shade | Unlikely | Low | Yes or No |
| Dehydration | Dehydration | Minor | Water supply, breaks, utilise shade | Unlikely | Low | Yes or No |

| Step 2b | Step 3 | | | Step 4 | | | | |
|---|---|---|---|---|---|---|---|---|
| ***Existing Controls:*** What are the existing controls that are already in place? | ***Risk Assessment:*** Consequence x Probability = Risk Level | | | ***Additional controls:*** Enter additional controls if required to reduce the risk level | ***Risk assessment with additional controls:*** | | | |
| | **Probability** | **Risk Level** | **ALARP? Yes/no** | | **Consequence** | **Probability** | **Risk Level** | **ALARP? Yes/no** |
| | | | | | | | | |
| Regular breaks, chilled water available, loose clothing, fatigue management policy. | possible | high | No | temporary shade shelters, essential tasks only, close supervision, buddy system | catastrophic | unlikely | mod | Yes |
| Appropriate shoes, clothing, protective glasses and 7m away from the scanner during use, cones and signs for pedestrians with no use if people adjacent to scanner | Unlikely | Low | Yes or No | None | Minor | Unlikely | Low | Yes or No |
| Use proper handling techniques | Unlikely | Low | Yes or No | None | Minor | Unlikely | Low | Yes or No |
| Appropriate clothing, sunscreen, hat, utilise shade | Unlikely | Low | Yes or No | None | Minor | Unlikely | Low | Yes or No |
| Water supply, breaks, utilise shade | Unlikely | Low | Yes or No | None | Minor | Unlikely | Low | Yes or No |

# Appendix C

## NLREG Code

This code was created by NLREG and used in NLREG software to best fit an ellipse to data.

```
Title "Ellipse fitted to data points";
Variables X, Y;
/*
 *  Definite parameters to be calculated.
 *  Specifying reasonable starting values greatly increases the chances for
convergence.
 */
Parameter Xcenter = 2;      /* X coordinate of center of ellipse */
Parameter Ycenter = 2;      /* Y coordinate of center of ellipse */
Parameter TiltAngle = 0;    /* Rotation of ellipse in counter-clockwise
direction (radians) */
Parameter Xdim;             /* Radius of ellipse along X axis */
Parameter Ydim;             /* Radius of ellipse along Y axis */
/*
 *  Work variables.
 */
    double DataDistance, DataAngle, Deviation, Angle, r, EllipseX, EllipseY;
/*
 *  Compute the polar rotation angle and distance of this (x,y) data point
 *  relative to the estimated center of the ellipse.
 */
    DataAngle = rtopa(x-Xcenter, y-Ycenter);
    DataDistance = sqrt((x - Xcenter)^2 + (y - Ycenter)^2);
/*
 *  Compute the angle for the point on the ellipse with the tilt angle.
 */
    Angle = DataAngle - TiltAngle;
/*
 *  Compute the radius of the ellipse (distance from center to perimeter) for
 *  this data angle. (Uses polar coordinate equation for an ellipse.)
 */
    r = sqrt((Xdim^2 * Ydim^2) / ((Xdim*sin(Angle))^2 +
(Ydim*cos(Angle))^2));
/*
 *  Compute the difference between the distance for the data point and the
ellipse.
 */
    Deviation = DataDistance - r;
/*
 *  Minimize the sum of squared deviations.
 */
    Function Deviation;
/*
 *  X, Y data values.
 */
    Data;
[ data goes here ]
```