

University of Southern Queensland
Faculty of Engineering and Surveying

**Testing of Robotic Total Stations
For Dynamic Tracking**

A dissertation submitted by

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Abstract

Robotic Total Stations (RTSs) were first invented by Geodimeter in the year 1990. In the recent years, 3D machine guidance systems have increased the productivity of construction works. Most machine guidance systems use RTSs with automatic targeting and tracking for position determination. The major applications for machine guidance systems can be found in construction industry and mining for the guidance of dozers, motor graders, excavators, scrapers as well as in agricultural applications for the guidance of tractors and harvesters.

Motorization and automation of the RTSs began a new, faster and more effective way for surveying measurement. Development of the RTSs with automatic searching and tracking opened new possibilities for their utilization in all areas of surveying, especially in the area of the engineering surveying. RTSs with automatic searching and tracking, offer the possibility to track and order cinematic processes such as movement and deformations of the building structures.

Since little information is known about the dynamic accuracy of RTSs in their real-time operation, the aim of this project is to determine the dynamic accuracy and reliability of RTSs.

It is vital to test various types of instruments in order to compare the results to the various manufacturers' specification. However, further research and testing will be carried out in the near future in order to obtain the relevant accuracies and reliabilities of the various types of RTSs.

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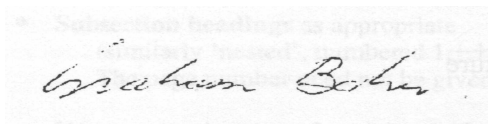
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A handwritten signature in black ink, appearing to read 'Chun Siong Chua', is written over a light grey, textured background.

Signature

28th October 2004

Date

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CHAPTER 1

INTRODUCTION

1.1 Background of Research

Robotic Total Stations (RTSs) have been available for more than 10 years and have a built-in Advanced Tracking Sensor (ATS) which can track, measure and store data automatically either internally; i.e. internal memory, or externally; i.e. to computer via a serial cable. It is sometimes refers to as “one-man” total stations.

The first Robotic Total Station was introduced by Geodimeter in the year 1990, which was known as the System 4000. It incorporated servos for automatic rotation of the instrument to a specific point. This development allowed remote surveying where only an operator was needed to point the instrument to a specific target. The System 4000

series also enabled robotic surveying; i.e. the instrument can be completely controlled from the prism pole, and required nobody at the instrument.

The major applications for machine guidance systems can be found in construction and mining industries for the guidance of dozers, motor graders, excavators, scrapers and for the guidance of tractors and harvesters for agricultural purposes. Modern 3D guidance systems have been developed from laser based machine guidance systems.

According to *Retscher (2000)* in his paper on *Multi-Sensor Systems for Machine Guidance and Control*, he had identified that motorization and automation of the RTSs starts a new, faster and more effective way for surveying measurement. Development of the RTSs with automatic searching and tracking of the reflected system opened new possibilities for their utilization in all areas of surveying, especially in the area of the engineering surveying (*Retscher, 2000*). RTSs with automatic searching and tracking of the reflected system offer, with help of the integrated tracking module, a possibility to track and order cinematic processes as movement and deformations of the building structures.

1.2 Statement of Problem

Even though the manufacturer has provided some accuracy on dynamic tracking on their fact sheet, little information is known about the accuracy of these systems in their real-time operation. This project will examine the dynamic accuracy of RTSs and their reliability.

1.3 Aim

The aim of this project is to determine the dynamic accuracy and reliability of RTSs.

1.4 Objectives

The objectives of this project are to establish the dynamic accuracy and the reliability of RTS through: -

- Simple testing in a fixed circular path with various “speeds”;
- Complex testing in a higher speed environment;
- Straight line testing;
- Analysis of the various testing results; and
- Comparison to various manufacturers’ specifications.

1.5 Instrument

The Trimble RTS 5000 Series was used throughout this project. Various types of instruments were also suggested by the supervisor of this project. Apart of Trimble, the types of instruments suggested were Leica and Topcon. Similar testing will be carried out in order to test the accuracy and reliability on dynamic tracking of individual system.

1.6 Project Planning and Methodology

The methodology chosen to undertake this project is in the form of a five-stage plan: -

- (a) Primary Research;
- (b) Data Collection and Testing;
- (c) Analysis;
- (d) Comparison of Systems and Discussion; and
- (e) Conclusion.

1.6.1 Primary Research

This stage includes a literature review of the relevant RTSs used in today's surveying environment using books, magazines and the internet to find the appropriate articles, journals, papers and university sites. This stage was time consuming and consisted of many notes being taken and articles gathered for future references. Much reading outside the specific topic area was also done in order to gain a better understanding of the use, accuracy and reliability of today's RTSs.

1.6.2 Data Collection and Testing

Two main types of testing were carried out throughout this project; i.e. a simple testing and "advanced" testing.

A simple test system has been established to test the accuracy of the RTS in a defined geometry. The RTS was set up and connected to the PC via a serial cable for capturing data. Prism was set up on a pillar with aluminium bar attached. The bar rotates at a radius of 0.31m. RTS was set to Autolock mode and data was captured on: -

- Point Code;
- Horizontal Angle;
- Vertical Angle;
- Slope Distance; and
- Time.

Since the RTS is tracking at 0.4 second per point, rotation of the prism was done at low speed.

"Advanced" field testing will be involving testing the RTSs dynamic tracking ability and reliability in a more complex way; i.e. with various speeds level, both in a circular

path and in a straight line. The same components as stated earlier will be applied for this testing.

1.6.3 Analysis

The data will be analysed using LisCad, Terramodel, MatLab and Microsoft Excel software.

The following stages were used throughout the analysis process: -

- (a) Transform all the information into the same format;
- (b) Eliminate the non-vital information;
- (c) Categorising the applications in a logical way;
- (d) Accessing the quality of the data; and
- (e) Refining the data.

The results of the analysis will be reported in the analysis of results section, where they will be further discussed.

1.6.4 Comparison of Systems and Discussions

All of the relevant data is analysed for validity, significance and use within the body of the project. There were several outliers observed and analysis of results using data analysis tools, such as Kalman Filter, may remove or smooth results for navigation purposes.

1.7 Conclusion and Recommendation

It is vital to test various types of instruments in order to compare the results to the various manufacturers' specification.

In general, this project has given me a better understanding of what I had to deal with throughout my project work. Literature review had given me some indication of testing and a better understanding of the systems, applications and some accuracy of the RTSs which will be discussed more detailed in the next chapter.

Since my knowledge on RTSs was limited, I will try my best to solve problems encountered as much as possible by gathered more information from other sources such as internet, news groups and other available sources.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter Overview

In this chapter, it is divided into three (3) main headings which consist of the followings: -

1. History of RTS and Definition of ATS;
2. Machine Guidance Systems, Data Synchronization and Latency and Manufacturers' Specification on Dynamic Tracking; and
3. Dynamic Testing of RTS and Data Analysis.

2.2 History of RTS

The first RTS was introduced in the year 1990, which is the System 4000 by Geodimeter (*Cheves, 2003*). It incorporated servos for automatic turning of the instrument to a specific point. This development allowed remote surveying where only an operator was needed to point the instrument to a specific target. Besides, the System 4000 series also enabled robotic surveying; i.e. the instrument can be completely controlled from the prism pole, and required nobody at the instrument. Furthermore, *Cheves (2003)*, pointed out in the magazine of *Professional Surveyors*, that the System 4000 RTS was the first robotic instrument introduced in the world.

Cheves (2003) stated that the System 500 was introduced in the year 1992, which fits with the design adopted by many manufacturers today. The instrument series provides choice of angular accuracies, EDM range, keyboards and software.

In the year 1994, the System 600 was introduced. With the introduction of this instrument, it brought all of the modular upgradeability found in Geodimeter instruments today (*Cheves, 2003*). The Tracklight is used for obtaining line and Autolock provides automatic fine-tuning to a target. The Autolock feature relies on an 'active' target which transmits the infrared signal for tracking and can be operated under low light situation. In the same year, the detachable keyboard was also introduced, which can be connected to a PC for downloading and uploading of data. The addition of the Remote Positioning Unit (RPU) radio-link enables full robotic mode for the RTS.

In the year 1997, as acknowledged by *Cheves (2003)*, that the Bergstrand model of RTS, which was also known as the 1" RTS, was introduced, with features of: -

- Measurable range up to 3,500m to one prism;
- Distance accuracy of $\pm 1\text{mm} + 1\text{ppm}$;
- Internal memory for 10,000 points;
- 15 software programs;
- 4-speed servo drives;

- Autolock and Robotic functions (Remote); and
- 33-key detachable alphanumeric keyboard.

2.2.1 Definition of Advanced Tracking Sensor (ATS) RTS

Trimble defined ATS RTS as: -

“...automatically lock on the active target and continuously measures the target’s position and transmits the data to the computer, which then determines the desired elevation and slope for that position.” (Trimble Data Sheet 2004)

ATS is used as a sensor for almost unlimited number of applications for guiding and controlling construction machinery as well as for surveying purposes.

How ATS Works?

As derived from the *Geodimeter 600®ATS 2004 Data Sheet*, ATS has a patented search system that ensures the quality of all sightings. This means that the operator can be absolutely sure that the instrument locks and measures to the right target. The automatic fine-tuning process can aim onto the target accurately and in relation to *Geodimeter 600®ATS 2004 Technical Notes*; it is comparable with or even better than an experienced surveyor’s ability to aim the instrument to the target manually.

On the other side, according to *Trimble 2004 Data Sheet*, the ATS instrument has built-in “search intelligence” that is able to search and find the target in a shorter time period. A target recognition feature will enables the ATS to lock on the desired target and ignore other moving targets; such as nearby survey parties, other machines, or reflective surfaces. If the instrument lost lock due to passing vehicles or other interruptions, the ATS will relocate the target automatically.

As shown in Figure 2.1 below, RTS can be applied to almost all types of construction machines. RTSs were set up in the field to track the movement of the construction machineries in order to determine their position, elevation and desired points.

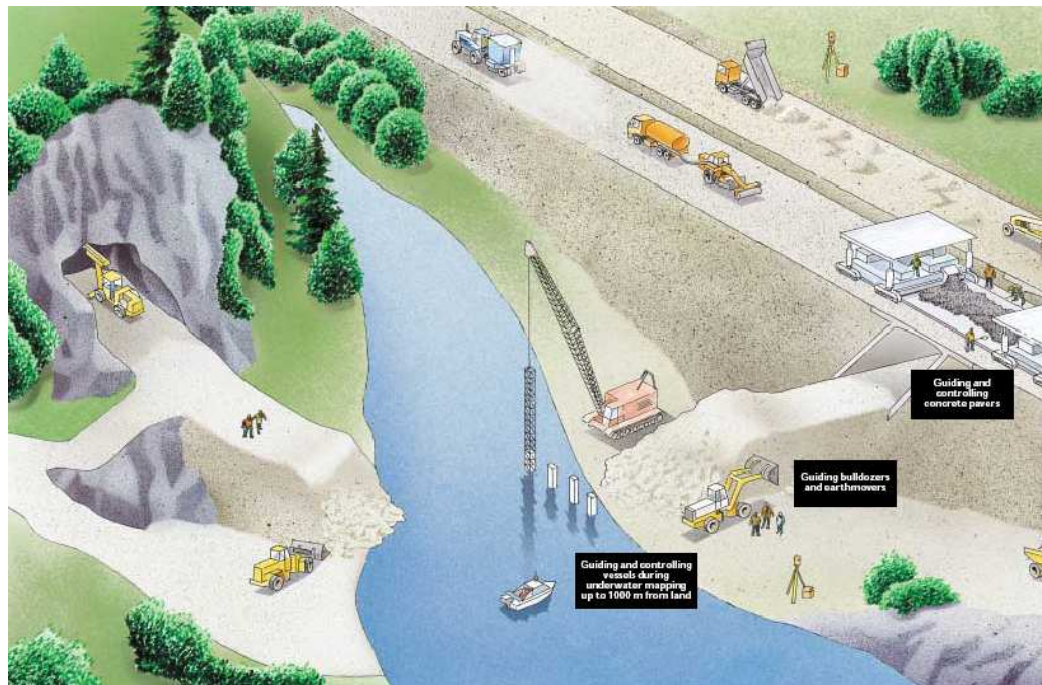


Figure 2.1: ATS Used in Determining Various Construction Machineries.

(Source: Geodimeter, 2004)

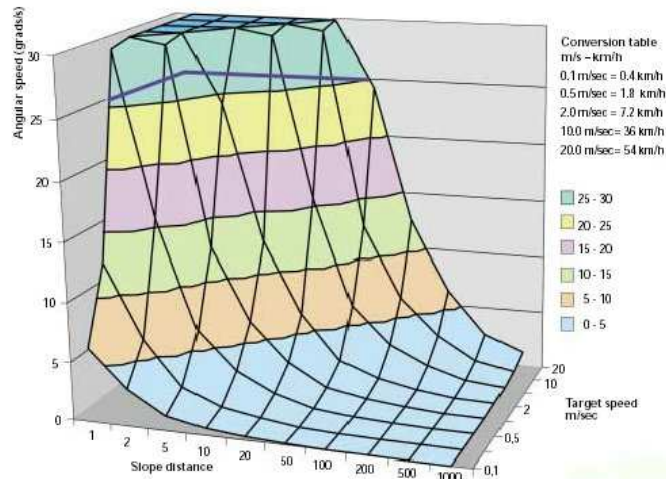


Figure 2.2: Relationship between Speeds of Machine, Instrument’s Angular Speed and the Distance between the Machine and the Instrument.

(Source: Geodimeter, 2004)

Figure 2.2 was used for the purpose of determining the minimum distance required between the instrument and the machine in order to maintain the lock to the target in respect to machine speeds. In this case, as confirmed by *Geodimeter 600®ATS 2004 Data Sheet*, the angular speed must not exceed 25 gon/s. For instance, if the machine is moving at a speed of 18 kilometers per hour (km/h), the minimum distance to the survey instrument can be 12 meters (m) before the instrument loses lock to the target.

2.3 Machine Guidance Systems

The major applications for machine guidance systems can be found in construction industry and mining for the guidance of dozers, motor graders, excavators, scrapers and for the guidance of tractors and harvesters for agricultural purposes. Modern 3D guidance systems have been developed from laser based machine guidance systems (*Retscher, 2002*). In general, the 3D systems use RTS with automatic targeting and tracking. In order to guide the machine along the defined path, the position and orientation of the machine in 3D coordinate system has to be determined in real-time

and therefore, a machine coordinate system is used for its origin in the rotation point or centre of gravity of the machine (*Retscher, 1995*).

Retscher (2002), in his paper *Multi-Sensor Systems for Machine Guidance and Control*, confirmed that the orientation and rotation of the machine in 3D space are described by three (3) attitude parameters which can be obtained using either three (3) measurement points on the machine defining the body frame or in combination with observations of other sensors by using an electronic inclinometer or gyro compass.

