Establishment of Accuracy Assessment Facilities for Terrestrial Laser Scanners

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Division of Geomatics

By
Wayne Davison

Thesis Supervisor:
Associate Professor Dr. Julian Lloyd Smit

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ABSTRACT

Measurement instruments that are required for high precision and reliable work need to have regular checks to ensure they are always performing at the required level of accuracy. A Terrestrial Laser Scanner is one such instrument and with the vast amount of information that this machine is able to capture, it is especially important to run regular accuracy checks.

This research is building on the work that has been done by previous researchers on the assessment of instrument accuracy and the establishment of facilities specialized for this assessment.

Theoretical principles are investigated in the form of Least Squares Adjustments, similarities to panorama photography and photogrammetric accuracy.

Terrestrial Laser Scanners are reviewed with respect to their scanning principles and data acquisition.

The methodology incorporated in this research encompasses the positioning of targets, their survey to establish high accuracy coordinates through various methods of adjustment and thereafter the scanning of those targets. Comparisons were done using derived angles and distances between the targets to discover the point accuracy of the Laser Scanner. This was done for two facilities; a short range facility (1 to 15 meters) and a medium range facility (1 to 75 meters). The medium range facility also included a range testing baseline for distance accuracy assessments.

The outcomes from the comparisons between the surveyed control data and the laser scanner observed data indicated that the laser scanner is performing below the accuracy of the surveyed data. The laser scanner was further compared against the manufacturer quoted performance specifications and revealed the laser scanner to be performing below the quoted values. The laser scanner in question showed stronger results in the horizontal measurements over the vertical measurements. All results suggested the laser scanner was delivering weak results in the vertical observations due to a mis-alignment of individual scan halves.

This research was able to establish two accuracy assessment facilities specialized for Terrestrial Laser Scanners under these same conditions. Both facilities were used in conjunction, to analyze the Z+F Imager 5010C laser scanner and determine the point accuracy in terms of the observed angles and distances from this machine. The results are also able to identify errors in the performance of the laser scanner and whether or not it is performing within the manufacturer specifications by noticing any large values such as in the case of the vertical observations for this instrument.

ACKNOWLEDGEMENTS

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Another big thank you to the Z+F support team in Germany and especially Christoph Held for the many helpful tips and explanations for all my questions.

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To the UCT Geomatics staff and fellow students, in particular Prof. Dr. Heinz Rüther and Jason Schreiber. Prof. Rüther for his valued input and vast wealth of knowledge in the field and on the calculations (having written the majority of the notes I studied from) and Jason Schreiber for his motivation, guidance through the computer programming and encouragement throughout my studies.

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Lastly, and by no means least, to my family and in particular my parents Mike and Cathy. My mom who spent countless hours transporting me to and from places to get parts or simply to university. My dad for his help on the hands on stages of the project and the installation of the targets at the sports centre as well as the mounts. Also to my sister Lauren for her support during my entire project.

This project is dedicated to my parents.

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Chapter 1

Introduction

1.1 Background

Within the fields of Geomatics and Land Surveying the use of specialized equipment to measure the surrounding environment as efficiently and as accurately as possible is an everyday task. The nature of each survey is dependent on the desired outcome and client requirements, however, the requirement for an accurate deliverable is a necessity at all times. There are various instruments available to capture the most detail from the environment. Some of the more familiar instruments are the Theodolite, Total Station and Global Positioning System (GPS). One of the less familiar but extremely powerful instruments is the Laser Scanner which should be included in every Geomatician and Land Surveyor's toolbox. The Laser Scanner employs the same technology as the Theodolite and Total Station for measurement, the difference is in the quantity and rate of data captured by these machines. The Laser Scanner has a far superior ability to capture extremely large amounts of data from its surroundings in a much shorter time period when compared to the previously mentioned instruments.

The Laser Scanner is a powerful machine that is able to measure millions of points from a single setup. It works on the principle of sending out a pulse of energy and receiving the return signal and repeating that while the machine body rotates in two directions. This leads to what is termed a Point Cloud, a 3D representation of the surrounding area of the instrument made up of single points that are very densely populated.

The same could be done with a total station on reflectorless mode but to capture the same amount of data would take an extraordinary amount of time. Terrestrial Laser Scanners (TLS) offer a much greater detailed analysis of the area under investigation. The data is captured in a short period of time at the push of a button with very little involvement from the user and the data are easily exported. The data has a variety of applications and can be further interpreted through modeling; the process of meshing the points into a single solid surface to better represent the features in the scene.

In the Geomatics profession the ability to work effectively and efficiently is key and the TLS offers a huge advantage in terms of efficiency. The question of this research pertains to the effectiveness of the TLS and the quality of the data being produced. This means there is a need for regular testing and calibration of the TLS in order to confirm the accuracy requirements are being met. For this a test facility is needed with specific qualities that will be able to analyze the instrument's base observations of distance and angle. These values must be compared to some baseline set of values in order to determine if the TLS is performing within the manufacturer specifications and not generating incorrect data, which would require calibration at great expense (both in terms of direct calibration cost and lost productivity). An accuracy test facility could determine whether such a calibration process is required before committing to the expenditure or worse, delivering poor quality data.

1.2 Aim

Laser Scanning is a young technique and as with any measuring technique there are sources of error that need to be better understood. The accuracy of any instrument is hindered by the presence of systematic and random errors. In order to detect these errors, an accuracy test should be conducted in a specially designed facility that will highlight any accuracy deficiencies, which will need the instrument's manufacturer calibration in order to remove them. Once calibrated the instrument can undertake another accuracy assessment in order to determine the success of the calibration. The initial tests will identify any issues in the scanner, either physical or theoretical and following from a calibration the test results will be able to provide high quality comparisons and performance information about the scanner in question. It is therefore the stage of first identifying these error sources via an accuracy testing facility that is most significant in the maintenance of the performance of a laser scanner.

This project aims to create short and medium range testing facilities wherein Terrestrial Laser Scanners can be set up and analyzed by closer analysis of their point accuracy. This will allow a comparison of these determined accuracies against the manufacturer specifications to determine the performance of the laser scanner. The ultimate aim is to determine the performance of the laser scanner based on the presence of observation errors from the delivered point cloud produced. Identifying observation errors would help the user decide whether or not to send the instrument for a calibration.

Another area of comparison will be between different laser scanners to help decide which laser scanner is the best for the particular task at hand. This will require special facilities designed to highlight aspects of laser scanners that are known to give discrepancies in the data and to highlight any strengths or weaknesses. It is these strengths and weaknesses that will help the user determine which instrument is the best for the task at hand.

1.3 Motivation

Unlike the traditional survey instruments such as the total station and the GPS, the Laser Scanner is just gaining traction in the industry. The traditional survey instruments have been used for decades and adapted and evolved into the high precision and reliable machines used in the Geomatics industry today.

When laser scanners were developed there was limited understanding of where the technology might lead to or how the data might be needed. The recent leaps in the technology have inspired interest in many different areas of study from Geodesy to Engineering work to Accident Analysis and many more. Even the film industry has showed interest in the abilities of the Laser Scanner for digital modeling and visual effects. With so many people now being attracted to the Laser Scanner, there are more questions into the accuracy and performance of the scanners resulting in many institutions taking their own initiatives to gain better insights into the positives and negatives of Terrestrial Laser Scanners.

One of the main aspects of developing new methods to test instruments is to find a way to compare the results in order to analyze how different instruments function under the same conditions. The idea of such a comparison is in order to find the most suitable scanner for a particular task, not to find the so called ‘best’ laser scanner. The comparison will be based on a method to assess the quality of the measurements by each laser scanner. Each laser scanner is different based on factors such as the method of measuring the range, the rate of data acquisition and deflection mechanism of the laser beam. All play a role in how the end result appears from that laser scanner.

1.4 Research Questions

In order to investigate the accuracy of a Terrestrial Laser Scanner there are some aspects that can be individually assessed to fully interpret the performance of the instrument.

- Are the survey equipment and procedures available precise enough in order to establish a high accuracy coordinate network that is sufficient enough to establish an accuracy testing facility for a Terrestrial Laser Scanner? What procedures can be implemented to ensure that the required high degree of accuracy of the coordinate network is achieved?
- Are there design requirements that must be satisfied in order to optimize the establishment of an accuracy testing facility for a Terrestrial Laser Scanner, specifically, in terms of its angle and distance observations?

1.5 Hypothesis

- It is possible given thorough survey observation practice and detailed statistical analysis to establish an accuracy testing facility for a Terrestrial Laser Scanner. Repeat observations, statistical analyses and least squares network adjustments are some of the methods that aid in achieving the desired levels of accuracy for the coordinate network.
- It is possible given the correct venue and a well-established coordinate network to investigate the accuracy of a Laser Scanner with respect to its angle and distance observations. The location of the laser scanner within such a venue will have an impact on the outcome of any accuracy testing. There are requirements for the targets used for reference points within the scene in terms of their size, colour, range to target, incidence angle and target material.

1.6 Scope and Limitations

This project is aimed at focusing on the development of two testing rooms of different dimensions based on the ability of Terrestrial Laser Scanners. There is a short range facility (for analyzing between 0.5m and 15m) and a medium range facility (for analyzing between 1m and 75m). These rooms have the dimensions common with the values encountered in most scanning projects.

Only the performance of the instrument is investigated based on the accuracy of the laser scanner observations. There will be no determination of the calibration parameters in order to return the instrument to manufacturer standards. The focus on investigating the accuracy is in order to make decisions regarding the need for possible time-consuming and costly calibration at the manufacturer factory.

This project is strictly based on the use of angles and distances to determine the point accuracy of a Terrestrial Laser Scanner using high precision surveyed targets in the short range and medium range.

This project will not cover a third long range facility for testing extreme range conditions. The resolution and intensity values of the scanner will also not be analyzed here.

1.7 Dissertation Overview

This thesis is organized according to the following chapters:

Part 1 Research and Theory

- **Chapter 2:** Literature Review and Previous Works

This chapter looks at previous attempts to analyze a Terrestrial Laser Scanner in terms of its Accuracy. It is focused around the creation of a testing facility, how it has been established and how the Accuracy of the given instrument was determined. Many examples of the calibration of a laser scanner are examined in order to use the similarities in the facilities required to develop the methodology in this research. There are similarities drawn between the scanners and cameras in both development of the testing facility and the analysis of accuracy.

- **Chapter 3:** Laser Scanner Principles and Theory

In this chapter the principles that underly Terrestrial Laser Scanner are investigated along with the operational mechanics of the instrument. The fundamental aspects of what is required for the establishment of a testing facility for a Terrestrial Laser Scanner are analyzed in this section.

Part 2 Investigation

- **Chapter 4:** Design of the Laser Scanner Testing Facilities

This chapter examines the development of both the Short and Medium Range Testing Facilities, including the choice of venue and all the relevant factors that were considered and investigated in the design of each of the facilities.

- **Chapter 5:** Survey Procedure for the Testing Facilities

In this chapter the positioning and surveying methods that were followed in the survey of the targets (known references points) is explored.

- **Chapter 6:** Analytical Methodology

In this chapter a theoretical explanation of the concepts utilized in this research is investigated. Also included are the requirements for determining the accuracy of a measurement instrument as well as the limitations experienced during the course of this research.

- **Chapter 7:** Analysis of the Survey Network

In this chapter an examination of the survey data is conducted and the final coordinate lists for each of the two testing facilities is determined using various calculation techniques.

- **Chapter 8:** Laser Scanner Testing Approach

In this chapter an analysis of the equipment available and testing of specific factors relevant to a laser scanner are investigate and thereafter the various methods for the physical scanning of the two facilities are explained.

- **Chapter 9:** Results and Analysis of Laser Scanner Testing

In this chapter the results from the two testing facilities are examined in order to determine the point accuracy of the instrument in terms of its angle and distance observations.

Part 3 Conclusions and Recommendations

- **Chapter 10:** Conclusions

This chapter summarizes the findings of the project with regard to the initial research questions and aims that were originally set out and draws conclusions based on these findings.

- **Chapter 11:** Recommendations

In this chapter further testing of the laser scanner and testing facilities is proposed.

Part I

Research and Theory

Chapter 2

Literature Review/Previous Work

2.1 Establishing Testing Facilities For Laser Scanners

From investigation into the accuracy testing and calibration procedures for Terrestrial Laser Scanners there are factors that appear significant when attempting to recreate such tests. The factors included design of the coordinate and survey networks, target criteria (type, colours/textures and dimensions) as well as the coordinate transformations utilized in the experiment. Further investigation into these factors is required in order to establish any form of testing facility for the evaluation of a laser scanner's accuracy.

The first thing that one, as a researcher and experimenter, must do is to explore the available options to work in. This means looking at different venues to accommodate the required needs. This may vary depending on the range that is needed or how well distributed the targets can be over the entire hemisphere surrounding a setup. There have been many investigations into the calibration of measurement instruments and there are a variety of testing fields/rooms that have been used. Examples include classrooms at universities such as at the Geodesy Division of the Royal Institute of Technology (KTH). Their indoor testing field was situated in one of the rooms in their department and also contained a photogrammetric calibration field. They tested three scanners based on the ideas of the total station, looking at distance, horizontal angles and vertical angles. (Reshetyuk (2006))

The facilities used for testing and calibration varied from classrooms, such as in the case mentioned above, to large halls with larger ranges or even outdoors with even larger ranges and different options for targets. According to this source the use of longer ranges in a test facility improves the reliability of the least squares calculations and estimations of the parameters. (Glennie & Lichti (2010))

In one particular experiment regarding the point and plane based methods (will be explained in more detail in a later section), one of the testing fields was a soccer field and the other was a group of buildings with different slopes and aspects. This experiment was aimed at showing the effects of using each of the different methods and how each one can have its optimal scene to produce better quality results. (Skaloud & Lichti (2006)) In another investigation performed by Licht wherein he divided the idea of a calibration into two calculations; determining each parameter one at a time, or all at once. The problem with the first method was that a specialized facility was required with precisely measured baselines and this is expensive to construct and these types of facilities are rare. The second is the approach of the ”self-calibration” which is now highly favored as there is no need for special facilities. All that is required for the second method is a room similar in dimensions to that of a classroom, with targets located on the walls. (Lichti (2010*a*))

These two approaches used a room with dimensions 12 meters in length, 9 meters in width and 3 meters in height. The targets were placed on the walls, floor and ceiling. Results from this project suggested that the room size did not matter as long as the targets are symmetrically distributed around the point of observation. For a situation where this symmetrical pattern could not be followed, the conclusion was that the bigger the room the better the results could potentially be. (Lichti (2010*b*)) This meant that in the case where the results from a short range testing facility are not sufficient it could be possible to transfer the same test to a larger facility and improve the results.

In another test, the use of a large hall with the targets positioned on the walls and floors to investigate the laser scanner properties can be seen. However, due to the shape of the roof and its height this made it difficult to position targets there. The room contained several building pillars which created a nuisance by obscuring targets from certain setup positions. This meant using the space wisely and efficiently to capture the required information with additional instrument setups. (Reshetyuk (2010))

Once the location for the testing facility was decided on, the next factor to consider was the design of the network. In other words, where the setup locations for the instrument will be and how the targets will be positioned (if you will be using any). This step is crucial to the outcome of the project. Many sources indicate the number of setups they used and the number of targets they incorporated. There are, however, only a few that include images to see how they organized their setups and even fewer explaining why they organized their networks in those particular ways. The sources that do mention how they chose their setup positions explain that it was in order to capture the points using the maximum range they could get out of the venue. Thereby indicating that range would be an important factor in how the network should be set out. (Reshetyuk (2010)) Others explained that they chose their network layouts in order to have their range values just outside of the minimum allowable range for the instrument. (Lichti (2010*b*)) There are also those researchers that used random, but well distributed locations and found the coordinates later. (Lichti & Licht (2006)) All have an impact on the results and if the end result is not sufficient it is possible to repeat the experiment with a different design and investigate the outcome. There is a method that was used by García-San-Miguel & Lerma (2013) using a triangle of setup locations with precise coordinates. With these highly accurate coordinates they are able to hold the distances between them fixed in a constrained adjustment by giving the setup positions high weights to strengthen the scale of the network and the adjustment of the observations to the targets. With these adjusted observations, the accuracy of the coordinates of the targets would be improved. (García-San-Miguel & Lerma (2013)).

To find the best locations for a setup Bae & Lichti (2007) used a plane based self-calibration in order to find the most accurate determination of the calibration parameters. (Reshetyuk (2010)) With a good network design and strong geometry between the setups there will be less correlation between the parameters due to the fact that everything has been constructed in such a way as to minimize inter-dependency and creating lots of redundancy. (Reshetyuk (2006))

Two very common topics of interest are the targets and the coordinates used. In any testing or calibration there are targets (either specialized for the testing or simply features that are easily recognized in the

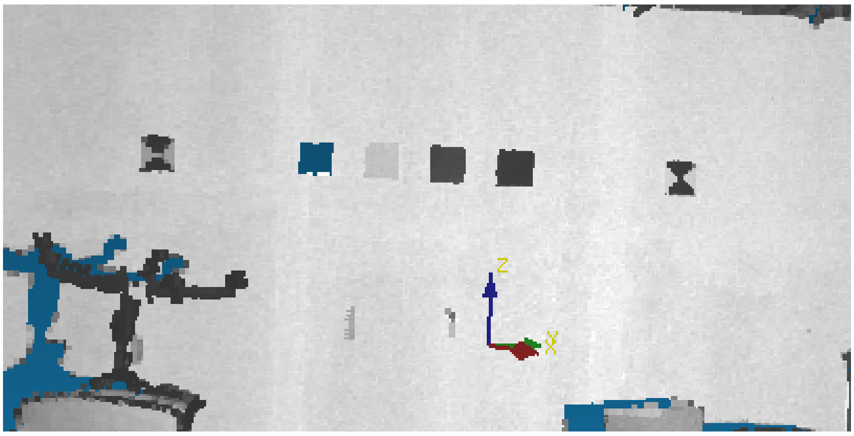

Figure 2.1: Screen shot of the colour targets on the wall in the short range facility. This image is illustrating how the high level of reflectance of the reflective tape, to the far left of the four colour target, causes a section of missing information where the target surface should be. This is a good indication of the impracticality of any reflective surface within the FOV of the laser scanner.

Field of View (FOV)) and they serve as a constant that should not change throughout the course of the testing or calibration. They can serve as fixed points with coordinates or without, they can be targets specially designed for the purpose of testing or they can be objects within the scene that are stable and distinct. All have been tried and tested by many researchers over the years.

The different forms of manufactured targets include printed targets from templates, spheres and square boards with the designs painted/printed on. These can then be subdivided further based on the different designs that have been tested. Designs change based on the preference of the user and the most suitable option is dependent on the situation in the field and the software preference. Designs that have been used in the sources found by this author are visible in image 2.2 below, compiled in Google SketchUp. The targets seen below are typically in Black and White (need high contrasting colours) and with as little use of highly reflective paints or inks as possible due to the laser scanner's inability to handle reflective surfaces (laser scanners struggle with materials such as glass or shiny metals and the results in a scan appear as a nest of point where the scanner could not perceive the true positions). Lichti (2010*a*) recommended not using retro-reflective targets because they can create a problem known as ”walk error” which is a bias in the range measurements (this can be visualized in the screen shot of the software in figure 2.1 where the highly reflective target is missing information, this is the most extreme case but the idea is to show how the determination of the position of the surface of a reflective material can be misinterpreted by a laser scanner). (Lichti (2010*a*)) For longer ranges Grey colours have been noticed to work better than the black. (Stroh (2015)) A tip given to this author in his time in the field is that anything ‘shiny’ is bad for laser scanning including bright sunlight acting on the surface. (Pearce (2015))

Targets can also vary in terms of their physical dimensions. Spheres can be the size of golf balls or soccer balls, square shaped targets can be as small as a playing card or as big as a full grown person. The size factor is normally dependent on the ranges that will encountered in the scans and a general rule of thumb taught to the author by Francois Stroh, is that for every meter away from the instrument the target should have one centimeter in size (height and width). For example, if a target is needed 25 meters away, the target would theoretically work best with a height and width of 25 centimeters. (Stroh (2015)) The reason for the increase in target size over the observed range is based on the laser scanner settings. If the

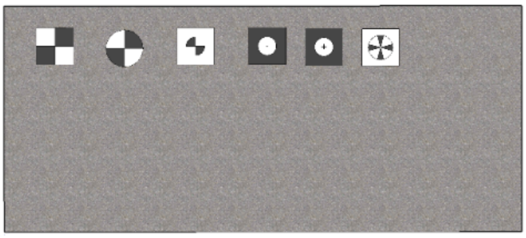

Figure 2.2: Illustration of the various targets types used by other sources based on personal preferences, drawn in Google SketchUp.

instrument settings (Resolution (number of points over a unit area) and Quality (time taken to emit and capture an individual energy pulse)) are kept constant and the instrument-target distance is increased, the number of points per unit area on the surface of the target will decrease. The more surface area available, the more laser scanner points will make contact with that surface. This can be important in testing and calibrations where the settings may not be allowed to change between different instruments to ensure fair testing which means the targets must be designed in order to handle lower resolutions that some instruments might have (although these guidelines can tend towards very extreme target sizes, it is the principle of increasing the target size to ensure the surface is sufficient to capture enough data to determine accurate coordinates for the centre point, this idea will be investigated in this project to explore the possibilities for target dimensions). Variations of the designs mentioned so far include 'tilt and turn' targets which are the same as those mentioned above but they have special designs that allow the target to turn and face the instrument without the center point moving. One of the problems found when using spherical targets can be the amount of reflection off the surface of the sphere and is sometimes why they are not the preferred choice. (Rietdorf et al. (2004))

The targets used during a scan do not always need to be the same targets, there have been cases where more than one kind has been used, the reason could be due to the type of mounting system being used or even simply having too few of one kind to cover the entire area. In an experiment by García-San-Miguel & Lerma (2013) there were 32 checkerboard targets on the walls and 15 spherical targets on the walls, ceiling and floor. (García-San-Miguel & Lerma (2013)) There is a possible issue with the use of non-standard target combinations that a user must be aware of before using several different targets. A range finder offset can be encountered due to the use of non-standard target combinations. (Chow et al. (2010))

In another testing situation the scans were performed in a large hall and High Definition Surveying (HDS) targets were used. These are high quality targets that can be printed and stuck onto flat surfaces. In this case there were 91 of these HDS targets placed on the walls and floor using adhesive tape but the ceiling was too high to reach in order to place targets. One of the important aspects of these targets was that they were assumed stable throughout the time of the experiment due to the short time period of the project (one week). (Reshetyuk (2010)) This was a good reminder that not all targets will remain stable if the setup is intended for any type of permanent testing facility.

There are also targets that can be used for the testing or calibration of different factors of a single instrument, such as the brightness level returns, angles (horizontal or vertical) or the range values. There have been several projects attempting to investigate each of these and even to compare these values between different laser scanners. In one such test to calibrate a laser scanner using it's brightness values, 8 targets were made of large polyester tarpaulin sheets coated first in Polyvinyl Chloride (PVC) and then with Titanium Dioxide and carbon black paint. A delustering agent was used to remove any glossy appearance and the end results were targets with brightness levels ranging from 5 percent to 70 percent. Each target was 5 meters in length and breadth and all were scanned using an airborne laser scanning (ALS) system, flying at altitudes of 200 meters, 1000 meters and 2000 meters. They also performed an indoor test using a laser scanner mounted on a tripod facing directly downwards towards targets with different intensities 110 centimeters below the instrument. At the end of this experiment it was noted that although there was good knowledge on the brightness values of a LIDAR (Light Detection and Ranging) scanner and how they are normally used to match the laser scan data to an aerial image, there was very little work done on the calibration of the brightness data due to the lack of knowledge in this area. (Kaasalainen et al. (2008))

Another test that was also attempting to calibrate a laser scanner using the brightness as well as distance was performed by Lichti. He used standard surveying targets but in order to analyze the brightness he attached 10 cm diameter acrylic targets to each of these survey targets. He used forced centering and the targets showed up as high intensity points in the FOV. In order to focus on the range values he used a dam in Australia that had been previously surveyed for a monitoring project and had fixed points from Differential GPS (DGPS) with an accuracy of 5 millimeters. No method of forced centering could be used at the dam site and therefore there was no known positions or orientation. In this experiment Lichti explains there was an issue with the returns from each of the targets in the brightness tests and there were multiple returns coming from the same target causing confusion in their identification (each target showed up as a cluster of returns). He explains that to fix this he used one of three techniques; either using the highest return value and claiming that belongs to the target at the center of the multiple returns, using the average of the four highest returns surrounding the center of the returns or he used the average of all the returns surrounding each target. With the second two methods he used a weighted average based on the intensity values. (Lichti et al. (2000))

In an experiment using a room with the approximate dimensions of typical classroom, there were two scan positions separated by 8 meters and 6 planar targets. This experiment used completely simulated data. The six planar targets (each 1.5 meters in length and breadth) were simulated to be in the center of each of the walls, ceiling and floor. Each was given 100 points that ‘fell’ onto them during the scans. With this unique approach there was a slight drawback which was the use of simulated data assuming a perfect laser scanner and perfectly flat walls. The solution they used was to add systematic errors to the data one by one. The problem they then experienced was the errors were becoming evident in the graphs they plotted but they could not tell whether it was the error in the data or the error they had just added in. (Bae & Lichti (2007))

Recalling the testing at KTH, in their scans they used two types of targets; 24 rhombus retro-reflectors and 23 black and white quarter-circle targets. They had targets on the walls and ceiling (not the floor to avoid people walking on them and damaging the targets). The coordinates of the targets were calculated in MATLAB and using a fitting program in the software called Cyclone. The first series of scans was done in order to test the accuracy of the coordinates and was done by comparing the coordinates that were calculated to those acquired by the scanner and the differences were the ’errors’ or ”non-modelled systematic trends”. They also performed a second set of scans using an arrangement of 7 targets in one scan and an arrangement of 12 targets in another. This second group of scans was performed in order to analyze the angular accuracy and precision, the method of analysis was once again a comparison of calculated ranges versus observed ranges. Of the three scanners they were testing here (Callidus 1.1, Leica HDS 3000, Leica HDS 2500), they found the Leica scanners to have better precisions than the Callidus. They noticed the errors were normally distributed and that the Callidus had an increase in errors with an increase in vertical angle (vertical scale error). They explained this was due to the maladjustment of the angular incrementation of the polygonal scanning mirror due to the vertical angle which was calculated from the sum of the angular increments. The errors were added into the calibration calculation and iterated until no further significant trends presented themselves. What was found was the Leica HDS 2500 had the highest accuracy despite its small FOV. They found 'range drift' in all of the scanners which they attributed to temperature changes outside the instruments during the first few hours of scanning (drift was about 3mm). (Reshetyuk (2006))

The coordinates used in a laser scanning project can be in a local reference frame or connected to some form of available higher order network such as the surrounding Town Survey Marks (TSM's). Either is used to be able to easily link one scan to another through correlation of the same targets viewed from different positions. Since there is no way to position a laser scanner over a particular point it is the objects in the FOV that get the coordinates for a scan and it is these objects that are common in more than one scan that will link the series of consecutive scans. These coordinates can be acquired through a variety of traditional surveying methods or more mathematical least squares calculations performed by software. According to Lichti (2007) they performed an Intersection using a total station and a Leica Scale Bar, in the scene for scale definition, in order to give the targets coordinate values. (Lichti (2007)) Lichti (2010*a*) used a method of forming the observation equations for every center point of the targets and solved for Exterior Orientation Parameters (EOP's), target center point coordinates and Additional Parameters (AP's). This approach has been used by many researchers including Lichti, Licht, Franke, Reshetyuk and Schneider. (Lichti (2010*a*)) Additional Parameters must briefly be explained here as a combination of physical and emprical parameters. The physical parameters include known systematic error sources (rangefinder offset, cyclic errors, collimation axis error, trunnion axis error, vertical circle index error and others). The other error sources that make up the rest of the additional parameters are those called emperical parameters and are not easily interpreted and "are inferred from systematic trends visible in the residuals of a highly-redundant and geometrically strong, minimally-constrained least-squares adjustment." (Lichti & Licht (2006), p. 155) Both are group as additional parameters in order to model both types to account for all possible sources of error. (Lichti & Licht (2006))

In terms of the coordinates of the instrument itself, this is a controversial topic and, as most in the field of Surveying will know, it is difficult to know where the precise mechanical center of an instrument such as a total station or laser scanner can be without opening up the machine housing to physically get to this point. This has resulted in most researchers using external methods and calculations to estimate this 'center' point. These methods have included intersections and resections as well as the rigid body transformation. (Lichti et al. (2000))

An important point to note is the type of coordinate system used in the scanner. The majority (if not all) of laser scanners capture the raw measurements in the Spherical coordinate system, because for most 3D scanners, the measurements form a point cloud closely resembling a globe and spherical coordinates can best represent these values. The observation equations are parametrized in terms of the Cartesian coordinate system for range, horizontal direction and vertical (elevation) angle. (Bae & Lichti (2007)) These two systems are related using a 3D Rigid Body Transformation with three rotations and three translations and is used by almost all researchers to this authors knowledge. The use of the self-calibration method thereafter allows for all the parameters and errors to be solved for simultaneously, including the target coordinates. (Chow et al. (2010))

In an additional source the coordinates of the targets were again acquired by total station, in this case a Leica TS-30. The instrument used a prism for some of the targets and reflectorless mode for others but unfortunately range was not measured in order to set the scale of the network. This source used the triangle of setup positions mentioned above. It was these positions of the triangle that had very accurate coordinates and these precisions were transferred to the coordinates in the network and gave it scale. The triangle of setups was measured 8 times using a sub-millimeter metallic tape and the measurements were averaged. The distances between the setups acted as the constrained values in a Free Network Adjustment. (García-San-Miguel & Lerma (2013))

One of the benefits of the Leica Scan Station is the ability to orientate itself using a high resolution scan of a target with coordinates. These coordinates can be entered into the Cyclone software and the azimuth found in order to directly geo-reference the point clouds. If the scanner is leveled properly and the coordinates of the various scanner locations and target positions are found with high accuracy the resulting EOP's will have greater stability, the precisions of the adjustment values will be stronger and there will be fewer correlations. In this experiment, along with the use of the geo-referencing ability of the Leica Scan Station, the Geodimeter 640M was used to determine the coordinates of the setups and the 8 targets that would be used for the geo-referencing. The Cyclone software was also used to calculate target centers. One of the problems encountered in this source was the low return signals when the incidence angle was too high and resulted in the target not acquiring enough data to allow it to be recognized by the software. The measurements were processed in a MATLAB program. The final coordinates were estimated in a free network adjustment with precisions in the horizontal and vertical under 1 millimeter. In this particular 'unified' approach the correlations between the parameters were reduced due to the effective use of geo-referencing. (Reshetyuk (2010))

In another method the raw measurements were used to reference the observations from all scan positions to the same local scanner coordinate reference frame. This technique worked in the same way as the bundle adjustment for a camera calibration and in this particular case they utilized the constrained adjustment. (Glennie & Lichti (2010))

Another source found target centers using "contrast centroiding" in the iQscene software and a free network adjustment. Three scans were captured using 45 targets. These targets were given coordinates through a survey with a theodolite using intersections from two setup locations. Scale for this network was determined through observation to a 900 mm Leica scale bar positioned in the scene. The targets had a mean accuracy of half a millimeter in the horizontal and 0.1 millimeter in the height. (Lichti & Licht (2006))

The number of targets used in the calibration of laser scanners is dependent on the intention of the experiment. If the purpose is to measure single entities such as a distance or a direction, much less targets are needed as in the case of a calibration of a scanner for an autonomous device. In the case of testing range values only a single target could be used and set up in front of the laser scanner and the distance between the two changed using a 'rail' system (scanner and target mounted on rail and they can be brought closer/further and the rail and scanner can be orientated precisely with respect to each other). Once the distance had been analyzed, the angles (horizontal and vertical) can be examined. These require some more targets positioned in a variety of positions and angles but can still have relatively low numbers of targets, in this case it was 13 targets. (Ye & Borenstein (2002)) In a situation where more parameters are needed and if there is a need to solve for them simultaneously, the number of targets will increase as in the case of García-San-Miguel & Lerma (2013) where they used 62 targets in total. Here there is another factor that determines the number of targets used; the availability of targets. This is usually the reason for combinations of target types. In this case there were 47 points in the scene used for reference, 32 of these were checkerboard targets and the other 15 were spherical targets. (García-San-Miguel & Lerma (2013))

Another factor that limits the types of targets used is the method of mounting. If the targets need to be mounted using permanent fixtures that require drilling into the surface or if they need to be stuck to the surface using adhesive tapes. Some facilities may not allow drilling or permanent damaging fixtures to be used which will alter the type of targets that can be used.

In the case above with the Leica Scan Station when there were multiple scan locations and multiple parameters that were solved together, there was a need for a large number of targets (in that particular case they used 91 targets). This allows enough redundancy between the separate scans from different positions. This test had a check for the incident angle on the target and had a limit in place to remove those targets with an incidence angle that was too high and resulted in 79 of the 91 targets being used in the further calculations. (Reshetyuk (2010)) The incident angle is significant because the lower this angle or the closer to 'head-on' the laser strikes the target the lower the residuals for that target will be. (Glennie & Lichti (2010)) This highlights a good reason to have more targets than required; if there are targets that need to be removed there must still be enough to perform adequate calculations. (Lehtomäki et al. (2010))

Lichti (2010*b*) conducted a variety of tests in order to analyze correlations between many factors and these tests included 180 targets spread all over the room. (Lichti (2010*b*)) In the test by Lichti & Licht (2006), they used 131 planar targets and in the test mentioned earlier that used an entirely simulated data set, they used 6 planar targets with one on each of the walls/surfaces in the room. (Bae & Lichti (2007)) The testing at KTH used 47 targets for one test examining range drift, another test used 7 for angular accuracy and another used 12 targets for angular accuracy again but there were obstacles present in the prior test that resulted in the need for additional targets. (Reshetyuk (2006)) There was no apparent rule for the number of targets, the best option seemed to be the use of as many targets as possible.

Some of the other details of the experiments include how many setups were used, how many scans were performed at each setup and how many were performed overall. These numbers vary as much as the number of targets and rely mostly on the level of redundancy the user will be happy with. The more scans captured will increase amount of data available and in the projects with more scan positions and good network geometry the higher the precisions and accuracies will be due to higher levels of redundancy. However, there is also a limit and the user does not want endless amounts of data and massive amounts of processing. The majority of sources recommend at least two scans per setup and depending on the size of the testing room, the number of setups will also vary. Setups should have the maximum distance separating them in order to minimize any correlations between the setups (extrinsic parameters are setup dependent). In one particular experiment the researcher set up a grid in a simulated scenario and placed the instrument at different locations to find the position that presented the best accuracies based on the range and elevation angle. The conclusion they arrived at was the best results could be found when the scan locations were as far apart as possible. This is because the collimation axis error is strongly dependent on the laser scanner's position. (Bae & Lichti (2007)) There are a few tips and recommendations given by various authors and researchers to avoid errors and acquire the best results during calibration. The general guide is to include good variation in the distances and vertical angles that will be observed. (Lichti & Licht (2006))

Some recommendations given by Lichti (2010*b*) for a strong calibration network include an asymmetrical target field, using the largest venue possible, using large numbers of targets (here the recommendation is more than 130) and allowing the scanner to start from different orientations for each scan. (Lichti (2010*b*))

In the case of Lehtomäki et al. (2010) they note that in order to be able to scan vertical 'pole-like' objects, it was possible to tilt the laser scanner unit itself to capture those vertical obstacles (this is only the case for 2D scanners). (Lehtomäki et al. (2010)) The majority of precise work employs the method of forced centering when mounting any devices. This holds true for laser scanning and what will now be looked at are the mounting systems that have been used by previous researchers. Included in these prior investigations are either tripods or permanent mounts to position the laser scanner. The use of the tripod was employed by Kaasalainen et al. (2008), Glennie & Lichti (2010) and Chow et al. (2010). Chow et al. (2010) was one of the sources that used a heavy duty 'spider' to damp out any vibrations acting towards the scanner. The mobile scanning industry usually rely on permanent mounts to attach the scanners to the vehicles which is usually on top of the car on the roof racks or on the front of the car on the 'bull-bar'. The airborne industry have either a permanent mount attaching the laser scanner system to the aircraft or they have a detachable setup allowing the removal of the device from the aircraft when not in use and it can be easily placed into the same position each time when needed. The airborne field have included several ingenious methods of removing external effects on the scanner such as gyro-stabilized mounting systems. The rest of the time it can be assumed the scanner is positioned using a concrete pillar or other permanent fixtures and some method of forced centering.

The first step in any testing or calibration is the network design and there are numerous sources that reiterate the importance of a good network design in order to reduce correlations and improve the estimates of the calibration parameters. The data in any adjustment or analysis that will be used in further calculations need to be of the highest quality in order to ensure that it does not pollute the data that is to be derived further down the line. One particular source used by this author gives some helpful advice that can be used in order to achieve higher accuracies and low correlations in the data. This advice includes a good distribution of targets or reference points in the vertical range of the instrument, the use of at least two setup/instrument positions, a large number of targets covering the field of view to create a strong network geometry, not over parameterizing (do not want unnecessary parameters) and an observation technique that involves rotating the scanner through an angle of either 90 degrees between different scans from the same location. This last tip is used to increase the level of redundancy in the data. (Reshetyuk (2010))

In the statistical analysis performed by García-San-Miguel & Lerma (2013) the distribution of the data was noticed to conform to a Normally distributed dataset around a mean value of zero. (García-San-Miguel & Lerma (2013)) Reshetyuk (2010) indicates that if the scanner is leveled properly and the coordinates of the scanner locations and targets are determined with high precision, the resulting EOP's will have greater stability and precisions will increase and correlations will decrease. There are also recommendations to observe azimuth observations separately in order to avoid correlations between the collimation axis error and scanner azimuth or to use a different method of parametrization. (Reshetyuk (2010))

2.2 Checking Instrument Accuracy

2.2.1 For Laser Scanners

An important characteristic of laser scanners is the fact that all their measurements are done in a 'reflectorless' mode. This term is usually coupled with total stations and theodolites when the target is not making use of a prism or 'reflector'. It means that the accuracy is slightly lower than it would be if there was a prism because of the uncertainty at the point of reflection. A laser scanner is able to measure millions of points in a single scan of the scene around it and the result is a group of points called a point cloud. This cloud consists of the coordinates of the reflected objects in the scene as well as the intensity value of the returning pulse (x,y,z,I).

In terms of an accuracy assessment for a laser scanner where millions of points are captured in a single scan, the uncertainty will grow considerably and have a definite impact on the accuracy of the overall results. Another factor that researchers consider in their accuracy analyses is the impact of laser scanners only having 'one face', whereas the total station has the ability to rotate the head of the instrument through 180° and perform the measurements again on a second face. This single face means that the horizontal and vertical readings are weaker than those that would be obtained using a device with the ability to use two faces. (Chow et al. (2010))

The different types of laser scanners can be sorted into groups based on their internal architecture. There are three groups to this author's knowledge; camera scanners, panoramic scanners and hybrid scanners. Camera scanners have narrow Fields of View in both the horizontal and vertical. Both panoramic and hybrid scanners gather data from a full 360° in the horizontal range of the laser scanner head rotation (there are different variations of this rotation). A panoramic scanner rotates around its vertical axis through an angle of 180° and has a vertical FOV that is almost a complete circle except for that section at the nadir (directly below the machine) of the instrument, which is only a few tens of degrees. Hybrid scanners have half the vertical range of the panoramic scanner and range from within a few tens of degrees from nadir to the zenith. (Lichti (2010*a*))

All measurement devices are assumed to comply with the accuracies quoted by their manufacturer, however, this is not always true. The reasons for a particular device deviating from its recorded accuracies include factors such as; the age of the instrument and its components, how often it might be used as well as unavoidable knocks to the instrument itself. Laser scanners are amongst these measurement devices that suffer from these factors including additional factors such as the environment of the scan site, distances (either too big or too small), angle of incidence and reflectivity of the target. (García-San-Miguel & Lerma (2013))

In order to bring accuracies closer to the manufacturer specifications, testing and calibration of the instrument is required. (García-San-Miguel & Lerma (2013)) In other words, a process of Quality Assurance (QA) is needed to ensure that the instrument in question is adequate enough to undertake the task at hand. (Lichti (2010*b*)) Calibration is always necessary for precise work. Professionals in any field will know this but with the growing attention to laser scanning in the recent years and the many new users, this may not be so obvious or just how significant a system calibration can be. (Lichti (2007)) This is becoming more and more the case as manufacturer specifications appear to be too optimistic. If the instrument is needed for precise work, then it will need to be checked and the calibration parameters specific to that instrument found and added to the observed data. (García-San-Miguel & Lerma (2013))

In a QA there are two main steps; systematic modeling and geometric calibration. The first step involves locating the systematic error to avoid any further negative impact on the accuracy of the generated results and the second step sets up a high quality method of estimating the adjustment coefficients. (Lichti (2010*b*))

With the attention to the field of laser scanning growing every year there have been many new developments in the areas of testing and calibration. There has been the distinction between a calibration and a 'self-calibration', with the latter being highly popular in the field. The term 'self-calibration' was initially used in the branch of photogrammetry. In terms of laser scanners, all calibration methods can be called self-calibrations, this is due to the fact that in this technique there are either points, planes or spheres used as targets, whereas in a normal calibration there is a form of calibration grid or calibration pattern in the scene being captured. The idea of using objects in the FOV to aid in the calibration is what separates a laser scanner 'self-calibration' from a typical calibration. Added to this interpretation of a self-calibration is the fact that it is a method of finding not only the system's parameters, but simultaneously determining the systematic errors (also known as the calibration parameters). A calibration is thus a general term used to describe the process of finding only the parameters needed to adjust the instrument observations to acquire results closer to the manufacturer specifications. (Reshetyuk (2010))

According to Lichti (2010*b*) there are some advantages to the method of self-calibration such as; optimal estimation of the model variables, no special equipment or facilities or EDM baseline are needed, only requires targets (points or planes) and can yield precise additional parameters. One of the advantages mentioned is that no special facility is required, which means this process is able to be modeled in any available space without the construction of a new facility or any special conditions. This also means the process is easy to update and improve results without having to break down the instrument body to analyze the true inner workings of the machine. (Chow et al. (2010))

There are two important aspects involved in a self-calibration; sensor (error) modeling (figuring out where the errors are originating and forming a model which encompasses them all to be able to adjust them) and network design (the physical design of the network of setups and targets). Of these two is it the idea of a good network design that is significant to this research. A good network design will cause good estimates of the calibration parameters which are needed in the error model for the adjustment. Therefore, the network design will work hand in hand with the sensor model and for the one to be accurate the other will also need to be. There will also be fewer correlations with a stronger network design. (Reshetyuk (2010))

Any self-calibration method can be further broken down into two techniques; Point or Plane (Feature) based. Whenever a self-calibration of a laser scanner is mentioned either of these two terms is sure to follow and depending on the researcher preference either could be used.

The Point based method uses targets where the coordinates of the center can be captured/calculated and thereafter used in the calibration process. In order to use the Point based method there needs to be several point clouds captured from several locations in different orientations. A strong geometric configuration of targets will be needed and thereafter will aid in the determination of the centers of each of the targets. The observation equations are formed for each of the center points and equations for the exterior orientation parameters, target point coordinates and AP's are solved simultaneously. To this author's knowledge there are many followers of this approach including Lichti, Licht, Franke, Reshetyuk and Schneider. (Lichti (2010*a*))

The Plane based method relies on the signal returns of the laser from the flat plane target surface. (Reshetyuk (2010)) An example is in the approach by Rietdorf et al. (2004), wherein several calibration panels were positioned in the scene. The panels were distributed throughout the room with variations in angle and orientation. The panels were then scanned from different locations to ensure all panels were observed. The captured point clouds were analyzed by segmenting them into those points that belonged to each of the different panels, then to condition each point to lie on its respective plane in order to formulate the equations for that particular plane and solve for the variables in a minimum constraint adjustment, i.e. plane fitting. In this investigation the exterior orientation parameters, plane parameters and AP's of the systematic error models were solved for. Other versions of such methodology was discussed in (Bae & Lichti (2007)) or (Dorninger et al. (2008)). (Lichti (2010*a*))

Although it was the Plane based method that was first used it is most often the Point based method which is preferred today. This can be attributed to its similarities in the observation equations to those of the normal surveying instruments and the ease with which targets can be printed from manufacturer templates. (Lichti (2010*a*)) Both methods have one factor in common; a high redundancy from the large number of observations using a multiple setups organized into a strong geometric configuration. (Lichti (2010*b*))

In the first few attempts some advantages of the plane method were discovered to be a higher level of redundancy over the point based method. Some later attempts exploited the similarities between laser scanners, theodolites and cameras and wanted to use those as a basis upon which they developed a means to tackle the laser scanner. As one can imagine, due to the differences in speed and quantity of data captured by these types of instruments, there are several drawbacks to assuming the scanner is similar to a camera or theodolite. These drawbacks included angular systematic errors and pseudo-observation equations for a camera do not truly represent those needed for a point cloud, which made estimating the true physical nature of the systematic errors of the laser scanner difficult. In order to try and resolve these drawbacks some researchers have tried to re-form the observation equations into spherical equations, as opposed to Cartesian equations (was briefly mentioned earlier), which are better for modeling point cloud data. Later methods performed similar tasks using the point based approach. (Lichti (2007))

When deciding on which approach to use it is also important to consider the contents of the scene. According to Skaloud & Lichti (2006), where they were testing an Airborne method of scanning. When observing a natural scene (as in the case of the soccer field they were using) it must be considered that there may be a lack of objects within the scene that could be used for the Plane based method because of the difficulty in fitting planes to natural objects. The reverse is also true, when observing a man-made scene such as a CBD, although a Point based method would still work, there would now be many more surfaces available for the fitting of planes due to the regularity of the buildings and man-made structures. The idea of this source's experiment was to show the effects of the geometry on the quality of the resulting parameters based on the particular method of self-calibration. They also mention that observations can be negatively affected by poor geometry, so it is imperative to know as much as you can about the scene is being observed. (Skaloud & Lichti (2006))

Regarding the use of targets there are a few researchers that have been incorporating calibration grids into their system calibrations. One example was previously mentioned where checkerboard targets were used in an experiment with 47 points for a reference and these points were comprised of the checkerboard targets positioned all over the walls, floor and ceiling. (García-San-Miguel & Lerma (2013)) Another example was an experiment by Zhao et al. (2007) where they were attempting the calibration of multiple sensors on a single platform. In order to register the data from both devices (Laser Scanner and a camera on a mobile platform), they used a calibration checkerboard and positioned it at different locations that were visible by both the laser scanner and camera. The coordinates of the checkerboard's positions were worked out in both devices' coordinate systems and the results were used to compute the locations of both the laser scanner and camera. (Zhao et al. (2007)) One source mentions the use of a calibration grid pattern similar to those used in the calibration of a camera. The grid is positioned so that it can be viewed multiple times from various locations with different angles and orientations. This source noted that this process requires a lot of time and effort spent re-scanning the same scene after changing the position and orientation of the calibration grid. They suggest an alternative whereby they would use more of the calibration grids positioned all around and at different orientations and this way they only need a single pass with the scanner to capture all the grid patterns which will all have varying angles and orientations. (Scaramuzza et al. (2007)) Although these methods used a calibration grid/checkerboard they still do fall into the category of self-calibration due to the fact that they attempted to determine all of the calibration parameters simultaneously, it is this crucial fact that links these approaches.

Despite the last few years of work in the field of laser scanner calibrations, testing and analysis one particular source claims that "unlike traditional photogrammetric bundle-adjustment with self-calibration technique, a standard, accurate, and rigorous laser scanner self-calibration routine has not yet been established." ((Chow et al. 2010, p. 161))

In one such experiment to find a way to analyze the accuracy of a terrestrial laser scanner, a new approach was adopted when deciding on the known values that were used to compare against the laser scanner observed values. In this case instead of installing a network of known points within the scene, this researcher used the unique method of positioning six large stainless steel geometric shapes in view of the Z+F 5006i laser scanner. These shapes range from 30cm to 100cm in their dimensions, three of which are the original metallic colour and the remaining three painted black. The shapes were positioned at various distances and repeat scans with different settings were conducted. Also included within the scene were twelve targets used for the registration of the the different scans. The shapes were scanned in all the available modes of the instrument for resolution; "high", "superhigh", "high", "superhigh" and "ultrahigh" mode. Thereafter each of the shapes was accurately measured with very fine calipers to give each shapes' width, height and depth. These measured values were compared to the laser scanner values for the same width, height and depth to find the differences over the different ranges to the target as well as using the different instrument settings. This determined the differences to be inversely proportional to the laser scanner intensity or resolution and directly proportional to the distance. (Alkan & Karsidag (2012))

Taking another look at the idea of calibration, it can be once again separated into two categories; Intrinsic or Extrinsic. Usually these terms are coincident with a camera calibration but the concepts can be extended to any measurement device. An Intrinsic calibration finds the parameters characteristic of that instrument such as the focal length of the camera, optical distortions and principal point. The Extrinsic calibration on the other hand will find the relative rotations and translations between the different sensor systems or in the case of the laser scanner these would be between the different object space and scanner space systems. The extrinsic parameters would change from setup to setup. Another difference is that an extrinsic calibration requires modification or altering of the natural environment by placing targets in the FOV. These are able to be seen at all times by all the sensors in order to serve as fixed or known tie points. One particular use of the extrinsic method was carried out in an experiment using a SICK LMS 200 laser scanner. The range data was processed for any discontinuities or orientation changes along specific directions and this results in series of Bearing Angle (BA) Images. These are very helpful in identifying point correspondences between a laser scanner and a camera. This is now the same concept as image paring in photogrammetry, where the same point is matched in both images/scans. (Zhao et al. (2007))

Laser Scanning is typically used in a Static (non-moving) manner and the scanner is then re-positioned to capture more data. This technique is preferred when more dense data is needed for higher precision work and accurate mapping projects. Despite the large variety of uses in the static world for laser scanning there is another form of laser scanning that is gaining great interest, the Mobile Scanning industry. Laser Scanning devices were originally used for the autonomous robot industry due to the fact that they could capture large amounts of data from the surroundings over much shorter time periods. This was useful to the robotics world because they needed to know as much about the surroundings as possible in order to navigate there machine safely. This type of work was in the realm of Mobile Laser Scanning because the device was moving while scanning and recording the data and then calculating its projected path to follow. This meant that laser scanners were now not only being attached to cars or moving mounts but also Airborne platforms such as planes and helicopters. This now added a new element of accurately positioning the laser scanner in space which was often through the use of Global Positioning Systems (GPS). (Kaasalainen et al. (2008))

Some of the first work was done in the field of robotics was using 2D laser scanners due to the 3D devices capturing huge amounts of data and taking more time to process. The use of the 2D scanners meant the processing time was improved to ensure the navigation of the robots could be done as efficiently as possible to avoid obstacles. In another scenario where railway mapping was the aim, a 2D scanner could be mounted on a train and aimed down on to the track to be able to map the track and detect any deformations or malfunctions. (Ye & Borenstein (2002)) Another source from the mobile laser scanning field was interested in showing how they used cross sections of point clouds to find trees and 'pole-like' objects. They analyzed stacks of horizontal cross sections to find where cylinders were in the FOV. This was done by lining up the cross sections to where the circles fell on top of each other. In order to make this easier they used a method of tilting the scanner slightly and this meant the same object, if vertical, would still receive multiple sweeps over it and the object could be identified in the cross sections by finding the now slightly ellipsoidal shapes falling on tops of each other. For those objects where they were vertical but have been altered (for example a lamp post that had been knocked at an angle), they collected the data manually. (Lehtomäki et al. (2010))

In the field of mobile laser scanning, the calibration of intensity values would now become a vital task due to the different sensors available and how they operate at different distances. According to Kaasalainen et al. (2009) if the calibration of intensity values was successful, this would create a calibrated reflectance image and the coordinates (*x,y,z,I*) would not need to be geo-referenced between the different datasets due to the fact that the intensity values from one dataset would be the same in another and this could link the datasets. (Kaasalainen et al. (2009))

The problems encountered in mobile laser scanning include the occlusions (obstructing) of data and the point density at the target surface. Mobile laser scanners can often be designed for mobile mapping and have a set resolution which will be too coarse for identifying targets beyond a certain range. For Glennie & Lichti (2010) where this was the case, they needed to find a new method of calibrating their scanner in a mobile friendly scenario. This is a factor that makes establishing a standard calibration facility for all laser scanners rather difficult with so many factors to account for in a single facility. The solution they came up with was to model features rather than individual points. (Glennie & Lichti (2010))

Zooming out and looking at the bigger picture, a process flowchart could be developed for the calibration of a laser scanner. The following flowchart in figure 2.3 is an example for the calibration process for a laser scanner, formulated by García-San-Miguel & Lerma (2013)

The same source created several of these flowcharts to simplify the process and they describe one that included a step for the removal of any outliers present in the data. There are also some very complex ones breaking down the tasks very acutely into very specific tasks. (García-San-Miguel & Lerma (2013))

2.2.2 For cameras

In the 80's and 90's the idea of the panoramic or omni-directional camera was generating more attention and many attempts were made to find ways to calibrate these sensors in all their forms; fish-eye, conic mirrors and so on. The main idea for the calibrations was to perform a constrained adjustment on the observations to find all of the intrinsic (specific to camera) and extrinsic (parameters that identify camera

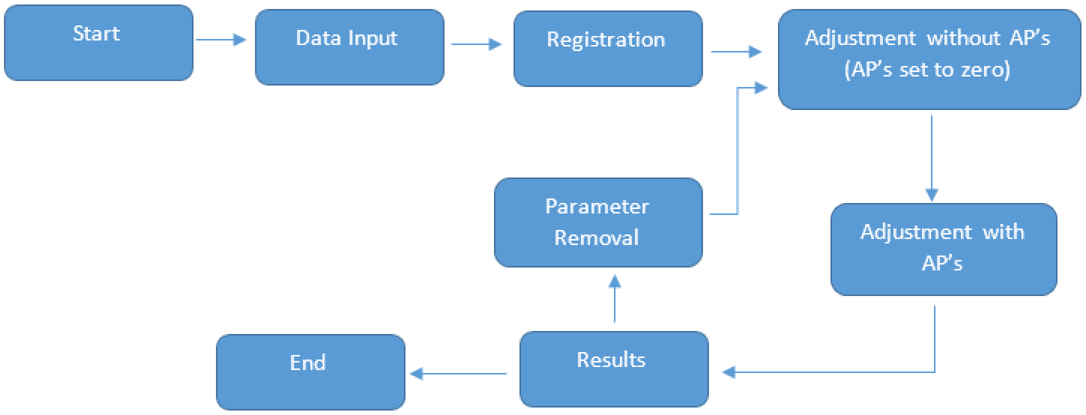

Figure 2.3: Calibration Process depicted in a flow diagram from inputting data to achieving results and including the possibility of iterations through the adjustment process.

in object space) parameters of the sensor simultaneously.

