University of Southern Queensland

Faculty of Engineering and Surveying

Dam Deformation Surveys with Modern Technology

A dissertation submitted by

Mr Jack Allan Atkinson

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ABSTRACT

Dam deformation surveys are repetitive surveys that must be undertaken periodically on high risk structures such as large earthfill dams. This dissertation is to examine and test the ability of the Leica Nova MS50 terrestrial laser scanner (TLS) and utilise these findings to develop a dam deformation survey procedure that can be amplified by the inclusion of TLS. The Leica Nova MS50 is an instrument that has only recently come onto the market. It provides the latest technology by combining a high precision total station technology with the capability of capturing highly accurate scanned data.

The existing dam deformation survey methods require manually placing survey targets on predefined stations located across the surveyed surface, placing the surveyor in danger from slips, trips and falls on often steep and unstable ground. There is an identified need for an automated remote process to be developed, providing safety for the surveyor whilst not compromising the survey accuracy.

It will be possible to determine the accuracy of the Leica Nova MS50 and its suitability to be utilised in dam deformation surveys by developing three separate testing scenarios:

- **Angle of incidence test** – determining the effect the angle of incidence has on a distance read;
- **Difference in length detection** – examine the accuracy of the instrument and determine the difference in length measurement capabilities at nominal lengths; and
- **Laser Dot Size** – to examine the size of the measuring laser at nominal lengths.

This dissertation found the Leica Nova MS-50 to be a very accurate and capable machine. It was determined from the testing conducted that scanning at 1000 hertz for deformation scanning had to be limited to distances less than 100 metres (m). It was also verified that survey control pillars would need to be constructed in the most suitable location; ensuring scanning procedures are conducted from the same location for each epoch.

This dissertation also found, the rabble rock surface that earthfill dam walls are covered by, creates exaggerated error when scanning due to the uneven surface. Therefore it was determined this survey method may be best suited to concrete structures are surfaces that are flat.

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CERTIFICATION OF DISSERTATION

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

Mr Jack Allan Atkinson

Student number: 0050057511

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Signature

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CHAPTER 1

1.1. INTRODUCTION

Terrestrial laser scanners are becoming increasingly popular for a variety of applications within the Surveying industry. Frohlich and Mettenleiter (2004) outlined the advancement of high precision systems, they claimed the terrestrial laser scanners (TLS) are capable of working in most real world environments under a variety of conditions. This has led to numerous applications being developed utilising this technology within the industry. Structural dam deformation monitoring is typically undertaken using sparse, point-wise observation techniques. TLS are attractive systems that provide dense three-dimensional (3D) information of the surface of an object (Tsakiri, Lichti & Pfeifer 2006).

In this dissertation the TLS was tested to determine its true accuracy and specification. The TLS was then used to survey a subject earthfill dam wall, known as Eucumbene Dam located in the Snowy Mountains, NSW. The TLS created a tight point cloud over the earthfill dam wall. I analysed the results of this instrument and determined if the instrument could replace or supplement current surveying methods for the process of dam deformation surveys.

I calculated the accuracy the TLS provided in a real world survey. Then compared the use of this TLS and its ability to replace or supplement current instruments and survey methods used in dam deformation monitoring. A new procedure for dam deformation surveys utilising this technology was also developed.

1.2. BACKGROUND

1.2.1. TERRESTRIAL LASER SCANNERS

Laser scanning is a technology increasingly being adopted by surveyors across the globe in their efforts to develop alternative means of conducting highly detailed surveys. These instruments are capable of measuring up to 976 000 points/sec (Faro Technologies 2014). TLS have recently received attention due to a number of measurement benefits they provide, including three-dimensional, fast and dense data capture, operation without the mandatory use of targets, and permanent visual recording (Tsakiri, Lichti & Pfeifer 2006).

The point cloud created by these devices can be utilised to produce a 3D computer image of the scanned location. Objects scanned can range from small mechanical components to large buildings and structures.

1.2.2. DAM DEFORMATION SURVEYS

Dam deformation surveys are a requirement for varying types of structures and objects, mainly focused on high-risk projects such as large dams, tunnels and buildings located in unstable ground.

Dam deformation surveys are used to document the movement of a structure very accurately, often to a sub-millimetre standard. These dam deformation surveys in the past have been undertaken by traditional surveying methods, such as angular triangulation and precise level runs. Previously these surveys had been conducted over strategically placed survey marks, located sparsely across the structure.

However, if the use of TLS was implemented in these dam deformation surveys, vast point clouds over the entire structure could be captured and examined. As a result, this could enable authorities to examine not only those few surveyed marks located on the structure, but the entire structure itself, developing a complete image of the movement of the surveyed structure.

1.3. RESEARCH AIMS AND OBJECTIVES

1.3.1. RESEARCH AIM

The research aim of this project is to test a TLS and determine the feasibility of using TLS for geodetic dam deformation surveys on earthfill dam walls.

1.3.2. RESEARCH OBJECTIVES

- Review TLS, their accuracy and compare their use in dam deformation monitoring;
- Review current software available for point cloud data analysis;
- Review current dam deformation survey methods in practice, including the advantages and disadvantages associated with these methods; and
- Determine the likely-hood of the current methods continuing to be the dominant survey method into the future.

1.3.3. JUSTIFICATION

Dam deformation surveys also known as surface movement control, are a requirement by the *Dam Safety Committee* (International Commission on Large Dams. Australian National Committee 1994). They are repetitive surveys that must be undertaken periodically. For high-risk earthfill dams such as our subject site, a surface movement control survey is required every five years (International Commission on Large Dams. Australian National Committee 1994).

As dams are often found in steep, rocky and otherwise dangerous environments, they provide significant risk to the surveyor. This can be in the form of slips, trips and falls, as well as working at heights and avoiding water hazards. If a process can be developed that incorporates the use of TLS in dam deformation surveys, removing the necessity of surveyors to be placed in dangerous locations or situations, a safer working environment can be created.

1.4. CONCLUSION

This dissertation aims to:

- test a chosen TLS on its accuracy and appropriateness for use in real world situations;
- further develop the use of modern technology within set survey projects that are frequently conducted;
- enable dam deformation surveys on earthfill dams to be conducted with TLS; and
- develop a procedure with increased efficiency and little to no loss in accuracy.

The literature review conducted will assess the subject technology, being a TLS, along with current dam deformation survey standard practices and earthfill dam structures. It will examine the need for dam deformation surveys, both legally and structurally, by further developing the existing principles and requirements associated with man-made structures, such as earthfill dams.

Fieldwork to test the TLS and prove the designed procedure will be conducted in correlation with the information gained by the literature review. Results will be analysed determining the accuracy and precision tolerances associated with this technology.

CHAPTER 2 - LITERATURE REVIEW

2.1. INTRODUCTION

This chapter will outline the relevant literature associated with the three areas addressed in this dissertation. They are TLS, dam deformation monitoring and earthfill dam structures. In recent years TLS have become widely used throughout the private surveying industry. The following review will address this new technology and its ability to be utilised in earthfill dam deformation surveys.

2.2. LASER SCANNER

2.2.1. OVERVIEW

Scanners allow rapid and very dense surveys of structures and objects in a very timely manner. Scanners work by transmitting a laser towards a structure or object being scanned which is subsequently reflected back to the device. TLS can measure upwards of 976 000 point/sec (Faro Technologies 2014). These millions of points collected each scan are transformed into a point cloud. This produces a 3D model of the object or structure being measured.

Software packages are continually being created and adapted to allow for data capture of point clouds. These software packages enable the surveyor to interrogate and develop an accurate 3D scan, modelling the object into the required format.

Once collected and imported into the software, a resulting photo can be 'draped' over the point cloud model, resulting in a survey accurate 3D colour image being produced.

The availability and variety of TLS have increased markedly since their widespread employment in the mid-1990s (Hetherington 2009). With so many different scanners specialising in certain types of surveys, it is vital to select the most appropriate TLS for this dissertation. For this reason I have chosen three different scanners to research:

1. Leica ScanStation P-20;
2. RiegleVZ-400; and
3. Leica Nova MS-50.

2.2.2. TYPES OF SCANNERS

There are three different techniques used by TLS for the calculation of distance, these are:

- phase modulation;

- pulsed time of flight; and
- laser triangulation.

One common technique is phase modulation. This technique is restricted to one hundred metres in range, and accuracy is possible to within a few millimetres. The time of flight principle is the most popular measurement system for TLS. It allows unambiguous measurements of distances up to several hundred metres. The final principle is close range laser triangulation, however this is more for industrial application as it has a range of only a few metres (Hetherington 2009).

2.2.3. ACCURACY

TLS can capture large point clouds of data in relatively short periods of time. However, the accuracy in which they collect this data varies between instruments. In terms of dam deformation surveys we require an instrument that can produce highly accurate results and do this consistently. Tsakiri, Lichti, & Pfeifer, 2006 state, in order to utilise the dense information obtained from the TLS, it is advisable to model surface dam deformation rather than trying to detect dam deformation of a single point. It is hoped the test produced within this dissertation will prove an instrument currently on the market will be able to provide the accuracy required for use of single point comparisons.

2.2.4 LEICA SCANSTATION P-20

The Leica ScanStation P-20 is an innovative combination of advanced time-of-flight range measurement plus modern Waveform Digitising (Leica Geosystems 2013). The Leica ScanStation P-20 can measure up to 1 million points/sec and is an ideal instrument for capturing High-Definition Survey data.

Measurement Range	Up to 120 meters (m)
3D Position Accuracy	3mm (at 50m); 6mm (at 100m)
Linearity Error	1mm
Angular Accuracy	8” horizontal and vertical
Measurement Rate	Up to 1 000 000 points/sec
Field of View	Up to 100° x 360°
Laser Product Classification	Class 2
Temperature Range	-20°C to 50°C

Table 2.1 - Technical specifications of Leica ScanStation P-20

Figure 2.1 - Leica ScanStation P-20 Scanner (Leica Geosystems 2013)

2.2.5 RIEGL VZ-400 SCANNER

The Riegl VZ-400 is a pulsed time of flight scanner that is capable of measuring up to 122 000 points/sec (Riegl 2014). The TLS Riegl VZ-400 provides high speed, non-contact data acquisition using a narrow infrared laser beam and a fast scanning mechanism (Riegl 2014).

Measurement Range	Up to 600m
Repeatability	3mm
Accuracy	5mm
Precision	3mm
Measurement Rate	Up to 122 000 points/sec
Field of View	Up to 100° x 360°
Laser Product Classification	Class 1
Temperature Range	0°C to 40°C

Table 2.2 - Technical specifications of Riegl VZ-400

Figure 2.2 - Riegl VZ-400 Scanner (Riegl 2014)

2.2.6 LEICA NOVA MS-50

The Leica Nova MS-50 is the world's first MultiStation. The Leica Nova MS-50 includes precise 3D laser scanning, extensive and precise total station capabilities, and digital imaging (Leica Geosystems 2013). This MultiStation's measurement system is based on waveform digitising technology, a specific type of a time-of-flight measurement system. This technology enables a fast measuring time, whilst providing a small laser spot size, over long ranges at high measurement accuracy.

Measurement Range	Up to 1000m
Precision	Less than 1mm at 50m
Measurement Rate	1000 points/sec (up to 300m range)
Field of View	360°
Laser Product Classification	Class 2
Temperature Range	-20°C to 50°C

Table 2.3 - Technical specifications of Leica Nova MS-50

Figure 2.3 - Leica Nova MS-50 (Leica Geosystems 2013)

The Leica Nova MS-50 provides a combination of Total Station capabilities with 3D laser scanning in one instrument. The Leica Nova MS-50 allows 3D laser scanning to be fully integrated into a regular measurement workflow, providing the ability to position the instrument accurately on-site before scanning is undertaken. The Leica Nova MS-50 also provides unprecedented accuracy in its scanning capabilities, although this comes at a reduction in measurement rate.

2.3 SOFTWARE

Dam deformation analysis requires the reconstruction of surfaces prior to comparing them in different epochs. According to Tsakiri, Lichti, & Pfeifer, (2006), all reconstruction methods require four basic stages:

1. pre-processing in order to eliminate erroneous and noisy data;
2. determination of the global properties of the object's surface, which considers possible 'constraints' to preserve special features (like edges);
3. generation of the polygonal surface such as triangular or tetrahedral meshes but also parametric surfaces (e.g. low order polynomials over a user-defined reference plane or more general free form surfaces) and implicit surface representations (e.g. for planes, spheres, cylinders, and tori) are used; and
4. post-processing of the model to refine and perfect the (polygonal) surface.

2.3.1 FORESOFT

Foresoft is professional software based around producing solutions for Civil Designers, Land Surveyors and Geologists since 1983. Foresoft produces a product called Civil Design and Survey (CDS), this provides intelligent 2D and 3D coordinate geometry calculations to assist with all survey fields. CDS also provides the ability to conduct terrain modelling with contouring, it can interpolate sections and shade models by height and slope (Foresoft 2014).

2.3.2 CLOUDCOMPARE

CloudCompare is an open source 3D deviation analysis software. It was originally designed to perform comparison between two 3D point clouds, and is capable of dealing with huge point clouds, typically more than 10 million points (DanielGM 2014). This software will enable the multiple point cloud data obtained in the field to be registered together and compared for deviation.

2.3.3 MESHLAB

MeshLab is an open source system for the processing and editing of unstructured 3D triangular meshes that have been developed with the support of the 3D-CoForm project. The system provides tools for editing cleaning, healing, inspecting, rendering and converting meshes typically found in models arising from TLS (3D-CoForm Project 2014).

2.3.4. MICROSURVEYCAD

MicroSurveyCAD is a complete desktop survey and design program created for surveyors. MicroSurvey has been building software for the surveying industry for over 25 years and are able to offer a CAD package capable of all the necessary surveying calculations. They have recently integrated point cloud manipulation into the package to make it a complete program (MicroSurvey 2014)

2.4. DAM DEFORMATION MONITORING

2.4.1 OVERVIEW

The construction of water storage dams started in earnest in the 1920's (Rueger 2006), with monitoring the static and dynamic behaviour being a topic of great relevance(Gonzalez-Aguilera, Gomeze-Lahoz & Sanchez 2008). Since the safety of people living downstream of these structures was important and the impact these structures have on the landscape, engineers wanted to know more about the behaviour of dams. This included the movements associated with pressure, water levels and air temperature variations.

2.4.2. PREVIOUS TECHNIQUES

Early attempts to conduct deformation surveys on dams included the use of levelling, clinometers and optical alignment (Rueger 2006). However the main aim of the developed plans has been to ensure the possibility of measuring displacements in a singular number of points.(Gonzalez-Aguilera, Gomeze-Lahoz & Sanchez 2008)

It was in the mid 1920s when the Swiss National Mapping Company was contracted to conduct multiple dam deformation surveys across the country. They employed a geodetic method proposed by H. Zolly. This originally incorporated two or three reference points used to intersect the dam deformation survey marks, this was mainly an angular survey (Rueger 2006).

To conduct dam deformation surveys, spatial measurement techniques must encompasses numerous desirable properties such as:

- precision;
- reliability;
- low cost; and
- ease of use.

Several methods have been developed that incorporate some of the required properties; the struggle has been to develop a method that incorporates all the properties listed(Gonzalez-Aguilera, Gomeze-Lahoz & Sanchez 2008).

As (Gonzalez-Aguilera, Gomeze-Lahoz & Sanchez 2008) describes below, there are three main methods that have been incorporated into dam deformation monitoring, however these do not provide the benefits that can be associated with the integration of TLS into the dam deformation monitoring process:

- **Classical Topographic methods** – is based on angles and distances along with the calculation of height variation. The equipment used consists of accurate and appropriate Theodolites or Total Stations, often indirect measurements such as angular intersections are used for inaccessible points.
- **Global Positioning Systems (GPS)** – has been used in structural monitoring of large dams. GPS have two significant limitations. Firstly as signals are received from satellites, coordinates cannot be measured indoors or through obstacles. The second limitation is that the current precision levels of GPS are limited to ± 1cm horizontally, and ± 2cm vertically.
- **Digital close-range photogrammetry** – is a low cost, highly accurate alternative. It also offers a quick, remote, 3D data acquisition with images providing a permanent visual recording. The downside to this method is the compulsory use of targets, especially when the access to the object is risky or inaccessible.

2.4.3. SAFETY

The failure of a dam in an urbanised area could have catastrophic results. Due to the possibility of loss of life and property, it is fundamental that the correct procedures and policies are implemented, minimising any chance of dam failure. For this reason, dam owners across Australia need to meet strict guidelines (International Commission on Large Dams. Australian National Committee 1994). This includes the requirement of a regimented dam deformation survey. This constant monitoring of the structure provides detailed insight into the health of the structure and can be used as an early warning sign to possible problems associated with the dam.

2.5. SUBJECT SITE

The earthfill dam chosen to be the test site for this dissertation is located on the boundary of Kosciuszko National Park, approximately 60km from the township of Cooma. Eucumbene Dam is one of the 16 dams built and used in the Snowy Mountains Hydro-electric scheme and is currently owned and operated by Snowy Hydro Pty/Ltd. (Snowy Mountains Hydro-electric Authority 1993).

Eucumbene Dam is a flagship dam in the Snowy Hydro Scheme. It stores the waters of the Eucumbene and the Upper Murrumbidgee Rivers for diversion through the Eucumbene-Tumut Tunnel to the Tumut River. The tunnel also transfers waters from the Snowy River, which are later returned to the Snowy-Murray Diversion. In times of high river flow, water is also diverted by tunnel to the lake for storage from the Tooma and Tumut Rivers (Snowy Mountains Hydro-electric Authority 1993).

Eucumbene is an earthfilled dam that stands 116.1m tall and has a crest length of 579.1m. Eucumbene Dam was constructed from May 1956 through to May 1958 (Snowy Mountains Hydro-electric Authority 1993).

