University of Southern Queensland

Faculty of Health, Engineering and Sciences

A Comparison Analysis into Flange Survey Techniques

A dissertation submitted by

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Abstract

The surveying industry is a rising at a rapid rate through advancements in technology. Other specific industries such as industrial metrology which were once segregated from surveying are now closely aligned through the form of measurement. The oil and gas industry provides an avenue for both to co-exist given the specifications and tolerances required to undertake highly accurate surveys. Flange surveys require a specialised form of measurement given the intent of the survey is predominantly for design and reverse engineering applications. Current techniques are not familiar in the surveying industry nor the accuracies that can be achieved.

In this study, a Leica AT402 laser tracker is used as a baseline reading to survey two existing flanges and a spool fabrication joining them. Two conventional survey methods will then be surveyed with the results then analysed and compared. The two conventional survey methods will be based on a Leica TS15 total station and a Leica HDS7000 laser scanner. The results will be based on three main components for calculation – Flange centreline coordinates, plane inclination and bolt hole rotation.

The datasets found that the total station performed better than expected with accurate and consistent results compared to the laser scanner readings and ultimately the baseline readings of the laser tracker. The flange centreline coordinate errors for the total station were submillimetre reading 0.69mm and 0.75mm respectively. The plane inclination and bolt hole rotation results were also similar if not more accurate. The laser scanner results varied between 1mm and 3mm with inconsistent results achieved due to a couple of factors mainly contributed to the manipulation of the point cloud when cleaning and trimming. The laser scanner results provide room for further research to investigate more advanced techniques when working with point clouds.

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Limitations of Use

Certification

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

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

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Chapter 1 – Introduction

1.1 Introduction

The surveying industry is evolving at a rapid rate through the rise of technology. Many modern elements that were once thought to be inconceivable many years ago are now normal practices within the profession. These advancements in technology have created techniques and practices to become more efficient, accurate and safer and one such element in the surveying profession which has benefitted from the rise in technology is – Dimensional control flange surveys.

Dimensional control in its purest sense is recognised as highly accurate measuring. The main objective of dimensional control is to determine the precise location of objects in a three-dimensional spatial world which in turn is used to create mathematical models of these objects in a CAD package for design and engineering purposes.

The fundamental difference between dimensional control and other elements within the surveying profession such as engineering or construction surveying is the means in which data is collected in an accurate, quick and efficient manner through the use of specialised instrumentation and devices, and also customised software packages.

A specific facet that relies on dimensional control is that of flange surveys. In the Oil & Gas industry, dimensional control is an essential element that can provide high accuracy data in a format that can be visually created in a software package to suit any fabrication or piping component. Dimensional control surveys rely on data to be captured extremely accurately so that models can be created from this data in a consistent and reliable fashion for proposed design works. Flange surveys are no exception as they play an important role in how pipe work is fabricated together.

Current techniques for flange surveys vary from different company perspectives and also scopes required from respective clients. Because of the relatively new nature of dimensional control, current procedures that exist are not 'tried and tested' methods compared to other industry standards within the surveying profession that have been around for a significant portion of time. This provides a challenge to companies relatively new to dimensional control to start a division or business model based on something with very limited experience or exposure. Survey companies engaged to perform flange surveys may be inexperienced to the dimensional control industry and as such their first inclination may be to revert to traditional forms of surveying that they are accustomed to and most comfortable with, due to the resources and knowledge available to them.

Although elements of traditional surveying are combined into dimensional control flange surveys, the use of specialised equipment and devices combined with the existing techniques allow these surveys to become more accurate and efficient than their counterparts.

Equipment such as laser trackers are not commonly found within the surveying industry because of their specialised use in metrology and manufacturing inspection analysis; however, with their precise measuring ability laser trackers are becoming more common within the dimensional control industry with the combination of existing surveying equipment such as total stations and laser scanners. Understanding the advantages and limitations of how different forms of surveying equipment such as laser trackers, total stations and laser scanners can work, flange surveys can be improved dramatically through the power of this knowledge. By comparing results of typical flange survey elements and understanding the various applications such equipment provides within the surveying industry, current techniques can become more recognised with standardised procedures outlining how flange surveys can be performed in a more accurate and efficient manner.

1.2 Research Aim

The aim of this research study is to compare and analyse different flange survey methods to assess the suitability of each one and to determine which method is the most effective based on the results they achieve, and their versatility in the surveying industry. This will be achieved by executing the following objectives in the study:

a) Identify current survey methods used for performing flange surveys and dimensional control and provide background information on their current use in the surveying profession.

b) Conduct field research of these survey methods to acquire the necessary data to 3D model the flanges for comparison. The survey methods and scope to be undertaken in this research include –

   1. Utilising a laser tracker to obtain baseline results to reverse engineer a flange for model calculations.
   2. Undertake the same survey utilising a conventional total station and laser scanner.

c) Compare and analyse the acquired data in CAD to assess the accuracy and effectiveness of each method compared to the laser tracker. The key elements that need to be achieved from this component include the following three data deliverables crucial to flange surveys –

1) <u>Flange centreline coordinates (3D)</u>
2) <u>Inclination planes across the flange faces</u>
3) <u>The bolt rotation</u>

d) Discussion about the results to ultimately determine the preferred method for conducting flange surveys.

1.3 Justification

In the pipeline industry, the need for high accuracy survey data is essential. Many large pipeline companies these days are leaning towards 3D dimensional control surveying to give them the high accurate results and reliability needed for a variety of reasons. This could be for designing new structures to tie into existing ones, replacing existing structures due to age or maintenance, collecting As-Constructed data of their assets so that in the future the data is ready and available to use for design; or even reverse engineering objects for re-works and design purposes.

There are several survey methods currently used today to locate and capture flanges for design purposes. Because there are no specified methods for completing flange surveys, companies engaged to complete flange surveys are going to perform them based on the following:

- Survey's that may be similar to previously completed projects.
- The available equipment and software already at their disposal.
- Preconceived ideas on how they believe the job can be completed within the required scope.

This may contribute to inferior methods being adopted to complete flange survey's which can lead to poor results and inefficient field and office practices.

As the process for flange surveys becomes more common and recognised, the techniques and procedures of the chosen methods will improve. This research will not only provide evidence as to the most comprehensive survey method for completing flange surveys, it will help identify procedures to undertake in the field and office to enable the chosen method to become consistent within the survey industry.

1.4 Dissertation Overview

This research dissertation is explored over seven main chapters. An explanation of these chapters is outlined below.

Chapter 1 – Introduction

This provides an introduction to the specified research area of choice. The aims of the research are outlined and the justification for choosing the topic is also explained.

Chapter 2 – Literature Review

Discusses the key elements of the research and identifies the thorough literature review exercised for this research paper. The literature review examines the following areas of interest – Dimensional control, measurement uncertainty and errors, flange & spools in Oil & Gas, new and existing flange survey techniques and the various applications these techniques can provide to other sections of the surveying industry along with how product and business development is necessary for a company.

Chapter 3 – Methodology

The method and processes used to achieve the aims of this research. The study area will be identified as well as the field techniques used for the data analysis. All CAD modelling and calculations will be explained in this chapter to identify how the data was compared.

Chapter 4 – Results

Identifies the data obtained from the methodology stage. Explanation of end results will be compared and evaluated to judge the validation of each method.

Chapter 6 – Discussion

The data obtained from the results and the analysis from the cost benefit study is combined to enable a desired outcome from the research. The suitability of each method will be explained to provide why the appropriate method was chosen.

Chapter 7 – Conclusion

This provides a conclusion to the research and any recommendations or suggestions for future research.

Chapter 2 – Literature Review

2.1 Introduction

A literature review was performed to highlight some specific areas key to the research that will help reinforce the topics covered in this dissertation. The aim of this review is to identify previous studies that have been conducted around this relevant topic to enable a broader view of the chosen professional field. This will be achieved by analysing and studying previous findings and discussing any relevant information that applies to this research aim.

The main objectives of this review will be to identify the key elements that need to be discussed further to enable a better understanding of the broader subject. These key elements include:

- *Definition of Dimensional Control*
- *Measurement Uncertainties, Redundancies & Traceability*
- *Accuracy, Precision & Error Analysis of Laser Trackers*
- *Flange Explanation & its Applications in the Oil & Gas Industry*
- *Current Applications Within the Surveying Profession of Laser Trackers, Laser Scanners and Total Stations*

2.2 What is Dimensional Control?

Dimensional Control (D.C) is a form of high accurate surveying that utilises specialised instrumentation and software to determine three dimensional coordinates of objects. Fugro (2019) explains that dimensional control is a combination of mathematical modelling with surveyed measurements which provides the ability to analyse or compare objects. D.C surveying is relatively new to the industry because of its reliance on new technology. The need for high accurate measuring devices has pushed the surveying industry to create new technologies that can provide sub millimetre or even micron type accuracy. Although electronic distance measurement techniques have been introduced and commercialised since the early 1960's (Rueger 1988), it has only been recently that Dimensional Control has taken off through the rise of technology and its close relation to the metrology profession.

Metrology can be defined as the science of measurement (NSAI 2019). Its purpose in surveying has been relatively sparse due to its specialised function within the industrial profession. Lester Franks (2019) describes some common practices of metrology that exists within the industrial metrology section, and these include but are not limited to:

- Geometric verification of components with direct CAD to part and model based inspection techniques.
- Functional geometric dimensional & tolerancing (GD&T) analysis
- Deformation analysis that identifies warping, shrinking and other manufacturing defects

The main function of industrial metrology caters for industrial type measurement. This includes services to the auto and aero industries and the machinery and boat manufacturing just to name a few. Because the measurement precision is a crucial aspect of industrial metrology, traceability is a key element. A traceability chain is an unbroken chain of comparisons which make certain that a measurement result, or value, is related to references at a higher level, ending at the final level with a primary standard (NSAI 2019). Understanding the measurement uncertainty of equipment is crucial to providing accurate and reliable results. Without the need for traceability, verification of data is compromised and cannot be determined consistent. This is where the calibration of equipment plays a role. The traceability of measurements can be determined through the design of instrument calibration and standards. Dimensional Control and metrology surveying although highly accurate and precise, still has measurement uncertainties that are required for the calculation of tolerances and error uncertainties. Through the proper calibration of equipment, the uncertainties can be achieved by a direct comparison against standards. NSAI (2019) describes the main reasons for ensuring instruments are properly calibrated:

- This ensures readings from an instrument are consistent with other measurements
- It is able to determine the accuracy of the instrument readings
- To establish the reliability of the instrument

As D.C surveying has evolved, its close relation to industrial metrology has relied upon the necessity to understand the traceability and reliability of instruments and respective datasets to achieve the highly accurate measuring results required.

2.2.1 Accuracy of Dimensional Control

There is no stated accuracy requirement that exists within D.C surveying nor are there current standards to abide by. Due to the vast amount of equipment and applications that can be used within D.C surveying, the procedure for completing a D.C survey is governed by the nature of the project or task which widely varies in opinion on how to undertake and complete said project or task. Many companies provide specified accuracies that can be attained through performing dimensional control surveying. Intertek (2019) supplies dimensional control services capable of providing distances measured to +/- 1mm accuracy. However, that specified distance may also be a reference to the generic measurement standards supplied from the manufacturer for the respective equipment. A Leica TDRA6000 is one of the most accurate total stations designed for industrial analysis use and its distance accuracy is 0.6mm + 1ppm (Leica Geosystems, 2019). A more precise measuring tool such as a Leica AT402 Laser Tracker can measure distances up to +/-10 microns (Leica Geosystems, 2019). It is important to remember that although a piece of equipment has the capability of measuring distances to a specified distance, there are many more factors that need to be considered within dimensional control to form an accuracy that is reliable and consistent. Measurement uncertainty for a piece of equipment is key to understanding what tolerances can be achieved. Maropoulos et al (2009) determine that the level of uncertainty will determine whether it can be proven that a part conforms to specifications. They further discuss that measurement frequencies published by manufacturers are often misleading since many instruments are capable of high frequencies, but a single measurement has a low accuracy due to environmental disturbances.

This brings into consideration redundant measurements within D.C surveying. If "pieces of information are exceeding what is necessary or normal, these pieces are called redundant" (FIG, 2008). It is a general practice within surveying to always have redundant observations, as they help in detection of mistakes or blunders (Chandra, 2005). By utilising redundant information, results can be verified and checked against tolerances with confidence levels. By utilising necessary calculation adjustments such as Least Squares, obtaining standard deviations and root mean square errors, measurement uncertainties can be obtained and then checked against available standards and calibration certificates.

When completing a D.C survey, it is important to comprehend the overall spectre of tolerance for a job. Understanding whether the equipment and applications for a start are within the required tolerance for a job, how data should be measured so that redundant shots can be calculated, and also how to best utilise the data in a software package. By identifying and recognising the uncertainty of the measurement calculations and equipment, the accuracy can then be confidently compared against specified tolerances and standards to determine the uncertainty.

2.3 Measurement Uncertainties, Redundancies & Traceability

Measurement uncertainty is an important aspect for data analysis as it provides tangible information on the accuracy and errors that have been encountered. Interpreting the data is a necessity to understand the quality of the data, the positional repeatability of the data and the traceability of the data. “In terms of metrology, the measurement results must be provided with a quantitative evaluation of their quality, which is called the uncertainty of measurement” (Cronin, 1999; Santolaria & Gines, 2013). Hack & Caten (2012) also express that the measurement uncertainty is as important as the measured value itself.

2.3.1 Measurement Uncertainty Methods

Measurement uncertainty is a globally accepted way to understand the reliability and traceability of measurement results and is a fundamental tool adopted by international quality standards. “It consists of a parameter associated with the outcome of a measurement, which determines the dispersion of possible values relative to that measurement” (Hack and Caten, 2012). The international Organisation for Standardisation (ISO) published in 1993 the Guide to Expression of Uncertainty in Measurement (GUM) which is a globally accepted method for the estimation of measurement uncertainty. Since this first published guide there have been circumstances surrounding some of the complex calculations that can be involved and the required pre-requisites which degrade the viability and suitability of the GUM method. Given the shortfall, ISO published a supplement guide to measurement uncertainty for the propagation of distribution utilising the Monte Carlo method. The Monte Carlo method maximises on the shortfall of the GUM method where pre-requisites are not necessary and utilises the use of experimental simulations, instead of the reliance on mathematical models.

As described in the Evaluation of Measurement Data guide, the GUM uncertainty framework consists of the following:

a) The best estimates of the input quantities
b) The standard uncertainties associated with the best estimates, and
c) The sensitivity coefficients

to form an estimate of the output quantity and the associated standard uncertainty.

The GUM uncertainty framework can be applied to many circumstances to lead to valid and successful outcomes of uncertainty. Usually the measured outcome is not obtained directly; it is contained from other measured variables that can then be referenced to one another through a function where the approach often works sufficiently well enough for practical purposes. The guide also explains that there will be some situations where the GUM uncertainty framework might not be satisfactory, which includes where:

a) The measurement function is non-linear

b) The probability distributions for the input quantities are asymmetric
c) The uncertainty contributions are not of approximately the same magnitude, and
d) The probability distribution for the output quantity is either asymmetric, or not Gaussian or a t-distribution

Monte Carlo Method

The ISO supplement 1 guide published in 2008 is a recommendation for the use of the Monte Carlo simulation or method (MCM) as an alternative to the evaluation of measurement uncertainty. MCM contains fewer conditions associated with its use than the GUM framework and is a method that is probabilistic which combines probability distributions by numerical simulation. The surveying and metrology industries face numerous factors that can impact measurement results, such as the instruments and equipment themselves, the existing environmental conditions, measuring and processing methods and the overall skills and abilities of the user. Given it is almost impossible to establish a global measurement model and process based on the factors listed previously, the Monte Carlo method is a much more effective tool for the evaluation of task specific uncertainty measurements. The measurement uncertainty is defined according to the coverage interval which is typically 95% after numerous repetitions.

In other words, the MCM is a more practical tool for applying the principle of propagation of distributions and is not reliant on a measurement model that is bound by the assumptions and limitations by the law of propagation. Bao-Zhong et-al (2014) discuss and compare the two methods of GUM and MCM to evaluate task-specific uncertainty in laser tracker measurements and provide a case study involving the uncertainty estimation of a cylindricity measurement process. The uncertainty results at 95% interval confirm that the information demonstrates that the two methods differ in their characteristics in task-specific uncertainty evaluations for the laser tracker measurements and that the Monte Carlo method is the more practical tool for the application of propagation of distributions and reduces the risk of unreliable measurement uncertainty estimation. One of the main situations encountered that applies directly to this dissertation is the evaluation method of the measurement data. Defining the impact of each measurement strategy and evaluation method can be analysed and the error factors that exist are comprehensively studied and processed without the dependence on the measurement model.

Least-Squares Method

The Least Square method originated from 1787 where French mathematician and physicist Laplace adopted the method to estimate eight unknown orbital parameters from 75 discrepant observations of the position of Jupiter and Saturn (Nielsen, 2001). Since then though least squares methods have been widely used and adopted within the surveying and metrology industries as a technique for data analysis. Least squares permits estimation of the parameters of a model function that show the best fit with a set of observations. Working with spatial cartesian coordinates requires the measured data to be known to a certain degree of accuracy, multiple measurements to known points are required to be processed and corrected to other known points to form data sets. It's impossible to re-produce the same measurement results to known points and this is a frequent problem faced in the surveying profession. Performing control survey's for surveying tasks requires measurements to already established known points that form the control datum. Re-producing and establishing the control can sometimes be problematic when certain accuracies and tolerances are required to be met. Understanding how the control points fit within each other comes down to variables that can sometimes be overlooked but are required to be known when calculating and propagating errors. As Nielsen (2001) describes, in order to evaluate the result of a general measurement, in which some redundant information has been obtained, one therefore has to apply the method of Least Squares in its general form.

Ghilani (2018) states that errors exist in all observations. This is attributed to random and systematic errors that are introduced when observing measurements. Least squares adjustments require redundant observations to determine the unknowns for a more precise final value. A simple explanation of what a redundant observation consists of can be the measurement of a line AB. If one is setup at point A and measures the distance to point B the measurement between AB is known. If this same procedure is again used but starting from point B and then a measurement is taken to point A then this measurement can be called redundant. The distance between AB was already measured but a redundant measurement was observed that can help identify any presence of errors in the actual measurement for the line AB. This is the benefit of the least squares method where redundant observations are a pre-requisite to understand and determine the precision of the final values computed. There are numerous adjustment methods available within the surveying and metrology industries; however, the least squares method is the preferred adjustment method of choice for surveyors. The advantages of the least squares method over its counterparts is due to two main components:

1. In terms of the adjustment, it is the most rigorous and enables great post-adjustment analysis.
2. The application can be applied with great ease.

The least squares method is based on mathematical probability where unknown and known values are analysed and adjusted based on redundant measurements to these values based on error distribution. Once an adjustment is finished and the results are determined, statistical data and information can be obtained of the adjustments to analyse the final outcome. The user can understand the size of the errors that were encountered, how the errors were distributed, run various tests against the data to check the quality of the dataset and see if the survey meets relevant tolerances.

Another benefit of the least squares method is the distribution of the weighting of measurements. As Ghilani (2018) in 'Adjustment Computations' explains, the weight of an observation is a measure of an observation's relative worth compared to other observations. Where an observation or measurement is known to be more precise, the weighting of that observation in the adjustment should be taken into account. Conversely, where a measurement with a lower precision is observed, the measurement should receive a larger percentage of the applied correction in the adjustment. The weighting system within least squares methods controls the corrections to the observations and the relevant sizes they should be distributed.

2.3.2 The Need for Redundancy and Traceability in Surveying

In order to understand measurement uncertainties, measurement observation parameters are critical in achieving reliable accurate datasets. Redundant observations play a key role in measurement uncertainties and the process in which data is adjusted using methods discussed previously such as Least Squares.

One of the most influential and overarching frameworks in Australia that relates to survey control is the 'Guideline for the Adjustment and Evaluation of Survey Control Special Publication 1' (SP1) by the Intergovernmental Committee on Surveying and Mapping (ICSM) 2014. When discussing geodetic survey control, SP1 (2014) describes redundancy as when repeated measurements are taken to estimate an unknown parameter, the additional measurements are said to be redundant. It offers that least squares adjustments are said to contain redundancy if the total number of measurements exceeds the minimum number required to compute the unknown parameters. For adjustments to achieve the desired accuracies in regards to the required measurement uncertainties, redundant observations provide the dataset a means in which the estimation of a value can be obtained usually tested at the 95% confidence level. When trying to test survey control for its errors, sufficient redundant measurements are required to ultimately identify and adjust/propagate out.

Clemen and Grundig (2008) elaborate the need for redundancy in photogrammetry and geodesy as redundant observations increase precision and reliability. Ghilani (2018) also corroborates this theory where after adjustments are made to obtain a final value for the unknown, then the final adjusted value will be more precise statistically than either of the individual observations.

Another form of redundancy in the surveying and metrology industries is that of instrument calibration. It has long been realised in the surveying profession that instrument calibration is a normalised procedure to develop traceability in terms of the quality of the instruments measurements against specified standards and regulations. The legally traceable measurement required in Australia is length. The electronic distance measurements (EDM) of an instrument can be tested and recognised for traceability to national standards through the used of baseline calibration ranges. Surveyors have a legal obligation to ensure that their surveying instrument is calibrated and standardised as per the Surveying and Mapping Infrastructure Regulation 2014 and the National Measurement Act 1960.

The Surveyor-General's Direction No.5 – 'Calibration of Electronic Distance Measuring (EDM) Equipment' outlines the necessity for why instruments are required to be calibrated and describes the procedures on how to calibrate instruments. The Direction also goes on to state that *..'surveyors are required by the Surveying and Spatial Information Regulation 2017, Clause 14, to verify their measuring equipment in relation to an Australian or State Primary Standard of measurement of length, and thereby achieve legal traceability of length.'*

The Surveying and Spatial Information Regulation 2017 requires that the length stated by surveyors should not differ from the true value by more than +/- (10mm + 50ppm) and that the required accuracy or uncertainty is to include the uncertainty of the length measurement arising from all possible sources.

Given calibration ranges are registered under the National Measurement Act 1960, surveyors are able to use the ranges to test that their equipment is calibrated within required tolerances whilst also maintaining a legal traceability of their survey equipment. By providing a traceability chain in regards to survey instruments and measurements, quality control can be attained. The International Organisation of Standards (ISO) defines traceability as:

"The property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

Given the metrology industry differs to that of surveying, calibration and testing is more specialised to metrology equipment. The National Measurement Institute (NMI) provides services to laboratories, universities, government and the industry as a whole and calibrates instruments to referenced standards and accreditations. Traceability is still an important aspect of measuring in metrology and providing a compliant quality system is crucial to instruments such as laser trackers. The NMI calibrates 3D coordinate metrology and EDM's for laser trackers which are traceable to Australia's primary standards as well as being recognised internationally through the Comite International des Poids et Mesures (CIPM).