One of the unique methods used by Benosman et al. (1998) was to focus on the projective geometry and to use two linear CCD's that rotated about a vertical axis and very precise adjustments of these CCD's in order to achieve very high precision values. They also turn the 3D problem into a 2D one as they view the panoramic image as a cylindrical projection onto a flat surface and thereafter give the flat 'image' some reference marks. These reference marks are to ensure that there is a specific relationship between the orthogonal reference lines and optical centers of the camera.

This approach was unique because it did not assume the intrinsic parameters were known values and allowed them to be adjusted and this helped to avoid 'aberrations' (in this case this term refers to the optical axis deviating from the center of the CCD). They were able to find an efficient and precise method to calibration a panoramic sensor using the idea of the cylindrical projection. (Benosman et al. (1998))

One of the more recent attempts looked at both panoramic cameras and laser scanners along with their similarities in order to develop a single model for the 'ideal' camera through the idea of the Bundle adjustment. The model was based on the cases noted previously and also describes how the ideal camera is corrupted by systematic errors which are modeled as additional parameters. The idea behind the error model believes that if the camera was positioned somewhere in space and rotated in one direction it would create a cylinder of images around the central axis of the camera's rotation and this cylinder can be opened up and given coordinates according to the pixels in the image with respect to their row (i) and column (j). The model for panoramic cameras was found to be very useful due to its 'flexibility' to be adapted to apply for sensors with similar geometry, which applies to the terrestrial laser scanner. Some conditions/requirements were set down to ensure that the laser scanner data conforms with the model from the ideal camera; scanning must only be in the horizontal by rotating the entire housing of the laser scanner using a turntable developed by this researcher for his experiment and there needs to be intensity information and/or enough features in the field of view to give range values (such as corners or spheres). (Parian & Gruen (2010))

Unfortunately the laser scanner is not a perfect match for the model of a camera and requires some assumptions to be made to account for the differences in operation and physical design. The laser scanner does not have a linear array because the laser scanner rotates horizontally while a rotating mirror/prism is also rotating in the vertical and the laser scanner also does not have the same optics as a panoramic camera. Due to these differences the assumptions made are that the scanner has a 'virtual' linear array instead of the rotating mirror. With this virtual linear array the instrument is positioned so that it is parallel to the turntables rotation, orthogonal to a normal vector of a plane containing the x and y axes and lastly is located at a constant non-zero distance from the turntable rotation axes. (*ibid*)

Just as in the case of an ideal camera deviating from the 'perfect' case, so too does the real world laser scanner and here it is assumed to have the following systematic errors; tilt, eccentricities of the projection center from the origin of the turntable's coordinate system, corrections to the angular pixel sizes, variation in the angular pixel size and 'tumbling' of the scanner. Tumbling is also known as "Trunnion axis error" and results from the mechanical operations of the turntable. Another important factor that was noticed was that as the rotating element of the scanner rotates through the vertical it is also moving horizontally and therefore the pattern produced is not a vertical scan line and is assumed small enough to coincide with the inclination of the virtual linear array. (*ibid*)

From the collinearity conditions, if a line is straight in object space it should be mapped into image space as a straight line and if there was any skewness it could be attributed to lens distortions and movements of the principal point and modeled with the additional parameters. Other methods have been known for going into more detail and adding in more measurements and parameters to improve the adjustment (decentring distortion, skewness of the sensor pixels and even earth curvature are some of the parameters that may be included as additional parameters to highlight more information about the system using a more detailed model). (*ibid*)

The testing was performed on two panoramic camera test fields with two panoramic cameras and a Z+F Imager 5003 laser scanner. The test fields had control points covering 360 degrees in the horizontal within two facilities at ETH Zurich and Technical University of Dresden (TU Dresden). The targets were 2.4cm circular targets made of aluminum and were stuck on black backgrounds for good contrast. The ETH Zurich test facility had 96 targets whereas TU Dresden incorporated more than 200 with dimensions of 1cm and 2 cm (these targets were the centers of retro-reflector targets). (*ibid*)

The calibration of the laser scanner was done in the form of a space resection from the single images and the targets needed to be changed due to poor intensity values. The orientation of the scanner could be determined using the intensity images. A bundle block adjustment was carried out after distinguishing between frame- and block-invariant additional parameters. The frame-invariant parameters are the parameters that remain constant during the capture of a single image and the block invariant parameters are the parameters that remain constant throughout the time of the capturing all of the images. They have been referred to as Stationary (block-invariant) and non-stationary (frame-invariant) parameters as well. (*ibid*)

The adjustment was performed in a minimal constraint analysis and free network adjustments, however, they did not converge due to the values of some of the additional parameters (varying angular pixel size and tumbling parameters) initially being estimated incorrectly. Once these values were changed to better estimations of the true values, based on the approximations from the resections, the adjustment was able to converge and acquire values for a 'partial' self-calibration. (*ibid*)

Tests were run on the two panoramic cameras and thereafter applied the model to the Imager 5003 and sub-pixel accuracy was achieved. Special mention is made to future developers to avoid 'over-parameterization'. These models were suitable for self-calibrations of panoramic cameras and laser scanners for measurement applications. (Parian & Gruen (2010))

The calibration of cameras and survey instruments is always essential in order to achieve the best results from their measurements. There are calibration models being developed for new devices such as range cameras, which are cameras with the added ability to measure 3D points using an array sensor with time-of-flight range finder. In the approach by Lichti et al. (2010) they analyze two range cameras, the SR3000 and SR4000, which are SwissRanger range finder camera systems. They developed a model similar to the Bundle adjustment with the collinearity conditions visible in the following section, but with the addition of the range observation equation (which can be seen below) in a single simultaneous adjustment using signalized targets (black backgrounds with circular white dots of varying radii). The calibration is shown to be effective in reducing the Root Mean Square (RMS) errors from the measurements and therefore improving the overall quality of the results for both camera systems.

$$p_{ijk} + \varepsilon_{ijk} = \sqrt{\left(X_i - X_j^c\right) + \left(Y_i - Y_j^c\right) + \left(Z_i - Z_j^c\right)} + \Delta p_{ijk}$$

Where p_{ijk} is the observation, ε_{ijk} is the respective random error, X_i, Y_i and Z_i are the object coordinates, X_j^c, Y_j^c and Z_j^c are the object coordinates for the perspective center.

The operation of a range camera is described as a "cone of amplitude-modulated NIR (Near Infra-red) light" being emitted from a set of LED's on the camera. This light hits the target surface and the backscattered light is captured by the lens and focused onto a solid-state detector. The signal that returns is broken down into individual cycles in order to determine the phase shift and therefore the range to the target. The benefits of such a system over the laser scanner are said to be the lack of the scanner mechanism, which would be the rotating mirror/lens. One of the factors in favour of the laser scanner is the ability to measure in 3D with only one sensor, whereas cameras required multiple images from different locations to establish depth for 3D measurements.

The results from this experiment showed a reduction of the residual RMS values by 54% and through an independent accuracy assessment the RMS values of the object coordinates were improved by 74% over the quoted values from the manufacturer for the SR3000.

In the particular software used by this source (name not mentioned) the center points were found using least squares ellipse fitting for the targets which were positioned on the front wall of a squash court. The range was determined using the four nearest neighbour pixels using bi-linear interpolation. There were 106 targets on the front wall and the squash court was selected based on its size and largely because of the flat walls. The cameras were setup and moved backwards for redundancy of the target values. Only one of the walls was used due to the scattering effect that is common among range cameras and also in an attempt to minimize the range finder offset from a planar target field. (Lichti et al. (2010))

Although there has been a focus on both accuracy testing and calibration of laser scanners, as well as cameras and other instruments used for measurement, it must be noted that the reason for the review on the research done into calibration of these instruments is for the significant similarities between the facilities and testing procedures that are relevant to the research being conducted in this project. The past research is able to indicate various helpful characteristics of the facilities required in all of these experiments as well as the different approaches to their own versions of testing and calibration. The similarities provide a base to work from for this research into the testing and assessment of the point accuracy of a laser scanner. Only the performance of the instrument is investigated based on the accuracy of the laser scanner observations, there will be no determination of the calibration parameters in order to return the instrument to manufacturer standards.

Chapter 3

Laser Scanner Principles and Theory

3.1 Overview of Terrestrial Laser Scanner Principles

Laser Scanning is still in the early stages and not well known outside of the realm of engineering surveying. There have been many advances in this technology over the past twenty years and Laser Scanning has become a means of fast, automated and comprehensive 3D data acquisition. The Terrestrial Laser Scanners (TLS) of today have been strongly influenced by the LiDAR (Light Detection and Ranging) systems of the 1970's. The change from these systems which were typically used for remote sensing and aerial surveying has included a shortening of the range and an increase in the accuracy, although some may suggest that longer ranges are being observed with each new development. These improvements can be attributed to the advancements in technology and processing abilities.

TLS systems work based on a method of indirect range determination, in other words the distance that is captured is accurately determined by the time difference measured between the emission of a laser signal and the return of that signal from the target surface. This is what is known as Time of Flight (TOF) due to the fact that the observable in these systems is the time difference. In addition to this method there are two others that are commonly used by laser scanners for measurement and are explained below. (Reshetyuk (2009), Schulz (2008)) All these methods are based on the principle of LiDAR (Light Detection and Ranging).

1. Pulsed ranging (TOF), the time from emission to capture of the return signal is directly measured. Usually operates in the medium to long range target range.
2. Amplitude Modulated Continuous Wave (AMCW) ranging or Phase-Shift ranging, the phase shift (difference) between the transmitted and received signal is measured and is proportional to the signals travel time. Usually operates in the medium target range.
3. Frequency Modulated Continuous Wave (FMCW) ranging, the signal's travel time is measured by measuring the beat frequency of an FMCW-modulated signal and its reflection, the frequency is related to the travel time of the signal. Usually operates in the close to medium target range.

These measurement types can be visualized in the figure 3.1 below along with the possible applications for each type.

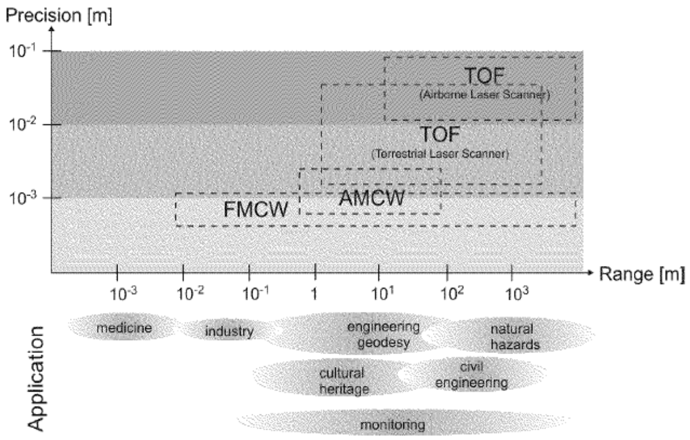

Figure 3.1: Technologies used for Distance Measurement based on LiDAR, including their operating range, precisions and applications. Courtesy of Schulz (2008).

The laser scanner in simplicity is an emitter, receiver and detector. The detector is the component that is responsible for detection of the returning signal in order to determine the distance to the target. Highly sensitive diodes are responsible for the detection of the returning laser beam. Each system deflects the laser beam from the emitter to the target, this deflection unit takes one of two forms; rotating or oscillating mirrors. It is this component that will determine the Field Of View (FOV) of the scanner. Due to the rotation ability of the laser scanner optics in both the vertical and horizontal planes, entire targets are now able to be captured. The physical operation of the Z+F 5010C laser scanner can be simplified into the basic motions illustrated in figure 3.2. The sketch is useful to understand how the laser scanner is able to acquire information in both the horizontal and vertical simultaneously.

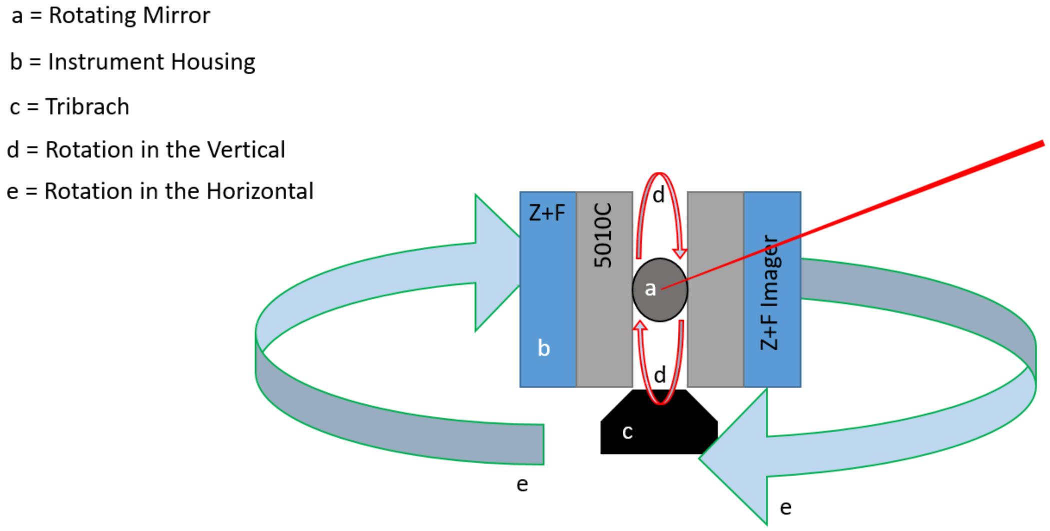

Figure 3.2: Illustrated in this sketch is the motion of the laser scanner in both the horizontal and vertical. The entire housing of the instrument is able to rotate around in the horizontal while the rotating mirror simultaneously rotates in the vertical plane while deflecting the emitted laser beam towards the target.

The laser scanner is able to emit millions of points within a single scan whereby the surrounding scene will be covered with the points. The degree to which the scene is covered is dependent on the resolution settings on board the instrument. The result of a scan is a highly detailed 3D group of points in view of the scanner all related to the origin of the coordinate system of the scanner unit, known as a Point Cloud. Any point cloud is random and not controlled by the user, which means specific points cannot be measured. Multiple scans are used to capture more complex objects and structures in order to obtain the full object shape. Along with the 3D coordinates of each point that is observed there is an amplitude of the reflected laser signal, known as the Intensity value, which is recorded. This intensity value is dependent on factors such as the surface properties of the target, angle of incidence and range. The intensity value is helpful in interpreting the scan data. The intensity aids in the visual interpretation of the scan based on the strength of the return. It is this 'strength' that gives the observer more information about the scene.

The observable range of a laser scanner varies depending on a variety of factors from manufacturer specifications to the on-board user-defined parameter settings. Laser scanners have been used for both static and mobile scanning applications. The scanning approach is usually dependent on the size and complexity of the object(s) in question. Mobile scanning has been in the form of aerial surveys from airplanes and helicopters as well as drones and other UAV systems. Terrestrial mobile systems can be positioned on board vehicles and it is the use of the vehicle that delivers an increased speed of operation of the overall scanning project.

Multiple scans are linked together, similar to giant puzzle pieces, using common features from the neighboring scans that also appear in the current scan. This process is known as Registration and will provide the complete target shape when all scans are registered together. One other step that may be carried out is to link the scans to a reference coordinate system (Geo-referencing), in order to integrate the scans with other survey data. Control point coordinates will need to be included in the scene that is being observed for this to be possible.

Following on from the scanning stage is the processing of the data wherein the data can be observed in the raw form of a point cloud or the data can be 'modeled' in order to create a high-resolution digital 3D model which can thereafter be imported into Computer-Aided Design (CAD) software and used for a wide range of applications.

The laser scanner has similarities with both the Total Station and a camera which has led to the combinations of the laser scanner with High Definition (HD) cameras. A colour point cloud can be generated using the RGB values and the meshed model is given a texture by overlaying the image upon the mesh. Another modern combination is the laser scanner with a GPS (Global Positioning System) in order to directly Geo-reference the point cloud. Integrated systems with laser scanners, cameras and GPS are being used more often in the 3D measurement fields today.

3.2 Data Acquisition

3.2.1 Venue Selection

When it comes to testing an instrument such as a laser scanner where the device operates by rotating and capturing data in all directions, the venue is going to be a major aspect of the testing. The key aspects of such a venue are the shape and dimensions. The shape should be as open as possible (and have few obstacles or features in the field of view) in order to observe all surfaces surrounding the instrument with as little ’noise’ in the scene as possible. If these two criteria are met the room has the potential to act as a testing facility. Another factor that should be considered is the surface material. Laser scanners are very sensitive to reflective materials such as glass, mirrors and water. If these materials can be removed or scanned in order to avoid negatively affecting the scan this would be ideal.

3.2.2 Target Options and Placement

When referring to targets in terms of laser scanners these can be random objects or specially placed patterns or objects that are recognizable in a program or by the user. Targets are used within the scene for the registration process during the alignment of the captured scans. Another use of the targets is in testing facilities where they serve as control points with high precisions. The main focus when choosing such targets is on the center point and how identifiable that mark is. Laser scanners have the ability to distinguish targets from within the scene and require sufficient information on the surface of the target in order to accurately determine the center point. With the variety of target types available it is important to select a suitable target for the task at hand as well as to ensure the target design will allow for the best determination of the center point.

The dimensions of the target required for the given task are dependent on the range values that are going to be encountered due to the resolution of the scanner and the amount of information reaching the target surface. For this research, the advice given to the author was to ensure that there is a centimeter in the height and width of the target for every meter of range. (Stroh (2015))

Targets can be in the form of pieces of laminated paper or sprayed on to a surface, they can also be more sophisticated and placed on boards and mounted. There are also targets that are recognizable shapes such as spheres. Their shape will depend on the user and the ability to easily find the target in the scene. Targets can be made of any kind of material from paper to even using hockey balls on a screw. The important factors to consider are the visibility of the target in the scene and if the material is visible to the laser scanner and not one of the ’trouble’ materials such as glass or highly reflective materials.

Another significant factor to consider when positioning the targets for a testing facility is the quantity. The number of targets required for the network of a testing facility is largely dependent on the scene and the ability to fill the field of view. This number varies greatly in all the sources encountered by this author and the best advice was to have as many targets as possible in the scene. This meant covering all the surfaces surrounding the scanner with as many targets as are available using as much variation in heights, horizontal angle and distance from the laser scanner (essentially trying to cover as much of the 360 degree FOV around the position of the laser scanner). Very little information is available on previous attempts with regard to the number of targets used or any recommendations on how to install and position the targets within the scene.

3.2.3 Terrestrial Laser Scanner Operating Mechanics

Laser Scanning has become increasingly popular over the last decade. Lichti (2007) This is mainly due to two factors; the large amount of data that they are able to capture and the short time they are able to capture this data in. With instruments that are typically used for measurement, such as the total station, it is impossible to capture the same level of detail from the scene as the laser scanner due to the vast amount and speed that this instrument operates at. 3D laser scanners capture many points very quickly which is why they are so attractive when there is a need for high speed, accurate and cost effective work covering large areas. (Wagner et al. (2004))

”A 3D scanning system is efficient if its precision and accuracy specifications as well as the repeatability of its measurements are verified.” (Galantucci et al. (2014))

The robotics and autonomous navigation realms are where the majority of laser scanner projects began. This is because in most cases the robot or vehicle will require some form of vision system and these are likely to be scanners in some form. These devices take on many different variations and often come together in competitions such as the DARPA Challenge where autonomous vehicles travel through a course unaided by the designer. (Glennie & Lichti (2010)) The vehicle will need to plot the route it will follow based on a scan of the area and then make decisions based on what they see in front of them. It is at these types of events that many laser scanner developments have been made. (Barawid et al. (2007))

Laser Scanning is a non-contact, active form of remote sensing. In other words, the device never comes into contact with the target and it requires no source of illumination on the target to be able to capture it. This is because the laser scanner produces the source itself in a similar way to flash of a camera. If the device cannot produce its own source of illumination it will use and external source such as the sun that is already shining on the target and this is known as a Passive sensor.

With respect to laser scanners there are two aspects that require some attention; the distance measurement and the angular measurement methods.

The Distance Measurement System is unique to each type of laser scanner and is a powerful element that is fundamentally responsible for the collection of the range data, but is also what determines the precision of the range measurements and the repeatability of precise measurements. (Schulz (2008))

There are three methods of determining the optical range; Interferometry, Triangulation and Time-of-Flight. (Bosch & Lescure (1995)) The first two do not normally refer to laser scanners and so the important one here is the TOF range measurement (triangulation is sometimes used but this limits the range of the scanner to a few meters and is so they will not be included here). As already mentioned this method involves the measurement of the time from emission to capture of an energy pulse or signal. The formula is derived based of the speed of light (c) and using a two way distance between the source and target(s).

$$s = c.\frac{\Delta t}{2}$$

Where Δt is the time measured from the emission of the signal to the capture of that same signal upon its return to the sensor. The speed of light (c) is a constant and the time is measured which allows the distance to be calculated. It is the time that is the observable and three methods of determining the time have already been mentioned; direct TOF, AMCW, FMCW or Polarization Modulation. Of these three, direct TOF observes the time and this can be directly inputted into the above formula. The remaining methods are indirect methods of determining the travel time are able to use the phase difference and beat frequency, respectively, to determine the observed distance. The two that are most often used amongst laser scanners are the direct TOF or the AMCW. All of these methods of Optical Distance Measurement can be visualized in the flow diagram that depicts the classification of these techniques in figure 3.3.

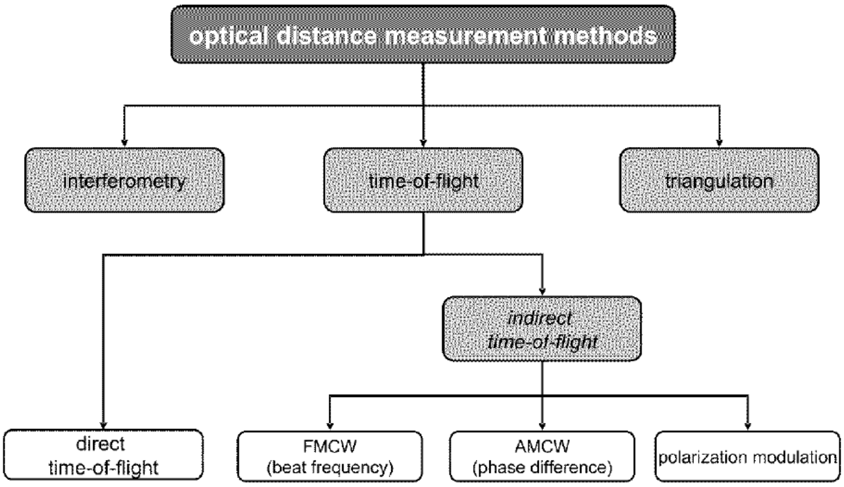

Figure 3.3: Methods of Optical Distance Measurement and their classification. Courtesy of Schulz (2008).

The intensity of the emitted laser gives us a fourth dimension which adds to the coordinate values. The laser is captured using a photo-diode and the amplitude of this detected signal is directly related to the intensity of the captured laser signal. There are some factors that influence the returning laser beam's intensity such as the range to the target, the surface properties (roughness, colour) and angle of incidence. Intensity is considered to be the amplitude or the energy (strength) of the captured signal. The term reflectance is explained as the ratio of the amount of Electromagnetic radiation returning/reflected to the amount that originally hit the surface.

There is a spectrum of Electromagnetic radiation that ranges from very short (cosmic radiation where λ $< 10^{-14}m$) to longer wavelengths (radio waves where $\lambda > 10^{6}m$). It is these Electromagnetic waves that are used in the transmitting of signals and the particular wavelength that is used is dependent on the medium that the signal will be passing through. The medium can have effects on the signal in terms of the arrival time and this must be considered for very precise work. The true speed of light is thus no longer a constant value and the atmospheric conditions must be evaluated in order to find the true value. (Schulz (2008))

The most commonly used electromagnetic wavelengths in geodetic and surveying applications are electro-optical waves. These range from 0.4μm $< \lambda <$ 1.3μm and are the favoured choice due to the best chance of transmission and least absorption in the lowest section of the Earth's atmosphere. (Hinderling (2004))

With the direct TOF, it is the time that is measured from emission to capture of a signal, Δt, between the source and the target surface. The speed of light is very fast and requires very accurate time measurement, this leads to the use of an average of more than one pulse. The measurement of a single event is not very accurate because of all the factors that could impact that measurement and hence why multiple observations are needed and the mean calculated. There is also the method of using the first and last pulses to identify the single measurement but this method has downfalls in the cases of multipath or edge effects where the signal sent out might not return to the same source position.

A benefit of the direct TOF method is the ability to measure long ranges. The time between successive pulses is limited and this means that the frequency of measuring distances is defined and this is what is known as the sampling frequency of the laser scanner. These values are usually either 1 kHz or 30kHz with distance accuracies for this method in the order of centimeters. (Schulz (2008))

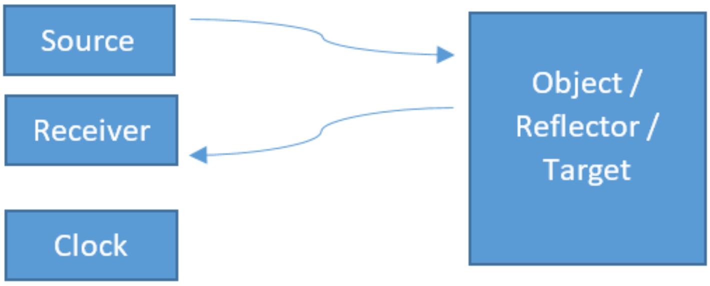

Figure 3.4: Simplified depiction of what happens between the laser scanner and a target within the instrument itself, courtesy of Parian & Gruen (2010).

From the figure 3.4, the clock starts when the signal leaves the source and stops again when it receives the signal. (Zetsche (1979))

The AMCW method breaks down the emitted signal into sine waves in order to look at the returning signal and determine the phase shift $\Delta\phi$. The phase shift is caused by the travel time from source to target and is directly proportional to the range. The time is not measured here and therefore the formula from earlier must be adapted to account for the known frequency, f, of the emitted pulse and to include the phase shift as the measured value.

$$s = \frac{c}{2} \cdot \frac{\Delta\varphi}{2\pi f}$$

The laser scanner observes the number of completed sine waves, N, that have been emitted and is able to determine the fractional part of the end wavelength,$\Delta\phi$, at the instrument completing a doubled distance (the phase shift).

$$s = \frac{1}{2}\left(N \,.\, \lambda + \,\lambda\frac{\Delta\varphi}{2\pi}\right)$$

Where λ is a constant term defined by $\lambda = \frac{c}{f}$. The resolution of the range is therefore dependent on the resolution of the phase shift and this value becomes more precise at higher frequencies. For longer ranges it is once again the norm to use more than one signal/frequency. The difficulty with this is the AMCW method cannot identify which pulse belongs to the one that was emitted and this makes it difficult to use the 'first and last pulse' idea resulting in "problem data" at edges and multipath.

The range of an AMCW laser scanner is limited to roughly 100m due to the energy of the pulse deteriorating over time and leading to unreliable resolutions of the phase shift. Modern scanners such as the Zoller and Frolich (Z+F) Imager 5003 have the ability to use more than one frequency through "bi-modulation" whereby one has a very low frequency and the other a very high frequency allowing them to be separated. Distance accuracies for this method are in the order of millimeters. (Schulz (2008))

The FMCW method, although not widely used in terrestrial laser scanners but rather in radar systems, operates on the principal of modulating a signal that has variable frequencies. A sine wave is emitted with different frequencies, they are combined and received after being low-pass filtered, creating what is termed the 'beat frequency'. If this beat frequency is observed, the range can be estimated. The range to the target is proportional to the maximum value of the beat frequency, B, which is a value for the absolute difference in the frequency between the emitted and received signals. (Hancock (1999))

$$s = \frac{c}{2} \cdot \frac{BT_r}{2\Delta f}$$

Angular measurement in a laser scanner refers to the orientation of the laser beam that is emitted. This is done with the aid of encoders that measure in the vertical and horizontal. The encoders function based on electro-optical methods of analyzing either transmitted or reflected light. A glass arc with alternating patterns of opaque and transparent areas allows some light to fall upon it and photo-diodes on either side of the glass arc capture the reflected or transmitted light and turn this into an electrical signal. From this analogue signal a digital output in the form of a digital number is derived.

Most common in terrestrial laser scanners is a method known as binary encoding due to the benefit of not needing any initialization and the angular resolution is high enough for laser scanning. The method of incremental encoding has the ability to achieve higher resolutions (by some milligons). (Schulz (2008))

Those aspects involved in the evaluation of a laser scanner significant to the investigation to be carried out in this research can be described as follows based on the literature that has been reviewed in the previous chapter.

Laser scanner parameters to be evaluated

In order to evaluate the performance of a laser scanner the following primary parameters have been assessed:

- Distance and Angle - Reshetyuk (2006), Schulz (2008), Glennie & Lichti (2010), Lichti (2010*a*)

In addition to these parameters, some factors have been investigated to assess the surrounding surfaces and their properties which may have an impact on the resulting point cloud:

- Brightness level returns - Lichti et al. (2010)
- Intensity, Incidence angle, Surface properties - Schulz (2008)

It must be mentioned that although these factors have been reported on, this research will focus on the primary parameters of Distance and Angle for the testing of Laser Scanner Accuracy.

Laser scanner test facility design

Focusing on the design of the testing facility, there are factors that have been evaluated to determine the suitability of the venue which included:

- Symmetry of the target network, Observable range - Lichti (2010*b*)
- Impact of the shape and size of the venue - Reshetyuk (2010)
- Impact of the Laser scanner model - Lichti (2010*a*)

Laser scanner target design

With regards to the targets there are certain elements of their design that have been investigated in order to determine the target design that will be most suitable for the software to locate the target and to precisely resolve the centre point. Such elements included:

- Shape and design of the target - García-San-Miguel & Lerma (2013), Chow et al. (2010), Kaasalainen et al. (2008)
- Material of target - Lichti et al. (2000)
- Dimensions of the target - Stroh (2015)
- Method of coordinate determination - Lichti (2010*a*)

3D control survey design

Prior to the scanning within a testing facility there must be a well-established coordinate network in order to provide an accurate control baseline of values to compare the laser scanner against. There are some factors that must be considered during the establishment of the coordinates for the control network:

- Design of the coordinate network for the optimum use of the space available, so as to ensure testing of the laser scanner specifically in terms of the primary parameters under investigation - Reshetyuk (2006)
- Survey procedure to ensure the highest quality results and most reliable accuracy assessment - Lichti et al. (2000)
- Scale within your coordinate network - García-San-Miguel & Lerma (2013), Lichti (2010*a*)
- Forced centring for precision surveying - Lichti et al. (2000)
- Geo-referencing for improved precision of the network - Lichti et al. (2000), Reshetyuk (2010)
- Impact of the incidence angle of the target - Reshetyuk (2010), Glennie & Lichti (2010)
- Level of redundancy in order to achieve the desired level of accuracy - Reshetyuk (2006), Reshetyuk (2010)
- Method of adjustment of survey data to achieve reliable baseline data for reliable comparisons between baseline data and observed laser scanner data - Parian & Gruen (2010), Reshetyuk (2006)

3D accuracy assessment

Once the coordinate network has been established and scanning of that network is complete, the next stage in the assessment pipeline is the accuracy evaluation. There have been different approaches to find methods to compare a control against the laser scanner observations, some examples of these methods include:

- Significant quantities being compared
  Point cloud to Point Cloud - Reshetyuk (2006)
  Shapes within point cloud to measurements with precise tools - Alkan & Karsidag (2012)
- Similarities between Laser Scanners and theodolites or cameras - Lichti (2007) , Lichti et al. (2010)

These are the factors that have been considered when moving forward with the development of a Laser Scanner testing facilities. All had significant bearing on decisions made for this project.

Part II

Investigation

Chapter 4

Design of the Laser Scanner Testing Facilities

4.1 Short Range Accuracy Testing Facility

4.1.1 Venue Selection

For the short range testing facility a venue with observable range values of several meters from a centralized location and a clear FOV in the horizontal and vertical was required. In the following sections various factors are investigated that were considered in the selection of this short range testing facility venue.

4.1.2 Accessibility of the Venue

The venue for the short range test facility needed to be somewhere close by to the university in order to be able to work on it regularly and with support available for any assistance or equipment manufacturing. The venue for the short range was selected as the workroom of the Geomatics Department at the University of Cape Town (UCT). This work room offered the perfect short range solution as this was in the same building and the same floor as the Geomatics Department so there was no need to be traveling far to work on the room. The additional benefit of this venue was the availability of the tools and equipment in the room that made manufacturing of any required items very easy.

4.1.3 Range and Angular Observation Possibilities

The workroom offered the ‘main setup location’ (a metal tripod that is permanently mounted to the floor) to be centered in the room which was a major advantage in terms of the shape of the room and being able to effectively utilize the space. The distance from the floor to the ceiling was roughly 3 meters with some large ventilation pipes running around the roof. The shape of the room along with the main setup location positioned roughly half way between the floor and ceiling, allowed for a good vertical angle range from the main setup with few obstructions.

The observable distances in this room were from 2 to 7 meters which meant any error in the measurements would be large due to these short range values and would require lots of redundant measurements to improve the overall precisions. The placement of targets in this venue was carefully explored with as many options for variation in angle and distance having been considered to allow for the full use of the space available to truly be able to analyze the instrument under inspection. The target placement will be further described in a later section. A photograph of the room can be seen in figures 4.1 and 5.6 in the section below on the survey of the targets.

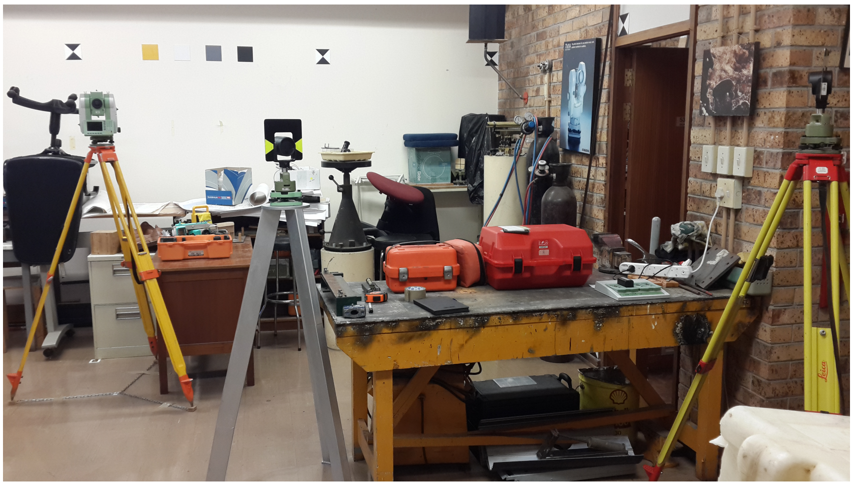

Figure 4.1: A photograph of the short range testing facility during its survey and also to help get an idea of the room along with its size, shape and contents.

4.1.4 Dimensions of the Venue

The room was comprised of one large open area, 3 store rooms and an office. There was a large amount of equipment that was stored in this room. This equipment added a small challenge to finding the positions for the survey setups due to constant moving of objects around the room. Despite this the space was used as effectively as possible and the survey was conducted on a weekend to avoid any movements or disturbances in the room. The room also had a shape that was not square, due to one of the store rooms, which meant the setups would not be in a regular geometric pattern which would have been preferred. This added a challenge with walls obscuring parts of the FOV from some of the setup positions and hence not all targets could be seen from every setup.

The dimensions of the room are 9m x 7m x 3m and there is a sketch in figure 5.1 to follow in the section on setup placement. The sketch is not to scale and is merely a representation of where the tripods were setup and to give an idea of the shape of the room.

4.2 Medium Range Accuracy Testing Facility

4.2.1 Venue Selection

The medium range testing facility needed to have similar specifications to the short range facility but on a larger scale with range values of up to 75 meters to account for most of the common scanning projects. The range in the horizontal and vertical would once again need to be 360 degrees or as close as possible in order to capture information from all around the device. The testing in this medium range facility was broken up into two parts; one for the angular testing and the second for the range testing. The following sections explain the various factors that went into finding and developing this larger testing room. Ultimately the reasons for deciding on both venues were highly influenced by the proximity to the university and availability. There were initially only three options for both rooms, a classroom in the Geomatics Division at UCT with a photogrammetry testing facility already in place, the workroom and the university sports center. The first option of the classroom had the correct dimensions for the short range facility but it was always in use (as a lecture venue) and had many desks, chairs and cabinets that filled the room making it unsuitable for the reuqired purposes. This left the other two and they were fortunately perfect for what was required for this research in terms of ease of access and availability.

4.2.2 Accessibility of the Venue

In the case of the short range testing room, the venue could have been any empty room. The challenge with this next step, for the medium range facility, was finding a room with the correct dimensions, availability, space, shape and lack of obstacles (which would have had an impact on the range). Most venues such as this would be warehouses or factories but these are not usually empty and need to be rented/purchased.

The suitable choice for the venue was once again offered by the university in the form of its Sports Center. Designed by the architect Roelof Sarel Uytenbogaardt in 1977 and comprised of three large indoor sports halls and multiple smaller specialized rooms such as a physiotherapist office and gym. Also being located on the campus meant that access was easy and available.

From the start a few important factors were mentioned to the author by the manager of the Sports Center and author's supervisor. The first was with regard to the fluctuations in temperature that may have an effect on the structure of the building. These changes in temperature are not only in the winter and summer months but even during the course of a single day with low evening temperatures and higher daytime temperatures. Along with the temperature's effect on the thermal properties of the building there was also mention of the possibility of dynamic structural motion of the building due to general load bearing. Another factor was the highway adjacent to the building, which might cause movements to the building especially during the heavy traffic hours of the early morning and late afternoons. Both needed to be considered when deciding on a time for observation to minimize the impact of these factors.

Although these factors of temperature and traffic are mentioned here, they were only considered when making a decision on which venue would be most suitable to house the testing facilities and will not be tested further in this research.

4.2.3 Contents of venue and its general use

The building houses the UCT sports administration. Throughout the course of the year the UCT sports center plays host to a large variety of activities including indoor hockey and netball tournaments, basketball practices and many others. The three main rooms are also used as examination venues during the June and end of year examinations.

The building is a combination of concrete and wood with plastic flooring for the sports fields. The roof is a unique design with triangular sections and beams flowing all around. The rooms are mostly empty unless there are exams taking place which would mean there are large numbers of students, tables and chairs covering the floors or if there are sporting events taking place. When there is nothing happening the tables and sporting equipment are kept in storage cupboards and the floors are empty and quiet (especially in the late evenings). A picture of the venue can be seen in the figure 4.2.

Figure 4.2: Photograph of the UCT Sports Center. The photograph is intended to show the shape and design of the venue along with the materials it is comprised of. At the time of the picture the venue was being utilized for the new year's student registrations.

4.2.4 Site Preparation and Manufacturing

Prior to any surveying or scanning there was some site preparation required. This venue would not allow for a permanent metal tripod to be left in the middle of empty space if there are regular activities taking place. This meant a new idea was needed to create permanent fixtures to the sports center that would not be too obvious, harmful or easily tampered with.

This was achieved by designing a flat mounting surface that could hold a tribrach and keep it stable while at the same time blending in with the sports center. The design for the mount was done in such a way that it could replace a section of the wooded railing that went around the entire venue.

The mount would need to be fixed to the railing which called for two legs that would extend into the concrete to keep it in position. A hole in the top would allow for a bolt to be turned into it with a portion of the bolt sticking out to allow the tribrach to be turned onto. The bolt would not have the usual head on it and instead would include a nut positioned half way down to stop it from turning further down and to ensure that a section would stick out from the mount. A socket set was used to tighten the bolt into place and to remove the nut and bolt at the end of use.

The mounts were made out of pieces of Aluminum and also include 'plugs' to keep people from inserting foreign objects into the holes in the mounts. The plugs had a unique section cut out to allow a special Alan-key to remove the plug when it would be used for scanning or surveying. The design and an image of the installed product can be seen below in figure 4.3 and 4.4.

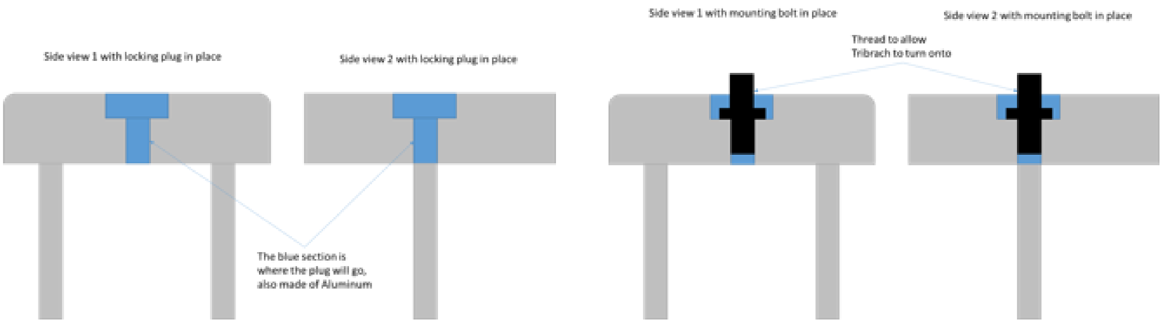

Figure 4.3: Illustration of the Mount Design for the medium range testing facility.

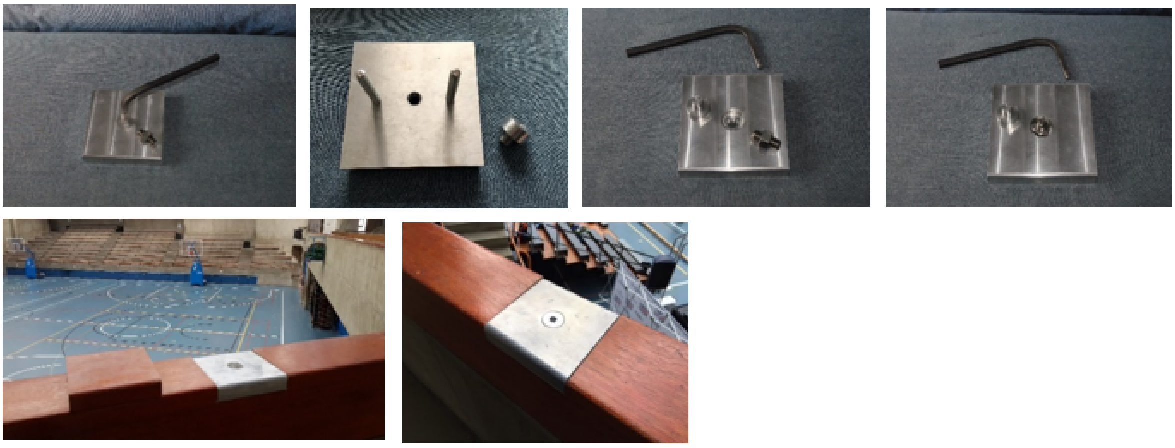

Figure 4.4: Images of the mounts before and after their installation at the UCT Sports Center and medium range testing facility.

Another feature that required some hands on manufacturing was the range target. In other words the target that would be setup over one of the mounts (WD3), but not a standard survey target. This target would need to be one of the same targets from around the venue and made of the same material but instead of on the building surface this target was positioned over a point with known coordinates in order to compare the observed range with the calculated range.

The design of this first mounted target setup can be seen in the images below in figure 4.5. This target setup was used in the first official scan of the venue and then in a final scan to analyze the observable range with the scanner setup over WD5 (some targets were selected to confirm the range values these were; B4, W1, B6 and U1). In these first two attempts the amount of data on the target at WD3 was very poor because of the scanner settings and the distance from the laser scanner. The range values were not very distorted but there was an argument to first test the same scenario with a bigger target to make a more conclusive statement about the range abilities.

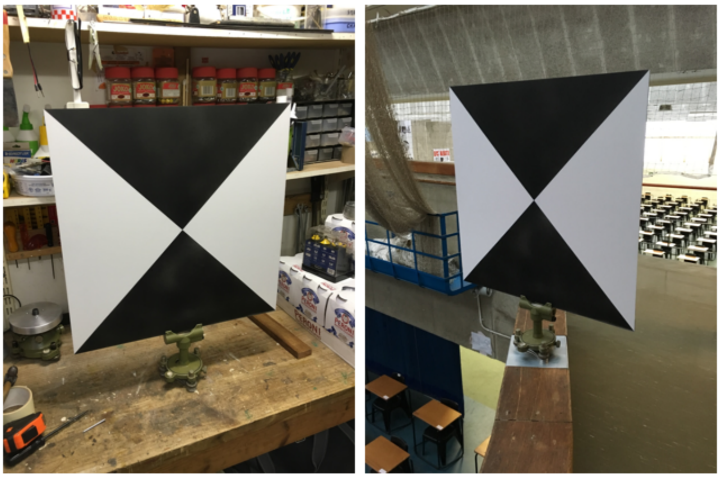

Figure 4.5: Image of the target designed for the distance accuracy testing in the medium testing facility, this design was 50cm by 50cm and was the first of two designed for this test.

It was at this stage that a new design of a much bigger target setup was developed. The desired dimensions needed to be longer than the range that would be encountered. This range was approximately 70 meters and so the target would need a ’minimum’ of 70cm along the length and width in order to make sure the resulting values for a success, or failure, could not be attributed to the ’size’ of the target.

There were still pieces of the PVC foam-lite board from the targets and with these pieces a 90 cm by 90 cm target was constructed. This target appeared to be sufficient but now there was an issue of how to mount such a massive target on the small holding mount. After several attempts to find a way, eventually the final design in 4.6 was developed and used for testing.

Figure 4.6: Image of the improved target designed for the distance accuracy testing in the medium testing facility, this design was 90cm by 90cm and was the final of two designed for this test.

4.2.5 Range and Angular Observation Possibilities

In terms of the observable range values, the position for the ”main scanner location” needed to be chosen carefully. There are large nets in place to separate the different rooms to stop birds and balls from moving between the rooms. This created a challenge as this meant the venue had essentially been cut into three and eliminated the possibility of using the full size and potential of the room.

This was worked around by focusing the angular observations to the first (and largest) of the rooms and covering as much of the 360 degrees around the selected point as possible. The range was dealt with by focusing the range observations to specific rays that would avoid the netting and fully utilize the size of the room (using the range between WD3, WD4 and WD5 as mentioned above with the specially designed targets over the mounts). This was done by choosing 3 positions (WD3, WD4 and WD5) that would be permanent setups locations and ensuring that one or two could be used to analyze angular accuracy and the other two could be spread out in order to analyze range accuracy. An AUTOCAD drawing of the sports center can be seen below in figure 4.7. The positions of the permanently placed mounts can be seen as the blue dots. In the drawing, North is to the right to help with the same naming convention as used before (with some new ones for upstairs = U and bottom = B, will be seen in the figure in the section on target placement).

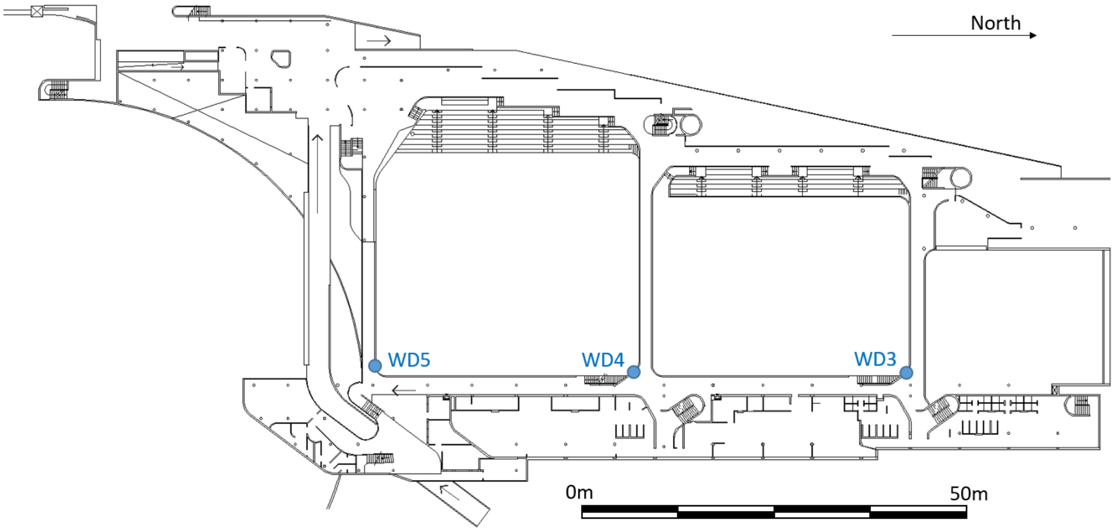

Figure 4.7: Sketch of the permanent setup locations in the Medium testing facility.

For better insight into why the center of this venue was not used for the main scanner position, refer to the photograph in figure 4.8. From this photo it can be seen that the position of the center of the sports center is on the bridge running through the middle of the rooms, but what must also be noticed is the position of the netting that is running adjacent to the bridge. This netting is very effective at obstructing the view of the laser scanner and had to be considered as a 'solid wall' when choosing the final laser scanner positions. This effectively cut the venue in half and resulted in the use of only the first and largest of the rooms. The setup that would have been positioned on the bridge would have been roughly in the middle of the two basketball hoops that is on the side of the bridge in the middle of the picture. Also visible in the picture is the setup position of WD5 towards the left hand side of the picture. It is the metal mount that has replaced a section of the wooden railing.

In order to fully appreciate how close the netting would have been to the position in the middle of the bridge the photograph in figure 4.9 is provided. It can be once again seen the basketball hoops on the side of the bridge indicating the rough position of the center of the facility. The position of WD4 can be seen in the railing as the metal mount that has replaced a section of the railing.

Figure 4.8: A photograph showing the position of the center of the venue along with the netting and position of setup WD5. Although not clearly visible, setup WD4 is also in the picture on the right hand side.

Figure 4.9: A photograph showing the close proximity of the netting to the proposed position of the central setup in the venue in the middle of the bridge between the two basketball hoops. Setup WD4 is also visible in the picture.

The observation conditions needed to be kept constant throughout the testing of the instruments and the temperature and any other factors needed to be kept in mind when deciding on the time of observation. Temperarture readings were observed with a household thermometer to ensure the temperature did not vary largely during the survey and scanning periods. This was also done to ensure consistency during subsequent scans of the same venue. In the end it was decided that the best time for working in this venue would be in the late evening (20h00 or later) in order to minimize the chances of having students in the halls as well as having the least amount of traffic flowing by on the highway.

The temperature could also be kept fairly constant if the work was done efficiently during the evening before the temperature began to rise for sunrise. These conditions would be kept constant throughout testing to ensure fair testing on all devices.