During recent years, the construction industry has undergone rapid changes. In order to get a more cost effective production, construction machines were equipped with guidance systems to automatically keep their position and orientation within a small specification of a designed path. *Kahmen and Retscher (2000)*, in their paper *Precise 3-D Navigation of Construction Machine Platforms* identified that for automatic machine guidance, a coordinate system of the machine has to be defined and information about its position and orientation with respect to the coordinate system of the construction site must continuously be available. Additionally, these requirements can be fulfilled if the following information is given: -

- The 3D position of a point in the machine centre line;
- The orientation or heading of the machine centre line;
- The inclination of the machine centre line; and
- The roll of the machine.

Further discussion in the paper of *Kahmen and Retscher (2000)* also identified that a motor driven total station can provide the above information with automatic target tracking functions. To get a higher reliability a two-axis electronic inclinometer can be added into the measurement system.

The development for the machine guidance for construction machines can be distinguished depending on the level of automation achieved. At present, the highest level of automation is achieved with modern 3D guidance systems and automatic blade

control (Retscher, 2002). Visual control is provided for the machine operator using a navigational display. Some machinery employs manual blade control and the guidance of the blades is controlled by the operator.

Orientation Determination of the Movable Platform

The position and orientation of the movable platforms has to be determined in the 3D coordinate system (x, y, z) of the carried out surveying works (Kahmen & Retscher, 2000). The orientation of one platform in the 3D space is described by three attitude parameters as described in Figure 2.3: -

- The orientation or heading of the platform (φ);
- The longitudinal tilt (ψ); and
- The transversal tilt (θ).

On the platform, a reference frame can be defined using measurement points which define a reference frame coordinate system where the ξ -axis runs from measurement of Point 1 to Point 2. The η -axis points to the left and the ζ -axis forms a right-handed system with the ξ - and η -axes (Kahmen & Retscher, 2000).

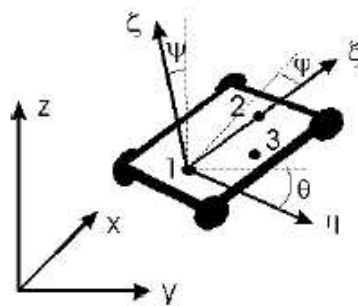


Figure 2.3: Orientation of the Platform Reference Frame.

(Sources: Kahmen & Retscher, 2000)

Furthermore, *Kahmen and Retscher (2000)* has pointed out that the aim of position determination is to obtain the direction and orientation of the platform reference frames in respect to the geodetic coordinate frame (x, y, z) . Thus, one measurement point on the platform is required to define the position and up to two additional points for the platform orientation. With two of the points; i.e. 1 and 2 measured, the position, the orientation (φ) and the pitch (ψ) can be determined. Measurements to a Point 3 on one side of the ξ -axis give the roll (θ). In order to obtain higher accuracy of attitude parameters, the separation between the points should be as far as possible (*Kahmen & Retscher, 2000*).

Application of Machine Guidance Systems

There are numerous types of construction machines available for different tasks. *Retscher (2002)* suggested that for the engineering construction works, some of the main tasks for the employed machinery are: -

- Bulk earthworks and earthmoving;
- Topsoil stripping;
- Sub base formation;
- Bridges and structures earthworks;
- Abutments and ramps;
- Embankments and noise embankments;
- Course grading of materials;
- Soil stabilizing;
- Soil or asphalt compaction; and
- Asphalt or concrete pavement.

According to *GOMACO Corporation (2002)*, in their article *Stringless Guidance System*, they have developed the control system of the future which allows paving

machines to be controlled by an automated 3D machine control system known as “Stringless Guidance System” in conjunction with Leica GeoSystems.

The system requires a survey of the site and information gathered from the survey is then used to create the project design and a 3D image.

GOMACO Corporation (2002), also reported that RTSs are set up on the site using reference points and a series of shots to the various reference points bring the RTSs into a 3D image of the site. A 3D Command Centre is mounted on the equipment and is connected to the Network Controller and at the same time, the RTSs have been loaded with the site information. The RTSs, via radio link, send information to and from the Command Centre throughout the process.

When the machine moves, the RTS will track and send radio signals to the Command Centre at a rate of 4 milliseconds (*GOMACO Corporation, 2002*). The designed plan coordinate data is then compared to the real time coordinate data.

GOMACO Corporation (2002) has confirmed that the stringless guidance system has several advantages as listed below: -.

1. It can accommodate superelevation automatically according to design data.
2. Real time navigation allows the project data to be created in CAD environment and directly put into paving process.
3. Improved product quality, operational safety and work rate.
4. Uninterrupted control of the machine over long distances.
5. Contractors have free choice of positioning for the RTS
6. No string line installation or maintenance.
7. Contractors will be able to move their equipment freely without worrying about running over the string line.

2.3.1 Data Synchronisation and Latency

Based on the technical notes from *Geodimeter*, data synchronisation is defined as: -

“...the angle and distance measurement sensors that the output data is computed for a single instantaneous location of the moving machine, compared with standard total station instruments that are optimized for static prism measurement.” (Geodimeter 600®ATS Technical Notes)

This can result in higher 3D position accuracy for dynamic measurements or machine tracking applications as shown in Figure 2.4 below.

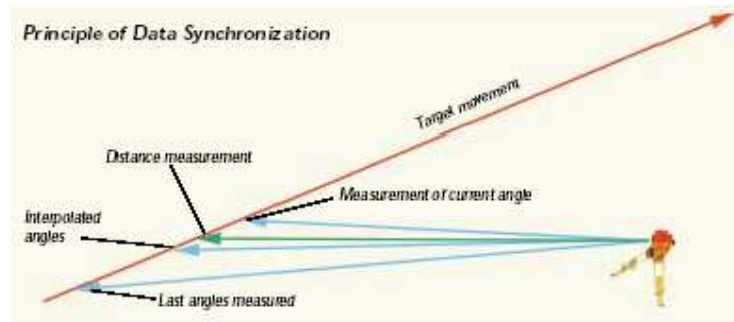


Figure 2.4: Data Synchronisation Principle

(Source: Geodimeter, 2004)

Latency, as described in the technical note from *Geodimeter 600®ATS*, means that the precise position of the machine at any given time is dependent on the period or latency of the positioning data received.

As shown in Figure 2.5, if the period of the data is small and specific, then the onboard application software can compensate for the errors associated with the data period by giving a more accurate location of the machine in real-time.

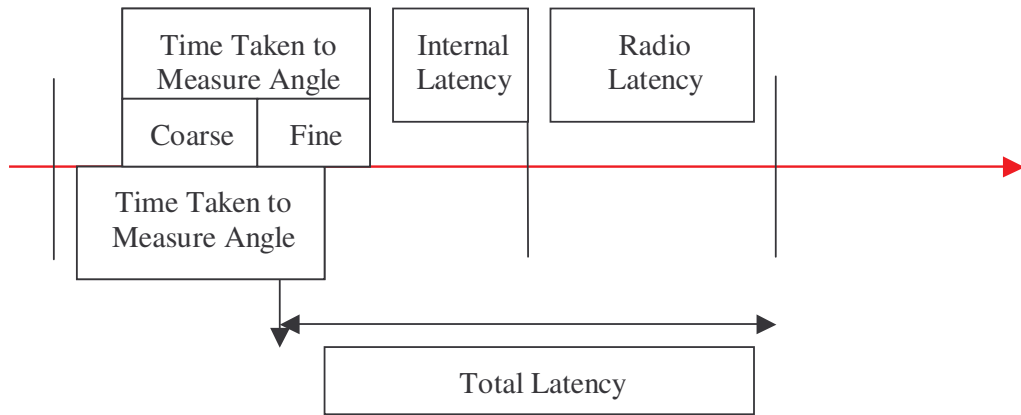


Figure 2.5: Latency Principle.

(Source: Geodimeter, 2004)

2.3.2 Manufacturers' Specifications on Dynamic Tracking

For this project, four (4) main manufacturers' specifications are compared on their accuracy of dynamic tracking; namely Trimble 5600, Geodimeter 600®ATS, Leica TPS 1100 and Topcon GPT 8001. The results are listed in Table 2.1 provided below: -

Table 2.1: Comparison of Manufacturers' Specifications

Types	Angle Reading (least count)	Accuracy (Tracking)	Measuring Time (Seconds)
Trimble 5600	2" (0.5 mgon)	± (10mm + 2ppm)	0.4
Geodimeter 600ATS	2" (0.5 mgon)	± (10mm + 2ppm)	0.4
Leica TPS 1100	2" (0.5 mgon)	± (5mm + 2ppm) ± (10mm + 2ppm)	0.3 0.15 (Fast Tracking)
Topcon GPT 8001	2" (0.5 mgon)	± (10mm + 2ppm)	N/A

(Sources: Trimble, Geodimeter, Topcon and Leica Technical Notes)

2.4 Dynamic Testing of RTS and Data Analysis

2.4.1 Dynamic Testing of RTS

The main characteristic component of the RTS is servomotors, which enable instrument rotation round the horizontal and vertical axis. Servomotors can search and track the reflected prism continuously in Autolock mode and automatically point to the middle of the reflected prism. This is known as Automated Target Recognition (ATR).

Hennes defined ATR as: -

“...identification of the reflected prism in a working area of the searching target function that is represented within the range of the telescope’s viewing field.” (Hennes, 1999)

The sequential scanning of the telescope’s viewing field in a whole working area carries out searching of the reflected prism. *Čeryová et al. (2002)*, in their paper *Dynamic Tests of Robot Stations*, identified that another principle of the target searching work, the RTS with the active reflected prism is equipped with a communication unit with a radio station that ensures a communication between the prism and the RTS.

The efficiency of RTS enables their utilization in engineering surveying by continually recording the measured values in remote mode; i.e. robotic mode.

Čeryová et al. (2002), identified a problem with RTS; i.e. the tracking ability of the RTS can only be unbroken in a static mode. For measurements in a cinematic mode, the RTS maintain a high accuracy only in the length measurement.

Several types of RTSS were used for *Čeryová et al. (2002)*, testing; i.e. the Leica TCA 1800, Leica TCRA 1101 plus and Zeiss Elta S10 (Table 2.2). From the measurement of

the cinematic reflected system on trails with the known geometry (the circle and the straight-line), the internal precisions of the tested RTSs were obtained.

Table 2.2: Accuracy of Measured Values Obtained by Manufacturers

	Leica TCRA 1101 Plus	Leica TCA1800	Zeiss Elta S10
Static Mode	2mm + 2ppm	2mm + 2ppm	1mm + 2ppm
Tracking (Measuring Time)	5mm + 2ppm (0.3 Sec)	5mm + 2ppm (0.3 Sec)	Undefined
Fast Tracking (Measuring Time)	10mm + 2ppm (<0.15 Sec)	10mm + 2ppm (0.15 Sec)	Undefined

(Source: Čeryová et al., 2002)

Movement of the Prism on a Circle

The experiment was carried out at the *Slovak University of Technology, Faculty of Civil Engineering* in a laboratory of the *Department of Surveying*. The experiment used a simulator for testing sensors of the circular path measurement systems (Figure 2.6). Its construction and attributes is suitable for such experiment. The main part is an arm that can rotate in a horizontal plane and at the end of the arm, there is fixed measurement board that rotates in the opposite direction to the spinning arm to ensure that the measurement board (and also the reflected prism which is fixed on the board) is always facing the observer (*Kopáček, 1998*). The platform is rotating in a circle with a 500mm radius and may be rotated at different speed as identified by *Kopáček (1998)*.

Moreover, the reflector system was fixed on the measurement board and the RTSs were fully managed by a program that observed the motion. Measured values were registered to a PC via serial communication cable (*Čeryová et al., 2002*).

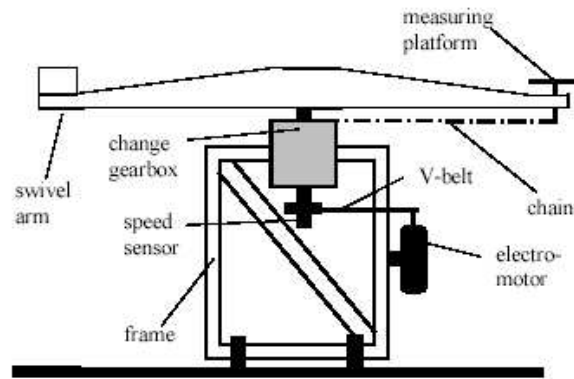


Figure 2.6: Simulator for Sensor Testing.

(Source: Čeryová et al., 2002)

Motion of the Reflected System on the Straight-Line

Concurrently, Čeryová et al. (2002) also performed a straight-line test on a 4m long metal block. In the middle of the block was a very exactly incised line (with an accuracy of 0.1mm) that produced an ideal straight-line. Measurements were observed from the three stations that were located at various relations to the straight-line; i.e. vertically, along the straight-line and in a general position.

Results

A linear regression analysis was used to estimate the prism path, parameters and accuracy. With the comparison of the both paths; i.e. the measured and the pre-defined path, the accuracy of the RTSs were obtained (Čeryová et al., 2002).

Figure 2.7 presents the movement of the prism on a fixed circular path. An oval shape was obtained from the observations and it is clearly shown that it varies from the “real” circular path. As all measurements show similar results, Čeryová et al. (2002) suggested that measurement of the cinematic target is influenced by a certain systematic

influence which is probably a result of the time slide between angular and length measurement.

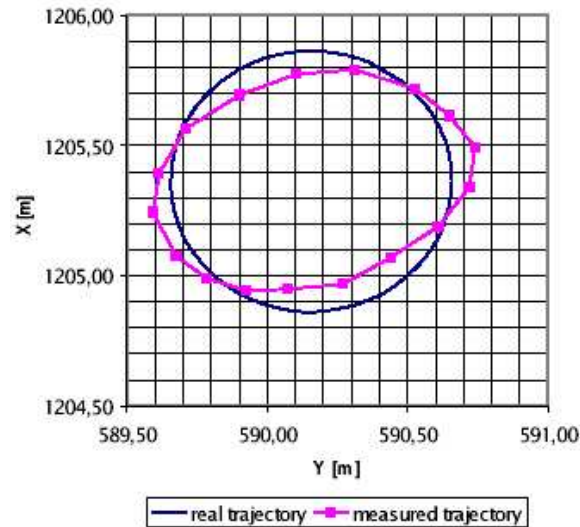


Figure 2.7: Trajectory of the Prism Determined by Zeiss Elta S10.