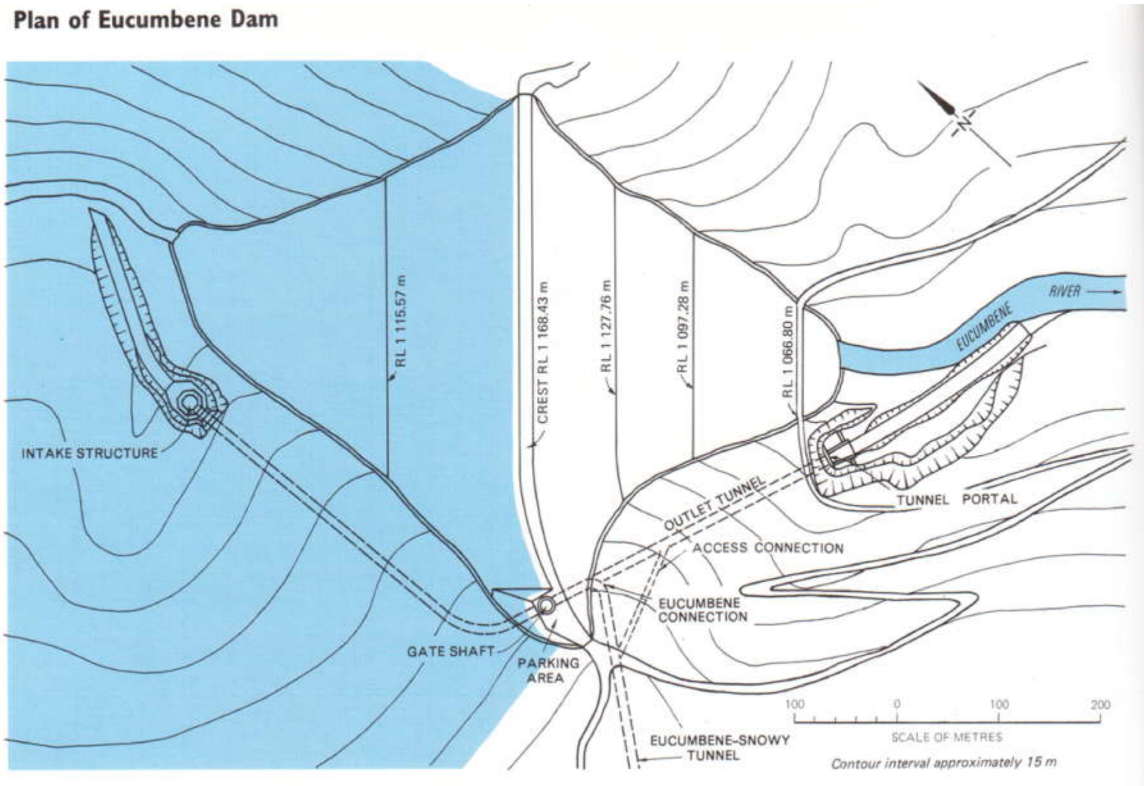


Figure D.1 Eucumbene Dam

Source: (Snowy Mountains Hydro-electric Authority 1993)

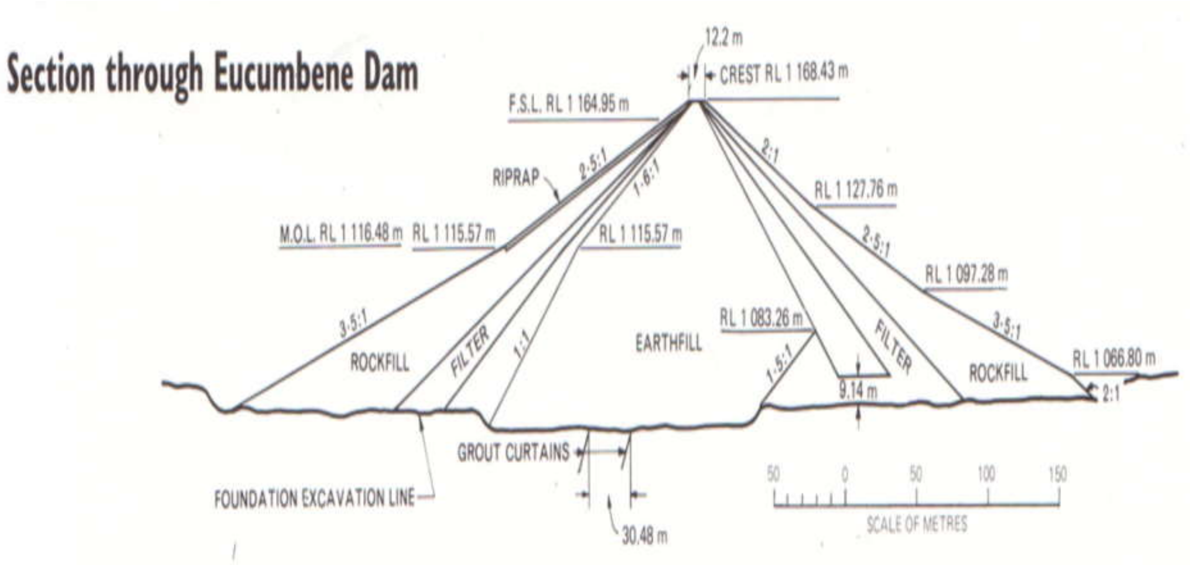


Figure D.2 Eucumbene Dam

Source: (Snowy Mountains Hydro-electric Authority 1993)

Previous site data

As this is an existing structure that is already under a continuous dam deformation survey procedure, both external survey control marks (pillars) and the dam deformation marks on the structure already exist. With many years of previous survey records attached to them, it is logical to use these marks in this dissertation's fieldwork. Targets were placed on all current dam deformation marks located across the subject site. This will enable the survey to include the existing surface and survey structures.

Horizontal and Vertical Control

As seen in the data provided by Snowy Hydro Pty Ltd, (see *figure 3.3*) control pillars and trig stations are located close to the survey site. These pillars will be incorporated into the survey, and utilised for the accurate horizontal coordinates that are currently available.

Targets were positioned on all pillars located in stable rock surrounding the subject site. The Leica MS-50 will utilise target recognition to accurately aim at each pillar target. After measuring to all visible pillars the resection will be completed and the TLS will output the resection residuals. It is at this point that further targets may be incorporated if the desired accuracy has not been met.

Snowy Hydro Pty Ltd surveyors have previously levelled the pillars located on our subject site. These heights will be used in the resection to ascertain the elevation of our TLS.

Targets

To help connect this survey method with existing epoch data currently obtained by Snowy Hydro Pty/Ltd, I placed Leica Dam deformation Monitoring Targets on existing survey pillars and utilising the existing survey information in the orientation of the instrument onsite.

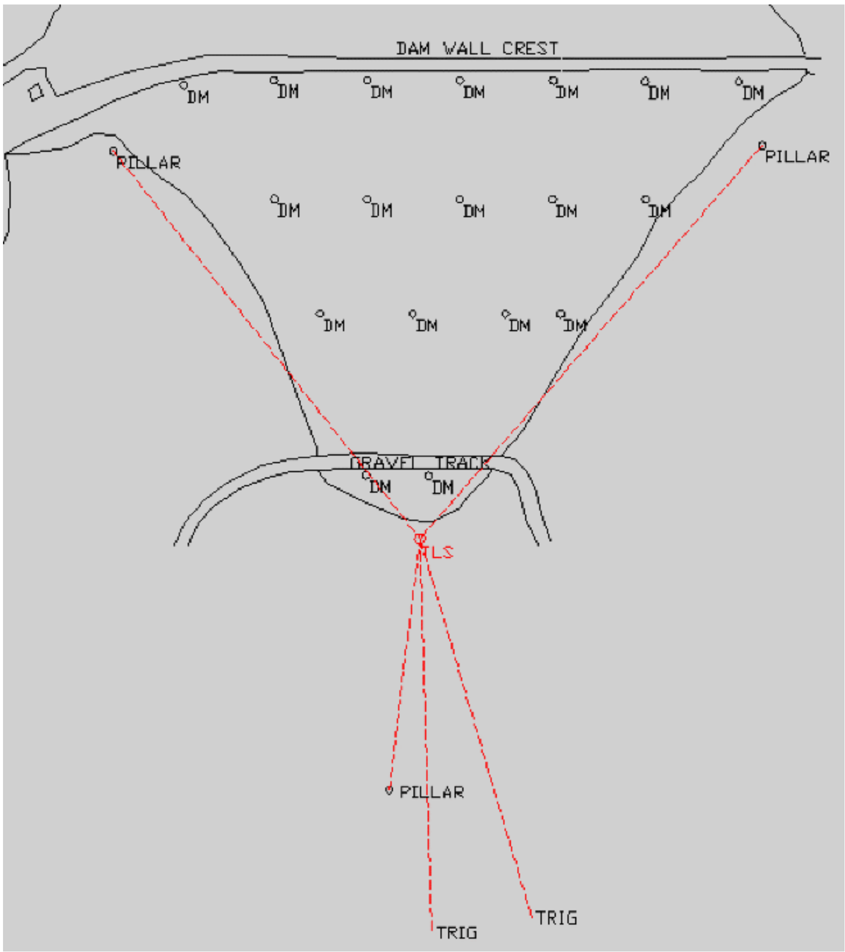


Figure D.3 Eucumbene Dam Survey Control

2.6. CONCLUSION

In conclusion, this literature review has demonstrated that limited previous research has been conducted on this proposed type of survey. The opportunity of utilising TLS in dam deformation surveys is highly possible and worthy of developing a standard procedure. It has explored the technologies used in this project along with existing and potential uses. The information obtained within this literature review will be utilised in the creation of a dam deformation program that is both efficient and accurate whilst providing a safe working environment for the surveyor.

It has been determined from this literature review that previous survey techniques do not tick all the required properties a comprehensive dam deformation survey should contain. The incorporation of TLS into the survey may provide a more complete data set.

The best TLS for this task has been determined to be the Leica Nova MS-50. Although this instrument has the slowest rate of measurement for each point, its ability to measure accurately outweighs the time constraint and meets the main purpose of this type of survey, being accuracy and repeatability.

Alternative survey methods can be developed, enabling this instrument to be utilised in an efficient manner, thus providing a wealth of data on the subject dam. The fact the instrument can also be used as a standard Total Station provides an added benefit when geo-referencing the station, and surveying the location of existing dam deformation marks.

Software to manage the large amounts of data provided by this TLS has also been covered by this literature review. It was determined that a combination of cloud comparison software along with Foresoft will be used to best analyse the collected data and produce a report detailing the movement of the subject site.

CHAPTER 3 - METHODOLOGY

3.1. INTRODUCTION

The aim of this chapter is to explain the methodology and procedures used within this dissertation. Relevant information will be provided in regard to the method of testing the chosen TLS and using the data collected to analyse its suitability in dam deformation surveying.

3.2. SAFETY CONSIDERATIONS

As with any fieldwork conducted by a surveyor, safety needs to be taken into consideration. With parts of this project being located at an earthfill dam located in a remote area, precautions around travel, working at heights and water hazards need to be considered.

3.3. RESEARCH AND TESTING OBJECTIVES

Objective 1: Identification of features required

To identify the features required to conduct the proposed dam deformation survey and the inherent errors associated with the TLS.

Objective 2: Select the suitable TLS Unit

To identify and select an instrument best suited for dam deformation monitoring.

Objective 3: Develop apparatus and test TLS

To design testing apparatus that can be used to test the chosen TLS.

Objective 4: Analyse and evaluate results obtained

Upon completing the testing stage, data analysis will be conducted; comparing results obtained with manufacturers specifications. Procedures for best practice can be developed from this analysis.

Objective 5: Develop a new dam deformation survey method and conduct a field test on the selected subject site

Upon completion of analysis, a procedure will be developed that takes into consideration the results obtained. A manual for best practice can be established that removes identified errors found during the testing phase.

Objective 6: Review results of dam deformation survey

Process the conducted survey and review the results.

3.4. RESEARCH AND TESTING METHODOLOGY

3.4.1. IDENTIFICATION OF FEATURES REQUIRED IN TLS

Dam deformation monitoring requires high precision and repeatability. If a method is to be developed that will enable dam deformation monitoring to be conducted with a TLS, certain attributes must be present. The main attribute would be precision, in earthfill dam monitoring it is advisable to utilise a survey method that can produce results down to millimetre accuracy; other monitoring scenarios may require sub-millimetre precision. Secondly, repeatability is necessary. This provides an assurance the instrument is providing results that are a true representation of the surface.

3.4.2. SELECT THE SUITABLE TLS UNIT

The above literature review details the Leica Nova MS-50. This multi-station instrument provides scanning capabilities similar to a TLS however is also provides the added benefit of complete total station abilities. This instrument is capable of surveying up to 1000 points/sec, whilst maintaining accuracy far greater than traditional TLS. The instrument can also be set to different speeds, the slower the scan the more accurate the results. The Total Station abilities provided within this instrument allow the surveyor to geo-reference their survey, prior to conducting a scan and ensuring repeatability is being met. It has been determined the Leica Nova MS-50 is the most suited survey instrument on the market for this dissertation. For this dissertation we examined the instrument at 1000 hertz scanning speed only.

3.4.3. DEVELOP APPARATUS AND TESTING METHODS

The aim of testing is to mimic scenarios that are present in dam deformation surveys; therefore the testing methodology must endeavour to address these scenarios. For this reason the distances chosen ranged from 10m to 250m with increments matching the specifications provided by Leica.

Angle of Incidence test – to determine the effect the angle of incidence has on a distance read when surveying an earthfill dam wall for dam deformation purposes. This test was conducted on the selected subject site (see Sec *2.5 for further details on the site).* The test consisted of a two-stage scan over the dam surface.

Firstly a scan was conducted over a section of the surface from a single station located centrally on the downstream face of the dam indicated as station 1 in the following figures. This scan was approximately 5m in thickness and cover from the toe of the surface to the edge of the road located approximately 50m up the surface.

The second scan station was located 10m to the side. This scan was conducted over the same portion of the surface as the initial scan. These two scan stations where geo-referenced on-site using the instruments Total Station capabilities.

After using MicroSurveyCAD to import the information, the data was transferred to CloudCompare. CloudCompare was then used to compare the two scans; this gave an indication of the inaccuracies that can be found when surveying from multiple locations is undertaken.

Figure 3.1 - Subject Site Eucumbene Dam

Figure 3.2 - Subject Site Eucumbene Dam - Diagram

Difference in Length Detection test – to examine the accuracy of the instrument and determine the difference in length measurement capabilities at nominal lengths.

The test for this involves developing two portable surfaces 3.6m by 0.9m. The portable surfaces will have steps 0.5m by 0.4m in diameter and located as shown in *figure 3.3*. This will vary in thickness from 0.0005m to 0.029m (also shown in *figure 3.3*). This surface was be painted in Kodak grey to help reduce error associated with changing reflective properties.

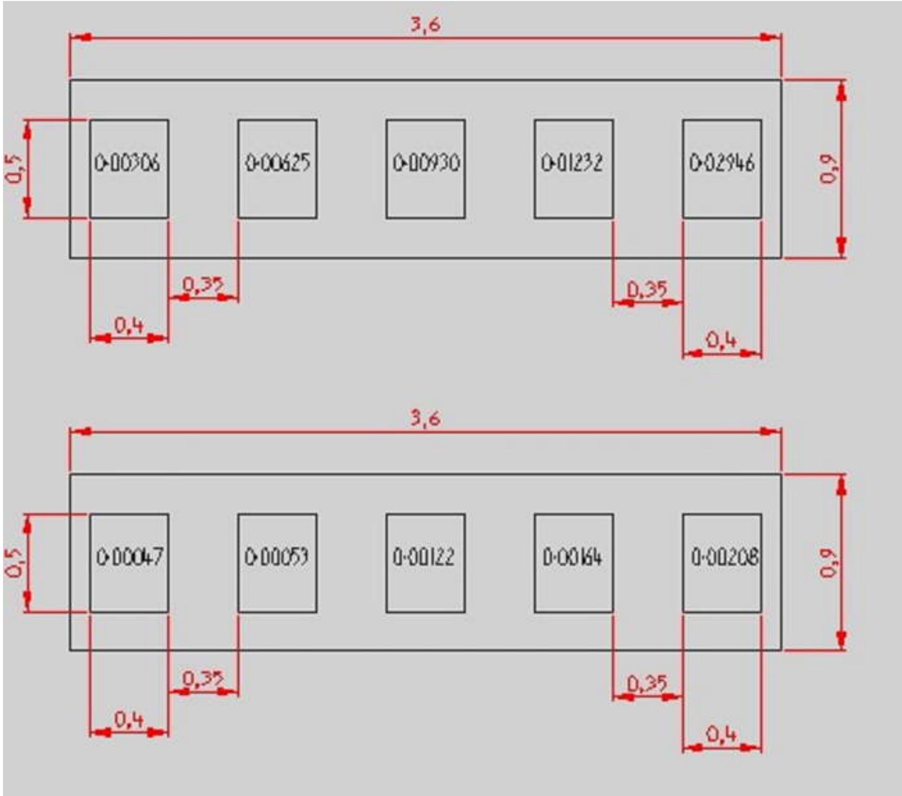


Figure 3.3 - Length Detections portable surfaces (Targets) Dimensioning

Figure 3.4 – Length Detections portable surfaces (Targets) Construction

These steps are to be measured by a digital level run while laying the board horizontally. This provides a base line measurement of true step thicknesses. This enables comparison of the scanned data later on.

The TLS was set up from 10, 25, 50, 100, 150, 200 and 250 meters away from the target. The target were be scanned with the Leica Nova MS50 at a grid of 0.005m vertical and horizontal at a frequency of 1000 hertz.

Figure 3.6 – Length Detections portable surfaces (Targets) Onsite Location

Figure 3.7 – Scanner and Target set up at 25m interval.

At the conclusion of these surveys, the scanning results were compared to the base line measurements provided by the previous precise level run. This can determine at what point the accuracies of the instrument move outside of the published measurements and dam deformation survey requirements.

Laser Dot Size test – to examine the size of the measuring laser at nominal lengths, and evaluate how this is affected by uneven surfaces.

A stepped board method was be used to calculate the laser dot size for the Leica Nova MS50 multi-station at nominal distance intervals.

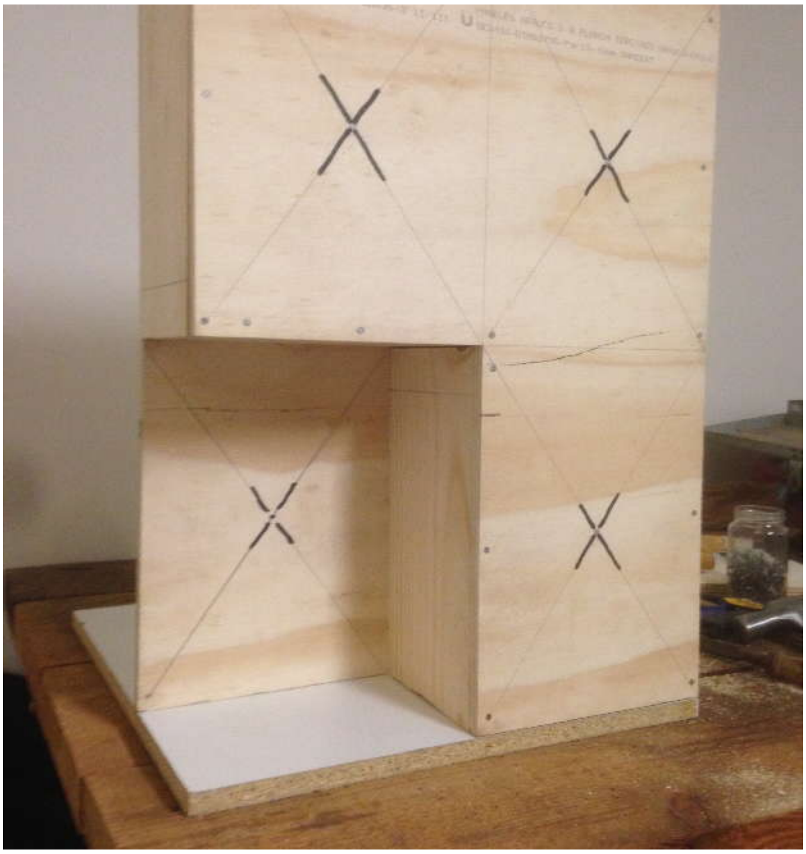


Figure 3.8 - Stepped Board Apparatus

The apparatus shown above was be set up at distances of 25m, 50m, 100m, 150m, and 250m from the multi-station instrument. At these nominal distances a set of measurements were be made in the horizontal and vertical planes.

The test begun with the instrument being aimed at the centre of the stepped-in rectangle. From this point measurements will continue to be made as the instrument is slowly rotated in the horizontal plane until it reaches the other centre point. We will find and note three important things as we rotate:

- the initial distance from the instrument will stay the same length until I go close to the step - it is this point when the distance begins to change that will be stored;
- as I move away from the step the distance from the instrument will once again stop changing - again this is the point stored; and
- the horizontal distance between these two points will define our laser dot size at the nominal length away from the instrument.