4.2.6 Dimensions of the Venue

The Sports Center offered up a perfect logical solution to the medium range testing facility with observable ranges that are most often encountered when using laser scanners. There are of course those laser scanners with greater range capabilities and these may even require a larger testing facility to test those ranges at the far end of the laser scanners.

Referring to the AUTOCAD drawing in figure 4.7, the inside of the venue has a maximum range of roughly 100 meters from end to end (left to right) with an average height from floor to roof of 10 meters. The main section is divided into 3 rooms, 2 large rooms and a smaller room at the northern end. The middle room has the best symmetry but is slightly smaller than the first room to the left. The small room has lots of mirrors on the walls for the Judo/Karate classes and this removed this small room as an option (laser scanners do not operate well with highly reflective surfaces). The two bigger rooms were both suitable venues, however, the biggest of the two would ultimately be chosen for the testing due to the possibilities for distribution and geometry of the target network.

4.3 Problems Encountered

Initial problems for the medium facility involved finding a venue with the required size and open space. The desired venue would allow for a setup in a central position with surfaces evenly surrounding the instrument and a clear FOV in all directions. The surfaces were required to be evenly distributed around the laser scanner at distances between 10 and 100 meters for this particular scenario and a clear FOV would have ensured the angular observations had the potential to be investigated from any section of the FOV.

The first decision of finding a large enough room was fortunately an easy find because of the Sports Center being located at the university. The rest of the specifications proved to be a bit more challenging. The venue itself has a very interesting design and due to the materials and the internal shape there was a lot of deliberating on the positions for any permanent fixtures. The large nets that were mentioned earlier proved to be the biggest problem because they halved the potential of the room and also resulted in some difficulty in final positions for the mounts. The surfaces inside the building comprised of concrete, glass, wood and plastic flooring. There are large walls at strange angles, bridges and angular roof struts. The roof is also very high above the floor making it very difficult to be able to place any targets on this surface. The floor with its high activity and reflectivity made it a challenge as well.

The size of the range target in the medium testing facility needed to be big enough to capture enough data and this meant the first design was slightly too small and led to the re-manufacturing of the larger 90cm by 90cm target.

Another small issue was with regard to the targets at the Sports Center, problems with communication and permissions resulted in the first set of targets being removed and delaying the project a few weeks. Some of the targets had been damaged or lost and needed replacing. The university also experienced some student protests which resulted in the university being difficult to access.

Chapter 5

Survey Procedure for the Testing Facilities

5.1 Survey of the Short Range Facility

The survey of the short range facility took a few stages and these stages are discussed in detail below.

5.1.1 Positioning of Setups

An old fixed-leg metal tripod was bolted to the floor in the center of the room, adjacent to a wooden work bench, which served as the main setup location for the laser scanners. This metal tripod can be seen in the image below and was originally rusted and black, but after some maintenance and new paint it was ready for its new place in the testing room. An additional three setups were positioned throughout the available space in the room with the idea in mind of good network geometry (strong angles between the setups that are between 45 and 90 degrees and avoiding small angles or larger angles close to 180 degrees) between the setups. These additional three were temporary setups on Leica survey tripods with ‘foot chains’ to hold the legs in place and these were also taped to the floor to avoid the legs sliding around on the slippery floor. Photos of these different setups and their locations in the room can be seen in figure 5.1 below.

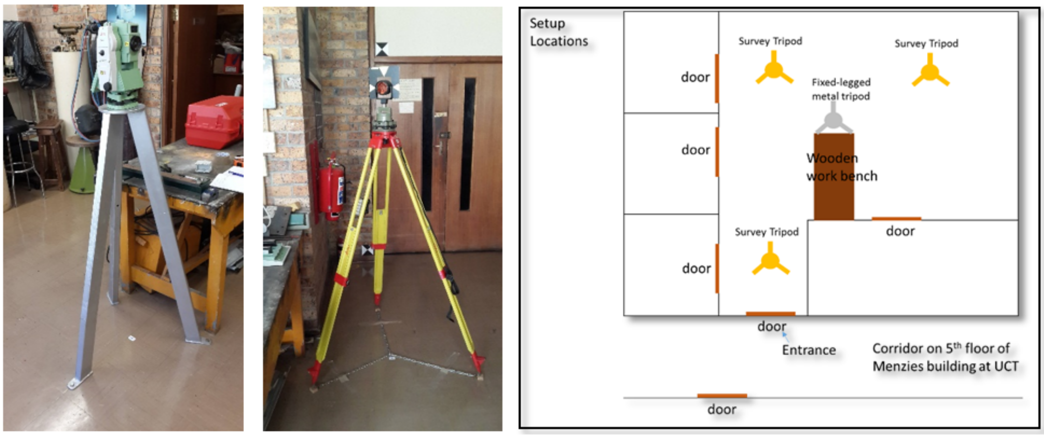

Figure 5.1: Images of the permanent and temporary setups as used in the short range testing facility, along with a sketch of the locations of these setups within the short range facility.

The positions of the temporary setups were selected to allow the maximum number of targets to be visible from each setup while at the same time ensuring good network geometry between setups. There was a hope to include a fifth setup position in the empty space in the sketch on the right hand side but in reality there was a large amount of equipment there and a doorway to the store room which made this unsuitable for a setup which would need to be there for several hours, at least, during the observation time.

5.1.2 Positioning of Targets

Target Types

The targets used for this room were made of a PVC foam sheet with the design spray painted onto the surface. The design chosen was of two black and white alternating triangles pointed to the center from the top and bottom and sprayed matt black and the white left as is. The design can be seen below in figure 5.2. This design was preferred based on the software by Zoller and Frolich (Z+F) called LaserControl and its ease in identifying this target design.

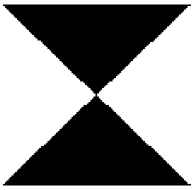

Figure 5.2: Chosen Design of the targets used throughout this research.

Also included in the room were 4 intensity targets which comprised of a black (0-10%), grey (40-60%), white (80-90%) and highly reflective yellow (100%). These were placed on the North wall in increasing order of intensity from right to left. The intensity targets can be seen in figure 5.3 below. Initially these targets were positioned to analyze the intensity values of the scanner but as mentioned at the outset of the project it was decided to focus on range and angular measurements alone.

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Figure 5.3: Image of the intensity targets positioned in the short range facility.

Target Sizes

The size of the targets was based on the advice mentioned earlier, given to the author by Francois Stroh, that for every meter of measurement the target should have a dimension of 1cm. (Stroh (2015)) This short range room had a maximum of 8 meters that was possible to observe and so the target size was measured to be a comfortable 10cm x 10cm. These proved to be sufficient and the program was able to find each target and they were also big enough to be able to survey the center point without confusion.

Placement Considerations

The targets were placed strategically around the room. The majority were at a height of roughly 6 feet from the ground at regular intervals around the room to make sure the angular range of the instrument was being fully utilized. Also included were targets low down and on the ceiling and at varying distances from the permanent tripod location. Targets were not placed on the floor due to the high level of activity in this room and the high likelihood of being disturbed. A total of 23 targets were installed.

In order to ensure there were still some targets at very low angles, some targets were positioned low down on the walls just above the floorboard. 5 targets were also placed on the roof above the permanent setup position to add to the vertical angle measurements. All the targets are visible from the permanent tripod setup. The naming convention used here was according to the direction of the room using the compass directions, i.e. if the target is on the North wall it received a name with a preceding N and incrementing from left to right. The target positions can be seen in the sketches seen in figures 5.4 with the wall mounted targets and 5.5 with the roof mounted targets.

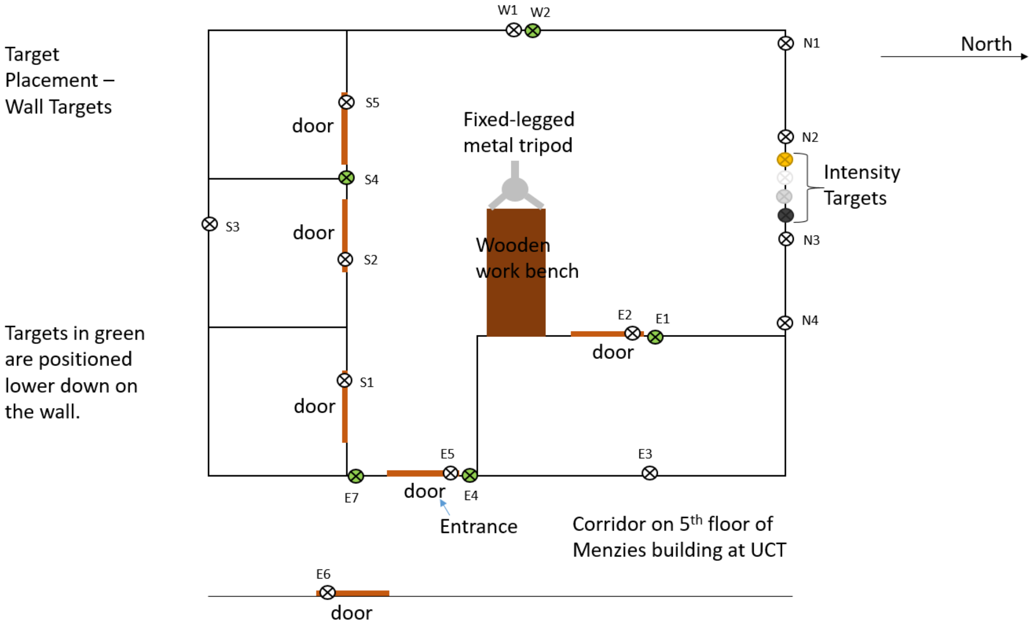


Figure 5.4: Sketches of the target positions within the short range facility, this sketch contains the targets that were positioned on the walls within the room.

5.1.3 Survey of the Targets

In order to give these targets coordinate values, a survey was completed using a Leica 1201 Total Station. Prior to the survey the temporary tripods were all positioned and taped to the floor and Leica Circular Prisms placed on each with the forced centering kits (the instrument and forced centering kits can be seen in the image below). The use of the forced centering kits was to maintain a high level of precision during the survey (during the movement of the total station and prisms around to the different setups). The origin of the survey was set to the permanent tripod with the coordinates (1000,1000,100). These values were utilized to avoid any negative values. The observation origin was set to the target known as S3 because of its position in the room, it was at the same height as the first survey position and almost exactly South facing.

The network survey of the targets was performed with all parameters (stations and target coordinates) as unknowns. The first setup at WD1 on the permanent tripod was established as the origin and thereafter

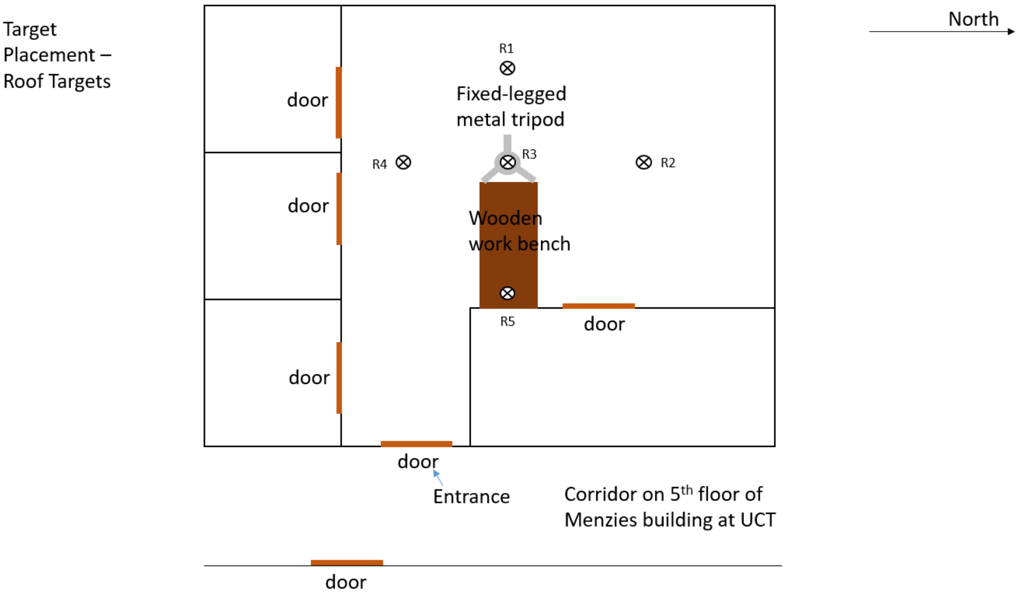


Figure 5.5: Sketches of the target positions within the short range facility, this sketch contains the targets that were positioned on the roof above the laser scanner setup.

Figure 5.6: Image of the Total Station at work with the prisms and targets in the short range testing facility.

a selection of up to 10 targets from this setup was used in each successive setup's orientation to find the new setup's position and initial estimates of the target coordinates. The observations to the targets were done in reflectorless mode and each target was intersected from each of the different setups. Each target was surveyed 4 times per setup and ultimately 16 times in total from the four setups. This procedure was used to ensure high levels of redundancy in the least squares adjustment that would later follow. There was some difficulty in observing the target directly above the metal tripod (R3) but this was dealt with through the use of a diagonal eyepiece provided by Tritan Surveys as well as noted for further experiments to avoid positioning targets directly above the instrument. A sketch of the setup positions within the short range facility during the survey can be seen in figure 5.1 including the main scanner location with the permanent metal tripod in the center known as WD1.

5.2 Survey of the Medium Range Facility

5.2.1 Positioning of Targets

The Targets were positioned in the evening of the 14^{th} of September 2016. The positions were decided based on the number of targets and space available. As many targets as possible needed to be placed while at the same time getting sufficient coverage and spacing for the angular readings. The shape of the room allowed for targets to be placed on the majority of surfaces, except for the floor and the roof. The floor experiences large amounts of activity. The laser scanner setup was decided as the middle of the three blue dots (WD4) in figure 5.7 due to its central location and best position to view the largest and most varied amount of data in terms of angles. 20 large targets were placed at the larger distances, 3 medium targets were placed at similar distances but their size allowed them to be placed strategically without becoming an obstacle and 20 small targets were placed in closer proximity to the laser scanner setup with 6 going down the stairs just below the instrument position (all targets including the ones in the short range facility were mounted using 'No More Nails' which allowed easy and fast positioning with no need for hammers or nails). No targets were placed above the scanner due to the height of the roof and also to avoid the experience from the short range facility where the scanner could not see the target. The installation process can be seen in the appendix in figure 11.2. The positions of the targets can be seen as the colour-coded dots in the CAD drawing below in figure 5.7.

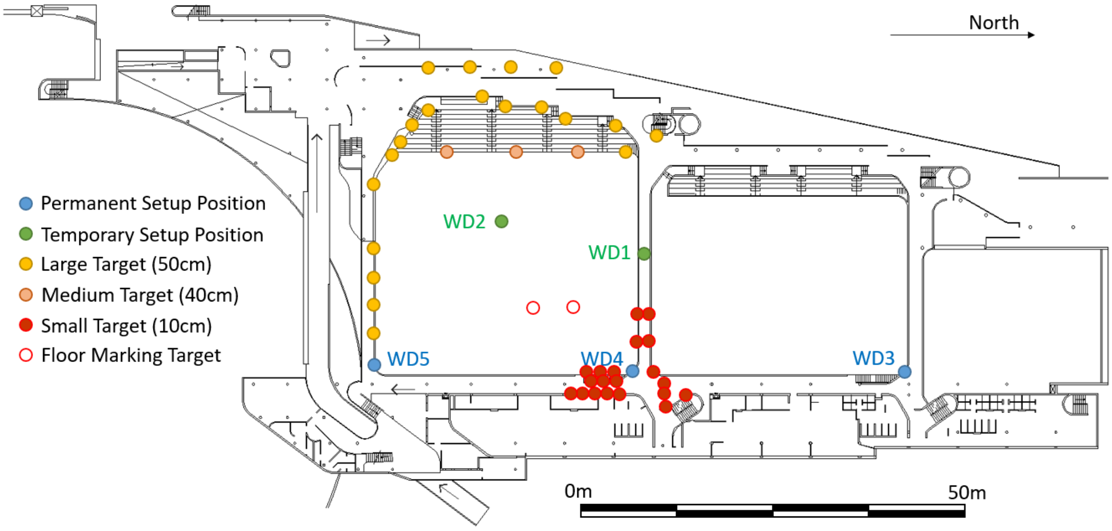


Figure 5.7: Sketch of the target positions in the Medium testing facility.

5.2.2 Survey of the Targets

The survey of the targets was conducted on the evening of the 17^{th} of September 2016 at roughly 21:45 in the evening. The first stages of the survey involved deciding on the positions of the setups to get strong geometry between the setups and enough redundancy. For this survey it was decided that two sweeps (once around to the left and then to the right, which is a single arc of circle left only but in two directions (clockwise and anti-clockwise)) of the targets per setup were sufficient to gather the required information to ensure redundancy in the observations. Although modern total stations do account for circle slip and instrument tilt with built in compensators, this method was used in order to reduce the impact of observer bias through averaging of the Circle Left and Circle Right observations.

The locations for the four setups were identified to ensure good network geometry and redundancy for the calculations.The survey was conducted under constant temperatures by surveying in the late evening and before the vibrations from the nearby M3 highway, as well as the sunrise (which would increase the ambient temperature). Two of the setups were temporary on tripods with chains that were taped to the floor and the other two were on the permanent mounts positioned in the walkway railings. The locations of the setups can be seen as green dots for the temporary tripods and blue dots for the permanent mounts in the CAD drawing below in figure 5.8.

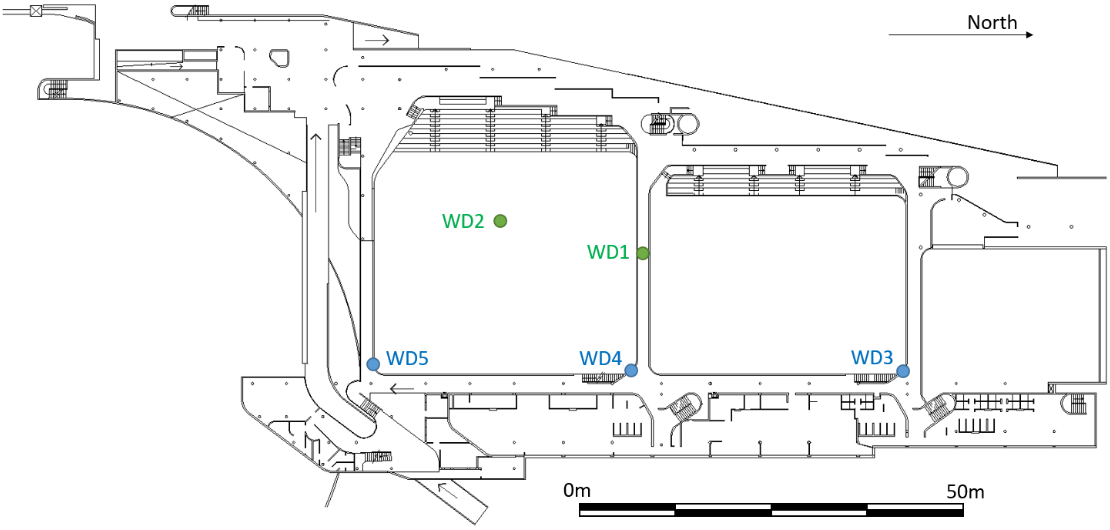


Figure 5.8: Sketch of the setup positions in the Medium testing facility (permanent setups are blue dots and green dots are the temporary setups).

The point WD3 was not actually set up over during the survey. This point was used for distance analysis and so was treated as a point in the survey. The same instrument was used for both the surveys of the small and medium testing facilities. The first setup (WD1) was on the bridge in the middle of the two large rooms on a tripod and the second was in the middle of the basketball court (WD2), also on a tripod. The third (WD5) and fourth (WD4) setups were on the permanent mounts. The same method of survey adopted in network survey of the short range test facility was utilized here. At each of the setups, as many targets were surveyed as was visible.

The forced centering kits and Leica circular prisms were once again used here for high precision work. The shape and design of the sports center meant placing targets everywhere would be a challenge, but there were some ways around this. There are lots of floor markings, from the many different sports, all over the floors. These could be used as targets that would be manually identified in the laser scanner software later on. In order to make use of natural features within the scene, such points were required to be easily identifiable within the scan. This is to ensure the accurate determination of the same position from the scan that was captured during the survey. Two such markings were used. They were sharp corners of little white squares on the floor and the outside corners were surveyed with the Leica Mini prism. The other stations were surveyed using the standard Leica circular prisms. The survey lasted 4 and a half hours with the assistance of Mike Davison.

Chapter 6

Analytical Methodology

Upon completion of the design and survey of the testing facilities there was a need to analyze the surveyed data. Multiple adjustment methods were incorporated to serve as checks on one another and to gather as much information about the final target coordinates as possible. Least Squares adjustment calculations are favoured for large computation problems due to their ability to simultaneously determine solutions to complex problems along with various other valuable information such as the standard deviation of the observations, unknown values and residuals. A 3D Least Squares adjustment program was used, that belongs to Tritan Surveys, to determine the final coordinate values and estimates of their precisions for the targets in both facilities. Further checks were done using the software called JAG3D and a Photogrammetric Bundle Adjustment, to compare the outcomes from both adjustments. The theoretical principles behind each of these adjustment methods is explained in detail in the following sections.

6.1 Theoretical Background of Least Squares in Network Analysis

6.1.1 Forms of Least Squares Relevant to Network Analysis

When it comes to any Least Squares calculations there are a few approaches that can be used and some of which will be discussed in the upcoming section. Each has their own criteria and it is worth mention here to name some of the common approaches that have aspects that could have been applied to this project. Each of these was considered and thought through to decide which might work best with this particular scenario.

The first two that were looked at were the Free Network and Constraint adjustments. These two adjustment theories were focused on due to their application in the field of survey calculations. With a constraint adjustment there are known parameters that will remain unchanged throughout the course of the adjustment and these are typically points such as control points or points with high precision estimates. These values will be held fixed throughout (given a high weighting) and are thus constrained. In the case of the free network there are no values held fixed and all values are allowed to change. This is normally the case where there are no known values and everything must be allowed to influence one another in the adjustment. Both could be used in a typical survey calculation such as resections or traverses but value in the free network adjustment is the change in value of any known points which allows for comparison of the final values of the known points with their true values to give an indication of the performance of the adjustment.

Two applications of least squares theory that were closely looked at were the Bundle Adjustment from the field of photogrammetry and the Traverse from traditional surveying calculations. The bundle adjustment was a very helpful method which is largely used for laser scanners nowadays due to the close geometric similarities with cameras. The calculations can be adapted to fit to the laser scanner observations and solve for the unknown coordinate values, precision estimates and any additional parameters (such as the observation centre) of the instrument in one simultaneous calculation. As mentioned above, the similarities between cameras and laser scanners make the adjustments of both these devices very similar and hence why the bundle adjustment has been utilized for calculations within this project. There was also a method found that was able to transform the laser scanner observations from distances and angles to image coordinates which aided in the computation of the bundle adjustment.

The ideas that follow are combinations of these methods such as; a free network bundle adjustment where the same calculations might be carried out but all values were allowed to fluctuate or a traverse with no values held fixed or a constraint traverse with the known coordinates of the setups held fixed or the distances between the setups held fixed to give the network a scale and all other values left free. All of these have aspects that suggest they could be successful in determining the required target coordinates and some are mentioned below and further explained in more detail with their theoretical derivations. Going through the derivations helps to fully understand how each approach used the observations to acquire high precision results.

Reasons for Testing or Calibration Facilities

There are a few methods of Electronic Distance Measurement (EDM), that will be mentioned in more detail in the upcoming section including for example; TOF (Time-of-Flight). In all of the techniques there are some recognized possible sources of error;

1. the wavelength of the measurement signal
2. the phase measurement
3. error at the reflector
4. the atmosphere
5. or the relationship between the electronic and physical 'centers' of the instruments.

When referring to the atmosphere, this error source is due to the fact that the signal that is emitted will travel differently through varying densities of air, which in turn impacts on the velocity and therefore the distance measured. This is accounted for by measuring the atmospheric conditions at the time of observation. However, this has the potential to lead to further errors in the measurements of these variables themselves and in the instruments used here (for example in the reading of the temperature).

In most cases these errors have very little impact over short distances. Despite this there is still the suggestion to always record these values due to some errors that are inherent to that instrument and will always plague the measurements irrespective of the distance. Another scenario could be in the event that there is degradation over time with respect to the instrument. For precise projects the corrections must be determined to eliminate these errors. The first part of detecting the errors is known as the testing stage and the second part of removing them is the calibration. Both testing and calibration are ways of identifying the performance of the equipment so that the user may have a certain level of confidence in their measurements.

A manufacturer will quote the accuracy of a machine as some standard error for a single measurement plus a scale error (for example ± 5mm + 5ppm). In order to maintain these values over time the instrument must undergo regular calibrations. These calibrations are used to examine the influence of 3 random error sources; index, scale and cyclic. Their influence can be compensated for through adjustments of the measurements. The testing and calibration will give indications of accuracy and any approach can be adopted as long as they comply with BS5750 in terms of quality assurance (QA). (*Guidelines for the calibration and testing of EDM instruments, EDM calibration - RICS guidance note* (2007))

Theory of Least Squares Adjustment

If looked at from a statistical stand point, an adjustment is a method of determining estimates for unknown variables (usually coordinates in surveying) as well as their precision estimates. The first step in any Least Squares problem is the establishing of a Functional Model. This functional model must refer to the system under consideration and be determined from the variables involved and their relationships. There is always a minimum number of variables required in order to solve for a particular system (a unique solution).

”Adjustment is meaningful only in those cases in which the data available exceed the minimum necessary for a unique determination (redundant data).” ((Mikhail & Ackermann 1982, p. 3))

It is possible for any scenario to be represented by more than one functional model. Once a particular functional model has been decided upon, it is only at this stage that the minimum number of variables for that model, (n_o), can be known. If there are fewer observations (n) than this value then the system is said to be deficient. All observations must be independent of one another. As in the quote above, for any adjustment there is a level of redundancy and this is achieved from more observations than required variables for a unique set of estimates for these variables. Redundancy is represented by r and is given by $r = n - \ n_o$ and also serves as a representation of the degrees of freedom (dof).

Along with these criteria the redundant observations must also be the ’correct’ observations required to solve the system. For example; if there is a triangle; in order to solve for the shape it is required to measure all 3 angles for a unique solution and if one angle is measured a second time there will be 4 observations with 3 unknowns. This will provide sufficient redundancy to solve for the shape of the triangle. However, if only one angle is measured 4 times there is redundancy (more observations than unknowns) but not enough to solve for the shape. A method to serve as a check is therefore required. (Mikhail & Ackermann (1982))

The check involves a few steps. The first is labeling the original observations with redundancy as l and another set of observations that will solve the model as Î. There is a difference between these two sets and this difference is known as the residual, v: v = Î – l.

These residual values test the suitability of a chosen model. For any model there are an infinite number of solutions for $\hat{l}$ and v. This is where the Principle of Least Squares becomes valuable. It attempts to get the set $\hat{l}$ as close to the sampled observations, l, as possible.

In the scenario of r = 0, $\hat{l}$ = l and therefore v = 0 the Least Squares (LS) principle is;

$$\phi = v^T P v \ \rightarrow min$$

Where P is the weight matrix (square matrix with order = n, $P_{ll} = Q_{ll}^{-1}$ and where Q_{ll} is the cofactor matrix). The elements in P give the stochastic properties of the observations, in other words it contains values that give an indication of estimates of the observations and their correlations. If there is a case where all of the observations are uncorrelated this will be a *special case* of Least Squares. In this situation the P matrix will only have values along the diagonal with zeros on the off-diagonal elements. This will also result in a change to the original LS principle;

$$\phi = \sum_{i=1}^{n} \left(P_i V_i^2\right) \rightarrow min$$

Where P_i is the ith element in P and V_i is the associated residual for the corresponding observation.

Another special case occurs when the observations have equal precisions and are uncorrelated. This will result in P = I = Identity matrix and again a change to the original LS principle. This resulting equation is the most classical case of the LS principle. $\phi = \sum_{i=1}^{n} (V_i^2) \rightarrow min$, which is the minimizing of the square of the residuals. (*ibid*)

Note: There is no need to know about any distributions thus far. Only P or Q are required to be known.

Least Squares has found use in several realms of calculations including photogrammetry, geodesy, surveying and so on. The reason for its success is due to its ability to obtain an answer that is unique even in a computationally complex scenario. Once the functional model has been selected it will only be seen again after closer inspection of the results in order to determine whether the choice was successful or not. The overall process can be simplified as below in figure 6.1.

In step 2 the updated estimates for the model variables and their cofactor matrices are obtained. In step 3 the results are evaluated and depending on the results, the model may be left as is or may need to be changed in order to achieve different results.

In the model there are variables which are the observations but there are also the parameters, u (unknowns). These values get estimates from the adjustment which are added to the original values. After the adjustment they are then treated as the new ”original” variables for the future calculations, iterating this process until the estimates and precisions become sufficiently small. (*ibid*)

The LS algorithm appears in two forms; condition and constraint equations. Condition equations are the equations which contain one or more observations, whereas the constraint equation has no observations

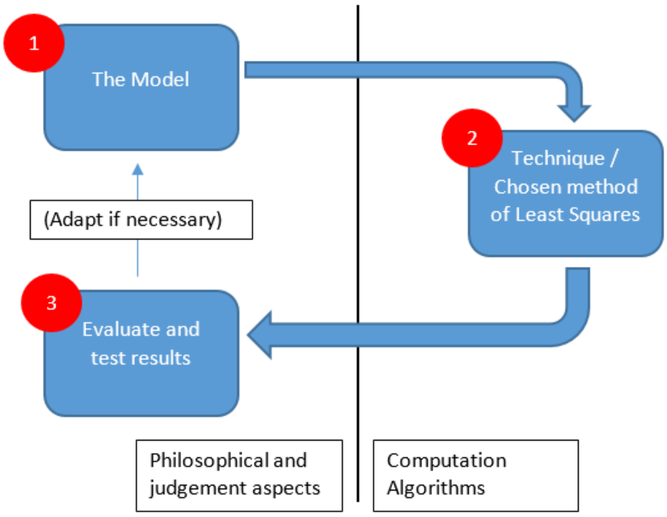


Figure 6.1: Least Squares Process illustrating the three main stages involved in any Least Squares Adjustment.

but instead only contains the parameters and constants. These two types of equations separate the LS process into two methods of adjustment, those with conditions and those with conditions and constraints. The difference is seen by the presence of observations and unknowns or only observations which would result in a unified LS adjustment.

Any advantages of the outcome of the adjustment are directly related to the functional model originally decided upon. Most LS problems are only concerned with finding estimates for the model but the true problem is to refine the model if the adjustments obtained were not sufficiently close to the true value. (*ibid*)

The idea of linearity must be briefly explained before proceeding further. A problem can be non-linear for a Least Squares Adjustment (LSA) but the norm is to linearize so that there is a linear system. The Taylor Series of Expansion is the preferred method of linearization. Only the zero and first order terms are required for an adjustment. In order to do this, the approximate (provisional) values for the unknowns and these provisional values are very important because the initial values need to be fairly close to the final values to ensure the result converges. This may come from experience but there are also calculations that can be used to get close values (such as joins and polars to get the approximations of the true value).

Example: let F(x) = 0 → m non-linear equations, linearize for $x = x_0$

$$F(x_0) + \frac{\partial F(x)}{\partial x}|_{x=x_0} \bullet \Delta x = 0$$

Where x_0 is the original set of unknowns and Δx is the vector of corrections to the provisional values and will replace the original vector of the unknowns, x. There is also the design matrix, A, which is the partial derivative matrix with respect to the unknowns. By letting $l = -F(x_0)$ the formula derives to: $A\Delta x = l$ where Δx is solved through the Least Squares. If the provisional values are close to the true values such that there is only a need for the zero and first order terms, then the final estimate is represented by$(x_0 + \Delta x)$. But in most situations this is not the case and there is a need to update the results once more, i.e. need to iterate the solution to improve the results. This process will be repeated until the values for Δx becomes sufficiently small. The final estimate $\hat{x}$ will be x_0 + all of the corrections from Δx.

LS only uses the outcome of a linearization as it aids in the computation ability. Linearization transforms a non-linear problem into a linear system that is then ready for the LSA. (*ibid*)

Least Squares Adjustment with Conditions Only, a General Case There are three main steps involved in the Condition Case:

1. Identifying the System Model
2. Identify the Functional Model (will give us the n_0 (unknowns))
3. Identifying the degrees of freedom (dof) = redundancy (r) = $n - n_0$, redundancy will ensure the system is not deficient (has no rank defect). From the dof the number of functions (conditions) that are required to be satisfied is known. This is due to the fact that there is a condition created for each redundant observation. Therefore when r=0 and $n = n_0$ the model fits perfectly with those observations.

In order to figure out the number of conditions needed, u is set as the number of independent unknowns and c as the number of conditions. The relationship is given by c = r + u. The number of conditions will be less than or equal to the number of observations unless there are dependent variables. (*ibid*)

Once c is determined, the condition equations between the observations and the unknowns must be set up. The general form is given by: $B\left(l+v\right)+A\Delta x=d$ and if $f=d{-}Bl$ then;

$$Bv + A\Delta x = f$$

Which represents the general case for the Combined LSA. This can be further separated into three different cases:

1. u = 0 and r = c with no parameters
2. u = n_0 and c = n
3. c = n and B = I

In order to obtain a unique solution an added requirement is needed: $\emptyset = v^T Pv \ \rightarrow min.$ This is enforced and will get a solution if the LaGrange multipliers (k) are used to constrain the system. This can be visualized as follows:

$$\phi' = v^T Pv - 2k^T \left(A\Delta x + Bv - f\right)$$

If the last part in brackets is equal to zero then $Bv + A\Delta x = f$ is satisfied. By minimizing ϕ' and partially differentiate with respect to v and Δx the solution is now:

$\frac{\partial\phi'}{\partial v} = 2v^T P - 2k^T B = 0$ and

$\frac{\partial\phi'}{\partial\Delta x} = -2k^TA = 0$

After rearranging the following can be derived:

$-Pv + B^Tk = 0$ and $A^Tk = 0$ (P is a symmetric matrix).

$$\begin{array}{c} n \\ c \\ u \end{array}\begin{bmatrix} -P & B^T & 0 \\ B & 0 & A \\ 0 & A^T & 0 \end{bmatrix}\begin{bmatrix} v \\ k \\ \Delta x \end{bmatrix} = \begin{bmatrix} 0 \\ f \\ 0 \end{bmatrix}$$

Which represents the total system of normal equations. The matrix of coefficients is symmetrical and non-singular (rank = order) unless the wrong model was used initially. After inversion the solution appears as the familiar Least Squares problem;

$$\begin{bmatrix} v \\ k \\ \Delta x \end{bmatrix} = \begin{bmatrix} -P & B^T & 0 \\ B & 0 & A \\ 0 & A^T & 0 \end{bmatrix}^{-1}\begin{bmatrix} 0 \\ f \\ 0 \end{bmatrix}$$

This can be used as is, but there might not always be a need for the v and Δx but rather only one of them and there is normally no need for k. Therefore a simplified version with the zeros in the sub-matrices can be derived to proceed fairly easily. (*ibid*)

Recalling the partial derivatives a few steps back, carrying on from the first one as follows:

$$v = P^{-1}B^Tk = QB^Tk$$

And sub this back into the original combined case:

$$BP^{-1}B^Tk + A\Delta x = f$$

Thereafter solving for k:

$$k = \left(BP^{-1}B^T\right)^{-1}(-A\Delta x + f)$$

And lastly by substituting this k into the second of the partial derivatives:

$$\left[A^T\left(BP^{-1}B^T\right)^{-1}A\right]\Delta x = \left[A^T\left(BP^{-1}B^T\right)^{-1}f\right]$$

And now if N = $\left[A^T\left(BP^{-1}B^T\right)^{-1}A\right]$ and t = $\left[A^T\left(BP^{-1}B^T\right)^{-1}f\right]$ the solution becomes NΔx=t. Therefore $\Delta x = N^{-1}t$ and by solving for k and substituting back to find v and then determining the *apostiori* variance factor:

$$\widehat{\sigma_0}^2 = \frac{v^TPv}{r}$$

Where $r = c - u$ is as before and for the last step if a least squares estimate is desired for the observations, the residuals can be added to those observations. Further computational checks and calculations that can be carried out are as follows:

Computational Check:

$$A^T(BPB^T)^{-1}Bv = 0$$

In order to see the cofactor matrices for the parameters and residuals, they can be represented as follows:

$$Q_{\Delta x \Delta x} = N^{-1}$$

$$Q = P^{-1}; W_e = Q_e^{-1} = \left(BQB^T\right)^{-1}$$

$$Q_{vv} = QB^T W_e BQ - QB^T W_e A Q_{\Delta x \Delta x} A^T W_e BQ$$

Special Cases of Least Squares Up till this point the general combined case for the adjustment of independent parameters and observations has been evaluated. From here two special cases will be investigated. The preferred functional model will decide which of the two will be derived. The two cases can be briefly described as follows, whereafter more detailed derivations and explanations will be given for each case (*ibid*);

1. Adjustment of observations only in the condition equations. This means u=0 and c=r and this case is normally used in simpler computations.
2. Each condition equation has only 'one' observation resulting in c=n and u=n_0 and B=I. Values for the parameters and cofactor matrices are derived directly along with the estimated observations.

In case 1, Adjustment of observations only, there are no parameters (unknowns):

$$B\,(l + v) = d$$

$$Bv = d - Bl = f$$

Where d and f are constants. There derivation follows the same approach as the general case if A=0:

$$\begin{bmatrix} -P & B^T \\ B & 0 \end{bmatrix} \begin{bmatrix} v \\ k \end{bmatrix} = \begin{bmatrix} 0 \\ f \end{bmatrix}$$

$$k = W_e f = Q_e^{-1} f = \left(BQB^T\right)^{-1} f$$

$$v = QB^T k = QB^T W_e f$$

Where Q_e^{-1} is the reduced coefficients matrix from the normal equations (there is no k in the solution thus far). The *apriori* estimate for the variance can now be calculated:

$$\widehat{\sigma_0}^2 = \frac{v^T P v}{r}$$

With the rest of the derivations as before with the general case if A=0.

In case 2, an adjustment with observations and unknowns but each condition equation has only ONE observation (c=n), proceeds as follows:

$$l + v + A\Delta x = d$$

$$v + A\Delta x = (-l + d) = f$$

From here v can be directly extracted and the LS can be done more directly as well.

$$\emptyset = v^T P v = (f - A\Delta x)^T P (f - A\Delta x)$$

$$= \Delta x^T A^T P A \Delta x - \Delta x^T A^T P f + f^T P f - f^T P A \Delta x$$

The second and fourth terms are identical in this last line and can all be reduced to the following:

$$\emptyset = \Delta x^T A^T P A \Delta x - 2 f^T P A \Delta x + f^T P f$$

In this line the Δx is the unknown and for $\emptyset$ to be a minimum the derivative with respect to the unknown, Δx, must be taken:

$$\frac{\partial \emptyset}{\partial \Delta x} = 2\Delta x^T A^T P A - 2 f^T P A = 0$$

And now if by transposing and rearranging:

$$\left(A^T P A\right) \Delta x = A^T P f$$

$$let\; N = \; A^T W_e A = A^T (P)^{-1} A = A^T P A$$

$$and\; t = A^T P f$$

$$N \Delta x = t$$

$$\Delta x = N^{-1} t$$

Now solve for the estimated observations by:

$$\hat{l} = l + f - A\Delta x$$

The computational check here is making sure that $A^T P A v = 0$ and the rest of the derivations proceed as normal.

Condition or Constraint Equations In a further scenario wherein the LSA has conditions and constraints where the constraints relate the unknowns and these unknowns are dependent, it is possible to evaluate as follows. Constraints can be created when there are relationships between the parameters due to the geometry of the physical properties of the situation. The number of dependent parameters (u) is equal to the number of constraint equations(s). (*ibid*)

$$s = u - u'$$

and

$$s < u$$

Where u' are the independent parameters and the condition that s be less than u is to ensure the system is consistent. A constraint will now be created based on a fixed relationship represented by:

$$c + s = r + u$$

The general case proceeds as follows:

$$A\Delta x + Bv = f$$

$$C\Delta x = g$$

If u<c there will be two sets of equations and two sets of LaGrange multipliers, k and k_c.
There will now be:

$$\emptyset = v^T Pv - 2k^T \left(A\Delta x + Bv - f\right) - 2k_c^T \left(C\Delta x - g\right) = min$$

The above now has two variables, v and Δx. Next derive with respect to these two variables:

$$\frac{\partial \emptyset}{\partial v} = 2v^T P - 2k^T B = 0$$

$$and\ \frac{\partial \emptyset}{\partial \Delta x} = 2k^T A - 2k_c^T C = 0$$

OR: $-Pv + B^T k = 0\ and\ A^T k + C^T k_c = 0$. The unknowns here are v, k, Δx and k_c. By forming the normal equations and solve by least squares as follows:

$$\begin{bmatrix} v \\ k \\ \Delta x \\ k_c \end{bmatrix} = \begin{bmatrix} -P & B^T & 0 & 0 \\ B & 0 & A & 0 \\ 0 & A^T & 0 & C^T \\ 0 & 0 & C & 0 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ f \\ 0 \\ g \end{bmatrix}$$

The matrix on the left has a rank of n+c+u+s and is non-singular and therefore has an inverse. As always this is only correct if the functional model was chosen correctly and the proper condition and constraint equations were used. Only Δx and v are needed, which means matrix partitioning can be used to aid in the computation process. (*ibid*)

The last case to be examined is in the adjustment with derived observations. In this case the idea of using a subset of the original observations to still achieve the same results as would have been seen by the full original set is adopted. Some conditions are put in place to ensure the outcome:

1. There can only be a subset and the derived observations must be less than the full set
2. The cofactor matrix of the new derived set must be evaluated, Q_{mm}, where m is the set of derived observations
3. Redundancy must remain the same, i.e. when switching between the set of observations the model should not change and the results should also remain unchanged.

There are now some small changes that can be seen here:

$$B_l v_l = -\left(B_l l + d_l\right) = f_l$$

And now with the derived set, m:

$$B_m v_m = -\left(B_m m + d_m\right) = f_m$$

Here f_l and f_m are still the same number but are derived differently because of the different conditions that were possible. The further steps in the derivation are all the same as before in the general case. (*ibid*)

6.2 Photogrammetric Accuracy

There is a similarity between the laser scanner and a camera in terms of the geometric qualities of both instruments. These similarities have been investigated to create accuracy tests for laser scanners based on the models developed for cameras, for example in the case of Parian & Gruen (2010). Due to these similarities between these devices an attempt was made to find a way to transform the observations from the total station into image coordinates that could be used in a photogrammetric accuracy analysis that would determine the coordinates of the targets. This calculation wherein the image coordinates and camera position are used to derive the object (target) coordinates is known in photogrammetry as the Bundle Adjustment. A Photogrammetric Bundle Adjustment was run on the survey data to derive estimates of the final coordinates of the targets as well as their precisions. This method of adjustment was to serve as a confirmation on the previous methods.

In order to look at the accuracy of a camera there first needs to be an understanding of the basics behind measurements and deriving point coordinates using photogrammetry. The principle can be broken down as follows: there is a camera center, the imaginary point that the view of the camera originates from, which is known as the projection center. This name is chosen as it is possible to think of the camera as a projector emitting rays outwards from this projection center. The image that is captured is a flat square/rectangular image and is placed at a specific distance perpendicular to the camera. The distance is the focal length of the camera. Looking at the image there are objects within the image that match objects on the ground in real life.

There is a special condition that claims if there are no distortions in the lens or image then the ray from the projection center through the image point through the object point will be a straight line called the ‘Photogrammetric ray’. This is known as the collinearity condition. This condition is the basis for the methods used to determine object or image coordinates due to the fact that if one is known, the other is located along the same line joined to the projection center. This technique has seen most of its applications in the field of aerial photography and this idea originated from the need to spy on the enemy movements during wars for strategic advantage. Nowadays it is used to create maps, gather information and as a method of coordinate determination with improved accuracy.

The relationship between the object point and the same point in the image using the concept of collinearity can be visualized in figure 6.2. Adding to the similarities between cameras, total stations and laser scanners is the similarity between panorama cameras and laser scanners. ”Due to the similarity of the operation of laser scanners to panoramic cameras the sensor model of the panoramic camera was extended for the self-calibration of laser scanners.” (Parian & Gruen (2010))

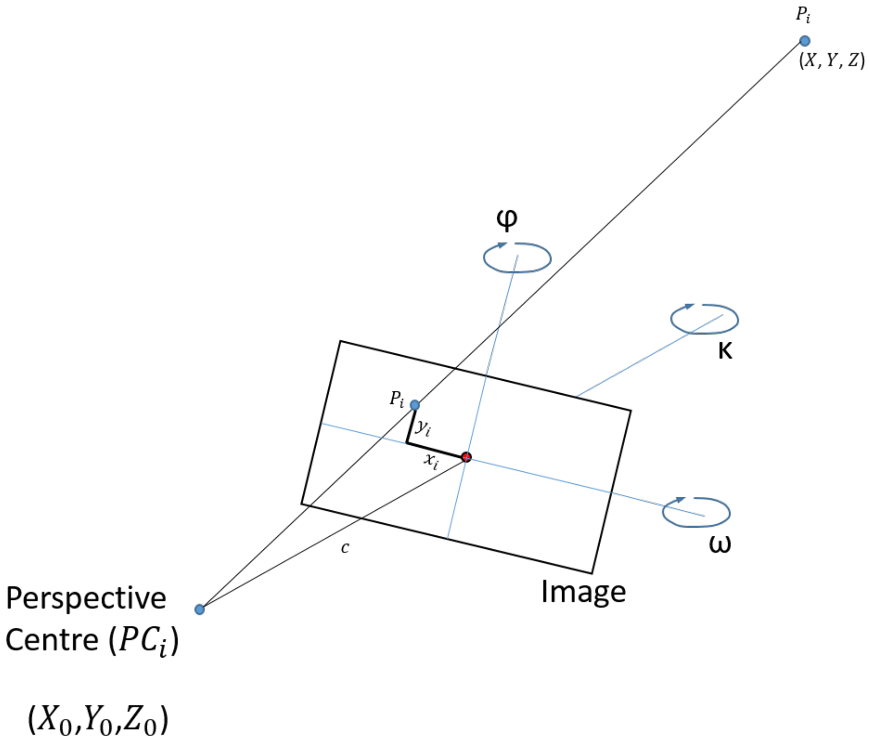


Figure 6.2: Relationship between Object Space and Image Space in the concept of the Bundle Adjustment.

Panorama Photogrammetry Panoramic sensor systems can be described in two separate categories; catadioptric and dioptric. A third must also be mentioned and is known as catoptrics. Dioptrics is the science of refracting lenses and Catoptrics is the science of reflecting mirrors. Catadioptrics is the science of the combination of both of these techniques and requires the use of one or more cameras/mirrors with wide viewing angles and post processing in the form of mosaicking and stitching. Dioptric systems can be further categorized as a 'camera cluster' (Several cameras mounted together facing outwards), 'fish-eye lens' (Camera with large viewing angle, usually more than 180°), 'stitching' (Uses stitching and mosaicking to produce panorama) and 'direct scanning' (Camera system with rotating camera/lens and creates a single seamless image (main method used by traditional terrestrial panoramic cameras)). The classification of the various Panorama camera systems can be seen in figure 6.3 courtesy of Parian & Gruen (2010).

6.2.1 The Bundle Adjustment

"The most accurate way to recover structure and motion is to perform robust non-linear minimization of the measurement (re-projection) errors, which is commonly known in the photogrammetry (and now computer vision) communities as *bundle adjustment*." ((Szeliski 2010, p. 320))

There are distortions and imperfections in the lens system as well as rotations of the image/camera system and result in deviations of the photogrammetric ray from a prefect straight line. The process of determining all the parameters and coordinates simultaneously is known as a Bundle Adjustment and is so named because it is attempting to recreated the 'bundle' of imaging rays at the time the image was captured and the term adjustment is referring to the process of iterating to minimize the error. Alternative

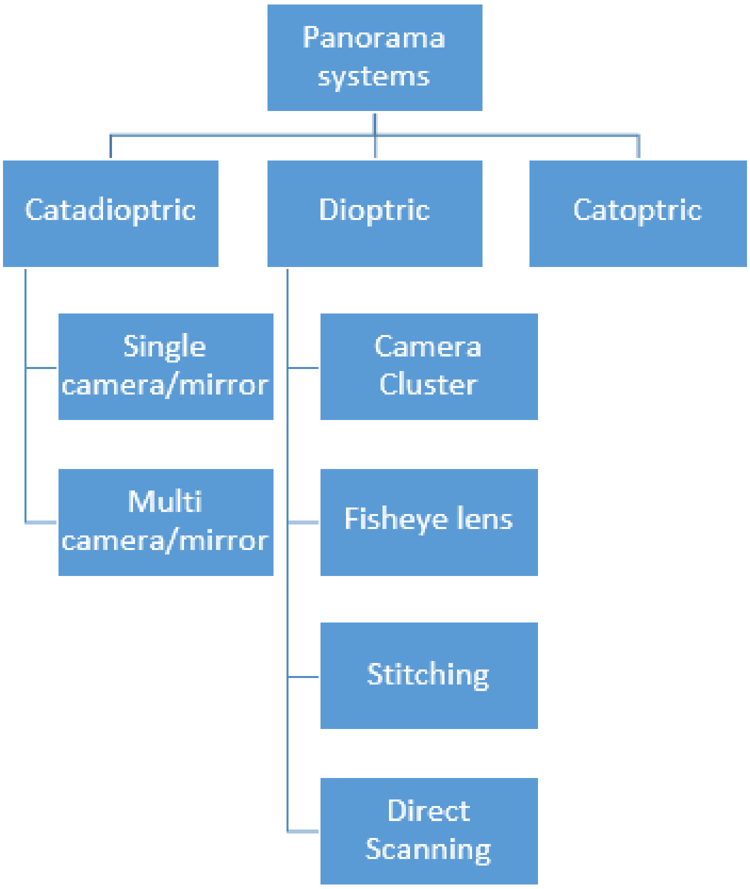


Figure 6.3: Panorama Camera Systems and their classifications, courtesy of Parian & Gruen (2010).

terminology is *optimal motion estimation* or *non-linear least squares*. (Szeliski (2010))

Originally developed for photogrammetry, where it is used for photogrammetric restitution and 3D point determination, the Bundle Adjustment has been built on and improved many times. It was developed by Duane Brown in 1958 and despite its initial design for photogrammetry, it has found use in theodolite engineering surveys due to the conversion between the theodolite observations and image coordinates through a transformation. (Brown (1958))

The bundle adjustment can be broken down into two parts known as the Interior Orientation and Exterior Orientations. Interior orientation is the reconstruction of the bundle of imaging rays as they existed at the time of capture and is defined by the parameters; calibrated principal distance of the camera, position of the principal point in the image plane (the principal point is the center point in the image) and the geometric distortion parameters of the lens/camera system. The Exterior orientation is the reconstruction of the position and attitude of the camera as it existed at the time of capture and defined by; position of the projection center and the rotations of the camera. (*ibid*)

The collinearity conditions are the basis for the bundle adjustment. The collinearity conditions show the relationship between the image space coordinate system and the object space coordinate system. Any deviations in the photogrammetric ray can be attributed to systematic errors which must be modeled in the adjustment. The bundle adjustment attempts to mathematically rotate and shift images in the object space to align the photogrammetric rays. The concept can be visualized in terms of the sketch in figure 6.4. (*ibid*)

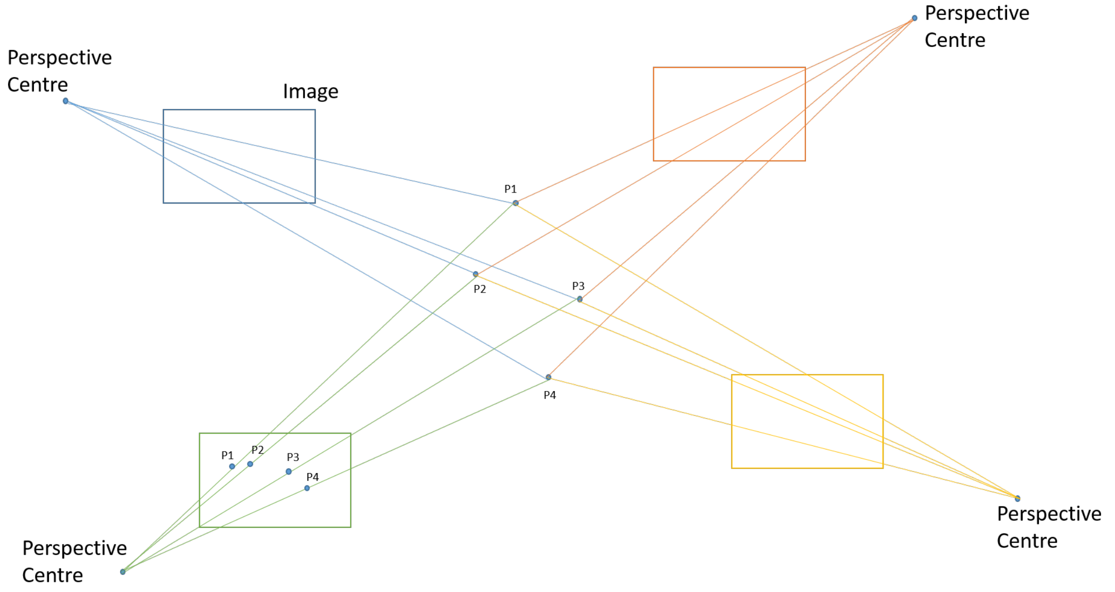


Figure 6.4: Concept of the 3-Dimensional Bundle Adjustment. (Brown (1958))

The conditions can be derived from the relationship between object space (X,Y,Z) and image space (x,y,c) (where c is the principal distance of the camera) represented by a 3D transformation as follows;
Case 1: Case 2:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = sR^T \begin{bmatrix} x \\ y \\ c \end{bmatrix} + \begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix} \qquad \begin{bmatrix} x \\ y \\ c \end{bmatrix} = kR \begin{bmatrix} X - X_o \\ Y - Y_o \\ Z - Z_o \end{bmatrix}$$

Where s/k is scale, R represents a rotation matrix and X_o, Y_o and Z_o are the perspective centre of the camera. By analyzing case 2 and expanding:

$$\begin{bmatrix} x \\ y \\ c \end{bmatrix} = k \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \begin{bmatrix} X - X_o \\ Y - Y_o \\ Z - Z_o \end{bmatrix} = k \begin{bmatrix} r_{11}(X - X_0) + r_{12}(Y - Y_0) + r_{13}(Z - Z_0) \\ r_{21}(X - X_0) + r_{22}(Y - Y_0) + r_{23}(Z - Z_0) \\ r_{31}(X - X_0) + r_{32}(Y - Y_0) + r_{33}(Z - Z_0) \end{bmatrix}$$

And now by dividing equations 1 and 2 by equation 3 to eliminate the scale factor k, the solution becomes:

$$x = c\left(\frac{r_{11}(X - X_0) + r_{12}(Y - Y_0) + r_{13}(Z - Z_0)}{r_{31}(X - X_0) + r_{32}(Y - Y_0) + r_{33}(Z - Z_0)}\right)$$

$$y = c\left(\frac{r_{21}(X - X_0) + r_{22}(Y - Y_0) + r_{23}(Z - Z_0)}{r_{31}(X - X_0) + r_{32}(Y - Y_0) + r_{33}(Z - Z_0)}\right)$$

Which are the collinearity conditions. The rotation matrix R is a combination of the rotations about the three separate x, y and z axes, omega phi and kappa respectively;

$$R = R_{xyz} = R_z * R_y * R_x = R_z(K) * R_y(\varphi) * R_x(\omega)$$

The scale in photogrammetry is determined by the relationship between the focal length and the flying height/distance to object point from projection center i.e.;

$$k = \frac{focal\ length\ (c)}{Flying\ Height\ \ (H)\ \ or\ Distance\ to\ Object\ Point\ (Ds)}$$

In order for these equations to apply there must be two or more photographs with common image points between them. Provisional object coordinate values are required and can be determined in any typical survey method such as 2D traverse and trigonometric heighting or a 3D traverse. Image coordinates are required to find the object coordinates and vice versa and the image coordinates are measured in terms of pixels in the image. Image coordinates must first be converted into the correct units (meters if the object coordinates are in meters) and are required for each image. With more than the required number of image points (the observations) a Least Squares adjustment can be performed in order to derive the object coordinates as well as the precisions and accuracies of the observations and unknowns (the object point coordinates). (*ibid*)

6.3 Viable Methods of Accuracy Determination

6.3.1 Requirements for Determining Accuracy

According to by Robert M. Graham and his research into the steps involved in measurement quality, there are some initial questions that can be asked to help determine the accuracy of a measurement. The questions can be interpreted as follows according to Graham (2006):

1. What quantities are required to be measured?
2. Are there accuracy/precision requirements that must be satisfied?
3. Is there a method to check that the measurements are precise and/or accurate enough to satisfy the requirements?
4. Is the project able to be reproduced under the same conditions and how is this confirmed?