(Source: Čeryová et al., 2002)

In Table 2.3, Čeryová et al. (2002) presented the maximum deviations of the measured points from the fixed circular path for the individual instruments and the speeds of rotation. From the table provided below, it can be seen that the differences increase when the rotation speed increases. As stated earlier, this is probably due to the time slides between the angular and length measurement. There may also be other factors such as increasing of the mean error in an automated pointing by the higher speed rotations (Čeryová et al., 2002).

Čeryová et al. (2002), reported that the smallest deviations from the circle were by the Leica TCRA 1101 plus instrument and the maximum deviations were by the Zeiss Elta S10 instrument.

Table 2.3: Maximum Deviations of the Measured Points to the Fixed Circular Path

Distance of the instrument from the middle of the circle	Instrument	One swing out lasting	Number of the points for one swing out	Maximum deviation of the point from the circle
[m]		[s]		[mm]
11,2	Leica TCRA 1101 plus	5	23	44,3
		7	24	15,0
		18	59	18,0
		48	135	9,9
	Leica TCA 1800	5	16	109,8
		7	21	95,1
		10	30	66,1
		47	144	16,7
	Zeiss Elta S10	10	9	180,9
		18	8	111,6
53		15	71,9	
2,5	Leica TCRA 1101 plus	6	24	50,2
		7	28	39,7
		9	35	34,7
		10	39	27,3
		16	58	19,0
	Leica TCA 1800	6	14	81,0
		7	20	95,5
		9	28	70,5
4	Zeiss Elta S10	10	10	74,7
		32	9	79,6
		3	14	42,6

(Source: Čeryová et al., 2002)

2.4.2 Data Analysis

Retscher (2002) recommended that by using either Kalman filter or Wiener filter approach for the estimation of the position and orientation of the machine reference frame embedded in the machine blades, the trajectory of the machine can be described in the coordinate system of the site in respective to the designed alignment and the blades can automatically maintain their design elevation and cross slope.

2.4.2.1 The Kalman Filter

The Kalman filter was introduced in 1960 by Rudolf Kalman and has become the fundamental component in thousands of military and civilian navigation systems (*Levy, 2002*). In order to provide current estimation of the system variables; such as position coordinates, the filter uses a statistical approach to weight each and every new measurement in relative to past information gathered. In addition, it also determines up-to-date uncertainties of the estimates for real-time quality assessments.

The algorithm of Kalman filter was well received by surveyors and engineers but the practical applications of the algorithm required careful attention.

Equation Free Description

The Kalman filter is a multiple-input and multiple-output of digital filter that can optimally estimate; in real time, the states of a system based on its noisy outputs (Figure 2.8). The Kalman filter filters the noisy measurements to estimate the desired signals. The estimates are statistically optimal in the sense that they minimize the mean-square estimation error. This has been shown to be a very general criterion in that many other reasonable criteria would yield the same estimator (*Levy, 2002*).

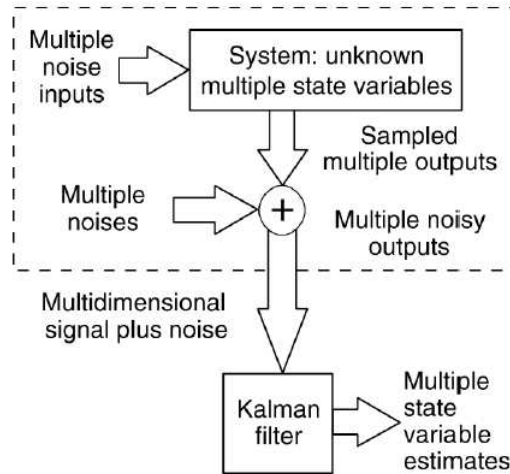


Figure 2.8: The purpose of Kalman Filter is to estimate the values of variables describing the state of a system from a multidimensional signal contaminated by noise.

(Sources: Levy, 2002)

Levy (2002) had illustrates the Kalman filter algorithm as described in Figure 2.9. Because the signal is typically a vector of scalar random variables rather than a single variable, the state uncertainty estimate is a variance-covariance matrix or covariance matrix. Each diagonal term of the matrix is the variance of a scalar random variable; i.e. a description of its uncertainty. The matrix's off-diagonal terms are the covariances that describe any correlation between pairs of variables (*Levy, 2002*).

Based on *Levy (2002)* in his paper *The Kalman Filter: Navigation's Integration Workhorse*, starting with an initial predicted state estimate (as shown in Figure 2.9) and its associated covariance obtained from past information, the filter calculates the weights to be used when combining this estimate with the first measurement vector to obtain an updated “best” estimation. If the measurement noise covariance is much smaller than the predicted state estimation, the measurement's weight will be high and the predicted state estimation will be low.

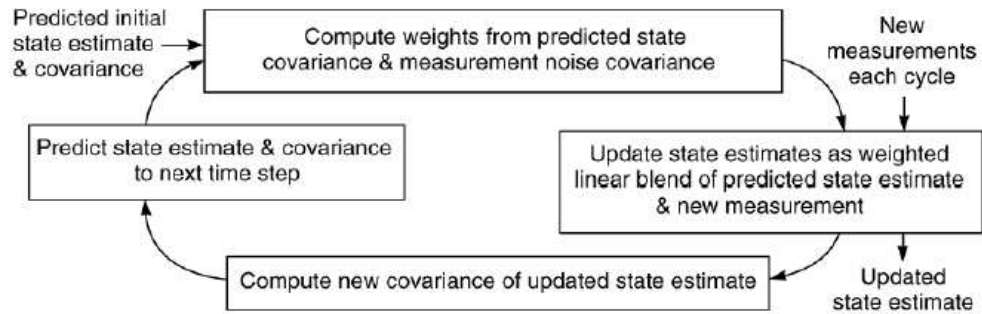


Figure 2.9: The Kalman filter is a recursive, linear filter. At each cycle, the state estimate is updated by combining new measurements with the predicted state estimate from previous measurements.

(Sources: Levy, 2002)

Since the filter calculates an updated estimation using the new measurement, the estimation covariance must be changed to reflect the new information so as to reduce uncertainty. The updated estimation and their associated covariance will form the Kalman filter outputs.

Finally, in order to prepare for the next measurement, the filter must project the updated estimation and associated covariance to the next measurement time. The actual system vector is assumed to change with time. Therefore, the predicted estimation will follow the deterministic transformation, because the actual noise value is unknown (Levy, 2002). Output of data will complete the Kalman filter's cycle.

Practical Designs

Regardless of an application's equipment, developing a practical Kalman filter based navigation system requires attention to a variety of design considerations.

As illustrate in Figure 2.10, the Kalman filter algorithm involves four main steps; i.e. gain computation, state estimate update, covariance update and prediction.

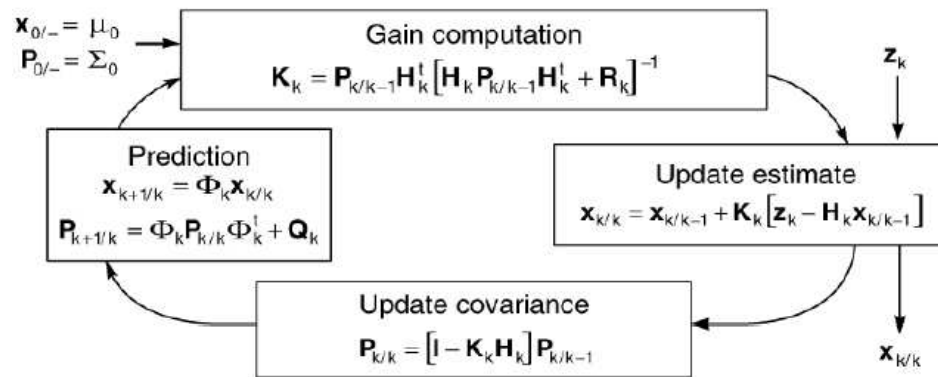


Figure 2.10: The Kalman Filter Algorithm.

(Sources: Levy, 2002)

According to Levy (2002), in some cases, one must implement the Kalman filter in a “small” computer with only a few states to model the process. Special covariance analysis algorithms that recognize the differences between the real-world model producing the measurements and the implemented filter model must evaluate this filter.

2.4.2.2 The Weiner Filter

The Weiner filter as reported by Kahmen & Retscher (2000) is an evaluation procedure for the position and attitude parameters of each platform that have to be determined in reference to the alignment of the track. Thus, the processing algorithm has to perform three main tasks: -

- The combination of the measurements from the RTS and the inclinometer;
- The filtering of the measurements; and
- The prediction of the positions of the movable platform between two measurement epochs.

The Wiener filter uses least squares adjustment, filtering and prediction in a more comprehensive manner. In Figure 2.11, the principle of Wiener filter used two stochastic components; i.e. the measurement noise (n_k) and the signal (s_k).

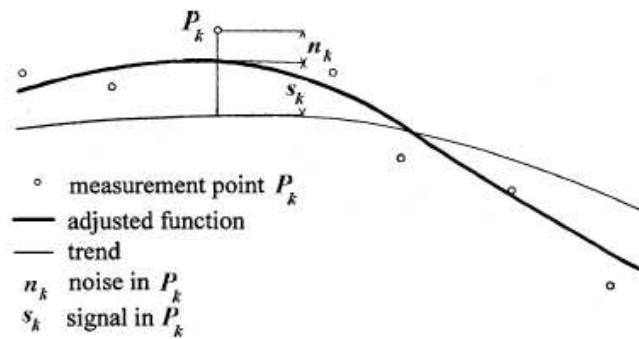


Figure 2.11: The Wiener Filter Principle.

(Sources: Kahmen & Retscher, 2000)

The origin of the platform reference frame coordinate system (ξ, η, ζ) is described in relation to the track alignment in the site coordinate system (x, y, z). The observation vector (l_k) contains the coordinate differences $\Delta x(k)$, $\Delta y(k)$ and $\Delta z(k)$ from the platform position to the reference point in the track and the changes of the attitude parameters $\Delta\phi(k)$, $\Delta\psi(k)$ and $\Delta\theta(k)$ (Kahmen & Retscher, 2000). The input parameters for the filter are calculated from the original measurements and are illustrated in Figure 2.12 below.

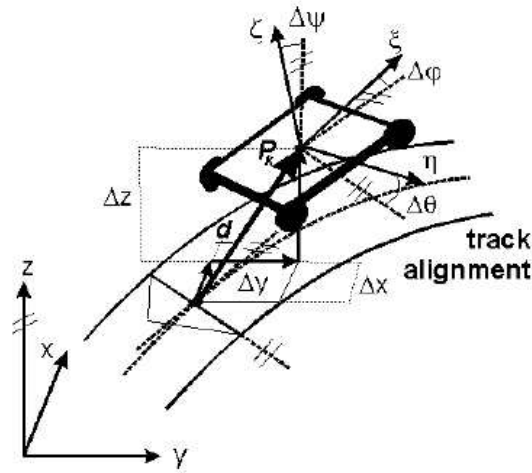


Figure 2.12: Filter Parameter.

(Sources: Kahmen & Retscher, 2000)

2.5 Conclusion

The use of modern surveying techniques in conjunction with advanced construction machines can mainly be controlled and guided automatically. According to *Retscher, (2002)*, 3D guidance systems will significantly reduce times for surveying and therefore achieve cost savings while increasing productivity of construction works.

Nowadays, systems using RTSs are the best method in machine guidance (*Retscher, 2002*). For the guidance of road paving machines, high precision requirements especially for the elevation and is still a very challenging task for the 3D machine guidance systems (*Retscher, 2000*). According to *Retscher (2002)*, in order to achieve the level of precision and to replace conventional labour intensive methods, the 3D systems still need further improvements.

The *Čeryová et al. (2002)* experiment suggests that the elimination of systematic influences of the cinematic measurement can improve the accuracy of the system.

According to Čeryová *et al.* (2002), there were some discussions about accuracy of the suggested mathematical promotions of the modifications of the measured values in a cinematic mode and about availability of the utilization of the cinematic way of measurement.

Nowadays, construction machines can mainly be controlled and guided automatically with the use of modern surveying techniques in combination with advanced filter algorithms (Retscher, 2002).

If either Kalman or Wiener filter approach is employed for the estimation of the position and orientation of the machine reference frame, the trajectory of the machine can be described in the coordinate frame of the site in respective to the designed alignment (Retscher, 1998).

CHAPTER 3

RESEARCH APPROACH

3.1 Introduction

As described in the earlier chapter that the aim of this project is to establish the dynamic accuracy and the reliability of RTS. In order to achieve the stated objectives, the following steps are carried out: -

- Simple testing in a fixed circular path with various “speeds”;
- Complex testing in a higher speed environment;
- Straight line testing;
- Analysis of the various testing results; and
- Compared to various manufacturers’ specifications

From the literature review as described in Chapter 2, several testing were carried out by Čeryová *et al.*, 2002, which had demonstrated that dynamic accuracy of the RTS can be achieved by carrying out both circular path testing and straight line testing.

It had been discovered from the literature of Čeryová *et al.* that for their circular path testing, no speeds were included in their test results and it was hard to compare to the manufacturers' specification. Furthermore, the distance between the set up station and the observed points were also not considered in their testing.

It has also been pointed out by Čeryová *et al.* that the results obtained from their tests were analysed using a linear regression approach and the major discovery from their paper being that the mean error in an automated pointing will be increased by the higher rotational speed.

3.1.1 Project Planning

The methodology chosen to undertake this project is in the form of a five-stage plan: -

- 1 Primary Research: This involves a literature review of articles, books, journals, magazines etc. to gather appropriate information about the RTS in terms of their use, accuracy and reliability.
- 2 Data Collection and Testing: This stage involves testing of RTS in a fixed circular path and at various speeds level on a circular path. "Advanced" testing will be carried out both in a fixed circular path with various distances and straight line tests.
- 3 Analysis: Data obtained from the testing will be prepared, adjusted, reviewed, compared using a least squares method and presented in graphical form.

- 4 Comparison of Systems and Discussions: All of the relevant data is analysed for validity, significance and use within the body of the project.
- 5 Conclusion: Reflect on what has been learned and to have a better understanding of the RTS.

3.2 Research Method

3.2.1 Literature Contribution to Research Method

The literature review has given a basis for understanding the RTS so as to achieve the best possible results. The important aspects to be considered from the literature review are: -

- (a) The efficiency of RTS enables their utilization in surveying industries, especially in engineering surveying, by continually recording the measured values in remote mode; i.e. robotic mode (*Čeryová et al., 2002*);
- (b) The tracking ability of the RTS can only be unbroken; i.e. not loses lock, in a static mode and for measurements in a cinematic mode, the RTS maintain a high accuracy only in the length measurement (*Čeryová et al., 2002*);
- (c) Accuracy of the results are closely associated with the speeds (*Čeryová et al., 2002*);
- (d) Shorter observation ranges have larger standard deviation (σ) compared to longer distances (*Retscher, 2002*);
- (e) Circular path testing and straight line testing are the key components in determining the dynamic accuracy of the RTSs (*Kopáček, 1998*); and

- (f) Filtering of data using data analysis tools such as the Kalman Filter and the Weiner Filter may remove and smooth the measured values for navigation purposes (Levy, 2002).