This procedure was be repeated in the vertical plane and then completed at each nominal distance from the instrument.

3.4.4. ANALYSE AND EVALUATE RESULTS OBTAINED

At the completion of all field testing the results were be sorted and processed, analysing any survey error present in the results. Tables, graphs and charts were developed outlining the results obtained from the field test, utilising statistics to calculate the quality of survey data obtainable from this TLS. Conclusions were be made from these results and recommendations drawn from these conclusions, to be later utilised in the following survey method.

3.4.5. DEVELOP NEW SURVEY METHOD FROM RESULTS, CONDUCT FIELD TEST ON SELECTED SUBJECT SITE

This survey method has been developed, accounting for errors in the TLS, determined by previous testing. The following procedure was undertaken on the subject test site detailed in *Sec 2.5* with permission from Snowy Hydro PtyLtd. This procedure was repeated five times over the course of one day, gaining data for later analysis.

3.4.6. REVIEW RESULTS OF DAM DEFORMATION SURVEY

Using the data obtained from the survey conducted on the subject site. The results were be analysed to compare single point accuracies of the survey. This comparison was be reviewed by calculated chainages and displayed as differences relative to the specific epoch.

TLS produce data-sets consisting of vast point clouds. The literature review above details the benefits of using the software package CloudCompare. This program will be used in conjunction with current software used in my workplace: Foresoft and MicroSurvey CAD to reduce the captured data and analyse the results obtained.

3.5. CONCLUSION

Tsakiri, Lichti, & Pfeifer, 2006, states that dam deformation monitoring with conventional surveying is superior in accuracy compared to TLS. They continue to say, individual sample points have low precision, however modelling of the entire point cloud may be effective for modelling the structure. A modelled surface will be a more precise representation of the subject site than the un-modelled observations. The use of modelled surfaces rather than single points is the key to dam deformation monitoring using TLS. The high speed in obtaining enormous sets of 3D dense data from the surface of a deforming object makes laser scanning at least a complementary technology for monitoring dam deformations.

However, what if we can conduct a TLS with accuracies comparable to conventional surveying? This was written in conjunction with TLS that have poor accuracy of over 0.015m. In this dissertation we are using a highly accurate TLS that can provide much greater results. It is hoped the increased accuracy in this TLS provides the opportunity to use vast point clouds of data on the subject site, and still be able to rely on single point accuracy for reporting purposes.

This chapter has discussed the chosen field tests to examine the TLS, along with apparatus utilised in field-testing. Methodology relating to the proposed survey has been discussed and potential sources of error along with best practices, to eliminate that error.

CHAPTER 4 – FIELD TESTING AND RESULTS

4.1. INTRODUCTION

With any research and development project the process and theories being developed need to be tested and evaluated to see if the project's objectives are being met and whether there are any improvements that can be made.

This chapter outlines the results obtained from the chosen field tests on the TLS. It will provide detailed analysis of the chosen TLS accuracies and quantify the results obtained to determine the potential of using the Leica Nova MS-50 as a dam deformation-scanning instrument.

4.2. ANGLE OF INCIDENCE TEST

This survey was conducted on the subject site as per the method previously outlined. I found immediately after observing the results, the two surfaces had 0.01m differences between them at best. This error increased to over 0.035m when the grade of the surface became flatter and the vertical angle of incidence increased.

The below figure demonstrates the inaccuracies of the compared scans with a side on view. We can see the majority of the first half of the scan is blue, indicating less than 0.01m differences. This I believe is due to the instrument's greater accuracies at short distances along with better geometry available as the surface is more vertical then the second half. The second half contains a lot of red dots, indicating this area was mainly between 0.035m and 0.05m in difference. It can also be seen that a portion of grey is located in the second half, due to two power lines being located between the instrument and the surface and have caused areas where only one of the scans contained data.

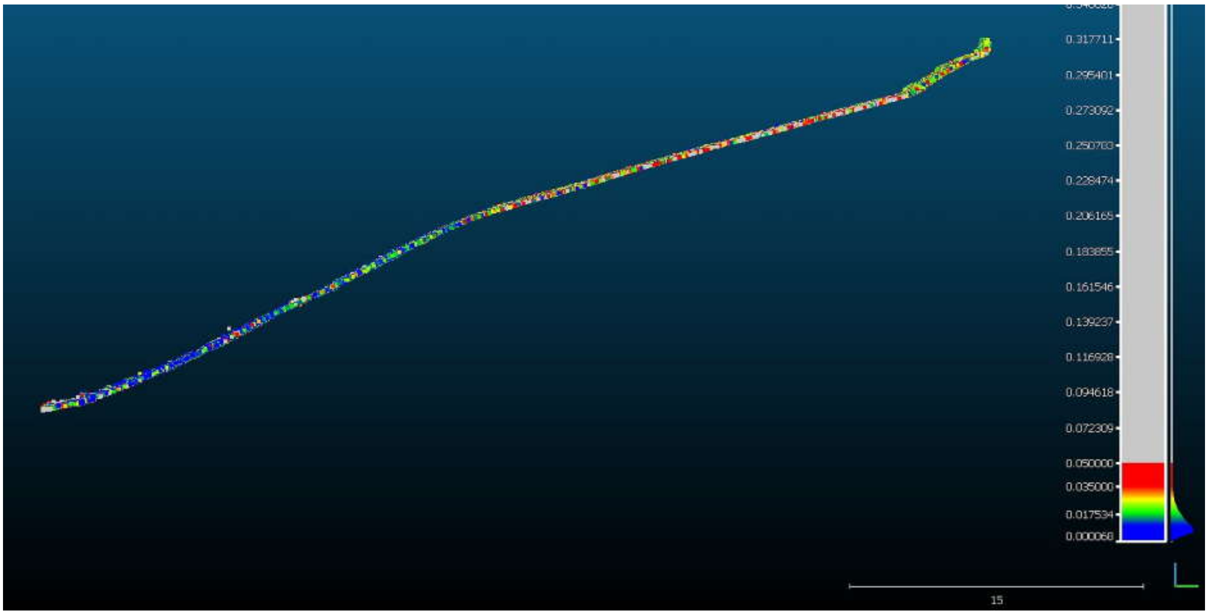


Figure 4.1 - Scan Surface Comparison - Side View - metres (m)

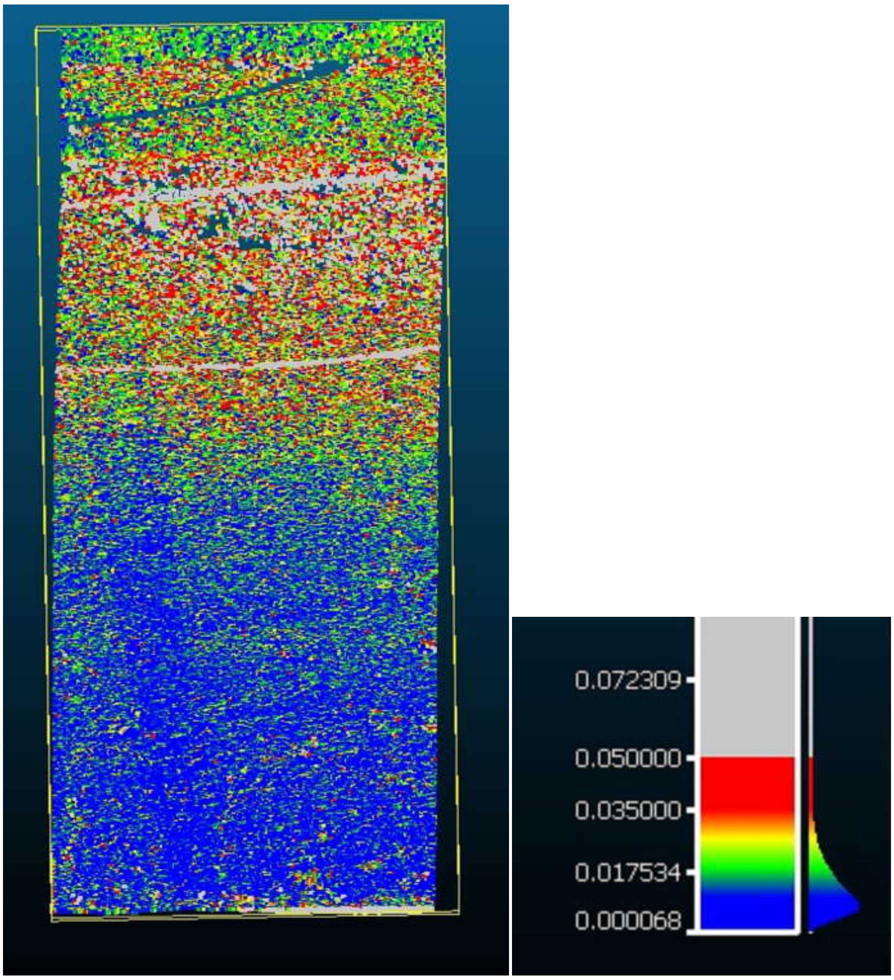


Figure 4.2 - Scan Surface Comparison - Plan View - meters (m)

4.3. DIFFERENCE IN LENGTH DETECTION TEST

The following figure displays the number of points measured on the target surface from each distance. It can be seen by this that although indicated in their specifications (*Appendix D*) 1000 hertz would be suitable. The data collection at 200m and 250m was insufficient to allow for analysis and has resulted in the omission of these scans from data evaluation.

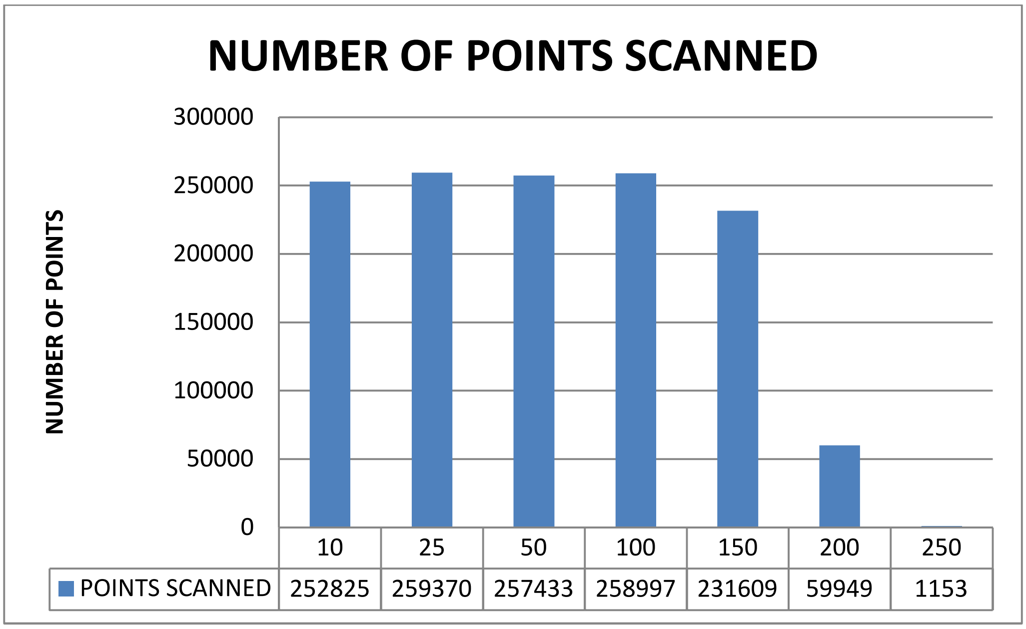


Figure 4.1 - Total points scanned from nominal distances

4.3.1. STANDARD DEVIATION

The following figures graphically display the standard deviation calculated from the scanned data.

The scanned data has been analysed by creating three (3) cross-sections on each target. These cross-sections have been used to provide statistical data to assess and analyse the accuracies obtained. See *figure 4.2* for details on cross-section locations.

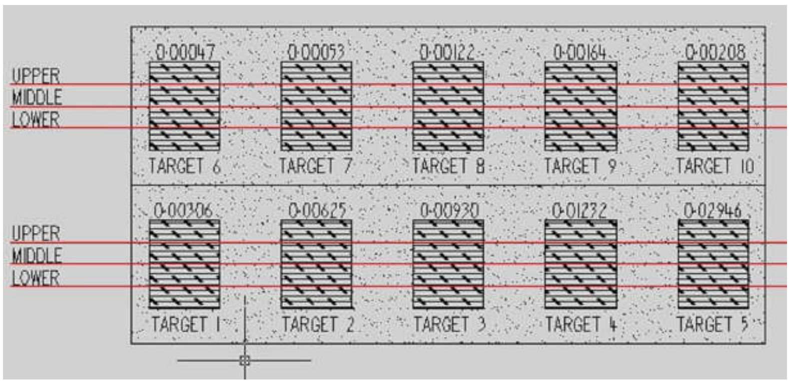
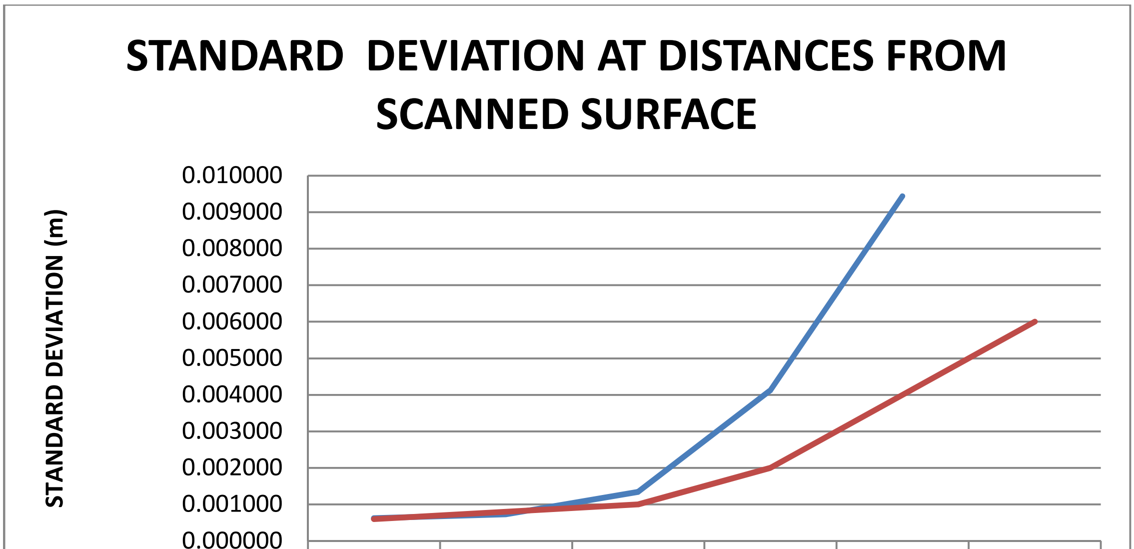


Figure 4.2 - Target and Cross-section Locations

The standard deviation calculated for each target represented above, increases in deviation the further the target is positioned from the Multi Station. In regards to the scans conducted at 10m, 25m and 50m, the standard deformations calculated on each target hold true to the manufacturer's tolerances (See *Appendix D* for manufacturer specifications and *Appendix E* for detailed graphs). The 100m and 150m scans demonstrate a greater standard deviation. It can be seen that these distances have more than doubled the standard deviation detailed in the manufactures specifications (see *figure 4.3* below).



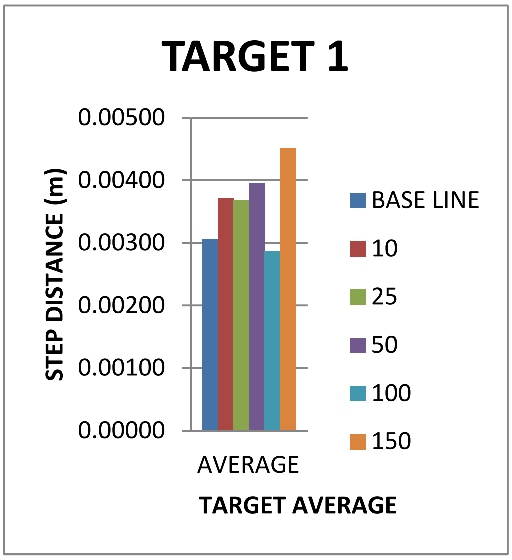
	10	25	50	100	150	200
AVERAGE	0.000627	0.000726	0.001348	0.004119	0.009440	
MANUFACTURER	0.000600	0.000800	0.001000	0.002000	0.004000	0.006000

Figure 4.3 - Standard Deviation for Leica Nova MS-50 in relation to length of measurement

4.3.2. STEP DETECTION

The following figures display the difference in step distances measured by the TLS when compared to the base measurement taken from the precise level run. It can been seen that targets 6 and 7 being the smallest steps do not have reasonable correlation to the base line with any scanned data. This can be attributed to the targets being smaller than the standard deviation previously calculated.

The remaining eight targets represent moderate results when compared to the base line measurements obtained from the precise level run. However, it is still evident that scans at a distance greater than 100m will result in poor accuracies due to the standard deviation errors previously calculated. *Appendix F* provides detailed figures of the step measurements taken at each cross-section, these figures were used to obtain the averages shown below.