With the first question the important measurements that are needed for this project must be determined. This must be broken down as far as possible to determine the specific important measurements as opposed to classing all measurements as important for the entire project.

In this particular case the measurements can be broken down into the base observations of distance and direction. Although the directions are the base measurements the derived angles are more useful for comparisons as the directions can be relative to each setup position and by using the angles created by these directions, the need to know where the setup origin is located is eliminated. This means the Range and Angular measurements are the important observations for the calculations within this research. These are the most significant as all other quantities obtained from the measurement devices are derived from these base measurements, including Areas or Volumes. If these quantities had been utilized and the base observations of range and angle were incorrect, there would not be a means of identifying where the error was coming from.

Once the base measurements have been decided on, the next step was to look at the units. In this case there was not much choice in the matter other than in the decimal position of the values. In terms of the range measurements, the decimals were chosen to show millimeter precision (three decimal places) in order to show as much information as possible while at the same time showing information that was realistic. With the angle measurements it was decided to use degrees, minutes and seconds with a decimal place on the seconds (DDMMSS,S) in order to get as much information for the comparison as possible.

If these values were derived incorrectly and in such a way that did not give enough information for the calculations it could be possible that the values that would be used for the ”true” value are not significant enough to be more accurate than the observations they are being compared to. This would lead to inconclusive results and no solution to the problem at hand. This is why as much information as possible is required and lots of redundancy to help with any least squares calculations.

Another important topic to consider was that if any measurement is to be confirmed, the norm is to find a known measurement and to measure this known value to confirm the measurement technique is working. If the same value is observed it can mean the technique is sufficient but this may not be entirely true. In order to say the method is sufficient the precision or uncertainty of the known measurement must also be known. An example could be seen as the range that is surveyed between two setups to serve as scale for the network. If this value is observed with a laser scanner and the laser scanner returns the same value it is possible the technique of measurement by the laser scanner is performing adequately. In order to confirm this the uncertainty of the surveyed range must be investigated to ensure that it is as close to the ”true” value as possible to ensure the observed range can be compared to a reliable value. This uncertainty may be affected by flexing of the building, temperature variations or even disturbance of the mount setups from interference from people, so this is important to confirm prior to making any conclusions.

Other factors that could be considered might have been the precision of the survey and how repeatable the survey and its resulting coordinates are to achieve. The same factors acting on the building or mounts that were mentioned previously can also impact on the repeatability of the survey and its precisions. Some factors may be considerably small or negligible and can be excluded for example; refraction on the ray between setups may be negligible due to the range values not being long enough to be affected on a noticeable level.

In terms of the second question, there are considerations into what effects the measurements such as the time available to use the equipment and variations in the conditions of the survey and scanning. For this research both played a role in deciding when to work. The university has many activities taking place at any time and this means finding a time during the day can be quite challenging which is what led us to using the facilities at strange hours when there was the least chance of any interference. In the case of the smaller facility this meant working on the weekend as this facility was in a small room and unlikely to be used when most people go home over this time. The facility at the sports center needed to be coordinated with the staff in order to find a time that would allow us to work for a few hours and be completely undisturbed. This is what led to us working in the late evenings, this was also due to factors such as temperature and traffic which have been mentioned in more detail in a previous section on deciding which venue to use for a testing facility. Another reason for the strange hours was the long periods of time needed to complete the surveys to ensure all the required data was observed. (*ibid*)

When deciding on the level of accuracy, decisions were made on how to conduct the surveys of the respective facilities. There was a minimum number of observations needed to achieve a certain result, but to improve the uncertainty of this value more measurements were conducted which in turn increased the redundancy. The use of more observations along with the high precision procedures (forced centering which will be discussed later and taping the legs of the tripods to the floor) that were adopted increased the time of the survey dramatically but also improved the results. The accuracy of the outcome can also be influenced by the instruments used and when attempting to find the highest quality results, the best available instrumentation was used.

When attempting to analyze the accuracy of the laser scanner the manufacturer quoted values must be found and these will be tested against the surveyed or ”control values”. The control values need to be better by an order of magnitude than the values they are being compared against. The trouble with this kind of statement is that there are many different scanners with many different abilities and so it made sense to use a high quality scanner to look at the specifications to gain an understanding of the achievable accuracy. Once this value is known roughly the required survey accuracy can be known but ultimately the best results will come from the instrument, observer and survey combination at the time with as much redundancy as possible.

The last question of whether or not an experiment is repeatable or not is answered through careful documenting of all procedures and observations in a well thought-out manner in order to ensure all information is stored and able to be referred to at a later stage and has the ability to answer any questions regarding the experiment. (*ibid*)

6.4 Limitations

6.4.1 Accuracy Determination Requirements

In order to determine what accuracies and precisions are attainable, considerations must first be taken with regard to the equipment being used. Any measurement tool has a manufacturer quoted accuracy or precision which can be found from the manufacturer directly or in a specifications sheet for that particular instrument. It is these values that are the best possible for the given measurement device and what is analyzed further in an accuracy assessment. These values are the best based on the conditions that the data was gathered under with the highest precisions and most careful measurements captured as possible. If attempting to test one device against another there needs to be one that is superior over the other. This can be found by a simple comparison of the specifications for the same measurement (for example both the range accuracies of the two instruments).

In the case of a survey with a total station and the testing of a laser scanner, the best scenario would be if the total station can obtain observations of a superior accuracy to those acquired from the laser scanner. This would allow sufficient confidence in the total station (or any device) observations over the laser scanner and with a larger difference the confidence will grow.

For examples of the specifications of some laser scanners, there is a spreadsheet of various factors pertaining to the laser scanners including their accuracy and range requirements. This spreadsheet can be seen below in figure 6.5.

The specification for the total station can be seen below in figure 6.6. These values are useful to substantiate the use of this instrument for the precise work that was required from the surveys of the target networks in both facilities. The accuracy testing facility would be required to validate the strength of the coordinate network and from this prove the coordinates are suitably accurate to evaluate the performance of a given laser scanner.

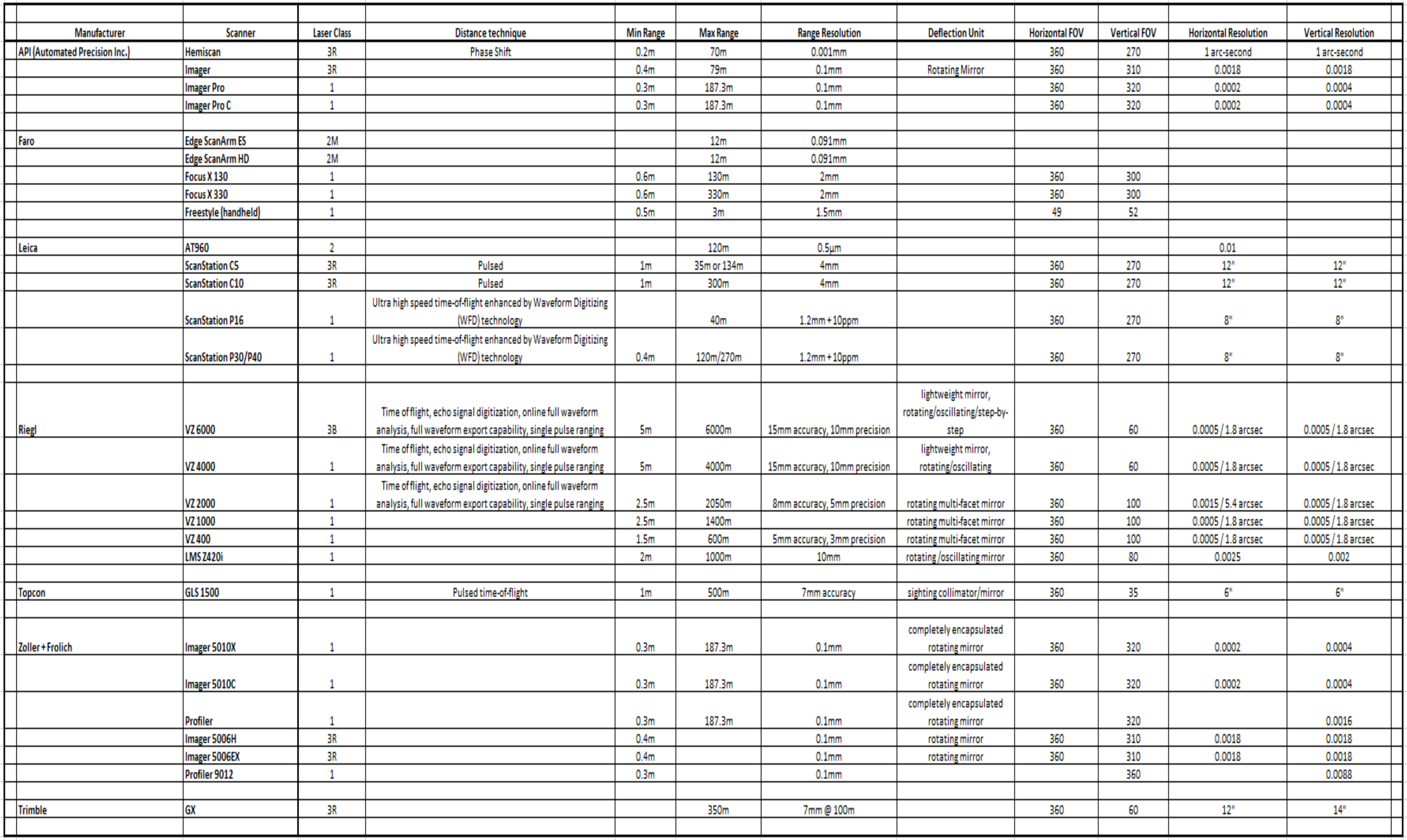
If there is no instrument that is superior in terms of its accuracy, there are the methods of least squares mentioned above that increase the redundancy, reliability and accuracy. This is especially helpful in the scenario where both instruments are fairly new technologies and they are both of a high measurement standard. In order to compare the one against the other, with one serving as the baseline, the observations need to be improved through an adjustment.

Aside from the laser scanner and total station comparisons there are also accuracy regulations that are in place through various acts and laws that govern the measurement professions. If these regulations are evaluated in terms of those that pertain to terrestrially based measurements, there are several that can be used to describe what projects the laser scanner can be used for and which it is not accurate enough for based on the minimum standard of accuracy. Some of these have been explored and tabulated below in figure 6.7 for the projects involved in the surveying and mining industries. These regulations each have a unique formula relating the accuracy standard for the given class to the distance between the two points involved. The formulae for the regulations can be visualized in table 6.1. (Grobler (2014))

From the formulae in table 6.1 the s represents the distance between the known and unknown points in meters. The L represents the distance between points in meters. The r represents the length of the maximum allowable semi-major axis in mm and d represents the distance to any station or between points in kilometers. The term c is an empirically derived factor for a particular standard of survey. All the values have been converted to meters for the table in figure 6.7. (Grobler (2014)) The values in this figure are useful in conjunction with the determined laser scanner accuracy to determine what projects the laser scanner is accurate enough to undertake.

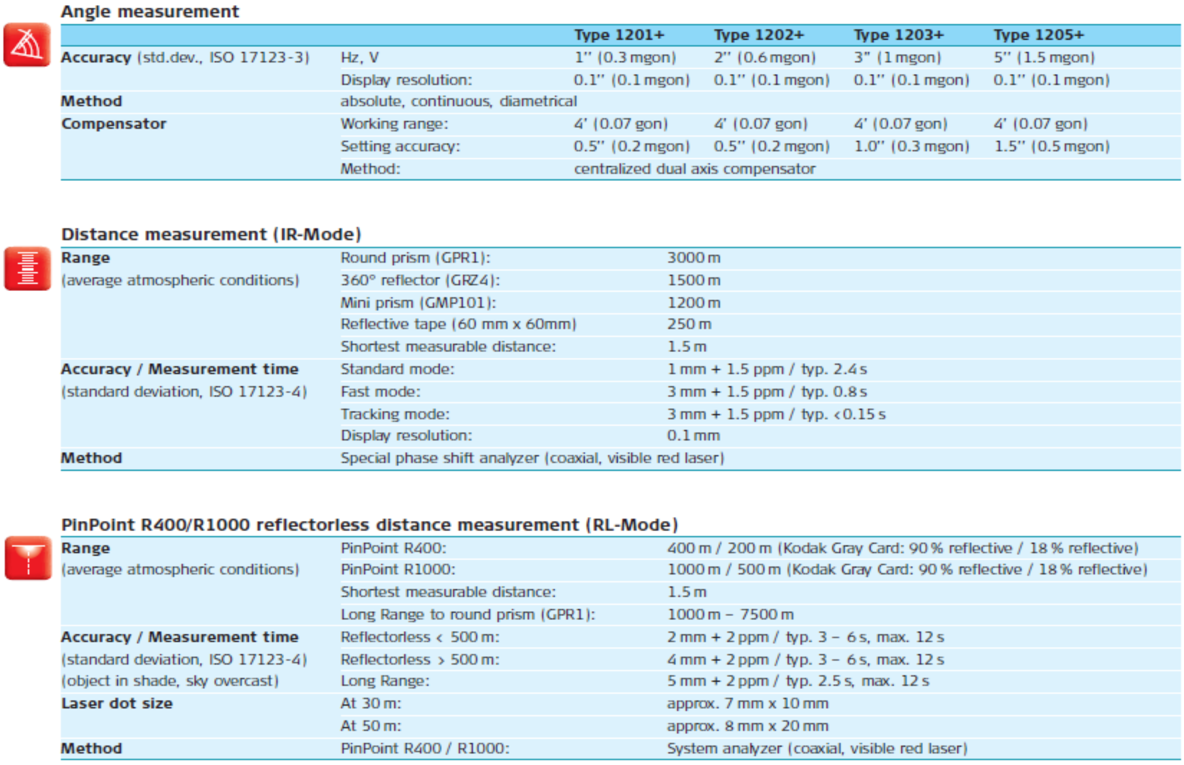
Table 6.1: Summary of the formulae required to calculate the minimum standards of accuracy for each of the regulations that were investigated. Courtesy of Grobler (2014).

Regulation	Class	Formula
Land Survey Act	A	$0,04 + \frac{s}{30000}$
Land Survey Act	B	1.5 x Class A
Land Survey Act	C	3 x Class A
Mine Health and Safety Act	A	$0,015 + \frac{s}{30000}$
Mine Health and Safety Act	B	1.5 x Class A
Mine Health and Safety Act	C	3 x Class A
Federal Geodetic Control Subcommittee	First Order Class 1	1 part in 100 000
Federal Geodetic Control Subcommittee	Second Order Class 1	1 part in 50 000
Federal Geodetic Control Subcommittee	Third Order Class 1	1 part in 10 000
ISO4463	Distance	$\left(0.75\sqrt{L}\right) mm$ *
ISO4463	Angle	$\left(\frac{0,045}{\sqrt{L}}\right) degrees$ *
Intergovernmental Committee on Survey and Mapping	3A (c = 1)	$r = c\,(d + 0,2)$
Intergovernmental Committee on Survey and Mapping	2A (c = 3)	$r = c\,(d + 0,2)$
Intergovernmental Committee on Survey and Mapping	A (c = 7.5)	$r = c\,(d + 0,2)$
Intergovernmental Committee on Survey and Mapping	B (c = 15)	$r = c\,(d + 0,2)$
Canadian Survey Standards	N/A	$r = 8\,(d + 0,25)$
New South Wales Coal	D (c = 50)	$r = c\,(d + 0,2)$



Manufacturer	Scanner	Laser Class	Distance technique	Min Range	Max Range	Range Resolution	Deflection Unit	Horizontal FOV	Vertical FOV	Horizontal Resolution	Vertical Resolution
API (Automated Precision Inc.)	Hemiscan	3R	Phase Shift	0.2m	70m	0.001mm		360	270	1 arc-second	1 arc-second
	Imager	3R		0.4m	79m	0.1mm	Rotating Mirror	360	310	0.0018	0.0018
	Imager Pro	1		0.3m	187.3m	0.1mm		360	320	0.0002	0.0004
	Imager Pro C	1		0.3m	187.3m	0.1mm		360	320	0.0002	0.0004
Faro	Edge ScanArm ES	2M			12m	0.091mm					
	Edge ScanArm HD	2M			12m	0.091mm					
	Focus X 130	1		0.6m	130m	2mm		360	300		
	Focus X 330	1		0.6m	330m	2mm		360	300		
	Freestyle (handheld)	1		0.5m	3m	1.5mm		49	52		
Leica	AT960	2			120m	0.5µm				0.01	
	ScanStation C5	3R	Pulsed	1m	35m or 134m	4mm		360	270	12"	12"
	ScanStation C10	3R	Pulsed	1m	300m	4mm		360	270	12"	12"
	ScanStation P16	1	Ultra high speed time-of-flight enhanced by Waveform Digitizing (WFD) technology		40m	1.2mm + 10ppm		360	270	8"	8"
	ScanStation P30/P40	1	Ultra high speed time-of-flight enhanced by Waveform Digitizing (WFD) technology	0.4m	120m/270m	1.2mm + 10ppm		360	270	8"	8"
Riegl	VZ 6000	3B	Time of flight, echo signal digitization, online full waveform analysis, full waveform export capability, single pulse ranging	5m	6000m	15mm accuracy, 10mm precision	lightweight mirror, rotating/oscillating/step-by-step	360	60	0.0005 / 1.8 arcsec	0.0005 / 1.8 arcsec
	VZ 4000	1	Time of flight, echo signal digitization, online full waveform analysis, full waveform export capability, single pulse ranging	5m	4000m	15mm accuracy, 10mm precision	lightweight mirror, rotating/oscillating	360	60	0.0005 / 1.8 arcsec	0.0005 / 1.8 arcsec
	VZ 2000	1	Time of flight, echo signal digitization, online full waveform analysis, full waveform export capability, single pulse ranging	2.5m	2050m	8mm accuracy, 5mm precision	rotating multi-facet mirror	360	100	0.0015 / 5.4 arcsec	0.0005 / 1.8 arcsec
	VZ 1000	1		2.5m	1400m		rotating multi-facet mirror	360	100	0.0005 / 1.8 arcsec	0.0005 / 1.8 arcsec
	VZ 400	1		1.5m	600m	5mm accuracy, 3mm precision	rotating multi-facet mirror	360	100	0.0005 / 1.8 arcsec	0.0005 / 1.8 arcsec
	LMS Z420i	1		2m	1000m	10mm	rotating /oscillating mirror	360	80	0.0025	0.002
Topcon	GLS 1500	1	Pulsed time-of-flight	1m	500m	7mm accuracy	sighting collimator/mirror	360	35	6"	6"
Zoller + Frolich	Imager 5010X	1		0.3m	187.3m	0.1mm	completely encapsulated rotating mirror	360	320	0.0002	0.0004
	Imager 5010C	1		0.3m	187.3m	0.1mm	completely encapsulated rotating mirror	360	320	0.0002	0.0004
	Profiler	1		0.3m	187.3m	0.1mm	completely encapsulated rotating mirror		320		0.0016
	Imager 5006H	3R		0.4m		0.1mm	rotating mirror	360	310	0.0018	0.0018
	Imager 5006EX	3R		0.4m		0.1mm	rotating mirror	360	310	0.0018	0.0018
	Profiler 9012	1		0.3m		0.1mm			360		0.0088
Trimble	GX	3R			350m	7mm @ 100m		360	60	12"	14"

Figure 6.5: Laser Scanner Specifications (as per available specifications provided by the manufacturer product brochures).



Angle measurement

		Type 1201+	Type 1202+	Type 1203+	Type 1205+
Accuracy (std.dev., ISO 17123-3)	Hz, V	1" (0.3 mgon)	2" (0.6 mgon)	3" (1 mgon)	5" (1.5 mgon)
	Display resolution:	0.1" (0.1 mgon)	0.1" (0.1 mgon)	0.1" (0.1 mgon)	0.1" (0.1 mgon)
Method	absolute, continuous, diametrical				
Compensator	Working range:	4' (0.07 gon)	4' (0.07 gon)	4' (0.07 gon)	4' (0.07 gon)
	Setting accuracy:	0.5" (0.2 mgon)	0.5" (0.2 mgon)	1.0" (0.3 mgon)	1.5" (0.5 mgon)
	Method:	centralized dual axis compensator			

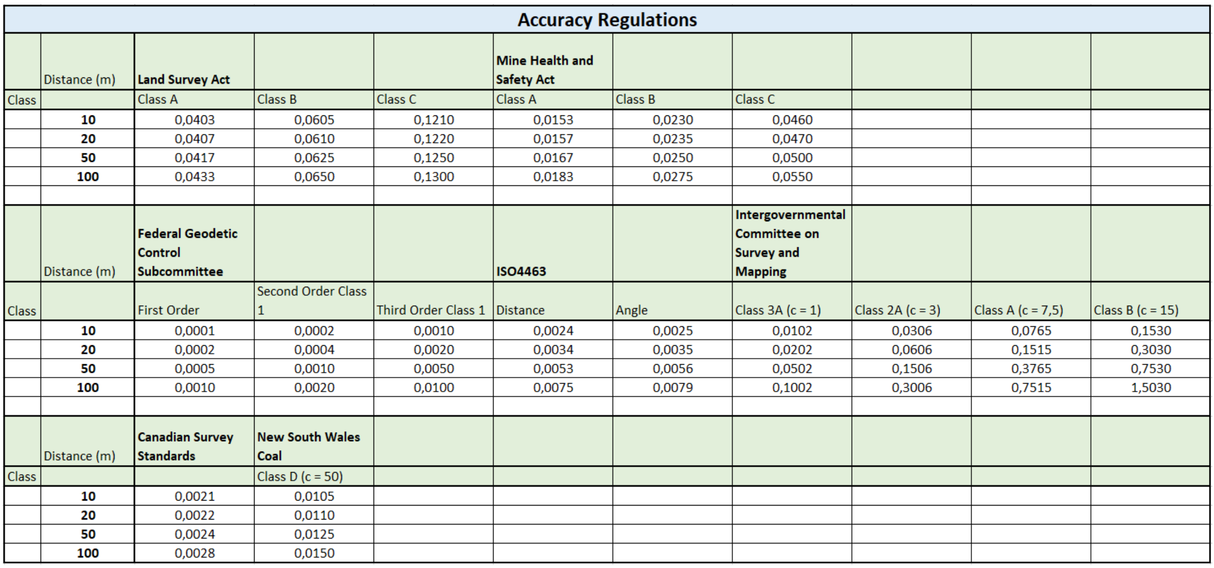
Distance measurement (IR-Mode)

Range	Round prism (GPR1):	3000 m
(average atmospheric conditions)	360° reflector (GRZ4):	1500 m
	Mini prism (GMP101):	1200 m
	Reflective tape (60 mm x 60mm)	250 m
	Shortest measurable distance:	1.5 m
Accuracy / Measurement time	Standard mode:	1 mm + 1.5 ppm / typ. 2.4 s
(standard deviation, ISO 17123-4)	Fast mode:	3 mm + 1.5 ppm / typ. 0.8 s
	Tracking mode:	3 mm + 1.5 ppm / typ. <0.15 s
	Display resolution:	0.1 mm
Method	Special phase shift analyzer (coaxial, visible red laser)	

PinPoint R400/R1000 reflectorless distance measurement (RL-Mode)

Range	PinPoint R400:	400 m / 200 m (Kodak Gray Card: 90 % reflective / 18 % reflective)
(average atmospheric conditions)	PinPoint R1000:	1000 m / 500 m (Kodak Gray Card: 90 % reflective / 18 % reflective)
	Shortest measurable distance:	1.5 m
	Long Range to round prism (GPR1):	1000 m – 7500 m
Accuracy / Measurement time	Reflectorless < 500 m:	2 mm + 2 ppm / typ. 3 – 6 s, max. 12 s
(standard deviation, ISO 17123-4)	Reflectorless > 500 m:	4 mm + 2 ppm / typ. 3 – 6 s, max. 12 s
(object in shade, sky overcast)	Long Range:	5 mm + 2 ppm / typ. 2.5 s, max. 12 s
Laser dot size	At 30 m:	approx. 7 mm x 10 mm
	At 50 m:	approx. 8 mm x 20 mm
Method	PinPoint R400 / R1000:	System analyzer (coaxial, visible red laser)

Figure 6.6: Leica Total Station 1201 Specifications (as per available specifications provided by the manufacturer online).



Accuracy Regulations

	Distance (m)	**Land Survey Act**			**Mine Health and Safety Act**					
Class		Class A	Class B	Class C	Class A	Class B	Class C			
	10	0,0403	0,0605	0,1210	0,0153	0,0230	0,0460			
	20	0,0407	0,0610	0,1220	0,0157	0,0235	0,0470			
	50	0,0417	0,0625	0,1250	0,0167	0,0250	0,0500			
	100	0,0433	0,0650	0,1300	0,0183	0,0275	0,0550			
	Distance (m)	**Federal Geodetic Control Subcommittee**			**ISO4463**		**Intergovernmental Committee on Survey and Mapping**			
Class		First Order	Second Order Class 1	Third Order Class 1	Distance	Angle	Class 3A (c = 1)	Class 2A (c = 3)	Class A (c = 7,5)	Class B (c = 15)
	10	0,0001	0,0002	0,0010	0,0024	0,0025	0,0102	0,0306	0,0765	0,1530
	20	0,0002	0,0004	0,0020	0,0034	0,0035	0,0202	0,0606	0,1515	0,3030
	50	0,0005	0,0010	0,0050	0,0053	0,0056	0,0502	0,1506	0,3765	0,7530
	100	0,0010	0,0020	0,0100	0,0075	0,0079	0,1002	0,3006	0,7515	1,5030
	Distance (m)	**Canadian Survey Standards**	**New South Wales Coal**							
Class			Class D (c = 50)							
	10	0,0021	0,0105							
	20	0,0022	0,0110							
	50	0,0024	0,0125							
	100	0,0028	0,0150							

Figure 6.7: Table displaying the minimum standards of accuracy required to perform tasks that fall under the realm of each of the given regulations. Each regulation is given in terms of a class and a distance over which that class applies. Courtesy of Grobler (2014).

Chapter 7

Analysis of the Survey Network

7.1 Analysis of Short Range Testing

The processing of data took many forms from calculating surveyed coordinates of the targets and their precisions, to looking at different methods of exporting the target coordinates from the laser scanner and its software and then lastly comparing the ”known” surveyed values to the ”observed” scanner coordinates with respect to their derived distances and angles.

7.1.1 Gathering the Surveyed Data

In order to extract the survey data from the total station, the Format Manager in Leica Geo Office was used to create the format file to ensure that the desired observation format was exported – *From, To, Hz, Vz, Ds, Prism type, Hi, Ht.* This format was set up to only include observation values and not use any of the coordinate values that may have been derived by the instrument and its on-board software.

Once the format was decided on and the observations had been exported, the raw data was brought into Microsoft Excel. The next step involved the reduction of the two arcs per setup into single arcs and thereafter to work through each individually to average out the final observations per setup location.

7.1.2 Calculating the Surveyed Coordinates and Precisions of the Targets

The data from the survey was used in two ways to determine final coordinate values and their precision values. The first method was a 3-dimensional (3D) adjustment program and the second was the Photogrammetric Bundle Adjustment.

3D Adjustment

The final coordinates and their precisions were calculated using a 3D Adjustment. The first step towards the adjustment was the reduction of all the observation arcs to a single arc from the first setup location, where all targets and stations were visible. This new reduced arc was used to determine the provisional coordinate values for all of the targets and stations using the metal tripod (WS1) as the origin (100,1000,10) (y,x,z). The provisional coordinate values were determined by 2D polars for the x and y values, and trigonometrical heighting from WS1 to gather the height values (z values). Below the equations for polar calculations can be seen;

$$y_2 = y_1 + d_{12} * \sin(\alpha_{12})$$

$$x_2 = x_1 + d_{12} * \cos(\alpha_{12})$$

The equations show how polars are used to find the x and y values for the target point, where the point 2 is the target and the point 1 is the station WS1. The angle alpha is the vertical angle observed to the target at point 2. The distance here is the horizontal distance and along with the height difference was calculated using Pythagoras. Height differences were added to the height for WS1 to derive the provisional heights of all the targets.

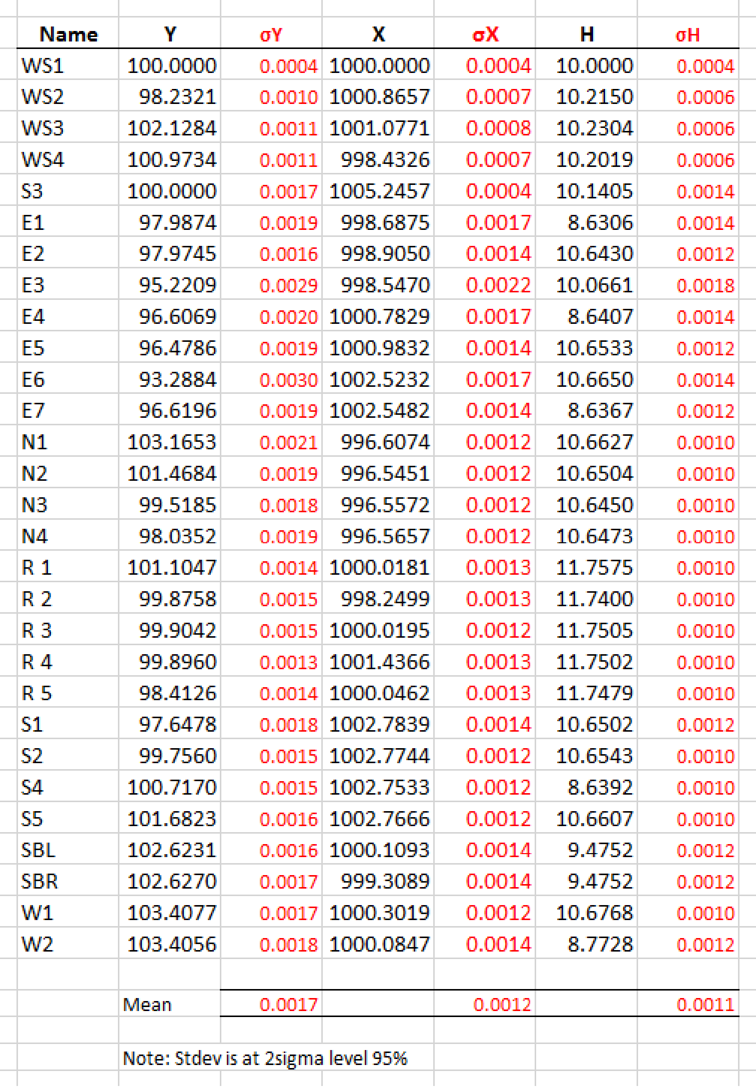
The earth curvature and refraction were also taken into account for thoroughness but over these short ranges these values were negligible. There was a heighting problem with one of the setups and the target used in the forced centering kit and therefore a height check was also calculated to adjust the heights to correct for the mishap with the target. The correction was an average subtraction of 2.1 millimeters per setup. It is believed that the error was due to the target not sitting correctly in the bracket.

The final observations and these new provisional coordinates were inserted into the 3D adjustment program and the final coordinates and their precision values were determined using statistical distributions and least squares calculations. The values returned included the precisions in millimeters for the observations and the error ellipse values in the x, y and z directions for each corresponding coordinate value. Target precisions were in the order of millimeters with the majority being sub-millimeter. The targets with the largest errors were the prisms on the setups and the targets on the roof due to the difficulty in their observation. It is not clear why the observations to survey prism targets were worse than reflectorless observations. The final coordinates along with their precisions (for 2 standard deviations), for both the targets and stations, that resulted from the 3D Adjustment program can be viewed in figure 7.1.

Bundle Adjustment In order to confirm at least one of these two methods mentioned above, a third approach was utilized to once again derive the target coordinates. The approach is the Bundle Adjustment most commonly used in the field of photogrammetry. It was imagined that if the laser scanner and total stations could be thought of as 3D cameras or even panoramic cameras, the observations could be adjusted in the same way. This has been attempted by various researchers referred to in the earlier literature review section such as Lichti.

The bundle adjustment requires provisional image coordinates and provisional object point coordinates in order to determine the parameters of the camera (the projection center, principal distance and any rotations of the camera) and final object point coordinates (the target values).

Within this research it was assumed there was a perfect camera with no lens imperfections or distortions and no principal point. The image coordinates required special attention and had to be derived from the observations from the total station. The image coordinates were taken from the reduced arcs that were determined earlier in the network survey. In order to get them into the image coordinate system a transformation was required. If the point at the center of the image is assumed to be at the origin (0,0) in the



Name	Y	σY	X	σX	H	σH
WS1	100.0000	0.0004	1000.0000	0.0004	10.0000	0.0004
WS2	98.2321	0.0010	1000.8657	0.0007	10.2150	0.0006
WS3	102.1284	0.0011	1001.0771	0.0008	10.2304	0.0006
WS4	100.9734	0.0011	998.4326	0.0007	10.2019	0.0006
S3	100.0000	0.0017	1005.2457	0.0004	10.1405	0.0014
E1	97.9874	0.0019	998.6875	0.0017	8.6306	0.0014
E2	97.9745	0.0016	998.9050	0.0014	10.6430	0.0012
E3	95.2209	0.0029	998.5470	0.0022	10.0661	0.0018
E4	96.6069	0.0020	1000.7829	0.0017	8.6407	0.0014
E5	96.4786	0.0019	1000.9832	0.0014	10.6533	0.0012
E6	93.2884	0.0030	1002.5232	0.0017	10.6650	0.0014
E7	96.6196	0.0019	1002.5482	0.0014	8.6367	0.0012
N1	103.1653	0.0021	996.6074	0.0012	10.6627	0.0010
N2	101.4684	0.0019	996.5451	0.0012	10.6504	0.0010
N3	99.5185	0.0018	996.5572	0.0012	10.6450	0.0010
N4	98.0352	0.0019	996.5657	0.0012	10.6473	0.0010
R 1	101.1047	0.0014	1000.0181	0.0013	11.7575	0.0010
R 2	99.8758	0.0015	998.2499	0.0013	11.7400	0.0010
R 3	99.9042	0.0015	1000.0195	0.0012	11.7505	0.0010
R 4	99.8960	0.0013	1001.4366	0.0013	11.7502	0.0010
R 5	98.4126	0.0014	1000.0462	0.0013	11.7479	0.0010
S1	97.6478	0.0018	1002.7839	0.0014	10.6502	0.0012
S2	99.7560	0.0015	1002.7744	0.0012	10.6543	0.0010
S4	100.7170	0.0015	1002.7533	0.0012	8.6392	0.0010
S5	101.6823	0.0016	1002.7666	0.0012	10.6607	0.0010
SBL	102.6231	0.0016	1000.1093	0.0014	9.4752	0.0012
SBR	102.6270	0.0017	999.3089	0.0014	9.4752	0.0012
W1	103.4077	0.0017	1000.3019	0.0012	10.6768	0.0010
W2	103.4056	0.0018	1000.0847	0.0014	8.7728	0.0012
	Mean	0.0017		0.0012		0.0011
	Note: Stdev is at 2sigma level 95%					

Figure 7.1: Coordinates and Precisions for Short Range Terrestrial Laser Scanner Facility.

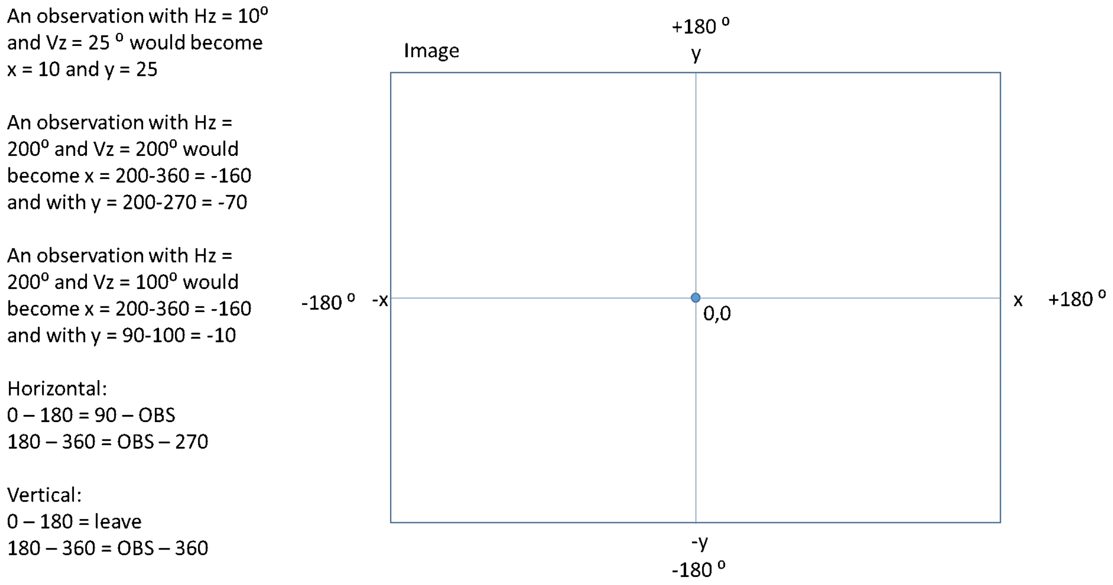
image, the observation values could be used in terms of the Horizontal and Vertical angles to be the horizontal and vertical measurements in millimeters away from the origin with any observations below the horizon and left of the center being negative. A transformation was calculated to transform the observed horizontal and vertical angles into image coordinates where the full observation field of view was now visualized on a single image for each setup. Each setup was treated as a camera with its observations on their own image. A diagram is given below in figure 7.2 for better understanding of the image from a single setup.

If the collinearity equations are examined further in order to determine what is needed for the calculation;

$$x = c\left(\frac{r_{11}\left(X - X_0\right) + r_{12}\left(Y - Y_0\right) + r_{13}\left(Z - Z_0\right)}{r_{31}\left(X - X_0\right) + r_{32}\left(Y - Y_0\right) + r_{33}\left(Z - Z_0\right)}\right)$$

$$y = c\left(\frac{r_{21}\left(X - X_0\right) + r_{22}\left(Y - Y_0\right) + r_{23}\left(Z - Z_0\right)}{r_{31}\left(X - X_0\right) + r_{32}\left(Y - Y_0\right) + r_{33}\left(Z - Z_0\right)}\right)$$

There is now a new set of image coordinates (x,y), provisional target coordinates calculated earlier (X,Y) and the observed slope distances acting as the height above target (Z). The values for the projection cen-



An observation with Hz = 10° and Vz = 25 ° would become x = 10 and y = 25

An observation with Hz = 200° and Vz = 200° would become x = 200-360 = -160 and with y = 200-270 = -70

An observation with Hz = 200° and Vz = 100° would become x = 200-360 = -160 and with y = 90-100 = -10

Horizontal:
0 – 180 = 90 – OBS
180 – 360 = OBS – 270

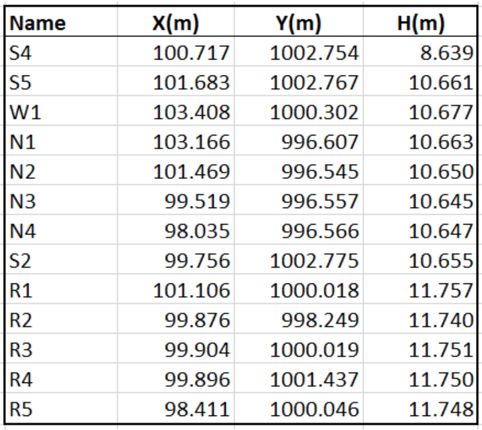
Vertical:
0 – 180 = leave
180 – 360 = OBS – 360

Figure 7.2: Illustration showing the process of transforming the surveyed observations into image coordinates.

ters (X_0, Y_0, Z_0) of each camera were chosen as the provisional values for the setups and the principal distance (c) was given a value of 10 cm as a starting estimate as we did not know what this value would be with respect to a laser scanner. The estimate allowed the adjustment to correct this value towards the ”true” value. The rotations were all set to zero in order to allow them to be adjusted.

The first attempt to code this adjustment in Python was successful in determining only the final coordinates and their precision values and not the station coordinates or any camera details. The code was improved to include these parameters in the adjustment. The solutions offered values that were then compared against the previous two methods. One particular issue with the coding was that it could only handle the calculation if the files from each setup with image coordinates and the provisional coordinate list all had the exact same number of points in each file. This meant that if there was a target seen from one setup and not another it had to be removed from all of the files in order for the program to work. This was due to the way in which the A matrix was being constructed. It was told to run through the length of the provisional object coordinates file with for example 20 targets and then came across a file where the setup only sees 19 targets. The matrix elements no longer lined up correctly and the program crashed. The program was created to follow the least squares methodology mentioned under the section on Theory and followed the Parametric case. The final coordinates that were able to be determined compared well with the coordinates calculated by the 3D Adjustment program and can be seen in figure 7.3. The dataset that would be used for the further analysis stages was the final coordinate set from the 3D Adjustment program. This list only contains a portion of the targets relating to those targets that are visible from all the stations (cameras) as per the code that was written. This was sufficient to serve as a check on the previous method of deriving the coordinates.

At this stage a portion of the coordinates for the targets on the walls had been determined with their precision estimates. The next step was to find coordinates from the device being tested in order to compare these values to our new calculated coordinates. The coordinates that have been calculated



Name	X(m)	Y(m)	H(m)
S4	100.717	1002.754	8.639
S5	101.683	1002.767	10.661
W1	103.408	1000.302	10.677
N1	103.166	996.607	10.663
N2	101.469	996.545	10.650
N3	99.519	996.557	10.645
N4	98.035	996.566	10.647
S2	99.756	1002.775	10.655
R1	101.106	1000.018	11.757
R2	99.876	998.249	11.740
R3	99.904	1000.019	11.751
R4	99.896	1001.437	11.750
R5	98.411	1000.046	11.748

Figure 7.3: Coordinate results from the Short Range Facility Bundle Adjustment, the list is shorter due to the fact that these targets are the only ones visible from all four setups.

will be known as the ”true” values from now on and the laser scanner coordinates will be known as the ”observed” values. It is this next stage that will determine the accuracy of the instrument under investigation.

7.2 Analysis of Medium Range Testing

The same file format as before was used to export the observations brought into Microsoft Excel to focus on distances and angle. Each setup was analyzed individually to reduce the observations into single arcs of observations. This was different from the first attempt in the short range facility due to the fact that only one arc of circle left (CL) readings was observed. This meant there were some added steps involved in determining the final format for the observations. The formulae used before were setup for circle left and circle right (CR) readings and needed to be altered to accept two single arcs of CL observations. Once the formulae had been adjusted and the observations were in the final format, they were ready to proceed with the adjustment.

7.2.1 Calculating surveyed coordinates of the targets and their precisions

As before the data would be analyzed in two ways. The use of the two methods meant that there was added clarification on the methods used and the values obtained. The first method was a 3-Dimensional (3D) adjustment program and the second was the Photogrammetric Bundle adjustment.

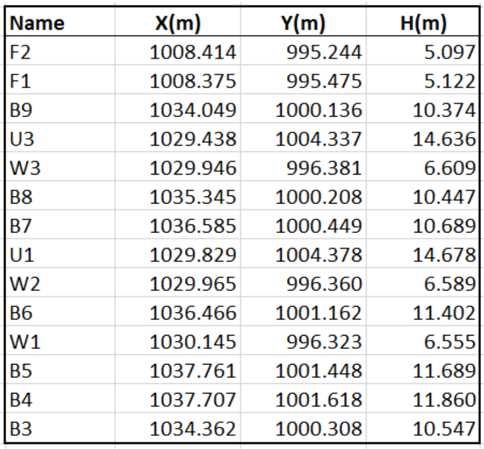
3D Adjustment

The 3D adjustment was calculated using the same 3D Adjustment program as before. Polars and trigonometric heighting were once again employed to find the provisional values and the formulae can be seen in the section on the short range facility. The difference in this survey was that the first setup location (WD1) was not the ’main scanner location’ (which would be WD4) and could not see all of the targets. This meant that once the provisional value for WD4 was found it was used along with consecutive polars to find the missing targets’ provisional values. This unfortunately meant that the origin was now no longer at the desired 1000, 1000, 100.

The earth curvature and refraction were again taken into account but once again the values were negligible. To check the heighting of the setups the same computational check was performed and in this case the average correction was 1.6 millimeters per setup.

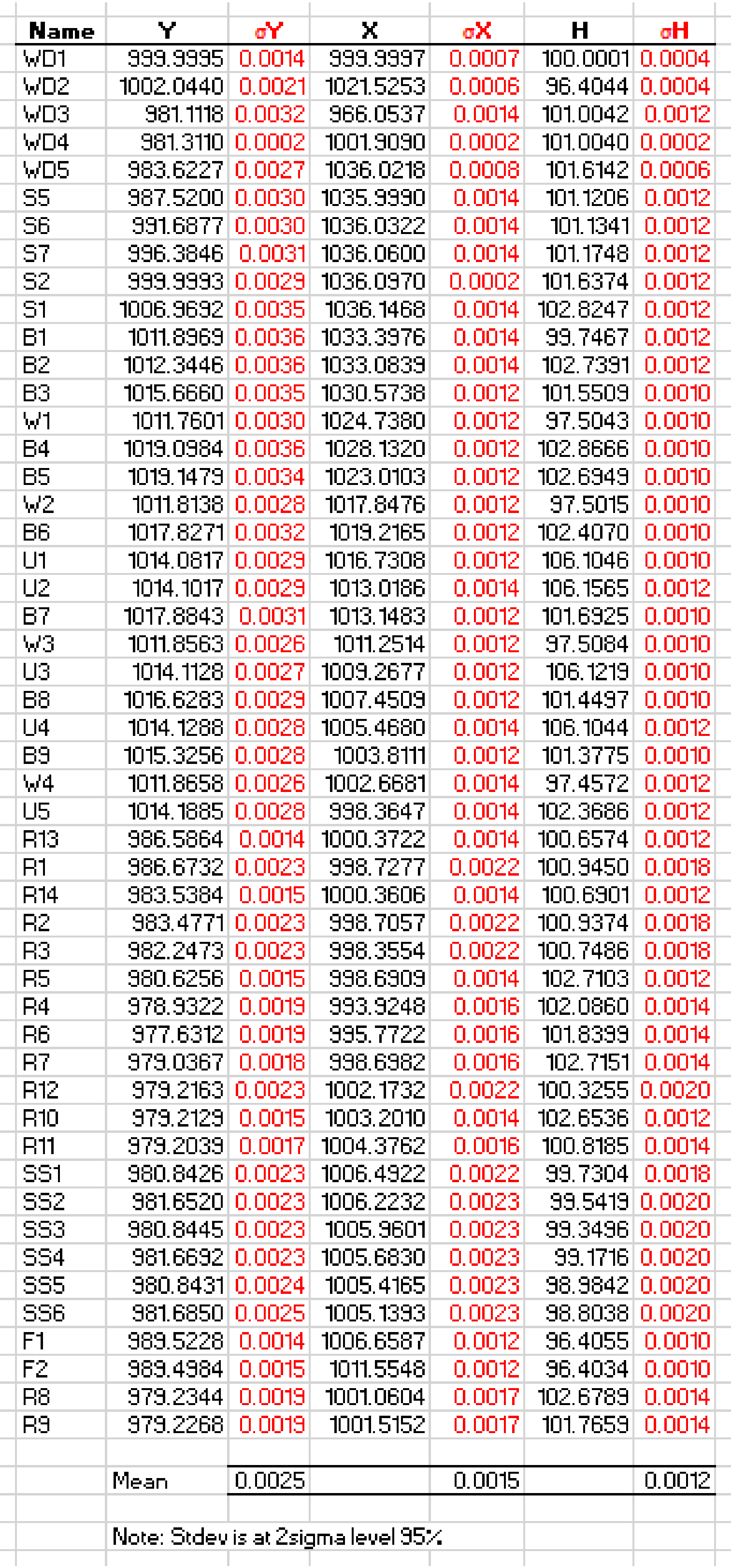
The final observations and the provisional coordinates were inserted into the 3D adjustment program and the final coordinates along with their precision values were determined. The coordinate precisions for this survey were again in the order of millimeters. The results were weaker in the vertical observations and were further weakened at the tripod setup positions. The wall mounted setups appeared to have improved accuracies in the observations. The averaging between the two CL readings may have improved these values because the results appear to be sufficient but there is still uncertainty as to why the tripod setups had such variation in the observations if precautions were taken to ensure precise work.

The results from both methods are shown below. The provisional coordinates were inserted into the Bundle Adjustment code and was able to achieve the values visible in figure 7.4. The final coordinates along with their precisions (for 2 standard deviations), for both the targets and stations, that resulted from the 3D Adjustment program can be viewed in figure 7.5. All precisions can once again be seen to be in the order of millimeters from the 3D Adjustment.