3.2.2 Data Collection and Testing

3.2.2.1 Equipment Utilised

The equipment used throughout this project was the Trimble 5603 Robotic Total Station (Figure 3.1).



Figure 3.1 : Trimble 5603 RTS



Figure 3.2: Trimble 360° Prisms

Components of RTS

The main components of the whole RTS system included: -

- (a) Robotic Total Station;
- (b) 360° Prisms (Figure 3.2);
- (c) Detachable Keypad (Figure 3.3); and
- (d) Radio (Figure 3.4).



Figure 3.3: Detachable Keypad



Figure 3.4: Prism and Radio

Operation of a RTS System

As describe earlier that RTS has four (4) main components; i.e. the RTS itself, detachable keypad, 360 ° prisms and a radio.

Firstly, the RTS takes measurements to the prism, which is equipped with a communication unit with a radio system that ensures a communication between the prism and the RTS. The measured values are then transmitted back to the RTS via the communication radio (*Trimble 5600 Operation Manual, 2003*). This procedure is illustrated in graphical form as shown in Figure 3.5.

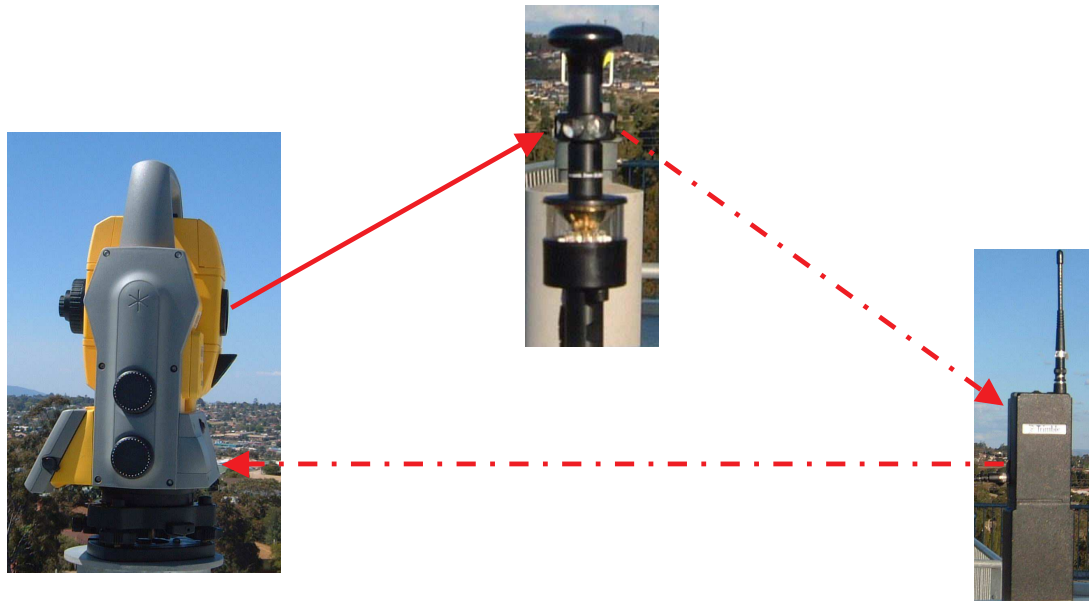


Figure 3.5: Operation of a RTS System

3.2.2.2 Field Testing

There were two (2) main types of testing carried out during the duration of this project, which comprises of: -

- (a) Circular Path Testing; and
- (b) Straight Line Testing.

These tests were carried out at the campus of *University of Southern Queensland (USQ), Faculty of Engineering and Surveying*. Both of the tests stated above were carried out at various distances and different speeds in order to test the dynamic accuracy of the RTS and the test results were compared to the manufacturer's specification.

Circular Path Testing

The circular path testing used an aluminium bar attached to the 360° Prisms, which were set up on a pillar allowing it to rotate while measurements were carried out. The platform was rotated in a circular path with a radius of 310mm and could also be rotated at different speeds. Measured values were registered into the internal memory of the RTS or to a PC via a serial communication cable.

The basis for the circular path testing was shown in Figure 3.6. It was only an example of how a circular path test was carried out. The real circular path tests were carried out in various distances and different speeds.



Figure 3.6: Circular Path Testing

There were 2 main types of circular path testing that were carried out: -

- (a) Simple testing – in which the test was carried out in an indoor environment; and
- (b) “Advanced” testing – in which the tests were carried out in various distances and different speeds outdoors.

Simple Testing

Under this test, the RTS was set up on a tripod at a corner while the prism attached to the aluminium bar, which was set up on a pillar. The radius of the bar was 310mm and the distance between the RTS and the prism was 5.2m. The prism was rotated in a circular movement at a very low speed while measurements were taken. In this test, the measured values were registered to a PC via a serial communication cable.

“Advanced” Testing

For this test, the prism was set up in various distances and rotated at different speeds. There were three (3) set ups for this test: -

- (i) In the first set up, the RTS was set up on Pillar 1 and the prism was set up on Pillar 2. The distance between the set up station and the prism was 4.9m and was rotated at a speed of 0.2m/s.
- (ii) For second set up, the RTS was set up on Pillar 1 and the prism was moved and set up on Pillar 4. The distance between these two pillars was 115.9m and the rotation speed was at 0.5m/s.
- (iii) For the final set up, the prism was moved from Pillar 4 to Pillar 5 and the distance between the RTS and the prism was 183.9m. The rotation speed was 0.8m/s.

Straight Line Testing

The straight line testing was carried out on the roof of the *Faculty of Engineering and Surveying, USQ*. For this test, a similar procedure was carried out and the only difference was that the prism was set up on a bench on the roof and moved horizontally along the bench. The length of the bench was measured at 3.2m and the distance from the set up station and the front corner of the bench was measured at 4.8m while to the rear corner was measured at 8.0m. Figure 3.7 shows how the straight line test was carried out.



Figure 3.7: Straight Line Testing

Since the distance between the set up stations and the target was relatively short, four similar tests were carried out and all of the observations were taken into consideration during analysis of results. Each test consists of five (5) or six (6) runs, which made up a total of 22 runs.

3.2.3 Data Analysis and Discussion

There were 4 main types of software were used in analysis of the test results comprising of: -

- (a) Terramodel;
- (b) LisCad;
- (c) MatLab; and
- (d) Microsoft Excel.

Terramodel and LisCad were used for transferring of measured values (Raw files) to field files, which then can be edited in the related software. MatLab was used for statistical analysis, such as the mean (\bar{x}) and standard deviation (s) calculations.

Data Transfer

The measured values obtained from the field survey was stored onto the internally memory of the RTS. It was then transferred into the PC via a serial communication cable attached to both the RTS and PC. The software that was utilized for transferring the data was the Geodimeter Communication Suite and the data was saved in a <.job> format. As described in Chapter 1, the field data was captured in the following format: -

- Point Code;
- Point Number;
- Horizontal Angle;
- Vertical Angle;
- Slope Distance; and
- Time.

The point code was used to differentiate between the set up stations and the measured values. Point numbers were used in conjunction with time to figure out the exact

movement along the pre-defined paths for both the circular path testing and the straight line testing. Horizontal angles, vertical angles and the slope distances were utilized for the calculation of the rotations and movements speeds.

Software

As stated earlier in this chapter, LisCad and Terramodel were utilized in transforming the measured values data (RAW data) into a graphical format of field files. After transferring from the RAW data into field file, an alignment was created from the pre-defined path. An offset table was then being created in order to check the measured values to the pre-defined path.

MatLab was then being used to calculate the mean (\bar{x}) and standard deviation (s) of the measured values. All the offset data obtained from both LisCad and Terramodel were then transformed into ASCII format in order to be “recognized” by MatLab software. In MatLab, by using the statistical analysis tool box, the mean (\bar{x}), variance (s^2) and standard deviation (s) were obtained.

Microsoft Excel was used to gather all the analysed data and put them into graphical form. Various graphs were generated by Microsoft Excel, such as the offset distances from the pre-defined path and the cumulative frequency graph.

Analysis of Results

The analyses of tests results are attached at the back of this report as Appendix C and Appendix D. With the comparison of the both the circular path testing and the straight line testing, the accuracy of the RTS was being obtained. However, there were several outliers observed and with the use of data analysis tool, such as the Kalman Filter (Appendix B), the analysis can remove and smooth the results for navigation purpose. This will be discussed in more detail in the next chapter.

The analysis processes are shown in Figure 3.8 below. It indicates the process of transferring from Raw Data to Field File and proceeds to the analysis of results and to final output in graphical form.

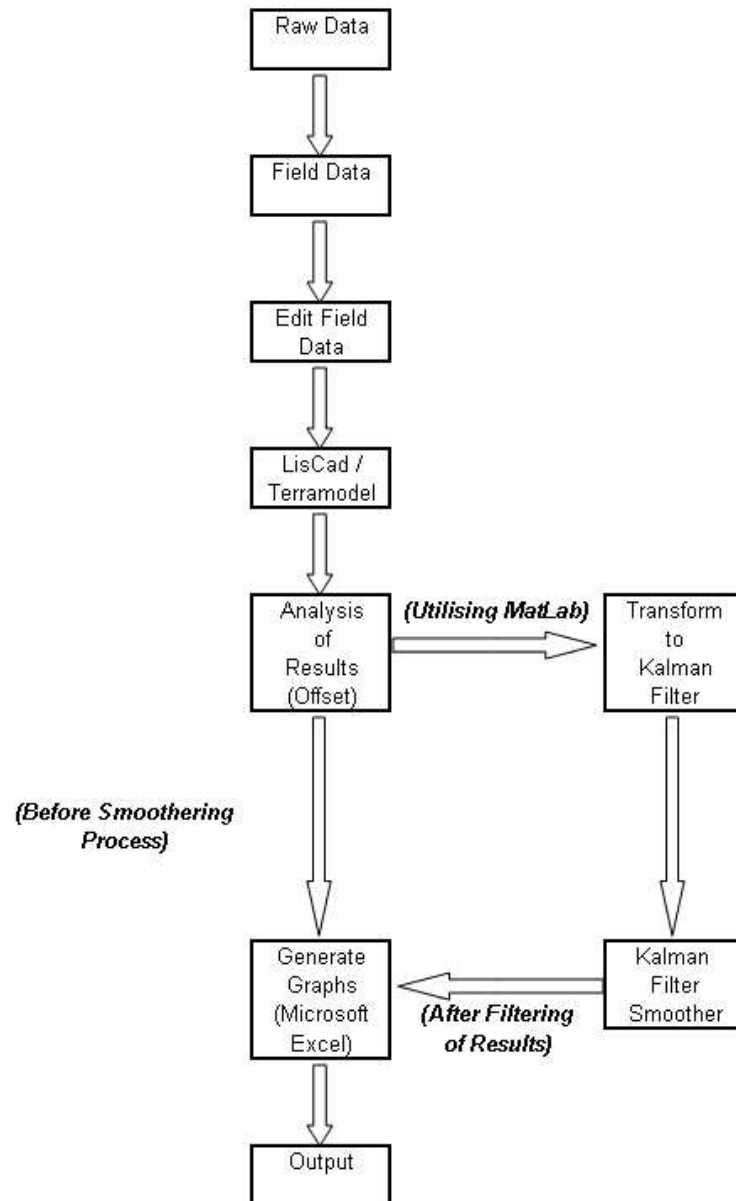


Figure 3.8: Analysis Processes

3.3 Conclusion

All the tests mentioned were completed successfully and the results will be discussed in the next chapter. Throughout this project only one (1) type of instrument was tested; i.e. Trimble 5603 RTS, due to time constraints. In order to obtain clearer results for comparison to various manufacturers' specification, other types of RTSs should be taken into consideration.

However, the analyses of results were completed without any major problem. There were also other types of analysis tools that could be used for analysis purposes, such as the Weiner Filter, unfortunately due to the same factor; i.e. time restriction, only the above stated software was utilized.

The next chapter will discuss the comparison of results in more detail.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

Efficiency of RTS enables their utilization in the tasks of the engineering surveying requiring continuous recording of measurements. It is also suitable for the continuous monitoring; such as construction of roads as well as the other building structures.

RTSs have been available for more than ten (10) years now and are widely used in the construction industries. However, little information about their real-time operation is acknowledged. Therefore, this chapter will discuss on the various test results and compare them to manufacturer's specification in order to obtain the real-time operational information for the RTS. As stated in the earlier chapter, both circular path

tests and straight line tests were carried out so the accuracy and reliability of the RTS can be determined.

A linear regression approach was utilised in the process of analysing the various test results. In order to compare the various tests results to manufacturer's specification, the mean (\bar{x}), variance (s^2) and standard deviation (s) for each individual test were calculated using MatLab software and will be discussed more detail in the later section.

Before any data can be analysed, several processes were undertaken as shown below: -

1. Transform all the gathered information into the same format;
2. Eliminate all non-vital information, such as outliers;
3. Categorizing the applications in a logical way;
4. Assessing the quality of the observed data; and
5. Refining the data.

After the above stated processes were completed, the analysis of results was commenced with caution.

However, before comparing the tests results to manufacturer's specification, statistical comparison; i.e. testing of mean (\bar{x}) and testing of standard deviation (s); were completed in the first instance.

More detail on the reliability of the RTS will be discussed later. Additionally, accuracy of the tracking also plays a vital role in determining the reliability of the RTS in dynamic tracking.

4.2 Analysis of Results

Using the methods of the mathematical statistics; i.e. linear regression analysis, it is possible to estimate a path of the prism in a space, its parameters and their posteriori accuracy characteristics. With the comparison of the both paths; i.e. the measured and the pre-defined path, it is possible to obtain parameters that characterised the accuracy of the RTS.

4.2.1 Circular Path Tests

Overview

There were 4 different types of tests carried out under this category and they can be further categorized into 2 main types; i.e. Simple Testing and the “Advanced” Testing. Under the simple testing, it was carried out under a controlled room environment. The distance between the set up station and the prism on a pre-defined circular path was 5.2m.

For the “Advanced” tests, they were carried out using the pillars around USQ campus. The RTS was set up in Pillar 1 and measurements were observed in various distances and different speeds. 3 pillars were utilised for this test; i.e. Pillar 2, Pillar 4 and Pillar 5. Individual pillars test results are attached in Appendix E.

The distances and speeds for each test were put into table, which is shown in Table 4.1.