2.4 Accuracy, Precision & Error Analysis of Laser Trackers

Laser trackers are supremely accurate measuring machines that can offer sub-micron results consistently and repeatably. Given the accuracy involved with laser trackers it is important to understand the geometric errors and limitations that are involved with the machines to fully comprehend the accuracy analysis. Most errors are commonly split into two different components, geometric and kinematic errors (Aguilar et al, 2013).

The most common form of understanding a laser trackers positional and geometric error is through the calibration and error compensation which are usually performed to improve the positional accuracy of machines. Liao et al (2016) propose and discuss an error compensation method with error similarity analysis to improve the absolute positional accuracy of industrial robots. Given their research, they also summarise that the repeatability of a machine is usually much better than the positional accuracy, however, the positional accuracy is more important than repeatability and state the necessity to calibrate machines so that the positional accuracy can meet the tolerance requirements of the products. The kinematic calibration of machines is typically adopted to improve the machines positional accuracy and understanding a model-based calibration method to focus on the position and posture relation between joints.

A kinematic model that has been widely used in mechanism modelling is the Denavit-Hartenberg model. The kinematic model establishes mathematical relations and obtains non-linear equations that relate the joint variables with the position and orientation of the end-effector (Aguado et al (2015). In order to estimate the positional errors of target points or measurements, the error identification and compensation with error similarity is implemented. As Liao et al (2016) describes, the error compensation for the target's positional errors is performed by modifying the position coordinates in the controlling commands. The estimation of the error can then be transformed to an optimizing problem which can be turned into solving a linear equation where the target's positional error can be estimated. As part of their research, Liao et al (2016) showed that the absolute positional error dramatically reduced after error compensation which proved the importance of fully calibrated machines to understand their positional and compensation error.

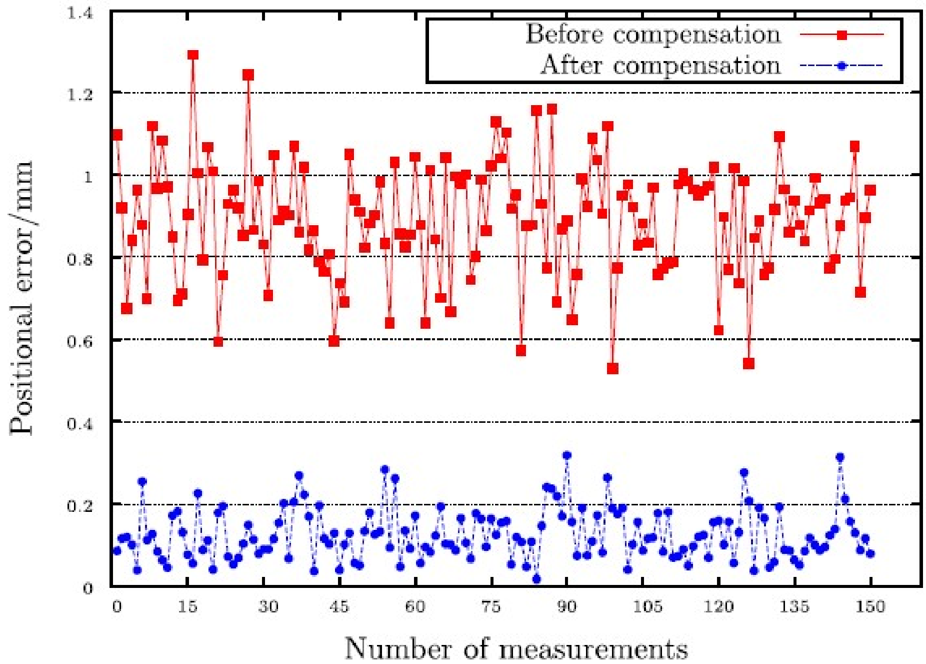


Figure 2.1 – Absolute Positional Error from Calibration

Aguilar et al (2013) discuss the errors described with laser trackers especially for laser trackers such as the Leica models and describe their attributed errors to:

- Transit Axis Offset which is the displacement of the tilting axis with respect to the azimuth
- Mirror Offset mirror plane displacement with respect to it nominal rotation centre
- Beam Offset
- Offset Plate Cover
- Mirror Tilt about the tilt axis
- Transit Axis Tilt
- Beam Axis Tilt
- Horizontal Encoder Eccentricity
- Vertical Encoder Eccentricity
- Vertical Offset Index: error angular position

The correction parameters of laser trackers will always be attributed to distances, angles and proportionalities. The most common form of kinematic modelling of laser trackers follows the method by Denavit-Hartenberg (1955) which was then modified by Hayatti-Mirmirani (1985) which introduces a number of error matrices correcting nominal models based on error parameters.

Another such thing that influences measurement uncertainty errors for laser trackers are the reflectors. An experiment by Aguilar et al (2013) determined the influence of the angle of incident of laser trackers on reflectors. The experiment studied the angle of the reflector in a range of +/-30 degrees in both the horizontally and vertically axis to determine the errors associated with the reflector. The results are shown below:

		θ (°)								
		-30	**-22,5**	**-15**	**-7,5**	**0**	**7,5**	**15**	**22,5**	**30**
φ(°)	**-30**	13,4	13	12,4	11,5	10	8,3	6,5	4,3	2,6
	-22,5	8,1	7,9	7,6	6,9	6,2	4,3	3,2	1,6	0
	-15	5	4,8	4,5	3,8	3	2,1	0,8	-0,5	-1,6
	-7,5	2,4	2,2	2	1,5	0,9	-0,2	-1,1	-1,8	-2,8
	0	1,2	1	0,8	0,4	0	-0,7	-1,5	-2,4	-3,4
	7,5	0	-0,2	-0,4	-0,8	-1,3	-2	-2,6	-3,3	-4,1
	15	0,8	0,6	0,4	0	-0,5	-1,1	-1,8	-2,6	-3,2
	22,5			-0,5	-0,8	-1,3	-2	-2,7		
	30			-1,2	-1	-1,6	-2,4	-3,1		

Figure 2.2 – Angle of Incidence

2.4.1 Angular Accuracy

Another form of error that's commonly associated with the laser tracker is the angular error. Although laser trackers these days are mobile and flexible, the three-dimensional accuracy of measuring the position of the sample point is typically limited by the angular errors (Cao et al, 2018). There have been many researchers that have proposed various ways to reduce the impact of angular errors within measurements with the main form being minimising the actual angle from the machine to the intended target. This is deterred by the fact that the laser tracker would need to be setup further away from the target to decrease the angle of incidence therefore increasing the measurement distance. Other methods include using at least four laser trackers to calculate coordinates based on the multilateration principle, however, this is very costly and inefficient. Cao et al (2018) propose using two laser trackers for measuring the flatness of an object where one is setup on a normal tripod height where the other is fixed onto the actual surface to measure the same points. Adopting the projective lengths from the surface laser tracker means that the laser tracker setup on the tripod can be accounted for and a highly accurate result can be measured. The research has provided that this method provides a much more consistent and reliable measurement when a large angle of incidence is surveyed.

2.4.2 Testing of a Laser Tracker

One of the most accurate and portable machines available today are the Leica AT401 and 402 laser trackers. These machines are used in a similar manner to that of a total station where the operator simply points and shoots to measure. These instruments have a working angular accuracy of +/- 15 microns + 6 microns/m and an absolute distance accuracy of 10 microns (Leica Geosystems 2019) which puts them into the industrial metrology sector of measurement accuracy. Dvoracek (2016) conducts laboratory testing on the Leica AT401 laser tracker to test the instrument's firmware errors, the warm-up effect of the instrument with respect to angle and distance measurement, the absolute distance meter, the additive constant and the stability of the distance measurement.

The first outcome described the shortcoming of software solutions available given the instrument does not measure and record on board or via a controller. On top of that, sometimes the basic operations preferred by surveyors by displaying and saving angles and distances and also performing instrument operations such as repeated measurement and two-face measurements are not available or very limited in function.

One main outcome that Dvoracek (2016) found was with the testing of the ATC400 meteostation which is capable of measuring air temperature, atmospheric pressure and humidity and applying real time corrections to measurements. In addition to the meteostation, an external temperature sensor can be connected for measuring the air temperature and/or the objects temperature for high accurate work. In the study, it was found that by using just the meteostation and the internal temperature sensor that measurements were erroneous by up to 4-5ppm. The source of the error was attributed to the sensor being covered (for moisture and dust resistance IP54 certification) so the electronics inside the ATC400 actually heats the sensor and provides incorrect temperature readings.

In all, Dvoracek (2016) found that the Leica AT401 fulfils the specifications set out by the manufacturer. There are some limitations to the instrument in regards to the software and firmware and also stressed the need to allow the inclination sensor to be properly warmed up by allowing the re-initialisation function to occur. Lastly for longer measurements in 'field conditions' the AT401 is very capable and usable, however, measurements should be made under favourable weather conditions i.e. stable, cloudy.

2.4.3 Flange Calculations

There are numerous facets that make up how a flange is calculated and designed after being surveyed. Understanding the necessary calculations applicable provide a means in which the flange can be reverse engineered for design purposes.

The calculation of the flange is relatively unknown and not previously reported on due to the limited market size and the specialised industry within the surveying sector. Therefore, it is important to understand what the key components are for the makeup of a flange when completing a flange survey. To determine the flange calculations, the following three components are a minimum:

1. Flange centreline coordinates

This involves the outside face of the flange to be measured as the exact coordinates of the flange centre are not measured. Instead the outside points of the flange are created into circles or cylinders to find the centre point. Similar to Makarov (2013), the origin is located in the centre and all the points are measured relative to it with appropriate checks taken to compare the standard deviation of the calculated object along with redundant independent checks to the surface face of the flange similarly completed by Cao et al (2018) for flatness measurements.

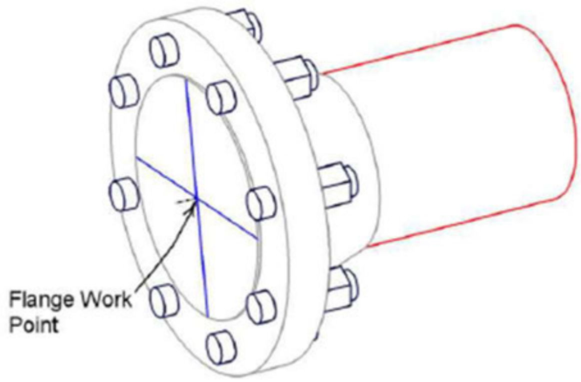


Figure 2.3 – Flange Centreline Calculation Point

2. Plane Inclination

As Makarov (2013) describes, it is important to build and inspect objects in three-dimensional space where large objects have to be aligned and assembled together with high precision. A flange can be sitting in a spatial setting where its axis is misaligned through both X and Y. Understanding the displacement through both the axis is key to calculating the correct plane inclination of a flange.

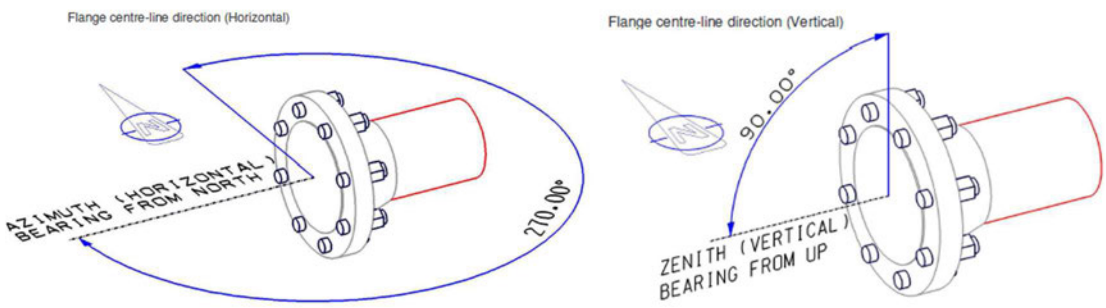


Figure 2.4 – Plane Inclination Calculation

3. Bolt Hole Rotation

All flanges are constructed to an appropriate standard which means a standard for the bolt rotation between each bolt along with a standard for the amount of bolt holes required. ASME B16.5 provides a standard to the bolting and orientation of a flange along with the diameter for each bolting hole. One crucial aspect to also understand is that outside of the typical standard, understanding the alignment of the flange in respect to the bolt holes is important for flange orientation for the construction of a flange. Expressing the rotation from zenith north clockwise to the first bolt hole allows the flange orientation to be found.

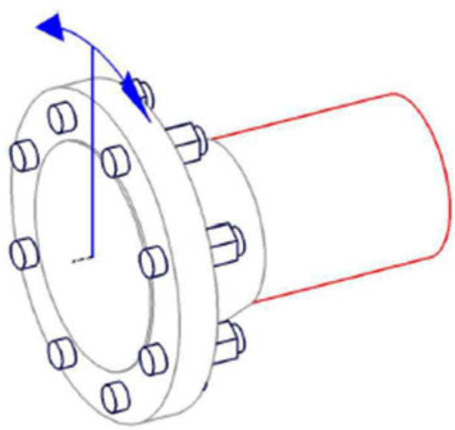


Figure 2.5 – Bolt Rotation Calculation

2.5 What is a Flange?

A flange plays an important role in the Oil & Gas industry in providing a method of connecting and joining pipe fabrications, valves and pumps to form piping systems. It also allows an access point to inspect, clean or even test systems for pipe degradation and corrosion. Flanges are constructed for a variety of uses, with many different forms of sizing, material construction and flange types depending on the required function. The most common material of flanges found in the Oil & Gas industry is carbon steel. Given its high strength and ductile properties, carbon steel is an ideal material to be used in piping systems. Also considering the dangerous properties and high amount of pressure the natural gas and oil are exposed under, carbon steel is able to safely allow the materials to flow to its intended destination.

2.5.1 Types of flanges

There are a diverse amount of flange types that exist within the Oil & Gas industry, all playing a different role in the way they connect piping systems. Ulma Piping (2009) describes the main flanges which exist within the Oil & Gas industry:

- **Welding neck flange**

  This type of flange is connected with a hub on the back of the flange that enables the flange to taper into the piping design. This is one of the more popular flanges given their ability to operate under high pressures at elevated temperatures. Stress distribution is also able to be evenly dispensed and the welded hub is easily radiographed for impurities and flaw detection.

- **Slip-on flange**

  As the name suggests, this flange is designed to slide over and sit on the outside of the pipe. Given the method of attachment to the pipe work, this flange is not designed for high stress applications.

- **Socket welding flange**

  The socket welding flange is similar to a slip-on flange given the fact that they slide over the pipe; however the flange also has a counterbore slightly larger than the pipe which acts as a socket for the end of the pipe to be inserted.

- **Lap joint flange**

These types of flanges are near identical to slip-on flanges except for the fact that there is a radius at the intersection of the bore and flange face to allow the flanged portion of the stub. These flanges are common when there is a need to frequently clean inside the pipe.

- **Threaded flange**

  As the name describes, these flanges are threaded in the bore so that they are then matched to a thread on a pipe. They are usually used in low pressure circumstances and when welding could be hazardous.

- **Orifice flange**

  An orifice flange is used in conjunction with orifice meters that measure the flow rate of liquids and gases in pipelines. A pair of pressure taps is used for the measurement of the pressure. The orifice flange is provided on three types of flanges: Welding neck, slip-on and threaded.

- **Reducing flange**

  These flanges are designed to change the diameters of pipes through the use of a reducer in the flange. The flange consists of the same connected pipe size with the bore having one specified for a smaller diameter pipe to be connected. Reducing flanges are usually adapted to three types of flanges: Welding neck, slip-on and threaded.

- **Blind flange**

  These flanges are used commonly for closures or seals to the end of piping systems and are constructed without a bore. Blind flanges are the most common flange when it comes to flange surveys. Because blind flanges are often used as a seal of an existing pipe system, the intention of using a blind flange is to seal off a pipe which can be used for future upgrades of an existing system such as a metering skid or compressor station. Flange surveys are the bridge between real world and design in which these new connections into blind flanges can occur accurately and precisely.

2.5.2 Standards

Standards are a necessity which allow the distribution of frameworks and policies to industries and organisations that allows for uniformity, improved health and safety, innovation and industry competitiveness. There are potentially life-threatening dangers involved in the oil & gas industry in Australia, not only exposed to workers within the industry, but to most residential areas that are affected by pipelines, gas cylinders and petrol stations to name a few. Given the high-risk industry, standards and regulations play a significant role in ensuring that potential hazards and threats are eliminated or at the very least minimised.

The British Standards Institutions (BSI) (2019) describes standards as – "..the wisdom of people with expertise in their subject matter and who know the needs of the organisations they represent". Standards provide knowledge to all aspects of industries and organisations, ranging from specific types of products or practices, to generalised overarching frameworks.

2.5.3 Flange Standard Organisations

There are a few main players that help contribute to the improvement of flange standards in Australia, and they consist of:

- Standards Australia (AS)
- International Organisation for Standardisation (ISO)
- American National Standards Institute (ANSI)
- American Society of Mechanical Engineers (ASME)
- British Standards Institution (BSI)

All five associations are not for profit organisations that help promote collaboration, knowledge, skills development and improvements in the oil and gas industry. Although all five associations cater to the improvement and enhancement of standards, they differ slightly to each other in terms of their benefits.

2.5.4 Current flange standards in Australia

There are a number of current flange standards that exist in Australia today. These standards cater to all aspects of a flange ranging from the following:

- The material of construction of a flange
- Pressure class rating and testing
- Flange configuration
- The nominal size of the flange (DN)
- Manufacturing requirements and tolerances

It has been over 80 years since the original flange standard was first published in Australia for commercial use (Standards Australia, 2019). This standard was AS B52-1931 which was an endorsement of the British standard BS10, the imperial inch series. Most pipeline and flange standards in Australia have been endorsed or adopted within the current standards in Australia given the existing platform and history behind other standards in the world such as the British and American standards and also Australia's close affiliation to Britain as a Commonwealth State. It is not uncommon to find standards such as the American standards ASME/ANSI referenced on design documents for flanges and pipelines within Australia given their close affiliation to the current standards in Australia. Standards Australia (2019) states in one of its principles to guide development: Australia will influence the development of and maximise use of relevant International Standards. Standards Australia is one of the leading voluntary organisations that develop standards in Australia. As APGA (2019) discusses, Standards Australia is the peak non-government body responsible for assisting in the development and maintenance of industry standards in Australia. As for the current flange standards within Australia, Standards Australia provides the relevant standards that form the framework in the Oil & Gas industry.

Some of the current standards that are being utilised in the Oil & Gas industry and specifically catered towards flanges are:

- AS4087

AS4087 is catered towards metallic flanges for waterworks purposes. These flanges are found in the oil & gas industry but used for carrying high pressure water either for distribution of clean water or for separation of dirty water from gas seams to name a few. Standard AS 4087 explores all facets of the flange ranging from the configuration of the flange, the manufacturing requirements and dimensioning, allowable tolerances and materials used. It is uncommon to complete a flange survey on water work flanges as the requirement to locate these flanges is not necessary on the higher tolerance spectrum that flange surveys are predominantly undertaken for.

- AS2129

This standard covers all maters to do with flanges for pipes, valves and fittings in the Australia Standards organisation. This is the most common standard utilised within Australia and it covers all aspects to do with a flange similar to AS4087. A large majority of design plans relating to design or as-built flanges would refer to the standards relating to AS and is a predominant player in the oil & gas industry.

AS2129 covers all flange sizes ranging from 95mm through to 850mm outside diameter (OD) and references its classes via tables C through to J. This standard originally derived from the British inch series standard BS 10:1962, and was implemented in Australia in 1970. There have been two revisions since the original standard was introduced with the first coming in a 1994 edition, and the last coming in 2000. The standard from 2000 has since been reconfirmed in 2016.

- ANSI/ASME B16.5

The B16.5 publication in 2017 is for pipe flanges and flanged fittings ranging from NPS ½ through to NPS 24 metric/inch. This standard for flanges covers all aspects from temperature and pressure ratings, materials, tolerances, dimensions, testing, marking and the methods of designating opening for flange fittings and pipe flanges. This standard covers the following flanges with rating class designations : 150, 300, 400, 600, 900, 1500 and 2500. Once such thing B16.5 standard is limited to is that it is limited to flanges and flange fittings that are made from cast or forged materials along with blind and certain reducing flanges that are made from cast, forged or plate materials.

- ANSI/ASME B16.47

This standard is a continuation from ANSI/ASME B16.5 as it is a standard that covers steel pipe flanges and flange fittings for larger sizes and pressure temperature ratings. Where B16.5 covers flanges up to 24 inches, B16.47 covers flange sizes from 26 through to 60 inches. The two standards are interchangeable given they are applied to the same applications however, the only major difference being the flange sizes that separate the standards.

- ISO 7005 (DIN)

This standard is established from the International Organisation for Standardisation and is a standard that has been produced to provide designers, manufactures and users with an international standard for flanges for use in pressure applications. It helps specify the different types of steel flanges and their facings, tolerances, threading, dimensions, bolt sizes, surface finishes, marking, testing and inspection. ISO7005 does not specify in the standard pressure and temperature ratings or the materials for flanges it only provides a guide for them. The standard provides a base specification for pipe flanges that are suitable for general purpose and industrial applications which includes chemical, electric, petroleum and gas industries.

- BSEN 1902-1

This is the major British and European standard for flanges for circular steel flanges with nominal sizes from DN 10 to DN 4000 and pressure ratings from PN 2,5 through to PN 400. Similar to AS2129 and B16.6 and B16.47 this standard covers all applications to do with flanges ranging from the type, facings, tolerances, dimensions, bolt sizes, threading, surface finish, materials, marking, pressure/temperature and approximate masses.

The six standards listed above highlight the major standards that are covered not just in Australia but also America and Britain/Europe. Given Australia's short tenure into the oil and gas industry, the standards that have been adopted within Australia are predominantly adopted from the standards created in Britain and America given their vast knowledge and experience over Australia in the industry. International standards provide the framework worldwide for the required benchmarks that should be met and with organisations such as Standards Australia, these relevant standards can be adopted and tailored to suit Australia's needs. There are numerous more standards that are relevant to flanges and the oil and gas industry that provide an important role in maintaining the standard of the industry; however, the six major standards covered here provide the fundamental framework for the core components of flanges.