Name	X(m)	Y(m)	H(m)
F2	1008.414	995.244	5.097
F1	1008.375	995.475	5.122
B9	1034.049	1000.136	10.374
U3	1029.438	1004.337	14.636
W3	1029.946	996.381	6.609
B8	1035.345	1000.208	10.447
B7	1036.585	1000.449	10.689
U1	1029.829	1004.378	14.678
W2	1029.965	996.360	6.589
B6	1036.466	1001.162	11.402
W1	1030.145	996.323	6.555
B5	1037.761	1001.448	11.689
B4	1037.707	1001.618	11.860
B3	1034.362	1000.308	10.547

Figure 7.4: Coordinate results from the Medium Range Facility Bundle Adjustment, the list is shorter due to the fact that these targets are the only ones visible from all four setups.



Name	Y	σY	X	σX	H	σH
WD1	999.9995	0.0014	999.9997	0.0007	100.0001	0.0004
WD2	1002.0440	0.0021	1021.5253	0.0006	96.4044	0.0004
WD3	981.1118	0.0032	966.0537	0.0014	101.0042	0.0012
WD4	981.3110	0.0002	1001.9090	0.0002	101.0040	0.0002
WD5	983.6227	0.0027	1036.0218	0.0008	101.6142	0.0006
S5	987.5200	0.0030	1035.9990	0.0014	101.1206	0.0012
S6	991.6877	0.0030	1036.0322	0.0014	101.1341	0.0012
S7	996.3846	0.0031	1036.0600	0.0014	101.1748	0.0012
S2	999.9993	0.0029	1036.0970	0.0002	101.6374	0.0012
S1	1006.9692	0.0035	1036.1468	0.0014	102.8247	0.0012
B1	1011.8969	0.0036	1033.3976	0.0014	99.7467	0.0012
B2	1012.3446	0.0036	1033.0839	0.0014	102.7391	0.0012
B3	1015.6660	0.0035	1030.5738	0.0012	101.5509	0.0010
W1	1011.7601	0.0030	1024.7380	0.0012	97.5043	0.0010
B4	1019.0984	0.0036	1028.1320	0.0012	102.8666	0.0010
B5	1019.1479	0.0034	1023.0103	0.0012	102.6949	0.0010
W2	1011.8138	0.0028	1017.8476	0.0012	97.5015	0.0010
B6	1017.8271	0.0032	1019.2165	0.0012	102.4070	0.0010
U1	1014.0817	0.0029	1016.7308	0.0012	106.1046	0.0010
U2	1014.1017	0.0029	1013.0186	0.0014	106.1565	0.0012
B7	1017.8843	0.0031	1013.1483	0.0012	101.6925	0.0010
W3	1011.8563	0.0026	1011.2514	0.0012	97.5084	0.0010
U3	1014.1128	0.0027	1009.2677	0.0012	106.1219	0.0010
B8	1016.6283	0.0029	1007.4509	0.0012	101.4497	0.0010
U4	1014.1288	0.0028	1005.4680	0.0014	106.1044	0.0012
B9	1015.3256	0.0028	1003.8111	0.0012	101.3775	0.0010
W4	1011.8658	0.0026	1002.6681	0.0014	97.4572	0.0012
U5	1014.1885	0.0028	998.3647	0.0014	102.3686	0.0012
R13	986.5864	0.0014	1000.3722	0.0014	100.6574	0.0012
R1	986.6732	0.0023	998.7277	0.0022	100.9450	0.0018
R14	983.5384	0.0015	1000.3606	0.0014	100.6901	0.0012
R2	983.4771	0.0023	998.7057	0.0022	100.9374	0.0018
R3	982.2473	0.0023	998.3554	0.0022	100.7486	0.0018
R5	980.6256	0.0015	998.6909	0.0014	102.7103	0.0012
R4	978.9322	0.0019	993.9248	0.0016	102.0860	0.0014
R6	977.6312	0.0019	995.7722	0.0016	101.8399	0.0014
R7	979.0367	0.0018	998.6982	0.0016	102.7151	0.0014
R12	979.2163	0.0023	1002.1732	0.0022	100.3255	0.0020
R10	979.2129	0.0015	1003.2010	0.0014	102.6536	0.0012
R11	979.2039	0.0017	1004.3762	0.0016	100.8185	0.0014
SS1	980.8426	0.0023	1006.4922	0.0022	99.7304	0.0018
SS2	981.6520	0.0023	1006.2232	0.0023	99.5419	0.0020
SS3	980.8445	0.0023	1005.9601	0.0023	99.3496	0.0020
SS4	981.6692	0.0023	1005.6830	0.0023	99.1716	0.0020
SS5	980.8431	0.0024	1005.4165	0.0023	98.9842	0.0020
SS6	981.6850	0.0025	1005.1393	0.0023	98.8038	0.0020
F1	989.5228	0.0014	1006.6587	0.0012	96.4055	0.0010
F2	989.4984	0.0015	1011.5548	0.0012	96.4034	0.0010
R8	979.2344	0.0019	1001.0604	0.0017	102.6789	0.0014
R9	979.2268	0.0019	1001.5152	0.0017	101.7659	0.0014
	Mean	0.0025		0.0015		0.0012
	Note: Stdev is at 2sigma level 95%					

Figure 7.5: Coordinates and Precisions for Medium Range Terrestrial Laser Scanner Facility.

Chapter 8

Laser Scanner Testing Approach

8.1 Equipment Analysis

8.1.1 Introduction

Before the discussion into the formal methodology of the laser scanner testing, there are a series of experiments that were carried out in order to confirm specific factors involved in the overall examination of the laser scanner.

These tests were aimed at investigating relationships between the range and the size of the target, the range and the colour of the target as well as the range against the maximum instrument settings for Resolution and Quality. Target material and incidence angle are also investigated to examine the derived target centre point coordinates.

These tests are examined and thereafter the formal laser scanner testing approach is explored.

8.1.2 Target Dimensions and Colour

This test was carried out on the 18th of August 2017 at the UCT Sports Centre. The test was designed to compare a surveyed range to a laser scanner derived range over regular distances of 10m, 20m and 30m for both black and grey target colours with five different sizes; 10cm, 20cm, 30cm, 40cm and 50cm (these sizes are for both height and width).

The aims of this test were to investigate the relationship between target size and range, the relationship between target colour and range and to investigate range performance at specific distances using the maximum laser scanner settings for resolution and quality.

The methodology followed for this experiment is outlined as follows:

- Two tripods were positioned approximately 10 meters apart (one with total station and the other with a Leica survey prism), initially with measuring tape and then with a test shot with total station to check it is sufficiently close to the desired 10 meters.
- The horizontal distance and height difference were measured to the prism with the total station, ten times to take the average. The height of the centre point of the prism was measured from top of tripod.

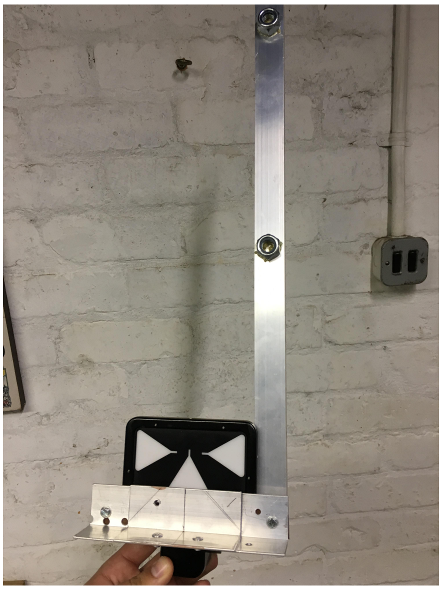


Figure 8.1: Design of the target holder attached to the target that is normally included in a forced centring kit. This target was used because of the ease to attach itself to the rest of the forced centring kit as opposed to fabricating a new attachment.

Figure 8.2: A photograph of the target holder in use with a 20cm target inserted and positioned on a tripod. The vertical aluminium arm can also be seen which was added for additional support for the larger targets.

- The prism was replaced with 'target holder' and first target (black 10cm x 10cm) and the total station was replaced with the laser scanner Z+F 5010C using forced centring kits. The target holder itself can be seen in figure 8.1 and the target holder with a target included can be seen in figure 8.2.
- Once the target was in the target holder and on the forced centring kit, the height of the centre point was measured from the top of the tripod. The target holder included a vertical piece of aluminium to keep the target surfaces as close to vertical as possible during the testing.
- Using a selection of the horizontal scanning range (scanning "window"), the target was scanned using the maximum settings available on the laser scanner.
- Resolution = ExtremelyHigh and Quality = High
- Once the scan was complete, the target was flipped around to reveal the grey target on opposite side and the scan was repeated on maximum settings.
- This process was repeated for all the targets with dimensions of 20cm, 30cm, 40cm and 50cm for both black and grey.
- Once the survey of the distance and the two window scans for each target (black and grey) was completed, only the target tripod was moved to the next distance of 20m and the laser scanner was replaced with the total station to repeat the entire process once more and then another time at a distance of 30m.

The results for this series of tests show the relationship between the sizes of the target over a measured range to determine the most suitable size for that range. Three graphs are presented below in figures

8.3, 8.4 and 8.5 to illustrate the performance of the different target sizes over three specific distances; 10 meters, 20 meters and 30 meters. The graphs include circled groups of targets indicating smaller sub-patterns in the results. The 200mm and 300mm targets perform the strongest over all the distances while the larger 400mm and 500mm targets perform the weakest. The smaller 100mm targets are performing in-between these two groups aside from the random result from the 100mmG target at 30 meters.

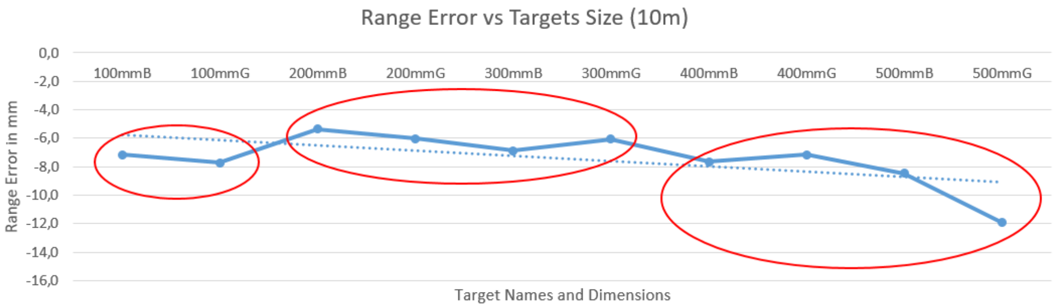


Figure 8.3: Graph showing the difference between the laser scanner derived range and the surveyed range (error) for the different target sizes and colours over the distance of 10 meters.

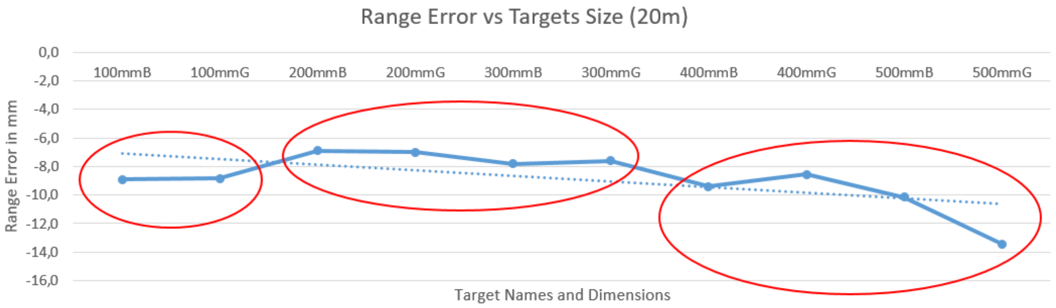


Figure 8.4: Graph showing the difference between the laser scanner derived range and the surveyed range (error) for the different target sizes and colours over the distance of 20 meters.

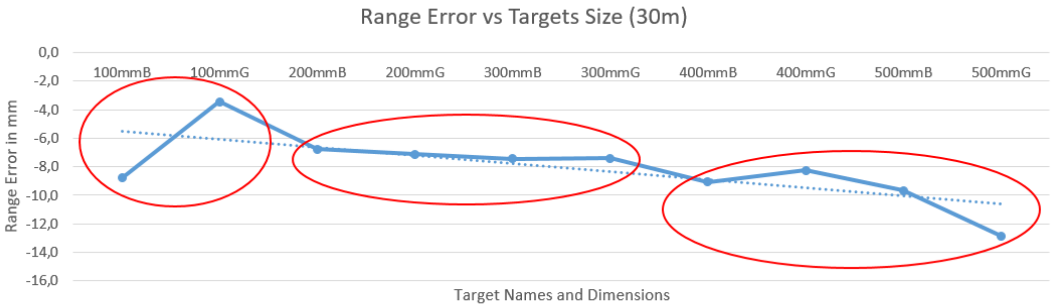


Figure 8.5: Graph showing the difference between the laser scanner derived range and the surveyed range (error) for the different target sizes and colours over the distance of 30 meters.

The results for the testing for the colour of the target over a given range can be seen in the next two graphs in figures 8.6 and 8.7. These graphs are showing how the colour of the target affected the derived range. These results are significant to determine the most appropriate colour of the target required over a given range. The graphs show the grey targets to be performing weaker than the black targets which can be seen by the lower values achieved for all three distances (10m, 20m and 30m).

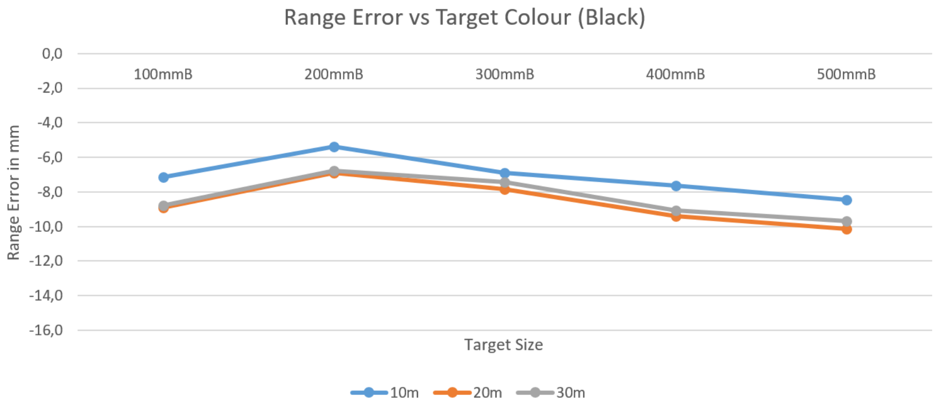


Figure 8.6: Graph showing the same errors in the range between the laser scanner and the surveyed distance but based on on the black targets alone.

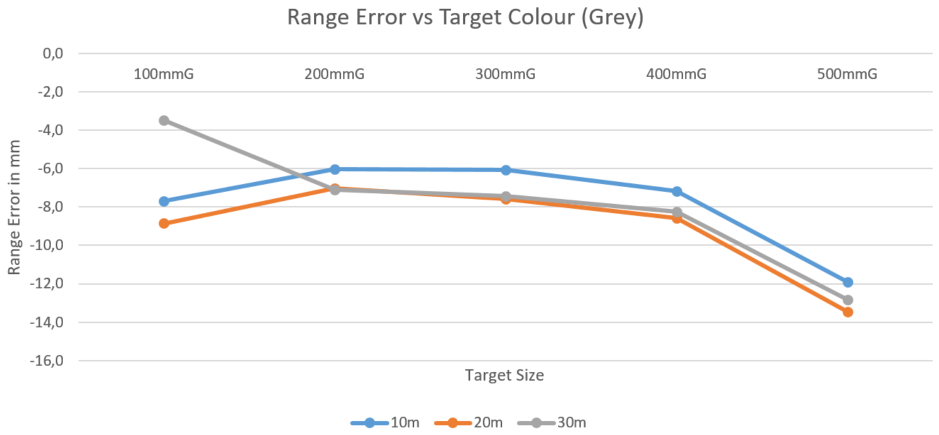


Figure 8.7: Graph showing the same errors in the range between the laser scanner and the surveyed distance but based on on the grey targets alone.

Analysis of the Results

The results from the range and size test require further analysis incorporating the distances of 40 and 50 meters to make a more convincing conclusion. There is no clear trend or preferred target size visible at this point. It is possible to identify that the 200mm and 300mm target sizes appear to be the most suitable of the options available for ranges up to 30 meters.

The results from the range and colour tests indicate the black targets to be performing more accurately over the grey targets. This substantiates the choice to use the black targets for the testing in this project.

The use of the maximum instrument settings was able to show the best possible performance by the laser scanner for this analysis and therefore deliver a set of results that represent the true ability of the laser scanner for these tests.

8.1.3 Target Material and Incidence Angle

The next two tests were performed in order to investigate different options for materials that could be used for targets as well as a investigate the effect of the incidence angle on the derived centre point coordinates of the target. The tests were performed at the UCT Sports Centre due to the open space and ability to control the conditions within the indoor facility.

The aim of these tests was to investigate the effect of different materials for targets on the centre point coordinates through comparisons of a surveyed distance and the derived distance from those coordinates and in the second test to investigate the impact of increasing the incidence angle on the centre point coordinates and the derived distance.

The methodology followed for these tests was as follows;

- Two tripods were setup approximately 10 meters apart as in the previous tests. This distance was selected because it corresponds to the minimum distance referred to in the specifications brochure for the Z+F 5010C laser scanner.
- The distance was surveyed to a prism 10 times to get the average of these for the baseline distance.

Target Material Analysis

- For the target material analysis, a special flat wooden base was created that can be installed on top of a standard survey tripod and screws in with the standard screw from the bottom of the tribrach.
- This flat base served as the base for the target holder to stand on while it held the targets with different materials. This base was also important because it is needed to help with the positioning of the targets each time to ensure the centre point was always in the same position.
- The targets are repeatedly positioned with the centre point in the same place with the help of a ”re-designed set-square”. This set-square was able to be positioned in the same location to ensure the attached marker can remain constant as the target is brought towards it. The target must then be adjusted to have the centre point touching the marker each time. This ensures that any material of any thickness can be used and the centre point will remain constant. The wooden board, target holder and re-designed set-square can be seen in figures 8.8, 8.9, 8.10 and 8.11.
- Once the target is in position, a window scan was captured using the maximum settings once more.
- This procedure was repeated for each of the five materials; foam board, white plastic, perspex, polystyrene and marble.

Incidence Angle Analysis

- The incidence angle analysis used the same setup over the same distance as above in the material analysis. The target holder and flat base were removed and replaced with a forced centring kit.
- On this standard kit a small addition was added in the form of a ‘compass’ which was a simple arrangement of lines around the tribrach that would help in rotating the target through small increments of 15 degrees.

- Once the target holder had been positioned and the target placed in the holder it was aimed at the laser scanner for the first position of zero degrees of incidence (head-on). The window scan of the target on the maximum settings was then captured.
- The target was then rotated through an angle of 15 degrees and another scan captured. This process was repeated for 0, 15, 30, 45, 60 and 75 degrees. The compass and target setup can be seen in figure 8.12.

In order compare the materials performance to the baseline distance that was surveyed, the horizontal distances and height differences were determined from each target's centre coordinates. The errors in the horizontal range have been compared and graphed below in figure 8.13. The graph in figure 8.13 is showing each of the target materials (Foam board, Marble, Perspex, Polystyrene and Plastic) as well as an additional 'version' of each. Each target was scanned on standard settings of High Resolution and Normal Quality and then on the maximum settings of ExtremelyHigh Resolution and High Quality. This was to confirm any differences in the coordinates for the materials and to ensure the settings of the instrument were not affecting those coordinates. The results from the evaluation of the height differences for each material showed very poor performance by the white plastic due to the difficulty experienced by the software in locating the position of the centre point.

The results from the incidence angle analysis can be visualized in the graph below in figure 8.14. The slope distances to each of the centre points were calculated to compare the different incidence angle values against a form of baseline. These differences are plotted against the respective incidence angle. From the graph it is possible to see a clear relationship between the incidence angle and the error in the distance; the larger the incidence angle, the larger the resulting error in the distance and therefore a larger error in the coordinates.

Analysis of the Results

The results from the target material analysis show the settings do not produce significantly different results which indicates that the settings and target materials have no obvious relationship. The graphs of these results are also able to give an idea of what materials are more accurate over this distance and according to the graphs the Foam board and Perspex are the stronger choices while the Marble, White Plastic and Polystyrene were less accurate and not suitable choices for the material of a target over a distance of 10 meters.

The results from the incidence angle analysis show a strong relationship between the incidence angle and the error associated with that incidence angle. This relationship shows the error in the coordinates of the target to be proportionally deteriorating as the incidence angle increases. It must also be noted here that although there are values on the graph for 60 and 75 degrees, these targets failed within the software. This is due to the software having a built in warning for incidence angles higher than 50 degrees despite still being able to determine the centre point coordinates (the coordinates can be determined but the software recommends using another target if the angle is higher than 50 degrees).

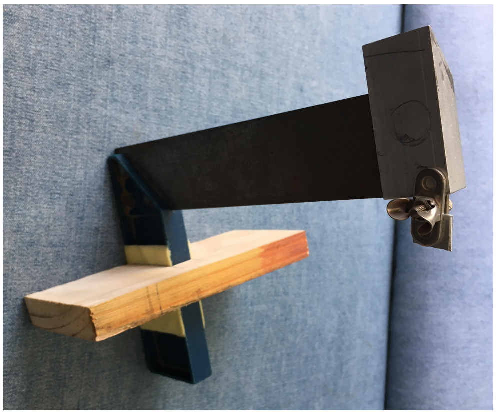


Figure 8.8: Photograph of the standard set-square with some additional pieces allowing for the accurate re-positioning of each target material in the same location. The ”marker” is the top sharp piece and the top corner is the point that all target centre points must be positioned against, the edge of this metal piece is also vertical to be able to check the target surface is vertical.

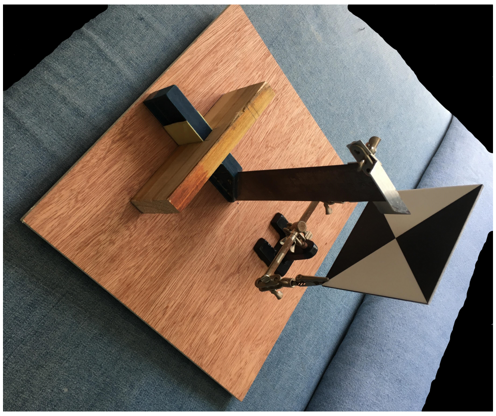


Figure 8.9: This photograph is showing the same re-designed set-square as in figure 8.8 but now including the target holder. Note in this photograph the target has not been aligned with the set-square, all elements are merely shown in approximate positions.

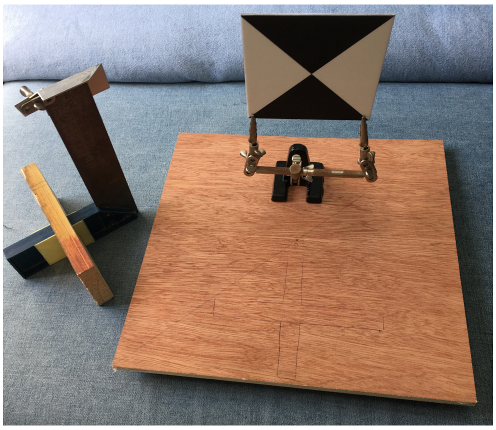


Figure 8.10: This photograph is showing the wooden board created to hold the target holder for the target material analysis. All elements involved in this setup can be seen along with the marked out location of the set-square on the board. Once mounted on the tripod the setup would be scanned in these positions.

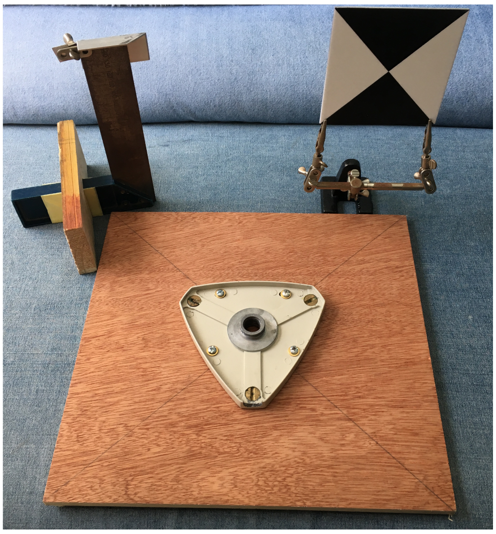


Figure 8.11: This is the same photograph as in figure 8.10 with the added view of the bottom of the wooden board to show the attachment used to attach the board to any standard survey tripod.

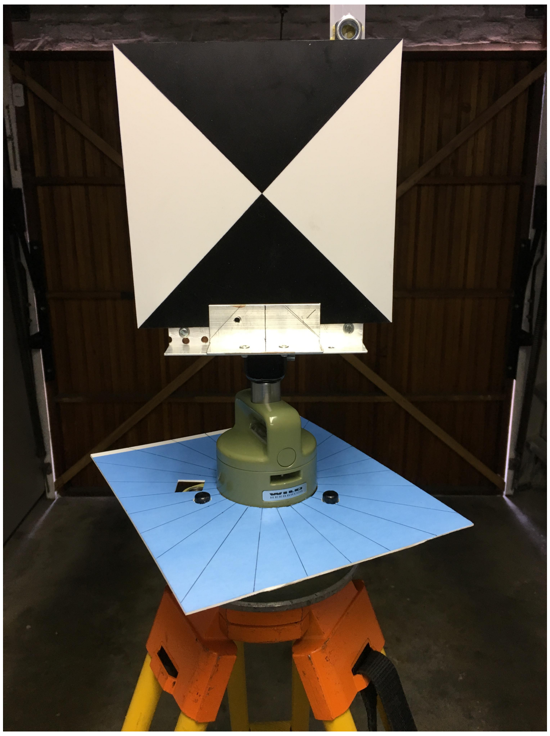


Figure 8.12: Photograph of the setup for the incidence angle analysis including the target holder, target and the improvised compass with increments of 15 degrees marked out to aid in the rotation of the target between each scan.

8.1.4 Target Dimensions

This experiment is the same as the analysis in the ”Target Dimensions and Colour” experiment with the exceptions of additional distances of 40m and 50m and *only black* targets for this analysis. These tests were performed using a Z+F 5006H laser scanner. This test along with the added distances was included to add to the previous analysis results to make a more convincing conclusion regarding the performance of the Z+F 5010C scanner using and independent scanner. This was due to the suspicion of a possible error in the 5010C and these tests would help identify whether range or target dimensions are contributing factors towards this ’error’. This test was performed on the 15th of September 2017 in the Sports Centre at UCT in the same location as the previous test.

The aims have briefly been mentioned but can be outlined as follows; to investigate the relationship between the range and the target size, to investigate the relationship between the laser scanner settings and the size of the target and to investigate the performance of this different scanner (Z+F 5006H) against the previous scanner (Z+F 5010C).

The methodology followed for this testing was the same as the previous attempt with the addition of the two longer distances of 40 and 50 meters to determine more comprehensive results from the targets of 40 and 50 centimeters. This testing focused on the black targets alone to highlight the analysis of size of the target and remove the possibility of any influence of the colour on the results.
The Z+F 5006H has the maximum instrument settings as follows:
Resolution = UltraHigh and Quality = High

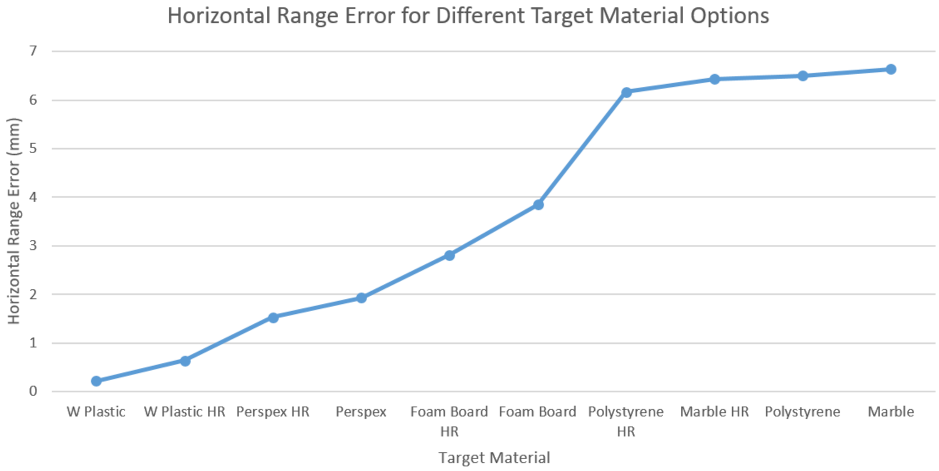


Figure 8.13: Graph showing the differences between the surveyed and laser scanner ranges to targets of different materials. Each material has a standard scan and a higher resolution scan.

The results from this analysis of the target size against the observed range (based on the derived centre point coordinates) can be visualized through 5 graphs in figures 8.15, 8.16, 8.17, 8.18 and 8.19, each from the respective distance between the instrument and target (10m, 20m, 30m, 40m and 50m). Each of the five targets (10cm, 20cm, 30cm, 40cm and 50cm) was scanned twice, once on the standard settings and then on the maximum settings for this laser scanner. The blue lines within the graphs represent the 'high resolution' scans difference in horizontal range between the laser scanner and the total station while the orange lines represent the differences between the 'lower resolution' scans and the total station. These lower resolution scans result in some targets disappearing at larger distances of 40 and 50 meters and in fact no targets were captured on standard settings at 50 meters.

The comparison between the Z+F 5010C and the Z+F 5006H scanners can be visualized by combining the graphs from the first series of tests and these tests into five new graphs. They focus on the same information (distance and target size) but now they can be visualized together in the following graphs in figures 8.20, 8.21, 8.22, 8.23 and 8.24 comparing the two scanners based on distance and target size.

Analysis of the Results

The initial results from this test with the Z+F 5006H scanner indicate the same trend as before where the size of the target may not need to increase with distance if the maximum settings are to be used. Although this is possible it is unlikely that scans will be run on the maximum settings, especially if the full scan is required which is most often the case. If the standard settings are used then the target size is a significant factor and the larger the target the better the chances of resolving the centre point coordinates. This was evident by the software's warning message that some of the smaller sizes did not have sufficient information and suggested using another target (despite being able to still solve for that target).

From the comparison of the two scanners it can be noticed that the 5006H is slightly under performing the 5010C but does not immediately confirm a weakness from this laser scanner. This 5006H had recently returned from a calibration in Germany and was assumed to be in accurate working order and what is likely being visualized above is the limit of these laser scanners. It is possible they may not be

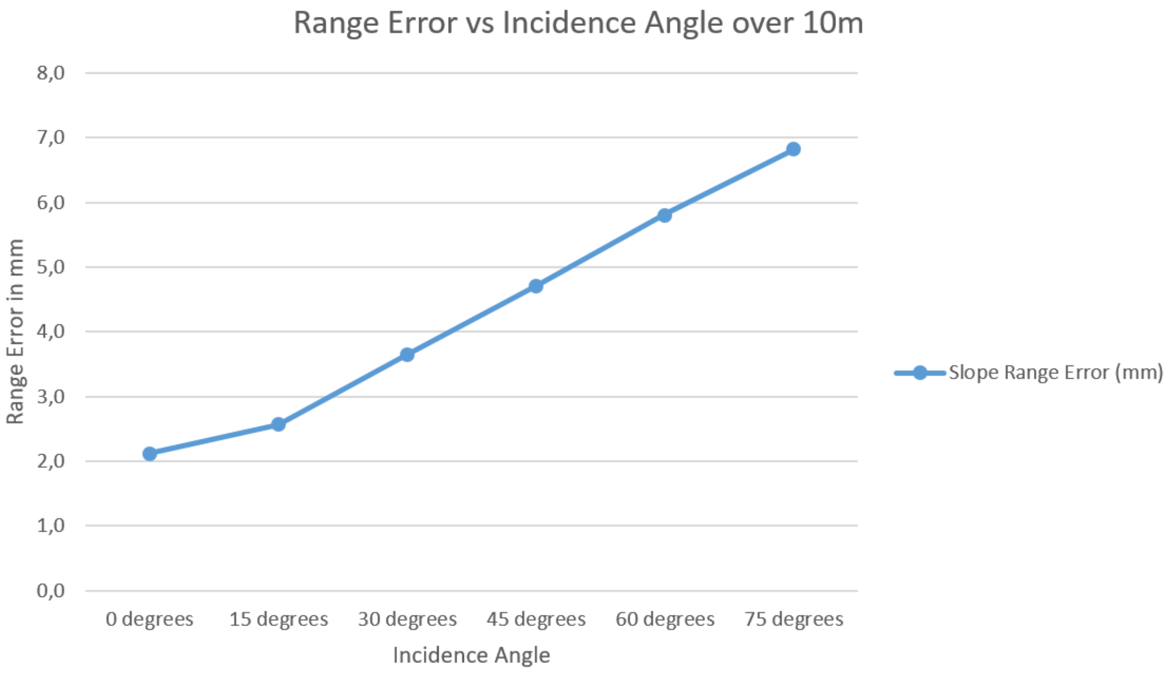


Figure 8.14: Graph showing the resulting error in distance and centre point coordinates with an increasing incidence angle of the target surface.

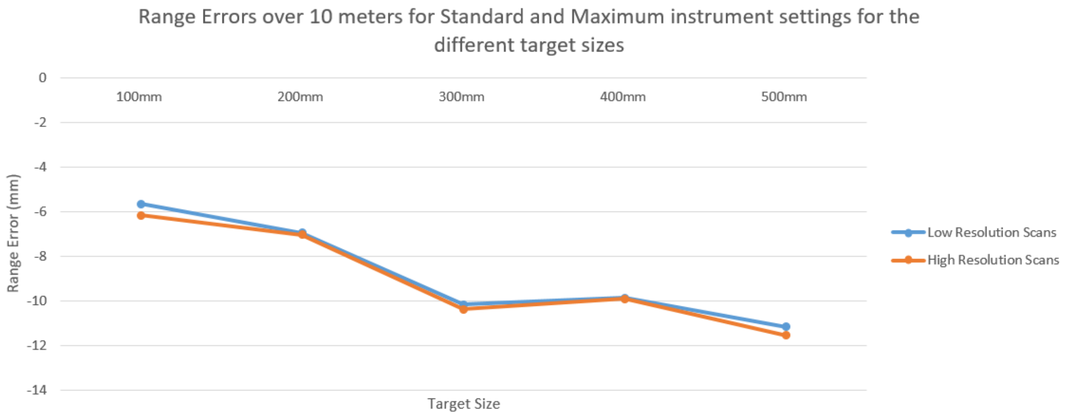


Figure 8.15: Graph showing the error in the derived range for the different target sizes using different instrument settings over a distance of 10 meters.

able to achieve better accuracies and the reason for the slightly improved values by the 5010C can be attributed to the higher settings available on this scanner.

The contradictory trend that has appeared from this testing is in the decrease in accuracy with an increase in target size. This is only very obvious at distances of 40 and 50 meters and marginally visible over the short distances. These trends are thought to be from the targets not being vertical at the time of their scanning but this idea may not be the case as the observing procedure that was undertaken was very precisely repeated for every target and if there was a verticality issue this would result in a constant trend in all five graphs and not only two.

A further exercise was run to investigate the verticality of the targets in the target holder. This test was

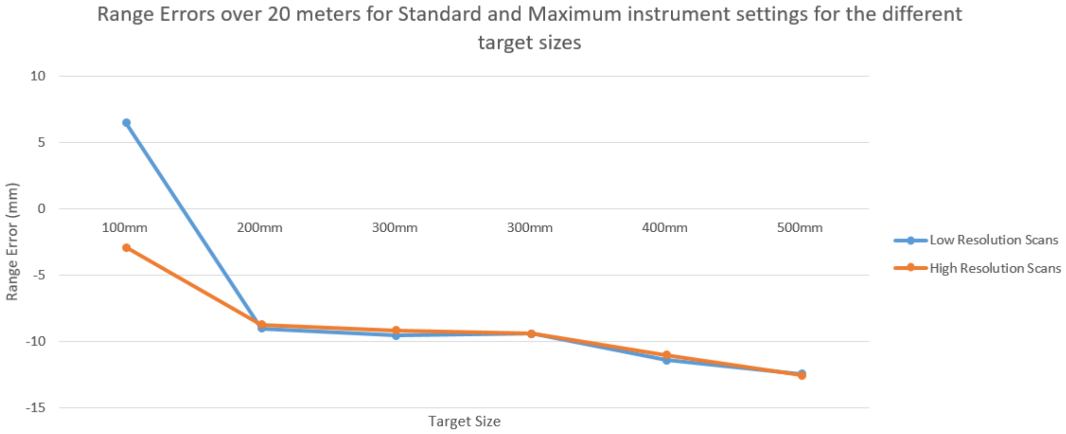


Figure 8.16: Graph showing the error in the derived range for the different target sizes using different instrument settings over a distance of 20 meters.

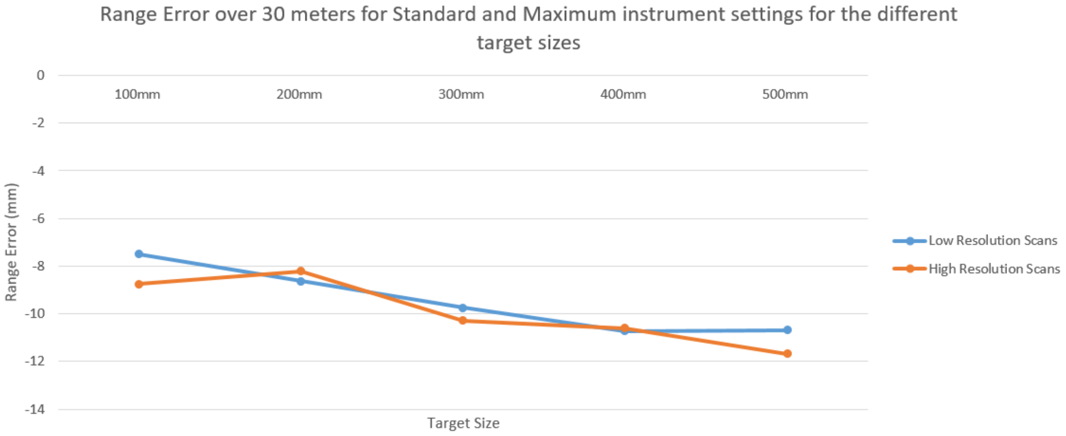


Figure 8.17: Graph showing the error in the derived range for the different target sizes using different instrument settings over a distance of 30 meters.

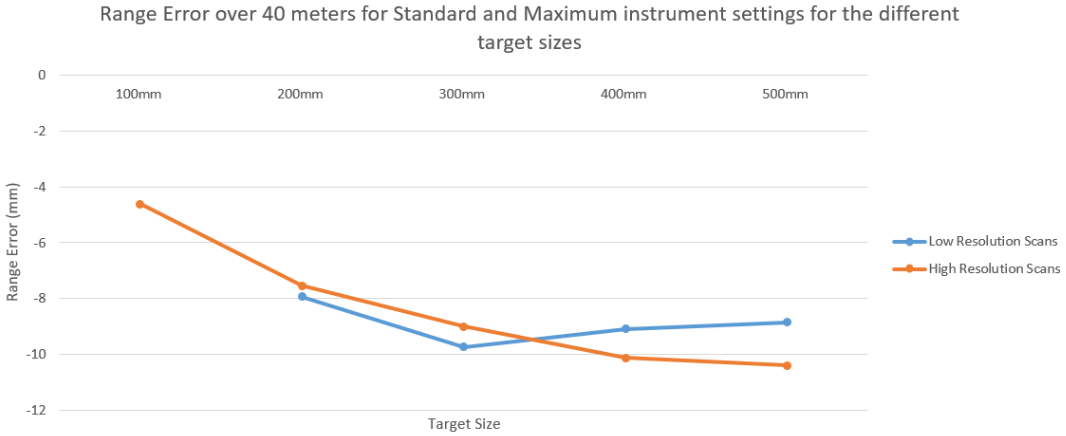


Figure 8.18: Graph showing the error in the derived range for the different target sizes using different instrument settings over a distance of 40 meters.

performed with two tripods approximately 10 meters apart and observations were first taken from the total station to a standard leica circular prism to measure the horizontal distance. The prism was then replaced with the target holder and the smallest target (dimensions of 10cm in width and height). This

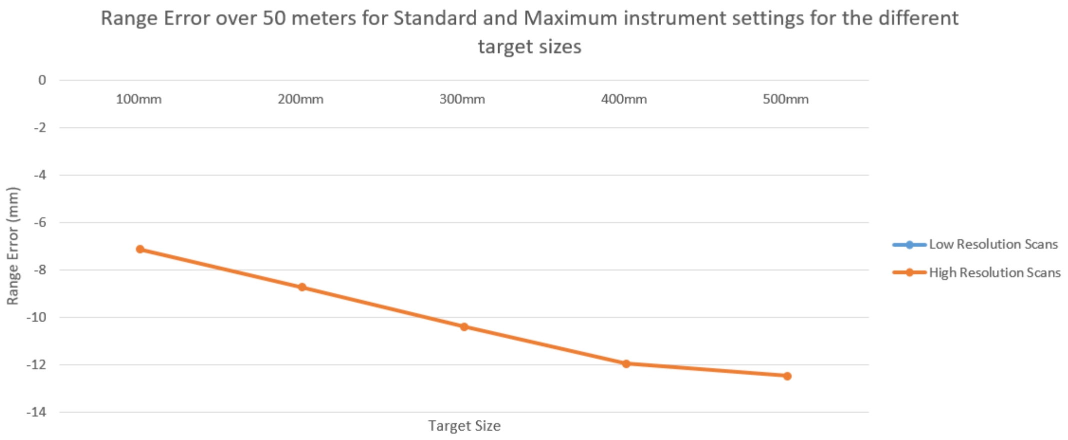


Figure 8.19: Graph showing the error in the derived range for the different target sizes using different instrument settings over a distance of 50 meters.

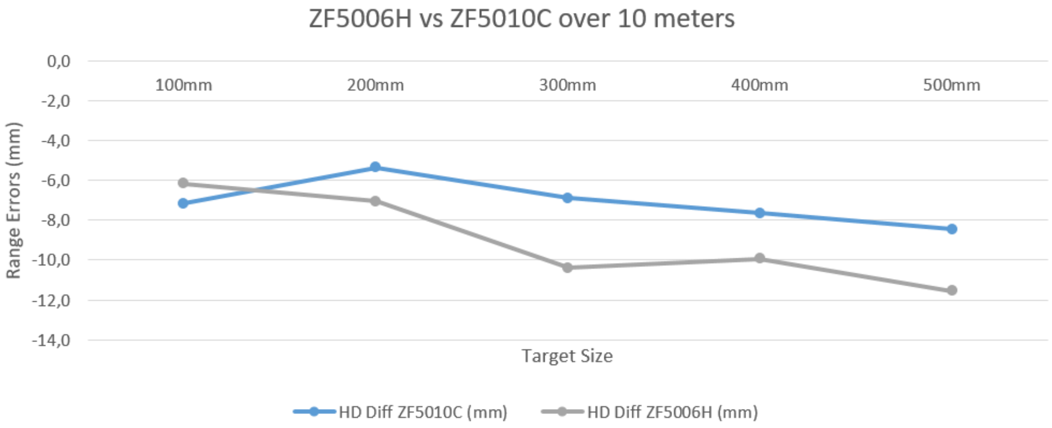


Figure 8.20: Graph showing the comparison of the Z+F 5010C (in blue) and the Z+F 5006H (in grey) based on the range errors of the laser scanner distance (derived from the centre point coordinates) against the surveyed baseline of 10 meters.

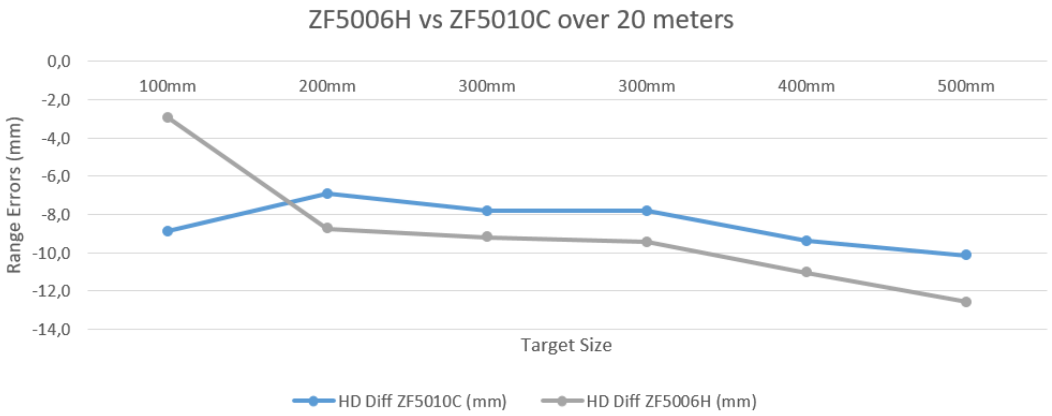


Figure 8.21: Graph showing the comparison of the Z+F 5010C (in blue) and the Z+F 5006H (in grey) based on the range errors of the laser scanner distance (derived from the centre point coordinates) against the surveyed baseline of 20 meters.

target was observed to the top and bottom corners to check the verticality of the target as well as the centre point to determine the horizontal distance to the centre point. This process was repeated using the

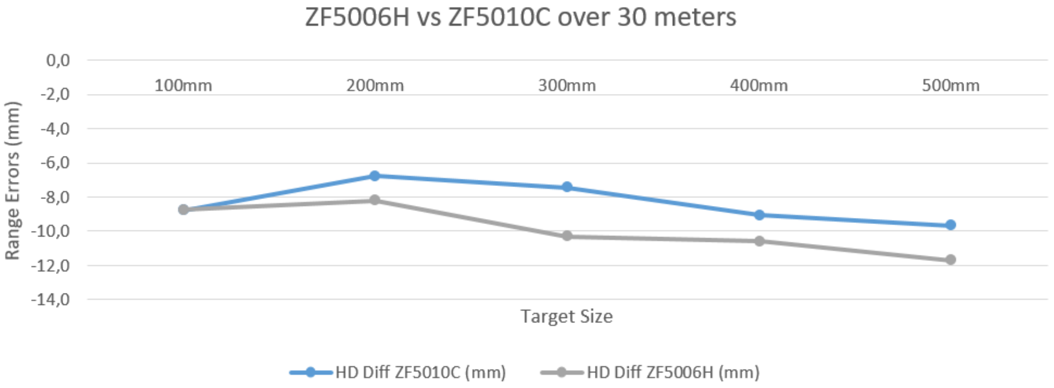


Figure 8.22: Graph showing the comparison of the Z+F 5010C (in blue) and the Z+F 5006H (in grey) based on the range errors of the laser scanner distance (derived from the centre point coordinates) against the surveyed baseline of 30 meters.

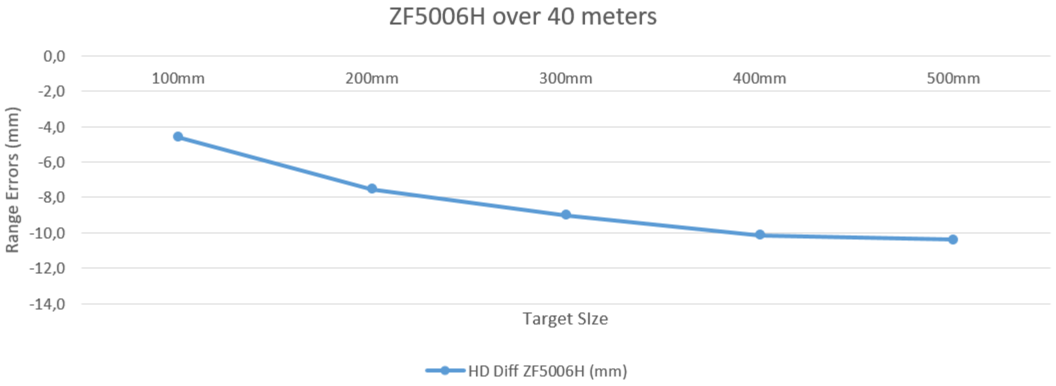


Figure 8.23: Graph showing the comparison of the Z+F 5010C (in blue) and the Z+F 5006H (in grey) based on the range errors of the laser scanner distance (derived from the centre point coordinates) against the surveyed baseline of 40 meters.

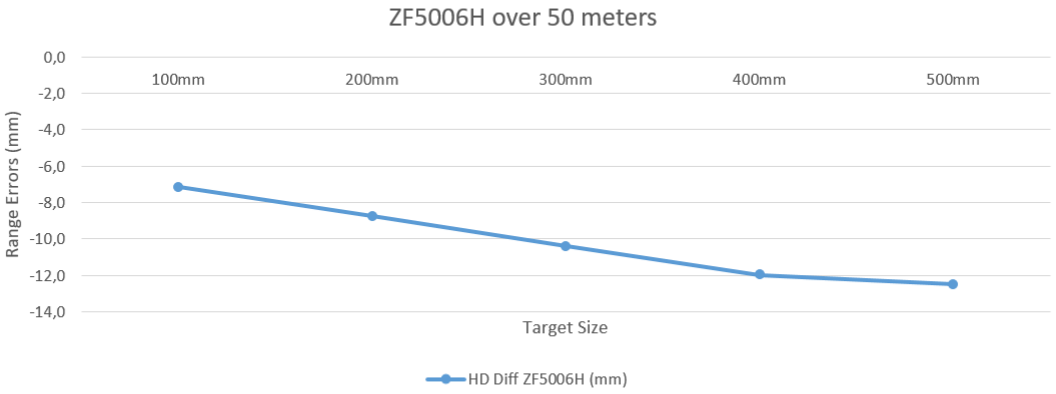


Figure 8.24: Graph showing the comparison of the Z+F 5010C (in blue) and the Z+F 5006H (in grey) based on the range errors of the laser scanner distance (derived from the centre point coordinates) against the surveyed baseline of 50 meters.

larger target of 50cm by 50cm. This exercise was performed in order to determine a possible offset in the position between the prism and the target in the target holder. Such an offset could explain the degrading results with the increased target size that had been experienced in the previous tests.

The results from this exercise showed how the target surface was more irregular as the size increased (not flat due to slight bends and the wind outside, this is not the case if the target it mounted on a wall, with this test performed outdoors, all care was taken to use a sheltered area to have calm conditions and as little movement in the target from the wind as possible). This was evident by the different distances observed for all four corners of the largest target while the smallest target remained relatively constant and flat. The positive outcome from the largest target results were the centre point observations. These remained constant due to the solid back support of the target holder. This gave a constant distance that was exactly 1 centimeter less than the surveyed distance with a prism. This was the same distance given by both target sizes. These results indicated that even with the increase in target dimensions and the un-even surface of the larger targets, the centre positions remained constant distances away from the instrument.

The 1 centimeter offset was added to the previous set of results from the Z+F 5010C laser scanner to investigate its influence on the graphs in figures 8.25, 8.26 and 8.27.

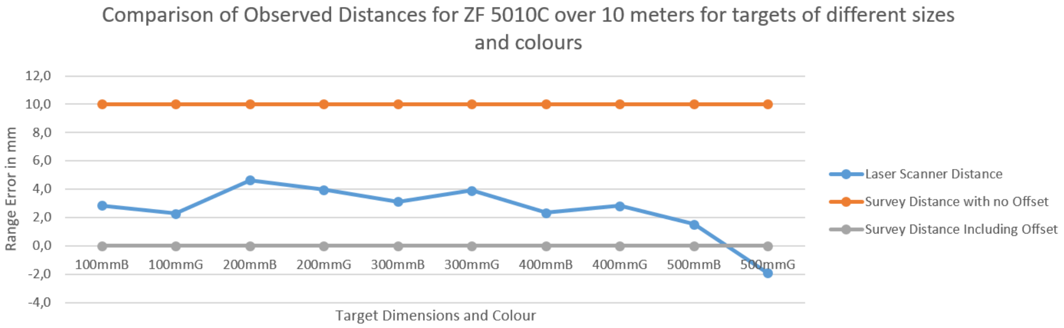


Figure 8.25: Graph showing the difference between the laser scanner observed horizontal distance (blue curve) and the surveyed horizontal distance (orange curve) for the different target sizes and colours over the distance of 10 meters with the addition of the horizontal distance with the applied distance offset (grey curve).

