University of Southern Queensland

Faculty of Engineering and Surveying

The development of a high precision terrestrial laser scanner calibration range at USQ

A Dissertation Submitted by

Allen Grant Ledger

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Abstract

Spatial science firms of today are required to deliver reliable and highly accurate data. Developing technologies have provided spatial science firms with the tools to deliver this data. The latest tool that the spatial scientist can use is the terrestrial laser scanner.

Terrestrial laser scanners are the latest development in the spatial science industry. They are becoming more popular throughout the industry and new applications for their use are constantly being developed. One of the most popular applications is to remotely capture large amounts of data in a short space of time or from locations where it would be dangerous for a human to occupy. For clients to have confidence in the spatial science profession it needs to have a testing procedure that ensures instruments are measuring correctly. It is the purpose of this research project to conduct investigations into developing a calibration range and calibration procedure at the University of Southern Queensland.

There are many design criteria that need to be considered when developing a calibration range. The first major criteria are to have targets located at high and low vertical angles for accurate estimation of the collimation axis error and a vertical angle correction. Having targets in a 360 degree circle around each scanner station is the second design criteria, which is used to calculate a horizontal angle correction. For the calculation of the scale error, multiple distance ranges are required. Finally at least two (2) scanner stations are required to be able to perform the calibration. This project will develop a calibration range at USQ that can be used to estimate corrections to TLS instruments.

The results of this project have found appropriate station geometry that can be used for the calibration of terrestrial laser scanners. It has found the optimum target geometry for an outdoor calibration range. Finally it has determined that the USQ calibration range is suitable for the calibration of terrestrial laser scanners.

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ENG4111 Research Project Part 1 & ENG4112 Research Project Part 2

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Student Name: Allen Grant Ledger

Student Number: 0050068403

Signature

Date

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Glossary

3D: Three dimensional. A description of the spatial environment in reference to its three dimensions.

Co-ordinate system: A set of numerical values that describe the position of a point in three dimensions.

Point Cloud: An array of three dimensional points in space.

Phase Shift: The shift in phase with reference to an electro-magnetic wave.

Total Station: An electronic optical measuring unit used within modern day surveying.

Reflectorless Total Station: A device that measures a distance to an object without the need of a prism to reflect.

Accuracy: The degree of closeness of a measurement to the true value.

Precision: The degree of repeatability of measurements under unchanged conditions that show the same result (may not be accurate).

Chapter 1 Introduction

1.1 Outline

This chapter will provide an outline of the project background, research problem, objectives and justification for this project. The dissertation describes the main aspects of Terrestrial Laser Scanner technology and the techniques involved to calibrate terrestrial laser scanner. It covers in detail the mathematical model required to calculate the corrections for the laser scanner. This project seeks to develop a high precision terrestrial laser scanner calibration range at the University of Southern Queensland.

1.2 Introduction

In the spatial science industry of today clients are requiring larger amounts of data faster and more accurately than before. As a response to this spatial science firms are utilising new technology on the market to achieve this.

The latest example of this can be seen with the Global Positioning System (GPS). It was once one of these new technologies that the spatial science industry had to accept and is now commonly used by the spatial science professional in the field. When it was first introduced to spatial science firms many professionals were not aware of it accuracies, errors, what causes those errors and how to manage them. Due to research these questions were answered and confidence was given spatial science firms that use GPS in the field. With this confidence GPS is now a widespread technology and is considered an industry standard in some applications. It would not be widely used if the researchers were not able to identify sources of errors and guarantee the accuracy of its data to clients.

1.3 Project background

Laser scanning is a relatively new technique to the spatial science industry. Spatial science firms are quickly adopting it into their firms. A major reason why these firms are using laser scanners is their ability to capture large amounts of data in a short space of time. This ability allows laser scanners to not only complete conventional tasks but also in ways that were previously thought impossible.

Surveyors have always had to operate to a set of stringent criteria, whereas non-professionals are not obliged to operate to the same standards. In Lichti, Gordon, and Tipdecho (2005) says 'the TLS has the least standardised control practices and error assessments'. This is where problems could arise if non-professionals are not aware of the measurement errors that could occur. ‘The increasing application of TLS systems and the ease of data capture they offer have enabled non-specialist operators from outside traditional surveying disciplines to efficiently generate detailed information in evermore challenging and complex environments’ (Large & Heritage 2009 p.6). This is because they are easy to use and operate and the apparently satisfactorily data outputs.

Calibration of instruments have been used in many different industries not just the spatial science profession. Engineers must have a regular calibration certificate for their measuring instruments. Since the early days of surveying surveyors have had to have a regular calibration policy in their firms. Calibration has been implemented by firms and regulated by the respected spatial science professional bodies of each state. This is because it was required to install confidence in the data given to clients. In Lichti (2009 p.171) ‘an important aspect of the quality assurance of three dimensional point clouds captured with terrestrial laser scanning (TLS) instruments is geometric calibration. Systematic errors inherent to such instruments can, if not corrected, degrade the accuracy of point clouds captured with a scanner’.

1.4 The problem

Calibration of measuring instruments has been widely used throughout many industries for many decades. The spatial science profession is no different to any other industry and as such any device that is used should be regularly calibrated. The purpose of calibration is to test the instrument against known values so that corrections can be calculated and then applied to the instrument so that the instrument will measure ‘true’. It is difficult to calculate the corrections to TLS because they are built in small series and manufacturers have their own calibration procedure and keep the corrections as a closely guarded secret.

1.5 Project aim

The aim of this project is to develop a terrestrial laser scanner calibration range at the University of Southern Queensland (USQ). That can be used by surveying and engineering firms as a quality control mechanism for their instruments.

1.6 Objectives

The objective of this project is to develop a terrestrial laser scanner calibration range. A review of the literature of the technology and their application is needed in order to design a calibration procedure in a controlled environment. From the calibration procedure corrections to the TLS needed to be calculated in order for the instrument to measure correctly.

- To determine the station geometry for the calibration.
- To determine an optimum target configuration for an outdoor site.
- To determine the capability of the range for TLS calibration.

1.7 Conclusion

As stated earlier the purpose of the project is to develop a calibration range at USQ. The focus of the project is to develop a calibration range that can provide corrections to instruments. It is important for surveyors to have confidence in their instruments that they are measuring accurately. This project focuses on producing a calibration range that these corrections can be calculated from. The scope does not include the development of mathematical models but use other researchers work in this respect. However through research and in using the equipment, opinions can be formed on other factors such as effectiveness and usability.

Chapter 2 Literature Review

2.1 Introduction

This chapter will outline the relevant literature associated with calibrating terrestrial laser scanners. It will also examine the technology of how terrestrial laser scanners operate. In recent years there has been a sizable amount of research performed on laser scanners. Much of the research has been on the accuracy and precisions of the instruments. There have however been a several researchers who have been successful with the calibration of laser scanners. This review will show and compare the different methods. It will also show the need for calibration of laser scanners

2.2 Need for calibration of Terrestrial Laser Scanners

Terrestrial laser scanning is a relatively new technology in the spatial science profession. It is becoming more popular with firms because new applications for the technology are being thought of. Surveying firms have always had to have a calibration policy for their measuring devices, whether it is an EDM or a steel tape. 'The need for calibration is obvious to professionals in those disciplines, it is perhaps more urgent given the significant growth in TLS use, particularly by 'non-experts' from other fields' (Lichti & Jamtsho 2006, p.142).The purpose of calibrating instruments is to define the instrumental errors and provide a correction so that the instrument will measure correctly. Schofield and Breach (2007 p.146) defined calibration as' the process of estimating the parameters that need to be applied to correct actual measurements to their true values'.

A large part of a surveyor's role is to manage the sources of errors from the field operations. For the surveyor to be able manage the errors they must know the accuracy of their instruments. 'The accuracy specifications given by laser scanner manufacturers in their publications and pamphlets are not comparable. 'Experience shows that sometimes these should not be trusted and that the accuracy of these instruments which are built in small series varies from instrument to instrument and depends on the individual calibration and the care that has been taken in handling the instrument since' (Boehler & Marbs 2003, p.2). For the surveyor to be confident in their instruments calibration is required. By having an instrument calibrated a spatial science professional is adding another quality control mechanism to its operation. This helps to install confidence in the client that the data that you are providing is a quality product that can be relied upon.

Laser scanners are being used where traditional methods would take weeks to gather the minimum amount of data required. In these situations it is not uncommon for the data that is required to be of a very high standard. Laser scanners can achieve these accuracies because of the amount of data that they can gather in a short space of time.

Laser scanners are being used more and more regularly by mining companies to provide the end of month volume calculations. If a spatial science firm does not have a quality assurance (QA) policy for its laser scanners that is similar to EDM calibrations. They could leave themselves open to be challenged by clients. By having QA policy spatial science firms are providing documentation that can be used as evidence to prove that their instrument is measuring correctly. If they do not have a calibrated instrument, clients could argue that the figures that they calculated are in error. For example if the mines earth moving contractor disagreed with the volumes of earth that was moved for that month and believed that they moved more earth than your calculations. You would not be able to argue that your instrument was measuring correctly because you do not having evidence claiming your instrument was correct. This would end up costing the mining company more money because the contractors get paid per cubic meter of earth they move.

Reshetyuk (2009) in his doctoral thesis says that the calibration of terrestrial laser scanners can be performed by one of the following methods.

- ***Component calibration***
  The components of the instrument, e.g. laser rangefinder and angle measurement system, are investigated separately. This type of calibration requires precise knowledge of the scanner error model. However, this knowledge is often very limited due to proprietary design of the scanners. In addition, component calibration requires the access to special facilities, e.g. calibration baselines, which may not be readily available to the users;
- ***System calibratio*****n**
  System calibration can be performed through what is known in the photogrammetric industry as self-calibration. *Self-calibration is the determination of all systematic errors of a terrestrial laser scanner simultaneously with all other system parameters. Unlike in component calibration, the knowledge of the scanner error model is not very important in system calibration (or self-calibration). Rather, the error model (or the correction function) is derived during the calibration, in a least-squares (LS) adjustment (Schulz 2007).*

This shows that the instrumental errors can be estimated without any knowledge of why they occur.

2.3 Terrestrial laser scanner overview

A Terrestrial Laser Scanner (TLS) is essentially a device that measures objects remotely. One of the major advantages of TLS is that you do not need to occupy a space to measure it. This means that delicate or danger areas can be surveyed without putting humans in danger or where they could do damage to a historical site. The basic principle method for this is to calculate a 3D point of the object. TLS do this by measuring a range, horizontal and vertical angle similar to Reflectorless technology in total station instruments. The difference to Reflectorless technology is that a TLS can measure thousands of points per second. Compared to one point for every ‘shot’ you take with reflectorless technology. Even though manufacturers are now developing software that can use reflectorless technology in a laser scanner fashion they are still superior for scanning surfaces.

2.3.1 Types of Terrestrial Laser Scanners

There are several ways to classify laser scanners but the most common or popular method is by which the range is measured to the object. Each manufacturer develops their instruments differently but the basic principles are the same. There are currently three different technologies available today, Time-Of-Flight, Phase Shift and Triangulation. ‘The time-off light (TOF) principle uses a laser source inside the scanner that emits a pulsed laser beam. If this beam hits an object, part of the beam is reflected back to the scanner and hits a detector inside the scanner. The time between transmission and reception of the pulsed signal is directly proportional to the distance between the scanner and the object. The laser pulse is diverted sequentially with a specific angular interval using an internal rotating mirror’ (Lee & Ehsani, 2008).

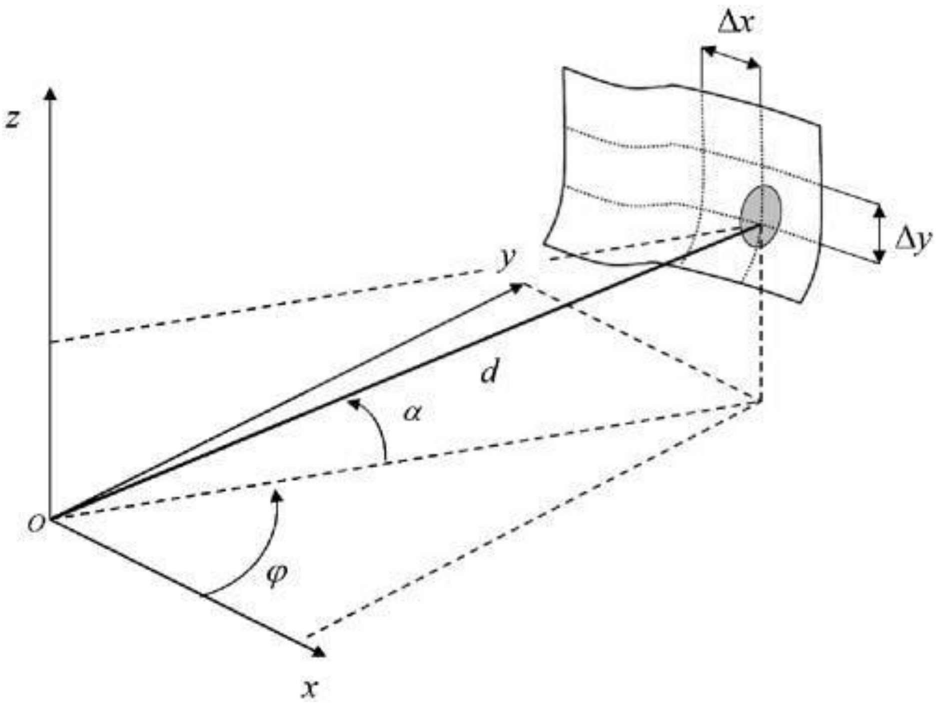

Figure 2.3-1: Principle of time-of-flight

'The phase measurement principle compares the difference between the outgoing and the returning signal' (Lee & Ehsani, 2008).

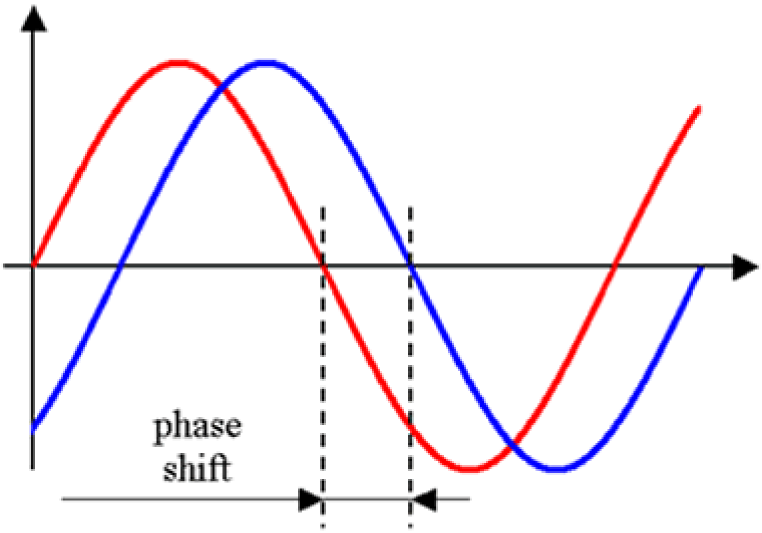

Figure 2.3-2: Calculating phase shift to calculate distance in phased based scanners.

The triangulation scanners solve the range determination in a triangle formed by the instrument's laser signal deflector, the reflection point on the object's surface and the projection centre of a camera, mounted at a certain distance from the deflector. The laser pulse is deflected by a small rotating device (mirror, prism) and sent from there to the object. The second angle, perpendicular to the first, may be changed using a mechanical axis or another rotating optical device. The readings for these angles are used for the computation of the 3D point coordinates.

Any errors caused by the axes/bearings or angular reading devices will result in errors perpendicular to the propagation path. Since the positions of single points are hard to be verified, few investigations of this problem are known. Errors can be detected by measuring short horizontal and vertical distances between objects (e.g. spheres) which are located at the same distance from the scanner and comparing those to measurements derived from more accurate surveying methods' (Boehler & Marbs 2003, p.4).

2.3.2 Accuracy

An investigation into the accuracy of laser scanner has been thoroughly in recent years. Before a calibration can begin an understanding of terrestrial laser scanners is required. This is required so that an appropriate calibration can be designed and procedure developed. Boehler and Marbs (2003) investigating laser scanner accuracy says *every point cloud produced by a laser scanner contains a considerable number of points that show gross errors. If the point cloud is delivered as a result of surveying, a quality guarantee, as possible for other surveying instruments, methods, and results, cannot be given.* If a regular calibration policy is implemented it will help with assuring clients.

There are many factors that affect accuracy, angular accuracy, range accuracy, influence of surface reflectivity and environmental conditions. Boehler and Marbs (2003) in *Investigating Laser Scanner Accuracy* talk about what causes instrumental errors and how to detect these errors throughout the article.

In Boehler and Marbs (2003) they give a detailed description of how to horizontal and how they occur. . He says that *any errors caused by the axes/bearings or angular reading devices will result in errors perpendicular to the propagation path. Since the positions of single points are hard to be verified, few investigations of this problem are known. Errors can be detected by measuring short horizontal and vertical distances between objects (e.g. spheres) which are located at the same distance from the scanner and comparing those to measurements derived from more accurate surveying methods.* This means that the angular accuracy is dependent on the internal components of the laser scanner.

Ranging errors can be detected when the computed range by the laser scanner is compared to the known distances between two points. If the scanner is not able to be set up over a fixed point then the measured range differences between the targets can be used. Boehler and Marbs (2003) say that 'Plane, cylindrical or spherical targets may be used if their precise positions are surveyed with instruments and methods more accurate than the laser scanner'.

Boehler and Marbs (2003) goes on to say

Whereas a systematic scale error will be present in any spatial distance measured, a systematic constant (zero) error will be eliminated when distance differences in range direction are determined. The constant error will influence distances between two points which are located indifferent directions as seen from the scanner, however. If both points are located in the same distance from the scanner, the deviation of their distance will amount to the zero error when the direction difference is 60°; it will amount to twice the zero error when the direction difference is 180°.

Boehler and Marbs (2003) believes that this statement is the main reason why a generally acceptable calibration and certification of laser scanners is not possible. Other researchers such as Lichti and Reshetyuk disagree with this statement. They have however in their calibration experiments not rigorously tested for a scale error in the range. This is because in their experiments were conducted in small rooms. Reshetyuk has made an attempt to test for the scale error by using a larger room, but was still not able to test the instrument sufficiently at different ranges.

Laser scanners are an active instrument that is they create a light source that is reflected off an object. 'The strength of the returning signals is influenced (among other facts such as distance, atmospheric conditions, incidence angle) by the reflective abilities of the surface' (Boehler & Marbs 2003, p.3).

Environmental conditions have been known to affect surveying measuring devices for some time. Therefore they have been studied comprehensively and models to correct for them are being used as a matter of course. Laser scanners operate in a similar fashion to reflectorless technology in total stations, which is why the assumption of using the same corrections for temperature and atmospheric can be used. The temperature correction can only be used if the laser scanner is allowed to warm up internally to a stable temperature. If the laser scanner is not allowed to warm up, then an error called 'range drift' will occur. Range drift occurs when the temperature changes significantly during the scanning operation. Määttä, Kostamovaara and Myllylä R (1993) say that the temperature of the laser transmitter should be stabilized in order to produce a stable pulse shape. If this is the case, the range drift due to the ambient temperature is linear, and may be compensated for by the software, for example, by reference to frequent temperature measurements'.

The placement of the targets to the scanner locations is very important and if it is not considered carefully can introduce unnecessary errors into the calibration. Chow et al. (2010) in a calibration performed on a Trimble GX TLS removed 21 of the total 162 targets prior to the adjustment being performed. The targets were removed because that target was only observed in one scan or it was measured with an incidence angle larger than 60 degrees'. This was reported by Lichti (2007) that for planar targets, the signal-to-noise ratio of the measured target centroid drops significantly when the incidence angle is greater than 60 degrees'. Careful considerations must therefore be given to the location of the laser scanner in relation to the location of the targets.

2.3.3 Applications

The use of terrestrial laser scanners are continuously increasing with spatial science firms realising the possible applications. Some of the areas that are being utilised most are where it requires a person to be put into a dangerous location. Michael Watson from I-SiTE Pty Ltd was' commissioned to survey a site a short distance below the Hoover Dam was in the United States of America (USA). To use traditional techniques would have lengthy and hazardous as the banks of the river is cliff like. Aerial surveying was not suitable due to the undercut of the valley faces on either side of the Colorado River. The field work for the whole project took only four days to complete. For the survey the I-SiTE Laser Imaging System was used, which has successfully completed the following applications.

- Excavated areas for volume calculations
- Stockpiles and dumps for volume calculations
- Mining areas for design analysis and geological mapping
- Underground cavities for survey and volume measurement
- Roadways for surface measurement visualisation
- Crime scenes for evidence recording and mapping
- Accident scenes for reconstruction and measurement process
- Industrial plant for measurement, planning and visualisation
- Grain storage facilities for volume calculations
- Disasters areas for scene mapping and recording
- Movie sets and scenery for digital animation and effect creation
- Military and defence applications
- Civil engineering works visual impact evaluation
- Rehabilitation studies in mines
- Vehicle studies for modelling and crash impact evaluation, (photogrammetry and remote sensing 2010, p.278).

As can be seen in the above list the applications are many and varied. The list is not complete there are many more uses for laser scanners.

2.3.4 The Leica Scan Station 2

In the last decade terrestrial laser scanning has become more available to spatial science firms. This is because the technology has decreased in price and the benefits are being realised. In the market today there are laser scanners available from many manufacturers. For this research project the Leica Scan Station 2 will be used. It is a pulsed time-of-flight instrument that uses a class 3R green laser. Cyclone software will be used as the operating and processing software.

The manufacture quotes the following accuracies and other important information.

- Modelled surface precision/noise: 2 mm 1 σ
- Scan rate: 50 000 points/second (maximum)
- Maximum sample density: <1 mm
- Field of view: 360˚ horizontal, 270˚ vertical.
- Range 300 m @ 90%; 134 m @ 18% albedo
- Dual-axis compensator: Selectable on/off Resolution 1", dynamic range +/- 5'
- Accuracy of single measurement
  - Position 6mm
  - Distance 4mm
  - Angle (horizontal/vertical) 60 μrad/60 μrad, one sigma
- Scanning Optics: Single mirror, panoramic, front and upper window design. Environmentally protected by housing and two glass shields

Figure 2.3-3: Leica Scan Station 2

For a full product specification sheet for the Leica Scan Station 2 see Appendix B

2.4 Other Terrestrial Laser Scanner calibration Research and Calibration theory

Terrestrial laser scanners have been a recent development in the spatial science industry. As a result the majority of the research has been completed and published since the start of the new century. Investigation into the accuracy of laser scanners has been comprehensively achieved by many researchers. This research has been vital in giving the spatial science industry the confidence in laser scanning technology. Without this confidence the industry would not be able to provide the services to clients.

'Calibration can be done relatively easily and inexpensively through what is generally called TLS self-calibration' (Chow et al. 2010). The benefit of this approach is that it can be performed in house and does not need to be sent away to the manufacturer. This is an important advantage because it is very expensive to return equipment to the manufacturer, not to mention the down time of having a very expensive instrument not returning profits.

There have been many researchers that have completed research into the calibration of laser scanners. The most notable amongst these and the most published is Derek D. Lichti from Curtain University of Technology. The paper by Lichti (2007) 'Error modelling, calibration and analysis of an AM–CW terrestrial laser scanner system' is the most quoted. In this paper he presents a rigorous method for TLS self-calibration using a network of signalised points. The laser scanner that is the focus of the paper is a 'phase shift' type scanner, the Faro 880. This paper presents a full mathematical model for point based, photogrammetric approach to self-calibration is provided. Lichti (2007) notes that 'the focus of this paper is on one particular make and model of amplitude-modulated– continuous-wave (AM–CW) or (phase shift) TLS system, the underlying mathematical models are derived independently of a particular instrument and can therefore be easily modified to suit others'. Lichti in a number of his publications recognises the similarities between a total station and a TLS and uses these similarities to estimate the corrections that need to be applied to TLS in the calibration.

Reshetyuk (2010) takes a similar approach in 'A unified approach to self-calibration of terrestrial laser scanners'. He to uses a point based calibration range as well a modified Helmert Least Squares adjustment. His mathematical model is based on the photogrammetric approach to self-calibration, 'the unified approach'. Both Lichti and Reshetyuk mathematical models are based on a least squares adjustment. Reshetyuk uses a Leica Scan Station as the laser scanner for the calibration instrument, which is the previous model to the TLS instrument used in this dissertation.

2.5 Mathematical theory

Terrestrial laser scanners have the same three fundamental axes as total stations, which are the trunnion axis, vertical axis and the collimation axis. It has been found by researchers such as Lichti that physical systematic errors are caused by these three axis's not intersecting with each other in a unique point in space. *To mathematically describe the systematic errors in TLS systems, the modelling can be performed in a spherical coordinate system. This approach is adopted here because despite the fact that most TLS systems outputs X, Y, and Z Cartesian coordinates, the scanner's raw measurements are horizontal circle readings, vertical circle readings, and range observations to the object space* (Chow et al. 2010).