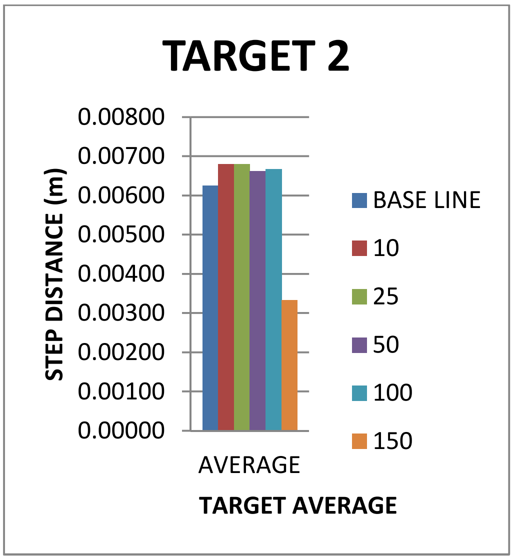
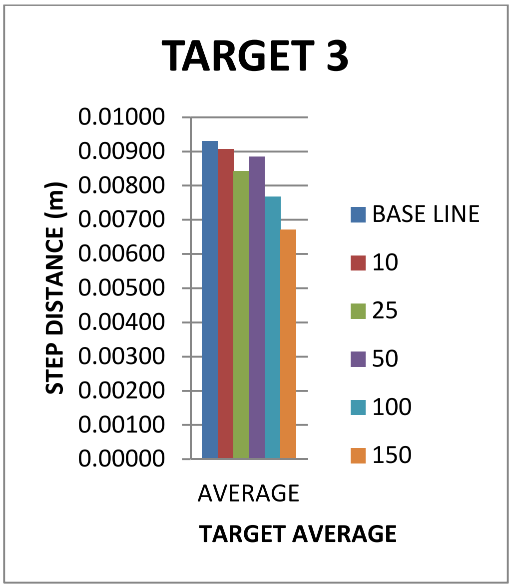


Figure 4.4 and 4.5 - Target 1 and Target 2 step measurement comparisons



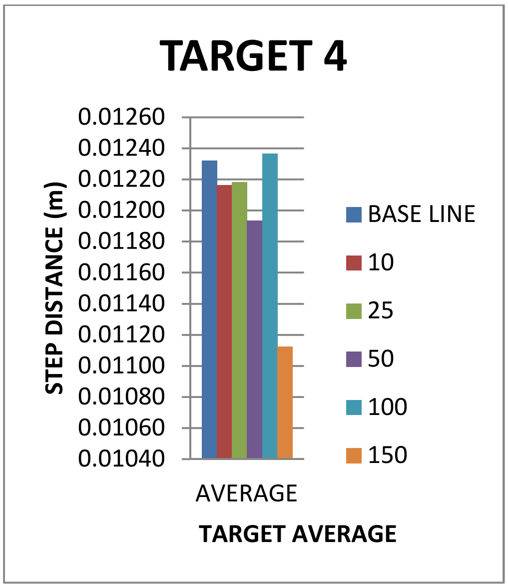
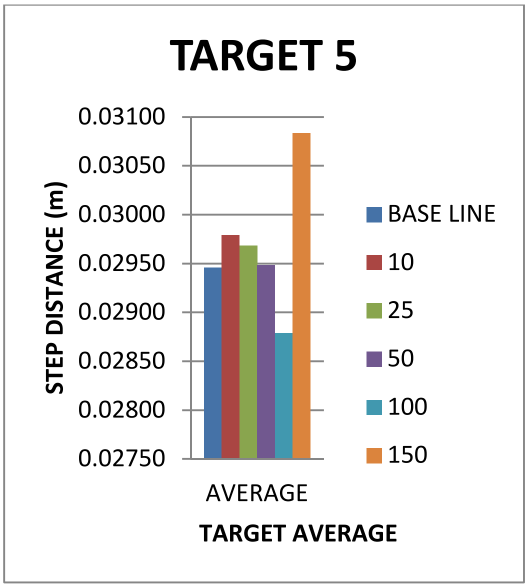


Figure 4.6 and 4.7 - Target 3 and Target 4 step measurement comparisons



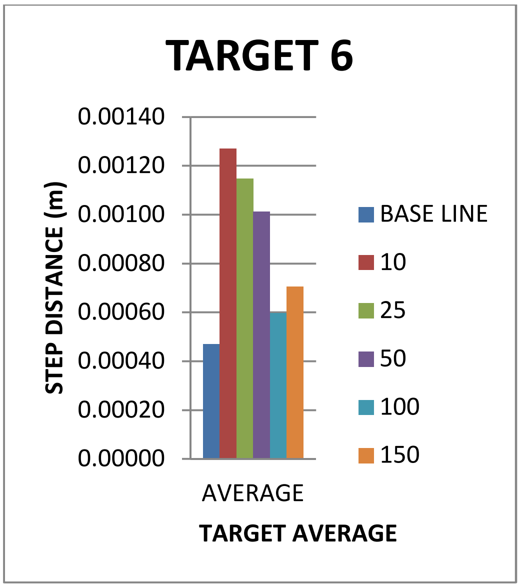
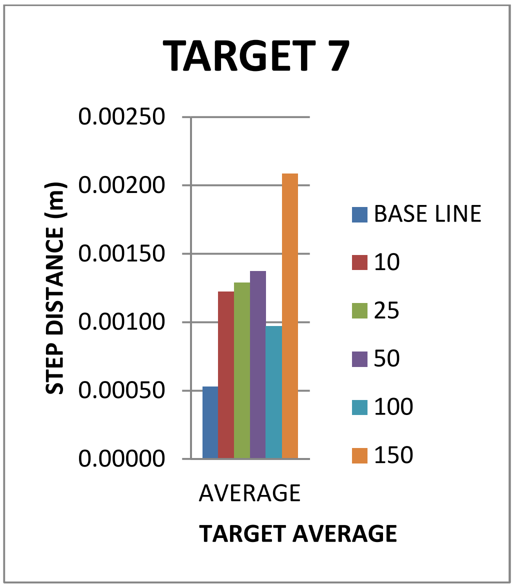


Figure 4.8 and 4.9 - Target 5 and Target 6 step measurement comparisons



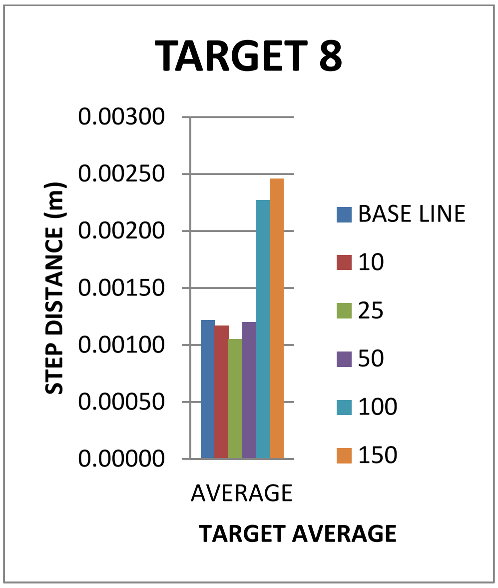


Figure 4.10 and 4.11 - Target 7 and Target 8 step measurement comparisons

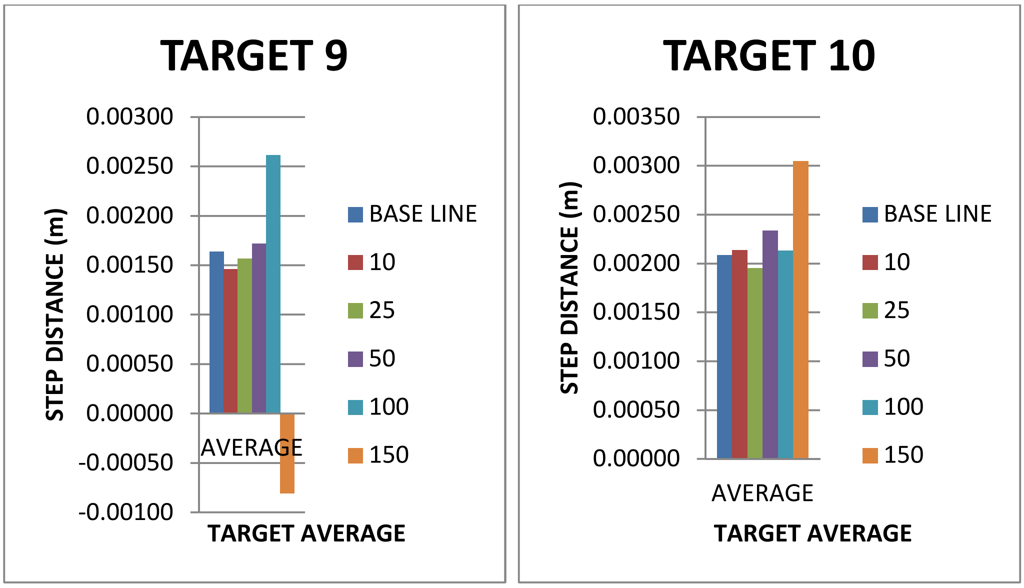
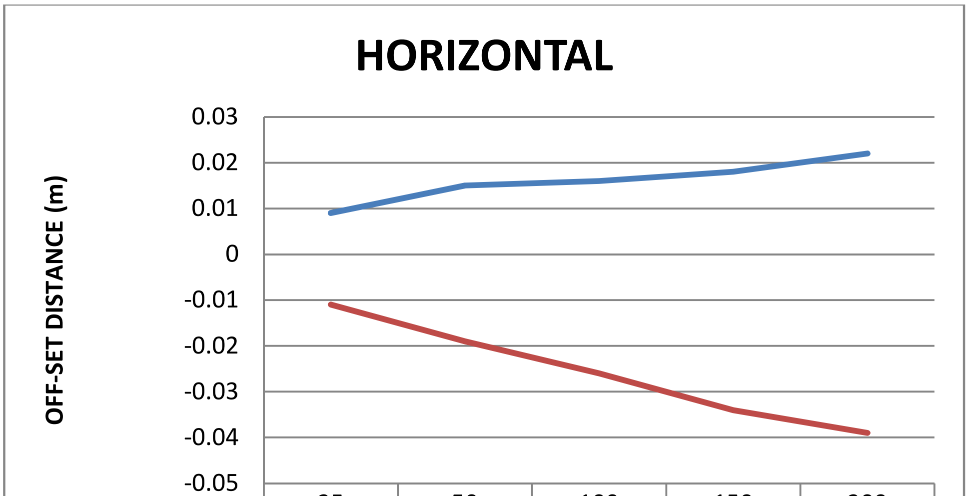


Figure 4.12 and 4.13 - Target 9 and Target 10 step measurement comparisons

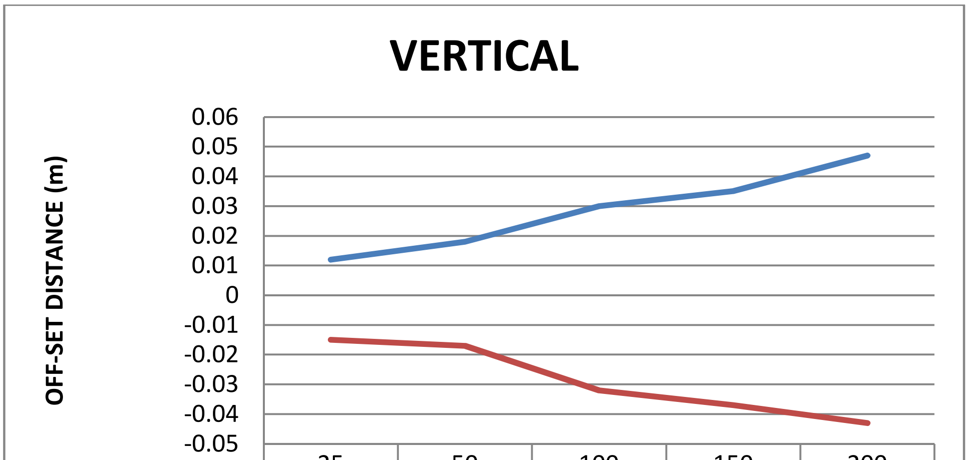
4.4. LASER DOT SIZE TEST

The following figures depict the off-sets measured from the step wall on the earlier described apparatus. It can be seen in the vertical test the off-set in and out closely mirror each other. In the horizontal test however, the off-set in can be seen to be only half as long as the off-set out.



	25	50	100	150	200
OFF-SET IN	0.009	0.015	0.016	0.018	0.022
OFF-SET OUT	-0.011	-0.019	-0.026	-0.034	-0.039

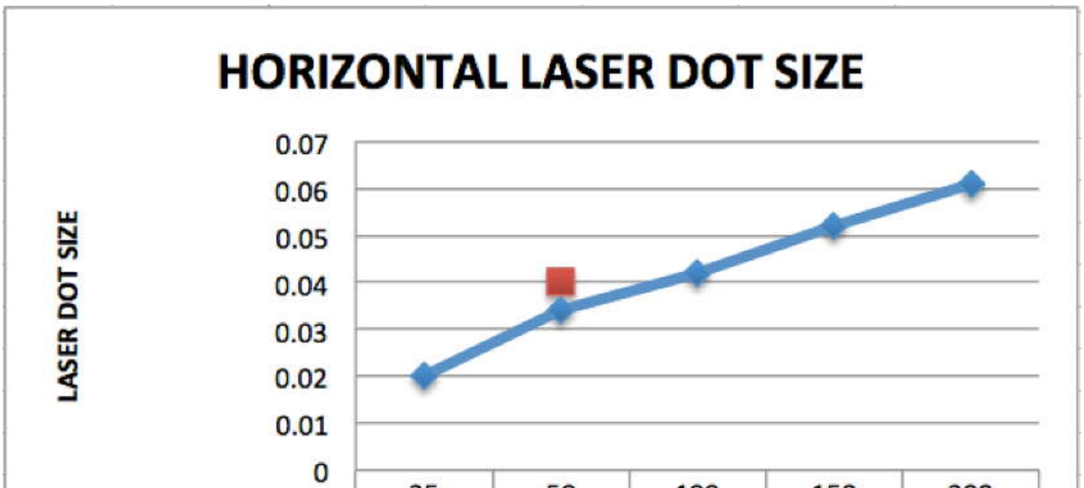
Figure 4.14 – Laser Dot Size - Horizontal Measurements.



	25	50	100	150	200
OFF-SET IN	0.012	0.018	0.03	0.035	0.047
OFF-SET OUT	-0.015	-0.017	-0.032	-0.037	-0.043

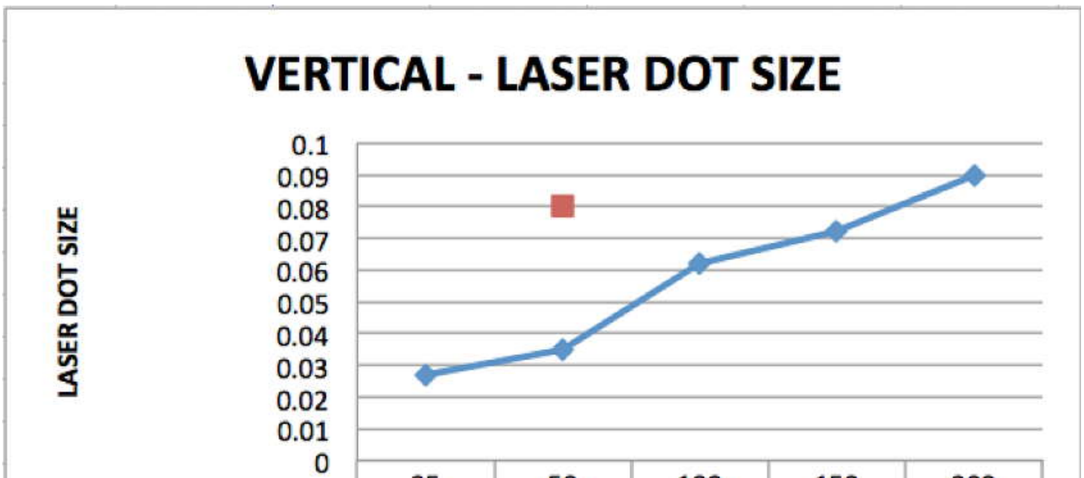
Figure 4.15 – Laser Dot Size - Vertical Measurements

Figure 4.16 and *4.17* depict the relationship between laser dot size and distance from the instrument for the Leica Nova MS-50. The manufacturer's specification details the laser dot size to be 0.04m horizontal by 0.08m vertical at a 50m measurement. These figures demonstrate the instrument is performing better than specified at the 50m test. As both figures represent linear lines, it can be assumed this laser dot size will continue to increase in diameter linearly, as it moves further away from the instrument.



	25	50	100	150	200
LASER DOT SIZE	0.02	0.034	0.042	0.052	0.061
MANUFACTURER		0.04			

Figure 4.16 - Horizontal Laser Dot Size Comparison



	25	50	100	150	200
LASER DOT SIZE	0.027	0.035	0.062	0.072	0.09
MANUFACTURER		0.08			

Figure 4.17 - Vertical Laser Dot Size Comparison

4.5. CONCLUSION

The field testing conducted in this chapter and the results obtained, indicate the Leica Nova MS-50 is less accurate than the manufacturer's specifications. It has been shown and proven that the standard deviation from conducting a scan at 1000 hertz is much larger than documented and as such, insufficient for use within a dam deformation scanning procedure.

It was determined that this machine was capable of accurate measurements at a cost of increase in time taken and a procedure can be developed from these results to test the instrument's abilities when conducting dam deformation surveys.

CHAPTER 5 – DAM DEFORMATION SURVEY PROCEDURE AND RESULTS

5.1. INTRODUCTION

A critical component of a research project is to evaluate the findings against the stated objectives by using a specific methodology.

This chapter will test the developed survey procedure on the chosen subject site. Then analyse and evaluate its potential at becoming a new method that is capable of reaching the necessary accuracies required in dam deformation surveys.

5.2. PROCEDURE DEVELOPED AND SITE SURVEY.

Procedure:

1. Locate TLS centrally on the downstream face of the dam approximately 30m from the toe of dam wall. Construct a permanent survey pillar in this location to ensure repeatability of results.
2. Orientate the Leica Nova MS-50 holding strong braced angles, using existing survey control located onsite.
3. Initiate reference plan and grid scanning program.
4. Select the reference plane.
5. Establish the scanning area.
6. Define the grid spacing.
7. Begin survey.
8. Finalise survey by checking azimuth.

5.3. ANALYSIS OF REPEATABILITY

The above survey procedure was conducted over the subject site, five times over the course of one day. The collected data from this survey was imported into office software for evaluation. To evaluate the repeatability that can be obtained from this survey procedure, the following steps were undertaken:

1. Create a base line perpendicular to the face of the surface, run the base line from the toe of the dam wall to the crest.
2. Calculate the chainage of the scanned points in relation to this base line.

3. Export these chainages into a suitable spreadsheet, set up for typical dam deformation analysis. This is when a scan epoch is compared to the first and last surveyed epoch. For example, scan three is compared to scan two and scan one, scan four is compared to scan three and scan one.
4. Calculate difference in chainages between points and graph the standard deviation.

As seen in the *figure 5.1* below it can be concluded that this survey method lacks repeatability that is required for dam deformation monitoring. It is clear that as the chainage increases, the standard deviation is well outside the allowable tolerances for dam deformation surveys.

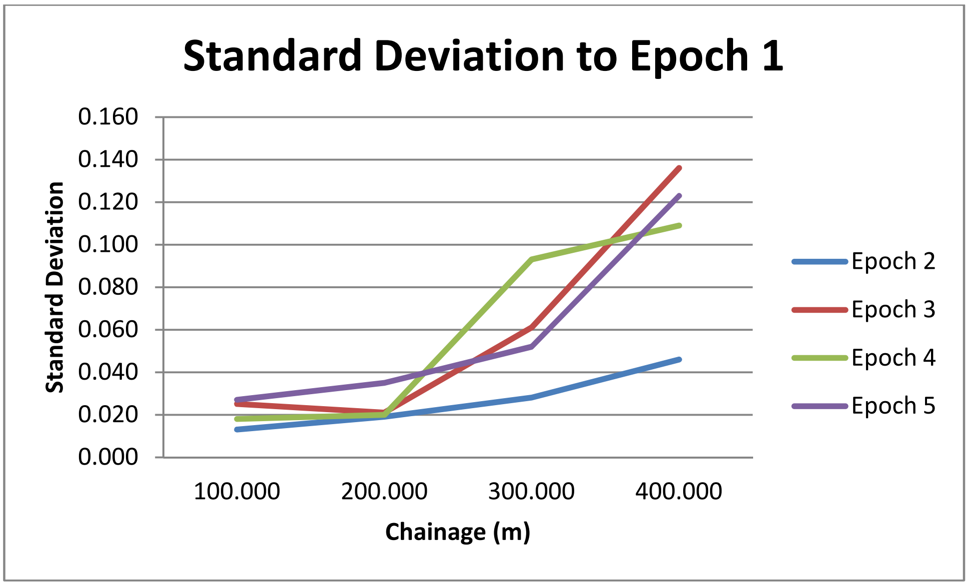


Figure 5.1 - Standard Deviation calculation for Epoch 1

Some contributing factors to this result could include:

- slight pointing error from the instrument, resulting in larger measurement errors;
- Irregularities in the rabble rock surface create more of an issue than previously anticipated; and
- changes in atmospherics contributing to errors on the long distance measurements.

5.4. PROBLEMS ENCOUNTERED

As previously stated, this procedure does not provide the opportunity to capture repeatable data, and as such is insufficient to be used in dam deformation surveys. Furthermore to these alarming results, the variance from the calculated plane to the true slope could fluctuate up to 6m due to the varying slope on the subject site as depicted in *figure D.2*. This variance resulted in the proposed equal grid measurements becoming curved, resulting in a non-uniform pick up of the structure in both the vertical and horizontal axis. Greater difficulty could be encountered in reporting to perspective clients, as the results cannot be presented in linear figures.