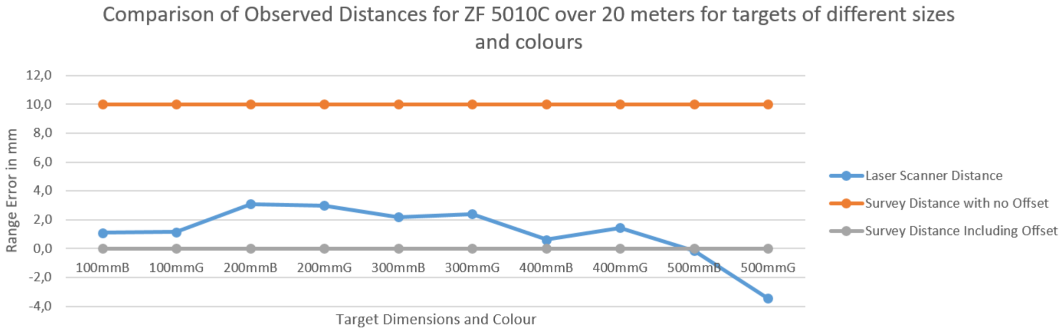


Figure 8.26: Graph showing the difference between the laser scanner observed horizontal distance (blue curve) and the surveyed horizontal distance (orange curve) for the different target sizes and colours over the distance of 20 meters with the addition of the horizontal distance with the applied distance offset (grey curve).

In the previous set of results from the Z+F 5010C the distance errors increased with the increase in

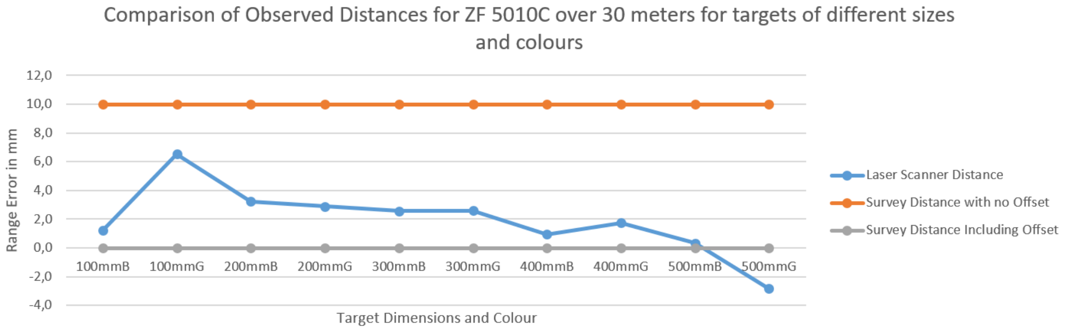


Figure 8.27: Graph showing the difference between the laser scanner observed horizontal distance (blue curve) and the surveyed horizontal distance (orange curve) for the different target sizes and colours over the distance of 30 meters with the addition of the horizontal distance with the applied distance offset (grey curve).

target dimensions which was contradicting the advice given at the outset of the project. This was evident in figures 8.3, 8.4 and 8.5 where the curve drops down from left to right. Referring to the graphs in figures 8.25, 8.26 and 8.27, the same curves are present as before but now with an additional curve for the horizontal distance with the included offset (grey curve). It is now evident that the target size is significant due to the blue curves (horizontal distance observed by the laser scanner) now moving towards the grey curves as the target size increases as opposed to the original data without the offset where they can be seen to move away from the orange curve (horizontal distance measured by total station).
The results of including the offset to the last series of tests with the Z+F 5006H laser scanner can be seen in the graphs in figures 8.28, 8.29, 8.30, 8.31 and 8.32 are produced. These are the results from the instrument on its maximum settings. The results from the standard instrument settings follow the same trends and can be seen in the appendix in figures 11.6, 11.7, 11.8 and 11.9.

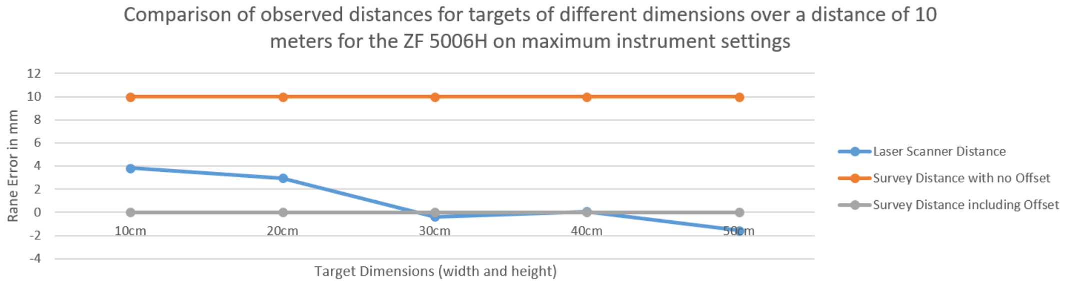


Figure 8.28: Graph showing the comparison of the laser scanner observed horizontal distance for the different target sizes against the surveyed horizontal distance with and without the offset over 10 meters for the instrument on maximum settings.

These graphs compliment the results from the previous graphs and show that the laser scanner range observations for both instruments are performing much stronger than initially noticed. These results are made more significant when the averages of the differences of all the different target dimensions are calculated from the distances observed. The results from the averaged values indicate a trend of improving accuracy with increased target dimensions and can be visualized in table 8.1 for the Z+F 5010C laser scanner and table 8.2 for the Z+F 5006H laser scanner. These results are also able to show how the black targets are performing more accurately than the grey targets as the differences are lower than those of the grey targets.

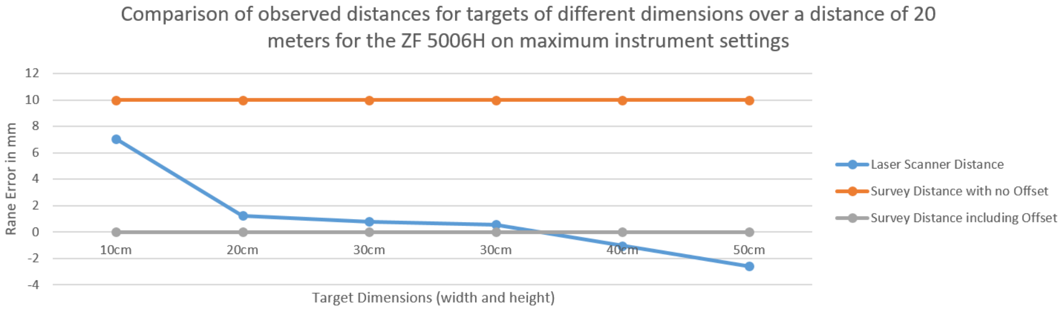


Figure 8.29: Graph showing the comparison of the laser scanner observed horizontal distance for the different target sizes against the surveyed horizontal distance with and without the offset over 20 meters for the instrument on maximum settings.

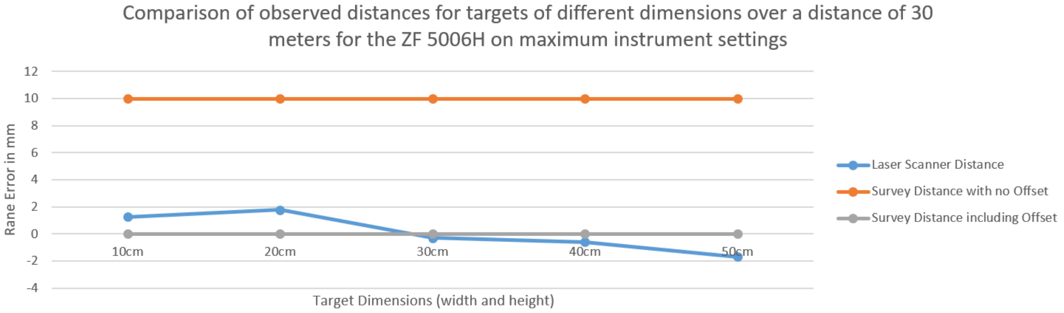


Figure 8.30: Graph showing the comparison of the laser scanner observed horizontal distance for the different target sizes against the surveyed horizontal distance with and without the offset over 30 meters for the instrument on maximum settings.

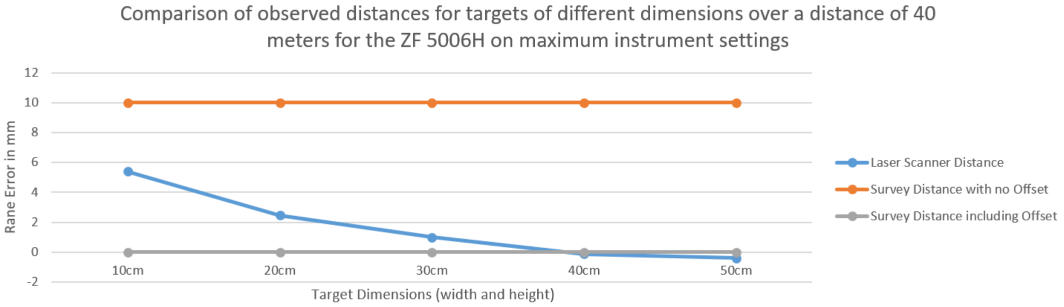


Figure 8.31: Graph showing the comparison of the laser scanner observed horizontal distance for the different target sizes against the surveyed horizontal distance with and without the offset over 40 meters for the instrument on maximum settings.

The purpose of this equipment analysis was to investigate possible influential factors involved in the resulting 3D point cloud from a laser scanner. The relationships that were suspected to exist between the instrument and the target were investigated in order to determine the magnitude of their impact on the derived coordinates for the centre position of the target. The results from this equipment analysis had significant bearing on the decisions made in this research, such as the colours of targets, their dimensions, etc. The fundamental scanning of the facilities will now be discussed having established confidence in the equipment incorporated in this project.

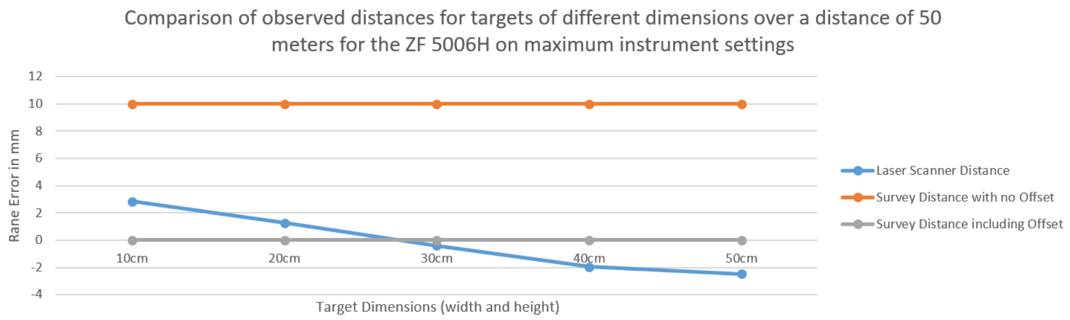


Figure 8.32: Graph showing the comparison of the laser scanner observed horizontal distance for the different target sizes against the surveyed horizontal distance with and without the offset over 50 meters for the instrument on maximum settings.

Table 8.1: Target Size Performance over all distances by the Z+F 5010C laser scanner.

Z+F 5010C			
Black Targets		Grey Targets	
Target Size (width and height)	Average of differences between Laser Scanner and Total Station for all distances (mm)	Target Size (width and height)	Average of differences between Laser Scanner and Total Station for all distances (mm)
10cm	1.7	10cm	3.3
20cm	3.7	20cm	3.3
30cm	2.6	30cm	3.0
40cm	1.3	40cm	2.0
50cm	0.6	50cm	-2.7

8.2 Scanning the Short Range Facility

A set of test scans was performed in order to run through the scanning procedure and to pick up on any mishaps to eradicate them in the future. The scanner used in this first test on the 29^{th} of February 2016 was the UCT owned scanner, a Zoller + Frolich (Z+F) 5010C. Three scans were observed at three different orientations (scanner was remounted without moving tribrach and aimed in a different direction each time using the feet that insert into the tribrach). The settings were on Normal Resolution and High Quality resulting in a set of three 6 minute scans. These scans indicated that all the targets were clear and visible but the resolution and quality could be increased to ensure the most suitable settings for the space were being used.

A further set of 3 scans scan was performed on the 13^{th} of May 2016 using increased settings resulting in a set of 16 minute scans with higher resolution and quality (Resolution = SuperHigh and Quality = High). This scan was done to be able to compare the results from both scan settings and make a decision on which to use for the rest of the testing and then to keep these settings constant between different laser scanners throughout the testing. Whichever option was selected would then be kept constant between successive testing to ensure that scanners of different makes and designs could be setup to have the same or as close as possible to these adopted scan settings. Settings of Super-high Resolution and High Quality were chosen as they were high enough to capture sufficient data and did not present computational difficulties. Any more would be unnecessary and the computer processing would suffer and in some

Table 8.2: Target Size Performance over all distances by the Z+F 5006H laser scanner.

Z+F 5006H	
Black Targets	
Target Size (width and height)	Average of differences between Laser Scanner and Total Station for all distances (mm)
10cm	4.1
20cm	1.9
30cm	0.2
40cm	-0.7
50cm	-1.7

cases would not even open. In upcoming sections ”window scans” or scans that only capture a selected portion of the entire FOV will be utilized. Window scans are rarely used in typical scanning projects. They do however become useful in the case where the user is interested in a particular section of the FOV. In a testing scenario there is a need to check the overlap of the full sphere of points in a scan which would require a full scan. Another benefit of a full scan is the ability to locate errors anywhere around the instrument, whereas if a window scan is used and the error is outside of the window then no error will be detected. The benefit of a window scan (as will be seen in a later section) is the ability to use the maximum instrument settings to evaluate instrument’s accuracy.

As with the surveying of the room, the target directly above the instrument (R3) was once again difficult to capture and resulted in this target not being visible in the scan and not being used. This was noted for the positioning of the targets within the medium range facility to avoid any targets at extremely low or high vertical angles.

The last scan of the venue with the Z+F 5010C was performed on the 28^{th} of July 2016 and was captured due to the need for a 360 degree scan. There are functions within the Z+F software that require a full 360 degree scan (essentially scanning all surfaces twice) in order to compare the first 180 degrees to the second. The settings were kept the same as the previous scan but now making the full 360 degree rotation. This new 360 degree scan would have the benefits in the software of viewing scanner performance reports and viewing different plan views to see and interpret both halves of a scan. This is useful to ensure that the two halves are fitting on top of each other perfectly as well as indicate any deviations in the scanner between the two halves that could indicate malfunctioning.

8.3 Scanning the Medium Range Facility

A single test scan of UCT sports center was captured on the 28^{th} of June 2016 with the Z+F 5010C. This was a scan to examine the field of view from the first installed mount in order to determine the positions of the next two and whether they were all ”inter-visible”. The scan was a 16 minute scan (13 minutes to scan and 3 minutes to capture the images for colour). The scans took place at 18h30 at a temperature of 13 degrees inside the sports center at the position of the mount (WD4). The time and temperature were recorded to notice any deviations due to temperature inside the building. The temperature was constant throughout the scan.

Figure 8.33: Image of the laser scanner running a test scan to analyze the field of view from this location.

An official scan of the sports center was carried out with the Z+F 5010C on the 3^{rd} of November at 7pm, this delay in progress was due to many problems on the campus by the student protests and the scanner being used elsewhere.

This new series of scans now included the now coordinated targets. Instead of a single scan at one location, a new approach was used here for the larger facility. It was decided to use two of the mounts as setup locations, WD4 and WD5. WD4 would serve as the setup for angular testing (main setup location) due to its centralized location and the ability to view all the targets from that position. WD5 was the 'range testing setup' and when the scanner was placed there, the only measurement that is of concern is the range observation to the target that was setup over WD3. From this setup four additional targets were measured to serve as checks on the observations alongside the observation to WD3, these targets were B4, W1, B6 and U1 as they have a good spread around the room and could be seen from this location with the greatest ease. An observation to WD4 was also included as a checking observation. A sketch of this scenario can be seen in figure 8.34.

As mentioned a single scan was not used here, instead a set of two scans per setup were used. First a 180 degree scan and then a 360 degree scan at both WD4 and WD5. This use of the two different size scans was to analyze any change or find any reason for one being more significant than the other in terms of the accuracy and to be able to manually select the targets in both halves of the 360 degree scans. This resulted in a set of four scans from that evening, two 180 degree scans at 13 minutes each and two 360 degree scans at 26 minutes each. The settings were held fixed on SuperHigh Resolution and High Quality. The temperature on the evening was around 18 degrees and remained constant for the duration of the scanning.

A further set of four scans were captured on the 20^{th} of January 2017. These scans were window scans captured from the setup over WD5 and focused on the target setup at WD3. The instrument settings (resolution and quality) were increased in order to capture enough of the target surface as a result of the large range between these two positions. This distance is roughly 70 meters and the first large target had dimensions of 50 cm by 50 cm which proved to be very small in the scans and not enough information

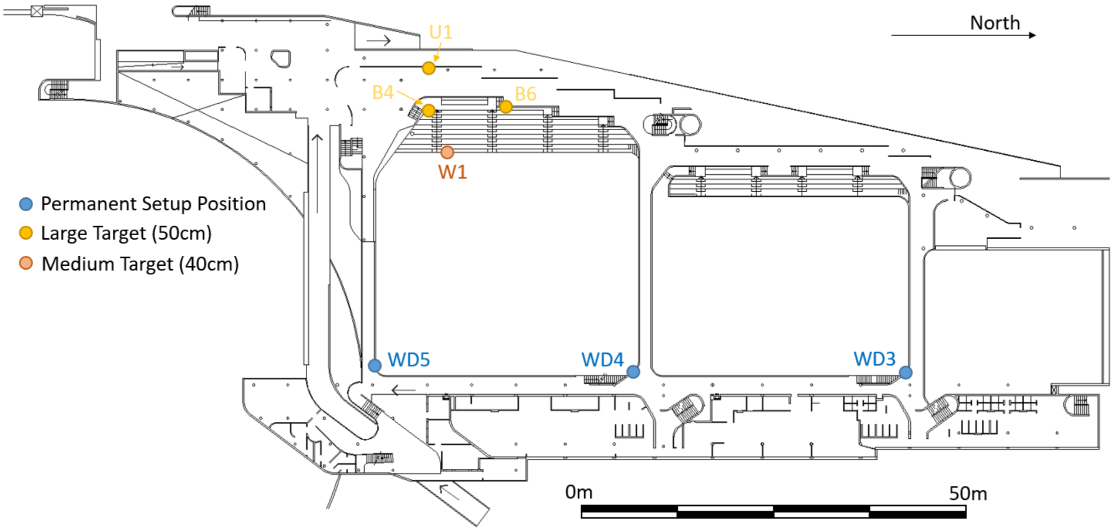


Figure 8.34: A Sketch of the Medium testing facility including the targets used during the observation from the Laser Scanner for the distance testing. The primary observation ray is from WD5 to WD3 but observations to B4, W1, B6, U1 and WD4 were included to serve as checks.

was being captured on the target surface to give reliable coordinates. This meant the target surface areas needed to be increased. Thereafter there was a need to confirm that the target size increase and the same settings did in fact improve the ability to derive the coordinates or not. Another second scan was captured from the same setup with the same window over the target at WD3 with settings increased to full Resolution capabilities and as high on Quality as the machine would allow. This scan was captured in order to analyze whether or not the resolution would have an impact on the coordinates and therefore the distance calculated. This process was repeated at position WD4. The resulting scan projects were significantly smaller and the computer was able to handle the information more efficiently than the entire scan if these settings had been used (the first scan at each setup lasted about 40 seconds and the second scan lasted approximately 4 minutes).

The procedure involved in selecting a section of the FOV to create a window scan can be described briefly as follows; the laser scanner was aimed (as best as one could) towards the target to create the edges of the window in the horizontal. The vertical was more of a challenge because the angle was chosen by the user on-board the instrument as there was no way of aiming the laser itself (the best option was to best guess a vertical section that would cover the target, for example if the target was at the same height as the instrument, a suitable estimate would be between 80 and 100 degrees (depending on the size of the target)).

The scans of the two facilities were conducted in such a way as to test the instrument in terms of its performance with respect to the angle and distance observations. At the end of the scanning stage there were a collection of scans with various settings, operating ranges, FOV variations and orientations. Some of the scans were needed to investigate the Laser Scanner settings available and other scans were for the extraction of the target coordinates for the comparison against the surveyed data. The coordinates from the final series of scans in each venue were used for the comparisons that followed in the upcoming sections. Tables summarizing the scans captured from both facilities can be seen in tables 8.3, 8.4 and 8.5 respectively.

Table 8.3: Summary of the scanning conducted in the Short Range Testing Facility by the Z+F 5010C Laser Scanner.

Scanning of Short Range Testing Facility by the Z+F 5010C Laser Scanner		
Instrument:	Z+F 5010C	
29 FEB 2016	Method	3 scans, 180 degree scans, 3 different orientations
	Settings	Normal Resolution High Quality
	Scanning Conditions	Daytime scan
13 MAY 2016	Method	3 scans, 180 degree scans
	Settings	SuperHigh Resolution High Quality
	Scanning Conditions	Daytime scan
28 JUL 2016	Method	1 scan, 360 degree scan
	Settings	SuperHigh Resolution High Quality
	Scanning Conditions	Daytime scan

Table 8.4: Summary of the scanning conducted in the Medium Range Testing Facility by the Z+F 5010C Laser Scanner.

Scanning of Medium Range Testing Facility by the Z+F 5010C Laser Scanner		
Instrument:	Z+F 5010C	
28 JUN 2016	Method	1 scan, 180 degree scan
	Settings	SuperHigh Resolution High Quality
	Scanning Conditions	Evening scan, 18h00 13 Degrees Celcius
03 NOV 2016	Method	4 scans, 2 locations, 2 x (180 degree scan and 360 degree scan)
	Settings	SuperHigh Resolution High Quality
	Scanning Conditions	Evening scan, 19h00 18 Degrees Celcius
20 JAN 2017	Method	4 scans, ”window” scans
	Settings	SuperHigh Resolution, High Quality for the first scans at each setup UltraHigh Resolution, High Quality for the second scans at each setup
	Scanning Conditions	Evening scan, 18h00 17 Degrees Celcius
30 AUG 2017	Method	10 scans, ”window” scans
	Settings	High Resolution, Normal Quality for the first scans for each material ExtremlyHigh Resolution, High Quality for the second scans for each material
	Scanning Conditions	Evening scan, 18h00 17 Degrees Celcius
30 AUG 2017	Method	6 scans, ”window” scans
	Settings	ExtremlyHigh Resolution, High Quality for each incidence angle
	Scanning Conditions	Evening scan, 19h00 17 Degrees Celcius
16 OCT 2017	Method	3 scans, full 360 degree scans each rotated 120 degrees
	Settings	SuperHigh Resolution, Normal Quality
	Scanning Conditions	Daytime scan, 11h00 20 Degrees Celcius

Table 8.5: Summary of the scanning conducted in the Medium Range Testing Facility by the Z+F 5006H Laser Scanner.

Scanning of Medium Range Testing Facility by the Z+F 5006H Laser Scanner		
Instrument:	Z+F 5006H	
15 SEPT 2016	Method	50 scans, ”window” scans
	Settings	High Resolution, Normal Quality for the first scans for each size UltraHigh Resolution, High Quality for the second scans for each size
	Scanning Conditions	Evening scan, 19h00 16 Degrees Celcius

Chapter 9

Results and Analysis of Laser Scanner Testing

9.1 Introduction

Up till this point, coordinate networks for both facilities have been established to the best of the ability of the technology available. The total station used observations of distance and angle to determine coordinates of the targets for each of the networks in both the short and medium range facilities. These observations and their respective coordinates can be compared to the laser scanner. Those same coordinate networks have been scanned on multiple occasions using a variety of settings and conditions (refer to the table at the end of the previous chapter). The laser scanner outputs coordinates based on a series of observations of distance and angle. These coordinates can be used to derive the observations. Those observations can then be compared to those of the total station. The same comparison can be done using the coordinate values themselves from both devices.

From the comparison of the laser scanner against a form of control (the total station observations forming a control network), the differences will be calculated to investigate the deviation of the laser scanner observations, as well as investigate the variation in two halves of the same scan. This is possible due to the fact that a single 180 degree scan captures the full FOV once and a 360 degree scan captures the FOV twice. It is these two 'halves' from a 360 degree scan that can be investigated further. Additional comparisons may be useful between successive scans of the same venue to investigate any deviations which may be the result of the system degrading over time. This would be achieved by planned regular scans of the same scene to monitor the performance over time to identify any errors as they begin to appear. For this research the differences will be examined based on distance, angle and direct coordinate comparisons.

The methodology can be visualized in the flow diagram in figure 9.1 illustrating the processes involved from beginning to end of the establishment of the two testing facilities and the outcomes.

9.2 Data Processing

Multiple scans were captured in both the short range and medium range facilities, resulting in several scans with various settings as per the table at the end of the previous chapter. Each of these scans was

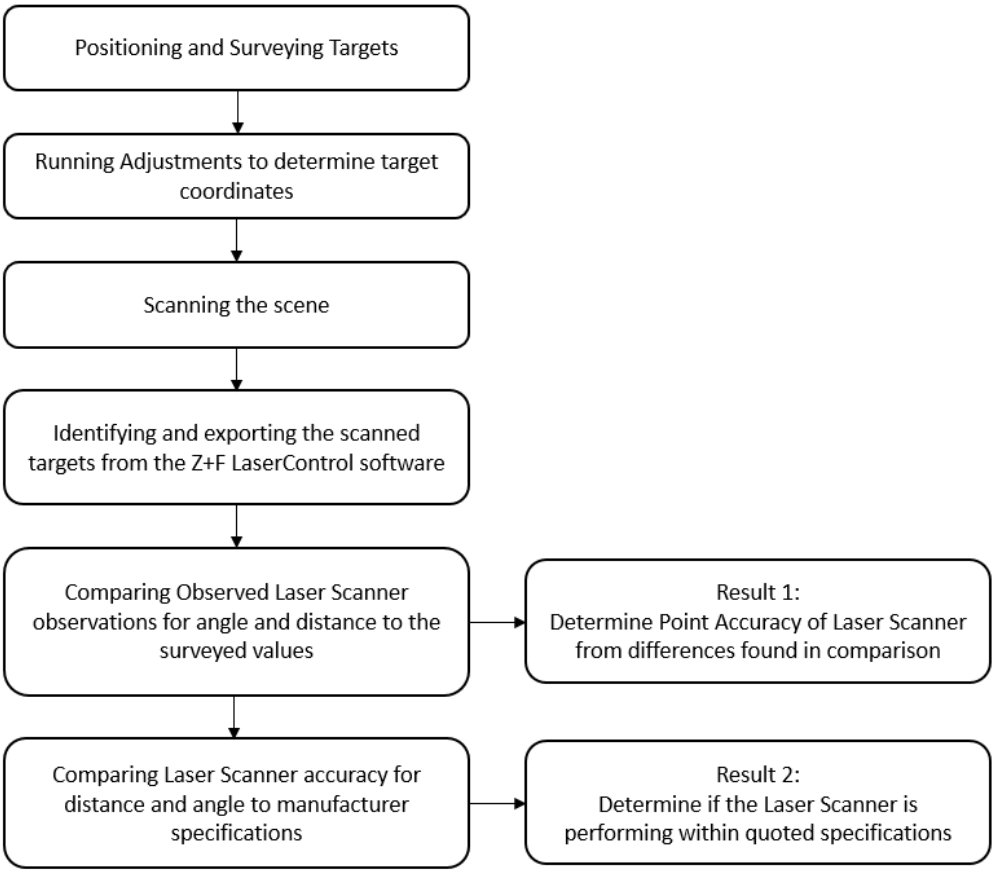
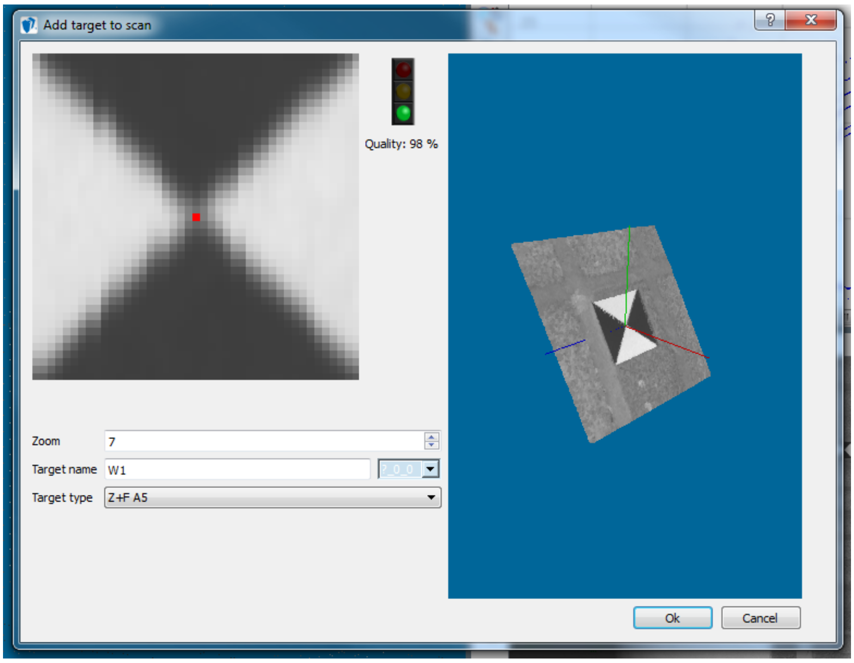


Figure 9.1: Flow diagram illustrating the process involved in the establishment of the two testing facilities from the positioning of targets to the outcomes from the testing of a particular laser scanner.

necessary to examine the options of horizontal range, resolution and quality on-board the laser scanner. The different options for the resolution and quality were investigated to determine their impact on the determination of the target centre point coordinates.

From each of the scans there was a set of coordinates that must be extracted. In order to do this a software called Z+F LaserControl was used to open and inspect the scans (this software was chosen due to the use of a Z+F 5010C laser scanner and its compatibility with this software). A screen grab of the LaserControl software from Z+F can be seen in the appendix in figure 11.3. The software allowed for two methods of identifying targets; either manually locating the centre point for each individual target or using a more automated approach after generally locating the target within the scene. Both methods were investigated to determine any difference between the two approaches. An example of the target selection window involved in the first method can be seen in figure 9.2.

With regards to the medium range facility scans, special attention was paid to the instrument-target range. The increased range in this venue resulted in some of the targets being deemed ”bad quality” by the software due to the lack of information on the target surface to confidently determine the centre point. This meant ensuring the target centre that was identified by the software was with the highest confidence before proceeding to the next target.



Quality: 98 %

Zoom 7

Target name W1

Target type Z+F A5

Figure 9.2: A screen shot of the window used in the identification of targets and their naming within the Z+F LaserControl software. The level of confidence can be seen in the upper middle along with where the software has found the center point and the naming allocation in the bottom left.

Once the targets had been identified from either of the two methods and exported, there was now a list of 3D coordinates for the centre points of all of the targets within the scene for each scan. At this point there were now two sets of coordinates per scan; the target centre coordinates from the laser scanner as well as the high accuracy surveyed coordinates. This procedure was the same for a scan with the horizontal range of 360 degrees or a window scan. Scans with a horizontal range of 360 degrees had an additional set of coordinates due to there being two halves of the single scan (each half had it's own set of coordinates for the targets). The target identification process can be visualized using the flow chart in figure 9.3.

In order to perform any comparisons of the laser scanner against the surveyed data, it was first necessary to establish what parameters would be compared. In this case the comparisons were based on distances and angles between the instrument position and the targets. In order to make this comparison possible the laser scanner observations of x, y and z coordinates needed to be transformed into observations of distances and angles based on the centre of the instrument. These were determined through join calculations.

The join calculations were used to determine the following observables for both the laser scanner and the surveyed coordinates; horizontal distance, vertical distance, slope distance, horizontal and vertical angles. Although the laser scanner is only able to deliver 3D coordinates, those coordinates themselves are based on observations of distance and angle. The use of these observables is to examine all of the base observations that are used to derive any coordinates in 3 dimensions. Thus far there have been a set of observations from the surveyed coordinates and the laser scanner coordinates, in the form of the five base observables mentioned above.

The observables were all determined in an Excel spreadsheet where the direct comparisons were also examined. Each observable (horizontal distance, vertical distance, slope distance, horizontal and vertical

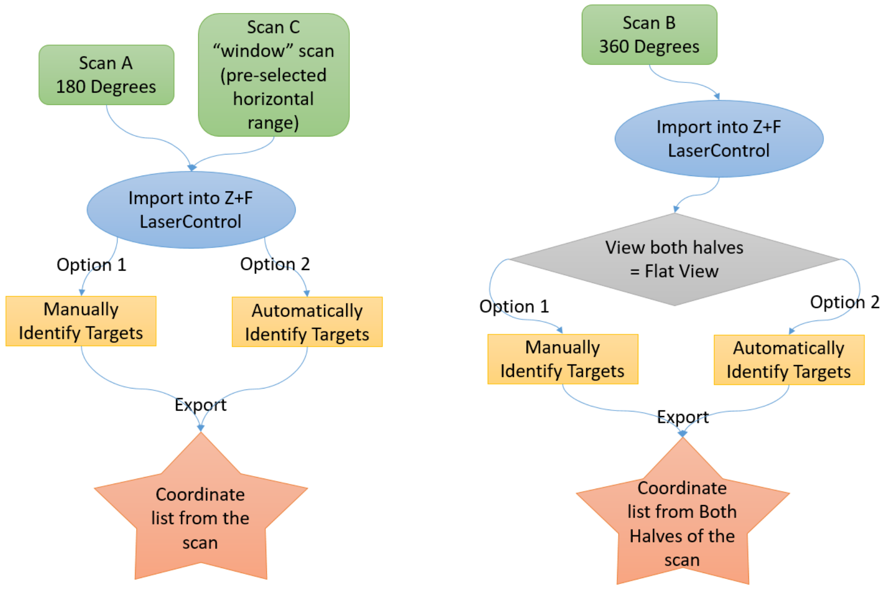


Figure 9.3: Flow charts depicting the process involved in obtaining the coordinates of known reference points within scans of different horizontal ranges using the Z+F LaserControl software.

angles) from both the surveyed (control) values and the laser scanner (observed) values was compared against one another to identify the difference between the laser scanner and the control data. These differences allowed valuable information to be deduced about the laser scanner in question.

The differences were further examined through statistical measures of dispersion. The mean and standard deviation of the differences were used for the interpretation of the performance of the laser scanner. The window scans allowed for much faster scan times with the higher instrument settings in order to evaluate the range accuracy of the laser scanner. The target coordinates that were extracted from these scans were used to determine the range from the laser scanner to the target which was then compared to the same range as observed by the total station.

9.3 Data Analysis

The methodology followed thus far has led to the creation of a high accuracy 3D coordinated target network. The need for this control network was in order to have a baseline set of data to compare the laser scanner performance against. These targets have been scanned and the corresponding targets identified within each scan to extract the laser scanner coordinates for those targets. The laser scanner does not capture specific coordinates for individual features within its scene and relies on the user to perform this task using the methods mentioned above. Once those coordinates had been identified and exported it was possible to perform a comparison of the laser scanner against a control in the form of the high accuracy coordinates for the reference points (targets).

The reason for testing in facilities with different dimensions was to investigate the performance accuracy of a laser scanner at a different scales. The short range facility was aimed at close range scanning and angular performance, while the medium range facility offered larger range values and allowed for the specific testing of the range performance of the laser scanner.

The comparison between the surveyed coordinates and laser scanner coordinates required the use of more meaningful data which led to the derivation of the base observables of distance and angle for each target coordinate. The comparison of the coordinates alone would deliver significant results but in order to expose more detailed results, the coordinates were broken down into their simplest observations using the five base observables (Horizontal Range (HR), Height Difference (HD), Slope Range (SR), Horizontal Angle (HA) and Vertical Angle (VA)). These quantities are useful because they reveal more information about the differences between the control data and the laser scanner data and give better indications of where the errors may exist (as opposed to in the x, y or z directions if only analyzing the coordinate differences). It is possible to perform such a comparison due to the fact that although the point cloud is in the form of x, y and z coordinates these values are derived through the observations of distances and angles from the laser scanner. It is also made easier through this comparison, to identify errors in the observations from the instrument (and not in the deliverables) in the horizontal and vertical planes.

Through examination of the differences between the laser scanner and the control data it is possible to evaluate the performance of the laser scanner. The exact differences and patterns within these differences are able to give indications of the quality of the results that will aid in decisions about the use of the laser scanner for particular tasks along with other decisions regarding the required deliverables from the scans.

The range testing using the window scans allowed for additional comparisons between the laser scanner range and the surveyed range to evaluate the range accuracy. These window scans were used for the investigation into the performance of the range observations from the laser scanner over the 70 meter baseline between the stations WD3 and WD5. These scans were useful to examine the maximum potential of the laser scanner based on it's highest settings. These high settings would output the best possible scans of the surface within the window that was selected, which would give the best possible centre point coordinates for the target and therefore indicate the true potential of the laser scanner (for its range measurements under these conditions).

Table 9.1 shows the distances observed by both the total station and laser scanner in the medium range facility, for the half scan (180 degrees) and full scan (360 degrees) from two locations towards the target located at WD3. The first location was at the main setup location at WD4 and the other is at the range testing setup at WD5. The observed distance was evaluated in terms of its three components; Horizontal Range, Height Difference and Slope Range. Table 9.2 shows the window scans whereby the instrument was aimed towards the target mounted at WD3 with two different options for the instrument settings and over two different baselines (roughly 35 and 70 meters). The first section of this table shows the results from a set of window scans using standard instrument settings for resolution and quality (these settings are increased in resolution from the previous standard settings due to the increased range of the facility). The second section displays the results from additional window scans with the settings on the highest available options (these extra scans were done to analyze the effect of increasing the settings on the measured range by the laser scanner and to examine the maximum potential of the laser scanner). These two tables indicate the difference between the laser scanner (observed) and the true (calculated) values for distance only (in red) while at the same time showing the differences in the results from the various laser scanner settings that are available as well as from a window scan.

In order to visualize the performance of the laser scanner within the medium testing facility, with re-

Table 9.1: Medium Range Testing Facility Distance Evaluation. A comparison of a set of observed distances from the laser scanner to the surveyed values over the high accuracy baselines between WD3 and WD5 with a range of approximately 70 meters.

Distance Evaluation from Observations captured from a full scan				
Instrument:	Z+F Imager 5010C			
Distance Testing				
Scan position: WD5	Target: WD3			
Range: approx. 70 meters				
Instrument Settings:		Resolution = SuperHigh Quality = High		
Scan Size		180 Degrees	360 Degrees	
			First Half	Second Half
Laser Scanner Distance (m)	**Horizontal Range**	70.0101	70.0093	70.0106
Total Station Distance (m)		70.0131	70.0131	70.0131
Difference (mm)		3.1	3.9	2.6
Laser Scanner Distance (m)	**Height Difference**	-0.4931	-0.6059	-0.4943
Total Station Distance (m)		-0.5690	-0.5690	-0.5690
Difference (mm)		-75.9	36.9	-74.7
Laser Scanner Distance (m)	**Slope Range**	70.0118	70.0119	70.0123
Total Station Distance (m)		70.0155	70.0155	70.0155
Difference (mm)		3.7	3.5	3.1

spect to the five observables, the graph in figure 9.4 can be examined. The graph displays the standard deviations of the five observables (Horizontal Range (HR), Height Difference (HD), Slope Range (SR), Horizontal Angle (HA) and Vertical Angle (VA)).

The graph in figure 9.4 shows how there is a significant weakness in the vertical observations resulting in the high error values for the Height Difference and Vertical Angle results. This may be attributed to the increased magnitude of the testing facility, coupled with the possible error in the vertical readings from the instrument. A similar trend was noticed in the research by Reshetyuk (2006) and Chow et al. (2010).

In order to interpret the angular results from the short range and medium range facilities, a single table can be used to illustrate the accuracy performance of the laser scanner. This can be visualized in table 9.3, which shows the direction and angle accuracies for the short and medium range facilities against the surveyed values and manufacturer specified values. The accuracies of the true/calculated values were determined using the formula; $s = r\theta$. The total station is quoted to have a single second accuracy for angles, which allowed the use of the formula; $s = r\theta$ over a maximum range of 70 meters to determine the maximum allowable angular accuracy (70 meters was chosen to encompass the maximum observed distances in the facilities excluding the range testing baseline). Also included are the manufacturer specifications for the ”Horizontal Resolution” and ”Vertical Resolution”. These values represent the requirements of the directions and angles by the laser scanner to conform with the manufacturer specifications. These along with the other specifications for the Z+F 5010C laser scanner can be seen in

Table 9.2: Medium Range Testing Facility Distance Evaluation using ”window” scans. A comparison of a set of observed distances from the laser scanner to the surveyed values over the high accuracy baselines between WD3, WD4 and WD5. These comparisons use two different options for the instrument settings of resolution and quality as well as including two range values for the baselines of approximately 35 (WD3 and WD4) and 70 meters (WD3 and WD5).

Distance Evaluation from Observations captured from a ”window” scan				
Instrument:	Z+F Imager 5010C			
Range Evaluation	Scanning with a Manually Selected Window			
Instrument Settings:		Resolution = SuperHigh Quality = High		
Range: approx. 70 meters				
Scan position: WD4	Target: WD3	**Horiontal Range**	**Height Difference**	**Slope Range**
Laser Scanner (m)		35.8654	0.2444	35.8663
Total Station (m)		35.8559	0.2542	35.8568
Difference (mm)		9.6	-9.8	9.7
Scan position: WD5	Target: WD3	**Horizontal Range**	**Height Difference**	**Slope Range**
Laser Scanner (m)		70.0275	-0.3949	70.0286
Total Station (m)		70.0131	-0.3560	70.0140
Difference (mm)		14.3	-38.9	14.5
Instrument Settings:		Resolution = UltraHigh Quality = High		
Range: approx. 70 meters				
Scan position: WD4	Target: WD3	**Horizontal Range**	**Height Difference**	**Slope Range**
Laser Scanner Distance		35.8656	0.2452	35.8664
Total Station (m)		35.8559	0.2542	35.8568
Difference (mm)		9.7	-9.0	9.7
Scan position: WD5	Target: WD3	**Horizontal Range**	**Height Difference**	**Slope Range**
Laser Scanner Distance		70.0272	-0.3965	70.0283
Total Station (m)		70.0131	-0.3560	70.0140
Difference (mm)		14.0	-40.5	14.6

the Appendix in figure 11.10.

The values in table 9.4 show a full analysis of the laser scanner in terms of the five different observables (Horizontal Range (HR), Height Difference (HD), Slope Range (SR), Horizontal Angle (HA) and Vertical Angle (VA)) along with the mean and standard deviations of the differences between the observed and true values (the distances are given in millimeters and the angles are given in decimal degrees). Both the mean and standard deviation are significant measures of dispersion. The standard deviation is the factor that is able to determine the accuracy of the instrument. In this case the standard deviation gives an indication of how well the observed values from the laser scanner performed against those true values in the form of the control network of targets.

The Height Difference and Vertical Angle were the highest of the quantities for the three scans within

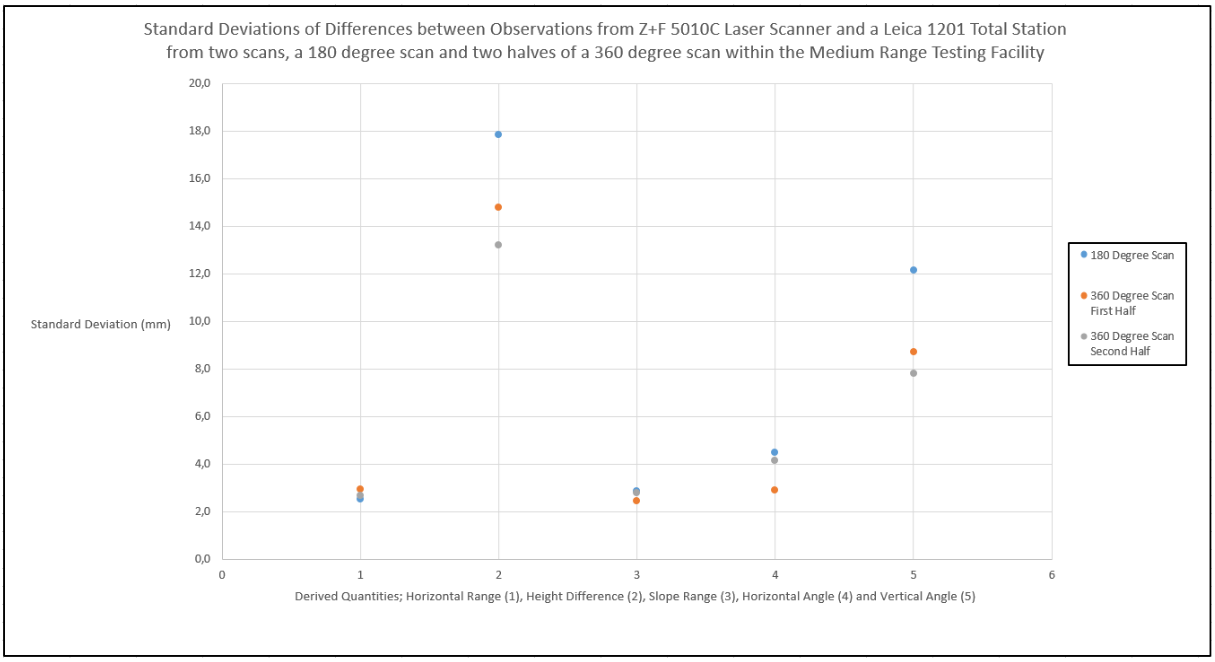


Figure 9.4: Standard Deviations of the five observable quantities from the laser scanner that result in the 3D point cloud coordinates captured within the Medium testing facility.

both facilities. This trend may be indicating a possible error in the vertical readings from the instrument which may be the result of poorly observed vertical angles. The Horizontal Range, Slope Range and Horizontal Angle were the strongest values, indicating the strongest elements in the observations from the laser scanner. The values are all larger in the medium range facility which can be attributed to the larger ranges encountered.

The original data comparisons can be seen in the appendix in figures 11.4 and 11.5 to show the variation in the differences between the observed and true values for the individual points which lead to the large standard deviations within a single scan for the vertical distance and vertical angles.

From the comparisons between the surveyed control data and the scan data along with the comparisons of the individual halves of the same scan there are helpful trends that can be identified from the results to determine the performance of the laser scanner. The comparisons between the control data and the scan data are able to help determine how the laser scanner output is performing to indicate any problems in the observations of the laser scanner.

The comparison of the two halves of the same scan are to identify errors within the scan data alone. Theoretically the two halves of a single scan should align on top of one another with no difference between the two point clouds. If there is a difference it is possible the laser scanner contains an error in its observing and this results in the two halves not aligning perfectly. It is important to notice how the difference between the two halves is displayed. The difference could be a shift from the one half to the other or a scale change resulting in the mis-alignment. To visualize this issue there is a sketch in figure 9.5. Both comparisons are important to understand the inner workings of the laser scanner and identifying any performance issues.

Table 9.3: Final Angular Accuracy Comparisons for directions and angles observed by the laser scanner against the surveyed values and the manufacturer specified values.

Laser Scanner Angular Accuracy Summary				
Instrument:	Z+F Imager 5010C			
Instrument Settings:	Resolution = SuperHigh Quality = High			
	Laser Scanner		True/Calculated	Manufacturer Quoted Resolution
Venue:	Short Range Facility	Medium Range Facility		
Horizontal Direction (degrees)	-0.0045	0.0060	0.0003	0.007
Horizontal Angle (degrees)	0.0005	-0.0005	0.0003	0.007
Vertical Direction (degrees)	-0.0327	-0.0514	0.0003	0.007
Vertical Angle (degrees)	0.0051	-0.0010	0.0003	0.007

Results: Accuracies for Horizontal Directions, Horizontal Angles and Vertical Angles are lower than Manufacturer Specifications
and Accuracies for Vertical Directions are higher than Manufacturer Specifications

The results have been presented to illustrate how the laser scanner results deviated from the control data and how vertical observations from the laser scanner appear to be the weakest of its observations. The latter was confirmed by the subsequent testing in the medium range facility. Although the results can show how the laser scanner performs internally (comparing individual halves of the same scan) as well as against a form of control, the results cannot show the reason for the instrument performing in such a manner. This would require a calibration facility to identify the exact reason for the error attributed to a laser scanner.

Upon inspection of the results from the distance testing using the window scans, visible in table 9.1, it was noticed that there were significant differences in the errors for the different scans, i.e. 180 degree and 360 degree scans. This was evident by the difference between the first and second halves of the 360 degree scan as well as the apparent relationship between the 180 degree scan's result and the second half of the 360 degree scan. In an attempt to investigate these relationships and find a reason for these differences, additional evaluations were performed.

In order to evaluate the different halves/hemispheres of the scans, each scan was opened in the Z+F LaserControl software and the horizontal angle of the scan was used to determine the "faces" or halves of each scan. The two halves were used to compare the angular errors from one halves against the other in order to investigate any differences in their performance. The reasons for these differences were then explored as well as the differences between different scans.

Table 9.4: Medium Range Testing Facility Standard Deviations and Means of the differences between the observed laser scanner data and the surveyed total station data in terms of the five observed quantities for three different scans.

Full scan Evaluation for Laser Scanner in Medium Range Facility

Instrument: Z+F Imager 5010C

Instrument Settings: Resolution = SuperHigh
Quality = High

Angle and Distance Testing

Observable Quantity	HR (mm)	HD (mm)	SR (mm)	HA (degrees)	VA (degrees)
Scan @ WD4: Scan Size = 180 Degrees					
Standard Deviation	2.5	17.8	2.9	0.0172	0.0288
Mean	-2.1	-15.7	-1.9	-0.0005	-0.0010
Scan @ WD4 First Half: Scan Size = 360 Degrees					
Standard Deviation	2.9	14.8	2.4	0.0118	0.0242
Mean	-2.4	13.0	-2.1	-0.0014	0.0027
Scan @ WD4 Second Half: Scan Size = 360 Degrees					
Standard Deviation	2.7	13.2	2.8	0.0136	0.0231
Mean	-2.4	-21.5	-2.0	-0.0008	0.0001
Average of all scans:					
Standard Deviation	3.1	14.2	2.8	0.0087	0.0163
Mean	-1.8	-9.9	-1.7	0.0005	0.0016

Directions were used to determine the angular errors due to their consistency regardless of the distance. A distance or height difference error is proportional to the distance between the surface and the instrument. This idea can be explained in figure 9.6. The distances d1 and d2 are not equal based on their distance from the origin of the observations, but the angles, a1 and a2, are equal at all distances. d1 and d2 represent the surfaces in front and behind the laser scanner at a point in time.

The directions for the two scans, a 180 degree and a 360 degree scan (360 first half and 360 second half), were compared to the surveyed values in terms of horizontal and vertical observations. These differences were plotted with respect to the front half of the each scan and thereafter the back half of each scan. The front half was defined as the FOV viewed by the scanner from the same face from the start of the scanning to the end of the rotation. For a 180 degree scan this means the front half is 180 degrees whereas the 360 degree scans have a front half of 360 degrees. The sketches in figures 9.7 and 9.8 will help to explain this. In theses figures the target angle errors were compared for the targets in the green face against the targets in the blue face.

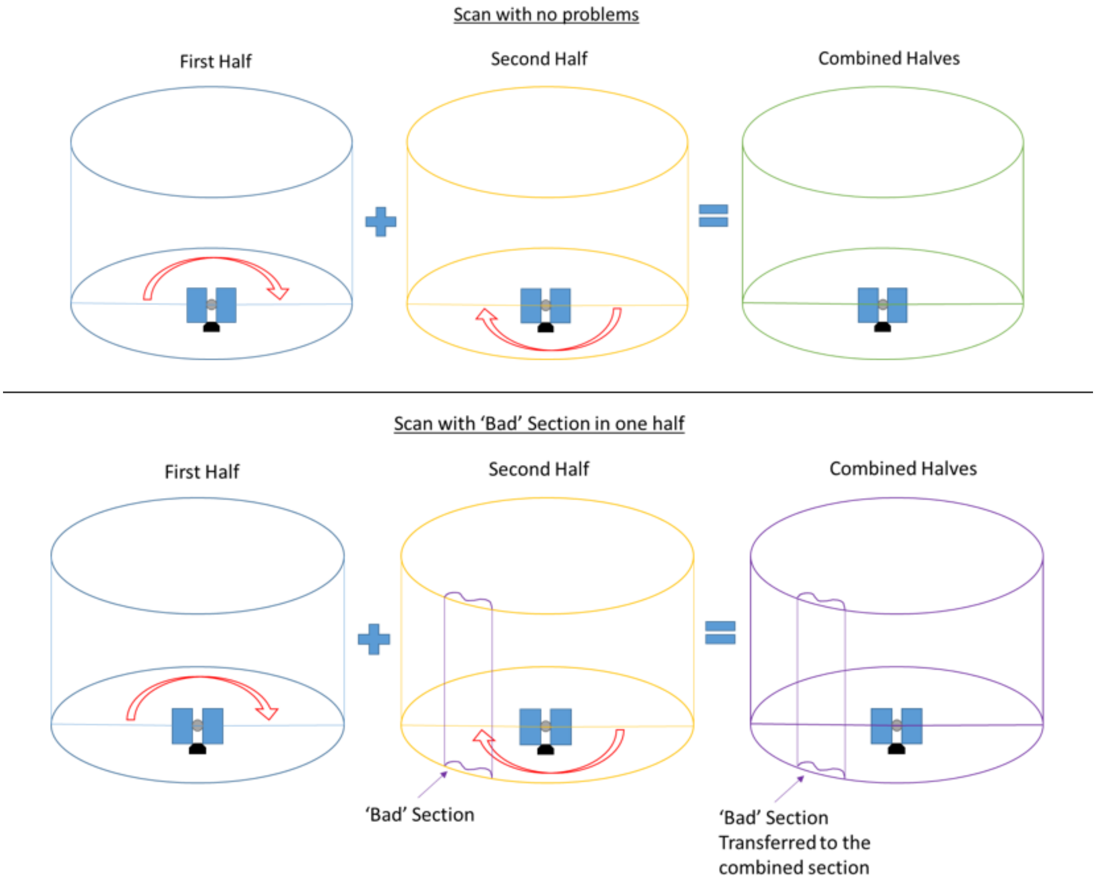


Figure 9.5: Sketch to illustrate the idea of positioning and fitting to halves of a single 360 degree scan on top of one another. The first series shows a scan with no problems. The second shows how a scan with bad data in one half of a scan will propagate through to the combined outcome. This shows how determining errors in both halves can find the errors in the outcome of the full scan.