This approach has been used in photogrammetric calibration for many years and is called the 'unified approach to self-calibration'. In this approach these raw observations are used and compared to each other. For example two targets are scanned from one scanner location. Using laser scanner software the X, Y and Z of the targets are calculated. The horizontal circle readings, vertical circle readings, and range observations can then be calculated between the two targets. A second scan is then performed and the same targets are scanned again. The angles and range are calculated from the second scanner location. The angles and range from each scanner location are compared with each other. The differences between the angles are used to calculate the Additional Parameters (APs) and Exterior Orientation Parameters (EOPs). *In a single scan captured by the TLS instrument, every point is uniquely determined. With zero degrees of freedom, the APs cannot be determined. In order to perform least squares adjustment and solve for the object space coordinate, exterior orientation parameters (EOPs) of each scan, and APs simultaneously, multiple scans of the same targets from different positions and orientations must be captured* (Chow et al. 2010).

For the unified approach to self-calibration there must be at least two scanner locations. For the calibration range at USQ we have used three scanner locations. By having three scanner locations there is one degree of freedom and will provide redundancies for the mathematical models.

2.6 Mathematical Models

The main aim of a TLS calibration is to separate the influences of distance and angle dependant errors. There are many mathematical models that are complicated or very simple. For this project it will show a simplified test procedure and a point based adjustment. Both achieve the objective of separating the angle and distances errors from each other and are run through a bundle adjustment.

2.6.1 Simplified procedure

The simplified test procedure was presented at a conference sponsored by Leica and is based on the kick-off document by Hans Heister. The topic was called 'ideas for field procedure to test terrestrial laser scanners (TLS)'. The procedure is valid for all types of scanner, whether they have tilt compensation or not. It does this by appointing common measure of standard uncertainties.

The range error will be calculated as follows (*Ideas for field procedure to test Terrestrial Laser scanners (TLS)*, 2008).

$$Scan\ from\ SC1: (1-2)sc1 = (1-2) + 2c$$

$$Scan\ from\ SC2: (1-2)sc2 = (1-2)$$

$$\text{Therefore} \qquad c = \frac{(1-2)sc1 + (1-2)sc2}{2}$$

The horizontal error (Hz error) will be calculated as follows (*Ideas for field procedure to test Terrestrial Laser scanners (TLS)*, 2008).

$$Scan\ from\ SC1: (2-3)sc1 = (2-3) + c$$

$$Scan\ from\ SC2: (2-3)sc2 = (2-3) + c * \tan(\theta) + Hz\ error - influence$$

$$Therefore\ Hz\ error - influence = (2-3)sc2 - (2-3)sc1 + tan(\theta) * c$$

The vertical error (V error) will be calculated as follows (*Ideas for field procedure to test Terrestrial Laser scanners (TLS)*, 2008.

$$Scan\ from\ SC1: (2-4)sc1 = (2-4) + c$$

$$Scan\ from\ SC2: (2-4)sc2 = (2-4) + c * \tan(\theta) + V\ error - influence$$

$$Therefore\ V\ error - influence = (2-4)sc2 - (2-4)sc1 + tan(\theta) * c$$

These formulas have been used in a Microsoft Excel spreadsheet to estimate corrections.

2.6.2 Point based adjustment

The rigid body transformation of point *i* from object scanner space to scanner space *j* in which observations are made, is given by (Lichti 2007, p309)

$$\begin{bmatrix} x_{ij} \\ y_{ij} \\ z_{ij} \end{bmatrix} = R_3(\kappa_j) \quad R_2(\phi_j) \quad R_1(\omega_j) \left\{ \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} - \begin{bmatrix} X_{ij} \\ Y_{ij} \\ Z_{ij} \end{bmatrix} \right\} = M_j \left\{ \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} - \begin{bmatrix} X_{ij} \\ Y_{ij} \\ Z_{ij} \end{bmatrix} \right\}$$

This is a rotational matrix that transforms all of the different scans onto the same datum.

The range, horizontal direction and vertical angle are calculated from the raw uncorrected coordinates of the targets in the scanner (Lichti 2007, p309).

$$\rho_{ij} + v_{\rho ij} = \sqrt{x_{ij}^2 + \quad y_{ij}^2 + \quad z_{ij}^2} + \Delta\rho$$

$$\theta_{ij} + v_{\theta ij} = arctan\left(\frac{y_{ij}}{x_{ij}}\right) + \Delta\theta$$

And

$$\alpha_{ij} + \mathrm{v}_{\alpha\mathrm{ij}} = \arctan\left(\frac{\mathrm{y_{ij}}}{\sqrt{x_{ij}^2 + \quad y_{ij}^2}}\right)\Delta\alpha$$

The error terms are modelled below (Reshetyuk 2009).

$$\Delta\rho = a_0,$$

Where a_0 is the laser rangefinder zero error (Reshetyuk 2009).

$$\Delta\theta = \frac{b_1}{cos\theta_j^{(i)}} + b_2 tan\theta_j^{(i)},$$

Where b_1 and b_2 are the collimation and horizontal axis errors, respectively (Reshetyuk 2009).

$$\Delta\alpha = c_0,$$

Where c_0 is the vertical circle index error.

The error models that have been presented are from Reshetyuk's doctoral thesis. The error models from Lichti's paper 'Error modelling, calibration and analysis of an AM–CW terrestrial laser scanner system' have not been used because they were designed for a different type of instrument. The error model that has been presented are designed for the phase shift TLS that has been used in this project. In Lichti (2007) he has identified 17 error sources for his TLS error models.

The groups of observation equations can be arranged in (linearised) hyper-matrix form as follows (Lichti 2007, p314).

$$\begin{bmatrix} A_{\rho e} & A_{\rho a} & A_{\rho o} \\ A_{\theta e} & A_{\theta a} & A_{\theta o} \\ A_{\alpha e} & A_{\alpha a} & A_{\alpha o} \end{bmatrix} \begin{bmatrix} \widehat{\delta_e} \\ \widehat{\delta_a} \\ \widehat{\delta_o} \end{bmatrix} + \begin{bmatrix} w_\rho \\ w_\theta \\ w_\alpha \end{bmatrix} = \begin{bmatrix} \widehat{v_\rho} \\ \widehat{v_\theta} \\ \widehat{v_\alpha} \end{bmatrix}$$

Where A_{xy} represents the Jacobian (design) matrix of partial derivatives of an observation group.

In Lichti (2007) paper inclinometer observations of the targets were made. The two (2) equations for the inclinometer observations have been left out. This is because inclinometer observations would not be made.

The weight matrix P is a block diagonal (Lichti 2007, p314).

$$P = \begin{bmatrix} P_\rho & 0 & 0 \\ 0 & P_\theta & 0 \\ 0 & 0 & P_\alpha \end{bmatrix}$$

The bordered system of normal equations follows standard parametric least squares and is given by (Lichti 2007, p314).

$$
\begin{bmatrix}
\begin{bmatrix} A_{\rho e}^{T} & P_{\rho} & A_{\rho e} \\ +A_{\theta e}^{T} & P_{\theta} & A_{\theta e} \\ +A_{\alpha e}^{T} & P_{\alpha} & A_{\alpha e} \end{bmatrix} & \begin{bmatrix} A_{\rho e}^{T} & P_{\rho} & A_{\rho e} \\ +A_{\theta e}^{T} & P_{\theta} & A_{\theta a} \\ +A_{\alpha e}^{T} & P_{\alpha} & A_{\alpha a} \end{bmatrix} & \begin{bmatrix} A_{\rho e}^{T} & P_{\rho} & A_{\rho o} \\ +A_{\theta e}^{T} & P_{\theta} & A_{\theta o} \\ +A_{\alpha e}^{T} & P_{\alpha} & A_{\alpha o} \end{bmatrix} & 0 \\
 & \begin{bmatrix} A_{\rho a}^{T} & P_{\rho} & A_{\rho e} \\ +A_{\theta a}^{T} & P_{\theta} & A_{\theta a} \\ +A_{\alpha a}^{T} & P_{\alpha} & A_{\alpha a} \end{bmatrix} & \begin{bmatrix} A_{\rho a}^{T} & P_{\rho} & A_{\rho o} \\ +A_{\theta a}^{T} & P_{\theta} & A_{\theta o} \\ +A_{\alpha a}^{T} & P_{\alpha} & A_{\alpha o} \end{bmatrix} & 0 \\
 & & \begin{bmatrix} A_{\rho o}^{T} & P_{\rho} & A_{\rho o} \\ +A_{\theta o}^{T} & P_{\theta} & A_{\theta o} \\ +A_{\alpha o}^{T} & P_{\alpha} & A_{\alpha o} \end{bmatrix} & G_{o} \\
 & & & 0
\end{bmatrix}
\begin{bmatrix} \widehat{\delta_e} \\ \widehat{\delta_a} \\ \widehat{\delta_o} \\ \widehat{k_c} \end{bmatrix}
+ \begin{bmatrix}
\begin{bmatrix} A_{\rho e}^{T} & P_{\rho} & w_{\rho} \\ +A_{\theta e}^{T} & P_{\theta} & w_{\theta} \\ +A_{\alpha e}^{T} & P_{\alpha} & w_{\alpha} \end{bmatrix} \\
\begin{bmatrix} A_{\rho a}^{T} & P_{\rho} & w_{\rho} \\ +A_{\theta a}^{T} & P_{\theta} & w_{\theta} \\ +A_{\alpha a}^{T} & P_{\alpha} & w_{\alpha} \end{bmatrix} \\
\begin{bmatrix} A_{\rho o}^{T} & P_{\rho} & w_{\rho} \\ +A_{\theta o}^{T} & P_{\theta} & w_{\theta} \\ +A_{\alpha o}^{T} & P_{\alpha} & w_{\alpha} \end{bmatrix} \\
0
\end{bmatrix}
= \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
$$

Where k_c is the vector of the Lagrange multipliers.

The rigorous mathematical formula requires that targets be coordinated by independent methods. This method will not be used in the reduction process. This is because it was one of the desires of this project that the scanner targets would not have to be coordinated before any scanning was performed.

2.7 Calibration field

There are many factors that need to be considered in the design and location a TLS calibration range. Lichti et al (2000) performed accuracy tests on a TLS instrument by performing tests on it over that were similar to a total station calibration. He found that ‘a bias was apparent from the EDM calibration baseline tests, which may be directionally dependent (i.e., due to eccentricity)’ (Lichti et al 2000). In Lichti (2007) and Reshetyuk (2010) they have used indoor calibration fields. In Lichti (2007) the room was quite small and was not able to test the scanner at different ranges. While Reshetyuk (2010) used a large room for his calibration field used doctoral research paper. While this room was larger it still was not able to test the TLS for range. Both these researchers in there calibration fields have used 100 plus targets so that they are ensured to have sufficient redundancies in their network design.

The unified approach to self-calibration requires that at least one scan is performed from two locations. Reshetyuk and Lichti both have used four different locations in their calibration fields. They state the reason for this is ‘a large redundant set of observations needs to be captured with the TLS from multiple positions and different orientations’ (Chow et al. 2010). By having four scanner stations there is twice the amount of data and are providing the calibration with a complete set of redundant data. It is meant that by a complete set the minimum stations required for a self-calibration is two and by having four you could use to perform many more calibrations with the same data. For example stations 1 and 2 could be used in the calibration but then if you thought that data was corrupted you could use stations 2 and 4. It could be taken further by having stations 1 and 3 in the calibration. A spreadsheet showing all the possible combinations is shown below.

	Stations			
Combination	1	2	3	4
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				

Table 2.7-1: Combination of stations

The location of the calibration field that has been chosen for our calibration field is situated on the University of Southern Queensland Toowoomba campus, between the Alison Dickson Centre and the east side of G-Block. An outdoor calibration field has been chosen so that we could simulate a real life scenario, whereas Reshetyuk and Lichti have used indoor calibration fields. They have done this so that all the conditions of the test can be controlled.

2.7.1 Targets

The targets that are being used for the calibration field are special high definition (HDS) targets. Printable Black and White (BW) targets will also be used in the calibration. These targets are used to complete the registration process and. The targets are used in conjunction with processing software to calculate their coordinates.

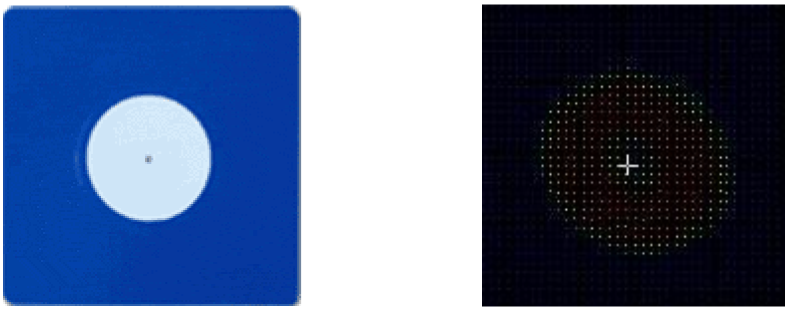

Figure 2.7-1: The HDS target that was scanned and what it looks like in the point cloud

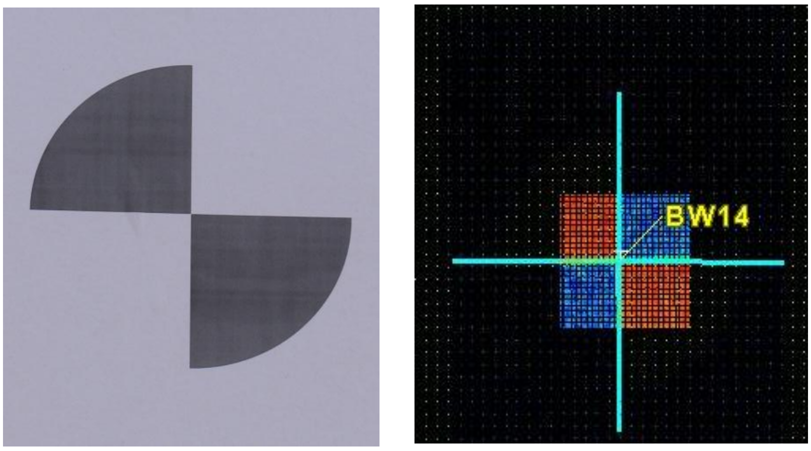

Figure 2.7-1: The Black and White target and what it looks like in the point cloud

2.7.2 Target Configuration

The target configuration design is a very important aspect in the calibration of TLS. The research that has been performed by Lichti and Reshetyuk has based their design on photogrammetric calibration. In Lichti (2007) he notes the following requirements for the design of target configuration.

- A large elevation angle range is needed for estimation of the collimation axis and trunnion axis errors
- At least two locations and a variety of ranges are needed for rangefinder additive constant determination. A large variety of ranges was also needed to estimate cyclic errors.
- Orthogonal scans captured from the same nominal location, a technique borrowed from photogrammetric camera calibration, was an additional measure incorporated to de-correlate the EO and the APs. High redundancy, and therefore a large number of targets, was desired so that trends in residual plots uncovered during the exploratory data analyses could be safely hypothesised to be due to un-modelled systematic errors.

These points are the same for ‘First Order Design’ datum definition in camera self-calibration. Reshetyuk in his doctoral thesis also uses the same principles for his calibration experiments.

Figure 2.7-1: An indoor calibration field

In the photo above is a calibration field that was used by Lichti (2007) in a series of experiments in 2007. It can be seen that a large number of targets have been used and that they are at high and low vertical angles. Other researchers have used similar sized rooms and placed targets on the ceiling as well.

2.8 Conclusion

This chapter has explored the technology used in this project as well as the existing and potential uses. It has presented a detailed mathematical model of Terrestrial Laser Scanner calibration and key elements in the calibration process. The information that has been gathered in this chapter will used to form a methodology to develop a calibration range.

Chapter 3 Methodology

3.1 Introduction

The aim of this chapter is to develop and calibration range at the University of Southern Queensland. The desired outcome of the methodology should be the ability to test TLS in a controlled environment where corrections can be calculated and applied with absolute consistency. In order to achieve this, a calibration range and procedure must be developed that compares fixed points with scanned data.

3.2 Calibration design

It was recognised early in the designing of the calibration range that it should be a simple design. It should be as basic as possible while still meeting all the design criteria. For a calibration range to function properly it must also be repeatable. This will allow for the calibration range to be used in the future and ultimately provide a rigorous calibration of the instrument. Finally the test should be able to be used by all the different types of scanners available on the market and any future instruments. In the figures below it can be seen where the target and scanner stations were located.

Figure 3.2-1: USQ TLS calibration showing station positions

In figure 3.2-1 shows where the scanner was positioned during the data capture. HDS targets have been placed on these tribrach's because they were originally going to be used in the calibration. It was decided not to use these targets because centring errors would be brought into the calibration. Any procedures that could introduce human errors into the calibration should not be used.

Figure 3.2-2: USQ TLS calibration showing maximum range

In figure 3.2-2 the maximum possible range is shown. It is possible to measure a maximum of 50 meters to the permanent HDS targets located on the far building. The maximum distance could be extended by placing HDS targets on tripods. The tripods would need to be located on the far side of a road and car park that can be seen in the figure.

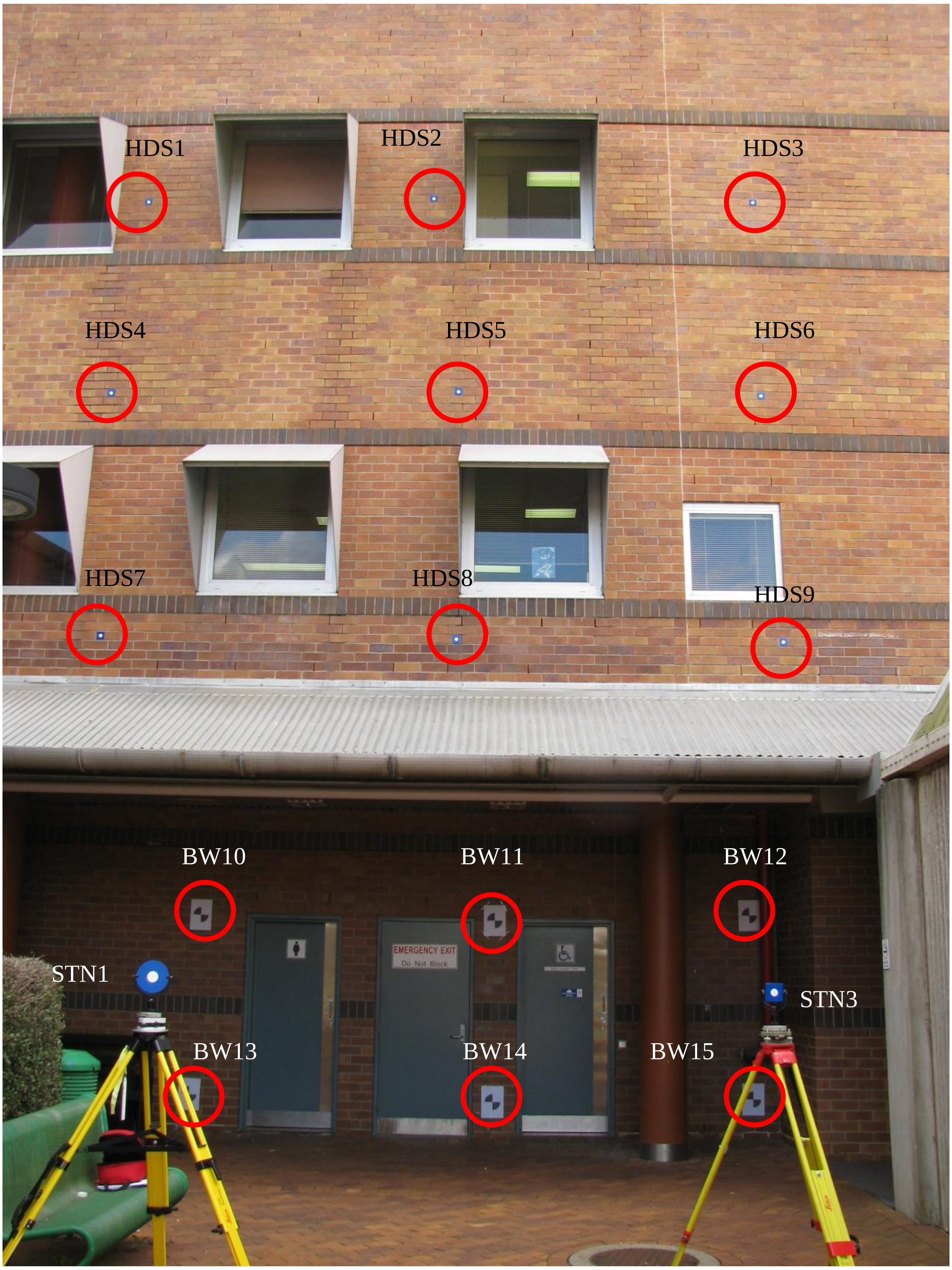

Figure 3.2-3: USQ TLS calibration range showing HDS and BW targets on West wall

In figure 3.2-3 nine (9) HDS and six (6) BW targets have been located on the West wall of the calibration range. The West wall provides for the steepest vertical angle to the targets. All of the scanner stations are located normal to the wall and do not have a large horizontal angle to these targets.

Figure 3.2-4: USQ TLS calibration range West wall BW targets only

In figure 3.2-4 the BW targets on the West wall can be seen. The targets were fixed to the wall on the day of scanning. They were fixed to the wall using sticky tape.

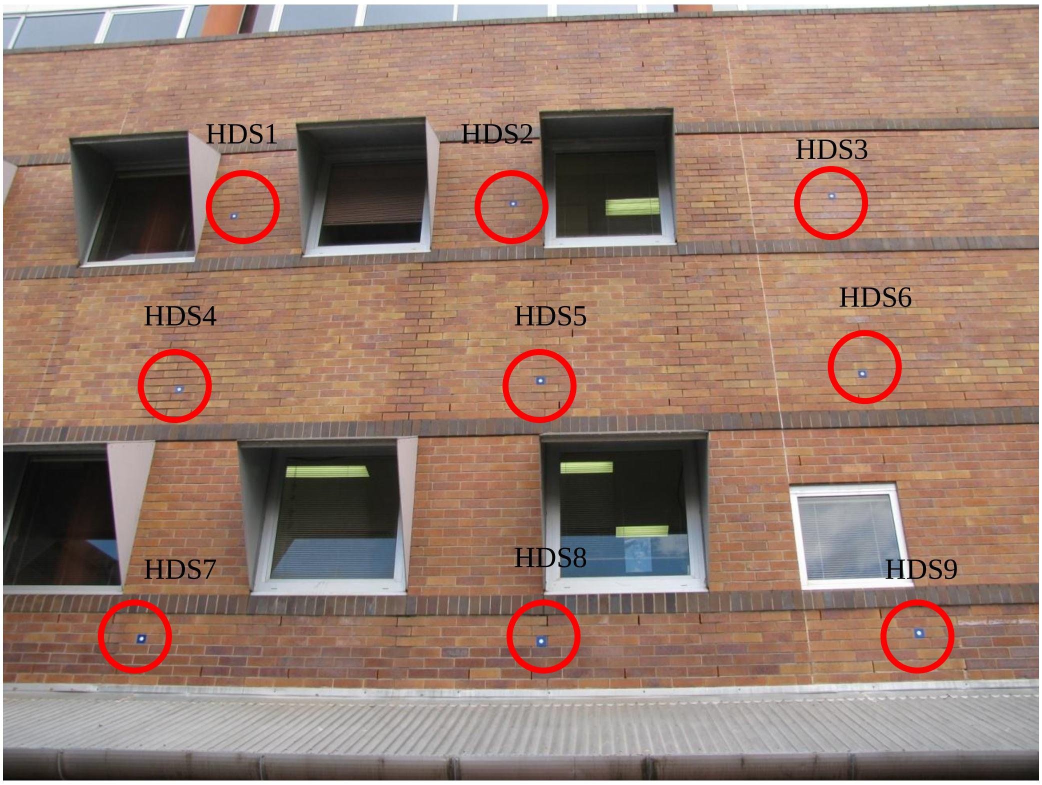

Figure 3.2-5: USQ TLS calibration range showing HDS targets only on West wall

In figure 3.2-5 the HDS targets located on the West wall can be seen. The targets have been located in a grid pattern. The image was taken from between Station 1 and Station 3. These two stations provided for the steepest vertical angles to the targets.