2.6 Laser Trackers and Applications to the Industry

Laser trackers are portable measuring systems that are highly accurate and precise machines. They measure specific reflector targets to determine the three-dimensional coordinates of objects. The first laser tracker was invented in the mid 1980's by Lau et al. at the National Institute of Standards and Technology (NIST) to facilitate robot metrology (Muralikrishnan et al. 2015). Laser trackers are supreme measuring devices given their stated accuracy for distance measurement to +/- 10 microns along with an angular accuracy up to +/-15 microns + 6 microns/m (Leica Geosystems, 2019).

2.6.1 Laser Tracker Theory

Laser trackers components have not changed significantly since the creation by Lau et al in the mid 1980's. The core components are made up of:

- Combination of two techniques utilising a laser meter that measures the relative distance and an optical encoder that measures the azimuth and elevation of a beam-steering mirror.
- Distance meter can be two types, a distance measuring interferometer (DMI) or an absolute distance meter (ADM).
- An Interferometer set up utilises a light source (laser) that is split into two beams – one as a reference beam while the other beam is reflected from a mirror otherwise known as a retro-reflector at a distance. The beams are then merged to produce an interference where the

wavelength of the laser is known and highly stable so that the distance can be calculated. Interferometers work by having a known 'home' position or distance where the tracker can calibrate itself on this position before starting a measurement. The user can then move the reflector where the laser tracks along providing a spatial coordinate of the reflector, however, if the beam between the reflector and laser tracker is broken, then the number of counts is no longer valid and the distance is unknown meaning the operator has to start again from the home position.

- The other type of measurement - absolute distance measurement (ADM) is a more portable measurement to that of the interferometer as a home point is not required and the operator can simply point the laser and shoot at the reflector. The ADM measures automatically even if the broken has been broken as it utilises infrared light from a semiconductor laser which reflects off the reflector and re-enters the laser tracker where it is converted into an electrical signal. That signal then determines the time of flight which is multiplied by the speed of light in air to finally determine the distance from the tracker to the reflector.
- The ADM is the most flexible and portable machine out of the two, however, the DMI is the most accurate and can even measure sub-micron but requires a continuous signal to the reflector without blocking the laser beam.
- Laser trackers today are also equipped with air temperature sensors that automatically calibrate and compensate the instrument on environmental variables that affect distance measurement.

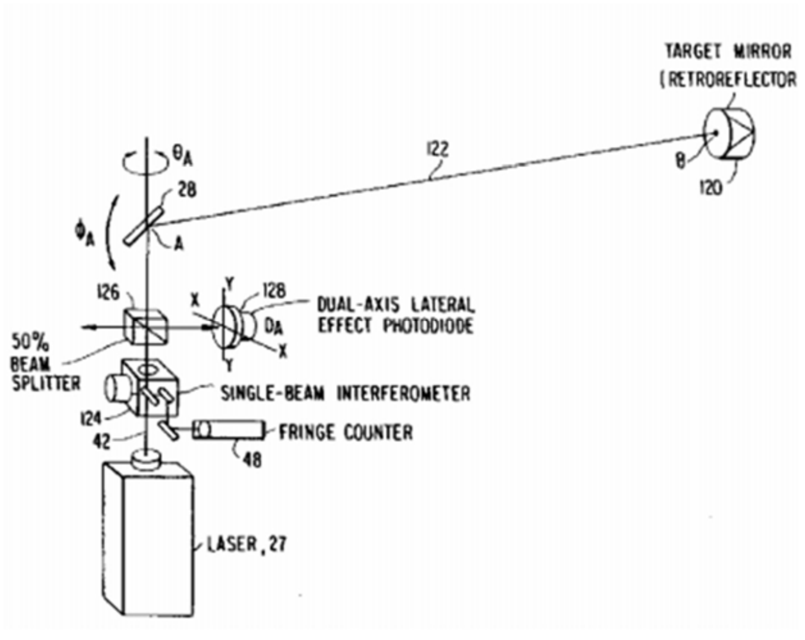


Figure 2.6 – Laser Tracker Components from US Patent #4,714,339

Burge et al (2019) describe that a laser tracker is especially useful for optical alignment for three reasons:

1. Accuracy of the machine: The laser tracker makes measurements to +/-10 microns accuracy without any special geometry or data processing and where applied in advantageous geometry it can track and measure to < 1 micron.
2. Flexibility: The laser tracker provides the flexibility to measure over a wide range of angle and distances and can even measure and track through mirrors and windows.
3. Ability to measure different optical spaces: Optical systems frequently incorporate fold mirrors to help on system packaging and as a laser tracker beam is also reflected by the mirrors, the laser tracker can determine optical coordinates directly.

2.6.2 Laser Tracker Applications

Although first developed and used as a surveying tool, laser trackers are more accustomed to being found on manufacturing floors and workshops utilised in the metrology industry. Given their expensive purchasing price of over $100,000, laser trackers are not commonly found within surveying companies given their specific measuring attributes and limited functionality. Laser trackers are predominantly required to be connected to a computer to measure and store spatial information. This limits their ability to be fully portable and manoeuvrable as opposed to a total station as most laser trackers are also not intended to measure longer distances beyond 20-30 metres at a time.

Figure 2.7 – Typical Laser Tracker Field Application (Leica Geosystems 2019)

Laser trackers can be predominantly found and used for the following purposes:

- Aerospace and aircraft manufacturing
- Shipbuilding
- Robot tracking, maintenance, testing and calibration

- Automotive manufacturing
- Inspection testing and alignment
- Reverse engineering applications

Laser trackers are often used for jig component inspection and wing component and fuselage assembly in the aerospace industry. Given the tight tolerances and strict regulations in the industry the accuracy of the laser tracker is very beneficial. Along with direct measurement components for alignment the laser trackers also help calibrate and inspect robot manufacturing. Within the likes of the automotive and shipbuilding industries laser trackers are directly applied to jig and parts assembly whilst also used for adjustments of industrial robots and for deformation and dynamic measurements.

2.7 Total Stations and Applications to the Industry

The total station today is one that is robust, accurate and manoeuvrable to the point that many assistants or 'chainman' have been made redundant. They have evolved throughout the years in comparison to the computer where technology has allowed these machines to become efficient measuring devices that have never been more accurate, reliable and consistent. From their humble beginnings a few hundred years ago, total stations have integrated to the point that measuring angles and distances is simply not enough, consumers today expect features that are standardised such as basic laser scanning, photogrammetry, survey control rounds and adjustments and numerous other programs for specialised surveying tasks.

Total stations first started out as theodolites in the 18th century where the first sighting telescope theodolite was created by Jonathan Sisson in 1725 (Avram et al, 2016). There were many advancements in the years to come where Jesse Ramsden in 1787 introduced the infamous great theodolite whist by the time the early 20th century turned, Heinrich Wild was popularised with surveyors when he made the Wild T2, T4 and A1 instruments.

2.7.1 Total Station Theory

The core components of a total station today are still the same as the first theodolite created back in the 18th century. The machine is typically mounted on a base such as tripod legs and the instrument itself consists of a telescope with a sight on top that is used to align to a target. A few other key parts and new advancements that have been made to the instrument include:

- A focus dial is positioned on the telescope to allow the instrument to focus to make objects clear. Another dial is used to enable fine cross hairs to be focused directly on the target.
- The base of the total station is usually threaded onto the tripod mount to enable a secure and stable position.
- An optical plummet or even a laser plummet is built into the instrument to enable to total station to be centred over a survey mark or reference point.
- A spirit bubble is provided to ensure the device is level to the horizon, today's total stations have digital spirit bubbles to fine tune the level within one second.
- Graduated circles are built in to find horizontal and vertical angles with one for each that allows the user to survey angles.
- An electronic distance meter (EDM) is built in to enable distances to be measured to objects either with a reflector or prism positioned on a target or by way of reflectorless laser measurement. Similar to a laser tracker EDM, a modulated infrared signal is generated by reflecting off a prism or the desired object where the signal is returned to the total station. The distance is achieved where these signals are emitted and received by determining the number of wavelengths between the total station and its target.
- Automatic targeting is capable with most total stations today which enables the instrument to dynamically follow a reflector prism. This has drastically changed the way surveyors complete routine projects as it has truly removed the need for a traditional chainman with most tasks and removed the manual operation of the machine. Leica Geosystems (2019) describe how their ATRplus feature works on total stations:
  "ATRplus consists of a laser source that emits an infrared laser beam (IR) coaxially, with a divergence of 1.5gon through the telescope. When the laser beam hits a prism, the beam reflects back into the telescope. A beam splitter, which is located in the optical axis of the telescope, decouples the beam from the optical path and guides the light through an IR band pass filter onto the CMOS sensor. On the CMOS sensor, the reflected laser beam appears as a light spot. Different algorithms evaluate the image data, identify the prism spot, and calculate the pixel coordinates of the spot centre with sub pixel accuracy. With these pixel coordinates, ATRplus calculates the deviations of the spot centre from the centre of the optical axis. Combining the deviation with the angular and inclinations sensor values, the final horizontal direction and vertical angle are calculated."
- The on-board interface on total stations now resemble that of a computer and the accompanying controller and tablets mirror the specs of most laptops. Programs built for total

stations have dramatically improved where the user is stepped through each functionality of the program and no manual booking nor field calculations are required.

Total Stations are typically manufactured to a certain degree of accuracy and their costs reflect whether they are on the lower or higher end of the spectrum. Most total stations come in three different angular error classes ranging from 1”, 3” and 5” seconds with 1” being the most accurate. Some total stations such as the Leica Nova TS60 are built to 0.5” (Leica Geosystems, 2019), however, these instruments are more specialised for high accurate work such as deformation and monitoring. The other main error function associated to total stations is the distance measurement function or EDM. On Leica Geosystems total station comparison chart (2019) their suite of total stations are all built to a distance accuracy of 1.0mm + 1.5 part per million (ppm) except their highly accurate total stations the TM50 & TS60 which are 0.6mm + 1ppm. Reflectorless distance measuring accuracies are stated for all Leica total stations as 2mm + 2ppm up to a range of 500m.

2.7.2 Total Station Applications

Total stations are a staple for surveyors they are the main working tool for their everyday tasks. As mentioned previously Leica Geosystems provide a suite of total stations within a comparison chart that provide eight options to choose from ranging from basic instruments such as their FlexLine products usually tailored for builders and basic construction through to the automated total stations such as the TS16 and TS60 for more survey related projects and tasks. Another option Leica Geosystems provide is more of a hybrid total station that is integrated with laser scanning which is their MultiStation MS60. This machine has all the functions of an automated total station, however, it has the capability of performing basic laser scanning functions similar to a laser scanner albeit at a much slower pace of 1,000 points per second compared to a laser scanner such as the Leica P50 which scans at up to 1,000,000 points per second (Leica Geosystems, 2019). The automated total station and MultiStation are equipped with imaging cameras which are five megapixel CMOS sensors that can be used for photogrammetric applications.

It must also be noted that other brands provide similar suites and lines to that of Leica Geosystems and one other main player in the surveying industry is Trimble. Trimble have for quite a while been running the S series of total stations which mirror that of Leica Geosystems automated total stations. The S5, S7 and S9 are automated total stations capable of angular accuracies ranging between 1” to 5” seconds. Their EDM accuracy is 1.0mm + 2ppm whilst the reflectorless distance measurement is 2.0mm + 2ppm. Trimble also offer an equivalent MultiStation to the Leica MS60 which is the Trimble

SX10. This instrument has an angular accuracy of 1” and an EDM accuracy of 1mm + 1.5ppm. The SX10 can perform a laser scan up to 26,600 points per second and has three in built cameras each with a five megapixel resolution (Trimble, 2019). Trimble state that the laser scanning measurement specifications for the SX10 uses a measurement principle based on ultra-high speed time-of-flight which is powered by Trimble Lightning Technology.

Some of the applications that total stations are used for within the surveying industry and their specific tasks are:

1. Construction and Engineering

- Setting out works for roads, rail, bridges, buildings and other infrastructure works.
- Surveying As-Constructed work for conformance reporting and As-Built mapping purposes.
- Machine control guidance with construction machines such as graders.

2. Cadastral

- Traversing purposes to locate cadastral survey marks and form control networks.
- Surveying topographic information for design works and titling referencing.
- Setting out and marking property boundaries.

3. Mining

- Underground works for setting out mine shafts and control traversing networks.
- Deformation and monitoring works.
- Blasting and drilling for open cut mines.

2.8 Laser Scanning and Applications to the Industry

Laser scanning is still recognised as a relatively new technology in the surveying industry, however, the technology has been around since the start of 1960 where the development of the ruby laser was introduced (Heritage & Large, 2009). For the past decade laser scanning has rapidly evolved into a common form of surveying and more companies provide laser scanning services as an everyday option. Laser scanning has been popularised due to its advantages over traditional survey techniques mainly in the form of data capture and more specifically the amount of data it collects. Leica Geosystems (2019) states that some of their laser scanners can collect up to 1,000,000 points per second which blows away traditional forms of surveying such as total and GNSS surveys. With advancements in computer power and processing and increased storage availability options, laser scanners are not just bound to those who have super computers and unlimited amounts of money.

2.8.1 Laser Scanning Theory

There are three main principle types of scanning, and Heritage & Large (2009) describe them as:

1. Time of Flight (ToF)

- This scanner has sensors that measures the time it takes for a pulse to travel a distance to a reflection off an object and its return to the sensor. Knowing the speed of light calculation and combining this with horizontal and vertical angles a three dimensional point can be created.
- ToF scanners are typically used for general purposes and are supreme over longer distances.

2. Phase Shift

- These scanners work by emitting a laser pulse into multiple phases and then comparing the different phase shifts of the returned laser. The phase of the emitted laser and the received signal are compared and the relationship between the phase differences can be calculated.
- Phase shift scanners are supremely quick compared to traditional ToF scanners and are capable of measuring up to 1M points per second. Briese & Pfeifer (2007) discuss the major differences between ToF and phase shift scanners where ToF scanners can produce a higher range for a "pulse round trip" and phase shift scanners produce higher measurement speeds and better precision.

3. Triangulation

- This method of scanning does not determine the range but instead the angle measurements. Laser energy is widened to enable a plane to be formed rather than a single beam and with a rotating mirror this plane is swept through object space. A sensor then detects the laser light and calculates the distance between the scanner and the object utilising trigonometry calculations.
- This form of scanning is restricted in depth because the quality of the intersection diminishes with range so it can only be applied to an object no more than a couple metres away. An advantage of the triangulation method is that portable handheld scanners use this technology and allow very quick scans to be completed of objects, but these scanners are typically restricted in a lower form of accuracy and resolution compared to ToF and phase shift scanners.

ToF and phase shift scanners are popular laser scanners within the surveying industry as they provide a market for a variety of tasks. ToF scanners are very capable scanners with a working range up to 1km (Leica Geosystems, 2019) that allows data to be captured of objects long distances away in a safe and accurate manner. Phase shift scanners on the other hand have a shorter effective working range under 100m (Alonso et al, 2011) but capture data at a much quicker rate than ToF up to a rate of 1M points per second (Leica Geosystems, 2019) which is nearly five to ten times faster. These two scanning options provide the consumer a selection of laser scanners that suit differing objectives but in their own right provide a need to the scanning market.

Around the year 2013 and 2014, a new electronic distance measuring technique was introduced by Leica Geosystems which is their Waveform Digitising (WFD) technology. In Leica Geosystems (2019) white paper datasheet, WFD is described as the perfect mix between ToF and phase shift scanners. WFD allows a scanner to adopt the ToF long range accuracy combined with the ultra-high speeds of a phase shift scanner. It is the perfect scanner that does the best of both and allows companies to invest in one piece of equipment as opposed to buying both a ToF and phase shift scanner or buying one and being constrained to its limitations. Leica Geosystems introduced WFD with their P series scanners and is available in their P30, P40 and P50 scanners.

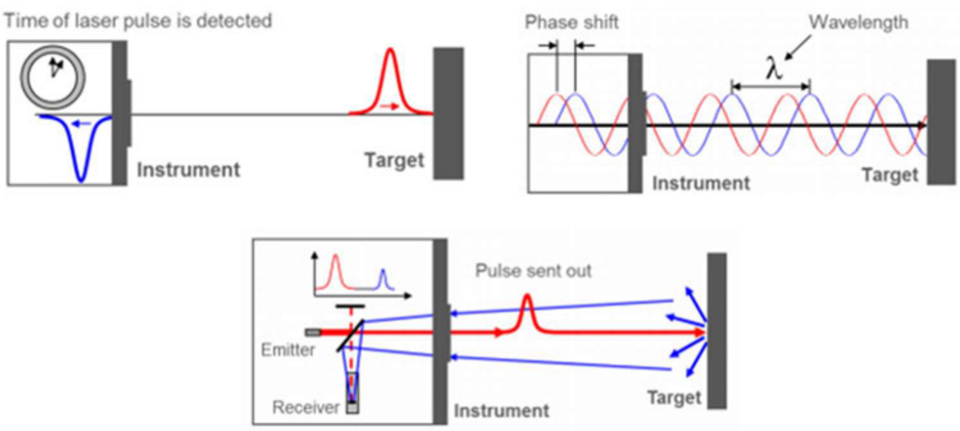


Figure 2.8 – Time -of-Flight (top left), Phase shift (top right) and WFD (bottom) measuring principles (Leica Geosystems 2019)

Trimble also released around the year 2016 a patented version of WFD which they call Trimble Lightning Technology (TLT) that also combined the advantages of ToF and phase shift measurements into one scanning unit which is introduced in their TX6 and TX8 scanners. TLT works the same way WFD does and allows the Trimble laser scanners to work at an extended distance range whilst maintaining a high rate of data capture up to 1M points per second (Trimble, 2019) whilst not decreasing on overall accuracy.

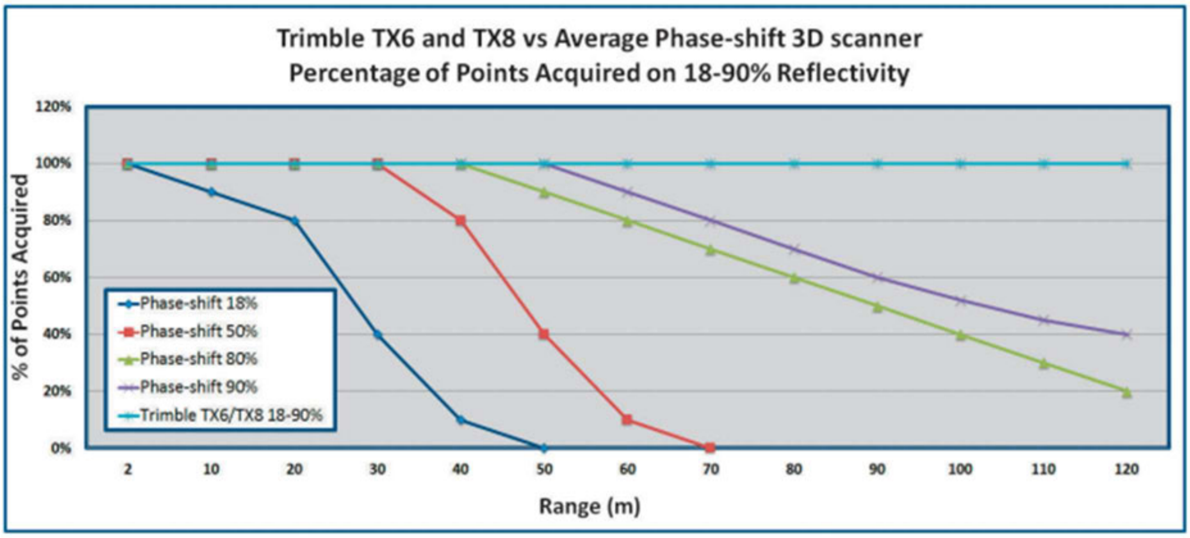


Figure 2.9 – Trimble Lightning Technology Benefits over phase shift scanners in the TX6 and TX8 scanners (Trimble 2019)

2.8.2 Laser Scanning Applications

Laser scanners have become an important device within the industry given their unique ability to capture enormous amounts of data at a quick rate but in a safe and effective manner. The California Department of Transportation (2018) lists typical terrestrial laser scanning types of surveys and they include but are not limited to:

- Pavement analysis scans
- Roadway/pavement topographic surveys
- Structure and bridge clearance surveys
- Engineering topographic surveys
- Detailed archaeological survey
- Architectural and historical preservation surveys
- Deformation and monitoring surveys
- As-built surveys
- Forensic surveys
- Earthwork surveys such as stockpiles, borrow pits and landslides
- Urban mapping and modelling

Another big advantage laser scanning is advantageous for is that it is non-contactless which means that in unsafe situations for people to be or when surveying highly delicate objects such as heritage sites, there is no need to physically survey an object with a prism or reflector. Alonso et al (2011) successfully scanned the Royal Pantheon in the Basilica of San Isidoro with laser scanners where a delicate heritage site had to be preserved. Gomez-Lahoz et al (2008) describe new techniques for monitoring a dam where terrestrial laser scanning was introduced given a large surface of the dam face required monitoring and the ability for a person to physically survey the face of the wall was near impossible. Comprehensive datasets where surveyed and compared to provide a complete analysis of the dam face deformation.

2.9 Conclusion

This literature review has covered the necessary topics relevant to the research project and identified and discussed important information in an unbiased view. Background information on flanges and their existence in the oil and gas industry have been highlighted and the core components required to complete flange surveys have been discussed in length. Understanding the data and how it can affect measurement results has been brought forward to report on the analytics on datasets. Recognising the relevant error accuracies in relation to laser trackers is important given the trackers provide the baseline readings for the two datasets to be compared. Researchers have provided information and procedures on the use of laser trackers and more specifically the Leica AT series which provides the underlying principles on its uses and capabilities.

Emphasising the need for continuous business development through R&D highlights the importance of how technology affects the industry and how businesses should align their overall goals and strategies to their specific development needs.

Furthermore, this review outlines the basis of flange surveys and their rise through rapid technological advancements; and the need to understand the overall picture through tangible information at hand.

Chapter 3 – Methodology

3.1 Introduction

This chapter will help identify the processes undertaken to successfully perform the aim of the research. The main elements of this chapter include:

- Study Area
- Equipment and various applications used
- Field Procedures
- Post Processing and CAD calculations

3.2 Study Area

The area that was selected to conduct the field research is located at WDS Pty Ltd Fabrications workshop at Link Drive, Yatala, 4207.

Figure 3.1 – Satellite view of the study area (Google Earth 2019)

The field testing was conducted on a flange and spool piece of piping that was positioned on pipe racks inside the fabrication workshop itself. The workshop is a large under covered shed roughly 43 x 50m with ventilation installed and access through roller doors which were opened at the time of the field work.