These direction errors were compared for the front and back of each scan to identify if there is a difference between the two halves from a single scan. A difference was found and the back half was identified to be performing weaker than the front half due to the worst results always being located within this half of the scan as well as the majority of the back halves performing worse overall when the mean values of the errors are calculated.

These errors were plotted for each of the halves for all the targets located within that particular half. From these graphs, the errors were noticed to have a pattern relating the error associated with a target to its distance from the laser scanner. The graphs were re-arranged to show the same results but with the target distance increasing from left to right, thus showing how the distance from the laser scanner influences the performance of the results. An example of the graphs before and after the differences were arranged according to their instrument-target distances in ascending order from left to right can be seen in figure 9.9 as well as in the appendix in figures 11.11, 11.12 and 11.13.

The graphs can be used to show how the targets furthest from the instrument have the lowest standard deviations and those closer to the instrument have more random and inconsistent differences. These re-

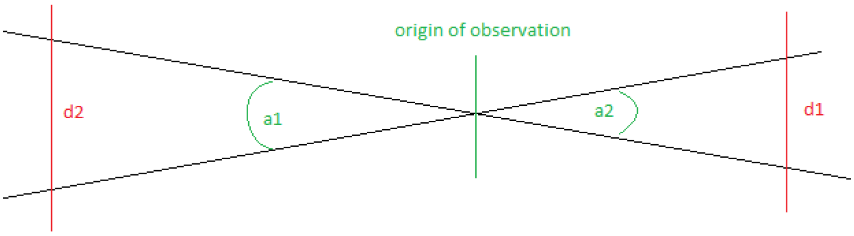


Figure 9.6: Sketch depicting the error in a direction and the relationship existing between the error and the distance. This relationship illustrates how a direction error in consistent over a distance, while distance and height difference errors will vary depending on the distance to the instrument.

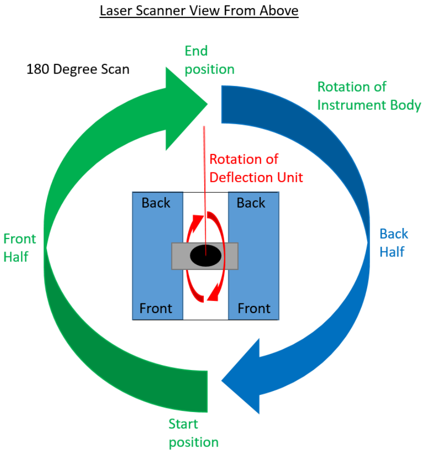


Figure 9.7: Sketch depicting the front and back faces from a 180 degree scan. This is to help understand which targets are located within which of the two halves in order to compare the performance of both halves.

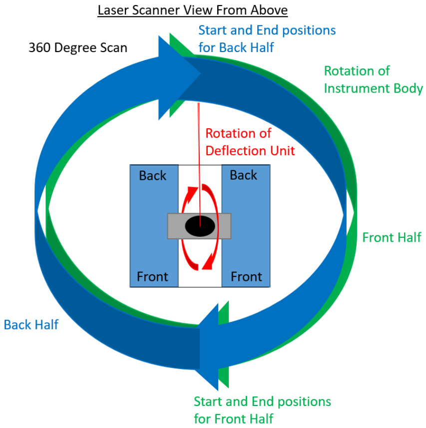
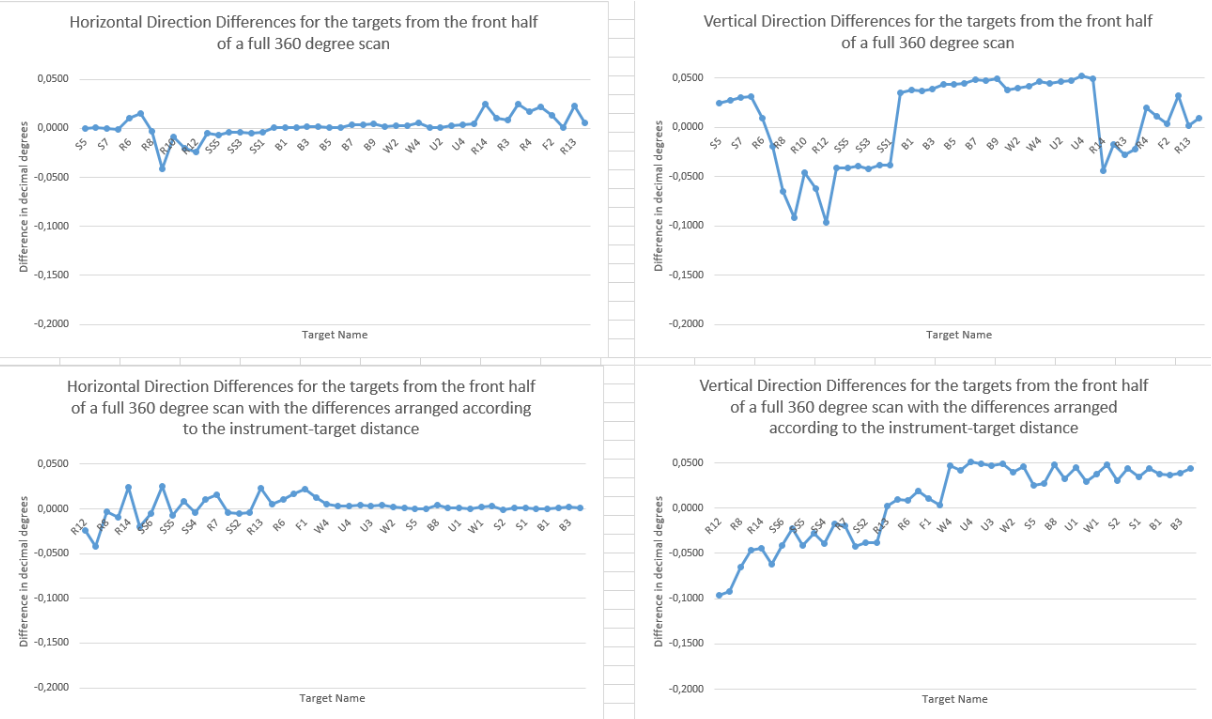


Figure 9.8: Sketch depicting the front and back faces from a 360 degree scan. This is to help understand which targets are located within which of the two halves in order to compare the performance of both halves.

sults validated the need for the larger testing facility. When this entire process was repeated for the three scans performed in the short range facility where each scan was rotated 120 degrees, the results were very random and no visible pattern emerged. This can be attributed to the short distances of the short range facility (up to maximum of 10 meters). These results are due to the imprecisions in the instrument making it difficult to acquire sufficiently accurate data to identify any consistency in these results. In order to find more significant results the medium range testing facility was more suitable (with longer range observations).

Returning to the re-arranged graphs based on distance, these graphs indicated the targets further from the instrument to be performing with greater consistency and smaller variation in the errors as opposed to the targets closer to the instrument with much higher variation in the errors. This can be explained by observation errors; a small observation error at a large range will translate to a small error on the target whereas that same small error on a target on a closer surface will translate to a larger error on that target. This is the same idea as described by the sketch in figure 9.6 where the error (error in this diagram is now a1 and a2) at the target is larger at a longer range for the same observation error.


Horizontal Direction Differences for the targets from the front half of a full 360 degree scan

Vertical Direction Differences for the targets from the front half of a full 360 degree scan

Horizontal Direction Differences for the targets from the front half of a full 360 degree scan with the differences arranged according to the instrument-target distance

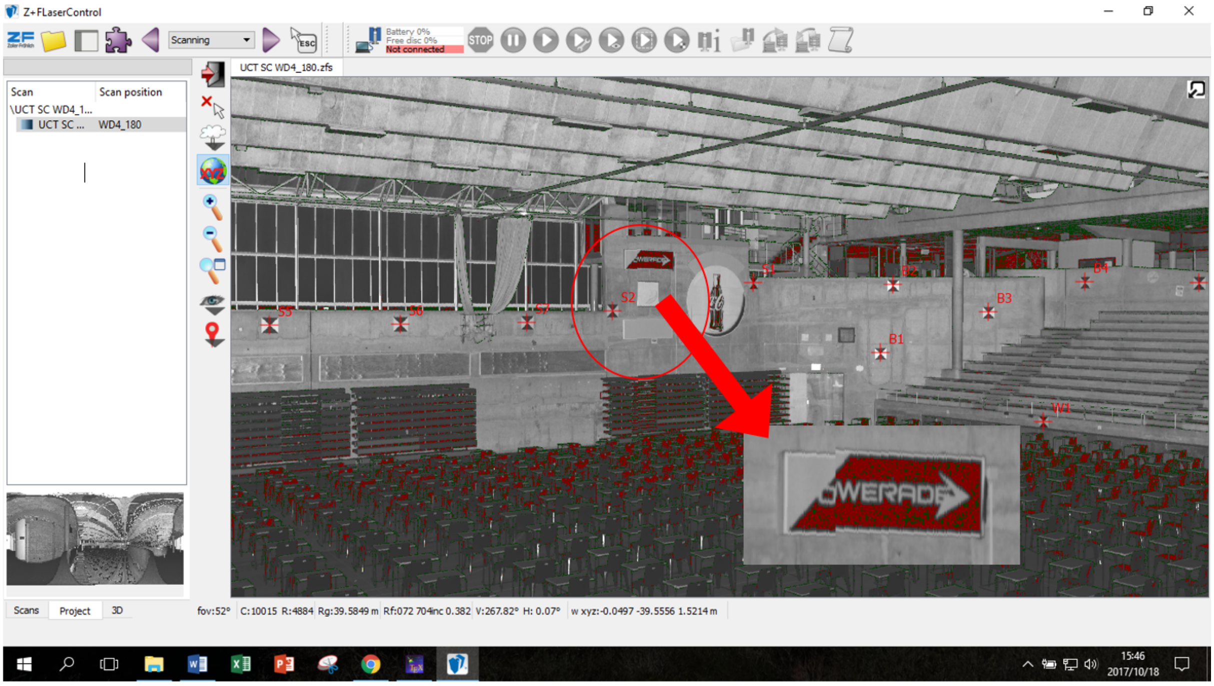
Vertical Direction Differences for the targets from the front half of a full 360 degree scan with the differences arranged according to the instrument-target distance

Figure 9.9: Graphs displaying the Direction Differences for targets in the front half of a full 360 degree scan with the differences arranged randomly and thereafter according to the instrument target distance in ascending order from left to right.

During an inspection of a 180 degree scan, there was a shift in the halves of a single scan which is visible in the screen shot in figure 9.10. This shift or mis-alignment is significantly visible and displays the shift as a drop down from one of the halves of the scan resulting in targets from one half being raised up (or dropped down depending on which half one is looking at) when comparing the halves and explains the poor performance in the vertical observations of the laser scanner.

The next phase was to identify whether or not the 'region' of the scan had an impact on the resulting errors. The regions of the laser scanner were defined to be the different sections of the FOV. In this research the first sections of the scene were divided into the top and bottom hemispheres, the second group is described as viewed from above the sphere and the sphere is divided into four equal 90 degree quadrants. If these divisions are adopted the FOV is separated into 8 octants and each was investigated for its own errors in terms of the horizontal and vertical observations. A sketch is provided in figure 9.11 to illustrate how the spherical FOV of a laser scanner has been divided up. The regions were created to determine if their were any errors observed by the laser scanner that were associated with a specific region. These results would then be used to determine the reasons for such errors within that region and to give more information about the performance of the laser scanner based on the instrument-target relationship (distance to the target and the target position in the FOV).

The results of looking at the regions of the laser scanner in terms of the horizontal and vertical direction errors (decimal degrees) can be seen in table in figure 9.12 below. This table is showing the performance of the laser scanner in each of the specified regions of the laser scanner's FOV. The values in red are indicating the weakest regions in terms of the horizontal and vertical errors. They are always the second and fourth quadrants.



fov:52° C:10015 R:4884 Rg:39.5849 m Rf:072 704inc 0.382 V:267.82° H: 0.07° w xyz:-0.0497 -39.5556 1.5214 m

Figure 9.10: Screen shot and zoomed in focus on the visible mis-alignment of two scan halves of the same 180 degree scan.

These regions can then be used in connection with the graphs from above to determine if the direction errors that are performing weaker than others, could be attributed to the region within the scan where that target is located and perhaps be indicating a weaker region in the laser scanner FOV for its observations.

If the tables are used to analyze the graphs to find the regions in which the targets are performing the weakest, it was noticed that these targets are situated towards the left of the bottom graphs in figure 9.9 and in figures 11.11, 11.12 and 11.13 in the appendix, where the differences exhibit greater variations than those targets towards the right and further from the instrument. The worst results from the back half of the 360 scan are in the bottom hemisphere and quadrant 2 and from the graphs we can also see that target R12 is performing the worst and this target is within this region. This indicates a possible relationship between the regions of the laser scanner's FOV and the performance of the laser scanner's observations.

To investigate this trend further and in order to ensure that the region performing the weakest is always the same and possibly a weaker region in the FOV of the laser scanner, an additional test was run where three 360 degree scans were run from the same location but each was rotated 120 degrees (using the three feet of the tribrach in each different position). This test would ensure that any error in a particular region would be attributed to the region alone and not the distance to the targets. If the region containing the error moves together with the rotation of the instrument, it is possible that the error may be attributed to that region of the laser scanner FOV. However, if the error remains in the same region, it may be possible that it is only the distance that is impacting on the results and there is no 'weaker' region of the laser scanner FOV.

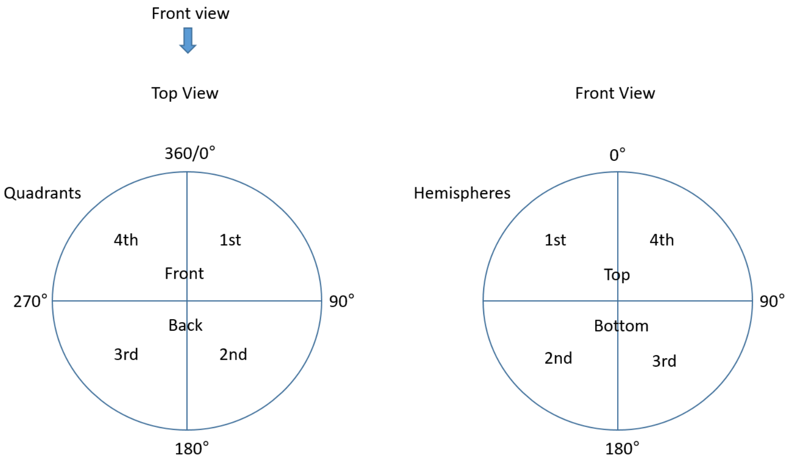
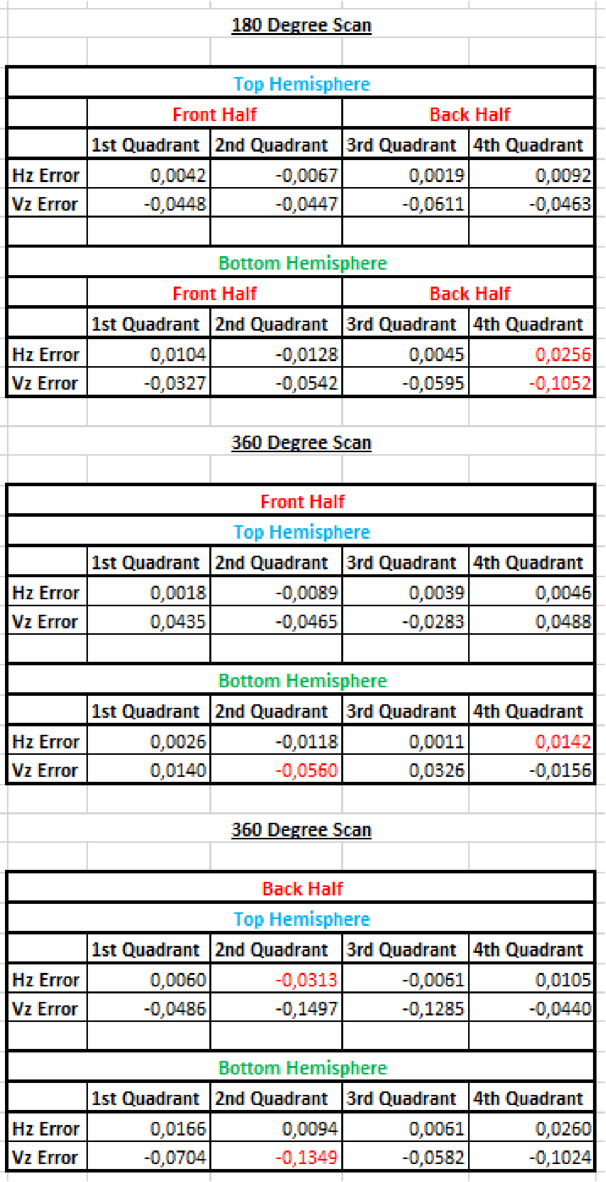


Figure 9.11: Sketch to illustrate how the idea of the spherical FOV of a laser scanner has been divided up to give performance results for each region of the laser scanner's visible scene.

The results from the tests with the three 360 degree scans rotated on the same position indicated the same two regions to be the weaker regions in all cases, these were quadrants 2 and 4. Both of these regions contain targets that are close to the instrument and demonstrates how the distance is the significant factor impacting on the results and not a specific region of the laser scanner FOV. Although the two regions are opposite to one another and this may seem to be the laser scanner region impacting on the results, the fact that it is always these two regions re-iterates that it is only the instrument-target distance causing the error. If these weaker regions moved from scan to scan as the instrument was rotated, this would have indicated the error to be moving with the instrument and thus attributed to the instrument's observations within those regions regardless of the distance to the target.

These last evaluations and tests were able to make deductions about the performance of the testing facility for the required testing and to determine that the distances encountered in the facility have a preferred operating range to determine the most accurate results. This was evident by the higher variation in the results at shorter distances due to the imprecisions of the instruments which delivered results that were inconsistent. At larger ranges the results have much lower variations and higher accuracy. The optimum distances based on the results from the graphs and range testing are those between 30 and 50 meters. The results over these distances have the potential to be the most consistent and accurate.



180 Degree Scan

Top Hemisphere

	Front Half		Back Half	
	1st Quadrant	2nd Quadrant	3rd Quadrant	4th Quadrant
Hz Error	0,0042	-0,0067	0,0019	0,0092
Vz Error	-0,0448	-0,0447	-0,0611	-0,0463

Bottom Hemisphere

	Front Half		Back Half	
	1st Quadrant	2nd Quadrant	3rd Quadrant	4th Quadrant
Hz Error	0,0104	-0,0128	0,0045	0,0256
Vz Error	-0,0327	-0,0542	-0,0595	-0,1052

360 Degree Scan

Front Half

Top Hemisphere

	1st Quadrant	2nd Quadrant	3rd Quadrant	4th Quadrant
Hz Error	0,0018	-0,0089	0,0039	0,0046
Vz Error	0,0435	-0,0465	-0,0283	0,0488

Bottom Hemisphere

	1st Quadrant	2nd Quadrant	3rd Quadrant	4th Quadrant
Hz Error	0,0026	-0,0118	0,0011	0,0142
Vz Error	0,0140	-0,0560	0,0326	-0,0156

360 Degree Scan

Back Half

Top Hemisphere

	1st Quadrant	2nd Quadrant	3rd Quadrant	4th Quadrant
Hz Error	0,0060	-0,0313	-0,0061	0,0105
Vz Error	-0,0486	-0,1497	-0,1285	-0,0440

Bottom Hemisphere

	1st Quadrant	2nd Quadrant	3rd Quadrant	4th Quadrant
Hz Error	0,0166	0,0094	0,0061	0,0260
Vz Error	-0,0704	-0,1349	-0,0582	-0,1024

Figure 9.12: Table of the results for the horizontal and vertical angular errors for each of the quadrants from the two hemispheres of the FOV of the laser scanner. Indicates the performance of the laser scanner for all the regions of the visible scene given in decimal degrees.

Part III

Conclusions and Recommendations

Chapter 10

Conclusions

This project aimed to establish two test facilities for Terrestrial Laser Scanners, a short range and a medium range facility. These facilities have been created to serve as permanent environments in which it is possible to perform an assessment of the point accuracy of these instruments. The locations of the facilities were chosen to ensure the test field would remain available to test any laser scanner at any point in time. The instrument under investigation can be setup in the same positions described in this project to allow for comparison between datasets from a single laser scanner as well as datasets from multiple laser scanners.

In addition to comparisons between the subsequent scans from a single laser scanner or various laser scanners, these facilities are able to compare the performance of a laser scanner against its own manufacturer specifications as per the instrument brochure in terms of its distance and angle observations. The laser scanner is not able to deliver such observations but rather a 3-Dimensional point cloud which has been derived from the observations of distance and angle. These observations are determined from the coordinates given by the point cloud which are used in the evaluation of the performance of the laser scanner.

The laser scanner observations to the targets were used to determine the angles and distances between the laser scanner and the targets and thereafter compare these values to the same quantities that were calculated from the surveyed targets. The comparison was focused on both angle and distance for both facilities to investigate the differences between the laser scanner and the “true” values (from the survey). The medium facility included an additional test to focus on the range accuracy of the laser scanner using two locations. The total station was setup over one and the distance was observed repeatedly to determine the distance between them to serve as a control baseline. The laser scanner was subsequently positioned on the same position to investigate it’s ability to observe that same distance multiple times and analyze the distance capabilities of the laser scanner against the surveyed value.

The results from this performance evaluation can identify any deviations in observations of the laser scanner from its manufacturer specifications as well as indicate to the user whether or not a calibration may be necessary. These decisions have time and cost implications that can be beneficial to any company or individual with such a valuable piece of equipment. A laser scanner may be under-performing for various reasons from internal observation errors to damage from a significant fall.

From the investigations carried out in this project the best available equipment and procedures were used to establish a high accuracy 3D coordinate network for laser scanners to observe and analyze the resulting data. The data from the survey of these facilities proved to be sufficient enough to notice weaknesses in the laser scanners used in this research. A least squares calculation with sufficient redundancy was able to determine the coordinates of the network and improve the accuracy to deliver submillimetre precisions for the target coordinates which proved to be low enough to evaluate the performance of a laser scanner. Various additional survey methods could be utilized that would allow for the determinations of coordinates for the targets, including photogrammetry methods or repeat scans from highly accurate laser scanners. In terms of the calculations, there are statistical tests and least squares algorithms which have the ability to determine highly accurate and precise target coordinates.

This project was able to establish test facilities that are able to evaluate the point accuracy of a laser scanner. This did not require a specific venue for such testing but rather an 'appropriate' venue with sufficient open space. Provided such an acceptable venue is chosen with the desired properties, for range and angle observations, it is in fact the coordinate network that is more significant if the results are to be meaningful. The target network needs to be well distributed throughout the Field of View of the laser scanner, but also within the operating ranges for the laser scanners. This however works hand-in-hand with the resolution settings of the laser scanner, which limits the software's ability to determine reliable coordinates beyond a certain distance. It is this distance that must be kept in mind and the targets should all be within this range. If different laser scanners are tested or higher settings are used this factor changes and the reliability of the coordinate determination will change. The use of instruments with higher or lower settings requires targets to be closer as well as further from the laser scanner in order to accommodate various instruments in the test facility.

The results from the equipment analysis indicated target size to be related to the observed distance based on the larger targets out-performing the smaller sizes. Larger targets are more accurate and a better choice as the distance between the instrument and target/surface increases. The larger targets are more recognizable at larger distances on standard instrument settings for resolution and quality. The ideal size for the testing observed in this project was the target with dimensions of 30 centimeters in width and height.

The colour of a target, with the options of grey and black, indicated black to be the superior choice over grey.

The material testing suggested two suitable materials for targets; PVC foam board as well as Perspex. The results would suggest not using marble, plastic or polystyrene for target designs.

The incidence angle analysis showed a proportional relationship between the derived error and the incidence angle, which suggested that targets with a low incidence angle deliver the best results. This angle is recommended to be lower than 50 degrees by the Z+F LaserControl software.

The comparison of results using the standard instrument settings for resolution and quality against the maximum settings did not indicate improvements in accuracy. The resolution and quality of the instrument are able to increase the range performance of the laser scanner and provide more information for the identification of the targets in the scene and subsequent centre point coordinate determination.

The results from the comparison of the Z+F 5010C and the Z+F 5006H laser scanners indicated the possible limits of the instruments' performance while the 5006H was slightly under-performing the 5010C.

This is a good example of how two scanners can be compared.

The targets within a testing facility should be well-distributed in order to perform a full evaluation of the instrument. With the targets covering as much of the FOV as possible there was a greater chance of locating a particular area within the scan that may be weaker than the rest but also when the two halves of a scan were compared this gave a more comprehensive and accurate result as opposed to a setup with a smaller arrangement of targets clustered together. This was evaluated from the three scans at different orientations. This procedure of rotating the laser scanner between scans was to ensure the regions of the laser scanner's observations are all performing sufficiently and that there was no region of the FOV of the instrument that was under-performing which would move with the rotation of the laser scanner. This also returns to the idea of an even and well-distributed target network which allowed for comprehensive evaluation of all regions of the laser scanner's FOV.

The results from the two facilities showed how the laser scanner performed in terms of five derived observations; Horizontal Distance, Vertical Distance, Slope Distance, Horizontal Angle and Vertical Angle. The results from the three scans for the short range facility were all very similar with respect to all these quantities and all less significant than the "true" values as well as the quoted manufacturer specifications. The same observables were used in the medium range facility and yielded results which were also less significant than the "true" values and manufacturer values. In both cases the two worst quantities were the vertical distance and vertical angle observations. This may have been attributed to an error in the vertical measurements of the laser scanner resulting in an offset. All the values for the medium facility were significantly larger due to the increased range that was encountered in this facility (an increase in range will also increase the magnitude of any errors). The distance analysis showed fairly strong performance by the laser scanner but was once again hampered by the observations in the vertical which were once again the worst of the three distances (Horizontal Distance, Vertical Distance, and Slope Distance). This once again indicated a problem in the vertical readings of the laser scanner. One of the positives that came out of the distance testing over the long baseline was that the horizontal and slope distances were under the manufacturer specifications.

In terms of the overall performance of the laser scanner from both facilities the results may have become less significant from the short range facility to the medium range facility but this was expected due to the increase in the range. The overall performance can be better interpreted by closer inspection of the observed accuracies of all the five quantities against the "true" values as well as the manufacturer specifications for the given laser scanner. This can be seen in table 9.3 in the previous section. These values all show that the laser scanner was performing with a lower significance than the surveyed values. In terms of the manufacturer values the laser scanner was performing with a lower significance level than the manufacturer values for the angles and vertical distances, but they were within the specifications for the Horizontal and Slope Distances. These values can also be compared to the table at the end of chapter 6 (figure 6.7) on the accuracy standards from different regulations to show that although the instrument was not performing within the manufacturer specifications, the overall results are all within the majority of these standards and indicated that the instrument was suitable for the work that falls under each of these regulations.

These comparisons show that for this particular laser scanner the observations may not be incorrect, but with regard to the vertical angle and distance results there may be errors present that are leading to poor performance from the vertical observations. In terms of the angle results the values were relatively weak and may be attributed to the target surfaces involved as well as the distance/resolution settings that were utilized. The distance measurements performed well and were within manufacturer specifications for the given instrument. The results given here were over a set of two operating ranges (1 to 10 meters and 1 to 70 meters) using constant settings for Resolution and Quality and these results are based on the factors and conditions encountered in this project. The results showed weaker performance by the laser scanner in the vertical observations and the errors in distance to be proportional to the distance. Similar results showing poor performance by the scanner in the vertical observations were found in the research by Reshetyuk (2006), Chow et al. (2010) and Alkan & Karsidag (2012).

There was a difference in the performance of the front and back halves of an individual scan which was further evaluated through comparisons of the angular errors in both halves. There was a visible shift from the front half to the back half of a scan which was most obvious in a 180 degree scan. This shift was believed to be the reason for the significant vertical observation errors in the Z+F 5010C laser scanner.

The investigation into the angular errors within the front and back halves from an individual scan using the different regions of the FOV indicated that there was no region that was weaker than the others but rather that the instrument-target distance was a significant factor impacting on the results from the laser scanner. This instrument-target distance is fundamental in the design of a testing facility for laser scanners. This distance along with the precisions of the measurement devices available will determine the consistency of the results and therefore the determine accuracy of the laser scanner. Shorter distances up to 10 meters are insufficient to deliver meaningful results with sufficient consistency. However, the coverage of the short range facility does make it a valuable testing area to examine a larger portion of the FOV of a laser scanner. The need for the larger ranges to improve the consistency of the results makes the medium range testing facility more appropriate as a testing facility. The optimum range requirements of such a facility are in the realm of 30 to 50 meters which is available at the UCT sport centre and where the most accurate results were obtained from.

The results from table 9.1 that displayed a significant difference between the first and second half of the same 360 degree scan can now be explained by the mis-alignment of the scan halves which measured approximately 10 centimeters in the vertical. Based on the results achieved by this laser scanner and the visible mis-alignment of the halves of the scans, this instrument is recommended for an adjustment or calibration prior to further accurate work.

The facilities established here were both able to find ways to use the surveyed observations and laser scanner observation in such a way to be able to derive distance and angle values that were comparable in order to give an indication of the accuracy of the laser scanner. The short range facility has the benefit of being able to fully utilize the angular range around the main setup location resulting in a good analysis of the instrument in terms of its angular observations. The medium facility is also able to test the angular observations of a laser scanner and has the additional ability to test the range capabilities of a laser scanner due to a long observation baseline that was installed across the entire venue. Based on the large variety of files that the Z+F LaserControl software can import, it is also possible to examine laser scanners of different brands within this facility and this software, provided that laser scanner can provide one of those required file types (either directly or through a file conversion). A list of these acceptable file types can be seen in the appendix in figure 11.14 from the Z+F software user manual. Both facilities remain constant and available for testing and can be used to investigate the accuracy of a laser scanner at any time. The location of the short and medium range facilities can be seen in figure 11.15 in the appendix on a map of the campus at the University of Cape Town.

In order to make full use of the testing facilities established in this research project it is suggested that a series of scans are observed by the laser scanner under investigation for a full evaluation. First a half scan (180 degree scan) and then a full scan (360 degree scan) in both the short range and medium range facilities should be observed. Thereafter a single high resolution window scan, using the range testing observation setups at locations WD3 and WD5 in the medium range testing facility, should be captured. The last series of scans should include 3 360 degree scans orientated in different directions within both facilities. This series of scans will allow for easy identification of mis-alignments within a single scan, comparisons of performance between the different halves of a single scan, investigations into the regions of the FOV, detailed point accuracy analysis based on the instruments observations as well as a range accuracy evaluations.

Although the facilities established here are able to determine the accuracy of a laser scanner, the surveyed values could be more accurate with more accurate survey equipment or methods for calculations. The results here were achieved using the best available equipment under constant conditions. It is not to say these are the final comments on the performance of this laser scanner and this research is merely an indication of the performance of the instrument in terms of the angle and distance observations under these conditions and settings. After close analysis of the results there is an error in the Z+F 5010C laser scanner based on its vertical observations. The testing facilities established within this research are able to deduce whether or not there are errors present in observations of a given laser scanner based on the point accuracy of the measured 3D point clouds.

Chapter 11

Recommendations and Further Testing

From the experience gained throughout the research and testing to establish the testing facilities, the following set of recommendations are made to provide possible solutions to problems experienced during the surveying of a high accuracy control point network along with additional tests that can be run to confirm aspects that may have had any impact on the results:

- The control points should be an order of magnitude more significant than any points against which they are compared to ensure reliability of the results. The use of strong network geometry between setups and targets will provide the best scenario to achieve the best results. An example of a strong geometric setup of survey stations is depicted in figure 11.1 below with strong angles between the stations (strong angles are those angles that are not close to 0/360 degrees or 180 degrees, ideally between 30 and 150 degrees). Such a network was difficult to establish in this research with the given venues that were available.

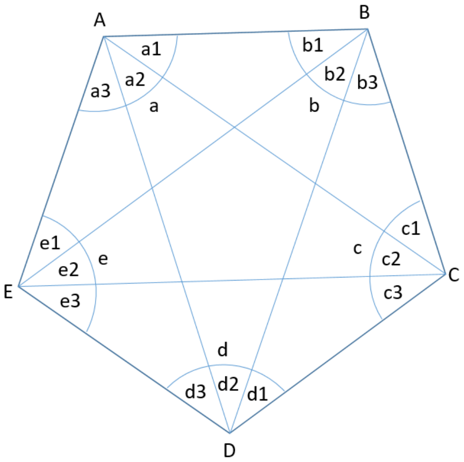


Figure 11.1: Sketch illustrating the use of well positioned setups to achieve good network geometry. The angles have all be kept within the acceptable range for strong angles which is significant in the computations process.

The geometry along with the method of survey are crucial aspects of any high accuracy survey and must be planned perfectly. The method of acquiring the coordinates for the targets or control points is the next most important step and can be done in a variety of ways, some of which were not included in this research and will be mentioned now for possible future analysis;

  - *Laser Scanners*: Investigation into whether or not it is possible to check one laser scanner's accuracy with another laser scanner, where one has a higher level of accuracy or using repeat scans of the same scene in order to raise the level of redundancy as well as aid the in the least squares derivations and ultimately improve the accuracy of those coordinates to compare with the lower accuracy laser scanner. This may even be done with a laser scanner that is designed for larger range observations with higher accuracy against a lower range laser scanner with lower accuracy.
  - *Photogrammetry*: The use of cameras to accurately determine coordinates is extremely effective and could be used to give the targets coordinates using various software designed to use the intersections of points from the different camera positions to determine the positions of the cameras and the targets in a simultaneous Bundle Adjustment.
  - *Surveying*: Aside from the procedure used to capture the points, the instrument itself can be of a higher accuracy. This would mean acquiring a total station with a much higher level of accuracy which would make the survey stronger and derive more significant outcomes.

- Additional testing that could be used to confirm the results determined by this research may include the following tests;

  - *Laser Scanner Compensator*: The laser scanner used in this research was the Z+F 5010C Imager and has the ability to use a built-in compensator designed to automatically correct the scans if the instrument body is not level (perpendicular to the direction of gravity). One of the possible tests on the resulting coordinates is to turn off the compensator and run a scan that is intentionally off-level to investigate whether the coordinates are effected in any way. If the coordinates are affected this would mean that if any of the scans were not perfectly level, there could be a chance that the coordinates may vary due to the center of the laser scanner not being over the same center point (due to the fact that if the center of the machine is not level the center point will lie off the vertical axis and swivel around giving different distances to points on opposite side). What is thought to happen if the compensator is switched on is if the instrument is off-level the distances on opposite side of the instrument might be averaged out to get rid of the error.
  - *Thermodynamics of the Venue*: The venue at the UCT Sport Center is rumored to expand and contract throughout the course of a single day due to the range in temperatures experienced. This impact of this can be avoided by conducting any observation at a time where the temperature can be monitored to ensure the temperature remains constant. If this was to be tested, scans could be captured from the same position at various times throughout the day to monitor for any changes in the data.
  - *Target Incident Angle*: One of the main issue experienced with the performance of the laser scanner used in this research was in the vertical observations. There is an idea that this may have been attributed to the angle of incidence at the target surface. This could be investigated by examining the incident angle at each of the targets and thereafter to analyze the results to identify patterns that may suggest that those targets with high incidence angles have high errors in the vertical observations. If this test does not present any trends in the data it may

be possible that the instrument is performing out of the specification of the manufacturer and may need to be analyzed further to ensure the data being produced is not incorrect, especially for high accuracy work.

- *Increased Range*: A last recommendation is to increase the dimensions of the testing rooms in the form of a long range testing facility which would include the maximum range that the scanner is able to observe and to test this accuracy at these large distances and to possibly include a long baseline for further analysis of the distance accuracy of a laser scanner. Once this facility and long baseline have been included, any scanners can be investigated and compared under the same conditions providing a conclusive report on the accuracy performance and give a good indication of which laser scanner is the best for the task at hand.

Part IV

Appendix

Figure 11.2: Target Manufacturing Process from creation through to them being scanned.

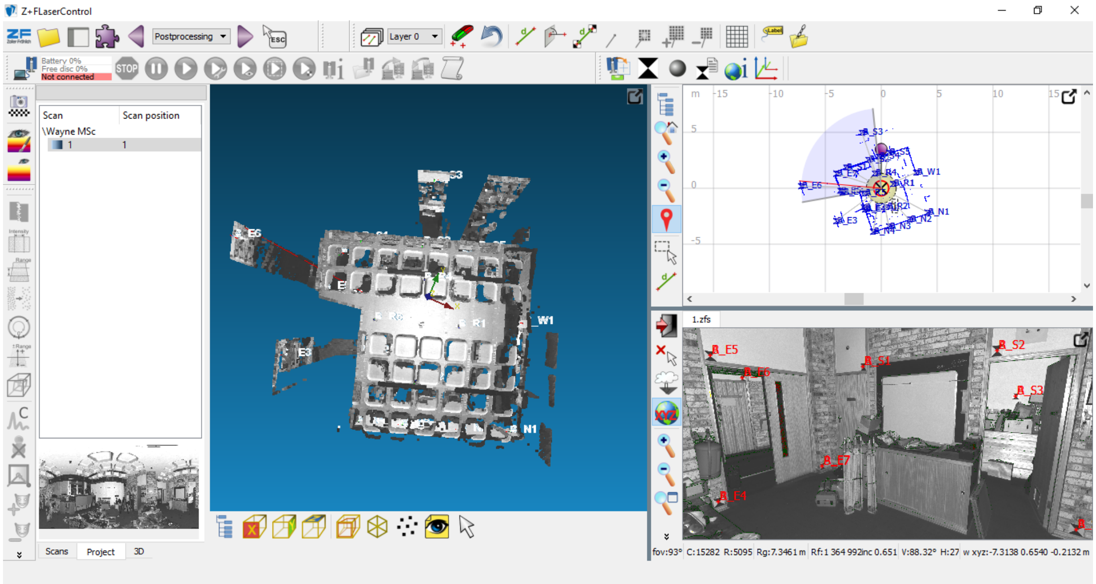


Figure 11.3: Screen shot of the Z+F LaserControl software and the many features it contains. The scan under inspection can be seen in a subsampled version on the left hand side, the plan view on the top right with the targets that have been identified through the use of the greyscale scan on the bottom right as seen from the point of view from the laser scanner. The targets can also be seen in the greyscale after having been selected as the red names and cross-hairs over the points/targets.

CoordTrans - Report

free Similarity Transformation Software

General

CoordTrans	:	v2.2.20161021
Transformation type	:	3D-Transformation
Date of calculation	:	06.12.2016 - 10:00:55
Adjustment type	:	Least square adjustment (Gauß-Helmert modell)
Flaw dislocation	:	No scheme
Probability value α [%]	:	0.1
Test power β [%]	:	80.0
Sum of squares of errors Ω	:	0.046065804919
Degree of freedom f = n-u+d = spur(R)	:	126
$\sigma^2_{a\text{-priori}} : \sigma^2_{a\text{-posteriori}}$	:	1 : 0.000
Globaltest $T_{Global} \leq F_{f,\infty,1-\alpha} \vert H_0$	:	H_0 *not* rejected, because 0.000 ≤ 1.047 ($\alpha'_G = 34.2\%$)
Critical value for point test K_{prio} ($F_{3,\infty,1-\alpha}$)	:	5.422 ($\alpha_{prio} = 0.1\%$)
Critical value for point test K_{post} ($F_{3,f-3,1-\alpha}$)	:	5.370 ($\alpha_{post} = 0.2\%$)

Form parameters – 3D-Transformation

Name	Value	σ_{Par}	Significant
Tx	981.310708444	0.005672600	

Ty	1001.908386086	0.005672946	
Tz	101.319330056	0.005674652	
q0	0.259570953	0.000179936	
q1	0.000053572	0.000172271	
q2	-0.001016091	0.000138633	
q3	0.965723503	0.000048364	
a11	0.999951862	0.000372622	
a12	-0.000129282	0.000442109	
a13	0.001221224	0.001824117	
a22	0.999975884	0.000237893	
a23	-0.001602716	0.001801234	
a33	1.000621674	0.001786028	
Mx	0.999951862	0.000372622	
My	0.999975893	0.000237909	
Mz	1.000623702	0.001786121	
Rx	6.281194969	0.000320558	
Ry	0.000424023	0.000304677	
Rz	3.666748312	0.000372644	
Sx	0.001601719	0.001800129	
Sy	3.140372191	0.001822873	
Sz	0.000129285	0.000442111	

Variance component analysis

System	r_G	Ω_G	$1 : \sigma^2_G$	K_G ($F_{r_G,\infty,1-\alpha_G}$)	$T_G \leq K_G \mid H_0$
Source	63.0115	0.0230	0.0004	1.1445	
Target	62.9885	0.0230	0.0004	1.1446	

Source System

Point-ID	X_0	Y_0	Z_0	X	Y	Z	σ_X	σ_Y	σ_Z	r_X
S5	11.715900	-32.613900	-0.232400	11.715553	-32.612205	-0.250736	0.014515	0.014515	0.014512	0.423723
S6	8.124900	-34.726600	-0.221000	8.125107	-34.727680	-0.239204	0.014381	0.014381	0.014377	0.434344
S7	4.074500	-37.106500	-0.182600	4.074627	-37.107084	-0.200690	0.014261	0.014261	0.014258	0.443686
S2	0.964700	-38.952000	0.278400	0.964871	-38.952052	0.260163	0.014207	0.014207	0.014204	0.447895
S1	-5.040600	-42.493600	1.460900	-5.041355	-42.491812	1.443165	0.014196	0.014196	0.014192	0.448771
B1	-10.682700	-42.579600	-1.620200	-10.682627	-42.580182	-1.633731	0.014110	0.014110	0.014106	0.455414
B2	-11.227900	-42.535100	1.372700	-11.228442	-42.534942	1.358202	0.014067	0.014067	0.014063	0.458743
B3	-15.359000	-42.027000	0.182300	-15.359838	-42.027351	0.171067	0.013994	0.013994	0.013990	0.464354
B4	-19.554900	-41.636900	1.493800	-19.555282	-41.636553	1.485960	0.014038	0.014038	0.014034	0.460952
B5	-22.166000	-37.229300	1.323900	-22.165853	-37.229315	1.320300	0.013987	0.013986	0.013982	0.464927
B6	-22.925000	-33.284600	1.038000	-22.924632	-33.284495	1.037545	0.013942	0.013942	0.013938	0.468293
B7	-26.014800	-28.062300	0.322200	-26.014946	-28.062261	0.328645	0.013993	0.013993	0.013989	0.464425
B8	-27.783700	-22.502200	0.082000	-27.783826	-22.502431	0.093156	0.014065	0.014065	0.014061	0.458884
B9	-28.481400	-18.699900	0.010000	-28.481252	-18.700010	0.024977	0.014117	0.014117	0.014113	0.454919
W1	-14.904600	-35.018800	-3.859100	-14.904086	-35.018685	-3.865036	0.014325	0.014324	0.014321	0.438755
W2	-18.404200	-29.082500	-3.860900	-18.404065	-29.082981	-3.860490	0.014313	0.014313	0.014310	0.439633
W3	-21.747400	-23.396000	-3.853200	-21.747264	-23.396651	-3.846637	0.014380	0.014380	0.014376	0.434387
W4	-26.056500	-15.974200	-3.906100	-26.057145	-15.974704	-3.890131	0.014596	0.014595	0.014592	0.417315
U1	-20.931200	-29.258100	4.739100	-20.931271	-29.257565	4.739008	0.014365	0.014365	0.014361	0.435605
U2	-22.810000	-26.055400	4.790900	-22.809731	-26.055216	4.794532	0.014387	0.014387	0.014384	0.433810
U3	-24.699700	-22.815700	4.756800	-24.699463	-22.815379	4.763923	0.014415	0.014415	0.014411	0.431632
U4	-26.619000	-19.535800	4.737200	-26.618351	-19.535562	4.749157	0.014473	0.014473	0.014469	0.427087
U5	-30.228100	-13.416700	1.002500	-30.227933	-13.417233	1.022129	0.014237	0.014236	0.014233	0.445628
R13	-5.336200	-1.317000	-0.681000	-5.335579	-1.316303	-0.670843	0.013753	0.013753	0.013748	0.482666
R1	-6.237100	0.064500	-0.394200	-6.235832	0.064105	-0.382113	0.013771	0.013771	0.013766	0.481310

R14	-2.705700	0.222400	-0.646200	-2.704450	0.222483	-0.636445	0.013778	0.013778	0.013774	0.480751
R2	-3.482000	1.686300	-0.399600	-3.480918	1.685723	-0.387911	0.013795	0.013795	0.013791	0.479470
R3	-2.592400	2.605900	-0.587700	-2.591754	2.605393	-0.575694	0.013811	0.013811	0.013807	0.478274
R5	-1.022000	3.129800	1.374700	-1.021375	3.128396	1.385755	0.013953	0.013953	0.013949	0.467494
R7	0.357700	3.920400	1.379300	0.357782	3.918843	1.390783	0.013987	0.013986	0.013983	0.464924
R6	0.106900	7.156800	0.500900	0.107422	7.155402	0.517467	0.013951	0.013950	0.013946	0.467679
R8	1.373000	1.776900	1.345700	1.371941	1.775574	1.353500	0.013972	0.013971	0.013967	0.466073
R9	1.609200	1.386100	0.432000	1.607586	1.385470	0.439983	0.013882	0.013882	0.013878	0.472881
R12	1.946200	0.820900	-1.008600	1.945968	0.821068	-1.000720	0.013837	0.013837	0.013833	0.476314
R10	2.466700	-0.066800	1.320100	2.464601	-0.066976	1.325931	0.013972	0.013972	0.013968	0.466043
R11	3.061900	-1.080600	-0.516300	3.061177	-1.079746	-0.510414	0.013843	0.013843	0.013839	0.475868
SS1	2.703300	-3.732600	-1.604700	2.703506	-3.731806	-1.600778	0.013831	0.013831	0.013827	0.476754
SS2	1.867900	-3.905900	-1.793500	1.868234	-3.904947	-1.789273	0.013825	0.013825	0.013821	0.477185
SS3	2.435300	-3.273500	-1.985700	2.435436	-3.272465	-1.981030	0.013850	0.013850	0.013846	0.475337
SS4	1.582100	-3.446700	-2.163800	1.582611	-3.445889	-2.158923	0.013849	0.013849	0.013845	0.475408
SS5	2.163800	-2.802300	-2.351400	2.164157	-2.801275	-2.345924	0.013876	0.013876	0.013872	0.473315
SS6	1.296100	-2.984700	-2.532100	1.296615	-2.983566	-2.526321	0.013881	0.013881	0.013877	0.472974
R4	-1.946700	8.103400	0.745400	-1.945376	8.101772	0.764254	0.013968	0.013968	0.013964	0.466324
WD3	-17.796400	31.118300	0.020900	-17.798423	31.121124	-0.111401	0.015034	0.015034	0.015031	0.381784
F2	-2.246500	-12.448500	-4.934500	-2.246727	-12.449289	-4.935011	0.014260	0.014260	0.014257	0.443766
F1	-4.720300	-8.225200	-4.933200	-4.721296	-8.225541	-4.928445	0.014268	0.014267	0.014264	0.443204

Target System

Point-ID	X_0	Y_0	Z_0	X	Y	Z	σ_X	σ_Y	σ_Z
S5	987.520000	1035.999000	101.120600	987.520542	1036.000604	101.138925	0.014514	0.014515	0.014518
S6	991.687700	1036.032200	101.134100	991.687330	1036.031125	101.152293	0.014380	0.014381	0.014384
S7	996.384600	1036.060000	101.174800	996.384410	1036.059395	101.192879	0.014261	0.014261	0.014265

S2	999.999300	1036.097000	101.637400	999.999414	1036.096833	101.655626	0.014207	0.014207	0.014211
S1	1006.969200	1036.146800	102.824700	1006.969435	1036.148691	102.842425	0.014195	0.014196	0.014199
B1	1011.896900	1033.397600	99.746700	1011.896665	1033.397033	99.760222	0.014109	0.014110	0.014114
B2	1012.344600	1033.083900	102.739100	1012.344204	1033.084280	102.753589	0.014066	0.014067	0.014071
B3	1015.666000	1030.573800	101.550900	1015.665094	1030.573894	101.562125	0.013993	0.013994	0.013998
B4	1019.098400	1028.132000	102.866600	1019.098240	1028.132477	102.874435	0.014038	0.014038	0.014042
B5	1019.147900	1023.010300	102.694900	1019.148018	1023.010206	102.698498	0.013986	0.013986	0.013990
B6	1017.827100	1019.216500	102.407000	1017.827471	1019.216406	102.407455	0.013942	0.013942	0.013946
B7	1017.884300	1013.148300	101.692500	1017.884196	1013.148420	101.686059	0.013992	0.013993	0.013997
B8	1016.628300	1007.450900	101.449700	1016.628080	1007.450785	101.438551	0.014064	0.014065	0.014069
B9	1015.325600	1003.811100	101.377500	1015.325679	1003.810960	101.362532	0.014116	0.014117	0.014120
W1	1011.760100	1024.738000	97.504300	1011.760600	1024.737830	97.510233	0.014324	0.014324	0.014328
W2	1011.813800	1017.847600	97.501500	1011.813676	1017.847117	97.501090	0.014312	0.014313	0.014317
W3	1011.856300	1011.251400	97.508400	1011.856094	1011.250782	97.501841	0.014379	0.014380	0.014383
W4	1011.865800	1002.668100	97.457200	1011.864995	1002.668019	97.441240	0.014595	0.014595	0.014599
U1	1014.081700	1016.730800	106.104600	1014.081907	1016.731299	106.104692	0.014364	0.014365	0.014368
U2	1014.101700	1013.018600	106.156500	1014.102027	1013.018631	106.152870	0.014387	0.014387	0.014391
U3	1014.112800	1009.267700	106.121900	1014.113169	1009.267873	106.114782	0.014414	0.014415	0.014418
U4	1014.128800	1005.468000	106.104400	1014.129486	1005.467904	106.092450	0.014472	0.014473	0.014476
U5	1014.188500	998.364700	102.368600	1014.188385	998.364194	102.348983	0.014236	0.014236	0.014240
R13	986.586400	1000.372200	100.657400	986.587291	1000.372512	100.647250	0.013752	0.013753	0.013756
R1	986.673200	998.727700	100.945000	986.674104	998.726746	100.932921	0.013770	0.013771	0.013774
R14	983.538400	1000.360600	100.690100	983.539527	1000.360065	100.680352	0.013777	0.013778	0.013782
R2	983.477100	998.705700	100.937400	983.477752	998.704682	100.925719	0.013794	0.013795	0.013799
R3	982.247300	998.355400	100.748600	982.247610	998.354661	100.736601	0.013810	0.013811	0.013815
R5	980.625600	998.690900	102.710300	980.625442	998.689394	102.699252	0.013952	0.013953	0.013956
R7	979.036700	998.698200	102.715100	979.035995	998.696834	102.703624	0.013986	0.013986	0.013990
R6	977.631200	995.772200	101.839900	977.630958	995.770762	101.823343	0.013950	0.013950	0.013954
R8	979.234400	1001.060400	102.678900	979.232822	1001.059799	102.671104	0.013971	0.013971	0.013975
R9	979.226800	1001.515200	101.765900	979.225090	1001.515480	101.757921	0.013881	0.013882	0.013886