Table 4.1: Pillars Distances and Movement Speeds

From	To	Distances (m)	Speeds (m/s)
Pillar 1	Pillar 2	4.9	0.2
Pillar 1	Pillar 4	115.9	0.5
Pillar 1	Pillar 5	183.9	0.8

Processing

As described in the earlier chapter, several software packages were utilised, including Terramodel, LisCad, MatLab and Microsoft Excel. Terramodel and LisCad transformed the observed data into a field file for editing while the MatLab software enabled the processing of measured values. MatLab was being used for statistical analysis process such as calculation of mean (\bar{x}), standard deviation (s), range and variances (s^2). In addition, an analysis tool named Kalman Filter was utilised to remove and smoother the observation results. Microsoft Excel was used for presenting those measured values into graphical form.

Outliers were taken into consideration during analysis of measured values. Those measured values which cannot be analysed due to lose of lock, were eliminated from further analysis. This is because for those mentioned measured values, were only comprised of a horizontal angle and a vertical angle. Distances were unable to be measured by the RTS and therefore were eliminated from the analysis.

Results

Test 1: Z120 Pillar Test

Figure 4.1 shows the realised motion measurement of the prism on a circular path. The green line represented the pre-defined circular path while the blue dots were those measured values obtained from the RTS. As all measurements show similar deviation, we can say that measurement of the cinematic target is influenced by the certain systematic influence, which is probably related to the time slide between angular, and length measurement.

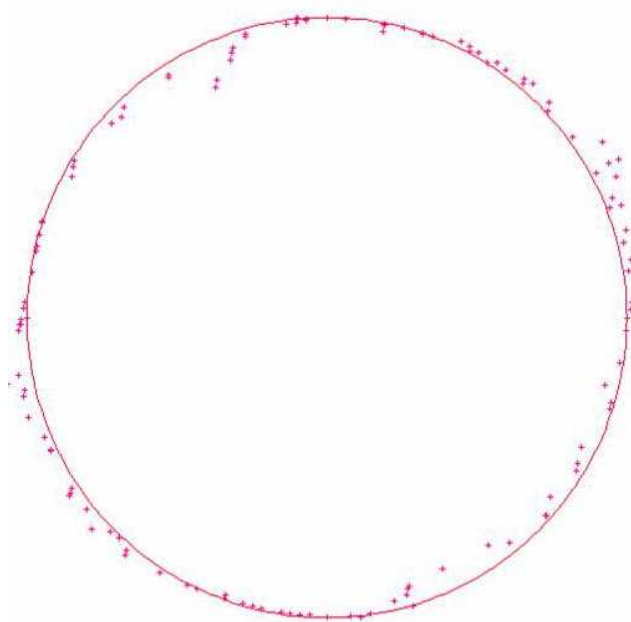


Figure 4.1: Circular Path Test Determined by Trimble 5603 RTS (Z120 Pillar)

Figure 4.2 indicates that the points offset from the pre-defined circular path under the room environment. Since the test was carried out over a short range, there were a numbers of outliers detected which are shown by the red circles in Figure 4.2. The percentage analysed was only 85% because due to short distance as the RTS loses lock quite easily. The remaining of 15% was unable to be analysed.

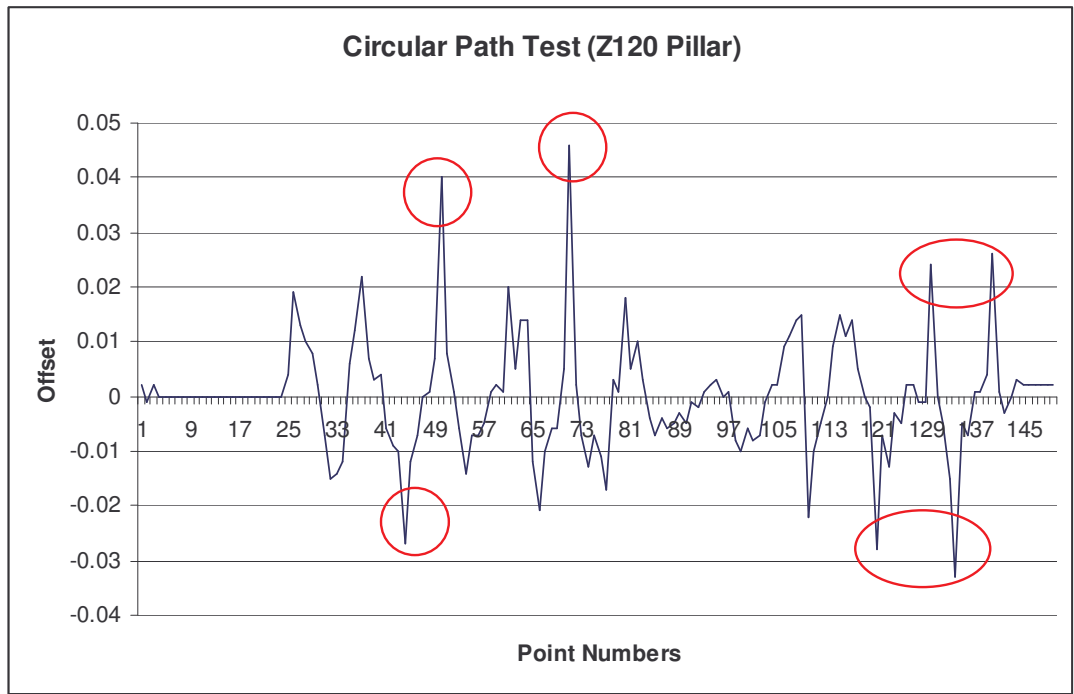


Figure 4.2: Graph Indicating the Offset of the Points from the Real Circular Path (Z120 Pillar)

The various statistical analysis values calculated are shown below: -

Percentage Analysed	=	85%
Mean (\bar{x})	=	-4.6E-20
Standard Deviation (s)	=	0.011
Variance (s^2)	=	0.00011
Range	=	0.079
Standard Error	=	0.0009
Confidence Level (95%)	=	0.0017

Based on the standard deviation calculated, this test had actually exceeded the manufacturer's specification, which will be discussed in more detail in the comparison section later in this chapter.

After the above calculations were completed, further analysis using the Kalman Filter analytical tool was employed to smooth the observed data. The Kalman Filter has smoothed the obvious outliers, which were circled in red as shown in Figure 4.2, and the new result can be visually compared to the original in Figure 4.3.

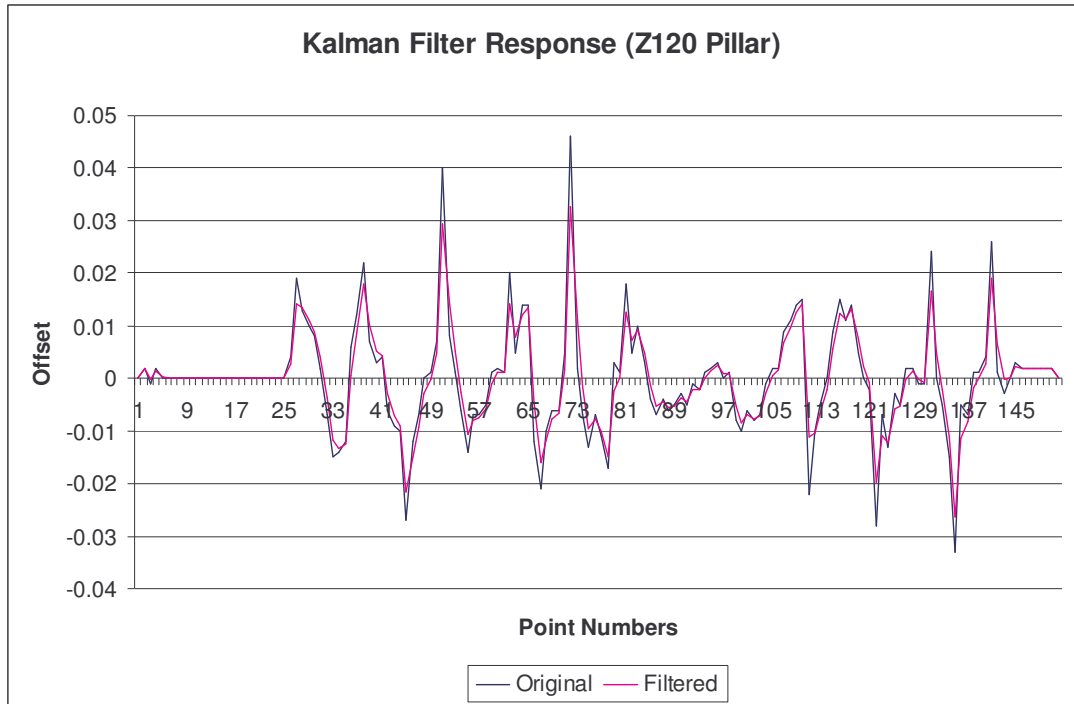


Figure 4.3: Comparison of Original and Filtered Values (Z120 Pillar)

The statistical results after the smoothing process are shown in Table 4.2.

Table 4.2: Statistical Comparison of Original and Smoothed Data (Z120 Pillar)

Z120 Pillar		Original	Filtered
Mean (\bar{x})	=	-4.6E-20	7.05E-09
Standard Deviation (s)	=	0.011	0.009
Variance (s^2)	=	0.00011	0.00007
Range	=	0.079	0.059
Standard Error	=	0.0009	0.0007
Confidence Level (95%)	=	0.0017	0.0014

Test 2: Pillar 2

In this test, the analysed percentage was 97%. The high percentage of measured values analysed was due to the slow rotation speed of the prism. As described earlier, the distance between the set up station; i.e. Pillar 1, and Pillar 2 is only 4.9m and if the rotation speed was high, the RTS tends to lose lock very easily. This was being experienced when the test was carried out for Z120 Pillar and therefore, the above-mentioned decision was being made. The analysed result is shown in Figure 4.4.

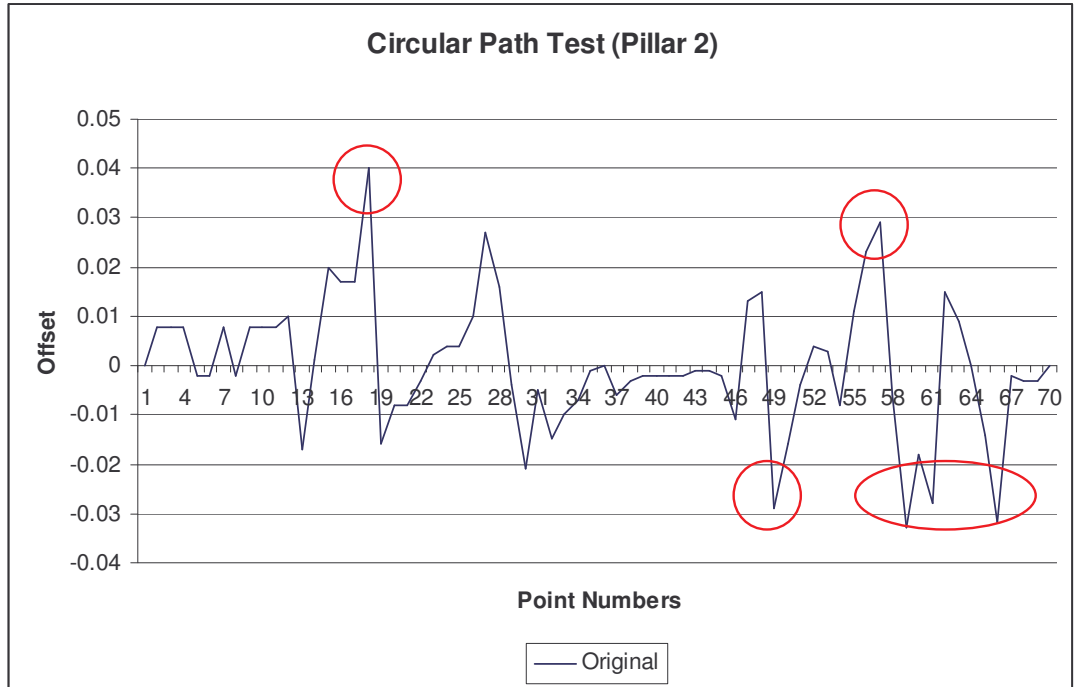


Figure 4.4: Graph Indicating the Offset of the Points from the Real Circular Path (Pillar 2)

The various statistical analysis values calculated are shown below: -

Percentage Analysed	=	97%
Mean (\bar{x})	=	-4.3E-05
Standard Deviation (s)	=	0.014
Variance (s^2)	=	0.00019
Range	=	0.073
Standard Error	=	0.0016
Confidence Level (95%)	=	0.0033

Based on the standard deviation calculated, this test had a similar outcome to Z120 Pillar i.e. exceeded the manufacturer's specification.

After the above calculations were completed, further analysis using the Kalman Filter analytical tool was employed to smooth the observed data once again. The Kalman

Filter has smoothed the obvious outliers which were circled in red, as indicated in Figure 4.4. The new result can be visually compared to the original in Figure 4.5.

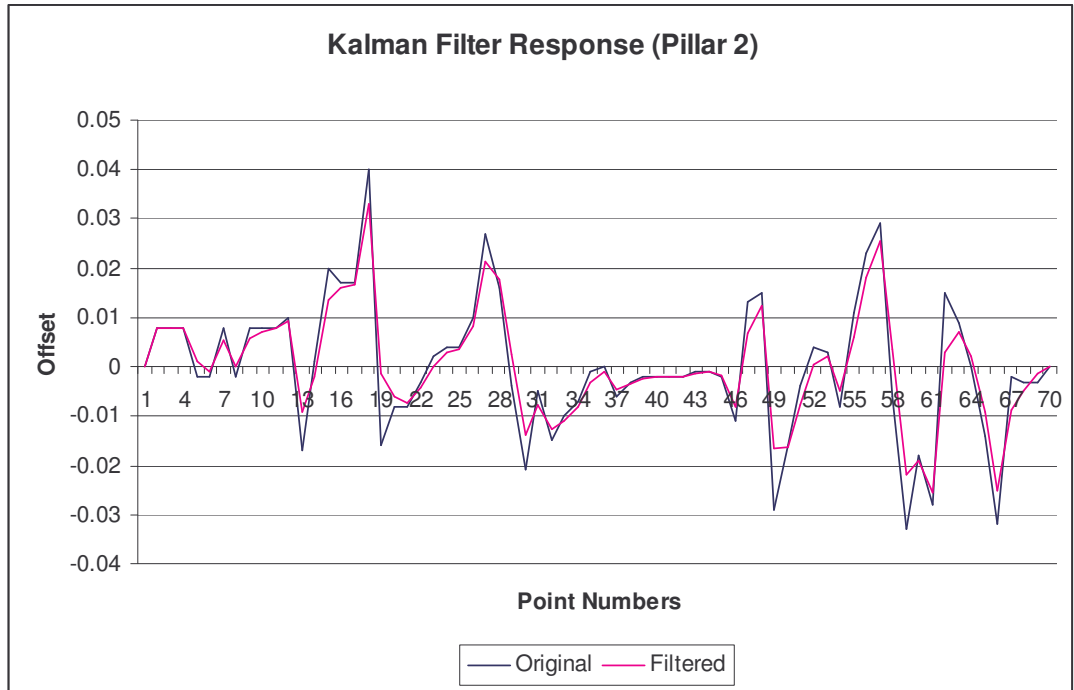


Figure 4.5: Comparison of Original and Filtered Values (Pillar 2)

The statistical results after the smoothing process are shown in Table 4.3.