The environment inside the workshop was controlled without much fluctuation in temperature, pressure and humidity which will provide a consistent result for each of the readings taken for each method. This was the desired atmospheric environment required to conduct the field testing so that the variables introduced through exposure to fluctuating temperature and pressure and also sun rays and wind would not influence the measurement results.

Figure 3.2 – Leica TS15 conducting a D.C survey on the pipe work

The piece of piping that the field work was being conducted on consisted of a U shape spool with a flange connected at either end. Positioned in the middle of the U curve was another flange which was pointing upwards but this however was not used in any calculations, due to the laser scanner not able to locate the bolt holes inside the flange due to the orientation of the flange. The two flanges at either end of the spool will form the basis of the field work testing as this will provide in assisting another set of results to hopefully reinforce any errors that are found between the different survey methods. Each flange that will be used in these calculations is an ASME Class 1500 flange.

3.3 Equipment

3.3.1 Laser Tracker

The Leica AT402 laser tracker was used for this study. The AT402 is a highly accurate mobile coordinate measuring machine that when fully calibrated can achieve an angular accuracy of +/- 15 microns + 6 microns/m and an absolute distance accuracy of 10 microns. Accompanying the laser tracker is a Leica Break Resistant Red Ring Reflector 1.5” (BRR) used as the main prism to locate the flanges and also utilised for the control to tie the survey together. This reflector comes in various sizes from 0.5” to 1.5” and has a centring error of <+/-0.01mm (10 microns). Alongside the BRR are two specialty adapters. The first adapter is a magnetic reflector holder called a drift nest for the 1.5” BRR that is used for the control points and the second is a magnetic reflector holder 1.5” Target Corner that is used for locating the edge of the flange. Both of these adaptors are Leica Hexagon branded pieces of equipment.

Figure 3.3 – Leica AT402 Laser Tracker & Target Corners (Leica Geosystems 2019)

Although the AT402 Laser Tracker has a designated controller that is utilised with the machine, the Laser tracker is reliant on a connection with a computer so that measurements can be made utilising the software installed on the computer. This can be completed with an Ethernet cable or over wifi with the first option chosen in this study. The software used in conjunction with the Laser Tracker was Spatial Analyzer and the computer used was a Dell Latitude E6520 with an Intel Core i5 processor, 8GB RAM and a 64-bit Operating System.

3.3.2 Laser Scanner

The laser scanner used in this research was a Leica HDS7000. This scanner is a phased based scanner and is capable of capturing >1million points per second. Accompanying the scanner were five Leica black and white tilt targets (six inch diameter) which were used for the scan registrations.

Figure 3.4 – Leica HDS7000 Laser Scanner (Leica Geosystems 2019)

Assisting in the scanning was the use of a Canon Nodal Ninja DSLR external camera used for providing the real life colour to the scans. The camera colour was not used for the calculation of the flanges and had no impact on the results. Its primary purpose was to provide an example of the deliverables that can be achieved through the use of scanning. The camera is fitted onto a specialised bracket (Nodal Ninja) to replicate the position of the Laser Scanner and utilises a fish eye lens to capture panoramic photos of the surrounding area. The camera takes eight photos on a 90 degree angle to form a complete panoramic of the area. The camera then captures eight photos on a 45 degree angled upwards so that any information above the scanner can be included in the panoramic photo. These photos can then be combined in a photo stitching software to form a complete panoramic photo of the scan area and are then 'burned' into the point cloud to provide real life colour.

3.3.3 Total Station

A Leica Total Station TS15 was used in this study. The TS15 Total Station is designed for the surveying industry with a wide range of uses available for the machine. The manufacturing standard of a TS15 in its accuracy is available in a few varying angular accuracies ranging from 1" to 5". The instrument that was chosen for this study consisted of an angular error of 1" and a distance error of 1mm + 1.5ppm. Alongside the TS15 was the same BRR prism used with the laser tracker and the two magnetic adaptors required for locating the flanges and control marks.

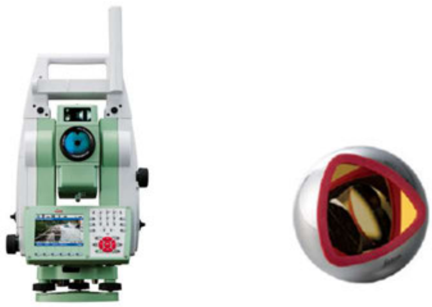


Figure 3.5 – Leica TS15 Total Station & BRR 1.5" Prism (Leica Geosystems 2019)

3.4 Field Procedures

3.4.1 Laser Tracker

Only one setup was utilised for the Laser Tracker which was mainly chosen to eliminate any errors that could be encountered from the control for the need of another setup. This meant that all measurements taken were all relative and the only foreseen error that could be encountered was that of the Laser Tracker itself (standard angular and distance errors), the error in the BRR prism and any human errors of holding the adaptor on the flange incorrectly. Inside the workshop the atmospheric readings were roughly 20C in temperature, 46% humidity and 1006mbar in pressure. This was consistent over the course of the field work with no fluctuations greater than this that would affect the measuring accuracies. It must be noted that the AT402 Laser Tracker is accompanied with a Leica MCA15 2m external temperature sensor that is connected to the machine and relays back the atmospheric readings into the software so they are taken into consideration for the measurements automatically, unlike the TS15 total station which is manually entered into the machine based on external readings.

The Laser Tracker was setup strategically in front of the two flanges so that both faces of the flanges were in view of the setup and all bolt holes could be located. Before any measurements were taken, five 1.5" magnetic reflector holders were placed around the outside of the piping area itself to provide the survey control so that the Laser Tracker data can be transposed onto the data of the other survey methods. These five holders were placed in an ideal geometry around the outside of the piping area mainly attached to the metal supports of the building itself. These marks ranged from 4m to 20m away from the machine and formed the shape of a pentagon around the Laser Tracker. These control marks were located at the beginning of the survey and were located using the same BRR for all five points which required moving the prism after every control point was located. This was completed to eliminate any errors that could exist between different BRR prisms and their offset constants, even though the error between BRR prisms would be hardly recognised it was still taken into consideration for the purpose of this survey.

After the control was surveyed, the face of the flange was now measured. This consisted of the BRR and the special target Centre adaptor to be used. The target centre adaptor has an offset of 10.94mm (either planar or radial depending on which way the reflector is mounted onto the flange) and this is taken into consideration when the measurements are taken along with the 19.05mm planar offset for the radius of the BRR. Roughly eight measurements were taken around the face of the flange so that the flange can be modelled successfully in CAD as either a circle or cylinder. The measurements are recorded as a three dimensional position of each point and are stored in the Spatial Analyzer software utilised with the laser tracker. The bolthole measurements were taken next and this was completed by placing the BRR inside the bolt hole so that it fit snug inside the hole. Because there was no specific point on the bolthole that needs to be measured or calculated, as long as the bolthole centres are measured relative to each other in the same methods then this would suffice as the only calculation required from this is the rotation from the centre of the flange. There were sixteen bolt holes found on the flange which is standard for an ASME Class 1500 flange, as all sixteen bolt holes were all located in this study. Usually the bolts are fixed on the flange due to a blind flange being installed as a seal, which means the bolt is located by placing the prism inside the magnetic locator and centred on the bolt itself. The bolthole rotation calculation is not affected whether the bolt is fixed or not, as the rotation is calculated from centre of the pipe/flange through clockwise with zenith being vertical.

Figure 3.6 – BRR positioned on a reflector target corner of the flange

Independent redundant measurements were then surveyed around the flange outside to provide a check against the actual flange measurements that will be adopted for the CAD modelling. These measurements are compared to the objects to enable an independent check against the results.

Following the measurements on the flange and the bolt holes, the control was located again to provide a quality assurance check that the laser tracker measurements had not differed from the first round of control measurements. The results between the measurements from the first control shots to the second were minimal.

Point No.	Easting	Northing	RL
P1	-0.03	-0.07	0.07
P2	-0.04	-0.06	0.10
P3	-0.23	0.06	0.15
P4	-0.20	0.06	0.20
P5	-0.01	-0.08	0.27

Table 3.1 – Differences Between Laser Tracker Control (in millimetres)

The approximate time it took to complete the Laser Tracker survey was 45mins. This was the slowest survey of all three methods and although it was an identical methodology to the total station survey, it was still 15mins slower. This can be attributed to the experience of utilising a Laser Tracker and understanding a routine work flow from scratch. The actual measurement and recording of points was a similar time to that of the total station but with a novice understanding of using a Laser Tracker this attributed to the slower time to complete the survey. If the Laser Tracker was a routine piece of equipment in the surveying profession like a total station or laser scanner, then the time taken to complete this survey in the future would not differ far from what it would take to complete the same survey.

3.4.2 Total Station

The TS15 field procedure mirrors that of the Laser Tracker in relation to the setup, locating the control first and then measuring the flange face and the boltholes. Before any measurements had taken place, a control file was exported from the Laser Tracker to import into the TS15 so that the survey could be aligned to the Laser Tracker for the field measurements. This was completed by locating the same control points which were the magnetic reflector holders with the same BRR cradled in the holders in a resection. The results of the TS15 resection were:

E: 0.000m **N:** 0.000m **RL:** 0.000m **Orientation:** 0.0001”

These results are what are expected of a high accuracy 1” total station and by achieving these types of results between the total station and the Laser Tracker, any issues or errors between the control datum can be eliminated.

The control was located again separately after the resection for a record of the observation and the flange face was located with the special adaptor and BRR. Again, eight shots around the circumference of the flange face were recorded and all sixteen bolt holes were located along with the independent redundant checks. A backsight shot was taken after the completion of the survey to provide a quality assurance check of the data and this was completed to control point P1: Angular error = 0.0002" Distance error 0.000m. All data is stored on a SD data card and is then imported into the desired software accordingly. The time it took to perform the total station survey was roughly 30mins from the start of the resection to the final backsight check of the survey.

3.4.3 Laser Scanner

The HDS7000 was scanned using a total of three setups. This was completed to ensure that the flange edges were located and not just the face of the flange (which would have occurred from only one setup) so that cylinders could be constructed and modelled from the point cloud.

Setting up the job or project on the scanner is reasonably simple as this is input into the scanner on the main interface where the file extensions and project names are required.

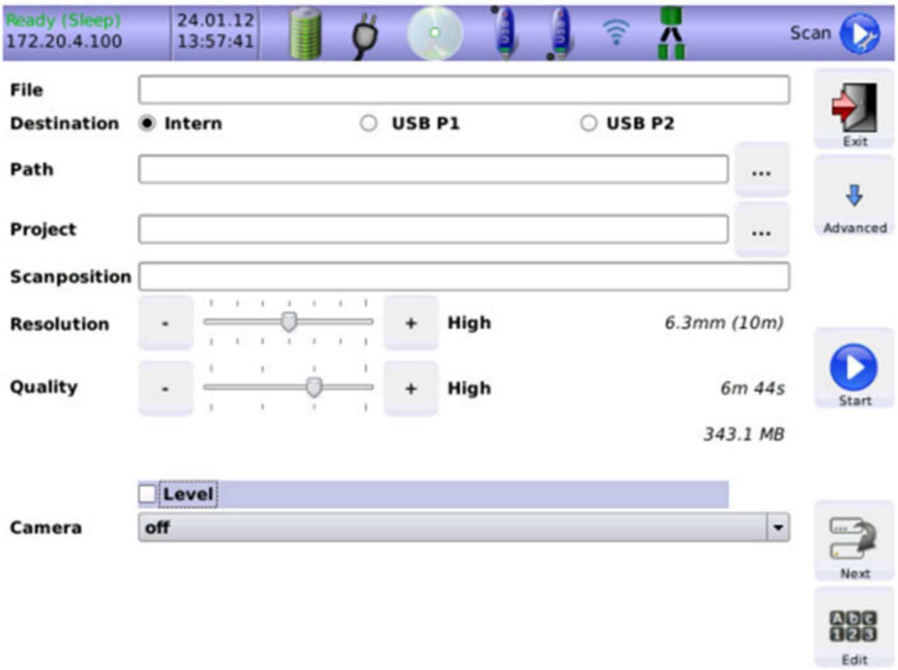


Figure 3.7 – Typical interface screen for Leica HDS7000 (Leica Geosystems 2019)

On this screen the user is able to setup the project and provide a destination where the filenames and paths for the data will be stored. The data can be stored either internally or on an external USB device as the data for this project was stored internally and then copied out on a USB after completion. A scan position is required to be entered which indicates the scanner location or station name setup, for this project the scan positions were named S1 through to S3 with 'S' representing the word station.

The last two settings are the two main critical settings required to be entered for the resolution and speed of the scans. The resolution indicates the incremental point spacing the scanner will capture, which for this project was set at ‘High’. The high setting provides a point spacing of 6.3mm over a standard distance of 10m; in reality for this project the laser scanner was positioned approximately 3m from the flanges which would equate to a point spacing closer to 3mm across the objects. Other resolution settings available are outlined in the below figure.

Resolution level	Increments (Hz / V)	Point spacing at 10 m	Pixel/ 360°	ZFS file size (compressed)[2]	Ideal object distance [3]
Preview[1]	0.288° / 0.288°	50.3 mm	1250	ca. 4 MB	> 0.5 m
Low	0.144° / 0.144°	25.1 mm	2500	ca. 15 MB	> 1 m
Middle	0.072° / 0.072°	12.6 mm	5000	ca. 60 MB	> 2 m
High	0.036° / 0.036°	6.3 mm	10000	ca. 240 MB	> 5 m
Super High[3]	0.018° / 0.018°	3.1 mm	20000	ca. 960 MB	> 20 m
Ultra High[3]	0.009° / 0.009°	1.6 mm	40000	ca. 5 GB	> 40 m
Extreme High[3, 4]	0.004° / 0.004°	0.6 mm	100000	ca. 34 GB	> 100 m

Figure 3.8 – Leica HDS7000 Resolution Settings (Leica Geosystems 2019)

The last setting to be chosen on the scanner is the scan quality or speed. The options provided for this range from low quality through to premium quality. The scan speed goes hand in hand with the resolution as these two settings provide the overall quality of the scans. The speed option chosen was the ‘normal quality’ which outputs 25rps, 254KHz and takes approximately 3:22mins to complete. The quickest time that can be selected is when the low resolution and low quality options are chosen, the scan takes approximately 26seconds to complete. The longest option is when the extreme high resolution and high quality are selected, this option takes approximately 2:42hrs. This method should not be chosen given the enormous amount of storage capacity required for the data as Leica Geosystems advise that only selection scans are performed; which means window scans of selected features and not full 360 degree scans.

Resolution level	Pixel/ 360°	Low quality[2]	Normal quality[2]	High quality[2]	Premium quality[2]
Preview[1]	1250	---	25 rps 31.75 KHz 0:26 min	---	---
Low	2500	50 rps 127 KHz 0:26 min	25 rps 63.5 KHz 0:52 min	12.5 rps 31.75 KHz 1:44 min	---
Middle	5000	50 rps 254 KHz 0:52 min	25 rps 127 KHz 1:44 min	12.5 rps 63.5 KHz 3:22 min	6.25 rps 31.75 KHz 6:44 min
High	10000	50 rps 508 KHz 1:44 min	25 rps 254 KHz 3:22 min	12.5 rps 127 KHz 6:44 min	6.25 rps 63.5 KHz 13:28 min

Figure 3.9 – Leica HDS7000 Quality Settings (Leica Geosystems 2019)

There were five Leica black and white tilt targets placed around the outside of the pipe work in similar positions to the laser tracker and total station points for control. This was completed to reference the different scans to each other otherwise known as registering the scans and allows the total station to locate these tilt targets to allow the scan data to be overlayed onto the laser tracker and total station data. The targets have reflective properties that allow the black and white sections of the target to be recognised by the software in order to create a centre point of the targets in the scans. This allows the three scans to be referenced together by adopting common target points within each scan. These common points are then aligned to each other in the software and are able to be registered together to form one complete point cloud with a standard error provided for the registered misclose. In order for the registration to work there must be at least three common points referenced between the scans and in this study all five points were scanned at each setup.

The TS15 total station located the black and white tilt targets to allow the scan data to be registered to each other. These points were located whilst the TS15 was setup for the total station survey and was completed by using the BRR and respective drift nest adaptor. The BRR was cradled inside the reflective holder and this was then held on the centre point of the black and white target with the offsets of the BRR and adaptor taken into account when locating the control so that the front surface of the targets were found. The registration results between the three scans equated to an overall error 0mm which signifies the accuracy in the total station readings and scan alignments.

After each scan was completed, the Canon Nodal Ninja DSLR camera was used to capture panoramic photos of the area. The special 'Nodal Ninja' bracket allows the camera to be centred on the laser scanners position and can capture each photo as if it was on the same point of axis as when the scanner was setup. This is performed to enable real-world colour to be applied to the scan point clouds in the software. The camera is fitted with a fish eye lens and sixteen photos were taken with eight taken on a 90 degree angle and another eight taken angled 45 degrees upwards. Once the photos were completed the scanner was shifted to the next station for the process to be completed again.

The time it took to complete the scanning was roughly 20mins. This takes into consideration the time the total station required to locate the scan control through to the actual scan and photo capturing aspects.

3.5 Post Processing and CAD Calculations

3.5.1 Laser Tracker & Total Station Data

Spatial Analyzer (SA) is software created by New River Kinematics for the use of specialised metrology equipment such as laser trackers. The software allows users to create three dimensional models out of point objects and specialises in the analysis and inspection of these models for design checking and reverse engineering. The advantage the software has is its ability to not only provide thorough inspection and analysis out of creating objects, but its ability to work sub-millimetre to ensure that it is powerful enough to handle the most demanding tolerances available.

The data which was stored from the laser tracker was automatically stored in SA when the field measurements were recorded. These are stored in group names selected by the user such as Flange 1 or Flange 2 and the point names, coordinates and codes are recorded in the group name folder accordingly to provide adequate structure and organisation of each point.

The total station data was exported from the TS15 machine as a text file and then imported into SA as the same extension. This stored all the data under a group name and the attributes of each point were similar to each laser tracker point where the name, coordinates and code were stored.

3.5.1.1 Calculating CAD Objects

Once all the data for the laser tracker and total station were imported into SA, the data could now be calculated into CAD objects. Specifically the points around the face of the flange were to be constructed as circles so that the centre of the circles can be used as one of the main calculation points for the study – the centre line of the flange. This was completed by constructing a circle out of the laser tracker and total station data using the best fit calculation method. This creates a perfectly round circle out of the eight shots surveyed around the outside of the flange and averages a best fit based on those shots.

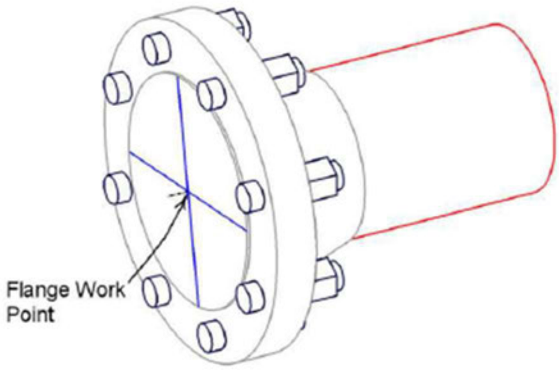


Figure 3.10 – Flange Centre Line Point

Because of the method used to create the circles, it was important to understand what errors were associated in the calculation of the circles and more importantly the standard deviation of each point from the calculated circle. This would enable the data calculations to be verified and validates the gross error achieved in the model calculation of each method. This was completed by creating a relationship in SA between the points and their object. This relationship is stored in SA and a report is available to be generated which describes the errors that exist and the measurement uncertainty calculations of each point compared to the modelled flange circle. The delta errors are provided for each calculated point for the object in their X, Y and Z value. The magnitude of these delta errors is also provided in the calculation to give the user an understanding of the length of the errors vector. A statistic table is created which simplifies the error relationship by providing a minimum and maximum value, the standard deviation of the error and also the Root Mean Square (RMS) value of the figures. From these reports the user is also able to identify the connection between the errors found in the circle calculations and the standard errors attributed to the respective pieces of equipment from manufacturing standards. Although this is not included in any calculations for this research, it is a useful tool to know whether or not the machine is working within its manufacturing specifications.

Once the calculations of the circle centres have been completed and the error reports of the calculations have been generated, the data is then exported out as an IGES extension to then be used within AutoCAD 3D to calculate the plane inclinations of the flanges and the bolt hole rotations from the 3D models already created in SA.

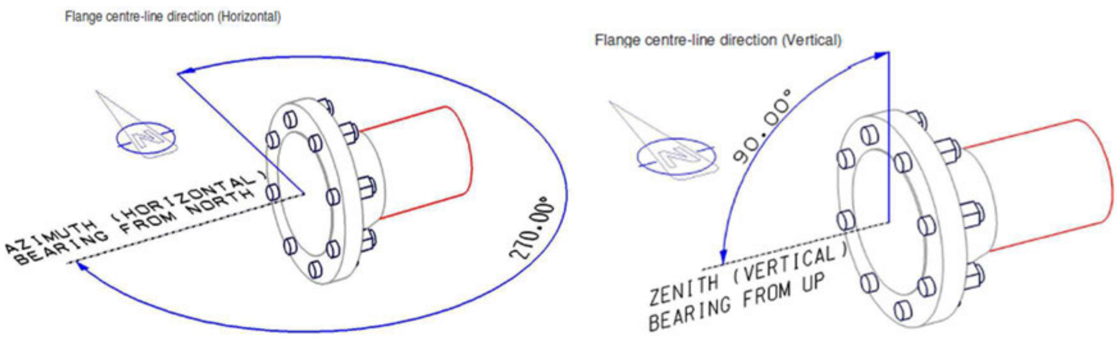


Figure 3.11 – Horizontal and Vertical Plane Inclinations of a Flange

The calculation of the flange inclination faces is reliant on two things – The horizontal and zenith (vertical) direction of the flanges to provide the desired calculation. All calculations are relative to the coordinate system datum used which was an arbitrary datum in this study. The calculation shown for the inclination angles are reported as a linear deviation over 1000 units and also as a linear deviation over the outside diameter of the flange (across the flange face).

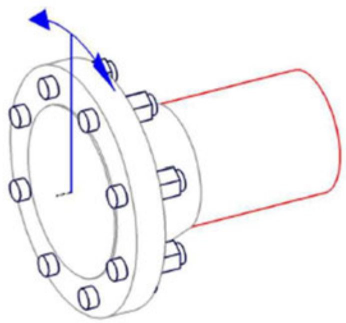


Figure 3.12 – The Bolt Rotation Orientation

The bolt rotation is similar to the flange inclination planes. This is reported as an angle from the nominal top centre of the flange to the first bolt in a clockwise direction and is shown in a decimal degree figure. Included with this report will be the displaced difference distance that the calculated bolt rotation reads to what a Class1500 ASME flanges normal rotation should be. The report will be able to unveil the differences that the two survey methods differ from the base readings of the laser tracker and also the differences that the three methods differ from the original ASME Class1500 rotation orientations.