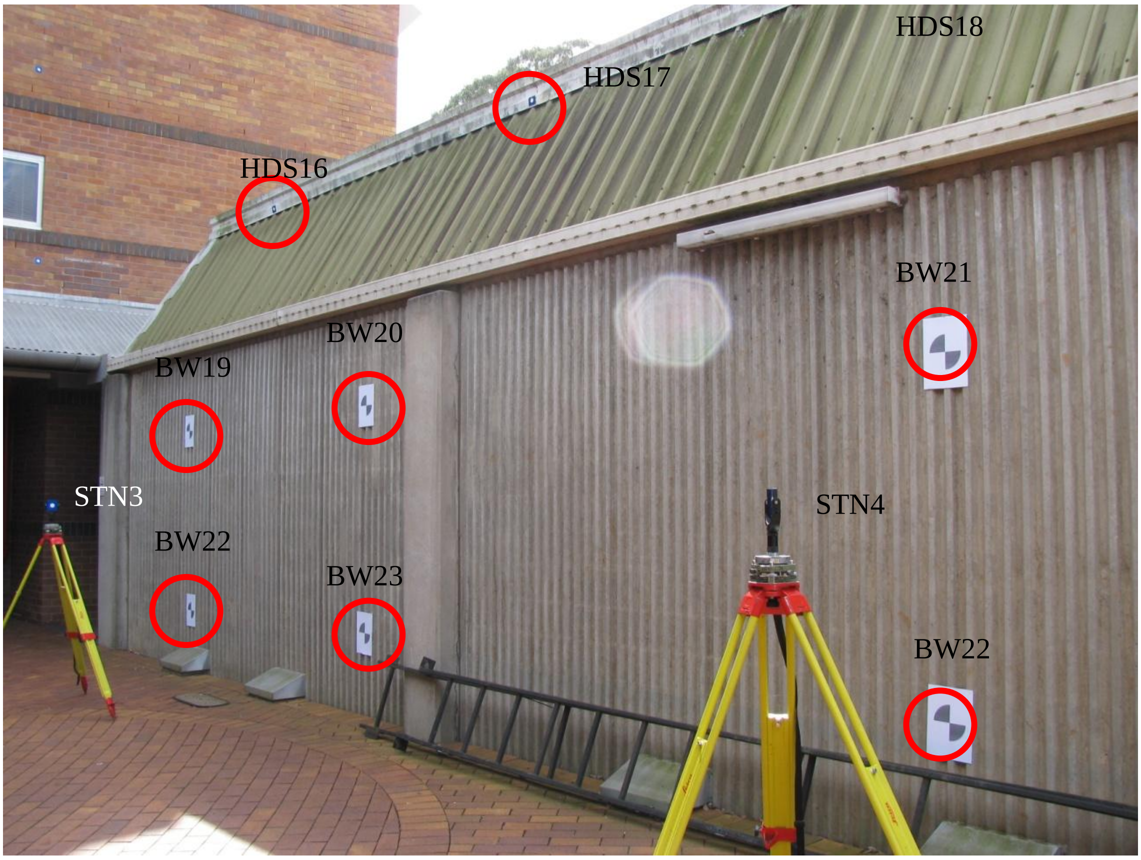

Figure 3.2-6: USQ TLS calibration range showing North wall

In figure 3.2-6 the location of two (2) HDS target and six (6) BW targets can be seen on the North wall. The temporary BW targets were fixed to the wall on the day of scanning. The wall is concrete with purpose built corrugations in them. Normally a rough surface would not be suitable for the location of a target. To overcome this problem the A4 sheets of paper were glued onto a stiff piece of cardboard and then fastened to the wall using double sided tape. HDS18 cannot be seen in this image as it is out of the shot but is located directly above BW21. The low vertical angle tested because of the closeness of Station 3 and Station 4. These stations also provide a large horizontal angle between the targets because the stations are about one (1) meter from the North wall.

Figure 3.2-7: USQ TLS calibration range showing South wall

In figure 3.2-7 location of the six (6) HDS targets on the South wall can be seen. This wall provides a high vertical angle because of the closeness of Station 1 and Station 2.

3.3 Terrestrial laser scanner

It was mentioned in the literature review that the terrestrial laser scanner that will be used in this project is a Leica Scan Station 2. This instruments operating and functioning software is Cyclone. A Panasonic Tough Book is loaded with Cyclone, which is then used to control the laser scanner in the field.

The Leica Scan Station 2 is terrestrial laser scanner that is capable of filling all the requirements of performing a full calibration. This is because it has a dual axis compensator and has a 360 degree horizontal field of view and more importantly 270 degree vertical field of view. It is important to have a large vertical field of view because it is required to properly estimate the collimation and trunnion axis correction. It was mentioned in the literature review that targets that a larger elevation angle is required for the estimation of the collimation and trunnion axis correction. Some researchers have argued that the compensator should be turned off when scanning the calibration range. They believe that it a better way to estimate the trunnion axis correction. The accuracy of the scanner is not important in the calibration. It will be used however to determine that the scanner is measuring to the manufacturer's specifications. These are quoted for a single measurement of 6mm position and 4mm for distance. For the horizontal and vertical angle is 60 µrad at one sigma.

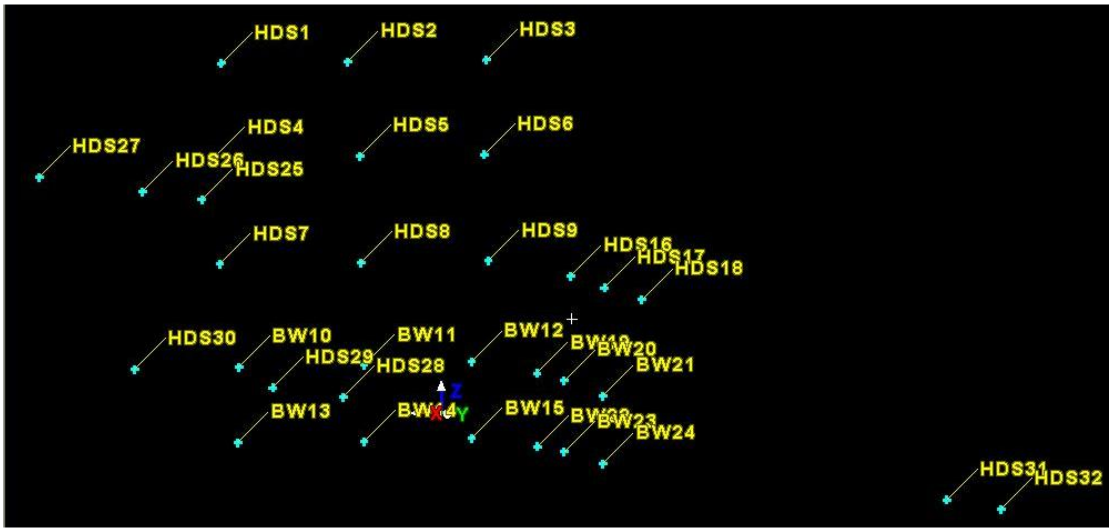

Figure 3.3-1: Screen shot in Cyclone of all the targets in Control space

In figure 3.3-1 all the targets that were scanned can be seen. This figure is a screenshot of how the targets appeared in Cyclone's control space.

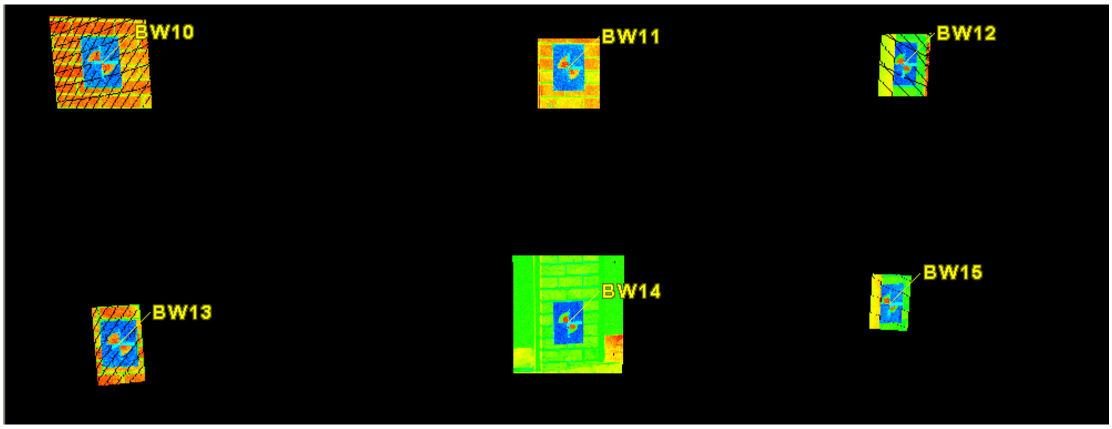

Figure 3.3-2: Close up screen shot from Cyclone in Control space of the targets

In figure 3.3-2 a close up screen shot of the targets in Cyclone's control space can be seen. The different densities in the scanner can be seen. The fine scans that were used to determine the target centre can be seen in the middle of the course scan data. The course scan data is used to determine the location of the target, where a fine scan can then be used on the target only.

The Leica Scan Station 2 is completely controlled by the Cyclone software. All functions are controlled through the software as well as the processing. It this case the software was loaded on a Panasonic Software Tough Book but could be loaded on to any computer that can be operated in the field. The scanner and processing equipment was made available by the University of Southern Queensland.

3.4 Calibration

As mentioned in the literature review it was decided to use the unified approach to self-calibration. It was decided that this approach was to be used because it was the simplest method for design and usability. Other methods that require fixed targets to be coordinated by independent methods have problems associated with them. For instance the targets must be ‘read in’ with more accurate methods than the laser scanner. As different laser scanners have different accuracies some laser scanners may not be able to be used on the calibration range. Another problem that could arise is if targets are located on buildings or any other structure the coordinated targets could move and would need to be re-observed.

In the unified approach orthogonal scans are performed from different locations. The angles between the targets are calculated from each scanner location. The angles from each scanner location are compared to each other. The angles are compared and adjusted in a rigorous least squares adjustment.

The location of the targets were located that filled the criteria set out in the literature review. They were set up on the outside of different buildings so that they could be seen from different scanner locations.

3.5 Calibration field procedure

The calibration field is located on the outside of Q Blocks east wing at the USQ campus, Toowoomba. This site was chosen because it is not a heavily used area by students. The locations of the scanner station have been located in positions that are not used by students. This location also has the ability of testing the scanner at high vertical angels. This was one of the most important criteria that the range had to pass as it will allow for the trunnion and collimation axis error to be estimated properly. Due to the nature of the location is will allow targets to be placed on both buildings. By doing this it will allow for a wide spread of horizontal angles between the targets. It also allows for varying different ranges for the scanner to be tested at. These ranges vary from about one (1) meter to about 50 meters. It is situated near a road so that it will allow easy transportation of equipment to the site.

Firstly, the HDS targets are placed on the walls in locations that can be seen by all the scanner locations. For a calibration a large number of redundancies are required for a rigorous calibration. To accommodate this BW targets have been printed out and are temporarily fixed to the walls on the day of scanning. These targets position can be assured for the day of scanning.

Four scanner locations have been chosen to perform that calibration. In the literature review it was shown that at least two scanner locations were needed to perform a calibration. Four have been chosen because it will allow for 2 degrees of freedom on the statistical testing and will therefore provide a better result.

The Leica Scan Station 2 was setup over 'station' and is levelled and setup properly. As part of the setting up process a 'warm-up' can must be performed. If this is not the done the range to the targets could be affected by range drift as was seen in the literature review. After the scan is setup, each target can be scanned. For the Leica Scan Station 2 this is done by firstly, the area is imaged using the scanner imagery function. This image is used by the operator to identify the locations of the targets that will need to be scanned with a higher resolution scan. This is a special function of the Leica Scan Station 2 which allows you to select different areas in the scanners field of view that can be scanned at a higher resolution. This speeds up the scanning process because the whole area does not need to be scanned at a high resolution. If a TLS scanner does not have this function then the whole area will need to be scanned at a high resolution. The highest resolution scan should be used in the calibration process. This is because it will allow for the most accurate determination of the targets, which will allow for the best estimation of the corrections that need to be applied to the TLS. This process is repeated for all the scanner locations.

After the field work has been completed the raw data is processed in Cyclone. An arbitrary datum has been used for the coordinates of the scanner stations. An arbitrary datum has been used because we are only comparing the angles between the targets not the actual coordinates of the targets. This raw data is outputted as an X, Y and Z of each target.

3.6 Calibration reduction

The simplified mathematical model that was shown earlier in this literature review was programmed into the Excel spreadsheet. This mathematical model was chosen because it can be easily programmed into the Excel spreadsheet. It is also a self-calibration adjustment whereas the point based mathematical model as the name suggests relies on the targets being coordinated by independent survey methods.

Cyclone only outputs X, Y and Z coordinates but not the raw horizontal angles, vertical angles and ranges that are needed in the calibration. To perform the calibration the coordinates are imported into an Excel spreadsheet. The spreadsheet uses these coordinates to calculate the angles and ranges between the targets. The software outputs the corrections that will need to be applied to the TLS, so that it is measuring correctly. The calibration is also an accuracy test this is because that if the correction is less than the manufacturer's specifications then the instrument will not need to be adjusted.

3.7-1 Outlier detection and removal

'The observations used in the adjustment can be falsified by gross errors, or outliers, which change the distribution of the observations' (Koch 1999. P. 255). It can be very difficult to identify these gross errors but by using statistical analysis on the observations they can be identified. By removing outliers from the adjustment it is ensuring that only data that is a true representation of how the TLS is measuring is used in the adjustment.

It was stated earlier that the simplified mathematical model will be used in the adjustment of the TLS. Another reason that the simplified procedure was chosen for the calibration is that any outliers can easily be identified and removed. This is because a residual is calculated between every target that is used in the adjustment. The main theory behind the simplified procedure is that a distance is calculated between two (2) targets the same distance is calculated between the two (2) targets by using a different formula. It is these distances that are compared against each other and the difference between them is the residual.

To identify the outliers the residuals will be the best indication if any observations are in gross error. For example if the residual was 0.003 or 0.008 and the positional accuracy of the scanner was 0.006 then it could be said that the residual was not in gross error. Whereas if the residual was 1.265 then it could be said that it was in gross error because it is very unrealistic that a TLS would be in such a large error unless the majority of the residuals showed a similar sized error. The best way to see the pattern in the observations is by graphing the residuals for each accuracy test. To show the overall quality of the adjustment the standard deviation of the mean is calculated, which shows how much each observation deviates from the mean. The smaller the standard deviation the more accurate the observations are. The standard deviation is then used to calculate the confidence interval of the observations. It is standard practice in the spatial science industry to use a 95% confidence interval when performing statistical analysis and has been used for this project as well. The upper and lower confidence interval limits have been calculated and also graphed onto the residual graph. This was done to show which of the residuals were outside of the confidence interval limits and to give an indication of the quality of the data.

Any outliers will be removed if the graphs show that any of the residuals are outside of the confidence interval limits. They will also be removed if they do not follow the trend of the other residuals. The residuals that get removed will be summarised in a table where any possible patterns can be seen.

3.8 Conclusion

This chapter has outlined how the methodology was formed for this project. The methodology designed a calibration range that would be able to calculate the corrections to TLS so that they are measuring true. The following chapter provides the results of this testing.

Chapter 4 Results

4.1 Introduction

In the methodology chapter, the development of a TLS calibration range and calibration procedure was discussed. A discussion on calibration methods has resulted in a self-calibration approach being adopted, with a further discussion taking place about the design of the target geometry. A calibration range has been designed that will test the accuracy of the laser scanner and be able to estimate corrections that can be applied to the TLS.

The purpose of this chapter is to provide the results of the calibration. Included will be an explanation of what the results show about the instrument. The results presented in this section will show the capability of the calibration range.

4.2 Target location

Before any scanning was completed targets were required to be located in suitable positions. Permanent HDS targets were located at high vertical angles with the use of a cherry picker. On the day of the field work was commenced temporary printable black and white (BW) targets were fixed to the walls at low vertical angles. These targets were printed out on A4 paper and attached to the walls using sticky tape. Six (6) targets were required to be located on an uneven surface where an accurate determination of the targets was impossible. For these targets the A4 sheet of paper was glued to a very stiff piece of cardboard before it was attached to the wall.

4.3 Terrestrial laser scanner

The field procedure was initiated with a course scan. This process involved the scanner being setup at the desired location and selecting the area to be scanned. The result of this scan is a point cloud of the area. This point cloud is used to identify the HDS and BW targets where a fine scan is then completed around only the target area. A fine scan is used to collect high intensity data at the smallest distance between observations. Cyclone, the operating software of the laser scanner uses this high density point cloud to determine the centre of the target.

The mathematical model that has been used for this project does not require that the different scans from each station are on the same coordinate system. During the field work the scanner was therefore left on an arbitrary coordinate system. The results from the calibration coordinates of the targets and stations can be seen in table 4.3-1 and table 4.3-2

Coordinates from station 1					Coordinates from station 2			
Target	X	Y	Z		Target	X	Y	Z
HDS1	-2.9144	4.6639	7.2457		HDS1	2.0337	-11.0496	7.267
HDS2	-0.0776	5.1959	7.2193		HDS2	-0.8489	-10.8111	7.27
HDS3	3.0653	5.7868	7.2523		HDS3	-4.0299	-10.5509	7.2733
HDS4	-3.0736	4.6346	5.1208		HDS4	2.1959	-11.0642	5.1411
HDS5	0.2113	5.2509	5.1213		HDS5	-1.1358	-10.789	5.1422
HDS6	3.0215	5.7809	5.1196		HDS6	-3.987	-10.5571	5.1407
HDS7	-2.9506	4.6651	2.7157		HDS7	2.0677	-11.0597	2.7356
HDS8	0.2322	5.2648	2.7165		HDS8	-1.16	-10.7968	2.7369
HDS9	3.1112	5.8077	2.7183		HDS9	-4.0796	-10.5582	2.7389
BW10	-2.5016	6.2868	0.3008		BW10	1.207	-12.5058	0.321
BW11	0.3142	6.8127	0.3047		BW11	-1.6481	-12.2677	0.325
BW12	2.7382	7.2661	0.3626		BW12	-4.1064	-12.064	0.3833
BW13	-2.5354	6.2798	-1.4125		BW13	1.2413	-12.5068	-1.3922
BW14	0.3129	6.8123	-1.4102		BW14	-1.6467	-12.2679	-1.39
BW15	2.7438	7.2683	-1.3778		BW15	-4.1118	-12.0636	-1.357
HDS16	4.9327	1.6907	2.6232		HDS16	-4.7482	-6.1072	2.6449
HDS17	5.6689	-2.2593	2.6016		HDS17	-4.4132	-2.1024	2.6232
HDS18	6.4854	-6.6168	2.6018		HDS18	-4.0478	2.3159	2.6239
BW19	4.1772	1.6958	0.432		BW19	-4.021	-6.312	0.4535
BW20	4.771	-1.4638	0.4591		BW20	-3.757	-3.1059	0.4807
BW21	5.6058	-5.9981	0.3814		BW21	-3.3624	1.4868	0.4038
BW22	4.1907	1.6071	-1.2214		BW22	-4.0102	-6.2223	-1.2004
BW23	4.7671	-1.4621	-1.1481		BW23	-3.7538	-3.1096	-1.1266
BW24	5.6026	-6.0015	-1.1412		BW24	-3.3584	1.4884	-1.1186
HDS25	-3.4242	-5.4683	4.7848		HDS25	5.2061	-1.4133	4.8055
HDS26	-4.7514	-2.4938	4.7895		HDS26	5.6983	-4.6325	4.8099
HDS27	-7.0261	2.619	4.7923		HDS27	6.5434	-10.1766	4.8269
HDS28	-0.2479	-14.2209	1.0898		HDS28	2.8647	1.9906	0.5217
HDS29	-1.8261	-4.6076	0.492		HDS29	3.4363	-1.8193	0.5136
HDS30	-4.9001	2.3628	0.4931		HDS30	4.5529	-9.3064	0.5107
HDS31	13.139	-37.5764	-0.0467		HDS31	-2.2734	33.9318	-0.0182
HDS32	14.3125	-43.9948	0.1373		HDS32	-1.7071	40.432	0.1657
STN1	0	1	0		STN2	0	1	0

Table 4.3-1: Coordinates from Station 1 and Station 2 of the calibration performed on 26/09/2011

Coordinates from station 3					Coordinates from station 4			
Target	X	Y	Z		Target	X	Y	Z
HDS1	-2.8524	6.7247	7.2676		HDS1	-1.7949	13.2908	7.2402
HDS2	-0.1009	5.8332	7.2704		HDS2	1.0217	12.6318	7.2433
HDS3	2.9358	4.8511	7.2739		HDS3	4.1297	11.9068	7.2463
HDS4	-3.0067	6.7751	5.1421		HDS4	-1.9523	13.3281	5.1147
HDS5	0.1729	5.7456	5.1429		HDS5	1.302	12.5675	5.1157
HDS6	2.8946	4.8664	5.1406		HDS6	4.0886	11.9191	5.1143
HDS7	-2.8843	6.7424	2.7359		HDS7	-1.8267	13.3065	2.7098

HDS8	0.1966	5.7475	2.737		HDS8	1.3269	12.5717	2.7104
HDS9	2.9841	4.8478	2.7388		HDS9	4.1803	11.9073	2.7124
BW10	-1.7154	7.9533	0.3216		BW10	-0.7623	14.61	0.2946
BW11	1.0093	7.0683	0.3254		BW11	2.0271	13.9552	0.2987
BW12	3.3548	6.3069	0.3835		BW12	4.4282	13.3921	0.3568
BW13	-1.7485	7.9633	-1.3918		BW13	-0.7956	14.6167	-1.4188
BW14	1.0081	7.0692	-1.3895		BW14	2.0261	13.9555	-1.4165
BW15	3.3613	6.3072	-1.357		BW15	4.4343	13.3914	-1.3837
HDS16	2.6167	0.3601	2.6437		HDS16	4.1745	7.3449	2.6165
HDS17	1.3751	-3.4611	2.6227		HDS17	3.269	3.4928	2.5959
HDS18	0.0091	-7.6806	2.6232		HDS18	2.2573	-0.8243	2.5953
BW19	1.9563	0.727	0.4527		BW19	3.4998	7.7193	0.4263
BW20	0.9664	-2.3323	0.4798		BW20	2.7668	4.5821	0.4535
BW21	-0.4688	-6.716	0.4026		BW21	1.7018	0.0969	0.3761
BW22	1.9249	0.6422	-1.2009		BW22	2.7644	4.5879	-1.1542
BW23	0.9634	-2.3299	-1.1278		BW23	1.6968	0.0962	-1.1464
BW24	-0.4742	-6.7168	-1.1203		BW24	3.4751	7.6271	-1.2279
HDS25	-8.1471	-1.9311	4.8052		HDS25	-6.3496	4.2251	4.7784
HDS26	-7.8902	1.3164	4.8094		HDS26	-6.3634	7.4823	4.7831
HDS27	-7.4436	6.8947	4.8125		HDS27	-6.3827	13.0914	4.7976
HDS28	-6.6468	-5.7799	0.5208		HDS28	-4.5326	0.5131	0.4941
HDS29	-6.3308	-1.9392	0.5123		HDS29	-4.5387	4.3678	0.4856
HDS30	-5.6987	5.652	0.5135		HDS30	-4.5398	11.9861	0.4867
HDS31	-8.9512	-38.0495	-0.0213		HDS31	-4.1431	-31.8358	-0.0484
HDS32	-10.9889	-44.2483	0.1618		HDS32	-5.6575	-38.1818	0.1349
STN3	0	1	0		STN4	0	1	0

Table 4.3-2: Coordinates from Station 3 and Station 4 of the calibration performed on 26/09/2011

4.4 Reduction

With all the data collected from the field, the coordinates could be run through the calibration program where the different data sets were compared against each other. Every possible combination has been analysed individually and then put into the one adjustment. The result of the calibration can be seen in table 4.4-1. The extended results from the calibration can be seen in APPENDIX C.