Table 4.3: Statistical Comparison of Original and Smoothed Data (Pillar 2)

Pillar 2		Original	Filtered
Mean (\bar{x})	=	-4.3E-05	5.64E-05
Standard Deviation (s)	=	0.014	0.010
Variance (s^2)	=	0.00019	0.00011
Range	=	0.073	0.058
Standard Error	=	0.0016	0.0013
Confidence Level (95%)	=	0.0033	0.0026

Test 3: Pillar 4

For this test at Pillar 4, the analysed percentage was only 78%, which could be due to faster rotation speed. Even though the distance between the set up station and the observed pillar were approximately 116m, it has been found out that if the rotation speed was too fast, the RTS will lose lock to the prism frequently. The analysed results are shown in Figure 4.6.

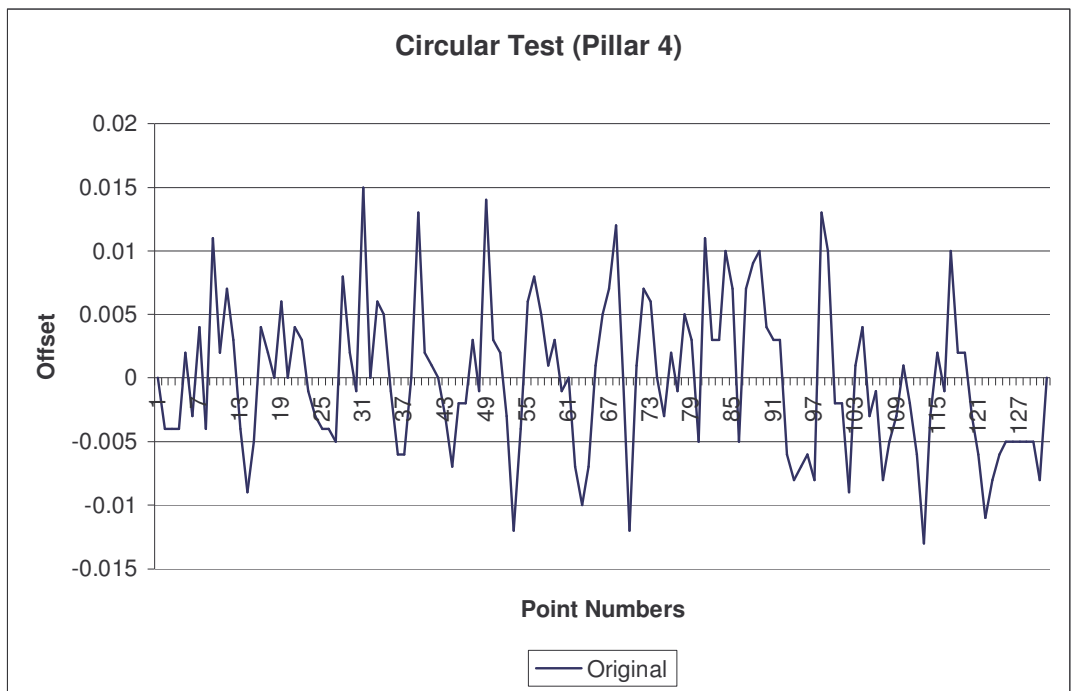


Figure 4.6: Graph Indicating the Offset of the Points from the Real Circular Path (Pillar 4)

Even though the analysed percentage was considerably low at 78%, from the graph it can be clearly identified that the measured values were actually within 15mm of the pre-defined circular path.

In short, the various statistical analysis values were calculated and are shown below: -

Percentage Analysed	=	78%
Mean (\bar{x})	=	-3.1E-05
Standard Deviation (s)	=	0.006
Variance (s^2)	=	0.00004
Range	=	0.028
Standard Error	=	0.0005
Confidence Level (95%)	=	0.001

Based on the standard deviation calculated, Pillar 4 test was within the manufacturer's specification, which is $10\text{mm} \pm 2\text{ppm}$.

After the above calculations were completed, further analysis using the Kalman Filter analytical tool was engaged to smooth the observed data and is shown in Figure 4.7. Once again, the blue line indicates the original offset from the pre-defined circular path and the pink line represents the smoothed values.

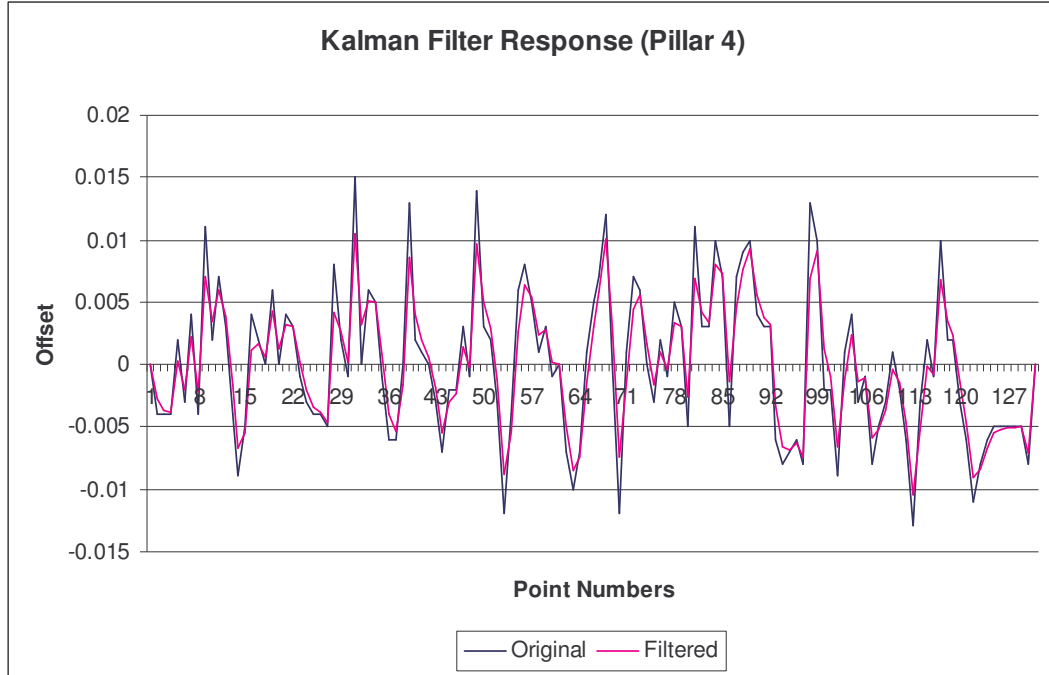


Figure 4.7: Comparison of Original and Filtered Values (Pillar 4)

The statistical results after the smoothening process are shown in Table 4.4.

Table 4.4: Statistical Comparison of Original and Smoothed Data (Pillar 4)

Pillar 4		Original	Filtered
Mean (\bar{x})	=	-3.1E-05	-7.3E-06
Standard Deviation (s)	=	0.006	0.005
Variance (s^2)	=	0.00004	0.00002
Range	=	0.028	0.021
Standard Error	=	0.0005	0.0004
Confidence Level (95%)	=	0.001	0.0008

Test 4: Pillar 5

For this test at Pillar 5, the analysed percentage was very high with around 98% of the measured values successfully analysed. The distance between the set up station and the observed pillar was approximately 184m and since this test had a fairly long distance, a high rotation speed was applied. It has been found out that with longer distance, the RTS would not lose its lock so easily. The analysed results are shown in Figure 4.8.

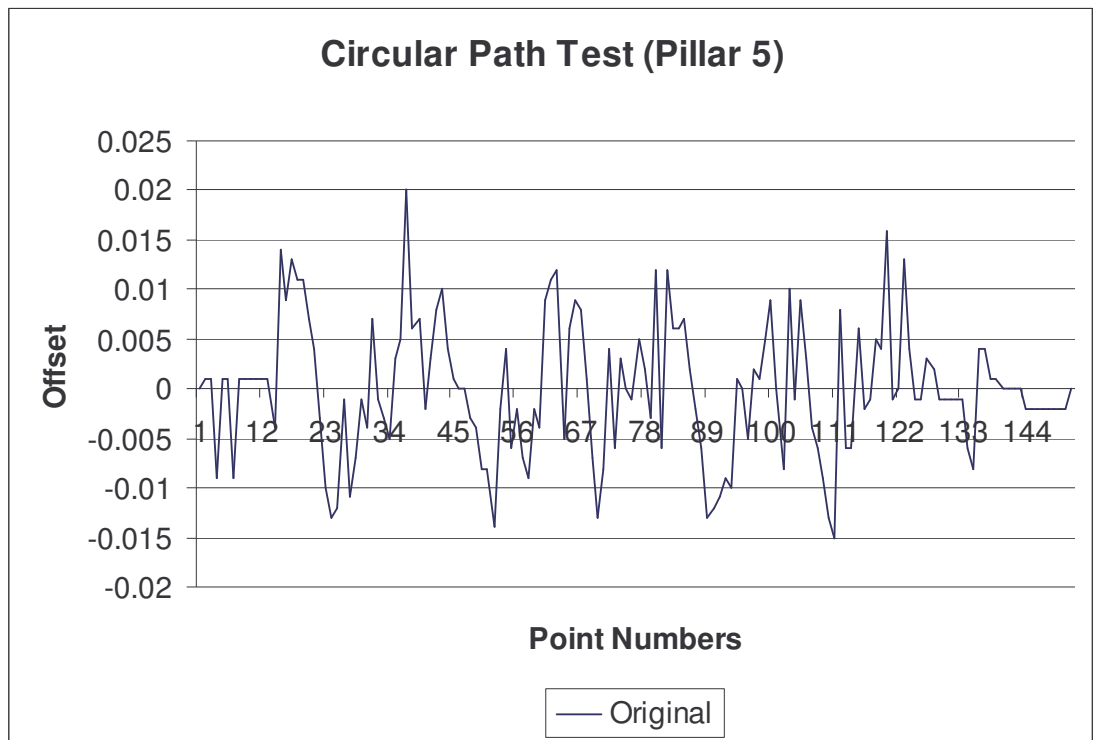


Figure 4.8: Graph Indicating the Offset of the Points from the Real Circular Path (Pillar 5)

From the graph, it can be clearly shown that the measured values were quite consistence with Pillar 4, which is 15mm to 20mm from the pre-defined circular path.

The various statistical analysis values were calculated and are shown below: -

Percentage Analysed	=	98%
Mean (\bar{x})	=	-4.6E-05
Standard Deviation (s)	=	0.007
Variance (s^2)	=	0.00004
Range	=	0.035
Standard Error	=	0.0005
Confidence Level (95%)	=	0.0011

Based on the standard deviation calculated, Pillar 5 test also managed to pass the manufacturer's specification.

After the above calculations were completed, further analysis using the Kalman Filter analytical tool was engaged to smooth the observed data and is shown in Figure 4.9. Once again, the blue line indicates the original offset from the pre-defined circular path and the pink line represents the smoothed values.

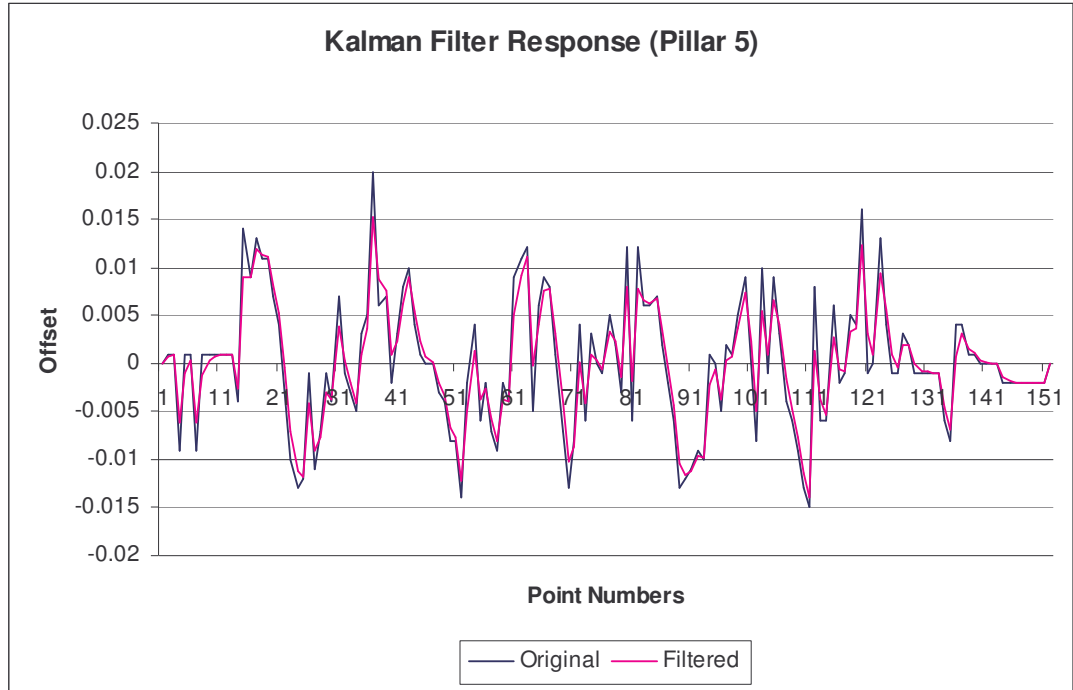


Figure 4.9: Comparison of Original and Filtered Values (Pillar 5)

The statistical results after the smoothening process are shown in Table 4.5.

Table 4.5: Statistical Comparison of Original and Smoothed Data (Pillar 5)

Pillar 5		Original	Filtered
Mean (\bar{x})	=	-4.6E-05	-4E-05
Standard Deviation (s)	=	0.007	0.006
Variance (s^2)	=	0.00004	0.00003
Range	=	0.035	0.029
Standard Error	=	0.0005	0.0004
Confidence Level (95%)	=	0.0011	0.0009

Summary of Circular Test Results

Summaries of the circular path tests are shown in Table 4.6. These results will be discussed later in this chapter. It can be clearly seen that after the Kalman Filter process, the results shown below are reduced.