3.5.2 Laser Scanning Data

Leica Cyclone version 9.1 is software that is compatible with all Leica scanners for post processing and CAD modelling of scan data. This software is capable of handling large point cloud files with the ability of registering the scans and also three dimensional CAD modelling and analysis. Point cloud colour mapping is also able to be overlayed on the scanned data with the panoramic photos captured by the Nodal Ninja. Because the camera used was an external camera to that of the scanner itself, this means that a manual geo-referencing of the photos is required to be completed before this can happen. This step happens by finding common points between the point cloud and the corresponding photo to align the photo onto the point cloud. This is similar to registering the scans together where common control points need to be aligned and referenced to each other. Once the geo-referencing is complete, the photo can be blended into the point cloud to provide a real life representation of the scanned area.

The files created from the scans were medium sized files as expected from a job that consists of only three scans. Each scan file was roughly 240MB which equates to around 700MB for the total size of the job. The three files took approximately twenty minutes to import into Cyclone on the same computer used in conjunction with the laser tracker and total station data. Before importing the data, the black and white tilt targets can either be chosen automatically by the software as control points or the user can enter these into each Modelspace created in Cyclone and complete this task manually. For this study the control points were estimated by the software on import and were checked and verified when completed. The appropriate labels for each control point were entered (P1-5) so our control point names match the control points from the laser tracker. This is performed so that when the scan data needs to be aligned onto the laser tracker data, these common control points can be related to each other inside the scan registration to enable a shift onto the correct datum for the job.

At this stage for the laser scanning processing it is now time to complete the registration of the individual scan stations. This is completed by creating a new registration of the job within Cyclone. Once created, the user will be taken to a new window of the registration and has the ability to choose each 'Scan World' (this is each individual station) to be selected for the registration. All three Scan Worlds are chosen and are now ready to be registered together. By registering the Scan Worlds together, the software is computing the scans together based on the common control points referenced within each scan. The registration now allows the user to inspect how the registration has performed based on the errors computed. This details a comprehensive report of each referenced control point within each matched Scan World and the error computed in the easting, northing and reduced level. The user has the ability to inspect each individual computed point and can manipulate what points they want included in the registration based on the errors found. This could be necessary if a job has a strict tolerance specified by a client and some computed control points included throw the result out of tolerance. Another reason could be a control point might have moved over the course of a job because it was not fixed correctly to a structure and the results to that specified control point are not acceptable to be used. This process is sometimes necessary to garner a result that the user deems suitable; however, removing too many points from the registration might not allow the registration to be computed with the limited control points available, or, the new geometry of the referenced scans could make the error even worse. This process is up to the discretion of the user and should be completed by someone experienced with point cloud registrations so that the most suitable and effective result can be achieved.

After completing the registration of the Scan Worlds with an allowable tolerance, a good quality assurance check of the registration is to run the registration again by computing cloud to cloud objects to each other. This is similar to computing the control targets to each other; however, the software instead matches objects it finds randomly throughout the scans such as a building corner or sharp edge of an object, which can give the user a good understanding of how accurate the registration is by this method. These cloud to cloud objects are then added into the original registration and the whole job is re-computed with these new control points. The errors found with the cloud to cloud objects should not be greater than the errors found with the control targets, as the cloud objects are reliant on these control points in the scans. If the software is able to identify cloud to cloud objects within the Scan Worlds, the user can be satisfied to know that the scans have aligned to each other within the specified accuracy and common points on a specific object will not deviate from the computed registration error. The user can remove these cloud to cloud points from the registration if they choose, or they can be left in to be included with the control target points for the overall registration.

At this point in the processing the registration of the Scan Worlds are complete, but the datum of the scans is still not aligned with that of the laser tracker and total station data. This process is relatively quick to perform which involves importing an ASCII text file into the scan job from where the scan data requires to be aligned to. A text file of the laser tracker with the point name, easting, northing and reduced level is now imported into the job. This text file is now created as a Scan World within Cyclone with the control points specified within the file. From here, the Scan World of the Laser Tracker text file is included into the registration as an individual Scan World. It is important that this Scan World is set to the 'Home Scan World' for the registration so that the registration will be basing the datum of the whole registration on this Scan World so the scan data can be aligned to this specified datum. Once applied, the registration is computed again and the user can check the errors associated from the scanner locating the control points compared to what the laser tracker surveyed. Once the user is happy with the registration it can now be frozen so that no edits can occur within the registration. A new Modelspace can be created with the combined files for any modelling and edits to occur.

The next stage of the laser scanning processing is preparing the data to be imported into Spatial Analyzer so that modelling of the flanges can occur. This means that individual point clouds of each flange need to be created in Cyclone so they can be imported individually. Modelspaces for each flange need to be created and cleaned so that when the points are imported into SA, they can be modelled straight away without any editing needed. The cleaning of each flange takes around ten minutes to complete so that any noise and unwanted points are eliminated from the data set. These flanges can now be exported from Cyclone as an ASCII text file to be imported into SA. From this stage on, the same method has been applied to how the laser tracker and total station data has been calculated and modelled.

3.6 Data Comparison

In order to establish a suitable method for conducting flange surveys, a comparison between the laser tracker, total station and laser scanning data must be performed. This will identify the accuracy differences that each respective method is able to produce and the errors that are associated with each survey method.

To perform such as task, two flanges will be surveyed and analysed. These two flanges will be first surveyed utilising a laser tracker to form a baseline result for the following two methods to be calculated against. The calculations that will be conducted consist of three different aspects. Firstly, the flanges will be modelled into cylinders so that the flange centreline coordinates can be established and compared. Secondly, the inclination planes across the flange faces will be determined in order to find out the displacement of the flange on its horizontal and zenith axis. Lastly, the bolt rotation for each flange will be calculated and compared to establish the displacement between each survey method.

The data obtained from these three calculation methods will be analysed and compared to identify which option is most suitable for conducting flange surveys.

3.7 Conclusion

This methodology chapter has outlined the appropriate methods that will be undertaken to fulfil the research aims. The study area and flanges used within the project have been identified. All the necessary equipment and applications used to capture and analyse/process the data were discussed, along with methods on how the data will be compared and analysed. All appropriate calculations and quality assurance checks on the data have been recognised to validate any results achieved for this project.

Chapter 4 – Results

4.1 Introduction

This chapter will identify the data that was captured in the methodology stage using the three methods for flange surveys. The differences between the data sets will also be presented and compared to allow analysis of the three components of calculation. All other data including checks will be outlined.

4.2 Flange centreline coordinates

4.2.1 Laser Tracker results

Flange Centreline Coordinates			
Flange 1 – Laser Tracker			
	X	Y	Z
Origin (mm)	**3123.59063**	**1594.15827**	**-395.10246**
Normal (mm)	**-0.980904**	**-0.194079**	**-0.012654**
Proj.Ang.	**Rx from Y**	**Ry from Z**	**Rz from X**
(deg)	**-176.2696**	**-90.7391**	**-168.8082**
Radius (mm)	**273.97479**	**Diameter (mm)**	**547.94959**

Table 4.1 – Flange 1 LT Results for Centreline Coordinates from SA

Flange Centreline Coordinates			
Flange 2 – Laser Tracker			
	X	Y	Z
Origin (mm)	**3348.40732**	**425.92690**	**-401.11480**
Normal (mm)	**-0.982076**	**-0.187786**	**-0.016210**

Proj.Ang.	Rx from Y	Ry from Z	Rz from X
(deg)	-175.0663	-90.9456	-169.1750
Radius (mm)	273.34589	Diameter (mm)	546.69177

Table 4.2 - Flange 1 LS Results for Centreline Coordinates from SA

4.2.2 Total Station results

Flange Centreline Coordinates			
Flange 1 – TS15			
	X	Y	Z
Origin (mm)	3122.95596	1593.97337	-394.90441
Normal (mm)	-0.980738	-0.194921	-0.012614
Proj.Ang.	Rx from Y	Ry from Z	Rz from X
(deg)	-176.2673	-90.7369	-168.7590
Radius (mm)	273.95961	Diameter (mm)	547.91922

Table 4.3 - Flange 1 TS Results for Centreline Coordinates from SA

Flange Centreline Coordinates			
Flange 2 – TS15			
	X	Y	Z
Origin (mm)	3347.77102	425.89271	-400.72434
Normal (mm)	-0.982032	-0.188016	-0.016188
Proj.Ang.	Rx from Y	Ry from Z	Rz from X
(deg)	-175.0691	-90.9444	-169.1615
Radius (mm)	273.14399	Diameter (mm)	546.28797

Table 4.4 - Flange 2 TS Results for Centreline Coordinates from SA

4.2.3 Laser Scanner results

Flange Centreline Coordinates			
Flange 1 – Laser Scanner			
	X	Y	Z
Origin (mm)	3122.07350	1592.17945	-393.45544
Normal (mm)	-0.983486	-0.180722	-0.009694
Proj.Ang.	Rx from Y	Ry from Z	Rz from X
(deg)	-176.3295	-90.5647	-169.5877
Radius (mm)	272.87454	Diameter (mm)	545.74908

Table 4.5 – Flange 1 Laser Scanner Results for Centreline Coordinates from Leica Cyclone

Flange Centreline Coordinates			
Flange 2 – Laser Scanner			
	X	Y	Z
Origin (mm)	3348.04234	425.70521	-399.20440
Normal (mm)	-0.981990	-0.188613	-0.011016
Proj.Ang.	Rx from Y	Ry from Z	Rz from X
(deg)	-175.1574	-90.6427	-169.1275
Radius (mm)	272.61431	Diameter (mm)	545.22862

Table 4.6 - Flange 2 Laser Scanner Results for Centreline Coordinates from Leica Cyclone

4.3 Standard Deviation & Redundancies of Flange Centreline Coordinates

The standard deviation results between the calculated objects compared to the individual points used for the model calculation. A model is calculated regardless of the accuracy of the surveyed points adopted, this method will identify the accuracy of those points and the modelled object. The independent redundant observations surveyed in the field are compared against the modelled flanges for further checks.

4.3.1 Laser Tracker Standard Deviation Results

Flange 1

Points to Objects Relationship Points to Flange 1 Laser Tracker (Reported in A::WORLD)				
Statistic	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Min	-0.03424	-0.00677	-0.00044	-0.04983
Max	0.04888	0.00966	0.00063	0.03491
Average	0.00000	0.00000	0.00000	-0.00000
StdDev from Avg	0.02561	0.00506	0.00033	0.02611
StdDev from Zero	0.02561	0.00506	0.00033	0.02611
RMS	0.02396	0.00474	0.00031	0.02442
Tol Range				
In Tol				
Out Tol				
Count	8			
Count	8			

Points to Objects Relationship Points to Flange 1 Laser Tracker (Reported in A::WORLD)										
Name	Point			Object			Delta			
	X1 (mm)	Y1 (mm)	Z1 (mm)	X2 (mm)	Y2 (mm)	Z2 (mm)	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
A::Flange 1::M,15,FEA002,A,F,F1	3141.30512	1486.17527	-111.46477	3141.35400	1486.18494	-111.46414	0.04888	0.00966	0.00063	-0.04983
A::Flange 1::M,15,FEA002,A,F,F2	3102.12262	1683.96592	-105.47456	3102.10903	1683.96324	-105.47474	-0.01359	-0.00269	-0.00018	0.01386
A::Flange 1::M,15,FEA002,A,F,F3	3068.89495	1862.30613	-262.66926	3068.88155	1862.30348	-262.66943	-0.01340	-0.00265	-0.00017	0.01366
A::Flange 1::M,15,FEA002,A,F,F4	3070.60294	1869.93988	-511.57121	3070.60710	1869.94070	-511.57115	0.00416	0.00082	0.00005	-0.00425
A::Flange 1::M,15,FEA002,A,F,F5	3103.02777	1716.46792	-672.64369	3103.02141	1716.46666	-672.64378	-0.00636	-0.00126	-0.00008	0.00648
A::Flange 1::M,15,FEA002,A,F,F6	3144.78967	1506.06752	-685.31374	3144.81279	1506.07210	-685.31344	0.02312	0.00457	0.00030	-0.02357
A::Flange 1::M,15,FEA002,A,F,F7	3177.94979	1328.33457	-532.18093	3177.94122	1328.33287	-532.18104	-0.00857	-0.00169	-0.00011	0.00874
A::Flange 1::M,15,FEA002,A,F,F8	3176.88739	1317.30705	-281.31453	3176.85315	1317.30028	-281.31498	-0.03424	-0.00677	-0.00044	0.03491

Figure 4.1 – Flange 1 Standard Deviation Results from Model to Points in SA

Flange 2

Points to Objects Relationship Points to Flange 2 Laser Tracker (Reported in A::WORLD)				
Statistic	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Min	-0.04578	-0.00875	-0.00076	-0.05365
Max	0.05269	0.01008	0.00087	0.04661
Average	0.00000	0.00000	0.00000	-0.00000
StdDev from Avg	0.03137	0.00600	0.00052	0.03194
StdDev from Zero	0.03137	0.00600	0.00052	0.03194
RMS	0.02958	0.00566	0.00049	0.03012
Tol Range				
In Tol				
Out Tol				
Count	9			

Points to Objects Relationship Points to Flange 2 Laser Tracker (Reported in A::WORLD)										
Name	Point			Object			Delta			
	X1 (mm)	Y1 (mm)	Z1 (mm)	X2 (mm)	Y2 (mm)	Z2 (mm)	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
A::Flange 2::M,15,FEA002,A,F,F59	3334.65158	472.01663	-101.66293	3334.67399	472.02092	-101.66256	0.02242	0.00429	0.00037	-0.02283
A::Flange 2::M,15,FEA002,A,F,F60	3310.03079	605.77204	-159.52108	3310.06730	605.77902	-159.52047	0.03650	0.00698	0.00060	-0.03717
A::Flange 2::M,15,FEA002,A,F,F61	3291.88310	715.50625	-331.27182	3291.86164	715.50215	-331.27217	-0.02146	-0.00410	-0.00035	0.02185
A::Flange 2::M,15,FEA002,A,F,F62	3301.44013	684.58741	-552.09582	3301.42212	684.58397	-552.09612	-0.01801	-0.00344	-0.00030	0.01834
A::Flange 2::M,15,FEA002,A,F,F63	3343.39227	477.96565	-700.12276	3343.37355	477.96207	-700.12307	-0.01872	-0.00358	-0.00031	0.01906
A::Flange 2::M,15,FEA002,A,F,F64	3383.38481	264.98946	-655.81732	3383.43750	264.99953	-655.81645	0.05269	0.01008	0.00087	-0.05365
A::Flange 2::M,15,FEA002,A,F,F65	3405.24037	133.71737	-459.19940	3405.23753	133.71683	-459.19944	-0.00284	-0.00054	-0.00005	0.00289
A::Flange 2::M,15,FEA002,A,F,F66	3392.99113	178.15925	-231.92748	3392.94535	178.15050	-231.92824	-0.04578	-0.00875	-0.00076	0.04661
A::Flange 2::M,15,FEA002,A,F,F67	3365.86027	310.48919	-121.20266	3365.85545	310.48827	-121.20274	-0.00482	-0.00092	-0.00008	0.00491

Figure 4.2 – Flange 2 Standard Deviation Results from Model to Points in SA

4.3.2 Total Station Standard Deviation Results

Flange 1

Points to Objects Relationship Points to Flange 1 TS15 (Reported in A::WORLD)				
Statistic	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Min	-0.38976	-0.07746	-0.00501	-0.25678
Max	0.25184	0.05005	0.00324	0.39741
Average	0.00000	0.00000	0.00000	-0.00000
StdDev from Avg	0.19134	0.03803	0.00246	0.19510
StdDev from Zero	0.19134	0.03803	0.00246	0.19510
RMS	0.17898	0.03557	0.00230	0.18249
Tol Range				
In Tol				
Out Tol				
Count	8			

Points to Objects Relationship Points to Flange 1 TS15 (Reported in A::WORLD)										
Name	Point			Object			Delta			
	X1 (mm)	Y1 (mm)	Z1 (mm)	X2 (mm)	Y2 (mm)	Z2 (mm)	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
A::UNI150620.txt::TIP01008	3149.38600	1446.16034	-165.72075	3149.31232	1446.14570	-165.72169	-0.07367	-0.01464	-0.00095	0.07512
A::UNI150620.txt::TIP01007	3173.65816	1334.25481	-323.62110	3173.61232	1334.24570	-323.62169	-0.04583	-0.00911	-0.00059	0.04673
A::UNI150620.txt::TIP01006	3168.14148	1377.05149	-556.02132	3168.11232	1377.04570	-556.02169	-0.02916	-0.00580	-0.00038	0.02973
A::UNI150620.txt::TIP01005	3134.94616	1551.13255	-665.12255	3135.01232	1551.14570	-665.12169	0.06617	0.01315	0.00085	-0.06747
A::UNI150620.txt::TIP01004	3097.05802	1739.21503	-625.72368	3097.21232	1739.24570	-625.72169	0.15431	0.03067	0.00198	-0.15734
A::UNI150620.txt::TIP01003	3070.00208	1861.92316	-418.31668	3069.61232	1861.84570	-418.32169	-0.38976	-0.07746	-0.00501	0.39741
A::UNI150620.txt::TIP01002	3078.46049	1807.09565	-228.72493	3078.71232	1807.14570	-228.72169	0.25184	0.05005	0.00324	-0.25678
A::UNI150620.txt::TIP01001	3113.24621	1625.23256	-123.02254	3113.31232	1625.24570	-123.02169	0.06611	0.01314	0.00085	-0.06741

Figure 4.3 – Flange 1 TS Standard Deviation Results from Model to Points in SA

Flange 2

Points to Objects Relationship Points to Flange 2 TS15 (Reported in A::WORLD)				
Statistic	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Min	-0.17250	-0.03303	-0.00284	-0.15032
Max	0.14762	0.02826	0.00243	0.17566
Average	0.00000	0.00000	0.00000	-0.00000
StdDev from Avg	0.13023	0.02493	0.00215	0.13262
StdDev from Zero	0.13023	0.02493	0.00215	0.13262
RMS	0.12182	0.02332	0.00201	0.12405
Tol Range				
In Tol				
Out Tol				
Count	8			

Points to Objects Relationship Points to Flange 2 TS15 (Reported in A::WORLD)										
Name	Point			Object			Delta			
	X1 (mm)	Y1 (mm)	Z1 (mm)	X2 (mm)	Y2 (mm)	Z2 (mm)	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
A::UNI150620.txt::TIP02008	3372.60354	276.61035	-173.31697	3372.75115	276.63861	-173.31453	0.14762	0.02826	0.00243	-0.15032
A::UNI150620.txt::TIP02007	3396.20177	166.76745	-329.11205	3396.05115	166.73861	-329.11453	-0.15062	-0.02884	-0.00248	0.15337
A::UNI150620.txt::TIP02006	3392.48323	205.72561	-556.01565	3392.55115	205.73861	-556.01453	0.06793	0.01301	0.00112	-0.06917
A::UNI150620.txt::TIP02005	3362.24917	373.31909	-668.41621	3362.35115	373.33861	-668.41453	0.10199	0.01953	0.00168	-0.10385
A::UNI150620.txt::TIP02004	3325.62366	561.87164	-636.51169	3325.45115	561.83861	-636.51453	-0.17250	-0.03303	-0.00284	0.17566
A::UNI150620.txt::TIP02003	3297.59351	691.42758	-440.81548	3297.65115	691.43861	-440.81453	0.05764	0.01104	0.00095	-0.05870
A::UNI150620.txt::TIP02002	3303.36583	644.22228	-242.71594	3303.45115	644.23861	-242.71453	0.08533	0.01634	0.00141	-0.08689
A::UNI150620.txt::TIP02001	3333.38853	477.96492	-133.01227	3333.25115	477.93861	-133.01453	-0.13738	-0.02630	-0.00226	0.13989

Figure 4.4 - Flange 2 TS Standard Deviation Results from Model to Points in SA

4.3.3 Laser Scanner Standard Deviation Results

Flange 1

Point Clouds to Objects Relationship Flange 1.xyz1 to Flange 1 Laser Scanner (Reported in A::WORLD)				
Statistic	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Min	-4.42839	-0.81375	-0.04364	-2.68979
Max	2.64537	0.48610	0.02607	4.50275
Average	-0.04590	-0.00843	-0.00045	0.04667
StdDev from Avg	1.36670	0.25114	0.01347	1.38965
StdDev from Zero	1.36748	0.25128	0.01347	1.39044
RMS	1.36405	0.25065	0.01344	1.38696
Tol Range				
In Tol				
Out Tol				
Count	200			
Sub-sampling ON. Thinned to 200 of 995				

Figure 4.5 - Flange 1 LS Standard Deviation Results from Model to Points in SA

Flange 2

Point Clouds to Objects Relationship Flange 1.xyz to Flange 2 Laser Scanner (Reported in A::WORLD)				
Statistic	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Min	-6.36895	-1.22331	-0.07143	-4.08765
Max	4.01403	0.77099	0.04502	6.48576
Average	-0.03814	-0.00733	-0.00043	0.03884
StdDev from Avg	1.79027	0.34386	0.02008	1.82310
StdDev from Zero	1.79067	0.34394	0.02008	1.82352
RMS	1.78619	0.34308	0.02003	1.81895
Tol Range				
In Tol				
Out Tol				
Count	200			
Sub-sampling ON. Thinned to 200 of 1866				

Figure 4.6 - Flange 2 LS Standard Deviation Results from Model to Points in SA

Following on from the standard deviation checks, the redundant observation checks from the laser tracker and total station are compared and summarised below.