Summary of Terrestrial Laser Scanner Calibration

Calibration with Outliers

	Hz Correction			95% CI			V Correction			95% CI			Distance Correction (c)			95% CI		
Combination of Stations	Hz Correction	Sample variance (s^2)	Standard deviation of the mean	Confidence Interval	Confidence Interval Limits		V Correction	Sample variance (s^2)	Standard deviation of the mean	Confidence Interval	Confidence Interval Limits		c Correction	Sample variance (s^2)	Standard deviation of the mean	Confidence Interval	Confidence Interval Limits	
STN1-STN2	-0.3911992	2.209992	0.4034876	0.144383518	-0.53558	-0.24682	-0.1447210	0.625879873	3.1317166	1.181268602	-1.32599	1.03655	-0.0002585	7.76E-08	4.4793E-08	5.0687E-08	-0.00026	-0.00026
STN3-STN4	-0.0027124	1.148719	0.2097265	0.075048283	-0.07776	0.07234	0.5938619	3.855997093	19.294262	7.277703744	-6.68384	7.87157	0.0002697	4.94E-08	2.8533E-08	3.22881E-08	0.00027	0.00027
STN1-STN3	-0.3886458	2.192065	0.4002146	0.143212314	-0.53186	-0.24543	-0.1492600	0.624404107	3.1243323	1.178483281	-1.32774	1.02922	-0.0003022	1.92E-08	1.2516E-08	1.2516E-08	-0.00030	-0.00030
STN1-STN4	-0.3915512	3.337008	0.6092516	0.218013872	-0.60957	-0.17354	0.4576744	4.646512176	23.249764	8.769700352	-8.31203	9.22737	-0.0000324	1.27E-07	7.352E-08	8.31945E-08	-0.00003	-0.00003
STN3-STN2	-0.0025727	0.000163	2.98E-05	1.06625E-05	-0.00258	-0.00256	-0.0063361	0.004969859	0.0248677	0.009379975	-0.01572	0.00304	0.0000437	2.29E-08	1.3213E-08	1.49521E-08	0.00004	0.00004
STN2-STN4	-0.0001705	1.148621	0.2097086	0.075041876	-0.07521	0.07487	0.5967349	3.854227745	19.285408	7.274364326	-6.67763	7.8710992	0.0002260	7.23E-09	4.1758E-09	4.72527E-09	0.00023	0.00023
STN1-STN2-STN3	-0.2608059	1.46815	1.2116722	0.250329471	-0.51114	-0.01048	-0.1001057	0.412412299	0.6421934	0.139852871	-0.23996	0.03975	-0.0001723	5.65E-08	0.00023772	0.000155305	-0.00033	-0.00002
STN1-STN2-STN4	-0.2609736	2.216111	1.4886607	0.307554845	-0.56853	0.04658	0.3032294	3.070998611	1.7524265	0.381632534	-0.07840	0.68486	-0.0000216	9.71E-08	0.00031164	0.000203601	-0.00023	0.00018
STN2-STN4-STN3	-0.0018185	0.748626	0.8652319	0.178755473	-0.18057	0.17694	0.3947536	2.588881574	1.6090002	0.350398045	0.04436	0.74515	0.0001798	3.07E-08	0.00017512	0.000114408	0.00007	0.00029
STN4-STN3-STN1	-0.2609698	2.209635	1.486484	0.307105134	-0.56807	0.04614	0.3007588	3.071900831	1.7526839	0.38168859	-0.08093	0.68245	-0.0000216	1.1E-07	0.00033221	0.000217043	-0.00024	0.00020
STN1-STN2-STN3-STN4	-0.1961420	1.664011	1.2899653	0.188447282	-0.38459	-0.00769	0.2246590	2.30866874	1.5194304	0.233976045	-0.00932	0.45864	-0.0000089	8.59E-08	0.00029311	0.000135407	-0.00014	0.00013

Calibration with Outliers Removed

	Hz Correction			95% CI			V Correction			95% CI			Distance Correction (c)			95% CI		
Combination of Stations	Hz Correction	Sample variance (s^2)	Standard deviation of the	Confidence Interval	Confidence Interval Limits		V Correction	Sample variance (s^2)	Standard deviation of the	Confidence Interval	Confidence Interval Limits		c Correction	Sample variance (s^2)	Standard deviation of the	Confidence Interval	Confidence Interval Limits	
STN1-STN2	-0.0005878	0.0001	1.895E-05	7.02082E-06	-0.00059	-0.00058	0.0037595	9.95683E-05	0.0004675	0.000187019	0.003572	0.00394648	-0.0002585	7.76E-08	4.4793E-08	5.0687E-08	-0.00026	-0.00026
STN3-STN4	-0.0030023	0.000298	5.739E-05	2.16486E-05	-0.00302	-0.00298	0.0006979	1.14029E-05	4.709E-05	2.11731E-05	0.000677	0.00071906	0.0002697	4.94E-08	2.8533E-08	3.22881E-08	0.00027	0.00027
STN1-STN3	0.0003685	3.9E-06	7.373E-07	2.7309E-07	0.00037	0.00037	-0.0023696	0.000826181	0.0038788	0.001551815	-0.00392	-0.00081775	-0.0003022	1.92E-08	1.2516E-08	1.2516E-08	-0.00030	-0.00030
STN1-STN4	-0.0031298	0.000317	6.338E-05	2.48438E-05	-0.00315	-0.00310	0.0046303	9.10031E-05	0.0003646	0.000168454	0.004462	0.00479872	-0.0000324	1.27E-07	7.352E-08	8.31945E-08	-0.00003	-0.00003
STN3-STN2	-0.0025727	0.000163	2.98E-05	1.06625E-05	-0.00258	-0.00256	0.0005504	3.72015E-05	0.0001786	6.99971E-05	0.00048	0.00062043	0.0000437	2.29E-08	1.3213E-08	1.49521E-08	0.00004	0.00004
STN2-STN4	-0.0003002	0.000484	9.309E-05	3.51141E-05	-0.00034	-0.00027	-0.0005450	1.37978E-05	5.698E-05	2.56198E-05	-0.00057	-0.00051939	0.0002260	7.23E-09	4.1758E-09	4.72527E-09	0.00023	0.00023
STN1-STN2-STN3	-0.0009688	9.03E-05	0.009504	0.002008648	-0.00298	0.00104	0.0006455	0.000314392	0.0177311	0.004067449	-0.00342	0.00471291	-0.0001723	5.65E-08	0.00023772	0.000155305	-0.00033	-0.00002
STN1-STN2-STN4	-0.0012851	0.000291	0.0170684	0.003740216	-0.00503	0.00246	0.0026757	7.29921E-05	0.0085435	0.002143982	0.000532	0.00481966	-0.0000216	9.71E-08	0.00031164	0.000203601	-0.00023	0.00018
STN2-STN4-STN3	-0.0019803	0.000303	0.0174171	0.003724645	-0.00570	0.00174	0.0002645	2.20083E-05	0.0046913	0.001158433	-0.00089	0.00142297	0.0001798	3.07E-08	0.00017512	0.000114408	0.00007	0.00029
STN4-STN3-STN1	-0.0018624	0.000198	0.014088	0.003087105	-0.00495	0.00122	0.0006514	0.000354308	0.0188231	0.004723609	-0.00407	0.005375	-0.0000216	1.1E-07	0.00033221	0.000217043	-0.00024	0.00020
STN1-STN2-STN3-STN4	-0.0015196	0.000218	0.0147756	0.002254503	-0.00377	0.00073	0.0010339	0.000194767	0.0139559	0.002408303	-0.00137	0.00344216	-0.0000089	8.59E-08	0.00029311	0.000135407	-0.00014	0.00013

Table 4.4-1: Summary of the results from the calibration performed on the 26/09/2011

4.5 Outlier removal

As can be seen in table 4.4-1, the corrections are quite large and are several times larger than the manufacturer's specifications of 4mm for range and 6mm for positional accuracy. It is obvious by looking at the residuals that there are several outliers. To remove the outlier's horizontal residual, vertical residual and confidence interval graphs were used to identify any erroneous measurements.

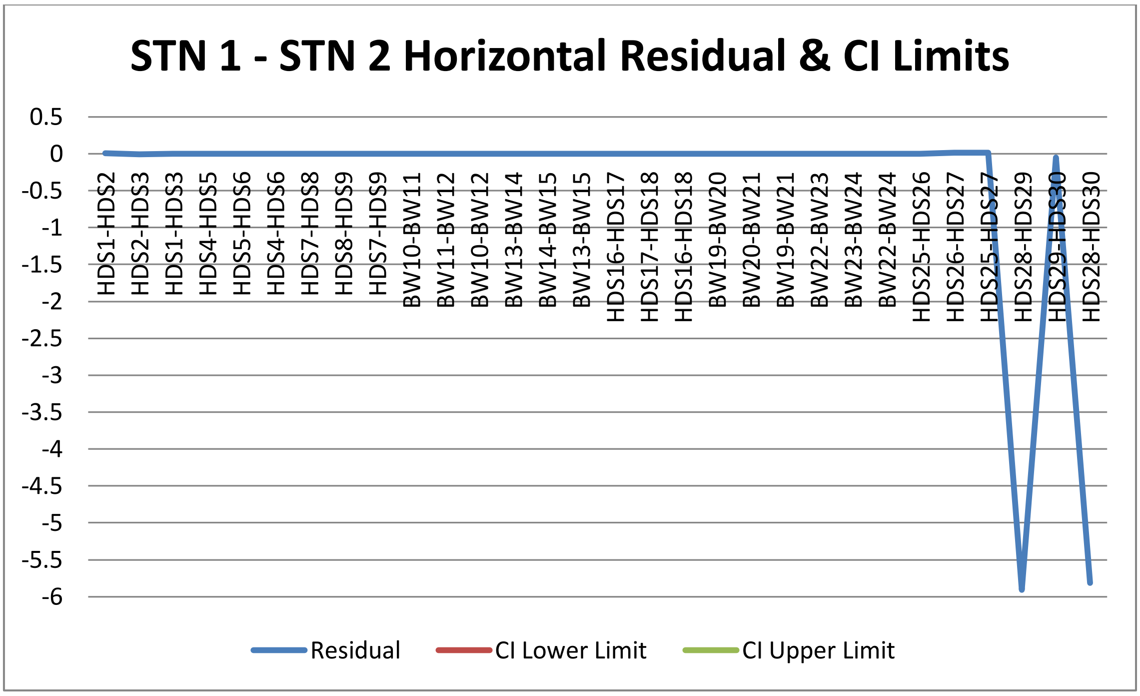

Figure 4.5-1: STN1-STN2 Horizontal residual & CI Limits graph

Figure 4.5-1 shows that there are two outliers that will need to be removed, HDS28-HDS29 and HDS28-HDS30

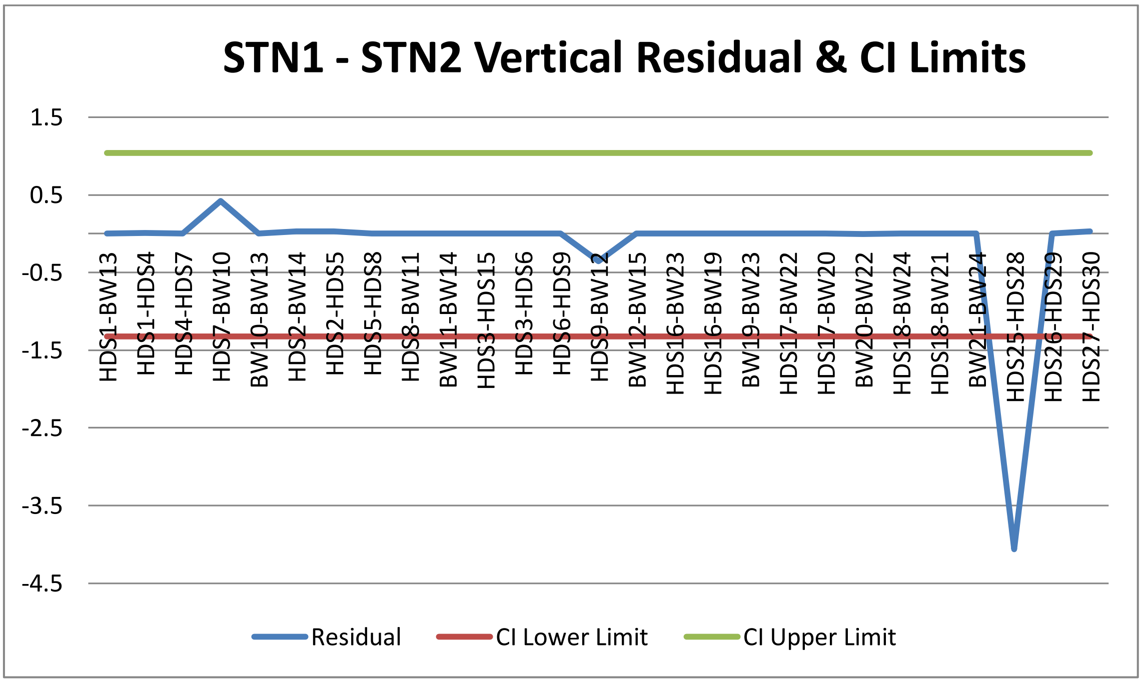

Figure 4.5-2: STN1-STN2 Vertical residual & CI limits graph

In figure 4.5-2 the outliers that will be removed are HDS7-BW10, HDS9-BW12 and HDS25-HDS28.

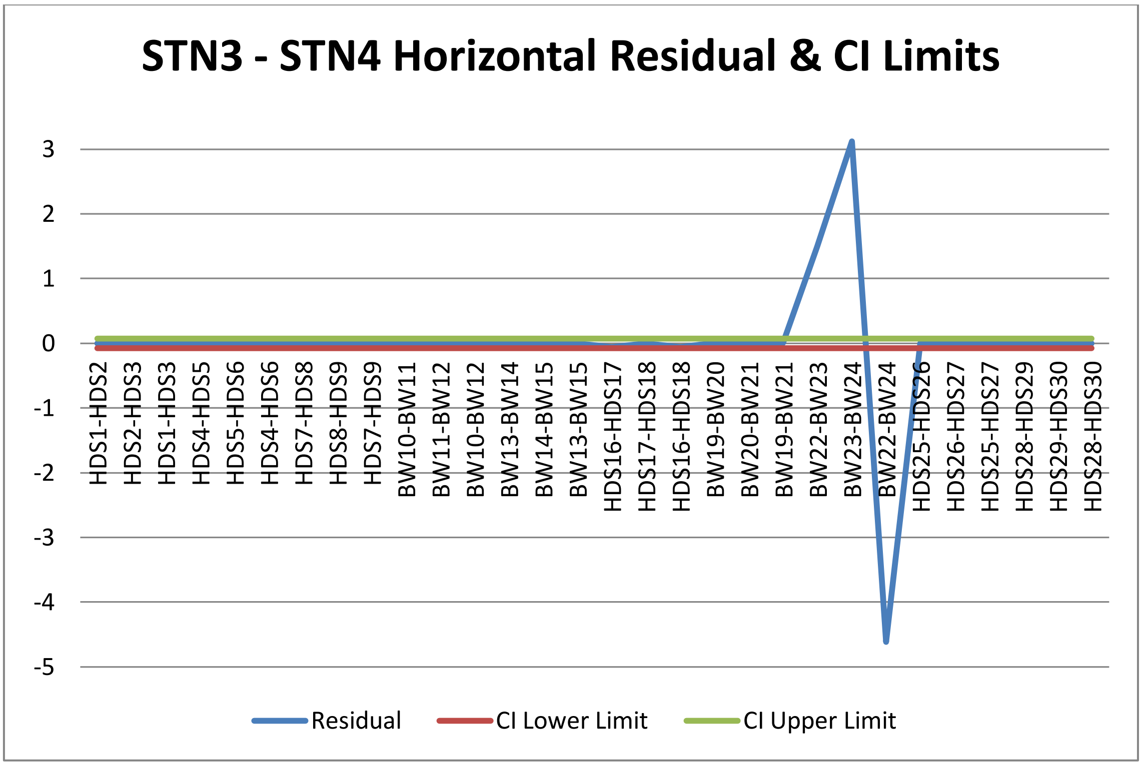

Figure 4.5-3: STN3-STN4 Horizontal residual & CI limits graph

In figure 4.5-3 the outliers that will need to be removed are BW22-BW23, BW23-BW24 and BW22-BW24.

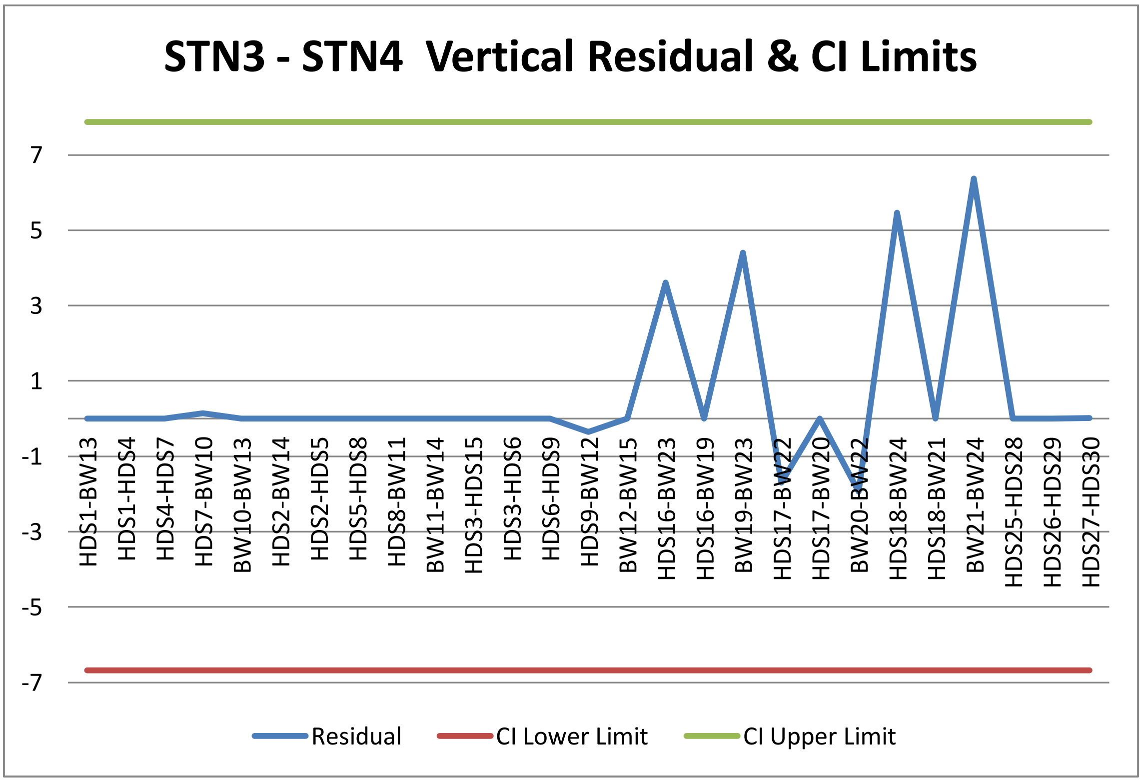

Figure 4.5-4: STN-STN4 Vertical residual & CI limits graph

In figure 4.5-4 the outliers that will be removed are HDS7-BW10, HDS9-BW12, HDS25-HDS28, HDS17-BW22, HDS18-BW24 and BW21-BW24.

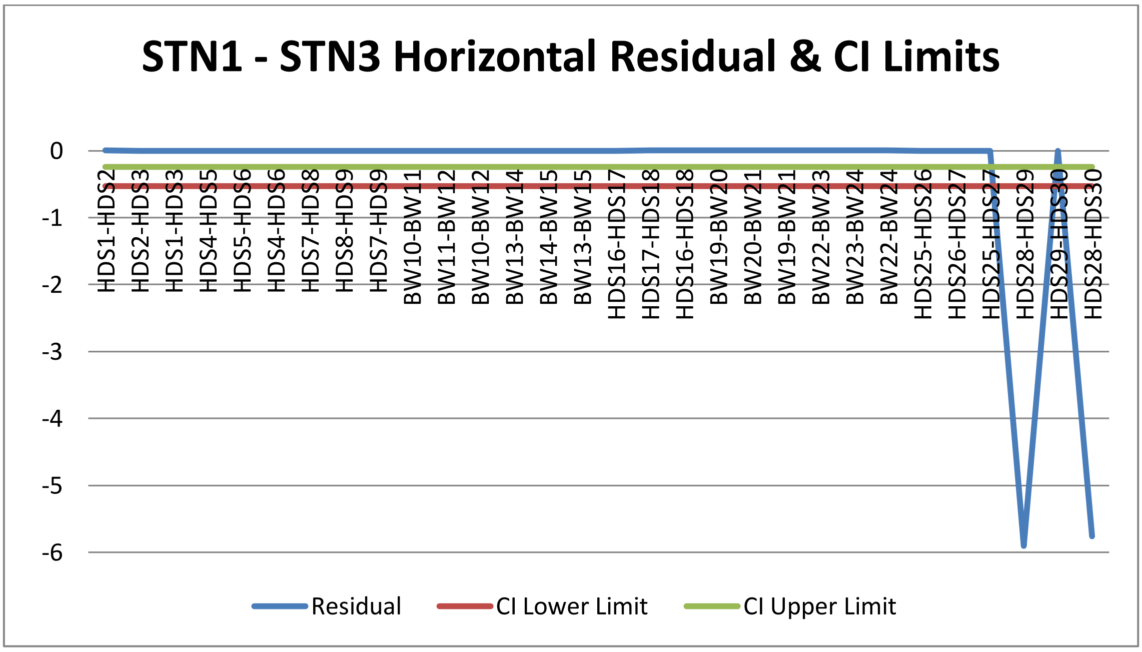

Figure 4.5-5: STN1-STN3 Horizontal residual & CI limits graph

In figure 4.5-5 the outliers that will need to be removed are HDS28-HDS29 and HDS28-HDS30.

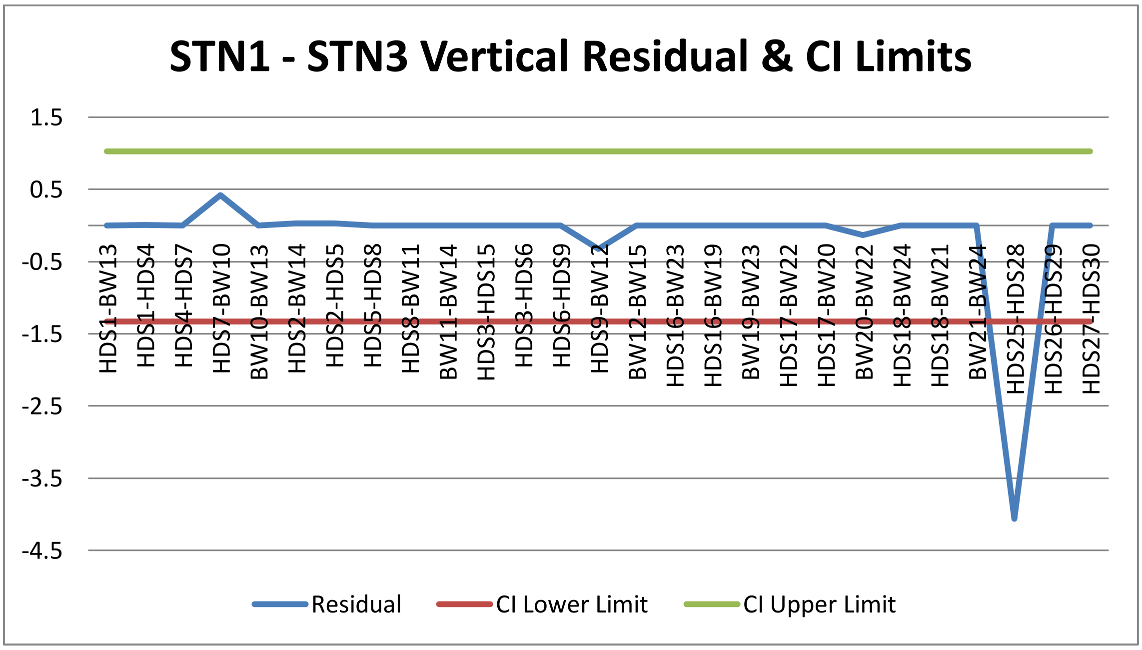

Figure 4.5-6: STN1-STN3 Vertical residual & CI limits graph

In figure 4.5-6 the outliers that will be removed are HDS7-BW10, HDS9-BW12 and HDS25-HDS28.

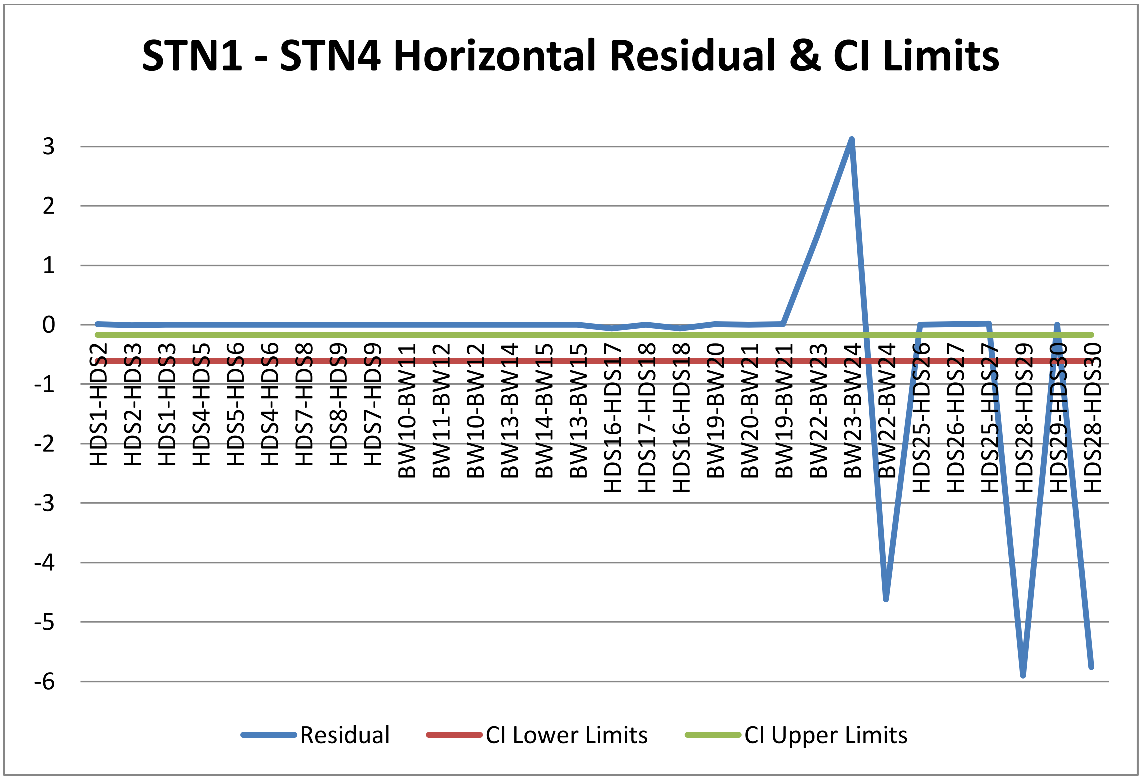

Figure 4.5-7: STN1-STN4 Horizontal residual & CI limits residual

In figure 4.5-7 the outliers that will need to be removed are HDS28-HDS29, HDS28-HDS30, BW22-BW23, BW23-BW24 and BW22-BW24.