Table 4.6 Table Showing Various Circular Path Tests Results

Pillars	Statistical Analysis	Original	Filtered
Z120	Mean (\bar{x})	-4.6E-20	7.05E-09
	Standard Deviation (s)	0.011	0.009
	Variance (s^2)	0.00011	0.00007
2	Mean (\bar{x})	-4.3E-05	5.64E-05
	Standard Deviation (s)	0.014	0.010
	Variance (s^2)	0.00019	0.00011
4	Mean (\bar{x})	-3.1E-05	-7.3E-06
	Standard Deviation (s)	0.0005	0.0004
	Variance (s^2)	0.001	0.0008
5	Mean (\bar{x})	-4.6E-05	-4E-05
	Standard Deviation (s)	0.007	0.006
	Variance (s^2)	0.00004	0.00003

4.2.2 Straight Line Tests

Overview

There were two similar types of tests carried out under this category. All of the tests were carried out on the roof of Faculty of Engineering and Surveying, USQ. The distance between the set up station and the prism on a pre-defined straight-line path was 4.5m.

The RTS was set up on pillar number 4 on the roof of Z-building; i.e. the Faculty of Engineering and Surveying, USQ. In order to test on the horizontal movement along a pre-defined straight-line path, the prism was attached to an aluminium bar with an L-shape steel bracket connected under the stated bar so that the prism would have a steady movement along the bench where the straight-line tests were observed.

It was also been mentioned in the last chapter that the length of the bench was 3.2m. The prism was moved forwards and backwards along the bench while the measurements were taken. Each test comprises of 11 runs with a total of 22 runs being observed throughout this test. Individual test result was attached in Appendix E.

Processing

Similar processing techniques to the circular path tests were utilised in the straight-line testing. Figure 4.10 indicates the results obtained from a straight line testing. The pink line indicates the pre-defined straight line path while the blue points representing the measured values by the RTS.

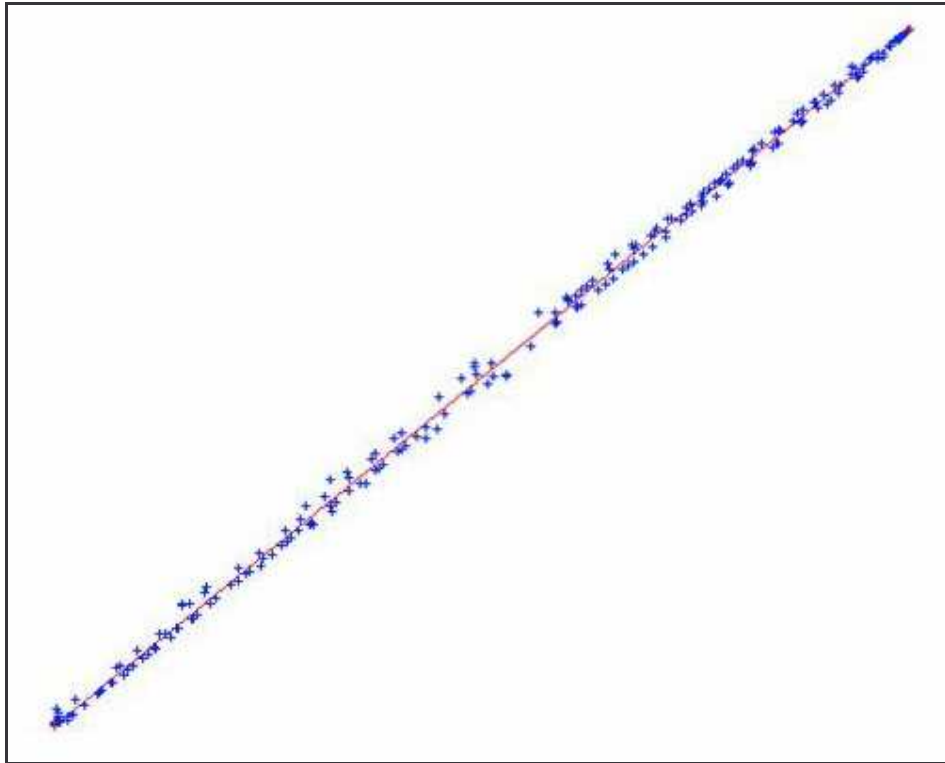


Figure 4.10: Straight Line Path Test Determined by Trimble 5603 RTS (Z-Roof)

Test 1: Straight Line Test

This straight line test was made up of 11 runs. Figure 4.11 illustrated the offset from the pre-defined straight line path. As the test was carried out over a short range, there were a numbers of outliers discovered, which are shown by red circles in Figure 4.11. Furthermore, the range as observed from the figure provided below was around 80mm, which is beyond the test expectation.

The main reason could be due to the RTS was not pointing towards the centre of the prism at the time of measurement. This will be discussed in more detail later in this report. Another reason could be due to the frequent loses in lock of the RTS. As described earlier that short distances, the RTS tends to lose lock very easily and frequently.

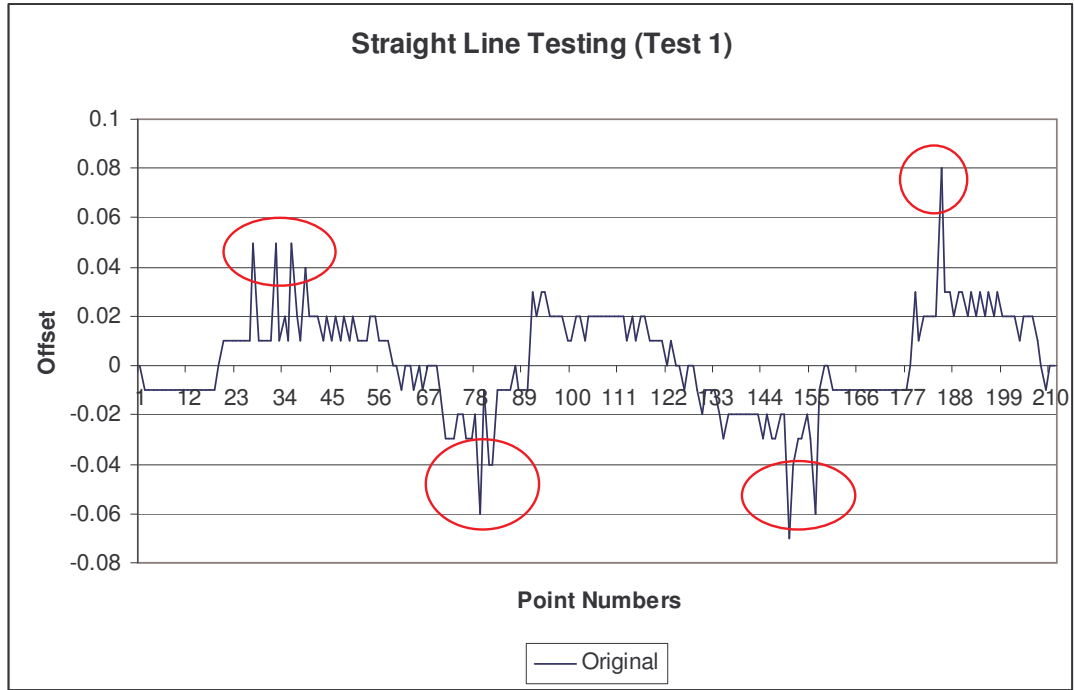


Figure 4.11: Graph Indicating the Offset of the Points from the Pre-Defined Straight Line Path (Test 1)

After performing all the relevant statistical analysis, the results are as follows: -

Percentage Analysed	=	80%
Mean (\bar{x})	=	0.002
Standard Deviation (s)	=	0.02043
Variance (s^2)	=	0.0004
Range	=	0.15
Standard Error	=	0.001
Confidence Level (95%)	=	0.003

Once again, the Kalman Filter was engaged to perform the analysis process; i.e. smooth the observed results and is shown in Figure 4.12. The blue line indicates the original offset from the pre-defined straight line path and the pink line represents the smoothed values.

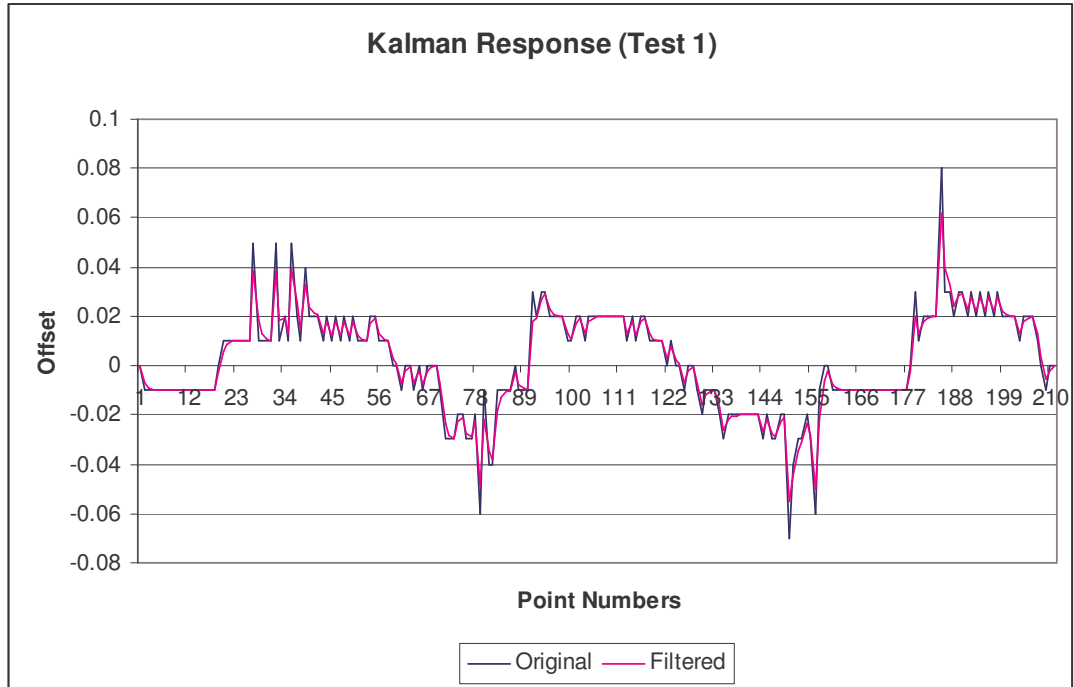


Figure 4.12: Comparison of Original and Filtered Values (Test 1)

The statistical results after the smoothing process are shown in Table 4.7.

Table 4.7: Statistical Comparison of Original and Smoothed Data (Test 1)

Straight Line Test 1		Original	Filtered
Mean (\bar{x})	=	0.002	0.002
Standard Deviation (s)	=	0.02043	0.0193
Variance (s^2)	=	0.0004	0.0004
Range	=	0.15	0.12
Standard Error	=	0.001	0.001
Confidence Level (95%)	=	0.003	0.002

Even though with the help of the Kalman Filter, this test had exceeded the manufacturer’s specification, this could be due to the short measurement distances. For such a short distance, the manufacturer’s specification was set to a standard deviation (σ) of 0.010.

It has been clearly seen that even the implementation of the Kalman Filter does not influence the original observation data.

Test 2: Straight Line Test

The second straight line test consisted of similar runs as Test 1 although the difference in this test was the movement speed along the bench was reduced. There were still some outliers detected as shown in red circles in Figure 4.13. The total percentage analysed was increased to 90% from 80% in Test 1. When comparing to the first test, the range reduced from 80mm to approximately 60mm. Unfortunately, this test again exceeded the specification set by the manufacturer.

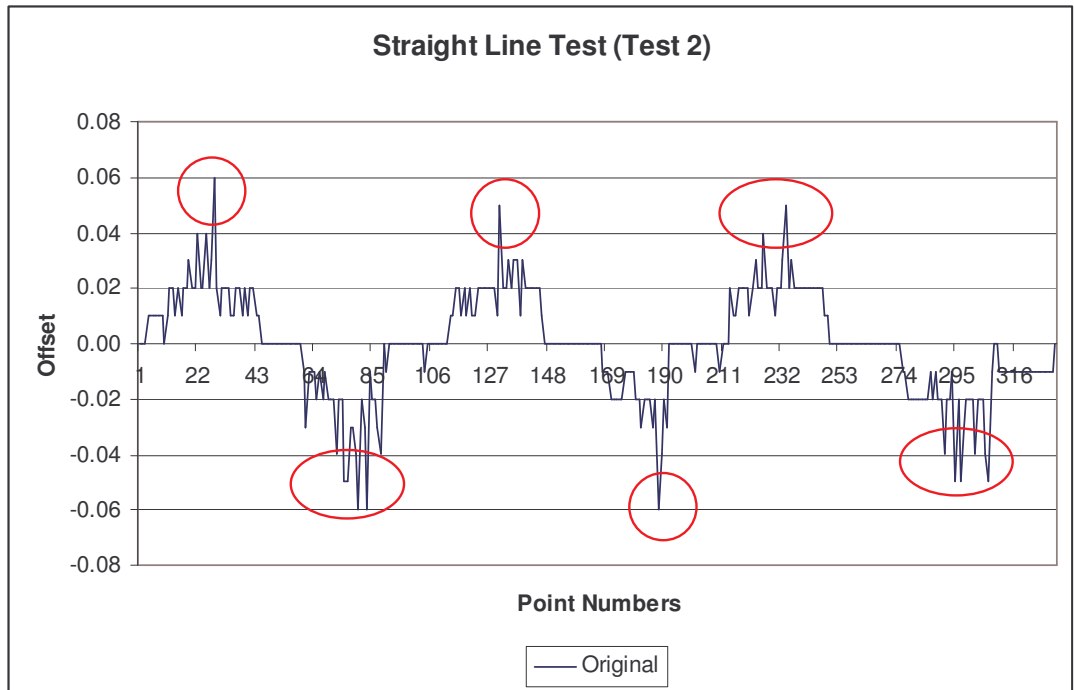


Figure 4.13: Graph Indicating the Offset of the Points from the Pre-Defined Straight Line Path (Test 2)

The various statistical analyses are shown as below: -

Percentage Analysed	=	90%
Mean (\bar{x})	=	0.00036
Standard Deviation (s)	=	0.013
Variance (s^2)	=	0.0002
Range	=	0.12
Standard Error	=	0.001
Confidence Level (95%)	=	0.002

As stated earlier, the test had exceeded the manufacturer's specification. After applying the Kalman Filter analysis tool, the results are shown in Figure 4.14.