5.5. CONCLUSION

The results obtained from these initial surveys indicate the Leica Nova MS-50 is far more accurate than its predecessors, although it is still not accurate enough to be utilised in dam deformation surveying. However, with further research and understanding of how this instrument works and having its' strengths and weaknesses fully outlined, I believe the Leica Nova MS-50 is a great leap forward for survey instruments and will be able to provide new and innovative ways to conduct surveys faster and more efficiently.

CHAPTER 6 – ANALYSIS AND DISCUSSION

6.1. INTRODUCTION

The results obtained in Chapter 4 will be discussed in greater detail. The field testing results that have provided the necessary information for the survey procedure to be created and the survey procedure results will be discussed and analysed. This will provide a detailed evaluation on how the Leica Nova MS-50 performed.

6.2. ANGLE OF INCIDENCE TEST

The initial field-testing undertaken in this dissertation was based on testing the errors associated with altering the angle of incidence from the TLS to the surveyed surface. Chapter 4 details the instrument used as being the Leica Nova MS-50 along with the testing procedure undertaken.

This test was undertaken using a small portion of the subject site, being Eucumbene Dam. The angle of incidence for this test was not measured, however the test was focused around numerically defining the error that would occur if the instrument was used from different locations to scan the uneven rabble rock surface.

The field test was conducted with the scanning distance starting at 30m and finishing at 120m. This did not provide a complete comparison for the lengths proposed to be used in these surveys, but was sufficient in identifying the errors that are present.

Having the instrument re-located 10m parallel to the surface, before beginning the second survey, provided the following observations:

- With two scans over the same surface from the same location, errors between them are minimal at short lengths; this error increases as the surface extends further away from the TLS.
- Significant errors are demonstrated when the uneven surface is surveyed from a second location.
- Errors found between the two surfaces are consistent with standard deviation of the instrument found in other testing.
- The data set is unable to be manipulated to correct for this error found.

6.3. LENGTH DETECTION TEST

Length Detection testing was undertaken using the apparatus previously described and shown in Chapter 4. This test was conducted with the chosen instrument and was developed to identify the instrument's potential in determining the difference in surfaces from varying measurement lengths.

Analysis of the results obtained, provided mixed results when compared to expectations. The instrument is classified by the manufacturer as a precise unit and is stated to provide highly accurate results. This testing indicated that whilst the instrument provided excellent results when working over relatively short distances, it simply could not hold reasonable standard deviation over longer lengths and in turn was incapable of reading the targets at the extreme lengths.

Although it was intended to scan this target up to 250m, it was apparent from the point clouds obtained that these scans were incomplete. and therefore insufficient to be able to make reliable calculations.

Shortcomings of this testing apparatus included both the size of the apparatus and small errors in its construction. Due to the large size of this apparatus (see Chapter 4 for specifications) it was virtually impossible to construct the portable boards on site, in such a way to ensure they are straight with no warping in them. This resulted in further reduction calculations to ensure the standard deviations were calculated accurately. The targets of varying thickness attached to the portable boards, at times, did not hold conformity as can be seen in the base line precise level run. This is due to the metal targets being insufficiently connected on the boards in the workshop and requiring further alterations onsite on the day of survey. In addition to this, the construction material for the targets varied, due to the materials available, and as such could provide varying properties for the scan. The results however do not indicate sufficient data to confirm this concern, and further study should be conducted in this field.

6.4. LASER DOT SIZE TEST

Laser Dot Size testing was undertaken as specified in Chapter 4. Results obtained from this test indicate that the dot size does increase in diameter as the target is moved further away from the TLS. It is also noted from this testing procedure that the results obtained for the horizontal are much smaller than the specifications stated by the manufacturer. The vertical results agree with this specification. This test indicated the laser dot for the Leica

Nova MS-50 is much more circular in shape as opposed to the oval type dimensions provided by the manufacture.

This decrease in dot size, when compared to manufacturer's specifications aids in the determination of the Leica Nova MS-50's suitability to dam deformation monitoring. As this test did not provide adequate redundant information, further research and testing should be undertaken to confirm these findings.

6.5. PROCEDURE DEVELOPED

A standard survey procedure was developed from the results obtained in the previous testing. To allow the implementation of the Leica Nova MS-50 into dam deformation surveys. I hypothesised the procedure developed would be sound and capable of producing accurate, precise data with repeatability. Field testing of this procedure indicated this was not the case. It was determined that although the instrument could provide accurate work, small errors combined together, resulting in inaccurate work. These errors included:

- automatic aiming;
- atmospheric changes;
- lengths of measurements being undertaken; and
- irregular surface on rabble rock covering the earth fill dam wall.

6.6. SUBJECT SITE SURVEY

The subject site, being Eucumbene Dam is extremely large. This earth fill dam wall is not only over 100m high it is also nearly 600m in length along its crest. It also contains multiple slope changes as you travel the surface face. These slope changes create further error. As the plane of best fit created over this subject site, it could vary from the surface by up to 6m. This difference between the surface and the plane created provides added difficulties, especially when producing results that can be presented to clients for analysis of the earth fill dam movement.

6.7. CONCLUSION

The results obtained from the initial testing stage of this dissertation indicates the Leica Nova MS-50 does not provide the accuracies required to conduct a scan over a dam wall surface that can be used in dam deformation monitoring. It was discovered that this instrument can still provide highly accurate results. Therefore further field testing was undertaken using other powerful programs in the Leica Nova MS-50 such as the reference plane grid scan.

This too however could not provide the accuracies required for dam deformation surveys when the survey is being conducted on an earthfill dam wall with rabble rock surface and varying slopes. The lengths of measurement exceeding 400m also attributed to the lack of accuracy. Although this procedure failed on this large earth fill dam, it is anticipated that surveys on smaller dams and on concrete dams could produce different results.

CHAPTER 7 – CONCLUSION AND RECOMMENDATIONS

7.1. INTRODUCTION

This project aimed to incorporate the new technology provided by TLS into dam deformation surveys. Conclusions will now be drawn from this dissertation into the effectiveness of integrating TLS into dam deformation surveys.

Recommendations will also be provided from the data obtained, along with details on areas where further study and testing can be undertaken to extend this research.

7.2 DISCUSSION

Research conducted for this dissertation identified the Leica Nova MS-50 as the most suitable TLS on the current market for the proposed survey style. It was identified to have unprecedented accuracies within its scanning capabilities, as well as hold all the necessary functions a traditional Total Station instrument would possess.

The research undertaken also identified the most suitable software readily available to analyse the data obtained from this instrument. The software chosen was influenced by financial and time constraints within this dissertation. Other software packages could be available to better suit this survey style, and therefore further investigation into these would be beneficial to the end result and reporting process conducted by the surveyor.

7.3. LEICA NOVA MS-50 SCANNING CAPABILITIES

Research and field testing that was undertaken as part of this dissertation has identified, the Leica Nova MS-50 to be capable of accurate scanning measurements when in a controlled environment and working in relatively short lines, less than 100m in length. It was outlined that using the 1000 hertz scanning frequency, accuracy deteriorated as the length of measurement increased. This dissertation noted that 1000 hertz is the fastest and least accurate measurement speed for the chosen instrument. Further research should be undertaken to identify the accuracies and repeatability that is obtainable from this instrument at the lower frequencies.

Further testing was also undertaken on the effect of instrument location when conducting a scan procedure over an irregular rabble rock surface. It was determined that any slight change in instrument location could in fact have detrimental effects in regards to the repeatability of the survey. This was outlined to be highly influenced by the laser dot size of the instrument.

The field testing also determined the laser dot size of the instrument at nominal distances. This testing provided knowledge as the instrument measured a surface further away from its location, the laser dot increased in size and resulted in a oval area being averaged before the signal returned with a distance.

7.4. LEICA NOVA MS-50 GRID REFERENCE SCAN CAPABILITIES

A survey procedure was developed following the initial field testing that would examine the full effectiveness of introducing TLS instruments into dam deformation surveys. The procedure was developed taking into consideration the results and research previously undertaken.

At the conclusion of this testing procedure, it was detailed that although the instrument chosen is capable of providing highly accurate results, it was increasingly difficult to maintain any form of accuracy or repeatability at the chosen subject site known as Eucumbene Dam.

Issues associated with this chosen location included:

- Irregular rabble rock surface; this surface created more trouble than anticipated. The result of a slight error in the automatic pointing process of the instrument would result in an entirely different surface being covered by the laser dot, before being averaged and returned to the instrument.
- Multiple sloping surfaces; this site had multiple grades as you travelled from the toe to the crest of the dam wall. This results in the slope plane of best fit being created and at some points being upwards of six meters away from the true surface location. Again this affected the automatic aiming process and resulted in a non-uniform survey of the surface, instead of the anticipated grid pattern.
- Overall scale of the site; the subject site was chosen as the largest site on the Snowy Mountains Hydro Scheme. This resulted in measurements being taken that exceeded 450m. The effect of measuring this far, was not fully tested in the initial testing stage. Further research on the topic has identified the length of measurement to be directly proportional to the accuracies obtainable when remotely measuring a surface.

7.5. RECOMMENDATIONS

This dissertation has conducted vigorous research on the subject topic of TLS and dam deformation surveys. It has followed this research with detailed testing of a chosen instrument, followed by further testing of the instrument in a real world situation.

The conclusions developed within this dissertation hold a strong base for further research on this topic. This dissertation was limited in its objectives to earth fill dam walls. The instrument was only tested in its worst case scenarios and was implemented on Eucumbene Dam, one of the largest dam walls within New South Wales.

When taking this into consideration, it would be inappropriate to state that due to the results obtained in this dissertation, the instrument should not be considered for further research into the combination of these two fields. The testing has proven the instrument shows promise in obtaining accurate results, however these are primarily based on measurement lengths being less than 100m.

At this stage the following recommendations can be made in relation to combining these two fields in the surveying worlds:

- Limit surface scans when working at 1000 hertz to under 100m.
- Experiment with expanding this maximum length of survey as the scan frequency is decreased, taking into consideration this has not been fully investigated.
- Construct permanent survey pillars at the location for the instrument to be used from. This will ensure repeatability is maintained when scanning a surface (monitor the height the instrument is set up to on the pillar as well).
- Limit scanning on surfaces to areas that provide a flat surface greater than the laser dot size at the nominal distance, or consider the possibility this survey method is more suited to concrete structures.
- When using a slope plane grid scan, limit the plane to only include a surface at one constant grade, ensuring the plane and existing surface match each other as best as possible.

7.6. FURTHER RESEARCH

Field testing for this dissertation was limited due to time, equipment availability, financial constraints and location accessibility. Further testing could be undertaken to expand on the results obtained.

Results obtained from the step detection test indicate a large discrepancy between the manufacture's results and this dissertation. Further investigation into this difference should be undertaken, including research into the scanning frequencies available from the instrument below the 1000 hertz and the standard deviations that are calculated from these scans.

Additional research has indicated that laser beams when travelling away from their source begin as a continuous thickness in the beam. At a certain point away from the source, this thickness begins to expand exponentially. The testing undertaken in this dissertation was not fully developed to calculate this issue, as such further research and testing should be undertaken to fully understand the true dynamics of the laser beam as it leaves its source before returning a measured distance.

It is anticipated from the results obtained within this dissertation, the Leica Nova MS-50 contains the necessary technology to be integrated onto dam deformation surveys, however strict guidelines would have to be investigated and researched before this can take place. The chosen instrument needs to be tested over a concrete structure to truly assess the full effects that were induced by the rabble rock surface on the subject site. Following this, limitations on the size of structures must be investigated to ensure the instrument can be used and provide results that are within the tolerances required for dam deformation surveys.

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APPENDIX A: PROJECT SPECIFICATIONS

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: Jack Allan ATKINSON

TOPIC: Dam Deformation Surveys with Modern Technology

SUPERVISORS: Glenn Campbell

PROJECT AIM: To determine the feasibility of using terrestrial laser scanners for geodetic deformation surveys on earthfill dam walls.

PROGRAMME: **Issue B, 6 June 2014**

1. Research:
   a. Review terrestrial laser scanners and their accuracy
   b. Review current software
   c. Review current Deformation Survey methods.
   d. Earthfill Dam Structures and deformation risks.

2. Critically evaluate current survey methods, efficiency and accuracy. Along with current instruments used.

3. Design and implement a survey method, integrating scanners into the deformation survey process on a subject earthfill dam structure.

4. Analyse and evaluate results obtained using multiple methods.

5. Present recommendation on appropriateness of utilizing scanners on deformation surveys.

6. Submit an academic dissertation on the research.

As time permits:

7. Implement similar procedure analysis for other dam structures.

8. Detail design brief for the creation of deformation specific software dealing with point cloud data, by an external source.

AGREED: __________________________(student) __________________________ (supervisor)

Date: / / 2014 Date: / / 2014

Examiner/Co-examiner:______________________________

APPENDIX B: LEICA SCANSTATION P-20

Leica ScanStation P20

Industry's Best Performing Ultra-High Speed Scanner

WFD Technology

Unprecedented performance in ultra-high speed laser scanning

Productivity & Accuracy
An innovative combination of advanced time-of-flight range measurement plus modern Waveform Digitising (WFD) technology enables the compact Leica ScanStation P20 to achieve ultra-high scan speeds and low-noise performance at extended range (to 120 m). Together with high-accuracy angular measurements and survey-grade tilt compensation, Leica ScanStation P20 delivers unprecedented ultra-high speed scan data quality for as-built and scene surveys.

Scan up to 1 million points per second
Leica ScanStation P20 is the ideal instrument when very short time windows are available for capturing High-Definition Survey™ data or when ultra-high density, full dome scan data is needed for client deliverables.

Unmatched environmental capabilities
Developed and manufactured by Leica Geosystems, Leica ScanStation P20 lets users apply ultra-high speed scanning in operating temperatures ranging from –20° C to +50° C. Moreover, with an Ingress Protection rating of IP54 and an eye-safe laser class 1 rating, users can reap the benefits of ultra-high speed scanning for even more sites and projects.

"Check & Adjust" for added confidence
Leica ScanStation P20 is the first laser scanner to feature a valuable "Check & Adjust" capability. Instead of sending the instrument to a service centre, users can electronically check the accuracy of their ScanStation P20 themselves and automatically adjust instrument parameters to ensure the highest level of performance.

PART OF HEXAGON

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Leica ScanStation P20
Product Specifications

General

Instrument type	Compact, ultra-high speed pulsed laser scanner with survey grade accuracy, range and field-of-view; integrated camera and laser plummet
User interface	Onboard control, notebook or tablet PC, PDA
Data storage	Integrated solid-state drive (SSD) or external USB flash drive
Camera	Auto-adjusting, integrated high-resolution digital camera with zoom video

System Performance

Accuracy of single measurement	
3D Position Accuracy	3 mm at 50 m; 6 mm at 100 m
Linearity error	≤ 1 mm
Angular accuracy	8" horizontal; 8" vertical
Target acquisition*	2 mm standard deviation up to 50 m
Dual-axis compensator	Selectable on/off, resolution 1", dynamic range +/– 5', accuracy 1.5"

Laser Scanning and Imaging System

Type	Ultra-high speed time-of-flight enhanced by Waveform Digitising (WFD) technology
Wavelength	808 nm (invisible) / 658 (visible)
Laser class	1 (in accordance with IEC60825:2014)
Beam divergence	0.2mrad
Beam diameter at front window	≤ 2.8 mm
Range	Up to 120 m; 18% reflectivity (minimum range 0.4 m)
Scan rate	Up to 1'000'000 points/s

Range noise**

Range	Black (10%)	Gray (28%)	White (100%)
10 m	0.8 mm rms	0.5 mm rms	0.4 mm rms
25 m	1.0 mm rms	0.6 mm rms	0.5 mm rms
50 m	2.8 mm rms	1.1 mm rms	0.7 mm rms
100 m	9.0 mm rms	4.3 mm rms	1.5 mm rms

Scan time and resolution (hh:mm:ss)

7 pre-set point spacings (mm at 10 m)

Spacing	Quality level			
mm	1	2	3	4
50	00:20	00:20	00:28	----
25	00:33	00:33	00:53	01:43
12.5	00:58	01:44	03:24	06:46
6.3	01:49	03:25	06:46	13:30
3.1	03:30	06:47	13:30	26:59
1.6	13:33	27:04	54:07	----
0.8	54:07	1:48:13	----	----

Field-of-View	
Horizontal	360°
Vertical	270°
Aiming/Sighting	Parallax-free, integrated zoom video
Scanning optics	Vertically rotating mirror on horizontally rotating base Up to 50 Hz with internal battery Up to 100 Hz with external power supply
Data storage capacity	256 GB onboard solid-state drive (SSD) or external USB device
Communications	Gigabit Ethernet or integrated Wireless LAN
Imaging	5 megapixels per each 17° x 17° colour image; streaming video with zoom; auto-adjusts to ambient lighting
Onboard display	Touchscreen control with stylus, full colour VGA graphic display (640 x 480 pixels)
Level indicator	External bubble, electronic bubble in onboard software
Data transfer	Ethernet, WLAN or USB 2.0 device
Laser plummet	Laser class 1 (IEC60825:2014) Centering accuracy: 1.5 mm at 1.5 m Laser dot diameter: 2.5 mm at 1.5 m Selectable ON/OFF

Electrical

Power supply	24 V DC, 100 – 240 V AC
Power consumption	40 W typical
Battery type	Internal: Li-Ion; External: Li-Ion
Power ports	Internal: 2, External: 1 (simultaneous use, hot swappable)
Duration	Internal > 7 h (2 batteries), External > 8.5 h (room temp.)

Environmental

Operating temperature	–20° C to +50° C / –4° F to 122° F
Storage temperature	–40° C to +70° C / –40° F to 158° F
Lighting	Fully operational between bright sunlight and complete darkness
Humidity	Non-condensing
Dust/Humidity	IP54 (IEC 60529)

Physical

Scanner	
Dimensions (D x W x H)	238 mm x 358 mm x 395 mm / 9.4" x 14.1" x 15.6"
Weight	11.9 kg / 26.2 lbs, nominal (w/o batteries)
Battery (internal)	
Dimensions (D x W x H)	40 mm x 72 mm x 77 mm / 1.6" x 2.8" x 3.0"
Weight	0.4 kg / 0.9 lbs
Battery (external)	
Dimensions (D x W x H)	95 mm x 248 mm x 60 mm / 3.7" x 9.8" x 2.4"
Weight	1.9 kg / 4.2 lbs
AC Power Supply	
Dimensions (D x W x H)	170 mm x 85 mm x 42.5 mm / 6.6" x 3.3" x 1.6"
Weight	0.86 kg / 1.9 lbs
Mounting	Upright or upside down

Standard Accessories Included

Scanner transport case
Tribrach (Leica Geosystems Professional Series)
4 x Internal batteries
Battery charger / AC power cable, car adapter, daisy chain cable
Data cable
Height metre and distance holder for height metre
1 year CCP Basic support contract

Additional Accessories & Services

B&W scan targets and target accessories
Range of Customer Care Products (CCPs) that include Support, Hardware & Software maintenance and Extended warranty.
External battery with charging station, AC power supply and power cable
Professional charger for internal batteries
AC power supply for scanner
Tripod and tripod star
Upside down mounting adapter

Control Options

Full colour touchscreen for onboard scan control.
Remote control: Leica CS10/CS15 controller or any other remote desktop capable device, including iPad, iPhone and other SmartPhones.