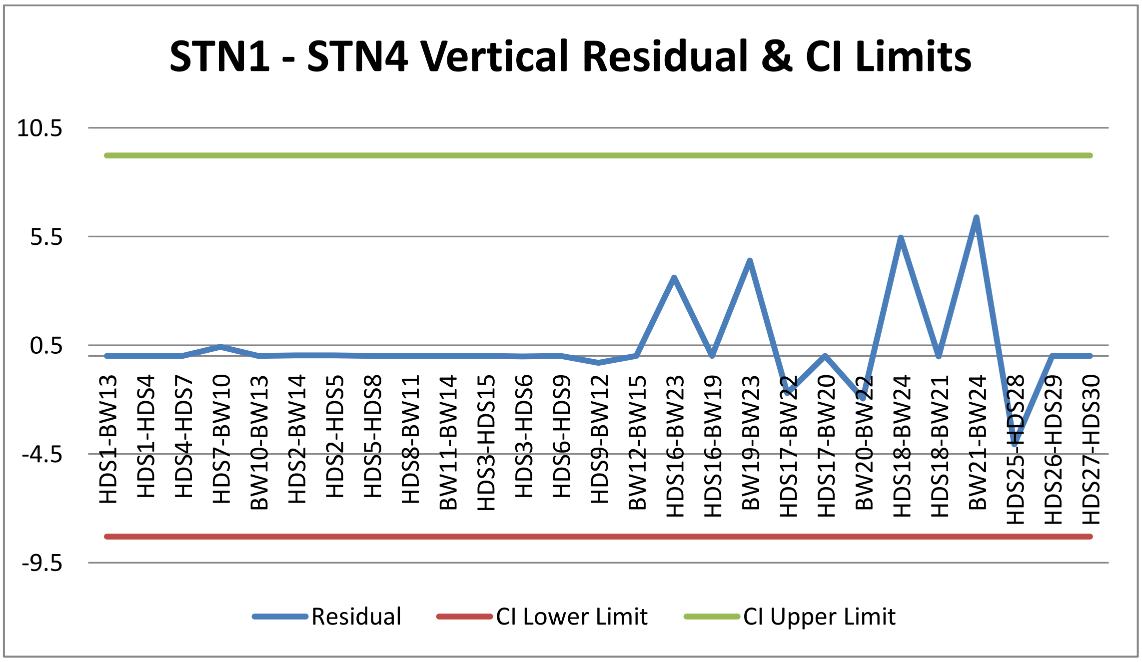

Figure 4.5-8: STN1-STN4 Vertical residual & CI limits graph

In figure 4.5-8 the outliers that will be removed are HDS7-BW10, HDS9-BW12, HDS25-HDS28, HDS17-BW22, HDS18-BW24, BW21-BW24, BW19-BW23 and HDS25-HDS28.

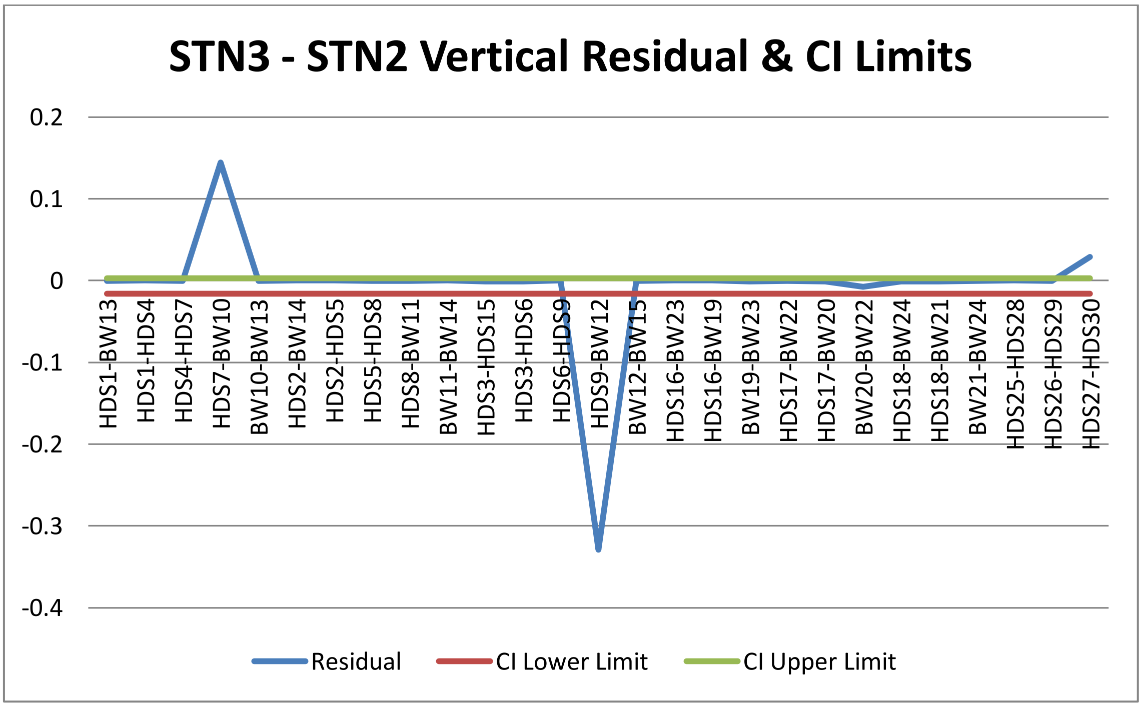

Figure 4.5-9: STN3-STN2 Vertical residual & CI limits graph

In figure the outliers that will be removed are HDS7-BW10 and HDS9-BW12.

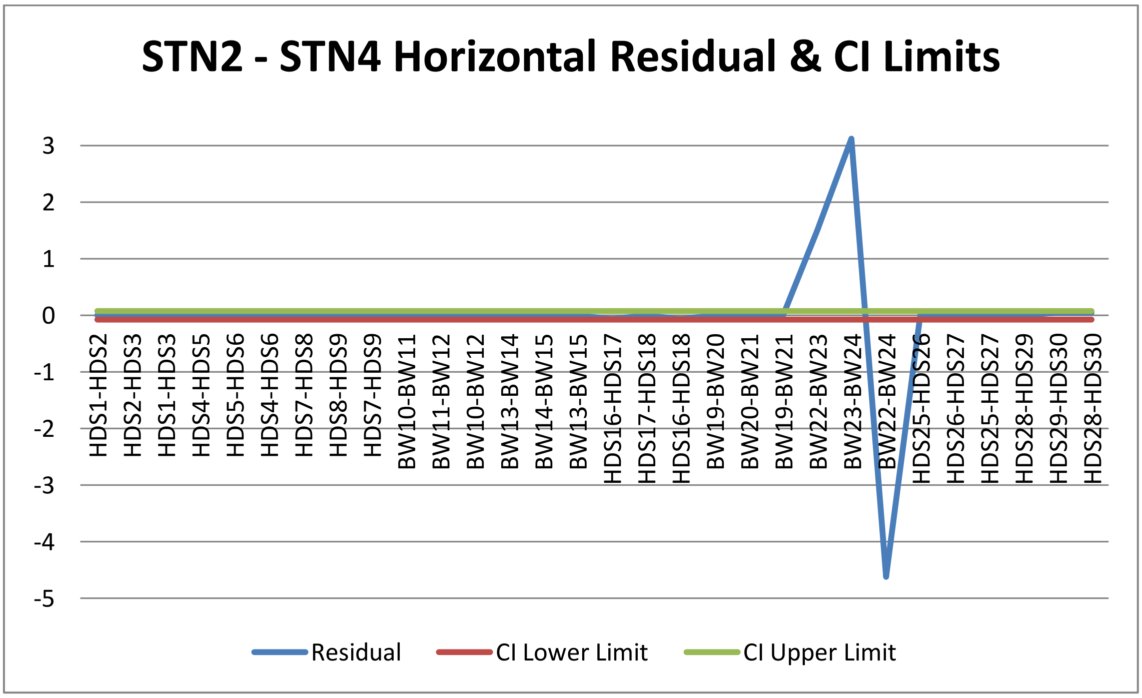

Figure 4.5-10: STN2-STN4 Horizontal residual & CI limits graph

In figure 4.5-10 the outliers that will be removed are HDS7-BW10, HDS9-BW12, HDS25-HDS28, HDS17-BW22, HDS18-BW24 and BW21-BW24.

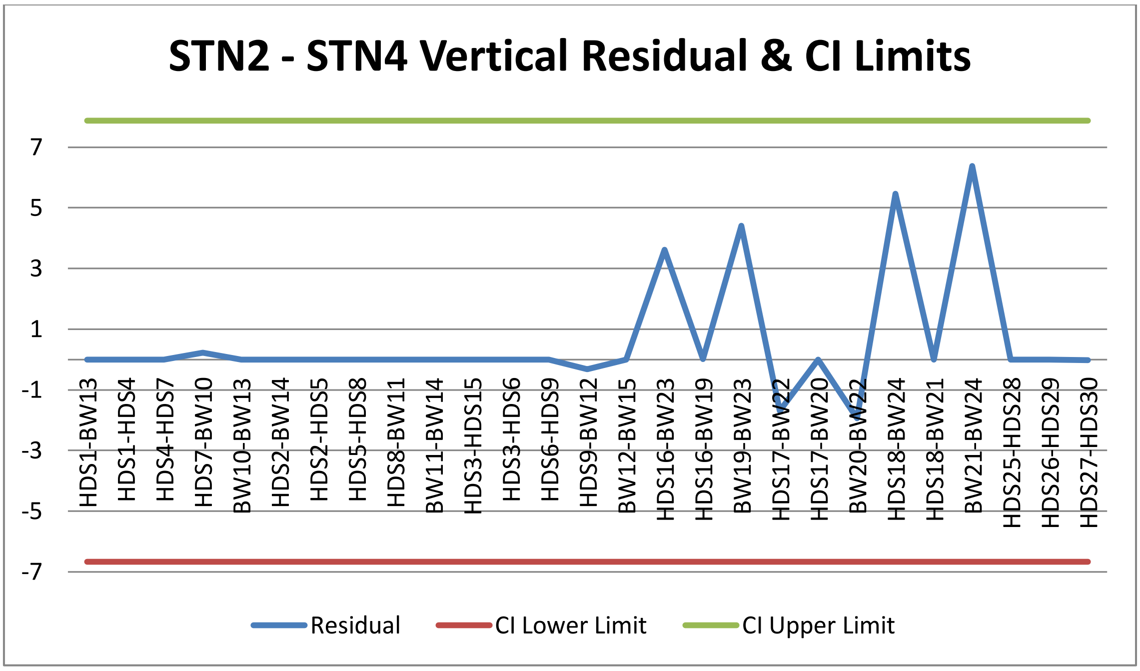

Figure 4.5-11: STN2-STN4 Vertical residual & CI limits graph

In figure 4.5-111 the outliers that will be removed are HDS7-BW10, HDS9-BW12, HDS25-HDS28, HDS17-BW22, HDS18-BW24, BW21-BW24, BW19-BW23 and BW20-BW22.

No horizontal residual and CI limits plot was made for Station 3 – Station 2. This station passed the horizontal accuracy test and there was no need to remove any outliers .After the outliers were removed the calibration was rerun. The results of the calibration after the outliers were removed table 4.4-1. Once the outliers were removed all the combinations of stations passed the accuracy tests.

4.6 Conclusion

The aim of this chapter was to provide the results of the calibration. The results of the calibration have been shown. Results have also been shown of the calibration after the outliers were removed.

Chapter 5 Analysis and Discussion

5.1 Introduction

The purpose of this chapter is to analyse and discuss the results of the calibration that was shown in chapter 4. The discussion will be based on the tables shown in chapter 4. It will analyse and provide comments as to why certain events occurred. The main areas of analysis will be in the following areas:

- The effects of the different station geometry
- The effects of the target geometry

This chapter will provide the reader with a better understanding of the effects that different target and station geometry can have on TLS calibration.

5.2 Calibration results overview

Every possible combination of stations has been tested in the calibration. This has been performed so that the best determination of best station geometry and which targets are best suited to the calibration.

The coordinates of the targets were all feed into an Excel spreadsheet that has used the formulas shown in the methodology chapter. As part of the statistical analysis of the data the sample variance, standard deviation of the mean and the 95% Confidence Interval (CI) were calculated.

The horizontal correction, vertical correction and distance correction are a measure of how accurately the scanner is measuring. The Excel spreadsheet has been programmed with conditional formatting so that if the accuracy tests are less than the manufacturers specifications that cell with be highlighted in green. If it exceeds the manufacturer’s specifications the cell is highlighted in red. For the users to perform the calibration they only need to enter the coordinates of the targets and accuracy specifications of the TLS into the spreadsheet on the appropriate page. All the calculations are performed automatically and the results are summarised onto a results page. After the data is first inputted into the spreadsheet, the only operation for the user is to delete any obvious outliers from the designated outlier’s page. A separate page has been made so that the original result of the calibration cannot be altered. The results of the calibration after the outliers have been removed are sent to the calibration summary page. The results of the calibration can be seen in the calculation pages but is hard to read and the user cannot compare the results against other stations easily.

5.2.1 Calibration results with no outliers removed

It was shown in chapter 4 that out of a possible 11 combinations of stations only four (4) pass the horizontal accuracy test. Three of the combinations are two station combinations while the fourth combination uses the stations that passed in the two station tests. The combination of stations that passed were Station3 – Station4, Station3 – Station2, Station2 – Station4 and Station2 – Station4 – Station3. These combinations were able to pass the test because they were more accurate than the 6mm positional accuracy of the TLS. The combinations that did not pass were well above the manufactures specifications for accuracy. The standard deviations of the combinations that did not pass ranged from 0.4 – 1.8. The higher the standard deviation value the more likely that there are several outliers that need to be removed. For the combinations that have more than two stations in the solution the standard deviation is larger because the errors are being compounded.

The vertical correction test did not have any possible combination of scanner stations pass. On close inspection of the results it showed that the combination of Station3 – Station2 fails by 0.0003361 which is below 1mm and could be considered as a pass. The standard deviation of this combination is 24mm with a confidence interval of ± 9mm. This shows that it is likely that there are only one or possibly two outliers that caused it to fail the test. The standard deviations of the other combinations are all above one meter except for the combinations of Station1 – Station3 and Station2 – Station4 – Station3. These showed that they had a standard deviation of 0.6244 and 0.4124 respectively. It is interesting to note that all the stations that passed the horizontal test except for Station3 – Station2 had very large standard deviations. Of these combinations Station3 – Station4 and Station2 – Station4 had almost identical standard deviations. This is probably because they have very similar outliers.

All combinations passed the distance correction without any outliers being removed. The standard deviations of all possible combinations are below 1mm as well as the confidence interval. It shows that the targets that were used for the distance test are reliable and well placed. As a result of this it is very likely that the TLS that was used in this project is measuring correctly for range.

5.2.2 Calibration results after outlier removal

Removing any outliers from a calibration is an important and necessary process. If it is done correctly then, the result will be a well calibration instrument. If it is not performed correctly the results could show that your instrument is measuring correctly but in truth it is not. It is a delicate process as you are removing measurements that are grossly in error. A cautious approach is required because you could be removing that vital information required to test the instrument. You could remove as much data that you like to make it look like a well calibrated instrument, which will only cause problems in the future when the instrument is being used in the field. It is not the purpose of removing outliers to make the instrument look good but to ensure that only those measurements that are grossly in error are removed, so that any bias is eliminated from the calibration. To ensure only the appropriate outliers were removed the residuals and confidence interval limits were graphed. These graphs were shown in the results chapter and the residuals that were removed in table 5.2-1.

The standard deviations in the first calibration showed that there were possible erroneous measurements in the calibration. The residual and CI plots were analysed to see which measurements were in error. Any residual that was outside of the confidence interval or did not follow the trend that the other residuals followed were removed. The outliers that have been removed have been removed in more than one station combination. For the horizontal correction the outliers that have been removed were all removed three times between all the different scanner station combinations.

When removing outliers from the calibration the distances should be removed first. This is required because the range to the targets is used in the horizontal and vertical formulas. No other measurements or formulas affect the calculation of the distance correction. For the calibration of the TLS that was used in the project no distance outliers were removed because every combination of stations passed the accuracy assessment test.

Outliers removed from Calibration								
stations	Hz Correction							
STN1-STN2	HDS28-HDS29	HDS28-HDS30						
STN3-STN4	BW22-BW23	BW23-BW24	BW22-BW24					
STN1-STN3	HDS28-HDS29	HDS28-HDS30						
STN1-STN4	BW22-BW23	BW23-BW24	BW22-BW24	HDS28-HDS29	HDS28-HDS30			
STN3-STN2	NIL							
STN2-STN4	BW22-BW23	BW23-BW24	BW22-BW24					
stations	V Correction							
STN1-STN2	HDS7-BW10	HDS9-BW12	HDS25-HDS28					
STN3-STN4	HDS7-BW10	HDS9-BW12	HDS16-BW23	HDS17-BW22	HDS18-BW24	BW21-BW24		
STN1-STN3	HDS7-BW10	HDS9-BW12	HDS25-HDS28					
STN1-STN4	HDS7-BW10	HDS9-BW12	HDS16-BW23	HDS17-BW22	HDS18-BW24	BW21-BW24	BW19-BW23	HDS25-HDS28
STN3-STN2	HDS7-BW10	HDS9-BW12						
STN2-STN4	HDS7-BW10	HDS9-BW12	HDS16-BW23	HDS17-BW22	HDS18-BW24	BW21-BW24	BW19-BW23	BW20-BW22
stations	C Correction							
STN1-STN2	NIL							
STN3-STN4	NIL							
STN1-STN3	NIL							
STN1-STN4	NIL							
STN3-STN2	NIL							
STN2-STN4	NIL							

Table 5.2-1: Summary of outliers removed from calibration on 26/09/2011

5.3 Horizontal residuals

There is only one scanner combination that did not require any horizontal residuals to be removed, which consisted of STN3-STN2. This was a surprising combination as it did not first appear to be the best combination that would provide for the best calibration. Even though the combinations of STN3-STN4 and STN3-STN2 passed the horizontal accuracy test, they have still had outliers removed because there were residuals that were obviously in error. The scanner station combinations with more than two stations have not be talked about in the outlier removal process, as they are made up of different two station combinations, where the outliers have already been removed.

In the scanner station combination of STN1-STN2 there were two outliers that have been removed. The targets that were used to calculate those residuals were HDS28-HDS29 and HDS28-HDS30. The same two residuals were also removed from the scanner station combinations of STN1-STN3 and STN1-STN4. The reoccurring target and station that is causing the error is HDS28 and STN1 respectively. It will be talked about later in this chapter as to the likely reasons for this target and station being in error.

In the scanner station combination of STN3-STN4 three residuals have been removed, BW22-BW23, BW23-BW24 and BW22-BW24 respectively. These residuals were also removed in the scanner combinations of STN1-STN4 and STN2-STN4 and are also the last residuals that were removed for the horizontal correction. It is not clear as to which target is in error. As all three targets are used twice in the residuals, which tends to lead to that all three targets are in error. STN4 is the commonly occurring station from the station combinations where these residuals have been removed from.

5.4 Vertical residuals

No combination of scanner stations passed the vertical accuracy test. This resulted in many outliers being removed, but by looking at the table 5.2-1 a pattern can be seen in the outliers that were removed. This pattern will now be discussed.

When the vertical correction outliers are looked at as a whole, a pattern can be seen as to which outliers are removed. The majority of outliers that were removed were between HDS targets and BW targets. There was a total of 30 residuals that were removed of them 24 were between a HDS and BW target. The remainder of the residuals were between like targets that is a HDS to a HDS target and a BW to a BW target. Only one residual was removed once, whereas all the other residuals were removed multiple times.

The residual between HDS7-BW10 and HDS9-BW12 get removed from all of the six station combinations. This shows that there is not a problem with the station geometry but with the targets used in that calculation. The error is complicated because none of the targets used here were removed during the horizontal residual outlier process. It could mean that there is a problem with the instrument in the vertical dimension or with the targets.

HDS28 was a target that was identified during the horizontal residual outlier removal process as a common element that caused multiple residuals to be removed. It has again caused multiple residuals to be removed during the vertical residual outlier removal process. HDS25-HDS28 was removed every time STN1 was used in a combination. This is consistent with the horizontal residual outlier removal process, where every time HDS28 was used in a combination from STN1 it was removed.

Station4 has caused the same problems as it did during the horizontal residual outlier removal process. The residuals that were removed only at STN4 were HDS17-BW22, HDS16-BW23 and HDS21-BW24. The common targets that caused the residuals to be removed from STN4 during the horizontal residual outlier removal process were BW22, BW23 and BW24. These three targets have also caused two other residuals to be removed, one of which was removed from two station combinations. The residual from BW19-BW23 was removed from STN2-STN4 and STN1-STN4. Station4 was also the cause for removing the residual BW20-BW22 which is the only residual to be removed once.

It can be seen in the table 5.2-1 that after these outliers have been removed that all the scanner combinations have passed all three accuracy tests. To determine whether these combinations of stations have been properly adjusted the standard deviation and confidence intervals are looked at closely. In the distance correction no outliers were removed, by looking at the standard deviation and confidence interval we can see that they are both under 1mm for all the different scanner combinations.

All of the two station combinations have a standard deviation of below 1mm in all categories. A low standard deviation value also helped produce a low confidence interval. Due to all the two stations combinations' having a low standard deviation it has produced a low confidence interval. A low standard deviation and confidence interval show that the data is of good quality. The confidence interval for all these stations is below the manufacturer's accuracy specifications. An instrument could pass the accuracy test but have a high standard deviation. By having a large standard deviation means that there could possibly be something wrong with the instrument or more outliers would need to be removed.

For the stations that have used more than two stations in the calculation a standard deviation of 9mm- 17mm can be seen. They also have a confidence interval from 2mm-3.7mm which is half of the manufacturer's positional accuracy specification. This shows that instrument is measuring correctly and reliably in the horizontally axis. In the vertical correction the standard deviation ranges from 4mm-18mm. These standard deviations are getting a bit large, but result in a confidence interval of 2mm-4mm, which is below the manufacturer's specifications.

5.5 Discussion

This section will give reasons as to why there were outliers in the adjustment that needed to be removed. It was stated in the literature review that if the incidence angle to the target was less than 60° it caused large errors in measuring to targets, which required those targets to be removed.

During the horizontal residual outlier removal process it was indicated that when HDS28 was observed to from STN1 it was the cause of several outliers. This station has a very sharp incidence angle to the target and is the likely cause of the erroneous measurement. HDS28 has not caused any outliers from any of the other station combinations, which shows that it is in the right position but is the wrong type of target. A type of target that can be used to replace it is a spherical target. This type of target is a round ball that can be forced centred. The TLS processing software interprets the observations to it and calculates the centre of the ball. It does not matter how sharp the angle to the target is because it is round and does not have a flat face where in the incidence angle will affect it. To mount it to the wall a bracket would have to be attached. By having a spherical target where HDS28 is currently positioned it would remove outliers in the horizontal and vertical correction.

By looking at the *outliers removed from calibration* table a pattern can be seen that has caused the most outliers to be removed. Every time STN4 is used it has caused many outliers to be removed. The targets that it has affected are BW22, BW23 and BW24. Every time these targets were used in the calibration they have caused outliers to be removed. These targets have not caused any outliers to be removed from any other stations. The targets in question are located on the North wall of the calibration range and are the bottom row of targets. STN4 is located about one meter off this wall and is on the far right of where the targets were located. For these reasons the vertical and horizontal angle is very acute and is below the 60° incidence angle. This is a puzzling scenario as two other rows of targets have been placed above this bottom row on the North wall but they did not cause any outliers to be removed during the horizontal and vertical residual outlier removal process. By having a sharp incidence angle in the horizontal and vertical dimension could have cause these three targets to be in error. A solution to solve for the sharp incidence angle is to install spherical targets instead of flat targets.

A second reason for the targets to be in error could be because they are temporary targets. These targets were installed by printing out the target design that was supplied by Leica onto an A4 sheet of paper. The location for the targets on the North wall was not a flat or smooth surface and would not have been suitable for the A4 sheet of paper. This problem was solved by gluing the A4 sheet of paper onto a piece of stiff cardboard. The cardboard was then attached to the wall with double sided tape. STN4 was the last station to be observed from and the time from the start of the first scan was approximately five hours. It is possible that a change in the atmospheric conditions during the day could have caused the cardboard to swell and move slightly. This would have caused a positional change in the centre of the target and given inaccurate results. The next question is, if that was true why did it not happen to the temporary targets that were located directly above the targets in question, which were installed at the same time, with the same method and were subject to the same environmental conditions. If the location of the temporary targets cannot be assured for the duration of scanning then permanent targets should be located in the place of the temporary targets. If permanent targets were located onto this uneven wall then the backing material that the target is attached to before it is located on the wall should be a material that will not be affected by atmospheric conditions.

A third cause for these targets can also be considered is that the geometry of STN4 is not suitable for the calibration. If the cause of just one target from just one station being in error was because of the incidence angle for example HDS28 and STN1 that was discussed earlier. Then you could say with confidence that the target is the cause of the problem. But with the situation that is being discussed at the moment there are three targets that are causing problems from only the one station. These stations are also in the same row and on the same wall. This is why it has lead the author to believe that STN4's geometry could be in an inappropriate location for a calibration.

Either of the solutions mentioned would solve the problem with the targets BW22, BW23 and BW24 it is only a matter of deciding which solution is better. Temporary targets were used during this project because of the limited amount of permanent HDS targets available. An infinite supply of HDS targets could not be acquired because they are very expensive and a small budget was allowed for this project. The cheapest solution would be to find a better location for the STN4. The same test that was performed during this research project would then need to be applied to determine if the geometry of STN4 was suitable for calibrating a TLS. A low cost solution could be manufactured out of a Styrofoam ball and attached to a metal bracket, which could be screwed into the wall where required. A problem could arise with the Styrofoam ball is if it is not perfectly round. This would lead to the centre of the target not being accurately determined. This would obviously not remove the problem that was causing the outliers. If a spherical ball was to be used it would have to be of a good quality design that provided accurate determination of the target.