4.3.4 Flange 1 Redundant Observation Summary for Laser Tracker (Radial offset check)

Points to Objects Relationship QA Redundancies Flange 1 Laser Tracker (Reported in A::WORLD)				
Statistic	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Min	-0.00613	-0.02547	-0.05803	-0.06794
Max	0.00521	0.03478	0.06039	0.06221
Average	-0.00000	0.00000	0.00000	-0.00000
StdDev from Avg	0.00388	0.01993	0.03240	0.03823
StdDev from Zero	0.00388	0.01993	0.03240	0.03823
RMS	0.00363	0.01864	0.03031	0.03576
Tol Range				
In Tol				
Out Tol				
Count	8			

Figure 4.7 – Flange 1 Redundant Observations LT

4.3.5 Flange 1 Redundant Observation Summary for Total Station (Radial offset check)

Points to Objects Relationship QA Redundancies Flange 1 Total Station (Reported in A::WORLD)				
Statistic	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Min	-0.00584	-0.02578	-0.02002	-0.03295
Max	0.00449	0.03787	0.02395	0.03845
Average	-0.00000	-0.00000	0.00000	-0.00000
StdDev from Avg	0.00352	0.02273	0.01543	0.02770
StdDev from Zero	0.00352	0.02273	0.01543	0.02770
RMS	0.00329	0.02126	0.01443	0.02591
Tol Range				
In Tol				
Out Tol				
Count	8			

Figure 4.8 – Flange 1 Redundant Observations TS

4.3.6 Flange 2 Redundant Observation Summary for Laser Tracker (Radial offset check)

Points to Objects Relationship QA Redundancies Flange 2 Laser Tracker (Reported in A::WORLD)				
Statistic	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Min	-0.00519	-0.04097	-0.02913	-0.03353
Max	0.00831	0.02744	0.03279	0.05096
Average	0.00000	-0.00000	0.00000	0.00000
StdDev from Avg	0.00413	0.02090	0.02133	0.03015
StdDev from Zero	0.00413	0.02090	0.02133	0.03015
RMS	0.00387	0.01955	0.01995	0.02820
Tol Range				
In Tol				
Out Tol				
Count	8			

Figure 4.9 – Flange 2 Redundant Observations LT

4.3.7 Flange 2 Redundant Observation Summary for Total Station (Radial offset check)

Points to Objects Relationship QA Redundancies Flange 2 Total Station (Reported in A::WORLD)				
Statistic	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Min	-0.00881	-0.02843	-0.04466	-0.05710
Max	0.00463	0.04663	0.04930	0.04797
Average	-0.00000	0.00000	0.00000	0.00000
StdDev from Avg	0.00478	0.02522	0.03003	0.03950
StdDev from Zero	0.00478	0.02522	0.03003	0.03950
RMS	0.00448	0.02359	0.02809	0.03695
Tol Range				
In Tol				
Out Tol				
Count	8			

Figure 4.10 – Flange 2 Redundant Observations TS

4.4 Flange Centreline Coordinate Differences

Flange Centreline Coordinate Differences			
Flange 1 – Laser Tracker to Total Station (mm)			
	X	Y	Z
Laser Tracker	3123.59063	1594.15827	-395.10246
Total Station	3122.95596	1593.97337	-394.90441
Total Difference	**0.63467**	**0.1849**	**-0.19805**

Table 4.7 – Flange 1 LS to TS Coordinates Differences

Flange Centreline Coordinate Differences			
Flange 1 – Laser Tracker to Laser Scanner (mm)			
	X	Y	Z
Laser Tracker	3123.59063	1594.15827	-395.10246
Laser Scanner	3122.07350	1592.17945	-393.45544
Total Difference	**1.51713**	**1.97882**	**-1.64702**

Table 4.8 - Flange 1 LT to LS Coordinates Differences

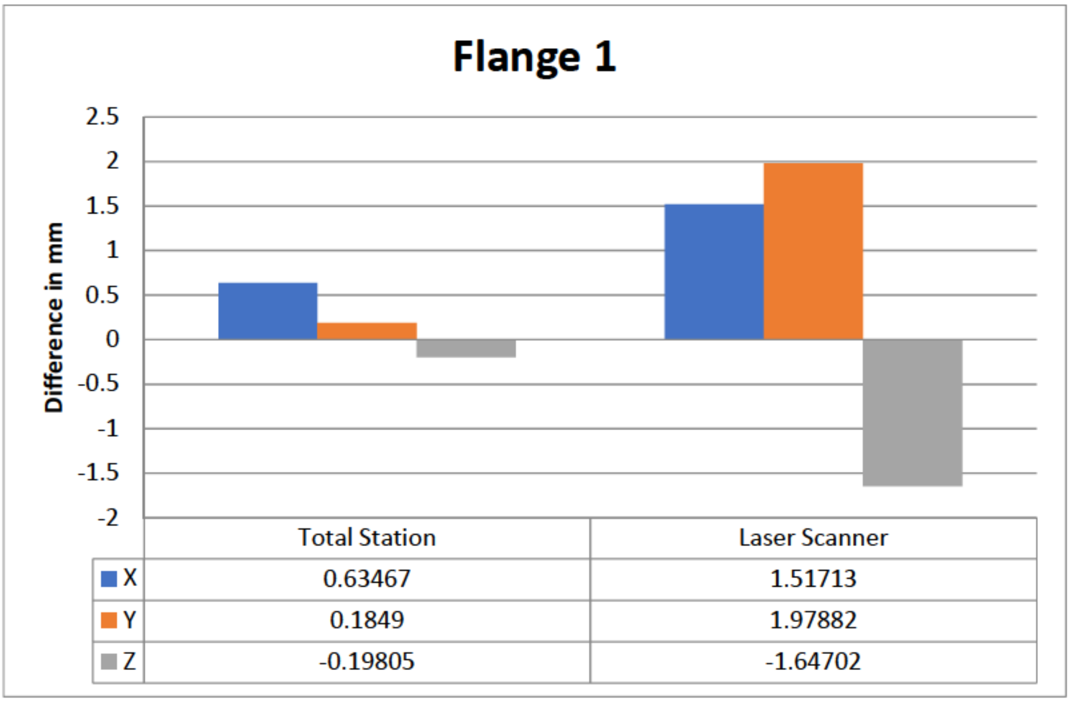


Table 4.9 – Flange 1 Coordinate Difference from Laser Tracker

Flange Centreline Coordinate Differences			
Flange 2 – Laser Tracker to Total Station (mm)			
	X	Y	Z
Laser Tracker	3348.40732	425.92690	-401.11480
Total Station	3347.77102	425.89271	-400.72434
Total Difference	**0.6363**	**0.03419**	**-0.39046**

Table 4.10 – Flange 2 LS to TS Coordinate Difference

Flange Centreline Coordinate Differences			
Flange 2 – Laser Tracker to Laser Scanner (mm)			
	X	Y	Z
Laser Tracker	3348.40732	425.92690	-401.11480
Laser Scanner	3348.04234	425.70521	-399.20440

Total Difference	**0.36498**	**0.22169**	**-1.9104**

Table 4.11 – Flange 2 LS to LS Coordinate Differences

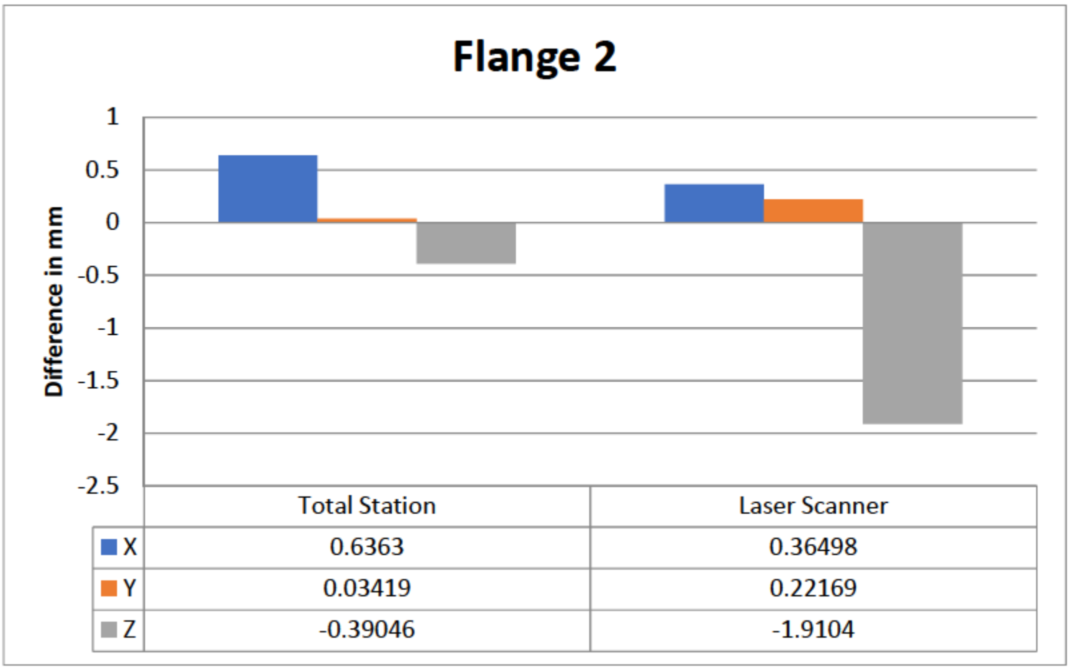


Table 4.12 – Flange 2 Coordinate Differences from LS

A summary of the flange diameter for the two flanges is illustrated below between the three survey techniques including the standard diameter for a ASME B16.5 Class 900 flange.

Instrument	Flange 1 Diameter (mm)
Flange Standard ASME B16.5 Class 900	546.10
Laster Tracker	547.95
Total Station	547.92
Laser Scanner	545.75

Table 4.13 – Summary of Flange 1 Diameters

Instrument	Flange 2 Diameter (mm)
Flange Standard ASME B16.5 Class 900	546.10
Laser Tracker	546.69

Total Station	546.29
Laser Scanner	545.23

Table 4.14 – Summary of Flange 2 Diameters

4.5 Plane Inclination Differences

The differences described with Delta to LS are the comparison to the baseline laser tracker measurements. A table summary highlights the inclination angles along both planes for flange 1 and 2.

Flange 1			
Plane Inclination	Laser Tracker	Total Station	Laser Scanner
North East (DMS)	176° 16'10.56"	176° 16'02.28"	176° 19'46.02"
North East (mm)	0	-0.02	0.57
Zenith North (DMS)	90° 44'20.76"	90° 44'12.84"	90° 33'52.92"
Zenith North (mm)	0	-0.02	-1.66

Table 4.15 – Plane Inclination Results Flange 1

Flange 2			
Plane Inclination	Laser Tracker	Total Station	Laser Scanner
North East (DMS)	175° 03'58.68"	175° 04'08.76"	175° 09'26.64"
North East (mm)	0	0.03	0.87
Zenith North (DMS)	90° 56'44.16"	90° 56'39.84"	90° 38'33.72"
Zenith North (mm)	0	-0.01	-2.89

Table 4.16 – Plane Inclination Results Flange 2

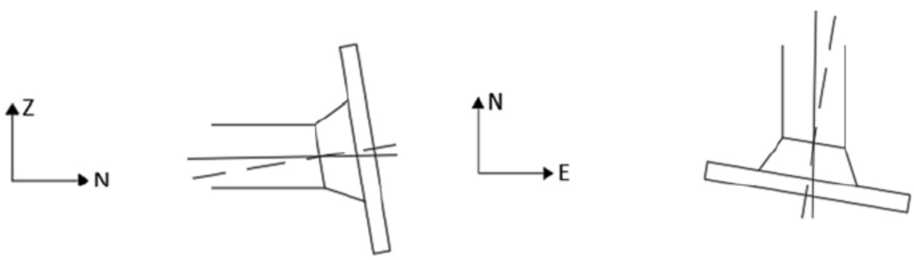


Figure 4.11 – Plane Inclination Examples

Flange 1

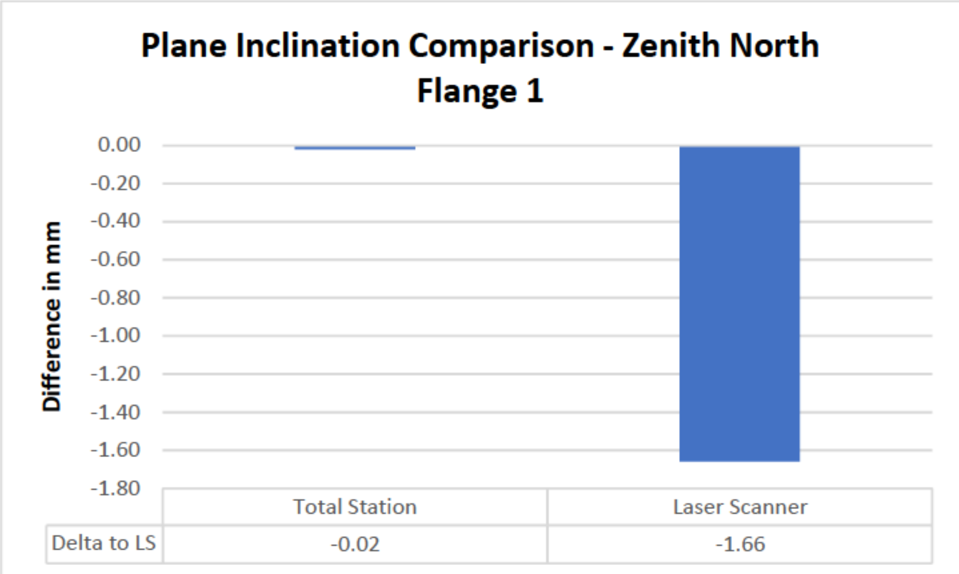


Table 4.17 – Plane Inclination Comparison Zenith North Flange 1

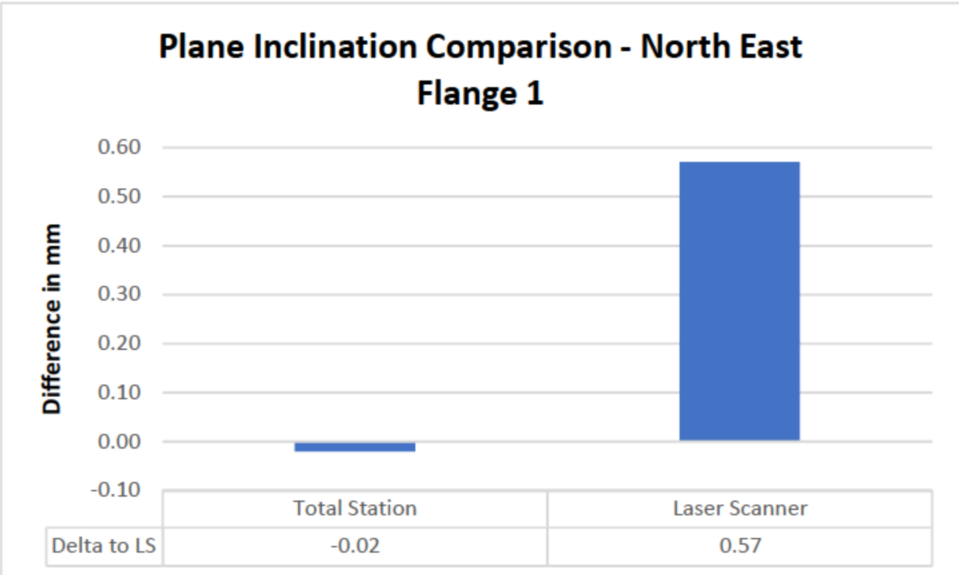


Table 4.18 – Plane Inclination Comparison North East Flange 1

Flange 2

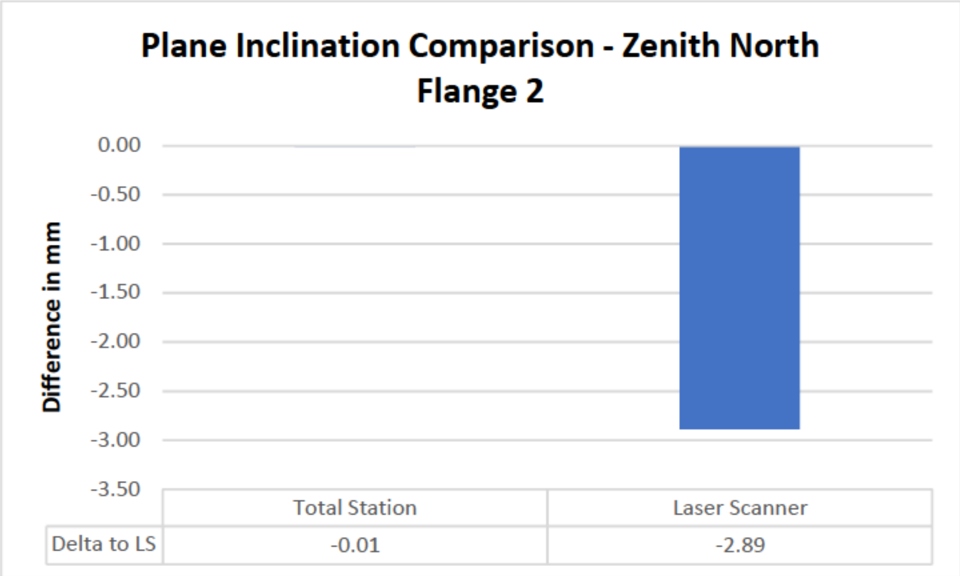


Table 4.19 – Plane Inclination Comparison Zenith North Flange 2

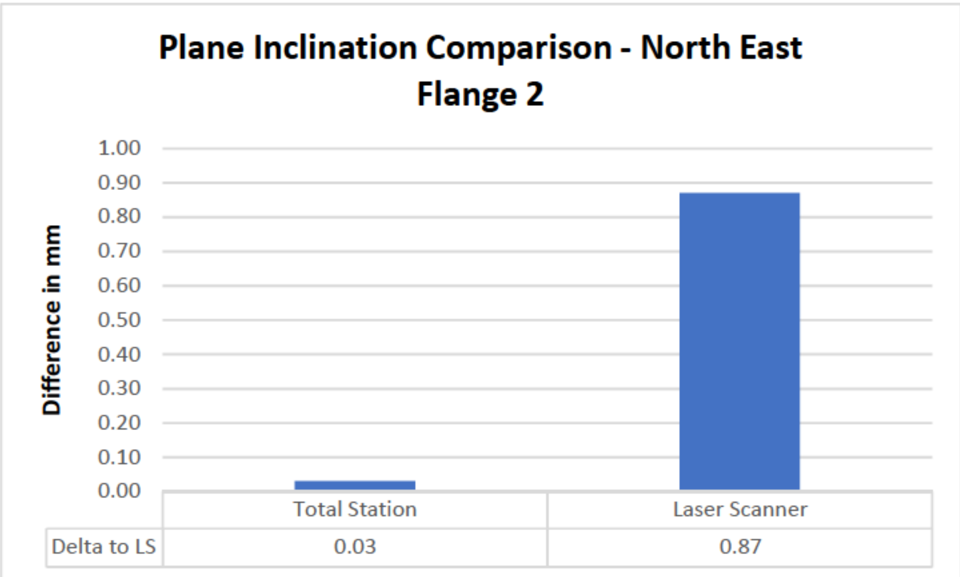


Table 4.20 – Plane Inclination Comparison North East Flange 1

4.6 Bolt Hole Rotation

The bolt hole rotation is calculated with zenith vertical and adopting the flange centreline coordinates as the base point and measuring the angle clockwise to the first bolt hole. The difference or 'delta' between the baseline laser tracker and the total station and laser scanner are then compared.

Flange 1			
Bolt Rotation	Laser Tracker	Total Station	Laser Scanner
Rotation (DMS)	11° 22'12"	11° 18'36"	11° 07'12"
North East (mm)	0	-0.25	-1.03

Table 4.21 – Bolt Hole Rotation Results Flange 1

Flange 2			
Bolt Rotation	Laser Tracker	Total Station	Laser Scanner
Rotation (DMS)	11° 24'36"	11° 27'36"	11° 33'48"
North East (mm)	0	0.21	0.63

Table 4.22 – Bolt Hole Rotation Results Flange 1

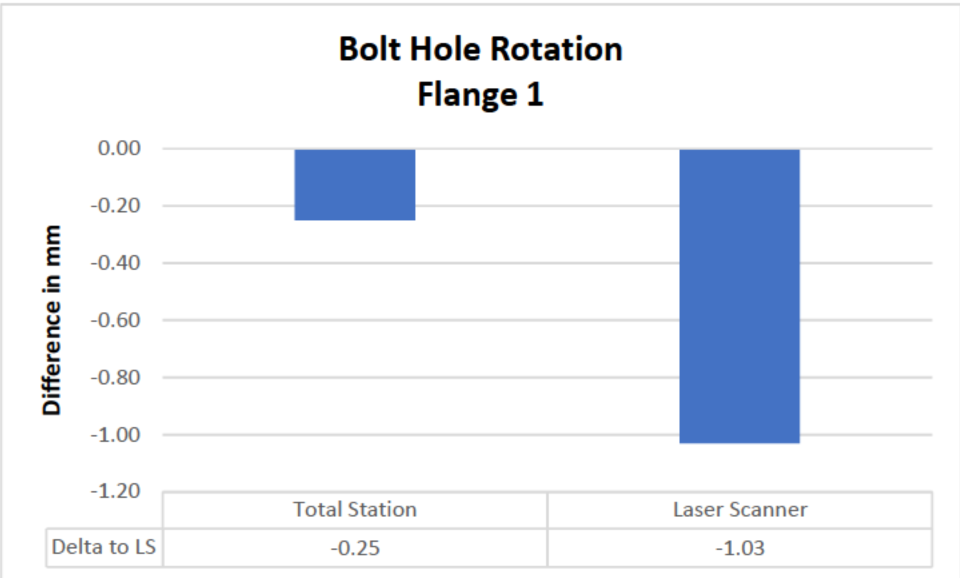


Table 4.23 – Bolt Hole Rotation Results Comparison Flange 1

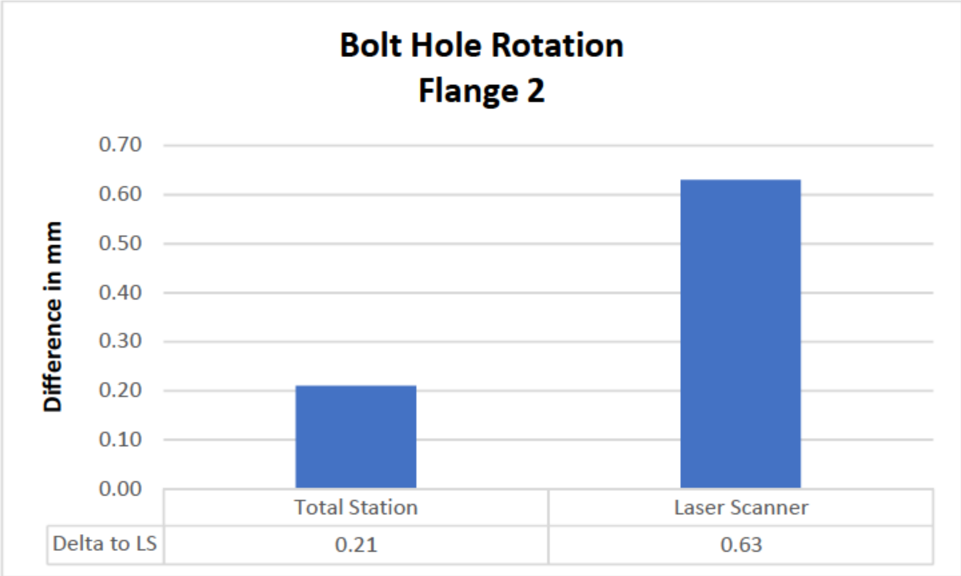


Table 4.24 – Bolt Hole Rotation Results Comparison Flange 1

4.6.1 Laser Scanner Flange Centreline Re-modelling

After the modelling of the laser scanner flanges, the results of the point cloud modelling were checked by adopting a different approach for the modelling. Instead of using the entire cleaned point cloud of the flange only eight points were included for the modelling. These points were chosen in a similar geometry to where the laser tracker and laser scanner measurements were taken around the flange with a summary of the results shown below.