Ordering Information

Contact your local Leica Geosystems representative or an authorised Leica Geosystems dealer.

All specifications are subject to change without notice.
All accuracy specifications are one sigma unless otherwise noted.
* Algorithmic fit to planar B&W targets
** Detailed explanation on request

Scanner: Laser class 1 in accordance with IEC60825:2014
Laser plummet: Laser class 1 in accordance with IEC60825:2014

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Leica Geosystems AG
Heerbrugg, Switzerland

www.leica-geosystems.com/hds

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Leica Geosystems

APPENDIX C: REIGLE VZ-400

RIEGL VZ®-400

- *high speed data acquisition*
- *wide field-of-view, configurable*
- *high-accuracy, high-precision ranging based on echo digitization and online waveform processing*
- *multiple target capability*
- *superior measurement capability in adverse atmospheric conditions*
- *high-precision mount for optional digital camera*
- *integrated inclination sensors and laser plummet*
- *integrated GPS receiver with antenna*
- *interface for external GNSS receiver*
- *various interfaces (LAN, WLAN, USB 2.0)*
- *internal data storage*

The *RIEGL* VZ-400 V-Line® 3D Terrestrial Laser Scanner provides high speed, non-contact data acquisition using a narrow infrared laser beam and a fast scanning mechanism. High-accuracy laser ranging is based upon *RIEGL*'s unique echo digitization and online waveform processing, which enables superior measurement performance even during adverse environmental conditions and provides multiple return capability.

The *RIEGL* VZ-400 is a very compact and lightweight surveying instrument, mountable in any orientation and even able to perform in limited space conditions.

Modes of Operation:

- stand-alone data acquisition without the need of a computer
- basic configuration and control via built-in user interface
- remote operation via RiSCAN PRO on a notebook, connected either via LAN interface or integrated WLAN
- well-documented command interface for smooth integration into mobile laser scanning systems
- interfacing to post processing software

User Interfaces:

- integrated Human-Machine Interface (HMI) for stand-alone operation without a computer
- high-resolution 3,5" TFT color display, 320 x 240 pixel, scratch resistant glass with anti-reflection coating and multi-lingual menu
- water and dirt resistant key pad with large buttons for instrument control
- speaker for audible status and operation communications

Typical applications include

- ***As-Built Surveying***
- ***Architecture & Facade Measurement***
- ***Archaeology & Cultural Heritage Documentation***
- ***City Modelling***
- ***Tunnel Surveying***
- ***Civil Engineering***
- ***Forestry***
- ***Research***

visit our website
www.riegl.com

RIEGL® LASER MEASUREMENT SYSTEMS

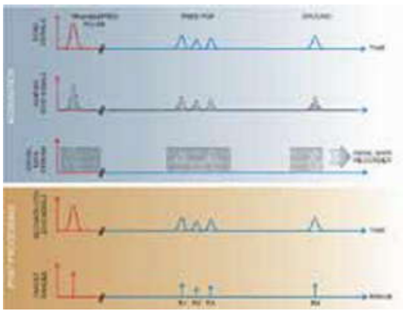
High Accuracy Performance

The 3D Terrestrial Laser Scanner *RIEGL* VZ-400 provides scan data acquisition with 5 mm accuracy / 3 mm repeatability, a measurement range up to 600 m, and an efficient measurement rate up to 122,000 measurements/sec. The fully portable, rugged and robust instrument offers a wide field of view of 100° vertical and 360° horizontal, and uses an invisible laser beam for eye safe operation in Laser Class 1.

Camera Option

A high-precision mount enables the integration of an optional DSLR camera. The camera can be easily integrated into the mount by means of two screws. Precise position and orientation of the camera is enabled by three supporting points. Power supply and a USB 2.0 interface are provided via the scanner directly.

The combination of scanner, software, and camera results in photorealistic 3D data, exact identification of details, position and distance measurements, as well as recreation of any virtual point of view.



Waveform Data Output Option

The digitized echo signals, also known as waveform data, acquired by the *RIEGL* VZ-400 are the basis for waveform analysis. This data is provided via the optionally available waveform data output and accessible with the associated *RIEGL* software library RiWAVELib for investigations and research on multi target situations based on the digital waveform data samples of the target echoes.

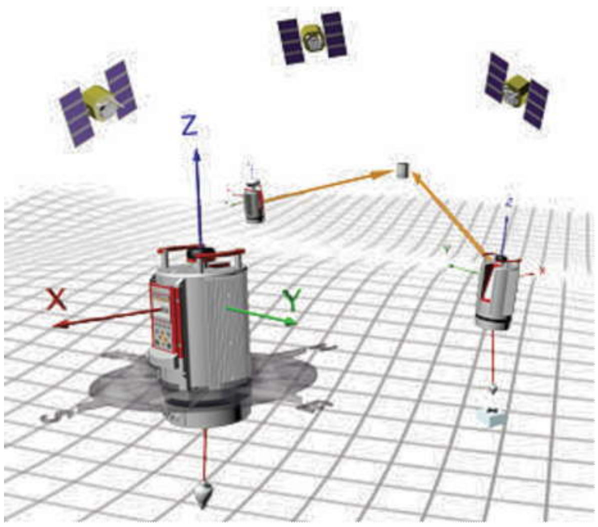
Compatible Software Packages

The *RIEGL* VZ-400 is compatible with the *RIEGL* software package RiSCAN PRO for terrestrial laser scanning, *RIEGL*'s interface library RiVLib, as well as the workflow-optimizing software packages, e.g. RiMINING. Combined with the one-touch workflow of the scanner, *RIEGL*'s ultimate 3D scene capture solution, RiSOLVE, enables fully automatic registration and colorization of scan data.

Supported Registration Methods

Direct Geo-Referencing

- integrated GPS receiver (L1) connected
- external high-end RTK GNSS receiver connected
- integrated compass, accuracy typ. 1°
  (one sigma value, available for vertical scanner setup position)
- on-board inclination sensors (tilt range ±10°, accuracy typ. ±0.008°)



GNSS Traversing

- GNSS position (RTK or autonomous)
- on-board inclination sensors
- automatic acquisition of well known remote target (reflector)

Free Stationing

- fast fine scanning of reflectors for precise determination of scanner position using control points

Backsighting

- setup on well known point
- on-board inclination sensors
- precise fine scanning of well known remote target (reflector)

WLAN antenna

Carrying handles

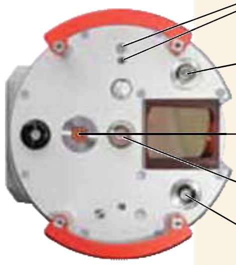
High-resolution color TFT display

Key pad for instrument control

Connectors for power supply and
LAN interface 10/100 MBit/sec,
power off/on button

Communication and Interfaces

- LAN port 10/100/1000 MBit/sec within rotating head
- LAN port 10/100 MBit/sec within base
- integrated WLAN interface with rod antenna
- USB 2.0 for external storage devices (USB flash drives, external HDD)
- USB 2.0 for connecting the optional digital camera
- connector for GPS antenna
- two ports for external power supply
- connector for external GPS synchronization pulse (1PPS)
- connector for external GNSS receiver



Mounting points (3x) and
mounting threads inserts (2x)
for digital camera

Connector for external GNSS
receiver (optional)

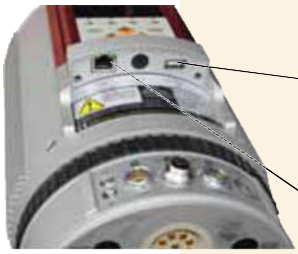
USB and DC power connector
for optional digital camera

Connector for GPS antenna
(internal receiver)

Connector for WLAN antenna

Scan Data Storage

- internal 32 GBytes flash memory
  (2 GBytes reserved for the operating system)
- external storage devices (USB flash drives or external hard drives) via USB 2.0 interface



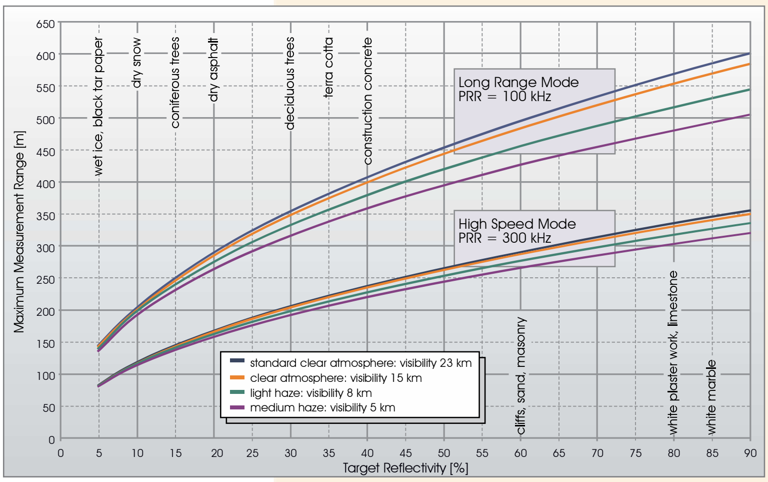
USB 2.0 slot for
external memory devices

LAN 10/100/1000 MBit/sec,
for rapid download
of scan data

Max. Measurement Range

The following conditions are assumed:

Flat target larger than footprint of laser beam, perpendicular angle of incidence, average brightness



Technical Data *RIEGL* VZ®-400

Laser Product Classification	Class 1 Laser Product according to IEC60825-1:2007 The following clause applies for instruments delivered into the United States: Complies with 21 CFR 1040.10 and 1040.11 except for deviations pursuant to Laser Notice No. 50, dated June 24, 2007.

CLASS 1 LASER PRODUCT

Range Performance 1)

	Long Range Mode	High Speed Mode
Laser Pulse Repetition Rate PRR (peak) 2)	100 kHz	300 kHz
Effective Measurement Rate (meas./sec) 2)	42 000	122 000
Max. Measurement Range 3)		
natural targets ρ ≥ 90 %	600 m	350 m
natural targets ρ ≥ 20 %	280 m	160 m
Max. Number of Targets per Pulse	practically unlimited 4)	
Accuracy 5) 7)	5 mm	
Precision 6) 7)	3 mm	

Minimum Range	1.5 m
Laser Wavelength	near infrared
Laser Beam Divergence 8)	0.35 mrad

1) With online waveform processing.
2) Rounded values.
3) Typical values for average conditions. Maximum range is specified for flat targets with size in excess of the laser beam diameter, perpendicular angle of incidence, and for atmospheric visibility of 23 km. In bright sunlight, the max. range is shorter than under overcast sky.
4) Details on request.
5) Accuracy is the degree of conformity of a measured quantity to its actual (true) value.
6) Precision, also called reproducibility or repeatability, is the degree to which further measurements show the same result.
7) One sigma @ 100 m range under *RIEGL* test conditions.
8) Measured at the $1/e^2$ points. 0.35 mrad corresponds to an increase of 35 mm of beam diameter per 100 m distance.

Scanner Performance

	Vertical (Line) Scan	*Horizontal (Frame) Scan*
Scan Angle Range	total 100° (+60° / -40°)	max. 360°
Scanning Mechanism	rotating multi-facet mirror	rotating head
Scan Speed	3 lines/sec to 120 lines/sec	0°/sec to 60°/sec 10)
Angular Step Width Δ ϑ (vertical), Δ φ (horizontal)	0.0024° ≤ Δ ϑ ≤ 0.288° 9) between consecutive laser shots	0.0024° ≤ Δ φ ≤ 0.5° 9) between consecutive scan lines
Angle Measurement Resolution	better 0.0005° (1.8 arcsec)	better 0.0005° (1.8 arcsec)

Inclination Sensors	integrated, for vertical scanner setup position, details see page 2
GPS Receiver	integrated, L1, with antenna
Compass	optional, for vertical scanner setup position, details see page 2
Internal Sync Timer	integrated, for real-time synchronized time stamping of scan data
Scan Sync (optional)	scanner rotation synchronization

9) Selectable.
10) Frame scan can be disabled, providing 2D scanner operation.

General Technical Data

Power Supply Input Voltage	11 - 32 V DC
Power Consumption	typ. 65 W (max. 80 W)
External Power Supply	up to three independent external power sources can be connected for uninterrupted operation
Main Dimensions	Ø 180 x 308 mm (diameter x length)
Weight	approx. 9.6 kg
Humidity	max. 80 % non condensing @ +31°C
Protection Class	IP64, dust- and splash-proof
Temperature Range	
Storage	-10°C up to +50°C
Operation	0°C up to +40°C: standard operation
Low Temperature Operation 11)	-20°C: continuous scanning operation if instrument is powered on while internal temperature is at or above 0°C and still air -40°C: scanning operation for about 20 minutes if instrument is powered on while internal temperature is at or above 15°C and still air

11) Insulating the scanner with appropriate material will enable operation at even lower temperatures.

RIEGL® LASER MEASUREMENT SYSTEMS

RIEGL Laser Measurement Systems GmbH
Riedenburgstraße 48
3580 Horn, Austria
Phone: +43 2982 4211 | Fax: +43 2982 4210
office@riegl.co.at
www.riegl.com

RIEGL USA Inc.
Orlando, Florida | info@rieglusa.com | www.rieglusa.com
RIEGL Japan Ltd.
Tokyo, Japan | info@riegl-japan.co.jp | www.riegl-japan.co.jp
RIEGL China Ltd.
Beijing, China | info@riegl.cn | www.riegl.cn

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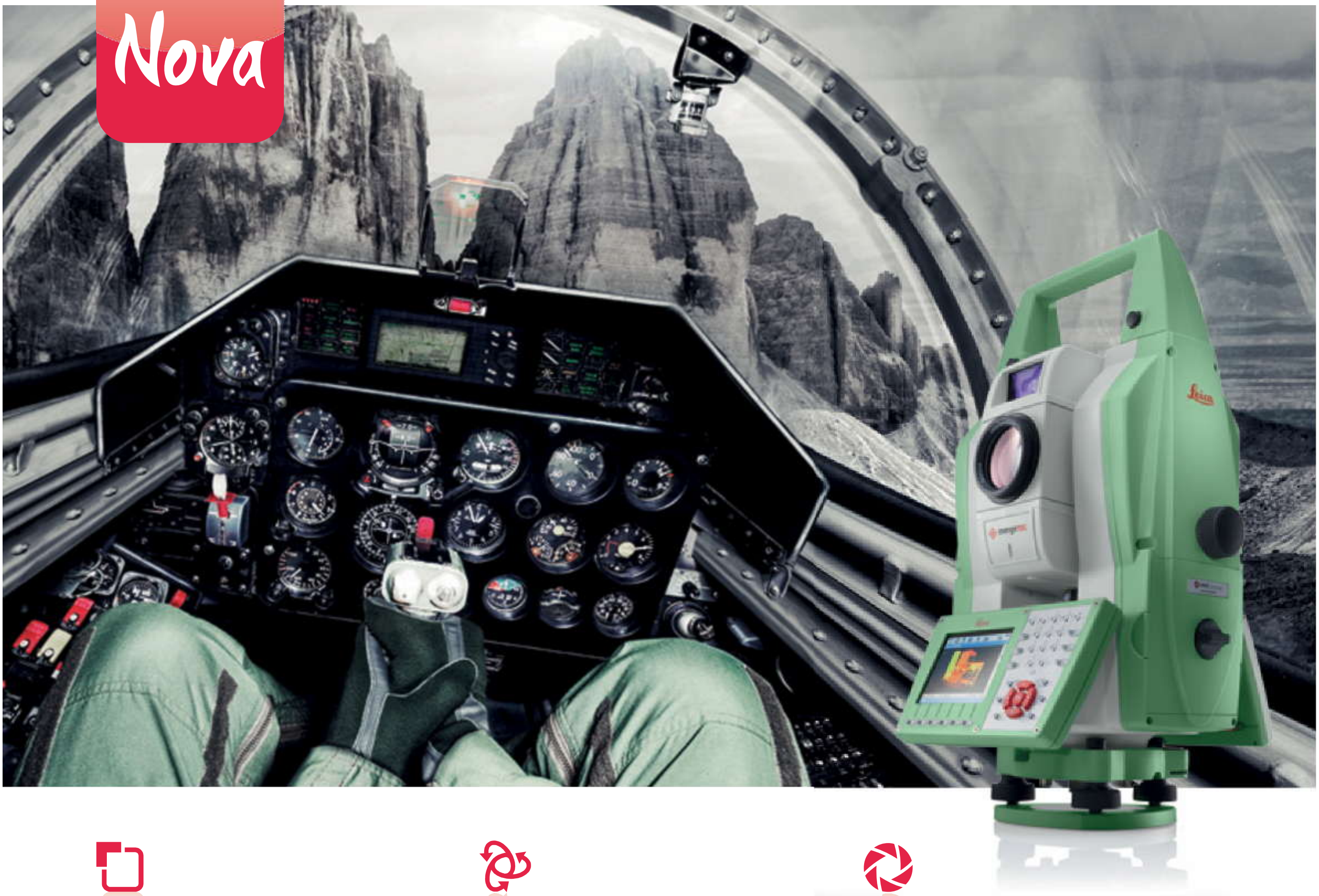
APPENDIX D: LEICA NOVA MS50 SPECIFICATIONS

Leica Nova MS50
Datasheet



INTEGRATED SCANNING OF EVERY DETAIL

The Leica Nova MS50 integrates 3D point cloud measurements into a regular survey workflow. This lets you collect and visualise your topographic survey data together with detailed high-precision scans. Save time by checking your data for integrity and relevance and avoid costly reworking or returns to the field. Benefit from better decisions with richer and more detailed data.

PROVEN TECHNOLOGY FOR UNMATCHED VERSATILITY

The Leica Nova MS50 provides proven total station functionality with superior sensor integration for highest precision, performance and full automation of measurement procedures. Together with the benefits of GNSS connectivity, the Leica Nova MS50 offers complete versatility by delivering reliable results wherever and whenever you need them.

IMAGE ASSISTANCE FOR EVERY SITUATION

The Leica Nova MS50 features an overview camera and a telescope camera with 30x magnification and autofocus. State-of-the-art image processing technology delivers live fluid video streaming of highest image quality. The imaging capabilities of the Leica Nova MS50 open up new opportunities of operating the MultiStation in an almost infinite range of applications.