During the vertical residual outlier removal process two residuals were removed from every combination of stations that was tried. The source of the reasons for this error is not obvious. This is because they were only removed from the vertical correction and none were removed from the horizontal correction and indicates that they are accurate in the horizontal direction. A possible explanation is that between those vertical angles the scanner is out of adjustment. But the targets located at the same height have not caused any outliers. Also the scanner station geometry has been designed so that different vertical angles are being observed from different scanner stations. At a glance all the targets that have been removed because of large residuals was between a HDS target to a BW target. It was first thought that this was the cause that a HDS target and a BW target could not be used in the calibration together. The error as to why some of the targets caused were answered earlier. These targets were BW22, BW23 and BW24 and are the only other targets that were used with a HDS target.

The incidence angles to the targets that are in question are HDS7, HDS9, BW10 and BW12 and are not above acceptable limits. This has lead the author to believe that the temporary targets were not fixed to the wall correctly and moved during scanning. The targets in question were fixed to the West wall and are a smooth brick wall. The temporary targets that were fixed to it, was the printed black and white design that was discussed earlier. A4 sheets of paper with the design were attached to the using sticky tape. If the paper was not stretched out tightly enough, the paper would be able to move when the breeze was blowing and cause the error in the observations. If the printer was not of a high quality it could also affect the observations because the scanner could not accurately define the image printed onto the paper. This problem could easily be fixed by placing permanent HDS targets where temporary targets are located.

5.6 Conclusion

This chapter has analysed and discussed the result of the TLS calibration that was performed at USQ. During this chapter it briefly talked about how the data was processed in the Excel spreadsheet and some of the features of the spreadsheet. The results from the calibration first showed that the TLS used in this project was not measuring correctly because it failed many of the accuracy tests that were applied. After careful analysis of the residual and confidence interval graphs outliers were identified. These outliers were removed and the calibration re-run and an analysis of the results performed. It showed that the TLS passed all of the accuracy tests and the statistical analysis results were within satisfactory standards. An investigation as to the reasons why there were outliers in the data was performed where recommendations were made to solve them for future calibrations. This chapter has provided advice and recommendations that will be used in the next chapter to answer the objectives that were set in chapter 1.

Chapter 6 Recommendation and Conclusion

6.1 Introduction

This chapter's aim is to provide concluding remarks on the results found during the course of this project. The results will relate to the recommendations made in the previous chapter. While making the recommendations it will answer the objectives that were set in chapter 1.

- To determine the station geometry for the calibration.
- To determine an optimum target configuration for an outdoor site.
- To determine the capability of the range for TLS calibration.

It will also discuss what limitations the calibration range has and any possible future research that can be performed.

6.2 Recommendations

Chapter four provided possible explanations as to why some of the targets caused outliers in the data. The discussion focused around whether the target geometry and scanner geometry was suitable for terrestrial laser scanner calibration. It was found that if the target and station geometry was not appropriate outliers were caused. A critical element when designing the calibration range was to ensure that an incidence angle of less than 60° with the face of the target and the laser was not achieved. This meant that the targets had to be well placed. The location of the scanner stations had to also be considered carefully because if they were put into the wrong location they would cause inappropriate incidence angles.

Station1 caused an outlier to HDS28 where it is believed a sharp incidence angle was the cause of this outlier. To solve this outlier it is recommended that a spherical target is located in its current position instead of the HDS target that is currently there. In the previous chapter it was identified that from station 4 there were several outliers in the horizontal and vertical correction. There could have been a problem with either the targets or the locations of the station 4. The cause of the outliers from station 4 is most likely a combination of the wrong type of target and the location of station 4.

Station 4 should be moved to a location that is closer to the West wall. This would reduce the sharp incidence angle to the targets on the North wall where the targets that are in question are located. The targets on the other walls would not be affected because it would not need to be moved a great distance and two other stations are further to the West, which did not have any trouble with sharp incidence angles. The targets that caused the outliers from station 4 were

BW22, BW23 and BW24. It is believed that a sharp vertical incidence angle was the cause of the outliers. But the horizontal incidence angle is also very acute and could cause outliers in future calibrations. This is the reason why it was decided to recommend moving station 4 to a different location. To remove the acute vertical incidence angle a spherical target should be placed where these targets are currently located. It has not been recommended to move the location of these targets because targets are required to be positioned at low vertical angles.

Another possible solution for the sharp incidence angle is to mount a bracket to the wall where the HDS targets that are screwed onto a tribrach's adaptor can be attached. These targets can be turned to face the scanner in any direction and remove the sharp incidence angles. The position of the centre of the target would also be assured because these targets rotate around the centre point of the target in a similar way to a total station traversing prism. This would be the lowest cost solution as the HDS targets are already purchased when you buy the TLS. It is also the most accurate solution because if the spherical balls are not perfectly round it will result in an inaccurate determination of the target centre.

During the vertical residual outlier removal process there were two sets of residuals that were removed from every station combination that was tried. The targets that were used to calculate the residuals were a HDS target to a BW target. It was first thought that the calculation did not like this combination. On further inspection of the temporary targets it was decided that they were not installed properly on the day of scanning. To make sure that the temporary targets are not installed incorrectly permanent HDS targets should be located where the BW targets currently are situated.

The North wall has purpose made corrugations built into it and any target that is fixed to the North wall will need to have a backing that will not be affected by atmospheric conditions. The temporary targets that were fixed to the wall on the day of scanning were glued onto a stiff piece of cardboard. It is possible that the cardboard could have swelled with the change of atmospheric conditions during the day. This could have helped cause the outliers from station 4 as the difference was approximately five hours from installing the temporary targets to the start of the scanning session from station 4.

The station geometry that was chosen for this project has worked well. Station 2 and Station 3 did not have any outliers removed from the data collected from them as a result of poor station geometry. Station 1 had a small number of outliers removed from its data, which was eventually tracked down to the one target. The most outliers that were removed as a result of poor station geometry, was Station 4. If any future scanning should take place a new location for Station 4 has been recommended.

Station 3 and Station 2 have showed that their station geometry has performed the best. If a calibration was needed in a hurry and time was limited, these two stations would be the minimum amount of data that would be needed to perform a TLS self-calibration. For a self-calibration only two stations are required, but the more stations you have the more redundant data in the calibration, which provides for a more statistical strong correction. As Station 2 and Station 3 did not cause any outliers to be removed the maximum amount of data possible for the least time spent in the field would be used in the solution. If the operator had a little extra time to spend in the field then Station 1 would be observed from next. It would be advisable that HDS28 was not scanned from that station. If time was not an issue all stations should be observed from. This is on the proviso that the location of Station 4 was moved slightly.

6.3 Discussion

This research project set out to develop a high precision calibration range at USQ. It has achieved this by developing a station and target geometry that can be used to calibrate a TLS. The testing has showed that the design of the calibration range has proven to be suitable. The testing showed that there was only one (1) target design problem with an inappropriate location chosen for a target and the location of only one (1) station proved to be in an inappropriate location. These problems can easily be fixed with the recommendations made earlier.

6.4 Problems encountered during the project

The calibration range that has been developed for this research project was not the first choice for a TLS calibration range. A design and location had been chosen to be in another location at the USQ Toowoomba campus. This location was not used because it would have been very expensive to fix the targets to the walls. To fix the targets in the desired locations would have cost thousands of dollars. This cost is very high because scaffolding would have been required to install the targets. This cost was well and truly above the limits of the budget for this project. If the cost is ignored the site has some positives but some negatives that the second site did not have. After the first site was rejected there was no backup location for the calibration range. After another canvass of the USQ campus the current site was found. It was immediately recognised as a suitable site that was just as good if not better than the first location. The second site allowed for the university cherry picker to be situated under the walls where targets were required to be situated at high vertical angles. The major advantage of the second site is that it could test the instrument over 50 meters in a straight line. It also has the possibility to extend that distance further. If the distance was to be extended tripods would need to be located on a sports oval on the far side of a road.

The field work took longer than anticipated to be able to observe all targets from the four scanner stations. It took a total of five (5) hours for the data capture and an hour for installation of the temporary targets. The field work took longer than expected due to the inexperience of the operator of the TLS. It was estimated that each scanner station would take approximately an hour to capture all the data. Before the start of this research project the author had a small amount of experience using a TLS and was not familiar with the operating software. By the end of the day that the data was collected the last station took approximately an hour to collect the data required. An experienced operator would be able to achieve this time, which means that the field work would only take four hours if temporary targets do not have to be installed on the day of scanning. The maximum time that was set while designing the calibration range was half a day to be able to collect the data. This time was chosen so that a whole day of down time was not used while calibrating the instrument. It also allows for travel time if the TLS needs to come from some distance away. Once the data has been exported from the TLS's operating software the processing of the data takes approximately half an hour. The majority of this time is taken up by sorting though the residuals for the outliers. This time is further reduced by using the residual and confidence interval graphs that was shown in chapter 4.

6.5 Limitations of the calibration range

The mathematical model that has been used in this research project is a basic model. The only corrections that it can calculate for the laser scanner, is a correction for the horizontal axis, vertical axis and for range. Lichti (2007) has identified 17 corrections that could be applied to a TLS. A more complicated model was not used because the more complicated the formulas the more complicated the programming that is required to perform the calibration. No researcher was willing to borrow or sell their calibration software so that it could be used to prove that the USQ calibration range would be able to calibrate a TLS. The simplified procedure that has been used and programmed into an Excel spreadsheet has worked very well. It has been able to test the instrument in three of the most important corrections that are required for the calibration of a TLS. A simplified mathematical model was all that was required for this project because it only needed to be able to prove that the design of the station and target geometry was suitable for a calibration range.

The mathematical model has provided a correction for the horizontal axis, vertical axis and range. This would cause problems when trying to apply it to data captured in the field because TLS only output data in X, Y and Z's. To calculate these coordinates the range correction first needs to be applied by turning the correction that we have provided into a scale factor. For the horizontal and vertical correction that has been calculated in this project it needs to have a formula developed so that it can be applied to TLS data. This is because to calculate the X and

Y and Z coordinate the range to the object is required. A simple block shift is not able to be performed because of the high correlation with the range being used to calculate the coordinates.

6.6 Future research

Future research for this project topic can be performed on developing a mathematical model that calculates an angular correction for the horizontal and vertical axis. The problem with the correction to the laser scanner that has been calculated during this research project is it is not easily applied to the TLS as it is a distance correction in the horizontal and vertical axis. Only the range correction could be easily applied by calculating a scale factor. Ideally an angular correction for the horizontal and vertical axis would need to be calculated. The mathematical model that was used for the USQ calibration was a basic model and had only three (3) error models. If future research was performed a new mathematical model that could handle more error models should be added to the solution. By having more error models in the calibration will provide more corrections that can be applied to the laser scanner. It will also provide for a better solution as the source of errors in the TLS can be isolated.

The final area that future research can be performed in is developing a mechanism where the corrections can be to applied to the TLS data. The TLS that was used for this project can measure up to 50 000 points per second. Trying to post process large amounts data after it has been observed in the field could become very time consuming. The calibration corrections should therefore be applied while the data is being collected in the field. This should take the form that is similar to applying corrections to a total station. For the corrections to be applied during data capture the operating software of the TLS would need to be modified to allow it to happen during data capture where the parameters of the correction can be inputted during the start up of the scanner.

6.7 Conclusion

This chapter has made recommendations that can be easily applied to the USQ range to solve the problems that were identified with its design. It has described the limitations of the corrections that it has calculated. It has further been discussed how best the corrections can be applied to terrestrial laser scanner data and identified areas of future research. This project will finish by stating that it has found appropriate station geometry that can be used for the calibration of terrestrial laser scanners. It has found the optimum target geometry for an outdoor calibration range. Finally it has determined that the USQ calibration range is suitable for the calibration of terrestrial laser scanners.

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Appendix A

Project specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/ENG4112 RESEARCH PROJECT
PROJECT SPECIFICATION

FOR: Allen Grant **Ledger**

TOPIC: Development of a high-precision terrestrial laser scanner calibration range at the University of Southern Queensland

SUPERVISOR: Dr Albert Kon-Fook Chong

PROJECT AIM: The aim of this project is to develop a terrestrial laser scanning system calibration range that can be used by surveying and engineering firms as a quality control mechanism

PROGRAMME: Issue B, 17 Mar. 11

1. Research terrestrial laser scanner calibration, target registration methods, different types of terrestrial laser scanners and how they function, control target configuration.
2. Design a calibration range with coordinated targets, read in with traditional surveying methods
3. Develop a calibration procedure and different evaluation methods
4. Do field trials on the calibration procedures and evaluation methods
5. Analyse the field data using a suitable program which will perform the calculations for the surveyor and provide a set of correction factors that can be applied to the instruments
6. Re-run the field trials with the correction factors as calculated
7. Analytically evaluate the results and validate the adjustment

As time permits:

8. Establish a set of guidelines for terrestrial laser scanner calibration

AGREED__________________(student) ____________________(supervisor)

Date: / / 2011 Date: / / 2011

Examiner/Co-examiner:____________________

Appendix B

Product specification datasheet

Leica Scan Station 2

Leica ScanStation 2
Product Specifications

General	
Instrument type	Pulsed, dual-axis compensated, very-high speed laser scanner, with survey-grade accuracy, range, and field-of-view
User interface	Notebook or Tablet PC
Scanner drive	Servo motor
Camera	Integrated high-resolution digital camera

System Performance	
Accuracy of single measurement	
Position*	6 mm
Distance*	4 mm
Angle (horizontal/vertical)	60 µrad/60 µrad, one sigma
Modeled surface precision/noise**	2 mm, one sigma
Target acquisition***	2 mm std. deviation
Dual-axis compensator	Selectable on/off Resolution 1", dynamic range +/- 5'
Data integrity monitoring	Periodic self-check during operation and startup

Laser Scanning System	
Type	Pulsed; proprietary microchip
Color	Green
Laser Class	3R (IEC 60825-1)
Range	300 m @ 90%; 134 m @ 18% albedo
Scan rate	Up to 50,000 points/sec, maximum instantaneous rate Average: dependent on specific scan density and field-of-view
Scan resolution	
Spot size	From 0 - 50 m : 4 mm (FWHH - based); 6mm (Gaussian - based)
Selectability	Independently, fully selectable vertical and horizontal point-to-point measurement spacing[1]
Point spacing	Fully selectable horizontal and vertical; < 1 mm minimum spacing, through full range[1]; single point dwell capability
Maximum sample density	< 1 mm[1]
Field-of-view (per scan)	
Horizontal	360° (maximum)[1]
Vertical	270° (maximum)[1]
Aiming/Sighting	Optical sighting using QuickScan™ button
Scanning Optics	Single mirror, panoramic, front and upper window design Environmentally protected by housing and two glass shields
Scan motors	Direct drive, brushless
Data & power transfer to/from rotating turret	Contact-free: optical data link and inductive power transfer
Communications	Static Internet Protocol (IP) Address
Integrated color digital imaging	User-defined pixel resolution: Low, Medium, High[1] Single 24° x 24° image: 1024 x 1024 pixels (1 megapixel) @ "High" setting Full 360° x 270° dome: 111 images, approx. 64 megapixels, automatically spatially rectified
Status Indicators	3 LEDs (on stationary base) indicate system ready, laser "on", and communications status
Level indicator	External bubble and via laptop

Electrical	
Power supply	36 V; AC or DC; hot swappable; two (2) Power Supply units provided with system
Power consumption	< 80W avg.
Battery type	Sealed lead acid
Power ports	Two (2) simultaneous use, hot swappable
Typical duration	>6 hours, typical continuous use (room temp.)
Power status indicators	Five (5) LEDs indicate charging status and power levels

Environmental	
Operating temp.	0° C to +40° C
Storage temp.	-25° C to +65° C
Lighting	Fully operational between bright sunlight and complete darkness
Humidity	Non-condensing
Shock	40 G's (max. to scanner transport case)
Dust/humidity	IP52 (IEC 60529)

Physical	
Scanner	
Dimensions	10.5" D x 14.5" W x 20" H 265 mm x 370 mm x 510 mm w/o handle and table stand
Weight	18.5 kg, nominal
Power Supply Unit	
Dimensions	6.5" D x 9.25" W x 8.5" H 165 mm x 236 mm x 215 mm w/o handles
Weight	12 kg, nominal

Standard Accessories Included

Scanner transport case
Tribrach (Leica Professional Series)
Survey tripod
Ethernet cable for connection of scanner to notebook PC
Two Power Supply cases. Each includes:
- Power Supply
- Cable for battery connection to scanner
- Power Supply charger

User manual
Cleaning kit
Cyclone™-SCAN software

Hardware Options

Notebook PC
Tablet PC
HDS scan targets and target accessories
Service agreement for Leica ScanStation 2
Extended warranty for Leica ScanStation 2

Notebook PC for Scanning[Δ]

Component	required (minimum)
Processor	1.4 GHz Pentium M or similar
RAM	512 MB SDRAM
Network card	Ethernet
Display	SXGA+
Operating system	Windows XP (SP1 or higher) Windows 2000 (SP2 or higher)

Cyclone-SCAN

Independent vertical and horizontal scan density[1]
Scan filters: range, intensity[1]
Selection of scan area via scribed rectangle or pre-sets[1]
Atmospheric correction
Customizable longitude/latitude grid lines
Targeted, single-shot pre-scan ranging[1]
Script management for auto scan sequencing[1]
View scanner locations and field-of-view
Level of detail (LOD) for fast visualization
Auto rechecking (re-acquisition) of targets[1]
Auto acquisition of HDS targets[1]
Target identification
Traverse[1]
Field Setup - Resection[1]
Field Setup - Known Backsight[1]
Field Setup - Known Azimuth[1]
Traverse and resection reports
Stakeout and id-point
Point to and dwell on preselected coordinates
Direct coordinate/station entry[1]
Dual-axis compensation on/off
Engage/disengage turret
Target and instrument height input
Lighting control for digital images
Acquire and display digital image
Set image resolution (high, medium, low)
Support of external digital images
Real-time 3D visualization while scanning[1]
Fly-around, pan & zoom, rotate clouds, meshes, models in 3D
View point clouds with intensity or true-color mapping
Auto creation of panoramic digital image mosaic[1]
Global digital image viewer[1]
Point-and-scan QuickScan to set horizontal FoV[1]
User-defined quality-of-fit checks
Measure & dimension: slope dist., ΔX, ΔY, ΔZ
Create, manage annotations and layers
Save/restore views
Save screen images
Undo/redo support

Direct Import Formats

Cyclone native IMP object database format, Cyclone Object Exchange (COE) format
ASCII point data (XYZ, SVY, PTS, PTX, TXT)
Leica's X-Function DBX format, Land XML, ZFS, ZFC, 3DD

Direct Export Formats

ASCII point data (XYZ, SVY, PTS, PTX, TXT), DXF
Leica's X-Function DBX format, Land XML, PTZ

Indirect Export Formats

AutoCAD (via AutoCAD, COE for MicroStation plug in)
MicroStation (via COE for MicroStation plug-in)
PDS (via MicroStation, COE for MicroStation plug-in)
AutoPLANT (via AutoCAD, COE for AutoCAD plug-in)

All specifications are subject to change without notice.
All ± accuracy specifications are one sigma unless otherwise noted
[1] SmartScan Technology™ feature
* At 1 m - 50 m range, one sigma
** Subject to modeling methodology for modeled surface
*** Algorithmic fit to planar HDS targets
Δ Minimum requirements for modeling operations are different. Refer to Cyclone data sheet specifications

Laser class 3R in accordance with IEC 60825-1 resp. EN 60825-1

760347en – VI.07 – RDV

Leica Geosystems AG
Heerbrugg, Switzerland
www.leica-geosystems.com/hds

- when it has to be **right**

Leica Geosystems

Appendix C

Extended Results

target	residual	deviations	Squared deviations
HDS1-HDS2	0.006308135	0.397507345	0.15801209
HDS2-HDS3	-0.006583408	0.384615803	0.147929316
HDS1-HDS3	7.97405E-05	0.391278951	0.153099218
HDS4-HDS5	0.000814835	0.392014046	0.153675012
HDS5-HDS6	0.000866075	0.392065286	0.153715188
HDS4-HDS6	0.001687735	0.392886946	0.154360152
HDS7-HDS8	-0.000414877	0.390784333	0.152712395
HDS8-HDS9	-0.000398601	0.39080061	0.152725117
HDS7-HDS9	-0.000822215	0.390376996	0.152394199
BW10-BW11	0.000491598	0.391690808	0.153421689
BW11-BW12	0.000675751	0.391874962	0.153565986
BW10-BW12	0.001184004	0.392383214	0.153964587
BW13-BW14	0.000180257	0.391379467	0.153177887
BW14-BW15	0.000237218	0.391436428	0.153222477
BW13-BW15	0.000436441	0.391635651	0.153378484
HDS16-HDS17	0.000789001	0.391988211	0.153654758
HDS17-HDS18	6.1817E-05	0.391261028	0.153085192
HDS16-HDS18	0.000838606	0.392037817	0.15369365
BW19-BW20	0.002122006	0.393321217	0.15470158
BW20-BW21	-0.000835602	0.390363608	0.152383747
BW19-BW21	0.001284096	0.392483307	0.154043146
BW22-BW23	0.000483142	0.391682353	0.153415066
BW23-BW24	-0.000627257	0.390571953	0.152546451
BW22-BW24	-0.000140746	0.391058465	0.152926723
HDS25-HDS26	-0.000624645	0.390574566	0.152548492
HDS26-HDS27	0.012187701	0.403386911	0.162721
HDS25-HDS27	0.011583693	0.402782904	0.162234068
HDS28-HDS29	-5.907755899	-5.516556689	30.4323977
HDS29-HDS30	-0.048322097	0.342877113	0.117564715
HDS28-HDS30	-5.811762821	-5.420563611	29.38250986
SUM	-11.73597632		64.08977994
Hz ERROR	-0.391199211	Sample variance (s^2)	2.209992412

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	0.403487565	0.144383518	-0.535582728	-0.246815693

STN1-STN2 Horizontal correction no outliers removed

target	residual	deviations	Squared deviations
HDS1-BW13	0.001022186	0.145743208	0.021241083
HDS1-HDS4	0.006308135	0.151029158	0.022809806
HDS4-HDS7	0.000463236	0.145184259	0.021078469
HDS7-BW10	0.420891997	0.56561302	0.319918089
BW10-BW13	-0.000133383	0.14458764	0.020905586
HDS2-BW14	0.029505115	0.174226137	0.030354747
HDS2-HDS5	0.028575677	0.1732967	0.030031746
HDS5-HDS8	0.00049575	0.145216773	0.021087911
HDS8-BW11	-6.98761E-05	0.144651147	0.020923954
BW11-BW14	7.99552E-05	0.144800978	0.020967323
HDS3-HDS15	0.000208745	0.144929768	0.021004638
HDS3-HDS6	8.638E-05	0.144807403	0.020969184
HDS6-HDS9	0.000443245	0.145164267	0.021072665
HDS9-BW12	-0.352328715	-0.207607693	0.043100954
BW12-BW15	-0.000142117	0.144578906	0.02090306
HDS16-BW23	0.000874828	0.145595851	0.021198152
HDS16-BW19	0.000195725	0.144916748	0.021000864
BW19-BW23	0.00098303	0.145704053	0.021229671
HDS17-BW22	0.000581272	0.145302294	0.021112757
HDS17-BW20	-0.000278473	0.14444255	0.02086365
BW20-BW22	-0.00747958	0.137241443	0.018835214
HDS18-BW24	3.33509E-05	0.144754374	0.020953829
HDS18-BW21	0.000125972	0.144846995	0.020980652
BW21-BW24	-0.000221846	0.144499177	0.020880012
HDS25-HDS28	-4.06625805	-3.921537028	15.37845266
HDS26-HDS29	-0.000450225	0.144270798	0.020814063
HDS27-HDS30	0.02902005	0.173741073	0.030185961
SUM	-3.907467616		16.2728767
V ERROR	-0.144721023	Sample variance	0.625879873

		95% CI (average ± Confidence Interval)	
		Confidence Interval	Confidence Interval Limits

Standard deviation of the mean	3.13171658	1.181268602	- 1.325989625	1.036547579

STN1-STN2 Vertical correction not outliers removed

Distance	residual	deviations	Squared deviations
HDS31-HDS32	-1.14184E-05	0.000247056	6.10369E-08
HDS8-HDS9	-0.000203661	5.48139E-05	3.00457E-09
HDS32-HDS8	-0.000560345	-0.00030187	9.11257E-08
SUM	-0.000775425		1.55167E-07
Range correction (C)	-0.000258475	Sample Variance	7.75836E-08

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	4.47929E-08	5.0687E-08	-0.000258526	-0.000258424

STN1-STN2 Distance correction no outliers removed

target	residual	deviations	Squared deviations
HDS1-HDS2	0.000264481	0.002976912	8.862E-06
HDS2-HDS3	-7.55131E-05	0.002636917	6.95333E-06
HDS1-HDS3	0.000141862	0.002854292	8.14698E-06
HDS4-HDS5	-8.34771E-05	0.002628953	6.9114E-06
HDS5-HDS6	0.0008623	0.003574731	1.27787E-05
HDS4-HDS6	0.000775583	0.003488013	1.21662E-05
HDS7-HDS8	0.000521478	0.003233908	1.04582E-05
HDS8-HDS9	0.000616454	0.003328885	1.10815E-05
HDS7-HDS9	0.00115343	0.00386586	1.49449E-05
BW10-BW11	0.000439265	0.003151696	9.93318E-06
BW11-BW12	0.000268478	0.002980909	8.88582E-06
BW10-BW12	0.000698141	0.003410572	1.1632E-05
BW13-BW14	0.000203722	0.002916153	8.50395E-06
BW14-BW15	-9.42277E-05	0.002618203	6.85499E-06
BW13-BW15	9.28367E-05	0.002805267	7.86952E-06
HDS16-HDS17	-0.06106487	-0.05835244	0.003405007