Flange Centreline Coordinates			
Flange 1 – Laser Scanner (Eight measurements for modelling)			
	X	Y	Z
Origin (mm)	3122.27918	1592.16451	-393.46743
Normal (mm)	-0.964114	-0.194436	-0.014224
Proj.Ang.	Rx from Y	Ry from Z	Rz from X
(deg)	-176.3174	-90.5821	-169.7885
Radius (mm)	272.89014	Diameter (mm)	545.78028

Table 4.25 – Flange 1 Re-modelled Flange Centrelines with Eight Measurements for LS

Flange Centreline Coordinates			
Flange 2 – Laser Scanner (Eight measurements for modelling)			
	X	Y	Z
Origin (mm)	3348.14854	425.48862	-399.22864
Normal (mm)	-0.964841	-0.189843	-0.012547
Proj.Ang.	Rx from Y	Ry from Z	Rz from X
(deg)	-175.1494	-90.6311	-169.1381
Radius (mm)	272.57483	Diameter (mm)	545.14966

Table 4.26 – Flange 2 Re-modelled with Eight Measurements for LS

Plane Inclinations for the re-modelled flanges compared to the laser tracker and original laser scanner results were then calculated.

Flange 1			
Plane Inclination	Laser Tracker	Laser Scanner	Laser Scanner (8 Measurements)
North East (DMS)	176° 16'10.56"	176° 19'46.02"	176° 19'02.64"
North East (mm)	0	0.57	0.46
Zenith North (DMS)	90° 44'20.76"	90° 33'52.92"	90° 34'55.56"
Zenith North (mm)	0	-1.66	1.50

Table 4.27 – Flange 1 Re-modelled Plane Inclinations with Eight Measurements for LS

Flange 2			
Plane Inclination	Laser Tracker	Laser Scanner	Laser Scanner (8 Measurements)
North East (DMS)	175° 03'58.68"	175° 09'26.64"	175° 08'57.84"
North East (mm)	0	0.87	0.79
Zenith North (DMS)	90° 56'44.16"	90° 38'33.72"	90° 37'51.96"
Zenith North (mm)	0	2.89	3.00

Table 4.28 – Flange 2 Re-modelled Plane Inclinations with Eight Measurements for LS

Chapter 5 Discussion

5.1 Introduction

Data has been surveyed and captured using a baseline reading from a laser tracker of existing flanges. The same flanges have then been surveyed by the two comparison techniques described in the methodology phase with a total station and laser scanner.

Analysis of this data is brought forward and compared in the results stage through post processing and CAD calculations which outlines the three main components for calculation: flange centreline coordinates, plane inclination and bolt hole rotation. All other results and analysis shall be discussed to compare each method to finally determine a suitable method to conduct flange surveys. A summary of the results compared to the laser tracker is provided below.

Flange 1 (mm)		
Description	**TS**	**LS**
Flange CL Coordinate (bearing/SD)	**253° 45’26.79"** **0.69**	**217° 28’36.52"** **2.99**
Plane Inclination East/West	**-0.02**	**0.57**
Plane Inclination Zenith North	**-0.02**	**-1.66**
Bolt Rotation	**-0.25**	**-1.03**

Table 5.1 – Flange 1 Results Summary

Flange 2 (mm)		
Description	**TS**	**LS**
Flange CL Coordinate (bearing/SD)	**266° 55’27.52"** **0.75**	**238° 43’31.34"** **1.96**
Plane Inclination East/West	**0.03**	**0.87**
Plane Inclination Zenith North	**0.01**	**-2.89**
Bolt Rotation	**0.21**	**0.63**

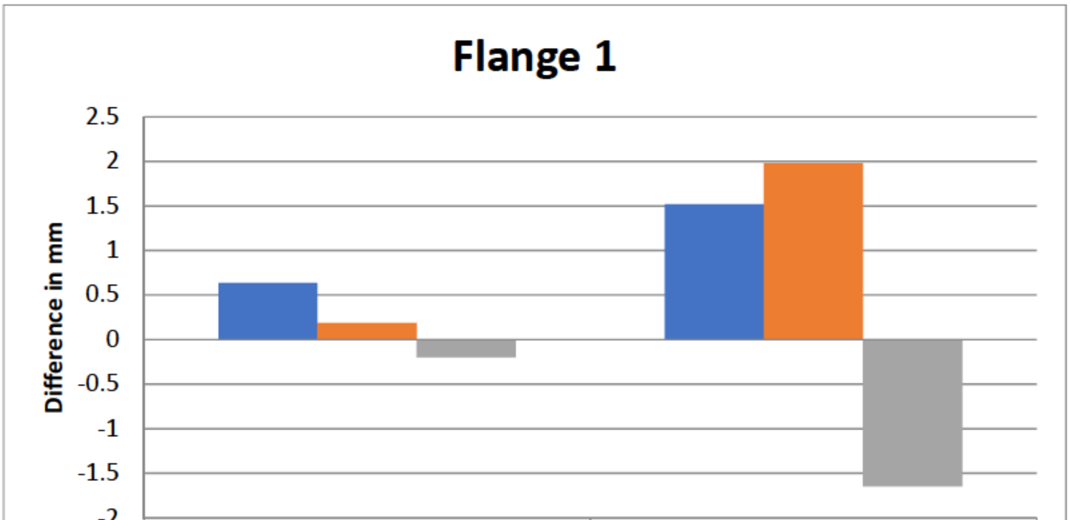
Table 5.2 – Flange 2 Results Summary

5.2 Flange Centreline Coordinates

The flanges were modelled in Spatial Analyzer by creating circles of the measured data which provided a three-dimensional representation of the face of the flanges. For the laser tracker and total station, the eight measurements around the outside face of the flange were calculated whilst for the laser scanner the point cloud of each flange were used. From the results, an easting, northing and reduced level were obtained.

5.2.1 Flange 1

The data for each method is provided in tables 4.2.A, 4.2.C and 4.2.E for each respective method. This table is an identical representation of the report generated out of Spatial Analyzer for the centreline coordinates. The results are expressed in millimetres given the high accuracy required for inspection and comparison. A summation of the results for flange 1 is provided below.



	Total Station	Laser Scanner
X	0.63467	1.51713
Y	0.1849	1.97882
Z	-0.19805	-1.64702

Table 5.3 – Flange 1 Summary Centreline Coordinates

The data for flange 1 shows that the total station method is comprehensive in its comparison to the laser tracker. The largest error found in the total station was less than a millimetre in the easting whilst the northing and reduced level were much better than expected given the standard accuracies associated with the total station. For a total error of approximately 0.7mm the total station provided a highly accurate reading for the flange when compared against the laser tracker.

Moving onto the laser scanner and the results for flange one can be expected with the working range and accuracy of a laser scanner. A consistent 1.5mm comparison against the laser tracker in both the easting and northing were found with the reduced level -1.65mm. The total error for the laser scanner is just under 3mm when comparing against the final location which was surprisingly high.

5.2.2 Flange 2

The data for flange 2 can be found in tables 4.2.B, 4.2.D and 4.2.F respectively for each method. Like flange 1, the tables represent the data from Spatial Analyzer and are displayed in millimetres. A summary for flange 2 is provided below.

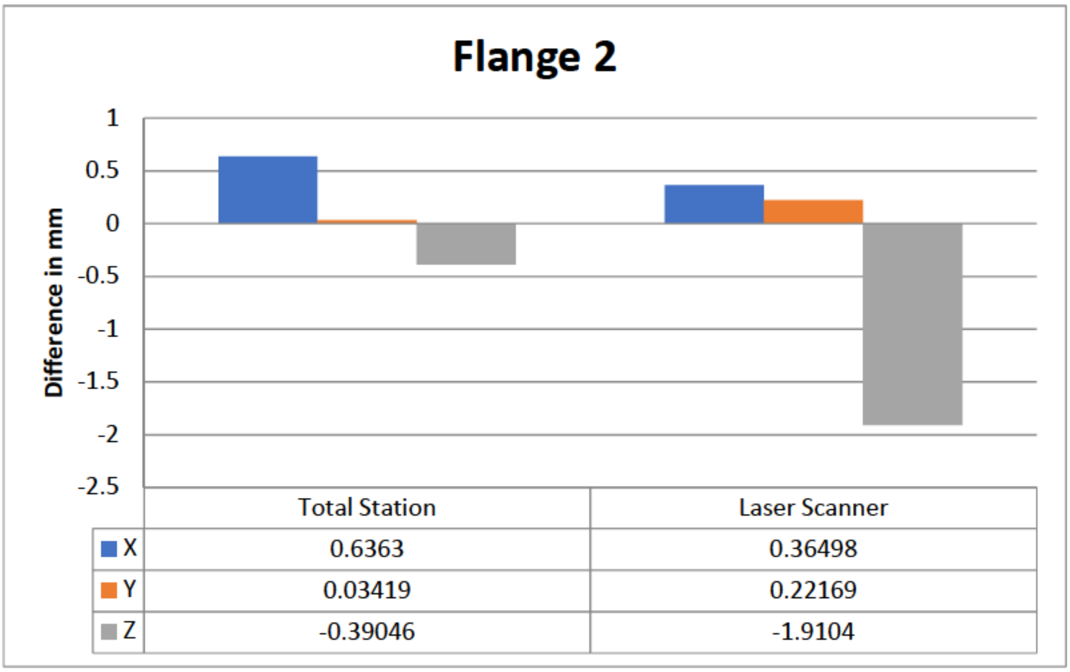


Table 5.4 – Flange 2 Summary Centreline Coordinates

The total station results for flange 2 mirror that of flange 1 where they provide consistent accurate results when compared against the laser tracker. The easting displays a 0.64mm error whilst the northing comes in within microns to 0.03mm. The reduced level sits below at -0.39mm. Given these results are fairly similar to flange 1 in terms of the overall error sitting at approximately 0.7mm, the total station datasets can be regarded as consistent between both flanges.

The laser scanner results for flange 2 have improved in the easting and northing where they are well below 0.5mm at 0.36mm in the easting and 0.22 in the northing. The reduced level sits at -1.91mm meaning the overall error when compared to the laser tracker is 1.96mm. This is an improvement by over 1mm when compared to flange 1 which provides a more accurate result for flange 2.

Given the variable results of the laser scanning centreline coordinates, a rationale of why there were differences between the two flanges can be put down to a couple ideas:

1. Modelling the CAD objects from the point cloud.

Compared to the laser tracker and total station measurements where eight surveyed points of the flange are used for CAD calculations, the point cloud provides thousands of points available for the calculation. It is up to the user to 'clean' the point cloud around the flanges which means removing any erroneous noise and trimming the point cloud to the outside of the flange for the objects to be created. This provides a lot of manual manipulation which is up to the discretion of the user on how much time is invested in this stage. Given the inexperience on modelling with point clouds, a caveat may be included on the calculations for the objects where a more experienced drafter and modeller may provide another method on cleaning and trimming the point clouds. This may attribute to the flanges where flange 1 was calculated first and flange 2 second which means that by the second flange calculation some experience had been gained when completing the first flange which may contribute to the slightly better results for flange 2.

2. The amount of points used for the CAD modelling

For both the laser scanning flanges most point cloud points were used for the calculation apart from points removed that were necessary for the calculations. Compared to eight points used for the laser tracker and total station, approximately one thousand points were included for the laser scanning flanges. To compare the datasets, the flanges were modelled again so that the same points were used in the scanning calculations to that of the laser tracker. Eight points were chosen from the point cloud and created into circles which were then compared to the laser tracker and the original laser scanner objects. The summary between the original laser scanner modelled object and the re-modelled objects compared to the laser scanner are provided below:

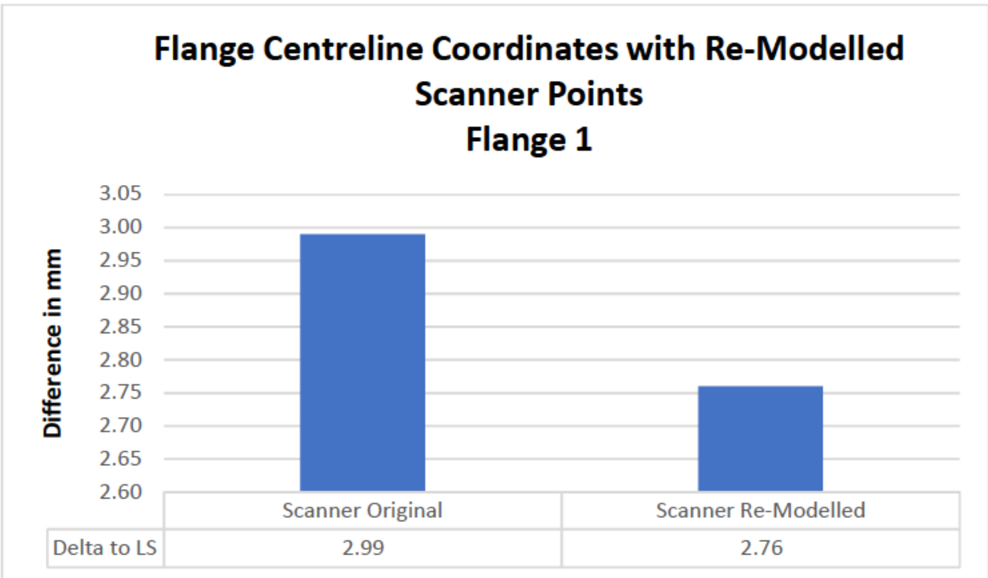


Table 5.5 – Flange 1 Summary Centreline Coordinates for Re-modelled LS Flange

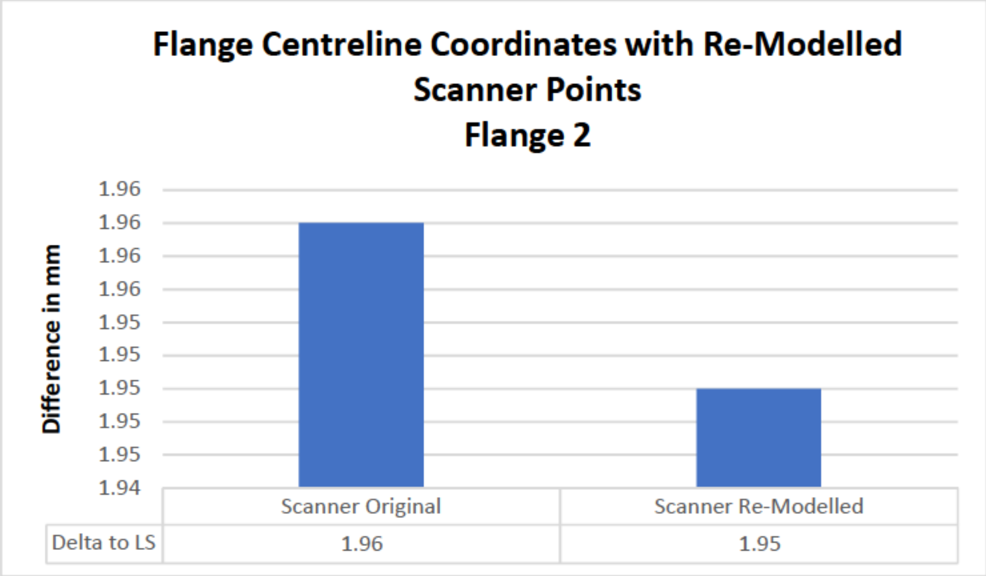


Table 5.6 – Flange 2 Summary Centreline Coordinates for Re-modelled LS Flange

The comparison for the overall error between the laser tracker and the two scanning objects provides a very small increase in accuracy. Flange 1 decreased slightly by 0.2mm whereas flange 2 was near identical to the original centreline coordinate for the laser scanner. There was not an obvious increase in accuracy in any of the easting, northing or RL's by adopting only eight points for the calculation compared to the entire point cloud for the flange.

5.2.3 Standard Deviations

The standard deviations of the CAD objects provide a reliable check against the quality of the datasets used. The circles are modelled from the datasets by a best-fit method from the chosen points and the standard deviations of those results will provide a good analysis on the quality of the modelling.

The figures for the standard deviations start from section 4.3.1 and portray the results for all three methods between the points and object relationships as described from Spatial Analyzer.

The laser tracker results provide micron type accuracies which should be expected given the accuracy of the machine. When you combine the instrument errors with the reflector and any other human errors, the results are expected. For flange 1 the minimum magnitude of the error equated to -50 microns whereas the maximum came in at 35 microns. Similar results again for flange 2 where the minimum and maximum statistics were -54 and 47 microns respectively. For the accuracies of the total station and laser scanner the accuracies derived from the laser tracker provide a good foundation for comparison.

The total station standard deviations can be located under section 4.3.2. Given the flange centreline coordinate results against the laser tracker were very impressive, the results from the standard deviations should be similar. The standard deviation from the average magnitude for flange 1 equates to 0.2mm whereas for flange 2 it equates to 0.13. Each point provides its own standard deviation error and for all sixteen measurements (both flanges) there was no greater than 0.4mm in error where some points even starting to fall into the micron type error.

The laser scanner results provided the greatest inconsistency in terms of the minimum and maximum errors. Given the amount points used for the calculation, the summary of the results is provided under section 4.3.3. For flange 1, the minimum and maximum error equated to -2.67mm and 4.50mm whilst for flange 2, the data did not provide any better results with -4.09mm and 6.49mm. In terms of the standard deviation of the average, this did dropdown to replicate the centreline coordinate errors that were found where for flange 1 1.39mm and flange 2 1.82mm. Given the large inconsistencies in the minimum and maximum values, some outliers existed in the point cloud. As described before where re-modelling had occurred, the manual manipulation of the point cloud in terms of cleaning and trimming was not straight forward and allowed too much exposure for the user to affect the results. These results prove this theory correct where there is a large inconsistency for each laser scanner object.

5.2.4 Redundant Observations

The redundant observations were measured in the laser tracker and total station field work stage where random independent observations around the flange outside were recorded with the RRR prism. This would provide another check against the modelled objects to ensure the accuracies of the measured points and CAD objects are reliable. It would also help define that the diameter of the flange was correct given the check points were taken in the radial axis.

The results can be found starting under section 4.3.4 where the laser tracker is compared first. For flange 1 the laser tracker QA points were calculated with a minimum and maximum magnitude error of -68 microns and 62 microns. The standard deviation from the average was 38 microns. For flange 2 the results were slightly better where the min and max were -34 microns and 50 microns respectively with the standard deviation from the average coming in at 30 microns. The results prove that the calculated circle objects are reliable and ensure that the baseline readings from flanges are true and correct.

Surprisingly though, the total station results were extremely accurate when compared to the laser tracker results with flange 1 coming in with a min and max of -33 microns and 38 microns. The standard deviation from the average was even more accurate than the laser tracker with 28 microns. Flange 2 also provided micron type results with the min and max of -57 microns and 48 microns along with 40 microns for the average. The results for the total station show that the modelled objects can be considered reliable given the supremely accurate results found from the independent checks.

1.1.1 Flange Diameter

Although not a requirement for this study, the flange diameters are automatically calculated when the objects are modelled. Given this is the case, a brief discussion on the diameters encountered is outlined below.

Instrument	Flange 1 Diameter (mm)
Flange Standard ASME B16.5 Class 900	546.10
Laser Tracker	547.95
Total Station	547.92
Laser Scanner	545.75

Table 5.7 – Summary of Flange 1 Diameters

Instrument	Flange 2 Diameter (mm)
Flange Standard ASME B16.5 Class 900	546.10
Laser Tracker	546.69
Total Station	546.29
Laser Scanner	545.23

Table 5.8 – Summary of Flange 2 Diameters

One surprise from the calculated diameters is for flange 1 where the laser tracker baseline reading modelled a diameter of 547.95mm. This was further proved through the standard deviation stage and then again from the redundant independent checks of the radial size of the objects. When comparing to the standard ASME B16.5 class 900 flange, a discrepancy of 1.85mm was encountered. Although it's not a great error in the diameter, the standard deviation as specified in ASME B16.5 should not differ by more than 1.5mm. This means that the working diameter range for the flange should be between 544.60mm and 547.60mm. This showed that flange 1 was outside its tolerance range for diameter size by 0.35mm which although does not affect the results in this study, it leads to another conversation for further research on flange construction standards. Flange 2 was calculated to be 0.59mm away from its true standard diameter which was well below the tolerance.

5.3 Plane Inclination

The plane inclination is important to understand as it allows the user to understand the skew of the flange in respect to both the X and Y axis. For this study, the inclination is expressed as the error across the flange face from one side to the other through degrees minutes seconds and the overall distance in millimetres as expressed in figure 5.11.

The results of the plane inclination in section 4.5 provide a clear indication of the accuracies for both the total station and laser scanner.

The total station results show micron type deltas when compared to the laser tracker which is consistent to the flange centreline coordinates and the redundant independent checks. For flange one the total displacement for both the axis equates to -0.02mm in north east and zenith north. For flange 2 the results are similar with 0.03mm in north east and 0.01mm in the zenith north. These calculations show supremely accurate results when comparing against the laser tracker with very little displacement across the flange face.

The laser scanner results for flange 1 especially in the north east axis show reasonably accurate data when compared to the laser tracker. With an error of 0.57mm in the north east and for flange 2 coming in at 0.87mm this provides reliable results to compare against. The zenith north calculations provide slightly higher results with flange 1 -1.66mm and flange 2 at 2.89mm. A couple discussion points around the higher values in the zenith may be attributed to the results found in the centreline coordinates especially for flange 2 where it recorded a much higher result in the RL. This may be attributed to the angle of incidence of the survey where the laser beam of the scanner was above the flange level such that is was looking down when measuring the two flanges. Although the angle was not drastic, it may provide some inconsistent results that could contribute to the results.