Leica Nova MS50 MultiStation

ANGLE MEASUREMENT		
Accuracy[1] Hz and V	Absolute, continuous, quadruple	1" (0.3 mgon)
DISTANCE MEASUREMENT		
Range[2]	Prism (GPR1, GPH1P)[3] Non-Prism / Any surface[4]	1.5 m to >10000 m 1.5 m to 2000 m
Accuracy / Measurement time	Single (prism)[2,5] Single (Any surface)[2,4,5,6]	1 mm + 1.5 ppm / typ. 1.5 s 2 mm + 2 ppm / typ. 1.5 s
Laser dot size	at 50 m	8 mm x 20 mm
Measurement technology	Wave Form Digitising	coaxial, visible red laser
SCANNING		
Max. Range[7] / Range noise (1 sigma)[4]	1000 Hz mode 250 Hz mode 62 Hz mode 1 Hz mode	300 m / 1.0 mm at 50 m 400 m / 0.8 mm at 50 m 500 m / 0.6 mm at 50 m 1000 m / 0.6 mm at 50 m
Visualisation of point cloud	Onboard 3D point cloud viewer, including true colour point clouds	
IMAGING		
Overview and telescope camera	Sensor Field of view (overview / telescope) Frame rate	5 Mpixel CMOS sensor 19.4° / 1.5° Up to 20 frames per second
MOTORISATION		
Direct drives based on Piezo technology	Rotation speed / Time to Change Face	max. 200 gon (180°) per s / typ. 2.9 s
AUTOMATIC AIMING (ATR)		
Range ATR mode[2] / Lock mode[2]	Circular prism (GPR1, GPH1P) 360° prism (GRZ4, GRZ122)	1000 m / 800 m 800 m / 600 m
Accuracy[1,2] / Measurement time	ATR angle accuracy Hz, V	1" (0.3 mgon) / typ. 2.5 s
POWERSEARCH		
Range / Search time[8]	360° prism (GRZ4, GRZ122)	300 m / typ. 5 s
GUIDE LIGHT (EGL)		
Working Range / Accuracy		5–150 m / typ. 5 cm @ 100 m
GENERAL		
Autofocus telescope	Magnification / Focus Range	30 x / 1.7 m to infinity
Display and Keyboard	VGA, colour, touch, both faces	36 keys, illumination
Operation	3x endless drives, 1x Servofocus drive, 2x Autofocus keys, User-definable SmartKey	
Power management	Exchangeable Lithium-Ion battery with internal charging capability	Operating Time 7–9 h
Data storage	Internal memory / Memory card	1 GB / SD card 1 GB or 8 GB
Interfaces	RS232, USB, Bluetooth®, WLAN	
Weight	MultiStation incl. battery	7.6 kg
Environmental specifications	Working temperature range Dust & Water (IEC 60529) / Blowing rain Humidity	–20°C to +50°C IP65 / MIL-STD-810G, Method 506.5-I 95%, non-condensing

[1] Standard deviation ISO 17123-3
[2] Overcast, no haze, visibility about 40 km, no heat shimmer
[3] 1.5 m to 3000 m for 360° prisms (GRZ4, GRZ122)
[4] Object in shade, sky overcast, Kodak Gray Card (90% reflective)
[5] Standard deviation ISO 17123-4
[6] Distance > 500 m: Accuracy 4 mm + 2 ppm, Measurement Time typ. 4 s
[7] Object in shade, sky overcast, uninterrupted visibility, static target object, Kodak Gray Card (90% reflective)
[8] Target perfectly aligned to the instrument

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Leica Geosystems AG
Heerbrugg, Switzerland

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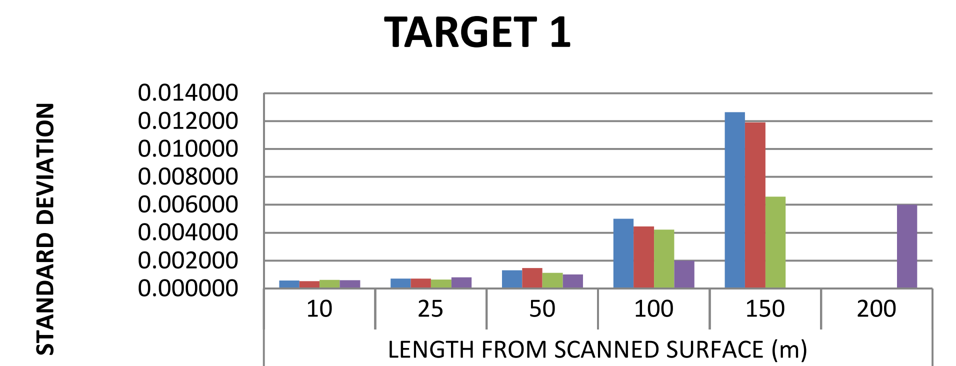
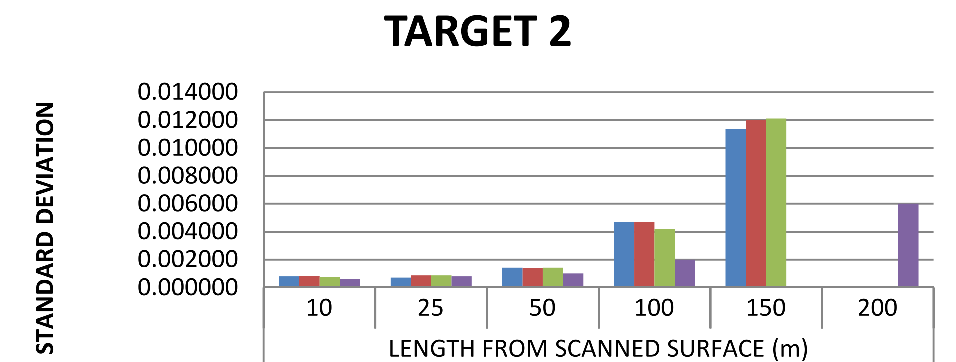
APPENDIX E: STANDARD DEVIATION PER TARGET



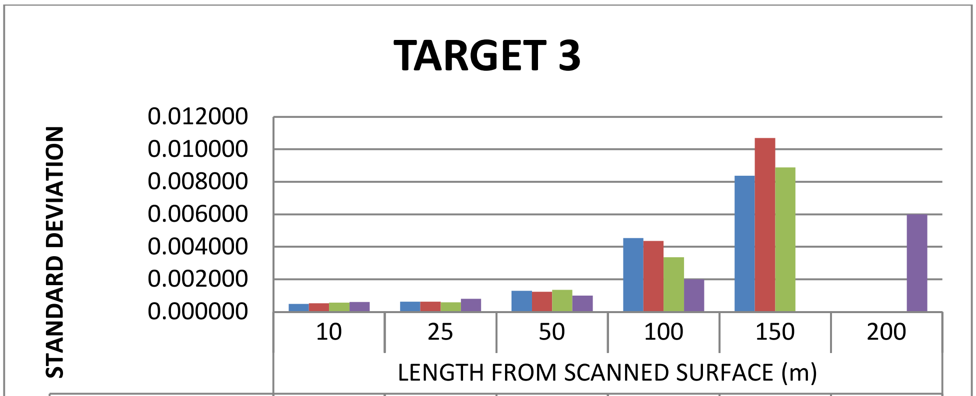
	10	25	50	100	150	200
LOWER PROFILE	0.000570	0.000720	0.001300	0.005010	0.012630	
MIDDLE PROFILE	0.000520	0.000720	0.001460	0.004440	0.011900	
UPPER PROFILE	0.000620	0.000650	0.001120	0.004220	0.006590	
MANUFACTURER	0.000600	0.000800	0.001000	0.002000		0.006000

Figure E.1 Standard Deviation on Target 1



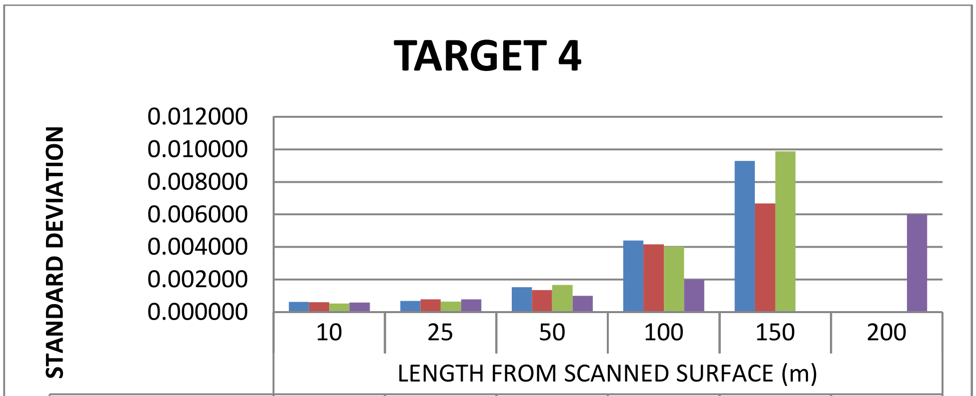
	10	25	50	100	150	200
LOWER PROFILE	0.000790	0.000720	0.001420	0.004670	0.011370	
MIDDLE PROFILE	0.000820	0.000880	0.001400	0.004710	0.011990	
UPPER PROFILE	0.000750	0.000880	0.001420	0.004170	0.012120	
MANUFACTURER	0.000600	0.000800	0.001000	0.002000		0.006000

Figure E.2 Standard Deviation on Target 2



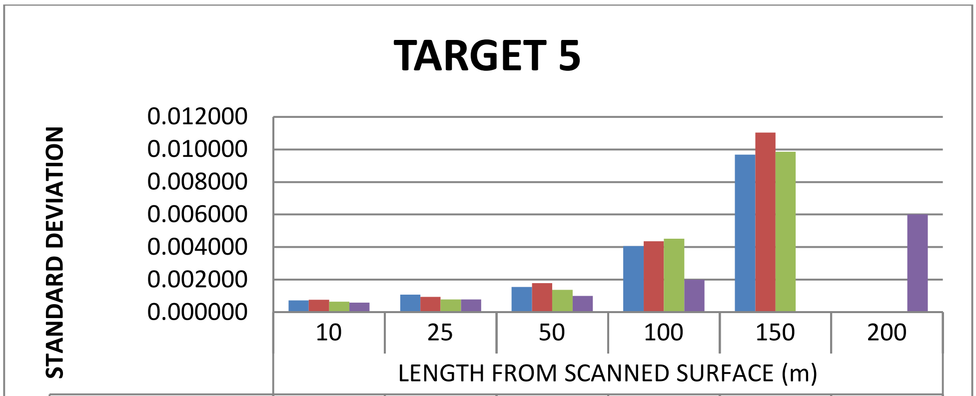
	10	25	50	100	150	200
LOWER PROFILE	0.000490	0.000620	0.001290	0.004550	0.008380	
MIDDLE PROFILE	0.000520	0.000620	0.001240	0.004370	0.010690	
UPPER PROFILE	0.000570	0.000590	0.001360	0.003370	0.008890	
MANUFACTURER	0.000600	0.000800	0.001000	0.002000		0.006000

Figure E.3 Standard Deviation on Target 3



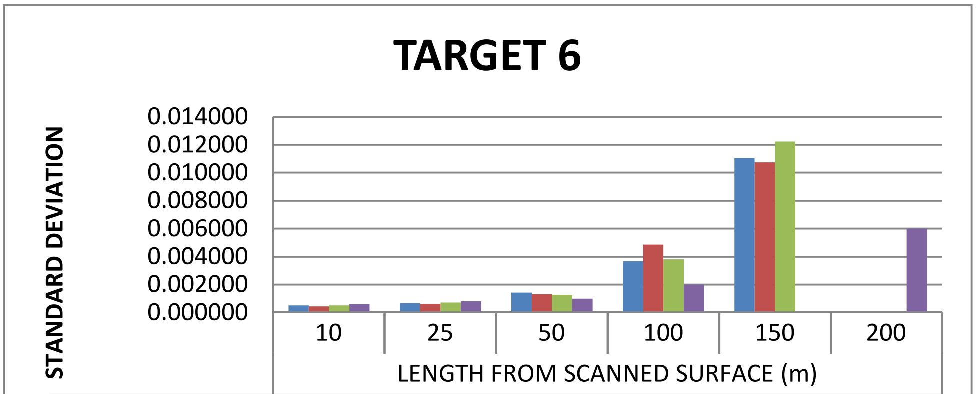
	10	25	50	100	150	200
LOWER PROFILE	0.000640	0.000700	0.001540	0.004410	0.009290	
MIDDLE PROFILE	0.000620	0.000790	0.001360	0.004170	0.006670	
UPPER PROFILE	0.000540	0.000650	0.001670	0.004030	0.009880	
MANUFACTURER	0.000600	0.000800	0.001000	0.002000		0.006000

Figure E.4 Standard Deviation on Target 4



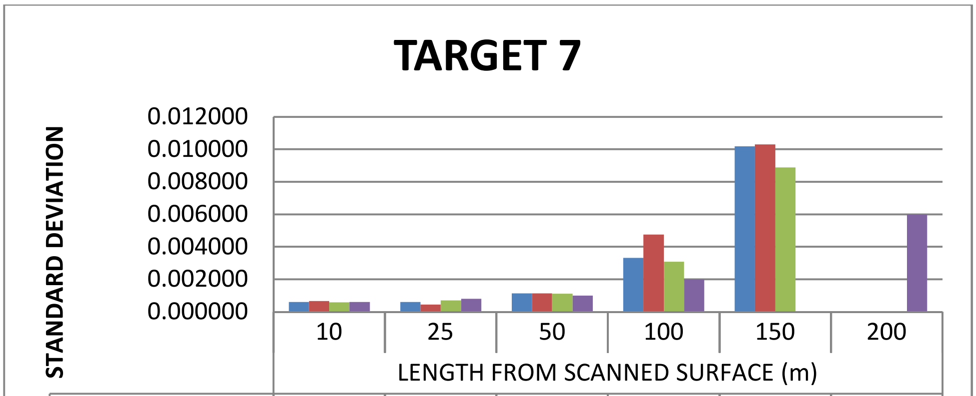
	10	25	50	100	150	200
LOWER PROFILE	0.000740	0.001080	0.001550	0.004070	0.009680	
MIDDLE PROFILE	0.000780	0.000940	0.001800	0.004370	0.011030	
UPPER PROFILE	0.000650	0.000790	0.001380	0.004520	0.009850	
MANUFACTURER	0.000600	0.000800	0.001000	0.002000		0.006000

Figure E.5 Standard Deviation on Target 5



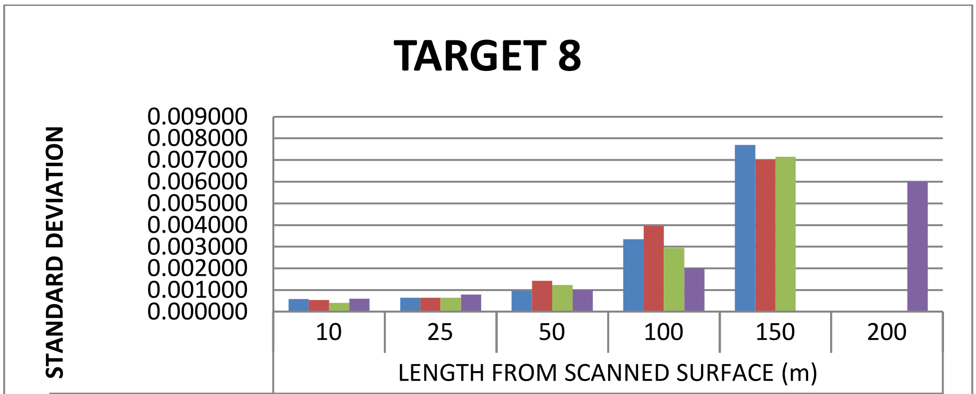
	10	25	50	100	150	200
LOWER PROFILE	0.000510	0.000680	0.001430	0.003680	0.011030	
MIDDLE PROFILE	0.000450	0.000620	0.001320	0.004860	0.010740	
UPPER PROFILE	0.000520	0.000710	0.001260	0.003800	0.012240	
MANUFACTURER	0.000600	0.000800	0.001000	0.002000		0.006000

Figure E.6 Standard Deviation on Target 6



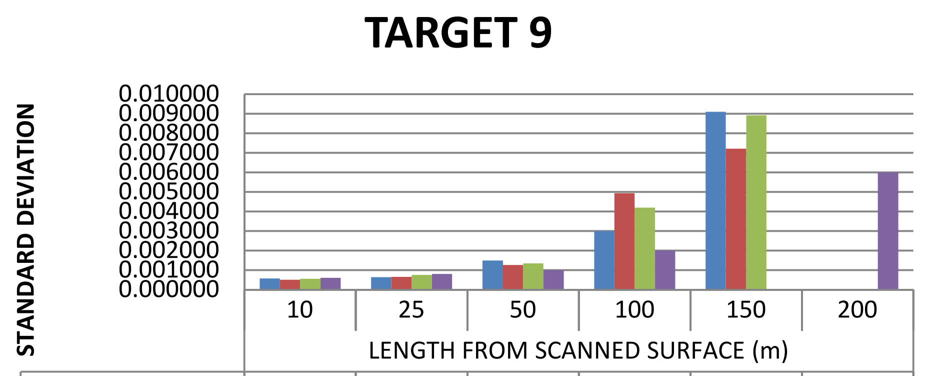
	10	25	50	100	150	200
LOWER PROFILE	0.000600	0.000610	0.001130	0.003330	0.010190	
MIDDLE PROFILE	0.000660	0.000450	0.001140	0.004760	0.010310	
UPPER PROFILE	0.000580	0.000710	0.001120	0.003090	0.008880	
MANUFACTURER	0.000600	0.000800	0.001000	0.002000		0.006000

Figure E.7 Standard Deviation on Target 7



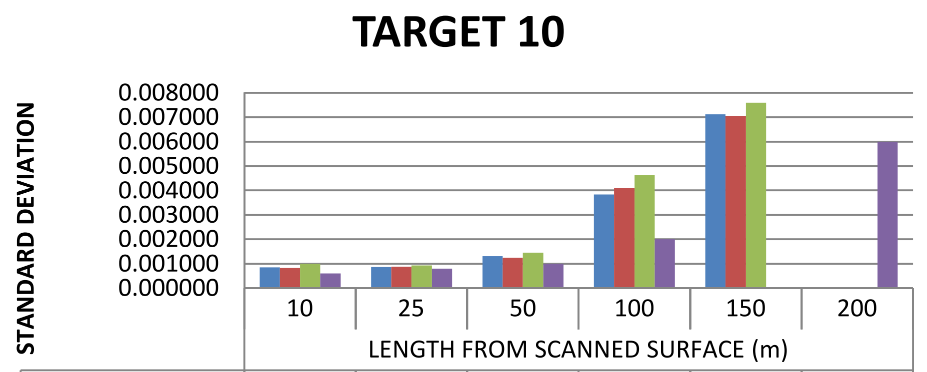
	10	25	50	100	150	200
LOWER PROFILE	0.000590	0.000650	0.000970	0.003340	0.007700	
MIDDLE PROFILE	0.000550	0.000640	0.001430	0.003970	0.007020	
UPPER PROFILE	0.000410	0.000640	0.001230	0.002950	0.007150	
MANUFACTURER	0.000600	0.000800	0.001000	0.002000		0.006000

Figure E.8 Standard Deviation on Target 8



	10	25	50	100	150	200
LOWER PROFILE	0.000570	0.000640	0.001490	0.003000	0.009100	
MIDDLE PROFILE	0.000510	0.000660	0.001260	0.004930	0.007210	
UPPER PROFILE	0.000560	0.000750	0.001340	0.004200	0.008910	
MANUFACTURER	0.000600	0.000800	0.001000	0.002000		0.006000

Figure E.9 Standard Deviation on Target 9



	10	25	50	100	150	200
LOWER PROFILE	0.000850	0.000870	0.001310	0.003830	0.007120	
MIDDLE PROFILE	0.000830	0.000880	0.001250	0.004100	0.007060	
UPPER PROFILE	0.001000	0.000930	0.001450	0.004640	0.007590	
MANUFACTURER	0.000600	0.000800	0.001000	0.002000		0.006000