R12	979.216300	1002.173200	100.325500	979.216187	1002.173478	100.317625	0.013836	0.013837	0.013841
R10	979.212900	1003.201000	102.653600	979.210997	1003.201911	102.647772	0.013971	0.013972	0.013975
R11	979.203900	1004.376200	100.818500	979.203705	1004.377313	100.812618	0.013842	0.013843	0.013846
SS1	980.842600	1006.492200	99.730400	980.843178	1006.492791	99.726480	0.013830	0.013831	0.013835
SS2	981.652000	1006.223200	99.541900	981.652769	1006.223865	99.537676	0.013824	0.013825	0.013829
SS3	980.844500	1005.960100	99.349600	980.845138	1005.960936	99.344933	0.013849	0.013850	0.013853
SS4	981.669200	1005.683000	99.171600	981.670051	1005.683455	99.166727	0.013848	0.013849	0.013852
SS5	980.843100	1005.416500	98.984200	980.843925	1005.417219	98.978728	0.013876	0.013876	0.013880
SS6	981.685000	1005.139300	98.803800	981.686017	1005.140034	98.798025	0.013880	0.013881	0.013885
R4	978.932200	993.924800	102.086000	978.932538	993.922765	102.067158	0.013967	0.013968	0.013972
WD3	981.111800	966.053700	101.004200	981.111409	966.056894	101.136418	0.015033	0.015034	0.015037
F2	989.498400	1011.554800	96.403400	989.497808	1011.554230	96.403911	0.014260	0.014260	0.014264
F1	989.522800	1006.658700	96.405500	989.521769	1006.658914	96.400748	0.014267	0.014267	0.014271

Transformed Points

Point-ID	X_S	Y_S	Z_S	X_T	Y_T	Z_T	σ_X	σ_Y	σ_Z
S5	11.715900	-32.613900	-0.232400	987.521080	1036.002245	101.157277	0.021844	0.021846	0.021858
S6	8.124900	-34.726600	-0.221000	991.686956	1036.030087	101.170506	0.021484	0.021487	0.021498
S7	4.074500	-37.106500	-0.182600	996.384215	1036.058825	101.210979	0.021164	0.021166	0.021178
S2	0.964700	-38.952000	0.278400	999.999523	1036.096702	101.673875	0.021019	0.021021	0.021032
S1	-5.040600	-42.493600	1.460900	1006.969666	1036.150617	102.860175	0.020991	0.020993	0.021004
B1	-10.682700	-42.579600	-1.620200	1011.896427	1033.396493	99.773761	0.020750	0.020752	0.020763
B2	-11.227900	-42.535100	1.372700	1012.343805	1033.084688	102.768097	0.020638	0.020641	0.020652
B3	-15.359000	-42.027000	0.182300	1015.664184	1030.574010	101.573365	0.020436	0.020438	0.020449
B4	-19.554900	-41.636900	1.493800	1019.098079	1028.132969	102.882280	0.020558	0.020561	0.020572
B5	-22.166000	-37.229300	1.323900	1019.148135	1023.010120	102.702099	0.020416	0.020418	0.020430
B6	-22.925000	-33.284600	1.038000	1017.827841	1019.216313	102.407910	0.020294	0.020297	0.020308

B7	-26.014800	-28.062300	0.322200	1017.884094	1013.148527	101.679611	0.020434	0.020436	0.020447
B8	-27.783700	-22.502200	0.082000	1016.627862	1007.450648	101.427388	0.020632	0.020634	0.020646
B9	-28.481400	-18.699900	0.010000	1015.325761	1003.810791	101.347546	0.020772	0.020775	0.020786
W1	-14.904600	-35.018800	-3.859100	1011.761097	1024.737672	97.516173	0.021328	0.021331	0.021342
W2	-18.404200	-29.082500	-3.860900	1011.813553	1017.846633	97.500678	0.021302	0.021305	0.021316
W3	-21.747400	-23.396000	-3.853200	1011.855890	1011.250151	97.495272	0.021485	0.021488	0.021499
W4	-26.056500	-15.974200	-3.906100	1011.864195	1002.667906	97.425261	0.022065	0.022067	0.022079
U1	-20.931200	-29.258100	4.739100	1014.082113	1016.731798	106.104786	0.021440	0.021442	0.021454
U2	-22.810000	-26.055400	4.790900	1014.102354	1013.018655	106.149236	0.021499	0.021501	0.021512
U3	-24.699700	-22.815700	4.756800	1014.113539	1009.268032	106.107654	0.021570	0.021573	0.021584
U4	-26.619000	-19.535800	4.737200	1014.130175	1005.467784	106.080486	0.021721	0.021724	0.021735
U5	-30.228100	-13.416700	1.002500	1014.188276	998.363649	102.329341	0.021095	0.021097	0.021109
R13	-5.336200	-1.317000	-0.681000	986.588184	1000.372804	100.637087	0.019770	0.019772	0.019784
R1	-6.237100	0.064500	-0.394200	986.675012	998.725769	100.920824	0.019820	0.019822	0.019834
R14	-2.705700	0.222400	-0.646200	983.540657	1000.359511	100.670590	0.019840	0.019843	0.019854
R2	-3.482000	1.686300	-0.399600	983.478407	998.703641	100.914021	0.019887	0.019890	0.019901
R3	-2.592400	2.605900	-0.587700	982.247923	998.353898	100.724586	0.019931	0.019934	0.019945
R5	-1.022000	3.129800	1.374700	980.625286	998.687866	102.688187	0.020320	0.020322	0.020333
R7	0.357700	3.920400	1.379300	979.035293	998.695446	102.692131	0.020412	0.020414	0.020425
R6	0.106900	7.156800	0.500900	977.630721	995.769290	101.806763	0.020313	0.020315	0.020327
R8	1.373000	1.776900	1.345700	979.231247	1001.059183	102.663297	0.020372	0.020374	0.020386
R9	1.609200	1.386100	0.432000	979.223383	1001.515743	101.749933	0.020127	0.020129	0.020141
R12	1.946200	0.820900	-1.008600	979.216077	1002.173739	100.309741	0.020004	0.020006	0.020017
R10	2.466700	-0.066800	1.320100	979.209097	1003.202811	102.641939	0.020373	0.020376	0.020387
R11	3.061900	-1.080600	-0.516300	979.203512	1004.378414	100.806731	0.020019	0.020022	0.020033
SS1	2.703300	-3.732600	-1.604700	980.843757	1006.493374	99.722557	0.019988	0.019990	0.020001
SS2	1.867900	-3.905900	-1.793500	981.653538	1006.224522	99.533447	0.019972	0.019974	0.019986
SS3	2.435300	-3.273500	-1.985700	980.845778	1005.961763	99.340262	0.020040	0.020042	0.020054
SS4	1.582100	-3.446700	-2.163800	981.670902	1005.683901	99.161848	0.020037	0.020040	0.020051
SS5	2.163800	-2.802300	-2.351400	980.844752	1005.417928	98.973251	0.020114	0.020116	0.020128

SS6	1.296100	-2.984700	-2.532100	981.687035	1005.140757	98.792244	0.020127	0.020129	0.020140
R4	-1.946700	8.103400	0.745400	978.932880	993.920693	102.048289	0.020361	0.020363	0.020375
B_S1	-5.035100	-42.488400	1.527800	1006.962256	1036.148875	102.927110	0.021008	0.021010	0.021022
B_B1	-10.677900	-42.583300	-1.553400	1011.894084	1033.402101	99.840612	0.020733	0.020735	0.020747
B_B2	-11.223500	-42.534000	1.440800	1012.339400	1033.085943	102.836240	0.020652	0.020655	0.020666
B_B3	-15.354400	-42.028300	0.251500	1015.660809	1030.577442	101.642613	0.020435	0.020437	0.020449
B_B4	-19.550300	-41.637100	1.567200	1019.094149	1028.135448	102.955729	0.020570	0.020572	0.020584
B_B5	-22.161600	-37.229300	1.393100	1019.144281	1023.012326	102.771345	0.020424	0.020426	0.020437
B_B6	-22.921000	-33.285400	1.102600	1017.824738	1019.219011	102.472555	0.020299	0.020301	0.020313
B_B7	-26.012400	-28.063700	0.384400	1017.882677	1013.150942	101.741854	0.020430	0.020432	0.020444
B_B8	-27.781600	-22.504900	0.138700	1016.627360	1007.454038	101.484129	0.020626	0.020628	0.020639
B_B9	-28.479500	-18.702900	0.065400	1015.325583	1003.814340	101.402987	0.020766	0.020768	0.020780
B_W1	-14.900800	-35.026200	-3.802400	1011.761480	1024.745981	97.572925	0.021294	0.021297	0.021308
B_W2	-18.402600	-29.090700	-3.808500	1011.816243	1017.854531	97.553128	0.021269	0.021272	0.021283
B_W3	-21.747900	-23.403700	-3.804200	1011.860149	1011.256563	97.544317	0.021454	0.021456	0.021468
B_W4	-26.058600	-15.982000	-3.859000	1011.869890	1002.673603	97.472404	0.022034	0.022037	0.022048
B_U1	-20.926000	-29.252500	4.798700	1014.074767	1016.729560	106.164415	0.021477	0.021480	0.021491
B_U2	-22.804600	-26.050200	4.848400	1014.095037	1013.016863	106.206765	0.021535	0.021537	0.021549
B_U3	-24.693500	-22.810900	4.812600	1014.105731	1009.266987	106.163484	0.021604	0.021607	0.021618
B_U4	-26.612600	-19.531600	4.791600	1014.122496	1005.467359	106.134915	0.021753	0.021756	0.021767
B_U5	-30.225200	-13.419100	1.056100	1014.186933	998.367180	102.382981	0.021096	0.021098	0.021110
B_R13	-5.338100	-1.318500	-0.672700	986.590574	1000.373149	100.645394	0.019770	0.019772	0.019784
B_R1	-6.237700	0.063400	-0.384400	986.676075	998.726420	100.930632	0.019820	0.019822	0.019834
B_R14	-2.706800	0.221700	-0.642300	983.541957	1000.359565	100.674493	0.019840	0.019843	0.019854
B_R2	-3.482900	1.686000	-0.393600	983.479332	998.703449	100.920025	0.019887	0.019890	0.019901
B_R3	-2.593600	2.606000	-0.582300	982.248908	998.353210	100.729989	0.019931	0.019934	0.019945
WD3	-17.796400	31.118300	0.020900	981.110985	966.060353	101.268809	0.023202	0.023204	0.023216
B_WD3	-17.799100	31.116700	0.077700	981.114084	966.060385	101.325645	0.023203	0.023205	0.023217
B_R5	-1.020400	3.127900	1.380600	980.624850	998.690313	102.694095	0.020321	0.020324	0.020335
B_R7	0.358200	3.917800	1.386200	979.036159	998.697946	102.699040	0.020414	0.020416	0.020428

B_R4	-1.946700	8.102300	0.759300	978.933422	993.921645	102.062199	0.020364	0.020366	0.020378
B_R6	0.106700	7.156200	0.512900	977.631187	995.769709	101.818772	0.020316	0.020318	0.020329
B_R8	1.372400	1.774400	1.349900	979.233016	1001.061046	102.667505	0.020373	0.020375	0.020387
B_R9	1.608900	1.385400	0.435800	979.223991	1001.516199	101.753736	0.020128	0.020130	0.020141
B_R12	1.947000	0.822300	-1.005700	979.214681	1002.172929	100.312641	0.020004	0.020006	0.020017
B_R10	2.464400	-0.067700	1.324600	979.211535	1003.202437	102.646442	0.020375	0.020377	0.020389
B_R11	3.062800	-1.080200	-0.511300	979.202529	1004.378519	100.811734	0.020020	0.020022	0.020033
B_SS1	2.705700	-3.733500	-1.598200	980.842127	1006.495356	99.729064	0.019987	0.019989	0.020001
B_SS2	1.870200	-3.907200	-1.787500	981.652196	1006.226800	99.539455	0.019971	0.019974	0.019985
B_SS3	2.438000	-3.274500	-1.980200	980.843939	1005.963982	99.345769	0.020039	0.020041	0.020053
B_SS4	1.584800	-3.448400	-2.158700	981.669415	1005.686725	99.166956	0.020036	0.020039	0.020050
B_SS5	2.166800	-2.803400	-2.346700	980.842704	1005.420384	98.977958	0.020113	0.020115	0.020127
B_SS6	1.299000	-2.986700	-2.527800	981.685525	1005.143941	98.796552	0.020125	0.020128	0.020139
B_S5	11.718600	-32.613300	-0.176900	987.518405	1036.003080	101.212812	0.021851	0.021854	0.021865
B_S6	8.128200	-34.726200	-0.164400	991.683862	1036.031395	101.227142	0.021491	0.021493	0.021505
B_S7	4.078300	-37.106700	-0.122200	996.380986	1036.060904	101.271419	0.021169	0.021171	0.021183
B_S2	0.968400	-38.951300	0.341000	999.995928	1036.097952	101.736515	0.021027	0.021029	0.021041
F2	-2.246500	-12.448500	-4.934500	989.497216	1011.553661	96.404421	0.021159	0.021162	0.021173
F1	-4.720300	-8.225200	-4.933200	989.520739	1006.659118	96.395990	0.021182	0.021185	0.021196
B_F2	-2.242100	-12.450100	-4.915800	989.494198	1011.557251	96.423138	0.021147	0.021149	0.021161
B_F1	-4.722000	-8.235200	-4.920400	989.527213	1006.666918	96.408816	0.021173	0.021176	0.021187

Covariance matrix

#	Tx	Ty	Tz	q0	q1	q2	q3	a11	a12
Tx	+3.2178e-05	-7.1292e-10	-4.0870e-09	+1.9071e-07	-5.1949e-11	-9.3077e-11	-5.1259e-08	-6.8162e-07	-9.1517e-0
Ty	-7.1292e-10	+3.2182e-05	+3.2147e-08	+3.2918e-07	-1.0823e-10	-1.6828e-10	-8.8477e-08	+3.9501e-07	-3.8022e-0

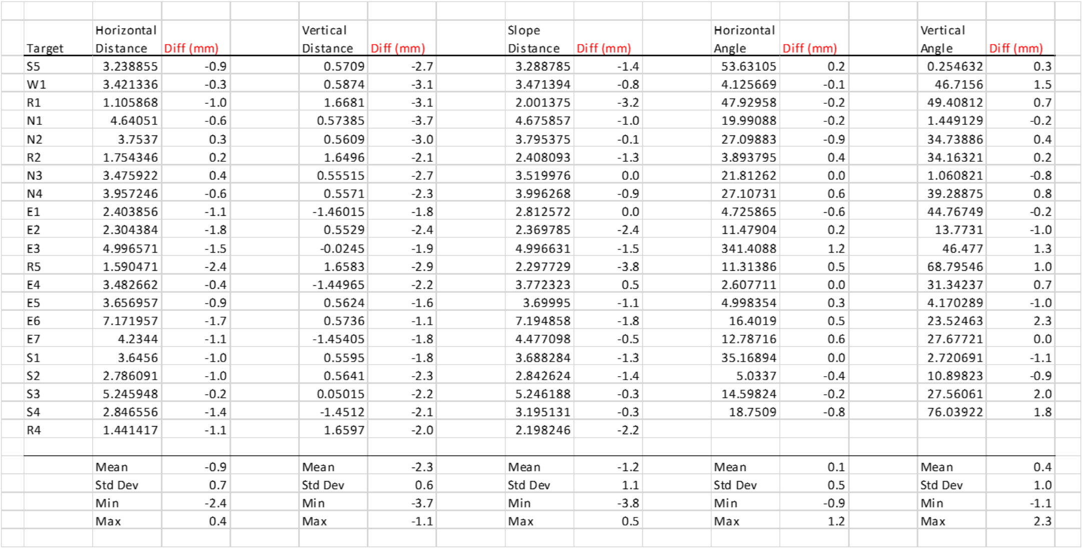
Tz	-4.0870e-09	+3.2147e-08	+3.2202e-05	+6.2444e-10	+4.5878e-07	+1.8826e-07	+4.7913e-12	+9.7854e-10	-1.4092e-0
q0	+1.9071e-07	+3.2918e-07	+6.2444e-10	+3.2377e-08	+2.6583e-11	+4.8598e-12	-8.7024e-09	+4.3571e-12	-6.7051e-0
q1	-5.1949e-11	-1.0823e-10	+4.5878e-07	+2.6583e-11	+2.9677e-08	-1.1500e-08	-2.0891e-11	+3.8649e-11	-1.2543e-1
q2	-9.3077e-11	-1.6828e-10	+1.8826e-07	+4.8598e-12	-1.1500e-08	+1.9219e-08	+1.9553e-11	-1.9654e-11	+4.1098e-1
q3	-5.1259e-08	-8.8477e-08	+4.7913e-12	-8.7024e-09	-2.0891e-11	+1.9553e-11	+2.3391e-09	-1.1939e-12	+1.8022e-0
a11	-6.8162e-07	+3.9501e-07	+9.7854e-10	+4.3571e-12	+3.8649e-11	-1.9654e-11	-1.1939e-12	+1.3885e-07	-2.9321e-0
a12	-9.1517e-07	-3.8022e-07	-1.4092e-09	-6.7051e-08	-1.2543e-10	+4.1098e-11	+1.8022e-08	-2.9321e-08	+1.9546e-0
a13	-2.0082e-06	+1.1642e-06	+7.9175e-07	+9.6361e-11	+6.3378e-08	-3.2216e-08	-6.3312e-11	+1.5779e-07	+1.9738e-0
a22	-3.0147e-07	-5.2037e-07	-1.6458e-09	+1.4146e-08	+2.0337e-11	-2.4177e-11	-3.8022e-09	+1.9223e-12	-2.9299e-0
a23	-1.1635e-06	-2.0083e-06	+5.9582e-07	-7.6069e-08	-6.9528e-09	+3.1174e-08	+2.0479e-08	-2.8248e-11	+1.5760e-0
a33	-1.2789e-09	-2.3015e-09	+2.3228e-06	-1.9628e-11	+7.8727e-08	-1.0671e-08	-1.0319e-11	+9.6226e-11	-1.1393e-1
Mx	-6.8162e-07	+3.9501e-07	+9.7854e-10	+4.3571e-12	+3.8649e-11	-1.9654e-11	-1.1939e-12	+1.3885e-07	-2.9321e-0
My	-3.0135e-07	-5.2032e-07	-1.6456e-09	+1.4155e-08	+2.0353e-11	-2.4183e-11	-3.8046e-09	+5.7131e-12	-2.9324e-0
Mz	-1.8662e-09	+2.3361e-09	+2.3228e-06	+1.0233e-10	+7.8816e-08	-1.0760e-08	-4.3198e-11	+2.8884e-10	-3.4226e-1
Rx	-6.9072e-11	-1.2430e-10	+1.2545e-07	+9.8018e-12	-3.7619e-08	+4.3091e-08	+4.4791e-11	-5.8023e-11	+1.1505e-1
Ry	+5.4170e-10	+9.7483e-10	-9.8384e-07	+1.2861e-11	-5.1350e-08	+1.2235e-08	+1.2265e-11	-6.4436e-11	+8.2726e-1
Rz	+3.9495e-07	+6.8172e-07	+2.2093e-09	+6.7052e-08	+1.0532e-10	-3.8042e-12	-1.8022e-08	+9.0871e-12	-1.3886e-0
Sx	+1.1628e-06	+2.0071e-06	-5.9916e-07	+7.6022e-08	+6.8224e-09	-3.1138e-08	-2.0467e-08	+2.8077e-11	-1.5750e-0
Sy	+2.0069e-06	-1.1635e-06	-7.8842e-07	-9.6176e-11	-6.3243e-08	+3.2183e-08	+6.3220e-11	-1.5769e-07	-1.9726e-0
Sz	+9.1523e-07	+3.8030e-07	+1.4094e-09	+6.7051e-08	+1.2543e-10	-4.1096e-11	-1.8022e-08	+2.9322e-08	-1.9546e-0

Rotation matrix

-8.6524583524361890e-01	-5.0134764864089210e-01	-4.2402337324412630e-04
+5.0134743090403380e-01	-8.6524377610310870e-01	-1.9903368455712220e-03
+6.3096711290873690e-04	-1.9347136951816267e-03	+9.9999792937956640e-01

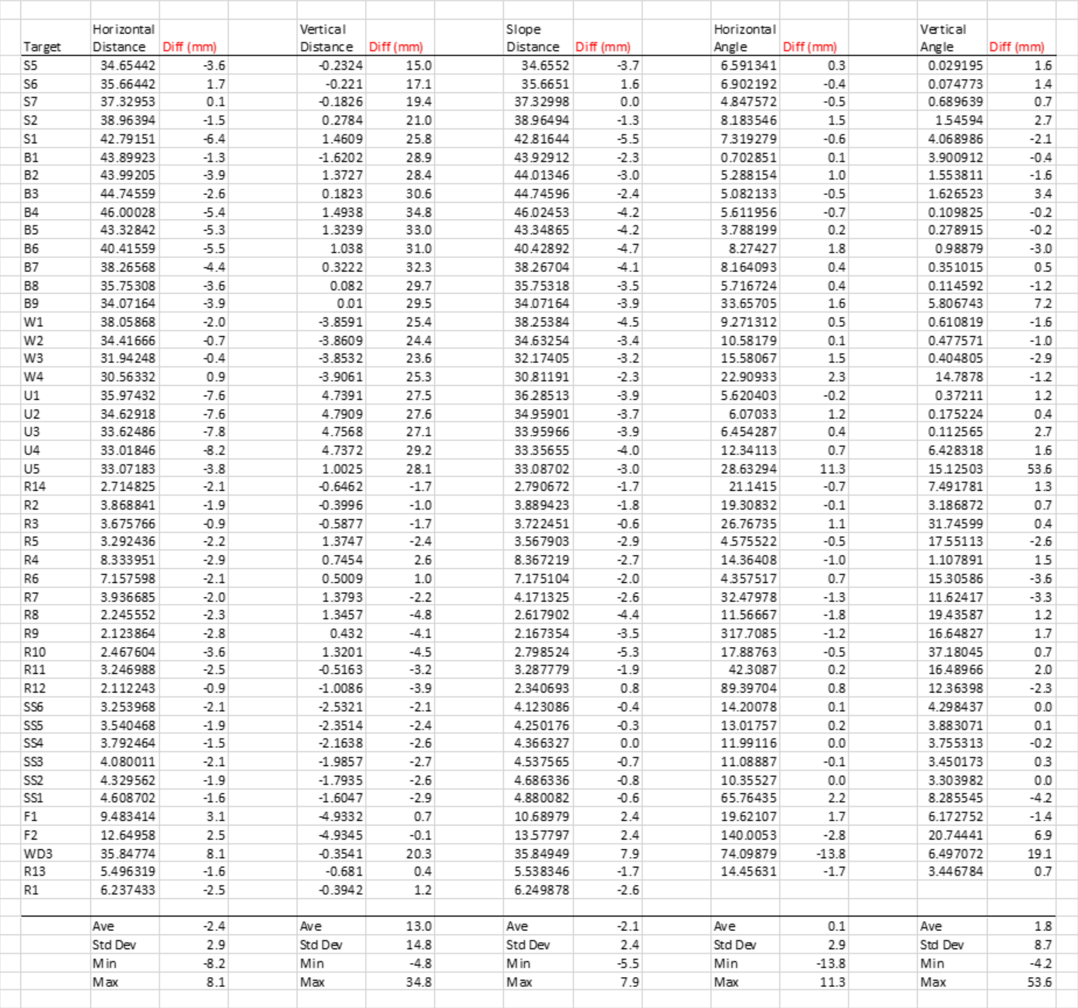
Transformation matrix

-8.6520418436468620e-01	-5.0122369771884690e-01	-6.7742793412479690e-04	+9.8131070844382790e+02
+5.0132329722976780e-01	-8.6528772519042840e-01	+7.4233044131833540e-06	+1.0019083860856523e+03
+6.3093673965091830e-04	-1.9347486106536630e-03	+1.0006234730148003e+00	+1.0131933005571263e+02
+0.0000000000000000e+00	+0.0000000000000000e+00	+0.0000000000000000e+00	+1.0000000000000000e+00



Target	Horizontal Distance	Diff (mm)	Vertical Distance	Diff (mm)	Slope Distance	Diff (mm)	Horizontal Angle	Diff (mm)	Vertical Angle	Diff (mm)
S5	3.238855	-0.9	0.5709	-2.7	3.288785	-1.4	53.63105	0.2	0.254632	0.3
W1	3.421336	-0.3	0.5874	-3.1	3.471394	-0.8	4.125669	-0.1	46.7156	1.5
R1	1.105868	-1.0	1.6681	-3.1	2.001375	-3.2	47.92958	-0.2	49.40812	0.7
N1	4.64051	-0.6	0.57385	-3.7	4.675857	-1.0	19.99088	-0.2	1.449129	-0.2
N2	3.7537	0.3	0.5609	-3.0	3.795375	-0.1	27.09883	-0.9	34.73886	0.4
R2	1.754346	0.2	1.6496	-2.1	2.408093	-1.3	3.893795	0.4	34.16321	0.2
N3	3.475922	0.4	0.55515	-2.7	3.519976	0.0	21.81262	0.0	1.060821	-0.8
N4	3.957246	-0.6	0.5571	-2.3	3.996268	-0.9	27.10731	0.6	39.28875	0.8
E1	2.403856	-1.1	-1.46015	-1.8	2.812572	0.0	4.725865	-0.6	44.76749	-0.2
E2	2.304384	-1.8	0.5529	-2.4	2.369785	-2.4	11.47904	0.2	13.7731	-1.0
E3	4.996571	-1.5	-0.0245	-1.9	4.996631	-1.5	341.4088	1.2	46.477	1.3
R5	1.590471	-2.4	1.6583	-2.9	2.297729	-3.8	11.31386	0.5	68.79546	1.0
E4	3.482662	-0.4	-1.44965	-2.2	3.772323	0.5	2.607711	0.0	31.34237	0.7
E5	3.656957	-0.9	0.5624	-1.6	3.69995	-1.1	4.998354	0.3	4.170289	-1.0
E6	7.171957	-1.7	0.5736	-1.1	7.194858	-1.8	16.4019	0.5	23.52463	2.3
E7	4.2344	-1.1	-1.45405	-1.8	4.477098	-0.5	12.78716	0.6	27.67721	0.0
S1	3.6456	-1.0	0.5595	-1.8	3.688284	-1.3	35.16894	0.0	2.720691	-1.1
S2	2.786091	-1.0	0.5641	-2.3	2.842624	-1.4	5.0337	-0.4	10.89823	-0.9
S3	5.245948	-0.2	0.05015	-2.2	5.246188	-0.3	14.59824	-0.2	27.56061	2.0
S4	2.846556	-1.4	-1.4512	-2.1	3.195131	-0.3	18.7509	-0.8	76.03922	1.8
R4	1.441417	-1.1	1.6597	-2.0	2.198246	-2.2				
	Mean	-0.9	Mean	-2.3	Mean	-1.2	Mean	0.1	Mean	0.4
	Std Dev	0.7	Std Dev	0.6	Std Dev	1.1	Std Dev	0.5	Std Dev	1.0
	Min	-2.4	Min	-3.7	Min	-3.8	Min	-0.9	Min	-1.1
	Max	0.4	Max	-1.1	Max	0.5	Max	1.2	Max	2.3

Figure 11.4: Original Data Comparisons in the short range testing facility. This data is presented to show the variation in the differences between the observed and true values which lead to the higher standard deviations for the vertical distance and vertical angle.



Target	Horizontal Distance	Diff (mm)	Vertical Distance	Diff (mm)	Slope Distance	Diff (mm)	Horizontal Angle	Diff (mm)	Vertical Angle	Diff (mm)
S5	34.65442	-3.6	-0.2324	15.0	34.6552	-3.7	6.591341	0.3	0.029195	1.6
S6	35.66442	1.7	-0.221	17.1	35.6651	1.6	6.902192	-0.4	0.074773	1.4
S7	37.32953	0.1	-0.1826	19.4	37.32998	0.0	4.847572	-0.5	0.689639	0.7
S2	38.96394	-1.5	0.2784	21.0	38.96494	-1.3	8.183546	1.5	1.54594	2.7
S1	42.79151	-6.4	1.4609	25.8	42.81644	-5.5	7.319279	-0.6	4.068986	-2.1
B1	43.89923	-1.3	-1.6202	28.9	43.92912	-2.3	0.702851	0.1	3.900912	-0.4
B2	43.99205	-3.9	1.3727	28.4	44.01346	-3.0	5.288154	1.0	1.553811	-1.6
B3	44.74559	-2.6	0.1823	30.6	44.74596	-2.4	5.082133	-0.5	1.626523	3.4
B4	46.00028	-5.4	1.4938	34.8	46.02453	-4.2	5.611956	-0.7	0.109825	-0.2
B5	43.32842	-5.3	1.3239	33.0	43.34865	-4.2	3.788199	0.2	0.278915	-0.2
B6	40.41559	-5.5	1.038	31.0	40.42892	-4.7	8.27427	1.8	0.98879	-3.0
B7	38.26568	-4.4	0.3222	32.3	38.26704	-4.1	8.164093	0.4	0.351015	0.5
B8	35.75308	-3.6	0.082	29.7	35.75318	-3.5	5.716724	0.4	0.114592	-1.2
B9	34.07164	-3.9	0.01	29.5	34.07164	-3.9	33.65705	1.6	5.806743	7.2
W1	38.05868	-2.0	-3.8591	25.4	38.25384	-4.5	9.271312	0.5	0.610819	-1.6
W2	34.41666	-0.7	-3.8609	24.4	34.63254	-3.4	10.58179	0.1	0.477571	-1.0
W3	31.94248	-0.4	-3.8532	23.6	32.17405	-3.2	15.58067	1.5	0.404805	-2.9
W4	30.56332	0.9	-3.9061	25.3	30.81191	-2.3	22.90933	2.3	14.7878	-1.2
U1	35.97432	-7.6	4.7391	27.5	36.28513	-3.9	5.620403	-0.2	0.37211	1.2
U2	34.62918	-7.6	4.7909	27.6	34.95901	-3.7	6.07033	1.2	0.175224	0.4
U3	33.62486	-7.8	4.7568	27.1	33.95966	-3.9	6.454287	0.4	0.112565	2.7
U4	33.01846	-8.2	4.7372	29.2	33.35655	-4.0	12.34113	0.7	6.428318	1.6
U5	33.07183	-3.8	1.0025	28.1	33.08702	-3.0	28.63294	11.3	15.12503	53.6
R14	2.714825	-2.1	-0.6462	-1.7	2.790672	-1.7	21.1415	-0.7	7.491781	1.3
R2	3.868841	-1.9	-0.3996	-1.0	3.889423	-1.8	19.30832	-0.1	3.186872	0.7
R3	3.675766	-0.9	-0.5877	-1.7	3.722451	-0.6	26.76735	1.1	31.74599	0.4
R5	3.292436	-2.2	1.3747	-2.4	3.567903	-2.9	4.575522	-0.5	17.55113	-2.6
R4	8.333951	-2.9	0.7454	2.6	8.367219	-2.7	14.36408	-1.0	1.107891	1.5
R6	7.157598	-2.1	0.5009	1.0	7.175104	-2.0	4.357517	0.7	15.30586	-3.6
R7	3.936685	-2.0	1.3793	-2.2	4.171325	-2.6	32.47978	-1.3	11.62417	-3.3
R8	2.245552	-2.3	1.3457	-4.8	2.617902	-4.4	11.56667	-1.8	19.43587	1.2
R9	2.123864	-2.8	0.432	-4.1	2.167354	-3.5	317.7085	-1.2	16.64827	1.7
R10	2.467604	-3.6	1.3201	-4.5	2.798524	-5.3	17.88763	-0.5	37.18045	0.7
R11	3.246988	-2.5	-0.5163	-3.2	3.287779	-1.9	42.3087	0.2	16.48966	2.0
R12	2.112243	-0.9	-1.0086	-3.9	2.340693	0.8	89.39704	0.8	12.36398	-2.3
SS6	3.253968	-2.1	-2.5321	-2.1	4.123086	-0.4	14.20078	0.1	4.298437	0.0
SS5	3.540468	-1.9	-2.3514	-2.4	4.250176	-0.3	13.01757	0.2	3.883071	0.1
SS4	3.792464	-1.5	-2.1638	-2.6	4.366327	0.0	11.99116	0.0	3.755313	-0.2
SS3	4.080011	-2.1	-1.9857	-2.7	4.537565	-0.7	11.08887	-0.1	3.450173	0.3
SS2	4.329562	-1.9	-1.7935	-2.6	4.686336	-0.8	10.35527	0.0	3.303982	0.0
SS1	4.608702	-1.6	-1.6047	-2.9	4.880082	-0.6	65.76435	2.2	8.285545	-4.2
F1	9.483414	3.1	-4.9332	0.7	10.68979	2.4	19.62107	1.7	6.172752	-1.4
F2	12.64958	2.5	-4.9345	-0.1	13.57797	2.4	140.0053	-2.8	20.74441	6.9
WD3	35.84774	8.1	-0.3541	20.3	35.84949	7.9	74.09879	-13.8	6.497072	19.1
R13	5.496319	-1.6	-0.681	0.4	5.538346	-1.7	14.45631	-1.7	3.446784	0.7
R1	6.237433	-2.5	-0.3942	1.2	6.249878	-2.6				
	Ave	-2.4	Ave	13.0	Ave	-2.1	Ave	0.1	Ave	1.8
	Std Dev	2.9	Std Dev	14.8	Std Dev	2.4	Std Dev	2.9	Std Dev	8.7
	Min	-8.2	Min	-4.8	Min	-5.5	Min	-13.8	Min	-4.2
	Max	8.1	Max	34.8	Max	7.9	Max	11.3	Max	53.6

Figure 11.5: Original Data Comparisons in the medium range testing facility using the scan data from the first half of the full scan done at position WD4. This data is presented to show the variation in the differences between the observed and true values which lead to the higher standard deviations for the vertical distance and vertical angle.

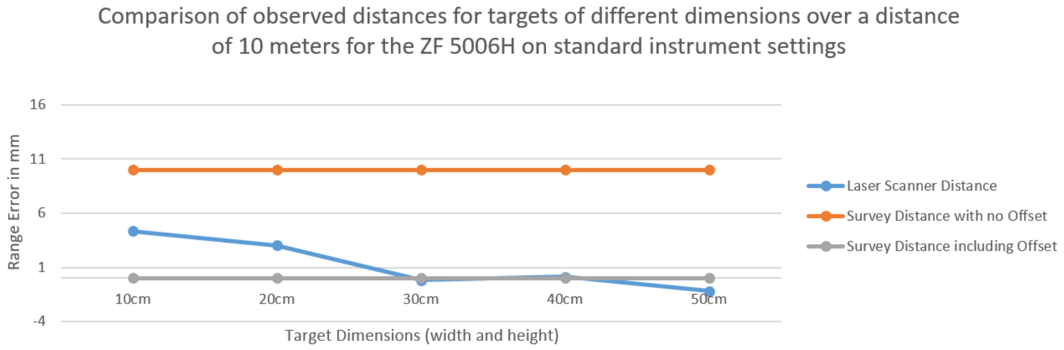


Figure 11.6: Graph showing the comparison of the laser scanner observed horizontal distance for the different target sizes against the surveyed horizontal distance with and without the offset over 10 meters for the instrument on standard settings.

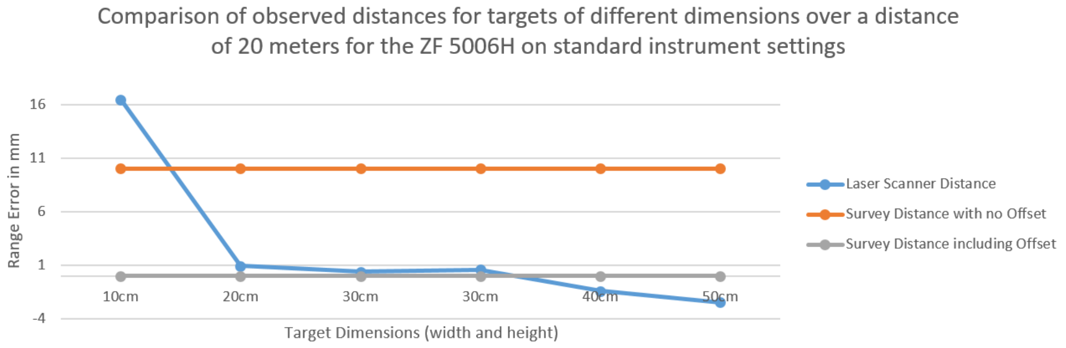


Figure 11.7: Graph showing the comparison of the laser scanner observed horizontal distance for the different target sizes against the surveyed horizontal distance with and without the offset over 20 meters for the instrument on standard settings.

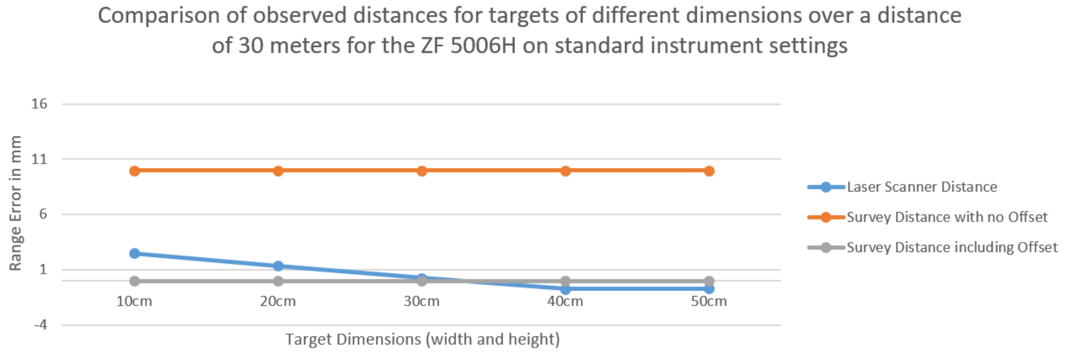


Figure 11.8: Graph showing the comparison of the laser scanner observed horizontal distance for the different target sizes against the surveyed horizontal distance with and without the offset over 30 meters for the instrument on standard settings.

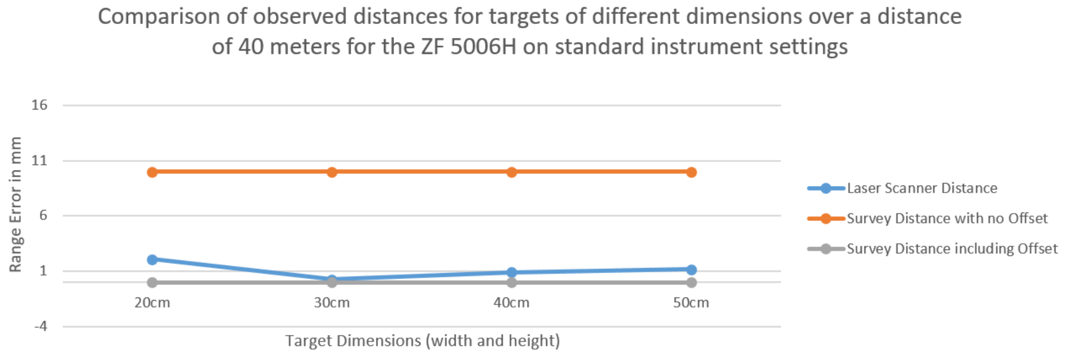


Figure 11.9: Graph showing the comparison of the laser scanner observed horizontal distance for the different target sizes against the surveyed horizontal distance with and without the offset over 40 meters for the instrument on standard settings.

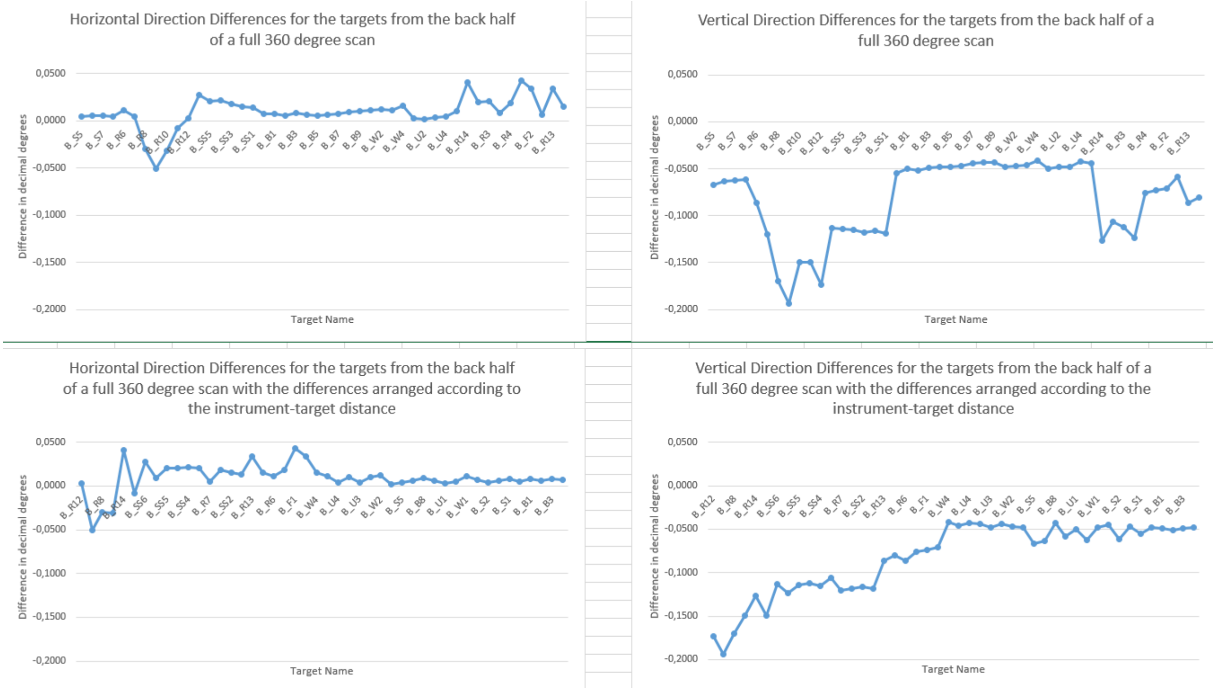
Technical Data

Compact high-speed phase-based laser scanner with great precision, range and spherical field of view. Unique stand-alone concept with integrated battery and color display with touch screen. Built-in dual-axis compensator and laser plummet.

Laser system			
Laser class	1		
Beam divergence	< 0.3 mrad		
Beam diameter	approx. 3.5 mm (at 0.1 m distance)		
Range	187.3 m (unambiguity interval)		
Minimum distance	0.3 m		
Resolution range	0.1 mm		
Data acquisition rate	Max. 1.016 million pixel/sec.		
Linearity error [1]	≤ 1 mm		
Range noise	black 14 %	grey 37 %	white 80 %
Range noise, 10 m [1,2]	0.4 mm rms	0.3 mm rms	0.2 mm rms
Range noise, 25 m [1,2]	0.6mm rms	0.4 mm rms	0.3 mm rms
Range noise, 50 m [1,2]	2.2 mm rms	0.8 mm rms	0.5 mm rms
Range noise, 100 m [1,2,3]	10 mm rms	3.3 mm rms	1.6 mm rms
Temperature drift	negligible		

Deflection unit	
Vertical system	completely encapsulated rotating mirror
Horizontal system	device rotates about its vertical axis
Vertical field of view	320°
Horizontal field of view	360°
Vertical resolution	0.0004°
Horizontal resolution	0.0002°
Vertical accuracy [1]	0.007° rms
Horizontal accuracy [1]	0.007° rms
Rotation speed	max. 50 rps (3,000 rpm)

Figure 11.10: Section of the Manufacturer Specifications for the Z+F 5010C Imager Laser Scanner system.


Horizontal Direction Differences for the targets from the back half of a full 360 degree scan

Vertical Direction Differences for the targets from the back half of a full 360 degree scan

Horizontal Direction Differences for the targets from the back half of a full 360 degree scan with the differences arranged according to the instrument-target distance

Vertical Direction Differences for the targets from the back half of a full 360 degree scan with the differences arranged according to the instrument-target distance

Figure 11.11: Graphs displaying the Direction Differences for targets in the back half of a full 360 degree scan with the differences arranged randomly and thereafter according to the instrument target distance in ascending order from left to right.

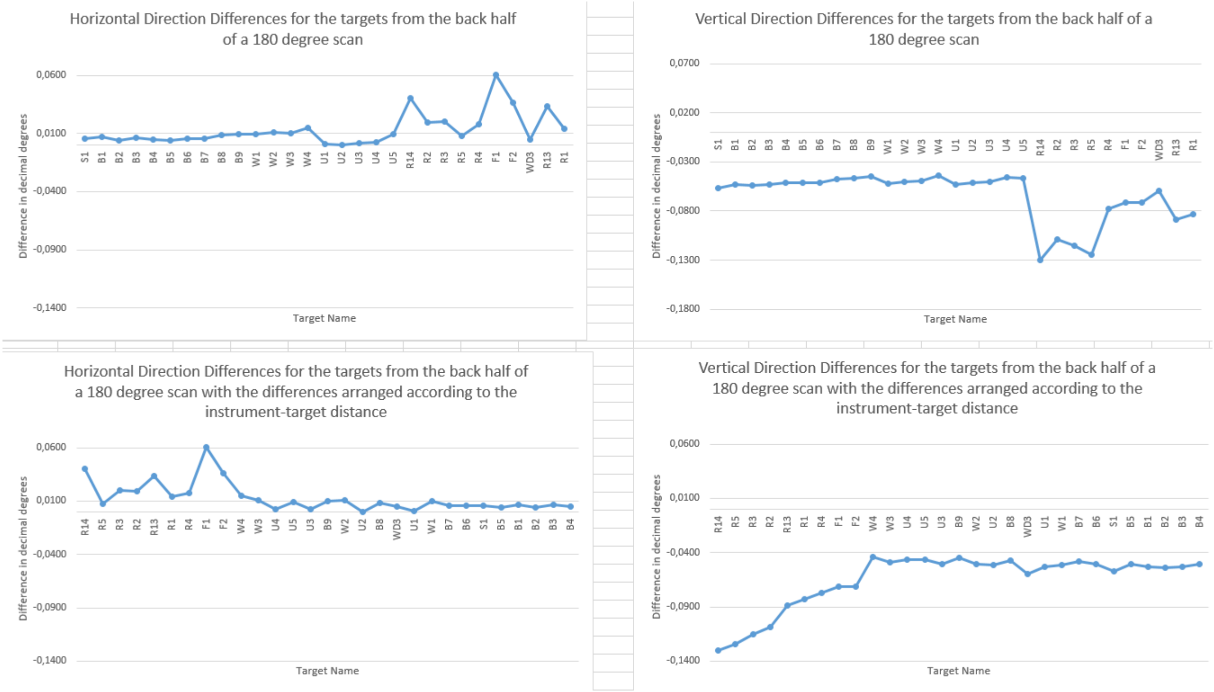

Horizontal Direction Differences for the targets from the front half of a 180 degree scan

Vertical Direction Differences for the targets from the front half of a 180 degree scan

Horizontal Direction Differences for the targets from the front half of a 180 degree scan with the differences arranged according to the instrument-target distance

Vertical Direction Differences for the targets from the front half of a 180 degree scan with the differences arranged according to the instrument-target distance

Figure 11.12: Graphs displaying the Direction Differences for targets in the front half of a 180 degree scan with the differences arranged randomly and thereafter according to the instrument target distance in ascending order from left to right.

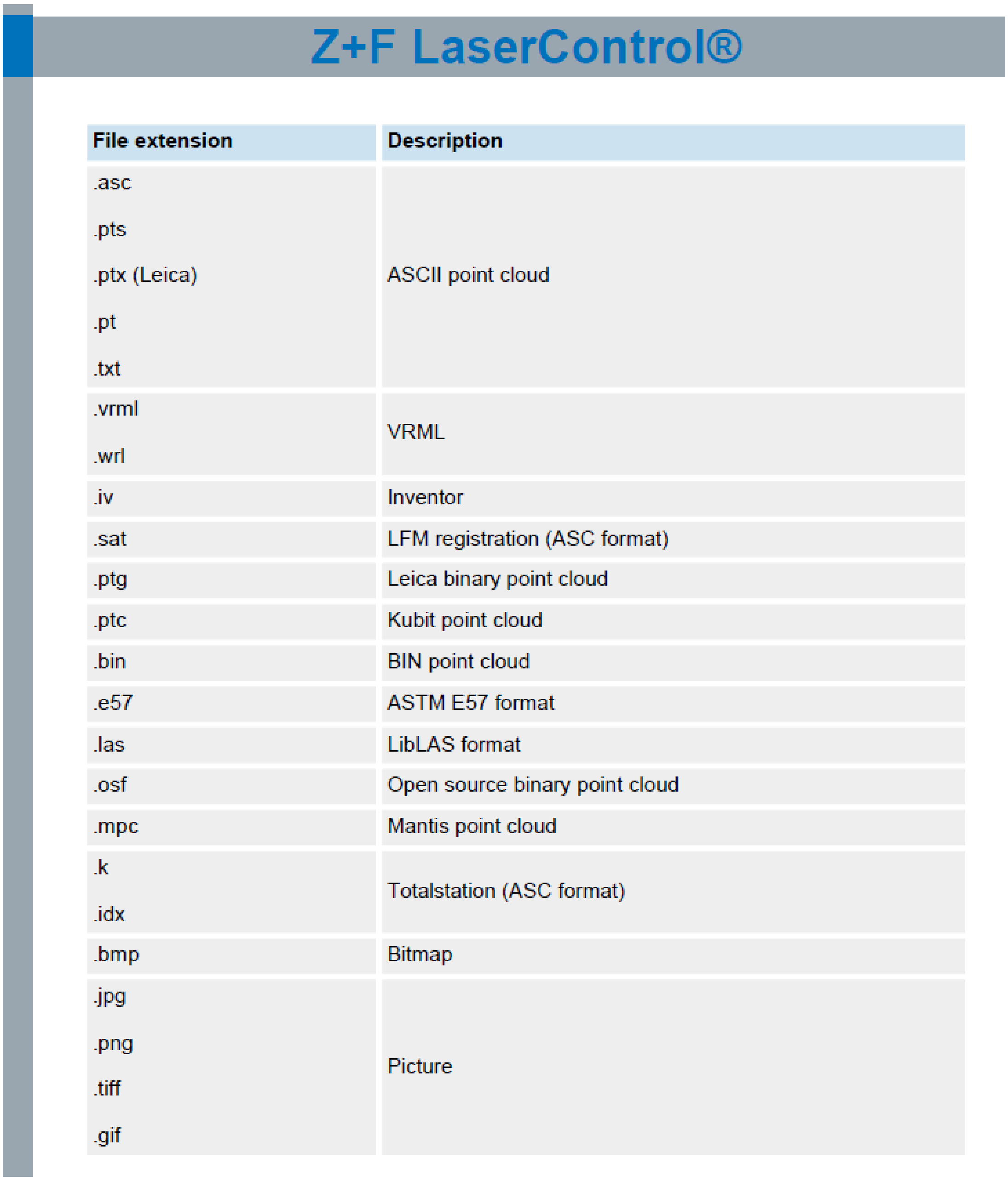

Horizontal Direction Differences for the targets from the back half of a 180 degree scan

Vertical Direction Differences for the targets from the back half of a 180 degree scan

Horizontal Direction Differences for the targets from the back half of a 180 degree scan with the differences arranged according to the instrument-target distance

Vertical Direction Differences for the targets from the back half of a 180 degree scan with the differences arranged according to the instrument-target distance

Figure 11.13: Graphs displaying the Direction Differences for targets in the back half of a 180 degree scan with the differences arranged randomly and thereafter according to the instrument target distance in ascending order from left to right.



Z+F LaserControl®

File extension	Description
.asc .pts .ptx (Leica) .pt .txt	ASCII point cloud
.vrml .wrl	VRML
.iv	Inventor
.sat	LFM registration (ASC format)
.ptg	Leica binary point cloud
.ptc	Kubit point cloud
.bin	BIN point cloud
.e57	ASTM E57 format
.las	LibLAS format
.osf	Open source binary point cloud
.mpc	Mantis point cloud
.k .idx	Totalstation (ASC format)
.bmp	Bitmap
.jpg .png .tiff .gif	Picture

Figure 11.14: Section from the Z+F LaserControl user manual listing the types of files that may be imported into the software. This is useful for user with laser scanners from brands other than Z+F to determine if they can produce a file that may be imported into the software to be evaluated.

Figure 11.15: Buildings Map of the University of Cape Town Upper Campus with the locations of the short and medium range testing facilities marked out.
Courtesy of url:
https://www.uct.ac.za/images/uct.ac.za/contact/campusmaps/big/uctuppercampus.jpg

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