Figure 5.1 – Laser Scanner Angle to Flange

It must also be discussed that from the re-modelled flanges with the eight measurements for the laser scanner, the plane inclinations did not improve significantly if at all. The tables found in section 4.6.1 show a slight increase of accuracy in the north east of 0.11mm for flange 1 and 0.08mm for flange 2. For the zenith north flange 1, again a slight increase by 0.16mm, however, flange 2 showed a worse accuracy of 0.11mm in the re-modelled flange objects. Although there were slight increases for some aspects of the plane inclination for the re-modelled flanges, the inconsistencies and exposure to the point clouds provides too many variables to consider the laser scanner data consistent and reliable especially when comparing against the total station data.

5.4 Bolt Hole Rotation

The bolt hole rotation provides a means of calculating the alignment of the flange with respect to the pipe alignment. It can be measured either positively or negatively from zenith north but usually expressed positively for easier understanding. Understanding the rotation of the bolt holes although is not as critical as the flange centreline coordinates and plane inclination, it is still required to be known to allow the alignment of the flange to be calculated.

For a class 900 flange, the flanges in this study have 16 bolt holes fixed on the flange evenly spaced apart. In a perfect world the spacing between each bolt hole is evenly spaced at 22.5 degrees apart. The actual spacing between each bolt hole was not checked against the applicable standard for this study as it did not serve the purpose for the aim.

The bolt holes were calculated and checked to the first positive bolt hole from zenith north and again, the total station provided more accurate results. For flange 1 the total station encountered an error of -0.25mm and for flange 2 was at 0.21mm. Consistent results from the total station which have been found in the two other calculations and including the standard deviation and checks.

Secondly the laser scanning results were compared which involved creating objects from the outside of the bolt hole to find the centre point. Given the small working area in the point cloud, this provided a much easier task to model the bolt holes compared to the overall flange size. The centre point will then act as the same point measured in the total station stage. For the laser scanner data, the results encountered were of similar quality to the previous centreline and plane inclination results. For flange one there was an error of -1.03mm and for flange 2 an error of 0.63mm. Given the overall quality found for the bolt hole rotations with the laser scanner, the data can be considered reliable enough for use but again the comparison to the total station leaves a little to be desired.

5.5 Time Comparison

There were two main considerations of time which were for the field work and post processing CAD modelling calculations.

5.5.1 Field Work

For the field work of the laser tracker the approximate time it took to complete the field survey of two flanges was 1 hour. This included the setup of the instrument with the computer and software and the location of survey control. The two flanges were surveyed which included the independent redundant checks on the stable mode of the laser tracker. The laser tracker automatically recognises movement from the RRR prism and when the measurement mode is in stable mode, the instrument will not take a measurement. This accounted for a bit of time at the start of the survey given the instrument is very sensitive to movement which involved a lot of concentration and stillness and understanding when the instrument will record a point. There was no time involved downloading or uploading data given the instrument was already recording measurements straight into Spatial

Analyzer. For future work with the laser tracker, time can be saved in the field work through experience by understanding the nuances of the machine and how it operates. Some time was spent ensuring that the meteostation and external temperature sensors were working correctly before starting and understanding how the software operates with the instrument on initial connection and measurement. Also trying to organise the datasets within Spatial Analyzer took some time to recognise given the format and structure in how the measured points are saved in the software. Approximately 20mins could have been saved if an experienced operator was completing the survey with the laser tracker who also understood Spatial Analyzer software.

For the total station survey, the time to complete the field work took approximately 30mins. This included importing a text file from the laser tracker survey control into the total station to complete an initial resection. From here, the flanges were surveyed using a controller and given the previous experience of using the instrument and software on the controller, this stage was fairly autonomous through field capture. Locating the survey control at the end of the survey was the last step for the total station and through this method not much more time could have been saved then the 30mins it took to complete.

The laser scanner was the last method completed and the total time to complete the survey was approximately 25mins. The five black and white tilt targets are surveyed in the 360 degree scans so control registration in the field is not required. This meant that after a quick setup of the onboard software of the scanner in terms of the project and folder structures, scanning could commence immediately. Given the scans lasted approximately 6mins each, there was some time available to walk around and turn the tilt targets to the next stations given they were scanned already from the current station. Once the first scan was completed the process was completed again for the next two setups. Downloading the data to a USB drive took approximately 2-3mins which is then uploaded into the computer to be brought into Leica Cyclone. Given the experience with the specific laser scanner the time to complete the field work was as efficient as it could realistically be.

The last time consideration for the laser scanner involves the use of the total station to survey the scanning control. The process for this took approximately 10mins. Given the scanning data was required to be georeferenced to the datum of the laser tracker and total station, a total station is required to locate the control. This provides a downside to the laser scanning method as another instrument is required for the field work which also adds to the time to complete the survey.

5.5.2 Data Processing and CAD Calculations

The data for the laser tracker as previously mentioned was already saved in Spatial Analyzer which meant no time was spent processing or editing data before it was brought into the software. With the points already available and saved in the software, the modelling of the flanges could begin straight away. This stage was relatively straight forward given the software prompts most of the actions. With the circles created in the software the two main calculations of the flange centreline and plane inclinations were completed. The last calculation for the bolt holes involved using the modelled flange objects and the bolt hole points to calculate the angle of rotation. Once the calculations were completed some QA reports were generated of the CAD objects including the standard deviations and independent checks. The time to complete this took approximately 30-45mins.

For the total station data the procedure was near identical to that of the laser tracker for calculating the three main components including the report generation. The only difference being that a text file of the total station data was imported into the software to begin with and 5-10mins it took to then re-structure the data into the correct layers and folders. The overall time it took to complete the processing and calculations of the total station data was approximately 45mins.

The laser scanning data took a different approach where the scan data needed to first be brought into Leica Cyclone. The first stage was to register the scans and involved importing a text file of the survey control into Cyclone. Manually picking the control tilt targets inside each scan to register the cloud on an arbitrary datum and then aligning the data to the laser tracker datum through the text file. Once registered, the data was ready for inspection and cleaning, and the overall time it took to register the point cloud to then clean and trim took approximately 2hours. Given the manual exposure to the point cloud in terms of cleaning and trimming the time for this stage could vary dramatically either side of 2hours. Very little time could be spent cleaning and trimming the point cloud depending on the accuracies required whereas if a tighter tolerance was needed, then more time could have easily been dedicated to this stage. With some exposure to Leica Cyclone previously, the registration was completed efficiently. With regard to the manual cleaning and trimming of the point cloud, a more experienced user of the software could have saved 20-30mins out of the overall 2hours in this stage. The data was then exported out of Cyclone in an XYZ format to be imported into Spatial Analyzer for the CAD calculations to start. The calculations were similar to the tracker and total station and the overall time it took for the scanning data in Spatial Analyzer took approximately 25mins.

5.6 Conclusion

The three main components have been calculated through the results phase which have highlighted the necessary information to sufficiently analyse and determine the most suitable method. The flange calculations have been appropriately checked through independent redundancies to ensure the validity and accuracy of the data.

From the findings that were discussed, it was evident that the total station results provided far superior accuracies on the two flanges surveyed. For the three components of calculation, the total station proved that it was capable of recording results even superior then the instruments specification tolerances when compared against the laser tracker and recorded micron type accuracies in some applications. The laser scanning data provided results that were inconsistent when calculated which was also attributed to the amount of attention and manual exposure required for the point cloud cleaning and trimming. Especially for the flange centreline coordinates, the absolute distance of the laser scanning data compared to the laser tracker varied by nearly 3mm for flange 1 and 2mm for flange 2. The results showed that the data was unreliable given the inconsistencies encountered which proved that the total station was the more suitable method in terms of accuracy and time.

Chapter 6 - Conclusion

6.1 Introduction

The overall research aim of this study has been achieved through the analysis and comparison of the datasets captured in the methodology stage, analysed in the results chapter and further reviewed for discussion. The data has proved through the comparison between the two survey methods that the total station has provided superior results that has satisfied the criteria for the three main calculation components.

6.2 Research Findings

The laser tracker provided a baseline reading for the foundation of the survey comparisons given its supreme accuracy for measurement. For the traditional methods of surveying utilising a total station and laser scanner, the comparison to the laser tracker for the flange centreline coordinates, plane inclination and bolt hole rotation formed the basis of the research.

The total station was found to be the more suitable method for conducting flange surveys given the higher quality accuracy, consistency and reliability. The laser scanning data was found to be too inconsistent in the results phase especially in the flange centreline coordinates. For flange 1, the total station results showed that the total error from the laser tracker was 0.69mm compared to the laser scanner at 2.99mm. For flange 2, the total station results came in at 0.75mm compared to 1.96mm for the laser scanner. These results were surprising given that the standard deviations for the laser scanner were significantly large which again proved the theory that there was too much manual manipulation for the operator when cleaning and trimming the point clouds which could affect the data substantially. For the plane inclination calculations, the total station recorded error results to the microns given the largest error was 30 microns. Again, the laser scanner recorded results between 1mm to 3mm which proved the inconsistencies working with the point cloud. The bolt hole rotations proved the best accuracy for the laser scanner given flange 1 results were within -1.03mm of the laser tracker, whilst flange 2 data was 0.63mm away. The total station though was still much more consistently accurate at -0.25mm and 0.21mm for flange 1 and 2 respectively. Given the results of the laser scanning data and more importantly the concerns with the editing of the point cloud, more work around improving the cleaning and trimming of the data would have been preferred to see if other alternatives methods would have provided more consistent results.

6.3 Further Research and Recommendations

The obtained results proved unequivocally that the total station was the far superior method for conducting flange surveys. Although the research proved this to be the case, technologies such as hybrid instruments with total station and laser scanning capabilities are relatively new to the industry and could provide the missing link between both conventional methods. Standard total stations provide the accuracy necessary to garner the appropriate results, however, they lack the overall volume and detail of data capture. Laser scanning on the other hand provides a rich dataset full of detail, however, the accuracies necessary for conducting flange surveys are too inconsistent and not reliable and they often rely on other instruments such as total stations to assist for survey control location. Hybrid instruments such as the Leica MS60 and Trimble SX10 provide the gateway of an accurate total station with scanning capabilities as this technology should be investigated for its ability to conduct flange surveys from an accuracy and cost benefit point of view.

Laser trackers are supremely accurate measuring machines which are often used for industrial type reverse engineering applications. Part of this research touched on the fact that the diameter for flange 1 was constructed outside of the working tolerances specified in the ASME B16.5 standard. Highlighting this issue even more so, further checks on the construction standards could be investigated to understand the applicable tolerances required for the construction of a flange such as the overall diameter, thickness, bolt hole spacing and raised face plate to name a few. Measuring a number of flanges and reverse engineering them could provide results that could be beneficial to a number of stakeholders to provide statistical analysis and more importantly the confidence that the construction tolerances have been achieved.

6.4 Conclusion

Flange surveys are unique to the surveying industry given the specialised equipment and accessories are usually found in other industries such as metrology. Understanding the technology involved and the correct methods to apply is not commonly known throughout the industry. The findings of this study have highlighted two conventional methods for surveying flanges, the field methodology in how it was applied and the necessary steps to calculating the flange objects to achieve the required results. Analytical datasets have been highlighted that outline the three main components for calculation which have been evaluated and compared. Through a comparison against the baseline readings of the laser tracker, the total station has been found to be the preferred method of choice over the laser scanner.

The statistical analysis of the results has highlighted the total station to be the preferred method for conducting flange surveys, however, new technologies provide an insight to the future of the industry and the combination between metrology and surveying enables new advancements to be discovered and explored.

Appendix

Appendix A – Project Specification

University of Southern Queensland

FACULTY OF HEALTH, ENGINEERING AND SCIENCES

ENG4111/4112 Research project
PROJECT SPECIFICATION

FOR: **Greg Lee**

TOPIC: A COMPARISON ANALYSIS INTO FLANGE SURVEY METHODS

SUPERVISOR: Shane Simmons

SPONSERSHIP: FYFE PTY LTD

ENROLMENT: ENG4111 – EXT S1, 2019
ENG4112 – EXT S2, 2019

PROJECT AIM: The aim of this project is to compare and analyse different survey methods applied to flange survey's based on their accuracy results through 3D modelling in order to find the three crucial calculations required on flanges – Centreline coordinates, plane inclination and bolt hole rotation. A full cost benefit analysis will be undertaken to determine the accuracy results compared to the required workflows and equipment expenditure to complete the survey methods. The project will conclude which survey method is the appropriate method to be applied to flange survey's through these processes.

PROGRAMME: Issue A 20TH March 2019

1. Research statistical information regarding the survey equipment to be used to understand accuracy errors and limitations. Research background information relating to flange survey's, dimensional control and flange/spool fabrications in the oil & gas industry.
2. Organise and design field survey procedures for each flange survey proposal and collect appropriate data from each method to model the flanges required.
3. Download field data and reduce survey information. Use appropriate software to model the flange for each survey method.

4. Research information needed to conduct a cost/benefit analysis of the survey methods performed.
5. Provide a conclusion to which survey method should be adopted based on the results from the field/modelling accuracies and the cost/benefit analysis.

As time permits:

6. Design a field and office procedure document for the nominated survey method to be adopted.

Appendix B – Risk Assessment

Project Number	**UNI THESIS**	**JHA No. for Project (eg. 3)**	1	**Date**	**29/05/2019**	**Page 1 of 1**	
Description of Project Activity	**Field work for surveying pipeline flange**						
Worksite	**Yatala Pre-cast yard WDS**	**Expected Duration**	**1 day**				
Has this Job Activity been done before? (delete one)	**No**	**If yes, has the previous JHA been reviewed?**	**N/A**				
Supervisor (or Permit Holder for remote work conducted under a Work Permit) approving the use of this JHA							
Company	**N/A**	**Name**	**Greg Lee**	**Signature**			
Risk Details							
L = Likelihood of Risk Occurring	**C = Consequence of Risk**	**RL = Initial Risk Level Number**	**Residual Risk: Use Risk Level table**				

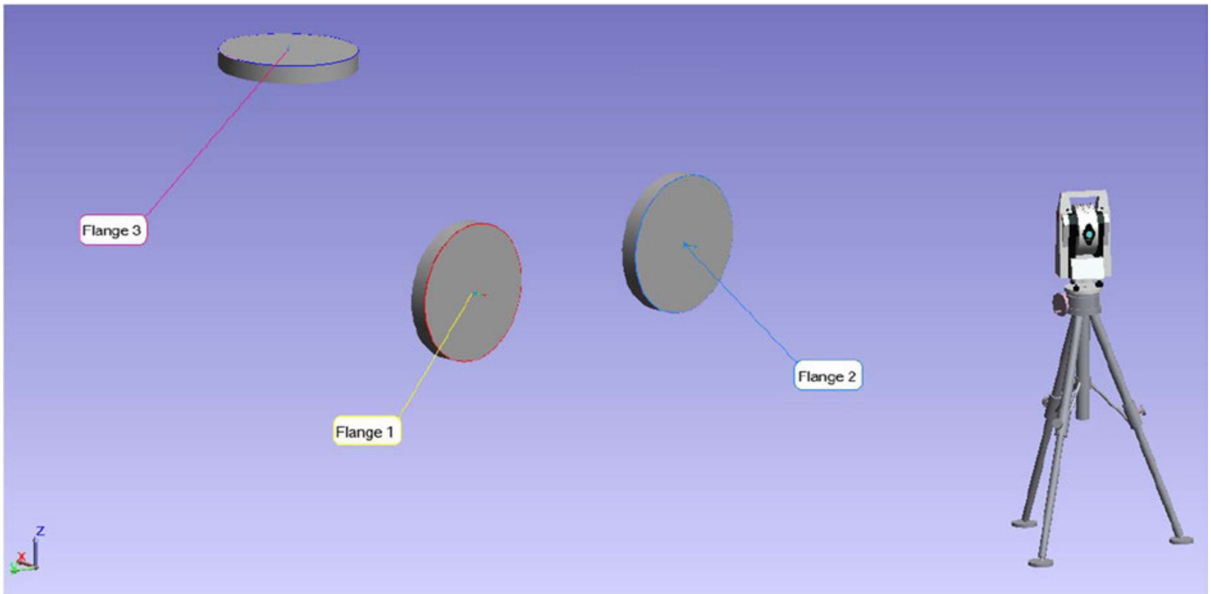
Key Job Steps	**Hazards**	**Risk Rating**			**Mitigation Actions**	**Residual Risk**			**Person Responsible**
		L	**C**	**RL**		**L**	**C**	**RL**	
Travel to/from site	Driving accidents	D	A	6	Drive to conditions Journey management plan if required Share driving duties if fatigued (If possible)	D	A	6	GL
Surveying pipeline flange	Slips, trips & falls	D	D	3	Clear work areas before starting Wear appropriate footwear for the job	E	D	2	GL
Surveying pipeline flange	Leaking gas pipe/flange	C	A	7	Carry a gas detector if working around live gas pipelines Avoid confined areas if possible, work in teams to have a spotter Do not carry ignition sources near pipelines Wear appropriate PPE for job	C	D	4	GL
Surveying pipeline flange	Heat Stress	D	C	4	Work in cooler parts of the day	E	C	3	GL

<table>
<tr><td>Project Number</td><td>UNI THESIS</td><td colspan="3">JHA No. for Project (eg. 3)</td><td>1</td><td>Date</td><td colspan="2">29/05/2019</td><td>Page 1 of 1</td></tr>
<tr><td colspan="2">Description of Project Activity</td><td colspan="8">Field work for surveying pipeline flange</td></tr>
<tr><td colspan="2">Worksite</td><td colspan="3">Yatala Pre-cast yard
WDS</td><td colspan="2">Expected Duration</td><td colspan="3">1 day</td></tr>
<tr><td colspan="2">Has this Job Activity been done before? (delete one)</td><td colspan="3">No</td><td colspan="3">If yes, has the previous JHA been reviewed?</td><td colspan="2">N/A</td></tr>
<tr><td colspan="10">Supervisor (or Permit Holder for remote work conducted under a Work Permit) approving the use of this JHA</td></tr>
<tr><td>Company</td><td>N/A</td><td colspan="3">Name</td><td>Greg Lee</td><td colspan="2">Signature</td><td colspan="2"></td></tr>
<tr><td colspan="10">Risk Details</td></tr>
<tr><td colspan="2">L = Likelihood of Risk Occurring</td><td colspan="3">C = Consequence of Risk</td><td colspan="2">RL = Initial Risk Level Number</td><td colspan="3">Residual Risk: Use Risk Level table</td></tr>
<tr><th rowspan="2">Key Job Steps</th><th rowspan="2">Hazards</th><th colspan="3">Risk Rating</th><th rowspan="2">Mitigation Actions</th><th colspan="3">Residual Risk</th><th rowspan="2">Person Responsible</th></tr>
<tr><th>L</th><th>C</th><th>RL</th><th>L</th><th>C</th><th>RL</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>Keep hydrated with water

Wear appropriate PPE for job</td><td></td><td></td><td></td><td></td></tr>
</table>

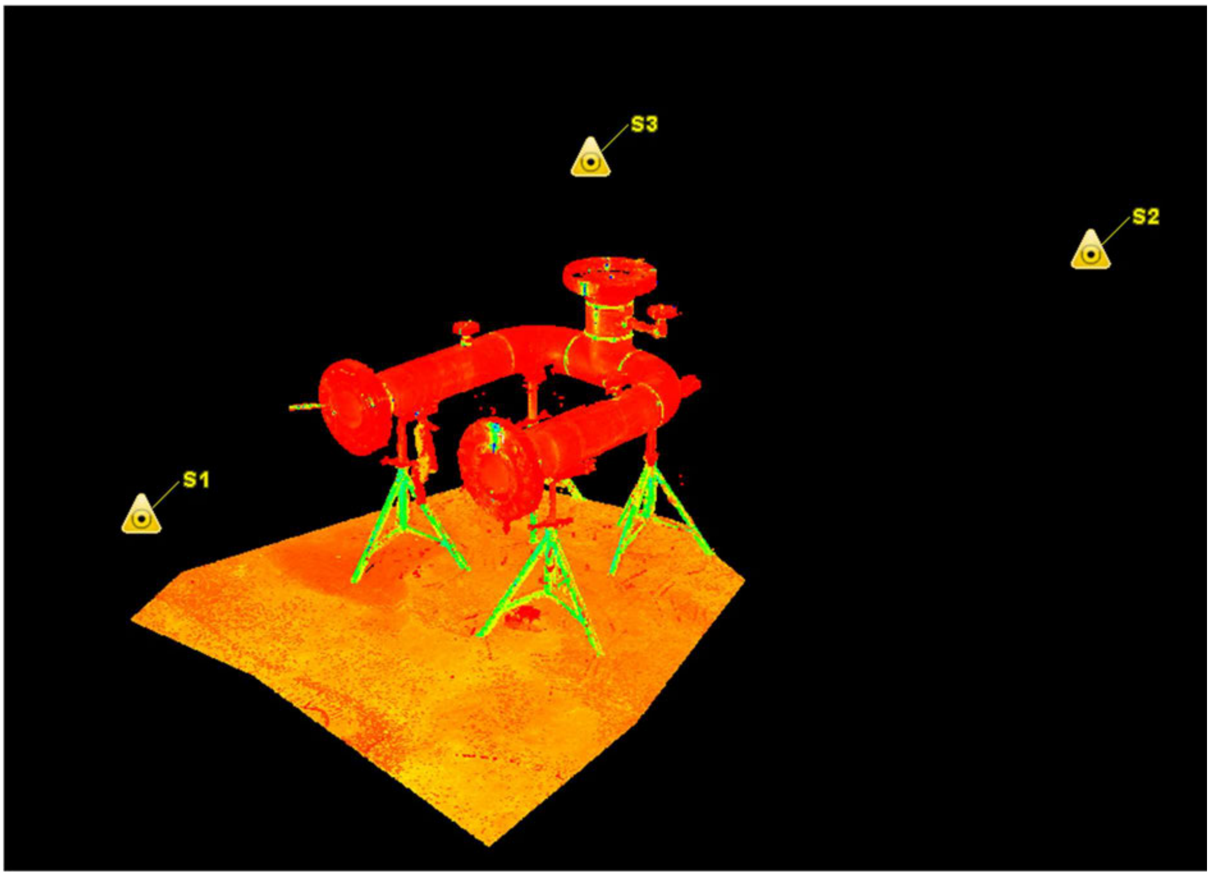
Job Hazard Analysis

Appendix C – Spatial Analyzer Overview



Modelled flanges in Spatial Analyzer

Appendix D – Laser Scanning Point Cloud Overview



Leica Cyclone point cloud with scanstations

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