Figure E.10 Standard Deviation on Target 10

APPENDIX F: STEP DISTANCE MEASURED PER CROSS-SECTION

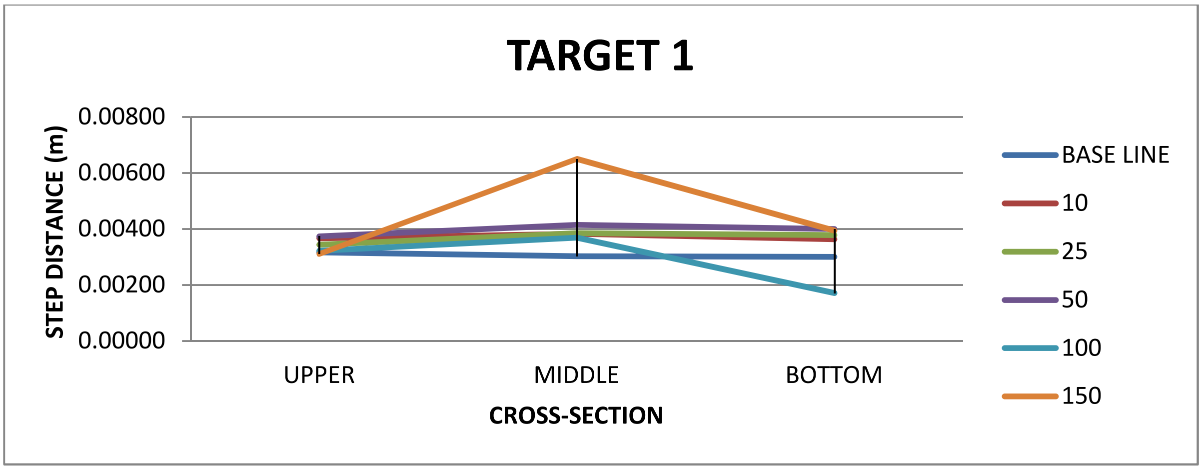


Figure F.1 Step Distance per cross-section – Target 1

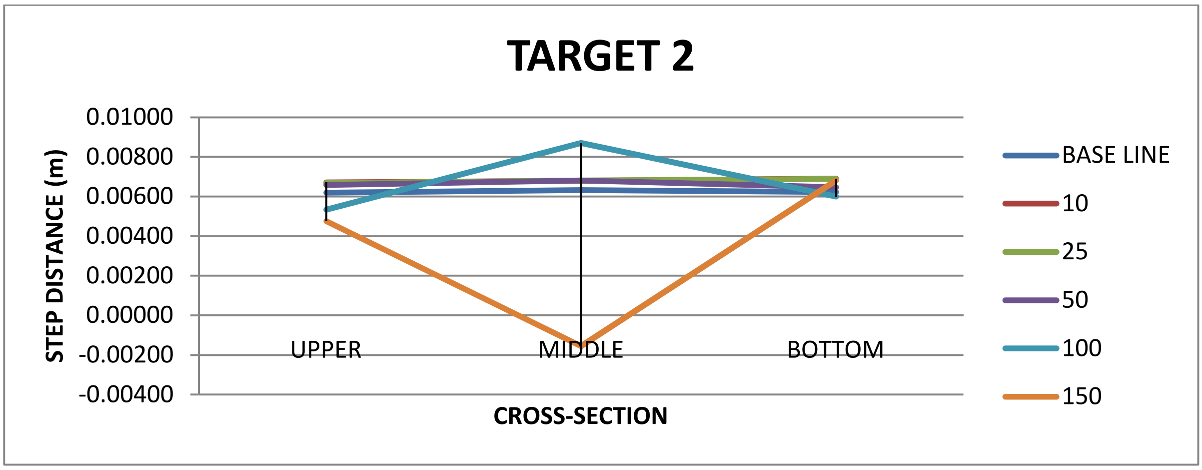


Figure F.2 Step Distance per cross-section – Target 2

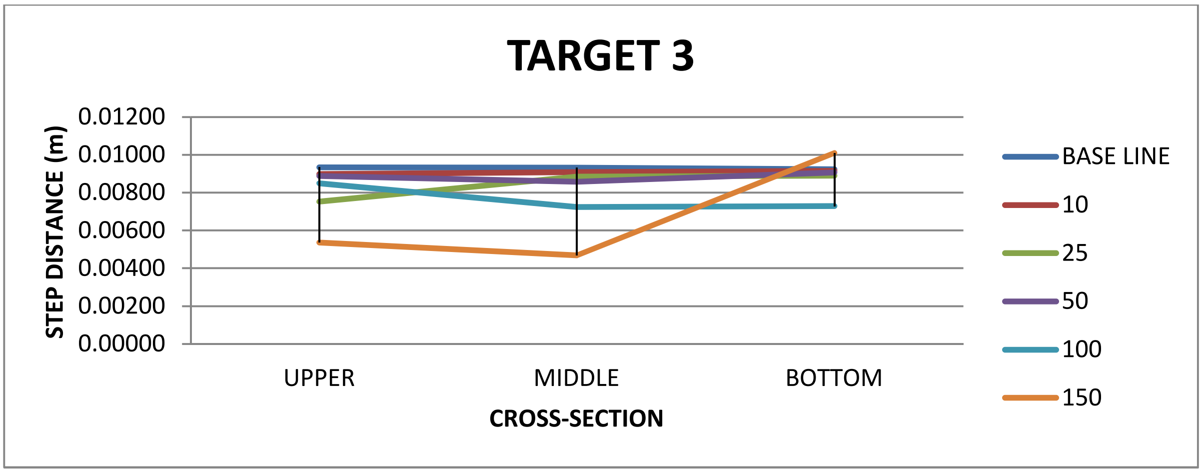


Figure F.3 Step Distance per cross-section – Target 3

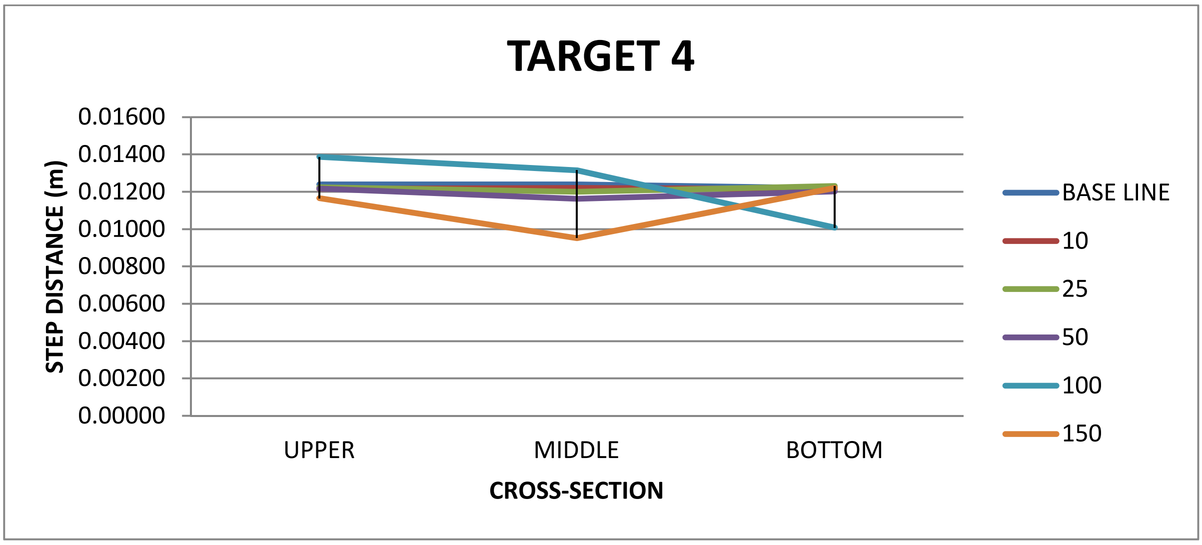


Figure F.4 Step Distance per cross-section – Target 4

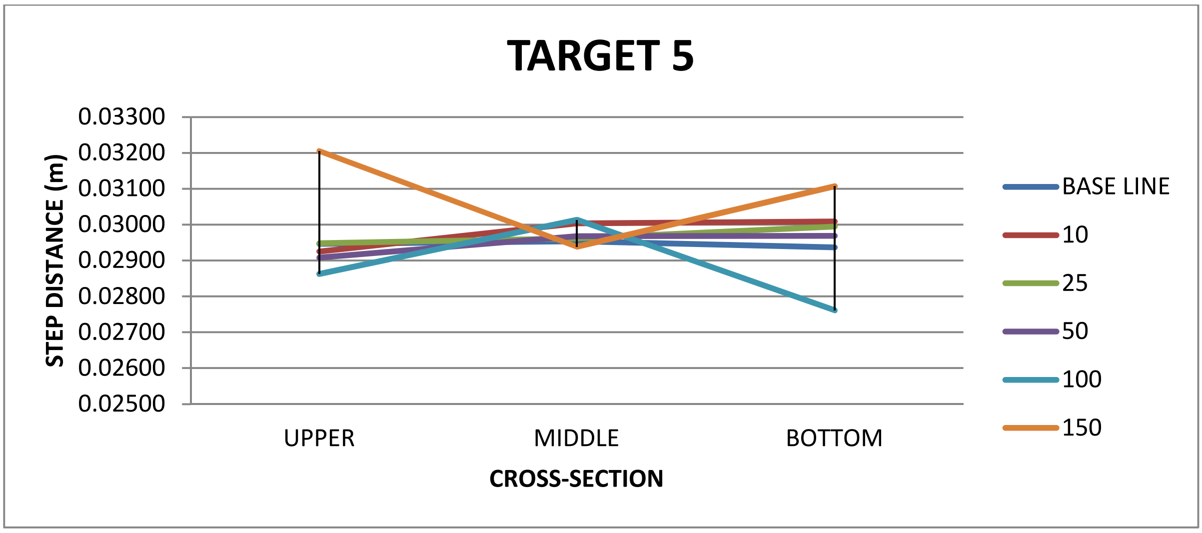


Figure F.5 Step Distance per cross-section – Target 5

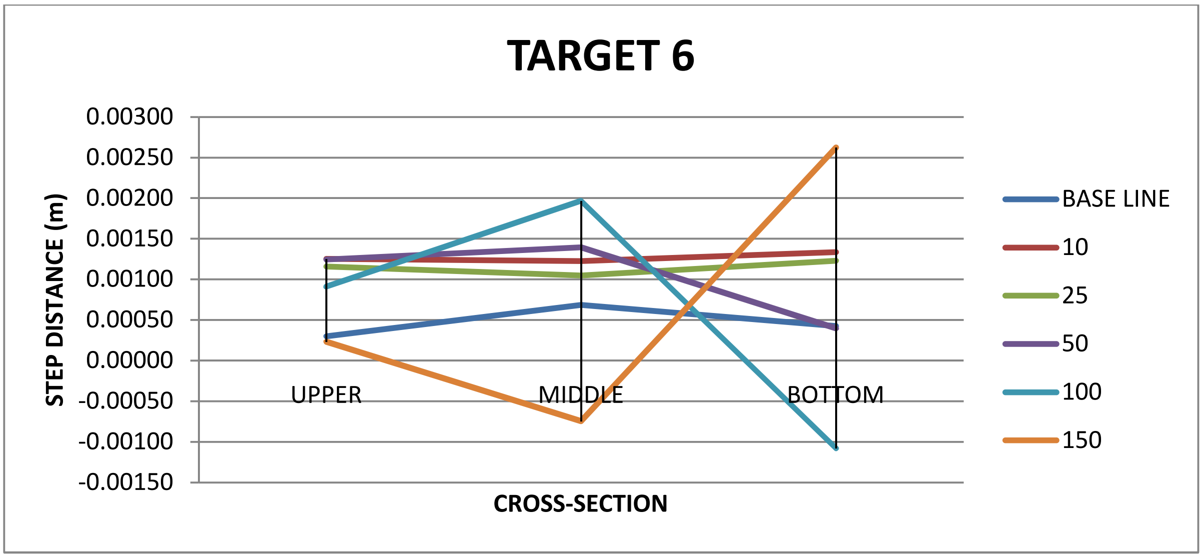


Figure F.6 Step Distance per cross-section – Target 6

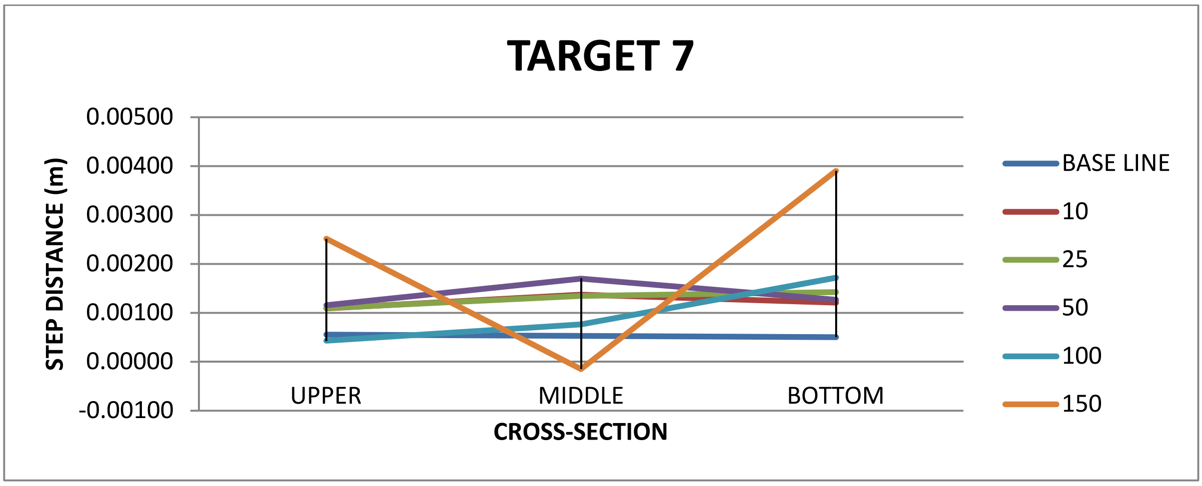


Figure F.7 Step Distance per cross-section – Target 7

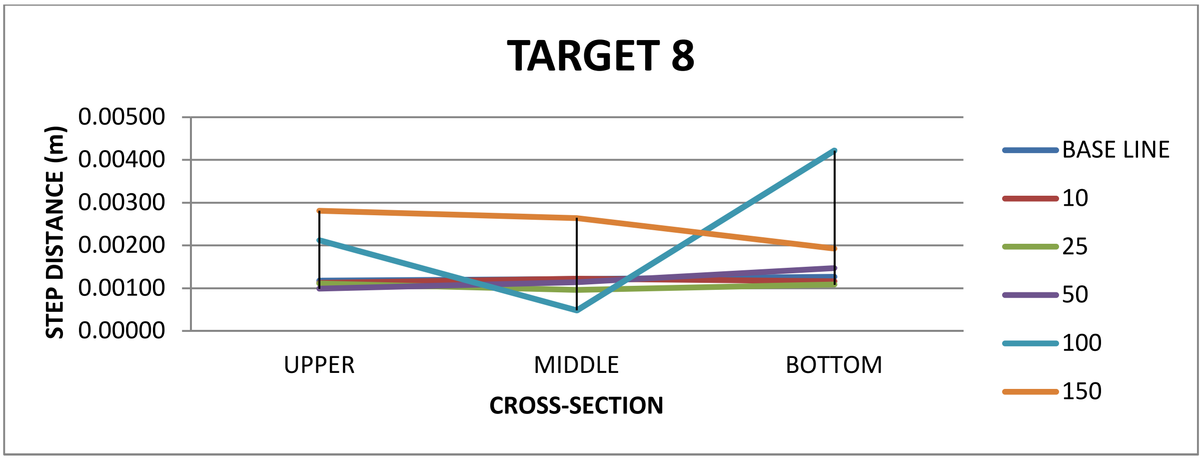


Figure F.8 Step Distance per cross-section – Target 8

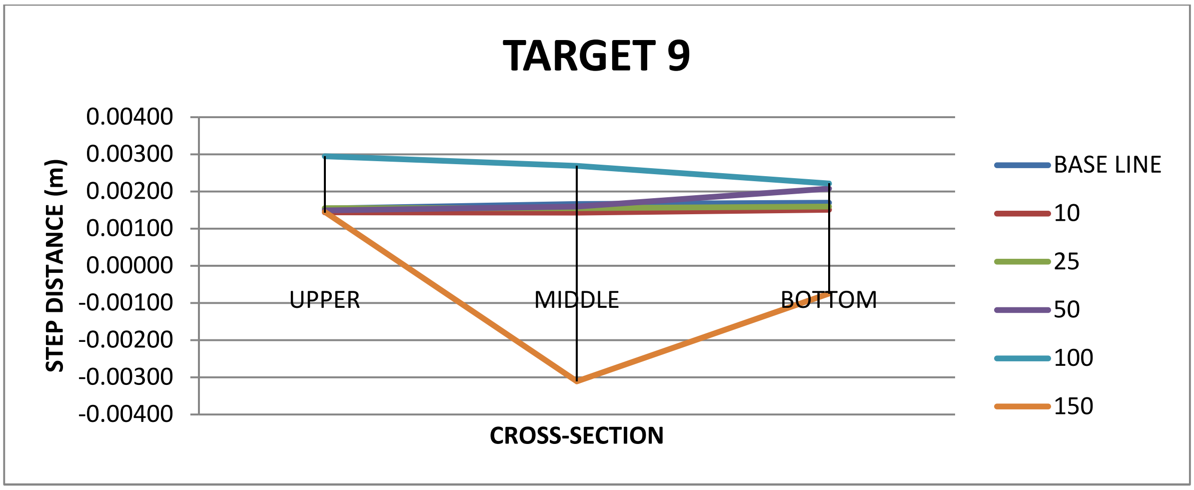


Figure F.9 Step Distance per cross-section – Target 9

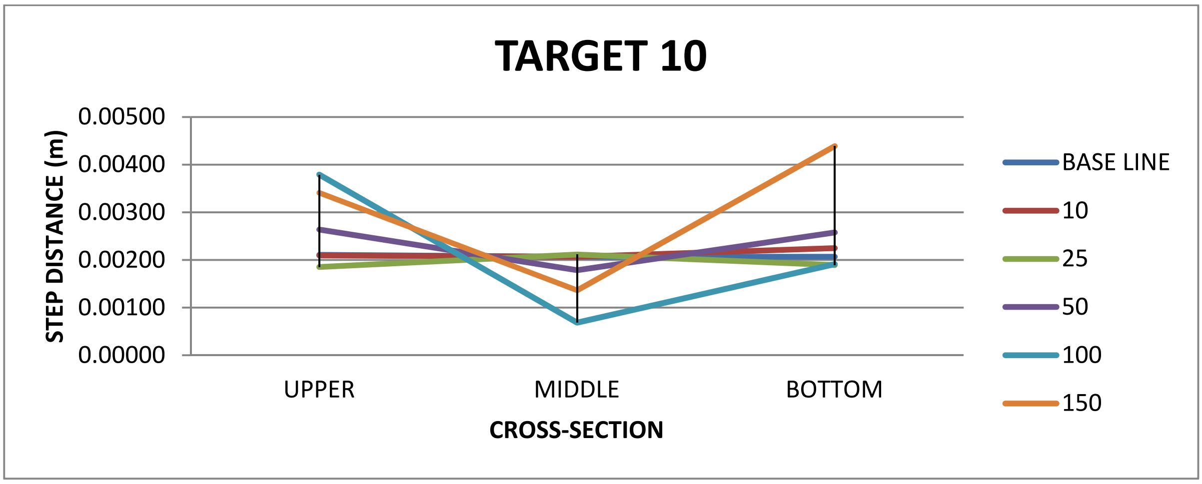


Figure F.10 Step Distance per cross-section – Target 10