HDS17-HDS18	-0.00150213	0.001210301	1.46483E-06
HDS16-HDS18	-0.062179778	-0.059467348	0.003536365
BW19-BW20	0.006446926	0.009159357	8.38938E-05
BW20-BW21	-0.001915456	0.000796974	6.35168E-07
BW19-BW21	0.003980719	0.006693149	4.47982E-05
BW22-BW23	1.495370673	1.498083103	2.244252984
BW23-BW24	3.121941152	3.124653582	9.763460011
BW22-BW24	-4.617622069	-4.614909638	21.29739097
HDS25-HDS26	-0.00044535	0.002267081	5.13966E-06
HDS26-HDS27	0.013023011	0.015735441	0.000247604
HDS25-HDS27	0.012565019	0.01527745	0.0002334
HDS28-HDS29	0.001399373	0.004111803	1.69069E-05
HDS29-HDS30	0.000812973	0.003525404	1.24285E-05
HDS28-HDS30	0.00203208	0.004744511	2.25104E-05
SUM	-0.081372912		33.3128601
Hz ERROR	-0.00271243	Sample variance (s^2)	1.148719314

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	0.209726493	0.075048283	-0.077760713	0.072335852

STN3-STN4 Horizontal correction no outliers removed

target	residual	deviations	Squared deviations
HDS1-BW13	-0.000252801	-0.594114692	0.352972267
HDS1-HDS4	0.000264481	-0.59359741	0.352357885
HDS4-HDS7	-0.001230601	-0.595092492	0.354135074
HDS7-BW10	0.145065391	-0.4487965	0.201418298
BW10-BW13	2.35717E-05	-0.593838319	0.352643949
HDS2-BW14	0.000144802	-0.593717089	0.352499981
HDS2-HDS5	0.000164304	-0.593697587	0.352476825
HDS5-HDS8	-0.000581553	-0.594443444	0.353363008
HDS8-BW11	-4.20818E-05	-0.593903973	0.352721929
BW11-BW14	0.000312196	-0.593549695	0.352301241
HDS3-HDS15	-0.001093564	-0.594955455	0.353971993
HDS3-HDS6	-0.001271904	-0.595133795	0.354184234
HDS6-HDS9	0.000143606	-0.593718285	0.352501402
HDS9-BW12	-0.348461775	-0.942323666	0.887973892
BW12-BW15	1.25506E-05	-0.59384934	0.352657039

HDS16-BW23	3.615380187	3.021518296	9.129572813
HDS16-BW19	0.004361396	-0.589500495	0.347510834
BW19-BW23	4.408491268	3.814629377	14.55139728
HDS17-BW22	-1.696741997	-2.290603887	5.246866169
HDS17-BW20	-0.001327541	-0.595189432	0.354250459
BW20-BW22	-1.940337306	-2.534199196	6.422165567
HDS18-BW24	5.459894703	4.866032812	23.67827533
HDS18-BW21	-0.001466098	-0.595327989	0.354415415
BW21-BW24	6.377720696	5.783858805	33.45302267
HDS25-HDS28	0.001228118	-0.592633773	0.351214789
HDS26-HDS29	0.000268642	-0.593593249	0.352352945
HDS27-HDS30	0.013602363	-0.580259528	0.336701119
SUM	16.03427105		100.2559244
V ERROR	0.593861891	Sample variance	3.855997093

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	19.29426165	7.277703744	-6.683841853	7.871565635

STN3-STN4 Vertical correction not outliers removed

Distance	residual	deviations	Squared deviations
HDS31-HDS32	0.000465208	0.000195492	3.82173E-08
HDS8-HDS9	0.000316048	4.6332E-05	2.14665E-09
HDS32-HDS8	2.78914E-05	-0.000241824	5.8479E-08
SUM	0.000809147		9.88429E-08
Range correction (C)	0.000269716	Sample Variance	4.94215E-08

		95% CI (average ± Confidence Interval)	
		Confidence Interval	Confidence Interval Limits

Standard deviation of the mean	2.85335E-08	3.22881E-08	0.000269683	0.000269748

STN3-STN4 Distance correction no outliers removed

target	residual	deviations	Squared deviations
HDS1-HDS2	0.005939868	0.394585684	0.155697862
HDS2-HDS3	-0.006543167	0.38210265	0.146002435
HDS1-HDS3	-0.000344713	0.388301104	0.150777747
HDS4-HDS5	-8.69531E-06	0.388637121	0.151038812
HDS5-HDS6	0.000403565	0.389049381	0.151359421
HDS4-HDS6	0.000431435	0.389077252	0.151381108
HDS7-HDS8	-0.001294827	0.38735099	0.150040789
HDS8-HDS9	-0.000586975	0.388058842	0.150589665
HDS7-HDS9	-0.001936552	0.386709265	0.149544055
BW10-BW11	0.000274008	0.388919825	0.15125863
BW11-BW12	-3.95004E-05	0.388606316	0.151014869
BW10-BW12	0.000226401	0.388872218	0.151221602
BW13-BW14	0.000246209	0.388892026	0.151237008
BW14-BW15	0.000198962	0.388844778	0.151200262
BW13-BW15	0.000447224	0.38909304	0.151393394
HDS16-HDS17	-0.000212613	0.388433203	0.150880353
HDS17-HDS18	0.001810137	0.390455954	0.152455852
HDS16-HDS18	0.001570596	0.390216413	0.152268849
BW19-BW20	0.000727751	0.389373567	0.151611775
BW20-BW21	0.002129532	0.390775348	0.152705373
BW19-BW21	0.002782726	0.391428543	0.153216304
BW22-BW23	0.000990531	0.389636348	0.151816483
BW23-BW24	0.000778218	0.389424035	0.151651079
BW22-BW24	0.001747144	0.390392961	0.152406664
HDS25-HDS26	0.000464961	0.389110778	0.151407197
HDS26-HDS27	0.000174922	0.388820739	0.151181567
HDS25-HDS27	0.000637598	0.389283415	0.151541577
HDS28-HDS29	-5.906624718	-5.517978901	30.44809116
HDS29-HDS30	-0.000697483	0.387948334	0.15050391
HDS28-HDS30	-5.763067045	-5.374421228	28.88440354
SUM	-11.6593745		63.56989934
Hz ERROR	-0.388645817	Sample variance (s^2)	2.192065494
		95% CI (average ± Confidence Interval)	

		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	0.400214573	0.143212314	-0.531858131	-0.245433503

STN1-STN3 Horizontal correction no outliers removed

target	residual	deviations	Squared deviations
HDS1-BW13	0.001051533	0.150311518	0.022593552
HDS1-HDS4	0.005939868	0.155199852	0.024086994
HDS4-HDS7	0.001188056	0.150448041	0.022634613
HDS7-BW10	0.420711071	0.569971056	0.324867004
BW10-BW13	5.06211E-05	0.149310606	0.022293657
HDS2-BW14	0.029458083	0.178718068	0.031940148
HDS2-HDS5	0.02835817	0.177618154	0.031548209
HDS5-HDS8	0.00103847	0.150298455	0.022589626
HDS8-BW11	0.000279076	0.14953906	0.022361931
BW11-BW14	6.03525E-06	0.14926602	0.022280345
HDS3-HDS15	0.001001789	0.150261774	0.022578601
HDS3-HDS6	0.000629878	0.149889862	0.022466971
HDS6-HDS9	0.000362232	0.149622216	0.022386808
HDS9-BW12	-0.327855239	-0.178595255	0.031896265
BW12-BW15	0.00010144	0.149361424	0.022308835
HDS16-BW23	0.000288732	0.149548717	0.022364819
HDS16-BW19	-0.000311905	0.14894808	0.02218553
BW19-BW23	0.001766208	0.151026192	0.022808911
HDS17-BW22	0.001046763	0.150306747	0.022592118
HDS17-BW20	0.000908275	0.150168259	0.022550506
BW20-BW22	-0.13197571	0.017284274	0.000298746
HDS18-BW24	0.001080173	0.150340158	0.022602163
HDS18-BW21	0.00067188	0.149931865	0.022479564
BW21-BW24	-3.73658E-05	0.149222619	0.02226739
HDS25-HDS28	-4.066005859	-3.916745875	15.34089825
HDS26-HDS29	0.000158498	0.149418483	0.022325883
HDS27-HDS30	6.96454E-05	0.14932963	0.022299338
SUM	-4.030019584		16.23450677
V ERROR	-0.149259985	Sample variance	0.624404107

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	3.124332285	1.178483281	-1.327743265	1.029223296

STN1-STN3 Vertical correction no outliers removed

Distance	residual	deviations	Squared deviations
HDS31-HDS32	-0.000155171	0.00014699	2.16061E-08
HDS8-HDS9	-0.000321315	-1.91545E-05	3.66895E-10
HDS32-HDS8	-0.000429997	-0.000127836	1.6342E-08
SUM	-0.000906482		3.8315E-08
Range correction (C)	-0.000302161	Sample Variance	1.91575E-08

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	1.10606E-08	1.2516E-08	-0.000302173	-0.000302148

STN1-STN3 Distance correction no outliers removed

target	residual	deviations	Squared deviations
HDS1-HDS2	0.006303243	0.397854492	0.158288197
HDS2-HDS3	-0.006700019	0.38485123	0.148110469
HDS1-HDS3	-0.000103896	0.391447353	0.15323103
HDS4-HDS5	-0.000214628	0.391336621	0.153144351
HDS5-HDS6	0.001299641	0.39285089	0.154331822
HDS4-HDS6	0.001085295	0.392636544	0.154163456
HDS7-HDS8	-0.000731088	0.390820162	0.152740399
HDS8-HDS9	-8.65355E-06	0.391542596	0.153305604
HDS7-HDS9	-0.000741708	0.390809541	0.152732097
BW10-BW11	0.000731409	0.392282658	0.153885684
BW11-BW12	0.000208975	0.391760224	0.153476073
BW10-BW12	0.000941592	0.392492841	0.15405063
BW13-BW14	0.000478895	0.392030145	0.153687634
BW14-BW15	8.94679E-05	0.391640717	0.153382451
BW13-BW15	0.000567709	0.392118958	0.153757277

HDS16-HDS17	-0.060892805	0.330658444	0.109335007
HDS17-HDS18	0.00077828	0.392329529	0.153922459
HDS16-HDS18	-0.060156053	0.331395196	0.109822776
BW19-BW20	0.006754728	0.398305977	0.158647651
BW20-BW21	-0.000704195	0.390847055	0.15276142
BW19-BW21	0.006118541	0.39766979	0.158141262
BW22-BW23	1.492744916	1.884296165	3.550572037
BW23-BW24	3.122791237	3.514342486	12.35060311
BW22-BW24	-4.616958383	-4.225407133	17.85406544
HDS25-HDS26	6.99309E-05	0.39162118	0.153367149
HDS26-HDS27	0.013169476	0.404720725	0.163798866
HDS25-HDS27	0.013240976	0.404792225	0.163856745
HDS28-HDS29	-5.905638833	-5.514087584	30.40516188
HDS29-HDS30	0.000168873	0.391720122	0.153444654
HDS28-HDS30	-5.761230397	-5.369679148	28.83345415
SUM	-11.74653748		96.77324179
Hz ERROR	-0.391551249	Sample variance (s^2)	3.337008337

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	0.60925158	0.218013872	-0.609565121	-0.173537377

STN1-STN4 Horizontal correction no outliers removed

target	residual	deviations	Squared deviations
HDS1-BW13	0.000899564	-0.456774861	0.208643274
HDS1-HDS4	0.006303243	-0.451371182	0.203735944
HDS4-HDS7	-0.000165162	-0.457839587	0.209617087
HDS7-BW10	0.421391792	-0.036282633	0.001316429
BW10-BW13	8.46884E-05	-0.457589737	0.209388367
HDS2-BW14	0.029508302	-0.428166123	0.183326229
HDS2-HDS5	0.028429792	-0.429244633	0.184250955
HDS5-HDS8	0.000501152	-0.457173273	0.209007401
HDS8-BW11	0.00020254	-0.457471885	0.209280525
BW11-BW14	0.000298271	-0.457376154	0.209192947
HDS3-HDS15	-0.000183283	-0.457857708	0.209633681
HDS3-HDS6	-0.000732201	-0.458406626	0.210136634
HDS6-HDS9	0.000554121	-0.457120304	0.208958973
HDS9-BW12	-0.311761652	-0.769436077	0.592031876

BW12-BW15	9.87602E-05	-0.457575665	0.209375489
HDS16-BW23	3.61647539	3.158800965	9.978023534
HDS16-BW19	0.004378802	-0.453295623	0.205476922
BW19-BW23	4.409592632	3.951918207	15.61765751
HDS17-BW22	-1.695442299	-2.153116724	4.635911626
HDS17-BW20	-9.39689E-05	-0.457768394	0.209551902
BW20-BW22	-1.940747476	-2.398421901	5.752427616
HDS18-BW24	5.460923212	5.003248787	25.03249843
HDS18-BW21	-0.000952696	-0.458627121	0.210338836
BW21-BW24	6.378119669	5.920445244	35.05167188
HDS25-HDS28	-4.064686504	-4.522360929	20.45174837
HDS26-HDS29	0.000359757	-0.457314668	0.209136706
HDS27-HDS30	0.013853028	-0.443821397	0.196977432
SUM	12.35720948		120.8093166
V ERROR	0.457674425	Sample variance	4.646512176

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	23.24976382	8.769700352	-8.312025927	9.227374777

STN1-STN4 Vertical correction no outliers removed

Distance	residual	deviations	Squared deviations
HDS31-HDS32	0.000310038	0.000342483	1.17294E-07
HDS8-HDS9	-5.26754E-06	2.71775E-05	7.38617E-10
HDS32-HDS8	-0.000402105	-0.00036966	1.36649E-07
SUM	-9.73351E-05		2.54682E-07
Range correction (C)	-3.2445E-05	Sample Variance	1.27341E-07

		95% CI (average ± Confidence Interval)	
		Confidence Interval	Confidence Interval Limits

Standard deviation of the mean	7.35202E-08	8.31945E-08	-3.25282E-05	-3.23619E-05

STN1-STN4 Distance correction no outliers removed

target	residual	deviations	Squared deviations
HDS1-HDS2	8.91717E-05	0.002661823	7.0853E-06
HDS2-HDS3	7.45325E-05	0.002647184	7.00758E-06
HDS1-HDS3	0.000151766	0.002724417	7.42245E-06
HDS4-HDS5	0.000935555	0.003508207	1.23075E-05
HDS5-HDS6	0.000433376	0.003006028	9.0362E-06
HDS4-HDS6	0.00136708	0.003939731	1.55215E-05
HDS7-HDS8	0.000832727	0.003405378	1.15966E-05
HDS8-HDS9	0.000233835	0.002806486	7.87636E-06
HDS7-HDS9	0.001067996	0.003640648	1.32543E-05
BW10-BW11	0.00019251	0.002765161	7.64612E-06
BW11-BW12	0.000744228	0.003316879	1.10017E-05
BW10-BW12	0.000932931	0.003505582	1.22891E-05
BW13-BW14	-0.000104783	0.002467868	6.09037E-06
BW14-BW15	6.34322E-05	0.002636083	6.94894E-06
BW13-BW15	-4.90826E-05	0.002523568	6.3684E-06
HDS16-HDS17	0.000934164	0.003506815	1.22977E-05
HDS17-HDS18	-0.001721447	0.000851204	7.24548E-07
HDS16-HDS18	-0.000787697	0.001784954	3.18606E-06
BW19-BW20	0.001471978	0.004044629	1.6359E-05
BW20-BW21	-0.003053821	-0.00048117	2.31524E-07
BW19-BW21	-0.001579485	0.000993166	9.8638E-07
BW22-BW23	-0.000512888	0.002059763	4.24262E-06
BW23-BW24	-0.001485187	0.001087465	1.18258E-06
BW22-BW24	-0.002001443	0.000571208	3.26278E-07
HDS25-HDS26	-0.001022984	0.001549667	2.40147E-06
HDS26-HDS27	0.012016167	0.014588818	0.000212834
HDS25-HDS27	0.010987886	0.013560537	0.000183888
HDS28-HDS29	-0.001139275	0.001433376	2.05457E-06
HDS29-HDS30	-0.047549778	-0.044977127	0.002022942
HDS28-HDS30	-0.048700997	-0.046128346	0.002127824
SUM	-0.077179534		0.004732933
Hz ERROR	-0.002572651	Sample variance (s^2)	0.000163205
		95% CI (average ± Confidence Interval)	

		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	2.97969E-05	1.06625E-05	-0.002583314	-0.002561989

STN3-STN2 Horizontal correction no outliers removed

target	residual	deviations	Squared deviations
HDS1-BW13	-0.000315355	0.006020725	3.62491E-05
HDS1-HDS4	8.91717E-05	0.006425251	4.12839E-05
HDS4-HDS7	-0.000611964	0.005724115	3.27655E-05
HDS7-BW10	0.144561231	0.15089731	0.022769998
BW10-BW13	-0.000200289	0.006135791	3.76479E-05
HDS2-BW14	0.000177952	0.006514031	4.24326E-05
HDS2-HDS5	0.000348222	0.006684302	4.46799E-05
HDS5-HDS8	-0.000581804	0.005754275	3.31117E-05
HDS8-BW11	-0.000308052	0.006028027	3.63371E-05
BW11-BW14	0.000103322	0.006439402	4.14659E-05
HDS3-HDS15	-0.000984112	0.005351968	2.86436E-05
HDS3-HDS6	-0.000746645	0.005589435	3.12418E-05
HDS6-HDS9	4.86214E-05	0.006384701	4.07644E-05
HDS9-BW12	-0.329396268	-0.323060188	0.104367885
BW12-BW15	-0.000196955	0.006139125	3.76889E-05
HDS16-BW23	0.000497774	0.006833854	4.67016E-05
HDS16-BW19	0.000379572	0.006715652	4.51E-05
BW19-BW23	-0.00071074	0.005625339	3.16444E-05
HDS17-BW22	-0.000300173	0.006035907	3.64322E-05
HDS17-BW20	-0.001087223	0.005248857	2.75505E-05
BW20-BW22	-0.007491547	-0.001155468	1.33511E-06
HDS18-BW24	-0.001318157	0.005017922	2.51795E-05
HDS18-BW21	-0.000829801	0.005506279	3.03191E-05
BW21-BW24	-0.000500176	0.005835904	3.40578E-05
HDS25-HDS28	-1.48283E-05	0.006321251	3.99582E-05
HDS26-HDS29	-0.000606307	0.005729773	3.28303E-05
HDS27-HDS30	0.028920379	0.035256459	0.001243018
SUM	-0.17107415		0.129216322
V ERROR	-0.00633608	Sample variance	0.004969859

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	0.024867693	0.009379975	-0.015716055	0.003043896

STN3-STN2 Vertical correction no outliers removed

Distance	residual	deviations	Squared deviations
HDS31-HDS32	0.000143752	0.000100066	1.00132E-08
HDS8-HDS9	0.000117654	7.39684E-05	5.47133E-09
HDS32-HDS8	-0.000130349	-0.000174035	3.0288E-08
SUM	0.000131058		4.57726E-08
Range correction (C)	4.36859E-05	Sample Variance	2.28863E-08

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	1.32134E-08	1.49521E-08	4.3671E-05	4.37009E-05

STN3-STN2 Distance correction no outliers removed

target	residual	deviations	Squared deviations
HDS1-HDS2	0.000149256	0.000319724	1.02223E-07
HDS2-HDS3	-0.000145212	2.52557E-05	6.37851E-10
HDS1-HDS3	-3.50221E-05	0.000135445	1.83454E-08
HDS4-HDS5	-0.001020541	-0.000850073	7.22624E-07
HDS5-HDS6	0.000429595	0.000600062	3.60075E-07
HDS4-HDS6	-0.000593079	-0.000422612	1.78601E-07
HDS7-HDS8	-0.000311966	-0.000141499	2.0022E-08
HDS8-HDS9	0.000383679	0.000554146	3.07078E-07
HDS7-HDS9	8.47212E-05	0.000255189	6.51212E-08
BW10-BW11	0.000245751	0.000416219	1.73238E-07
BW11-BW12	-0.000474453	-0.000303985	9.24071E-08
BW10-BW12	-0.000235892	-6.54244E-05	4.28035E-09
BW13-BW14	0.000307079	0.000477546	2.28051E-07
BW14-BW15	-0.000156227	1.42403E-05	2.02785E-10
BW13-BW15	0.000140379	0.000310847	9.66257E-08

HDS16-HDS17	-0.06195317	-0.061782702	0.003817102
HDS17-HDS18	0.000291194	0.000461661	2.13131E-07
HDS16-HDS18	-0.061334622	-0.061164155	0.003741054
BW19-BW20	0.00492547	0.005095937	2.59686E-05
BW20-BW21	0.000992781	0.001163248	1.35315E-06
BW19-BW21	0.005455275	0.005625742	3.1649E-05
BW22-BW23	1.495359929	1.495530396	2.236611167
BW23-BW24	3.123425205	3.123595672	9.756849921
BW22-BW24	-4.615793687	-4.61562322	21.30397771
HDS25-HDS26	0.000594542	0.000765009	5.85239E-07
HDS26-HDS27	0.001003219	0.001173687	1.37754E-06
HDS25-HDS27	0.001588721	0.001759189	3.09475E-06
HDS28-HDS29	0.002477696	0.002648164	7.01277E-06
HDS29-HDS30	0.048381289	0.048551757	0.002357273
HDS28-HDS30	0.050704067	0.050874535	0.002588218
SUM	-0.005114022		33.31001607
Hz ERROR	-0.000170467	Sample variance (s^2)	1.148621244

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	0.209708588	0.075041876	-0.075212343	0.074871408

STN2-STN4 Horizontal correction no outliers removed

target	residual	deviations	Squared deviations
HDS1-BW13	3.57813E-05	-0.596699082	0.356049794
HDS1-HDS4	0.000149256	-0.596585607	0.355914386
HDS4-HDS7	-0.000620048	-0.597354911	0.35683289
HDS7-BW10	0.227165061	-0.369569802	0.136581838
BW10-BW13	0.000223024	-0.59651184	0.355826375
HDS2-BW14	-2.78959E-05	-0.596762759	0.356125791
HDS2-HDS5	-0.00017842	-0.596913283	0.356305468
HDS5-HDS8	9.95741E-07	-0.596733867	0.356091309
HDS8-BW11	0.000266902	-0.596467961	0.355774028
BW11-BW14	0.000210238	-0.596524625	0.355841628
HDS3-HDS15	-0.000150307	-0.59688517	0.356271906
HDS3-HDS6	-0.000567667	-0.59730253	0.356770313
HDS6-HDS9	9.72821E-05	-0.596637581	0.355976403
HDS9-BW12	-0.330146216	-0.926881079	0.859108535

BW12-BW15	0.000214041	-0.596520822	0.355837091
HDS16-BW23	3.614986241	3.018251378	9.109841381
HDS16-BW19	0.00401092	-0.592723943	0.351321672
BW19-BW23	4.409116359	3.812381496	14.53425267
HDS17-BW22	-1.696381354	-2.293116217	5.258381983
HDS17-BW20	-0.000178898	-0.596913761	0.356306038
BW20-BW22	-1.941948038	-2.538682901	6.444910874
HDS18-BW24	5.461166162	4.864431299	23.66269186
HDS18-BW21	-0.000700255	-0.597435118	0.35692872
BW21-BW24	6.378238314	5.781503451	33.42578215
HDS25-HDS28	0.001290455	-0.595444409	0.354554044
HDS26-HDS29	0.000865556	-0.595869307	0.355060231
HDS27-HDS30	-0.015296186	-0.612031049	0.374582005
SUM	16.11184131		100.2099214
V ERROR	0.596734863	Sample variance	3.854227745

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	19.28540836	7.274364326	-6.677629463	7.871099189

STN2-STN4 Vertical correction no outliers removed

Distance	residual	deviations	Squared deviations
HDS31-HDS32	0.000321456	9.54261E-05	9.10615E-09
HDS8-HDS9	0.000198393	-2.76364E-05	7.63771E-10
HDS32-HDS8	0.00015824	-6.77897E-05	4.59545E-09
SUM	0.00067809		1.44654E-08
Range correction (C)	0.00022603	Sample Variance	7.23268E-09

		95% CI (average ± Confidence Interval)	
		Confidence Interval	Confidence Interval Limits

Standard deviation of the mean	4.17579E-09	4.72527E-09	0.000226025	0.000226035

STN2-STN4 Distance correction no outliers removed

target	residual	deviations	Squared deviations
HDS1-HDS2	0.006308135	0.006895906	4.75535E-05
HDS2-HDS3	-0.006583408	-0.005995637	3.59477E-05
HDS1-HDS3	7.97405E-05	0.000667512	4.45572E-07
HDS4-HDS5	0.000814835	0.001402606	1.9673E-06
HDS5-HDS6	0.000866075	0.001453846	2.11367E-06
HDS4-HDS6	0.001687735	0.002275507	5.17793E-06
HDS7-HDS8	-0.000414877	0.000172894	2.98923E-08
HDS8-HDS9	-0.000398601	0.00018917	3.57854E-08
HDS7-HDS9	-0.000822215	-0.000234443	5.49637E-08
BW10-BW11	0.000491598	0.001079369	1.16504E-06
BW11-BW12	0.000675751	0.001263522	1.59649E-06
BW10-BW12	0.001184004	0.001771775	3.13919E-06
BW13-BW14	0.000180257	0.000768028	5.89867E-07
BW14-BW15	0.000237218	0.000824989	6.80607E-07
BW13-BW15	0.000436441	0.001024212	1.04901E-06
HDS16-HDS17	0.000789001	0.001376772	1.8955E-06
HDS17-HDS18	6.1817E-05	0.000649588	4.21965E-07
HDS16-HDS18	0.000838606	0.001426378	2.03455E-06
BW19-BW20	0.002122006	0.002709777	7.34289E-06
BW20-BW21	-0.000835602	-0.000247831	6.14202E-08
BW19-BW21	0.001284096	0.001871868	3.50389E-06
BW22-BW23	0.000483142	0.001070914	1.14686E-06
BW23-BW24	-0.000627257	-3.94859E-05	1.55914E-09
BW22-BW24	-0.000140746	0.000447025	1.99832E-07
HDS25-HDS26	-0.000624645	-3.68733E-05	1.35964E-09
HDS26-HDS27	0.012187701	0.012775472	0.000163213
HDS25-HDS27	0.011583693	0.012171465	0.000148145
HDS28-HDS29			
HDS29-HDS30	-0.048322097	-0.047734326	0.002278566
HDS28-HDS30			
SUM	-0.016457597		0.002708079
Hz ERROR	-0.000587771	Sample variance (s^2)	0.000100299

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	1.89548E-05	7.02082E-06	-0.000594792	-0.000580751

STN1-STN Horizontal correction after outliers were removed

target	residual	deviations	Squared deviations
HDS1-BW13	0.001022186	-0.002737279	7.4927E-06
HDS1-HDS4	0.006308135	0.00254867	6.49572E-06
HDS4-HDS7	0.000463236	-0.003296228	1.08651E-05
HDS7-BW10			
BW10-BW13	-0.000133383	-0.003892848	1.51543E-05
HDS2-BW14	0.029505115	0.02574565	0.000662838
HDS2-HDS5	0.028575677	0.024816212	0.000615844
HDS5-HDS8	0.00049575	-0.003263715	1.06518E-05
HDS8-BW11	-6.98761E-05	-0.003829341	1.46639E-05
BW11-BW14	7.99552E-05	-0.00367951	1.35388E-05
HDS3-HDS15	0.000208745	-0.00355072	1.26076E-05
HDS3-HDS6	8.638E-05	-0.003673085	1.34916E-05
HDS6-HDS9	0.000443245	-0.00331622	1.09973E-05
HDS9-BW12			
BW12-BW15	-0.000142117	-0.003901582	1.52223E-05
HDS16-BW23	0.000874828	-0.002884636	8.32113E-06
HDS16-BW19	0.000195725	-0.003563739	1.27002E-05
BW19-BW23	0.00098303	-0.002776435	7.70859E-06
HDS17-BW22	0.000581272	-0.003178193	1.01009E-05
HDS17-BW20	-0.000278473	-0.004037938	1.63049E-05
BW20-BW22	-0.00747958	-0.011239044	0.000126316
HDS18-BW24	3.33509E-05	-0.003726114	1.38839E-05
HDS18-BW21	0.000125972	-0.003633492	1.32023E-05
BW21-BW24	-0.000221846	-0.00398131	1.58508E-05
HDS25-HDS28			
HDS26-HDS29	-0.000450225	-0.00420969	1.77215E-05
HDS27-HDS30	0.02902005	0.025260586	0.000638097
SUM	0.090227152		0.002290072

V ERROR	0.003759465	Sample variance	9.95683E-05		
		95% CI (average ± Confidence Interval)			
		Confidence Interval	Confidence Interval Limits		
Standard deviation of the mean	0.000467459	0.000187019	0.003572446	0.003946484	

STN1-STN2 Vertical correction after outliers were removed

target	residual	deviations	Squared deviations
HDS1-HDS2	0.000264481	0.003266802	1.0672E-05
HDS2-HDS3	-7.55131E-05	0.002926808	8.5662E-06
HDS1-HDS3	0.000141862	0.003144183	9.88589E-06
HDS4-HDS5	-8.34771E-05	0.002918844	8.51965E-06
HDS5-HDS6	0.0008623	0.003864621	1.49353E-05
HDS4-HDS6	0.000775583	0.003777904	1.42726E-05
HDS7-HDS8	0.000521478	0.003523799	1.24172E-05
HDS8-HDS9	0.000616454	0.003618775	1.30955E-05
HDS7-HDS9	0.00115343	0.004155751	1.72703E-05
BW10-BW11	0.000439265	0.003441586	1.18445E-05
BW11-BW12	0.000268478	0.003270799	1.06981E-05
BW10-BW12	0.000698141	0.003700462	1.36934E-05
BW13-BW14	0.000203722	0.003206043	1.02787E-05
BW14-BW15	-9.42277E-05	0.002908093	8.45701E-06
BW13-BW15	9.28367E-05	0.003095158	9.58E-06
HDS16-HDS17	-0.06106487	-0.058062549	0.00337126
HDS17-HDS18	-0.00150213	0.001500191	2.25057E-06
HDS16-HDS18	-0.062179778	-0.059177457	0.003501971
BW19-BW20	0.006446926	0.009449248	8.92883E-05
BW20-BW21	-0.001915456	0.001086865	1.18128E-06
BW19-BW21	0.003980719	0.00698304	4.87628E-05
BW22-BW23			
BW23-BW24			
BW22-BW24			
HDS25-HDS26	-0.00044535	0.002556971	6.5381E-06
HDS26-HDS27	0.013023011	0.016025332	0.000256811
HDS25-HDS27	0.012565019	0.01556734	0.000242342
HDS28-HDS29	0.001399373	0.004401694	1.93749E-05
HDS29-HDS30	0.000812973	0.003815294	1.45565E-05
HDS28-HDS30	0.00203208	0.005034401	2.53452E-05

SUM	-0.081062668		0.007753868
Hz ERROR	-0.003002321	Sample variance (s^2)	0.000298226

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	5.73936E-05	2.16486E-05	-0.00302397	-0.002980672

STN3-STN4 Horizontal correction after outliers were removed

target	residual	deviations	Squared deviations
HDS1-BW13	-0.000252801	-0.00095069	9.03811E-07
HDS1-HDS4	0.000264481	-0.000433408	1.87842E-07
HDS4-HDS7	-0.001230601	-0.00192849	3.71907E-06
HDS7-BW10			
BW10-BW13	2.35717E-05	-0.000674317	4.54703E-07
HDS2-BW14	0.000144802	-0.000553087	3.05905E-07
HDS2-HDS5	0.000164304	-0.000533585	2.84713E-07
HDS5-HDS8	-0.000581553	-0.001279442	1.63697E-06
HDS8-BW11	-4.20818E-05	-0.000739971	5.47556E-07
BW11-BW14	0.000312196	-0.000385693	1.48759E-07
HDS3-HDS15	-0.001093564	-0.001791453	3.2093E-06
HDS3-HDS6	-0.001271904	-0.001969793	3.88008E-06
HDS6-HDS9	0.000143606	-0.000554283	3.07229E-07
HDS9-BW12			
BW12-BW15	1.25506E-05	-0.000685338	4.69688E-07
HDS16-BW23			
HDS16-BW19	0.004361396	0.003663507	1.34213E-05
BW19-BW23			
HDS17-BW22			
HDS17-BW20	-0.001327541	-0.002025429	4.10236E-06
BW20-BW22			
HDS18-BW24			
HDS18-BW21	-0.001466098	-0.002163987	4.68284E-06
BW21-BW24			
HDS25-HDS28	0.001228118	0.000530229	2.81143E-07
HDS26-HDS29	0.000268642	-0.000429246	1.84253E-07
HDS27-HDS30	0.013602363	0.012904474	0.000166525

SUM	0.013259885		0.000205253
V ERROR	0.000697889	Sample variance	1.14029E-05

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	4.70883E-05	2.11731E-05	0.000676716	0.000719062

STN3-STN4 Vertical correction after outliers were removed

target	residual	deviations	Squared deviations
HDS1-HDS2	0.005939868	0.005571394	3.10404E-05
HDS2-HDS3	-0.006543167	-0.006911641	4.77708E-05
HDS1-HDS3	-0.000344713	-0.000713187	5.08635E-07
HDS4-HDS5	-8.69531E-06	-0.000377169	1.42256E-07
HDS5-HDS6	0.000403565	3.5091E-05	1.23138E-09
HDS4-HDS6	0.000431435	6.29612E-05	3.96411E-09
HDS7-HDS8	-0.001294827	-0.001663301	2.76657E-06
HDS8-HDS9	-0.000586975	-0.000955449	9.12882E-07
HDS7-HDS9	-0.001936552	-0.002305026	5.31314E-06
BW10-BW11	0.000274008	-9.44653E-05	8.92369E-09
BW11-BW12	-3.95004E-05	-0.000407974	1.66443E-07
BW10-BW12	0.000226401	-0.000142073	2.01847E-08
BW13-BW14	0.000246209	-0.000122265	1.49487E-08
BW14-BW15	0.000198962	-0.000169512	2.87343E-08
BW13-BW15	0.000447224	7.875E-05	6.20157E-09
HDS16-HDS17	-0.000212613	-0.000581087	3.37662E-07
HDS17-HDS18	0.001810137	0.001441663	2.07839E-06
HDS16-HDS18	0.001570596	0.001202123	1.4451E-06
BW19-BW20	0.000727751	0.000359277	1.2908E-07
BW20-BW21	0.002129532	0.001761058	3.10133E-06
BW19-BW21	0.002782726	0.002414252	5.82861E-06
BW22-BW23	0.000990531	0.000622057	3.86955E-07
BW23-BW24	0.000778218	0.000409745	1.67891E-07
BW22-BW24	0.001747144	0.001378671	1.90073E-06
HDS25-HDS26	0.000464961	9.64873E-05	9.3098E-09
HDS26-HDS27	0.000174922	-0.000193552	3.74622E-08
HDS25-HDS27	0.000637598	0.000269125	7.2428E-08
HDS28-HDS29			
HDS29-HDS30	-0.000697483	-0.001065956	1.13626E-06

HDS28-HDS30			
SUM	0.010317259		0.000105337
Hz ERROR	0.000368474	Sample variance (s^2)	3.90135E-06

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	7.37286E-07	2.7309E-07	0.0003682	0.000368747

STN1-STN3 Horizontal correction after outliers were removed

target	residual	deviations	Squared deviations
HDS1-BW13	0.001051533	0.003421098	1.17039E-05
HDS1-HDS4	0.005939868	0.008309432	6.90467E-05
HDS4-HDS7	0.001188056	0.003557621	1.26567E-05
HDS7-BW10			
BW10-BW13	5.06211E-05	0.002420186	5.8573E-06
HDS2-BW14	0.029458083	0.031827648	0.001012999
HDS2-HDS5	0.02835817	0.030727734	0.000944194
HDS5-HDS8	0.00103847	0.003408035	1.16147E-05
HDS8-BW11	0.000279076	0.00264864	7.0153E-06
BW11-BW14	6.03525E-06	0.0023756	5.64348E-06
HDS3-HDS15	0.001001789	0.003371354	1.1366E-05
HDS3-HDS6	0.000629878	0.002999442	8.99665E-06
HDS6-HDS9	0.000362232	0.002731797	7.46271E-06
HDS9-BW12			
BW12-BW15	0.00010144	0.002471005	6.10586E-06
HDS16-BW23	0.000288732	0.002658297	7.06654E-06
HDS16-BW19	-0.000311905	0.00205766	4.23396E-06
BW19-BW23	0.001766208	0.004135772	1.71046E-05
HDS17-BW22	0.001046763	0.003416328	1.16713E-05
HDS17-BW20	0.000908275	0.003277839	1.07442E-05
BW20-BW22	-0.13197571	-0.129606145	0.016797753
HDS18-BW24	0.001080173	0.003449738	1.19007E-05
HDS18-BW21	0.00067188	0.003041445	9.25039E-06
BW21-BW24	-3.73658E-05	0.002332199	5.43915E-06
HDS25-HDS28			
HDS26-HDS29	0.000158498	0.002528063	6.3911E-06
HDS27-HDS30	6.96454E-05	0.00243921	5.94975E-06

SUM	-0.056869556		0.019002167
V ERROR	-0.002369565	Sample variance	0.000826181

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	0.003878801	0.001551815	-0.00392138	-0.00081775

STN1-STN3 Vertical correction after outliers were removed

target	residual	deviations	Squared deviations
HDS1-HDS2	0.006303243	0.009433084	8.89831E-05
HDS2-HDS3	-0.006700019	-0.003570179	1.27462E-05
HDS1-HDS3	-0.000103896	0.003025944	9.15634E-06
HDS4-HDS5	-0.000214628	0.002915212	8.49846E-06
HDS5-HDS6	0.001299641	0.004429482	1.96203E-05
HDS4-HDS6	0.001085295	0.004215136	1.77674E-05
HDS7-HDS8	-0.000731088	0.002398753	5.75402E-06
HDS8-HDS9	-8.65355E-06	0.003121187	9.74181E-06
HDS7-HDS9	-0.000741708	0.002388132	5.70318E-06
BW10-BW11	0.000731409	0.00386125	1.49092E-05
BW11-BW12	0.000208975	0.003338815	1.11477E-05
BW10-BW12	0.000941592	0.004071432	1.65766E-05
BW13-BW14	0.000478895	0.003608736	1.3023E-05
BW14-BW15	8.94679E-05	0.003219309	1.03639E-05
BW13-BW15	0.000567709	0.00369755	1.36719E-05
HDS16-HDS17	-0.060892805	-0.057762965	0.00333656
HDS17-HDS18	0.00077828	0.00390812	1.52734E-05
HDS16-HDS18	-0.060156053	-0.057026212	0.003251989
BW19-BW20	0.006754728	0.009884568	9.77047E-05
BW20-BW21	-0.000704195	0.002425646	5.88376E-06
BW19-BW21	0.006118541	0.009248381	8.55326E-05
BW22-BW23			
BW23-BW24			
BW22-BW24			
HDS25-HDS26	6.99309E-05	0.003199772	1.02385E-05
HDS26-HDS27	0.013169476	0.016299317	0.000265668
HDS25-HDS27	0.013240976	0.016370816	0.000268004

HDS28-HDS29			
HDS29-HDS30	0.000168873	0.003298714	1.08815E-05
HDS28-HDS30			
SUM	-0.078246016		0.007605398
Hz ERROR	-0.003129841	Sample variance (s^2)	0.000316892

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	6.33783E-05	2.48438E-05	-0.003154684	-0.003104997

STN1-STN4 Horizontal correction after outliers were removed

target	residual	deviations	Squared deviations
HDS1-BW13	0.000899564	-0.003730698	1.39181E-05
HDS1-HDS4	0.006303243	0.001672982	2.79887E-06
HDS4-HDS7	-0.000165162	-0.004795424	2.29961E-05
HDS7-BW10			
BW10-BW13	8.46884E-05	-0.004545573	2.06622E-05
HDS2-BW14	0.029508302	0.02487804	0.000618917
HDS2-HDS5	0.028429792	0.023799531	0.000566418
HDS5-HDS8	0.000501152	-0.004129109	1.70495E-05
HDS8-BW11	0.00020254	-0.004427721	1.96047E-05
BW11-BW14	0.000298271	-0.004331991	1.87661E-05
HDS3-HDS15	-0.000183283	-0.004813544	2.31702E-05
HDS3-HDS6	-0.000732201	-0.005362462	2.8756E-05
HDS6-HDS9	0.000554121	-0.004076141	1.66149E-05
HDS9-BW12			
BW12-BW15	9.87602E-05	-0.004531502	2.05345E-05
HDS16-BW23			
HDS16-BW19	0.004378802	-0.00025146	6.32322E-08
BW19-BW23			
HDS17-BW22			
HDS17-BW20	-9.39689E-05	-0.004724231	2.23184E-05
BW20-BW22			
HDS18-BW24			
HDS18-BW21	-0.000952696	-0.005582957	3.11694E-05
BW21-BW24			
HDS25-HDS28			
HDS26-HDS29	0.000359757	-0.004270505	1.82372E-05

HDS27-HDS30	0.013853028	0.009222766	8.50594E-05
SUM	0.083344711		0.001547054
V ERROR	0.004630262	Sample variance	9.10031E-05

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	0.000364644	0.000168454	0.004461808	0.004798716

STN1-STN4 Vertical correction after outliers were removed

target	residual	deviations	Squared deviations
HDS1-HDS2	8.91717E-05	0.002661823	7.0853E-06
HDS2-HDS3	7.45325E-05	0.002647184	7.00758E-06
HDS1-HDS3	0.000151766	0.002724417	7.42245E-06
HDS4-HDS5	0.000935555	0.003508207	1.23075E-05
HDS5-HDS6	0.000433376	0.003006028	9.0362E-06
HDS4-HDS6	0.00136708	0.003939731	1.55215E-05
HDS7-HDS8	0.000832727	0.003405378	1.15966E-05
HDS8-HDS9	0.000233835	0.002806486	7.87636E-06
HDS7-HDS9	0.001067996	0.003640648	1.32543E-05
BW10-BW11	0.00019251	0.002765161	7.64612E-06
BW11-BW12	0.000744228	0.003316879	1.10017E-05
BW10-BW12	0.000932931	0.003505582	1.22891E-05
BW13-BW14	-0.000104783	0.002467868	6.09037E-06
BW14-BW15	6.34322E-05	0.002636083	6.94894E-06
BW13-BW15	-4.90826E-05	0.002523568	6.3684E-06
HDS16-HDS17	0.000934164	0.003506815	1.22977E-05
HDS17-HDS18	-0.001721447	0.000851204	7.24548E-07
HDS16-HDS18	-0.000787697	0.001784954	3.18606E-06
BW19-BW20	0.001471978	0.004044629	1.6359E-05
BW20-BW21	-0.003053821	-0.00048117	2.31524E-07
BW19-BW21	-0.001579485	0.000993166	9.8638E-07
BW22-BW23	-0.000512888	0.002059763	4.24262E-06
BW23-BW24	-0.001485187	0.001087465	1.18258E-06
BW22-BW24	-0.002001443	0.000571208	3.26278E-07
HDS25-HDS26	-0.001022984	0.001549667	2.40147E-06

HDS26-HDS27	0.012016167	0.014588818		0.000212834	
HDS25-HDS27	0.010987886	0.013560537		0.000183888	
HDS28-HDS29	-0.001139275	0.001433376		2.05457E-06	
HDS29-HDS30	-0.047549778	-0.044977127		0.002022942	
HDS28-HDS30	-0.048700997	-0.046128346		0.002127824	
SUM	-0.077179534			0.004732933	
Hz ERROR	-0.002572651	Sample variance (s^2)		0.000163205	
		95% CI (average ± Confidence Interval)			
		Confidence Interval	Confidence Interval Limits		
Standard deviation of the mean	2.97969E-05	1.06625E-05	-0.002583314	-0.002561989	

STN3-STN2 Horizontal correction after outliers were removed

target	residual	deviations	Squared deviations
HDS1-BW13	-0.000315355	-0.00086579	7.49593E-07
HDS1-HDS4	8.91717E-05	-0.000461264	2.12764E-07
HDS4-HDS7	-0.000611964	-0.0011624	1.35117E-06
HDS7-BW10			
BW10-BW13	-0.000200289	-0.000750724	5.63587E-07
HDS2-BW14	0.000177952	-0.000372484	1.38744E-07
HDS2-HDS5	0.000348222	-0.000202213	4.08901E-08
HDS5-HDS8	-0.000581804	-0.00113224	1.28197E-06
HDS8-BW11	-0.000308052	-0.000858488	7.37001E-07
BW11-BW14	0.000103322	-0.000447113	1.9991E-07
HDS3-HDS15	-0.000984112	-0.001534547	2.35483E-06
HDS3-HDS6	-0.000746645	-0.00129708	1.68242E-06
HDS6-HDS9	4.86214E-05	-0.000501814	2.51817E-07
HDS9-BW12			
BW12-BW15	-0.000196955	-0.00074739	5.58592E-07
HDS16-BW23	0.000497774	-5.2661E-05	2.77318E-09
HDS16-BW19	0.000379572	-0.000170863	2.91943E-08
BW19-BW23	-0.00071074	-0.001261176	1.59056E-06
HDS17-BW22	-0.000300173	-0.000850608	7.23534E-07
HDS17-BW20	-0.001087223	-0.001637658	2.68192E-06
BW20-BW22	-0.007491547	-0.008041983	6.46735E-05
HDS18-BW24	-0.001318157	-0.001868593	3.49164E-06
HDS18-BW21	-0.000829801	-0.001380236	1.90505E-06
BW21-BW24	-0.000500176	-0.001050611	1.10378E-06

HDS25-HDS28	-1.48283E-05	-0.000565264	3.19523E-07
HDS26-HDS29	-0.000606307	-0.001156742	1.33805E-06
HDS27-HDS30	0.028920379	0.028369944	0.000804854
SUM	0.013760887		0.000892837
V ERROR	0.000550435	Sample variance	3.72015E-05

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	0.000178567	6.99971E-05	0.000480438	0.000620433

STN3-STN2 Vertical correction after outliers were removed

target	residual	deviations	Squared deviations
HDS1-HDS2	0.000149256	0.000449459	2.02013E-07
HDS2-HDS3	-0.000145212	0.000154991	2.40222E-08
HDS1-HDS3	-3.50221E-05	0.00026518	7.03207E-08
HDS4-HDS5	-0.001020541	-0.000720338	5.18887E-07
HDS5-HDS6	0.000429595	0.000729797	5.32604E-07
HDS4-HDS6	-0.000593079	-0.000292877	8.57767E-08
HDS7-HDS8	-0.000311966	-1.1764E-05	1.38391E-10
HDS8-HDS9	0.000383679	0.000683882	4.67694E-07
HDS7-HDS9	8.47212E-05	0.000384924	1.48166E-07
BW10-BW11	0.000245751	0.000545954	2.98065E-07
BW11-BW12	-0.000474453	-0.00017425	3.03632E-08
BW10-BW12	-0.000235892	6.43107E-05	4.13587E-09
BW13-BW14	0.000307079	0.000607282	3.68791E-07
BW14-BW15	-0.000156227	0.000143975	2.07289E-08
BW13-BW15	0.000140379	0.000440582	1.94112E-07
HDS16-HDS17	-0.06195317	-0.061652967	0.003801088
HDS17-HDS18	0.000291194	0.000591397	3.4975E-07
HDS16-HDS18	-0.061334622	-0.06103442	0.0037252
BW19-BW20	0.00492547	0.005225673	2.73077E-05
BW20-BW21	0.000992781	0.001292983	1.67181E-06
BW19-BW21	0.005455275	0.005755477	3.31255E-05
BW22-BW23			
BW23-BW24			

BW22-BW24			
HDS25-HDS26	0.000594542	0.000894744	8.00567E-07
HDS26-HDS27	0.001003219	0.001303422	1.69891E-06
HDS25-HDS27	0.001588721	0.001888924	3.56803E-06
HDS28-HDS29	0.002477696	0.002777899	7.71672E-06
HDS29-HDS30	0.048381289	0.048681492	0.002369888
HDS28-HDS30	0.050704067	0.05100427	0.002601436
SUM	-0.008105468		0.012576817
Hz ERROR	-0.000300203	Sample variance (s^2)	0.000483724

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	9.30927E-05	3.51141E-05	-0.000335317	-0.000265088

STN2-STN4 Horizontal correction after outliers were removed

target	residual	deviations	Squared deviations
HDS1-BW13	3.57813E-05	0.000580793	3.37321E-07
HDS1-HDS4	0.000149256	0.000694268	4.82008E-07
HDS4-HDS7	-0.000620048	-7.50362E-05	5.63043E-09
HDS7-BW10			
BW10-BW13	0.000223024	0.000768035	5.89878E-07
HDS2-BW14	-2.78959E-05	0.000517116	2.67409E-07
HDS2-HDS5	-0.00017842	0.000366592	1.3439E-07
HDS5-HDS8	9.95741E-07	0.000546008	2.98124E-07
HDS8-BW11	0.000266902	0.000811914	6.59205E-07
BW11-BW14	0.000210238	0.00075525	5.70403E-07
HDS3-HDS15	-0.000150307	0.000394705	1.55792E-07
HDS3-HDS6	-0.000567667	-2.26555E-05	5.13273E-10
HDS6-HDS9	9.72821E-05	0.000642294	4.12541E-07
HDS9-BW12			
BW12-BW15	0.000214041	0.000759053	5.76161E-07
HDS16-BW23			
HDS16-BW19	0.00401092	0.004555932	2.07565E-05
BW19-BW23			
HDS17-BW22			
HDS17-BW20	-0.000178898	0.000366114	1.34039E-07
BW20-BW22			
HDS18-BW24			

HDS18-BW21	-0.000700255	-0.000155243	2.41004E-08
BW21-BW24			
HDS25-HDS28	0.001290455	0.001835466	3.36894E-06
HDS26-HDS29	0.000865556	0.001410568	1.9897E-06
HDS27-HDS30	-0.015296186	-0.014751174	0.000217597
SUM	-0.010355224		0.00024836
V ERROR	-0.000545012	Sample variance	1.37978E-05

		95% CI (average ± Confidence Interval)		
		Confidence Interval	Confidence Interval Limits	
Standard deviation of the mean	5.69776E-05	2.56198E-05	-0.000570632	-0.000519392

STN2-STN4 Vertical correction after outliers were removed

The distance correction results after the outliers were removed have not been included in the appendix. This is because no outliers were removed from the distance correction and were exactly the as the results from the original.