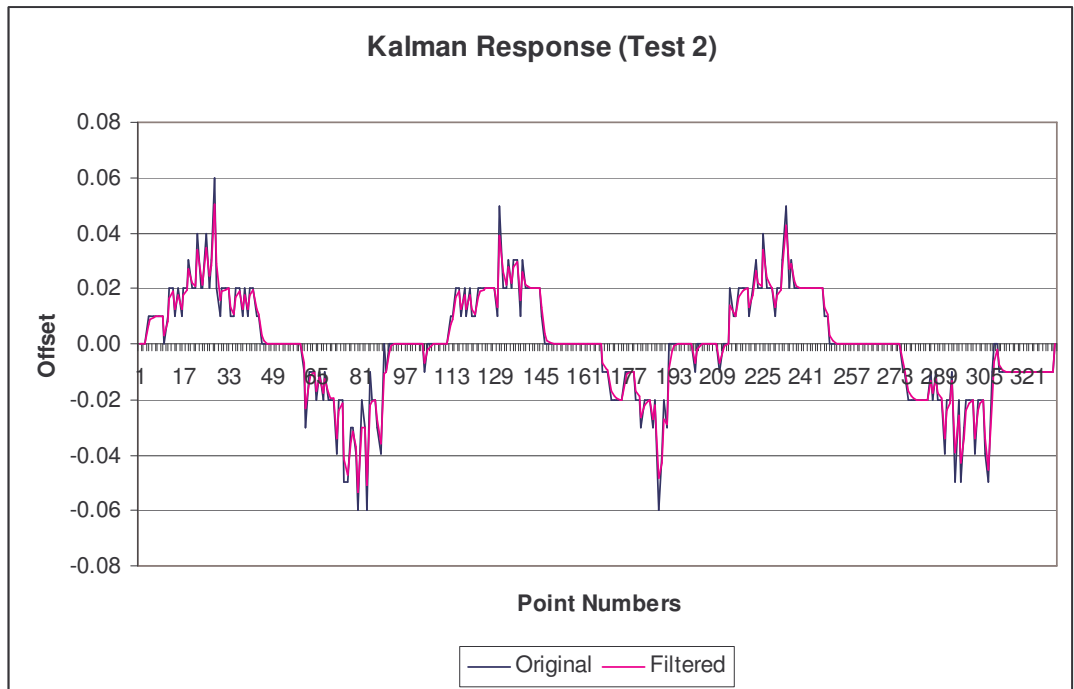


Figure 4.14: Comparison of Original and Filtered Values (Test 2)

The statistical results after the smoothing process are shown in Table 4.8.

Table 4.8: Statistical Comparison of Original and Smoothed Data (Test 2)

Straight Line Test 2		Original	Filtered
Mean (\bar{x})	=	0.00036	0.00030
Standard Deviation (s)	=	0.013	0.010
Variance (s^2)	=	0.0002	0.0001
Range	=	0.12	0.10
Standard Error	=	0.001	0.001
Confidence Level (95%)	=	0.002	0.002

After performing the Kalman Filter analysis, this test has just met the manufacturer's specification. The main reason could be due to the slow movement speed along the bench compared to the first test.

The standard deviation of the first test before adjustment was at 0.02mm and after adjustment; it only reduced to 0.019, which is not very different from the original data.

Summary of Results

A brief summary of the straight line tests are shown in Table 4.9. These results will be discussed later in this chapter.

Table 4.9: Table Showing Various Straight Line Tests Results

Tests	Statistical Analysis	Original	Filtered
1	Mean (\bar{x})	0.002	0.002
	Standard Deviation (s)	0.02043	0.0193
	Variance (s^2)	0.0004	0.0004
2	Mean (\bar{x})	0.00036	0.00030
	Standard Deviation (s)	0.013	0.010
	Variance (s^2)	0.0002	0.0001

4.3 Comparison to Manufacturer's Specification

As outlined by the *Trimble Datasheet (2003)*, the manufacturer's specification for dynamic tracking is $10\text{mm} \pm 2\text{ppm}$. The following table (Table 4.10) shows a clear differentiation between the test results compared to manufacturer's specification.

Table 4.10: Observed Results Compared to Manufacturer's Specification

Tests	Original Results (σ)	Filtered Results (σ)	Manufacturer's Specification
Z120 Pillar	0.011	0.009	10mm \pm 2ppm
Pillar 2	0.014	0.010	10mm \pm 2ppm
Pillar 4	0.006	0.005	10mm \pm 2ppm
Pillar 5	0.007	0.006	10mm \pm 2ppm
Straight Line Test 1	0.020	0.019	10mm \pm 2ppm
Straight Line Test 2	0.013	0.010	10mm \pm 2ppm

When the manufacturer's specification is transformed to the standard deviation format, it can be shown as in Table 4.11 below: -

Table 4.11: Table Showing the Manufacturer's Specification in Standard Deviation Form

Tests	Distances (m)	Manufacturer's Specification (σ)
Z120 Pillar	5.1	0.0100
Pillar 2	4.9	0.0100
Pillar 4	115.9	0.0101
Pillar 5	183.9	0.0102
Straight Line Test 1	4.5	0.0100
Straight Line Test 2	4.5	0.0100

Table 4.12 compares the original observed results to the manufacturer’s specification.

Table 4.12: Comparison of Original Results to Manufacturer’s Specification

Tests	Original Results (σ)	Manufacturer’s Specification (σ)	Exceeds
Z120 Pillar	0.011	0.0100	*
Pillar 2	0.014	0.0100	*
Pillar 4	0.006	0.0101	
Pillar 5	0.007	0.0102	
Straight Line Test 1	0.020	0.0100	*
Straight Line Test 2	0.013	0.0100	*

It can be seen from the table provided above that Z120 Pillar, Pillar 2, Straight Line Test 1 and 2 have exceeded the manufacturer’s stated specification. According to *Trimble Technical Notes (2003)* the manufacturer’s recommended distance for dynamic tracking is at least 100m between the set up station and the observation station. Pillar 4 and Pillar 5 had met this stated requirement.

With the filtered results, it appears that with the exception of Straight Line Test 1, the entire test had met the manufacturer’s specification. The results are shown in Table 4.13 below.

Table 4.13: Comparison of Filtered Results to Manufacturer’s Specification

Tests	Filtered Results (σ)	Manufacturer’s Specification (σ)	Exceeds
Z120 Pillar	0.009	0.0100	
Pillar 2	0.010	0.0100	
Pillar 4	0.005	0.0101	
Pillar 5	0.006	0.0102	
Straight Line Test 1	0.019	0.0100	*
Straight Line Test 2	0.010	0.0100	

4.4 Discussion

4.4.1 Reliability

The reliability of the RTS is closely associated with the movement speeds and the distance between the set up station and the observation station. It had been found out that the RTS will lose lock to the prism for short distances and higher speeds. The RTS tends to lose lock much more frequently and easily compared to longer distances.

The accuracy of the results is closely related to the speed of the prism. When the prism was moving too fast along a path, the accuracy of the observed data will reduce and sometimes may lead to the dropout of the signal; i.e. loses lock to the prism. However, since RTS had a built in ATS, it can track and resume lock to the target in a very short time period but the results obtained will be affected as there is a lapse in observation results caused by lose of lock.

4.4.2 Accuracy of Tracking

The accuracy of tracking of the RTS to the prism is vital. If the RTS is not pointing towards the centre of the prism, as described by *Stempfhuber et al. (2001)*, it may lead to large variations in the observation results. As pointed out by *Kopacik, (1998)*, the RTS should always be measuring to the centre of the prism, as shown in Figure 4.15.

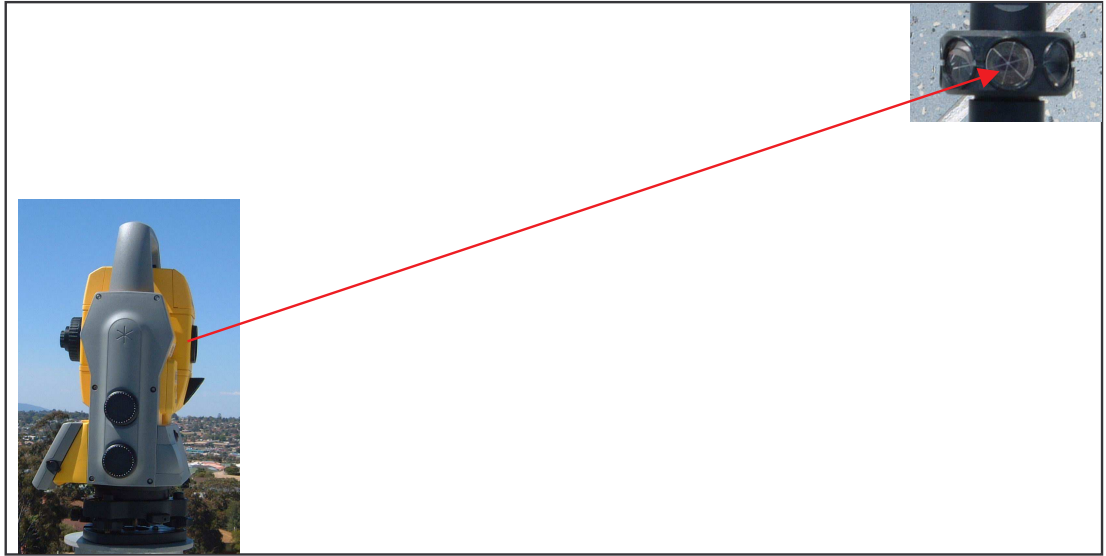


Figure 4.15: Accurate Pointing of RTS

Alternatively, if the prism is moving along a path and the RTS is not pointing directly towards the centre of the prism, then the measured values will have a large variation when analysis of results takes place. As seen in Figure 4.16, if the RTS is not directly pointed towards the centre of the prism, the observed results will tend to have a large offset from the pre-defined path, as shown by the red circles in Figure 4.16.

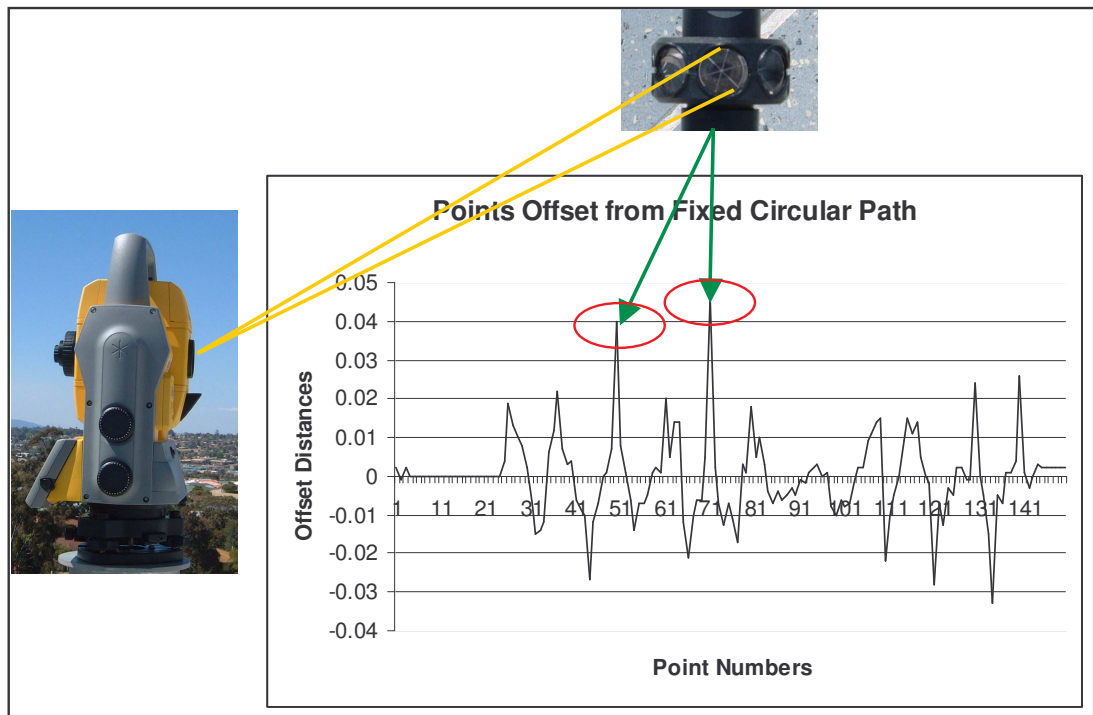


Figure 4.16: RTS Not Pointing Towards the Centre of the Prism

4.5 Conclusion

The aim of this project is to determine the dynamic accuracy and reliability of RTS. Since this project is only dealing with one type of RTS; i.e. Trimble 5603 RTS, it is hard to draw a final conclusion of the dynamic tracking and the reliability of the RTS.

However, based on the above tests, it can be concluded that the reliability of the RTS is greatly related to the speeds of the prism and measurement distances. If the measurements had taken place at a shorter range with a higher speed environment, the RTS will lose lock onto the prism easily and much more frequently compared to longer distances. Shorter distances tend to have larger standard deviation than longer distances and this has been 'proven' in the tests stated above.

However, the RTS measurement of each point takes 0.4 seconds. Even if the prism was moving along a pre-defined path and the RTS had locked its target onto the prism, the RTS may not always reflect the true centre of the prism.

With the assistance of the Kalman Filter, the original results have been smoothed. The filter uses a statistical approach to weight each and every new measurement in relation to the past information gathered. In addition, it also determines up-to-date uncertainties of the estimates for real-time quality assessments. The algorithm of Kalman filter is well received by surveyors; however, the practical applications of the algorithm require careful attention.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

As mentioned earlier, RTSs have been available for more than 10 years but little information about their real-time operation is available.

Nowadays, the major application of 3D machine guidance systems can be found in the construction and mining industries for the guidance of dozers, graders, excavators, scrapers, tractors and harvesters.

It has been pointed out by *Retscher, (2002)* that for the guidance of road and paving machines, high precision requirements for the height component are still very challenging for the 3D machine guidance systems. In order to achieve this level of

precision and to replace conventional labour intensive methods in this type of application, present 3D systems still require further improvements.

When carrying out the entire tests, the author had found out several limitations of the RTS. First and foremost, it has been shown that the distances measured by the RTS suffer from an error that is linearly dependent on the velocity of the target along the line of sight. This means that shorter distances tend to have much greater variation than longer distances. In other words, shorter distances measurement will have larger standard deviation, while longer distances measurement will have smaller standard deviation.

Another limitation of RTS is that when carrying out measurements, the RTS does not always point directly to the centre of the prism. When the prism is moving along a pre-defined path, the RTS with built-in ATS will automatically locked onto the prism during the measurement. In fact the RTS did not lose lock to the prism, but unfortunately the measurements did not reflect the true centre of the prism.

From the tests carried out throughout this project, approximately 80% of the measured values for circular path tests have passed the manufacturer's specification. For the straight line testing, there were around 25% of the measured values exceeded the manufacturer's specification (Refer to Appendix D).

In conclusion, the author believes that the time tagging problem is the most crucial in an RTS based monitoring system. Assuming that higher data rates become possible, robust velocity profiles of a moving target can be calculated and then used to correct the velocity-dependent distance errors. The corrected distances could then be used to calculate improved velocities and the entire correction process repeated.

5.2 Recommendations

As mentioned earlier in Chapter 3 that due to time constraints, there was only one type of RTS being tested throughout the duration this project; i.e. the Trimble 5603 Robotic Total Station. The results obtained and shown in Chapter 4 were only based on Trimble RTS and other types of RTSs such as Leica, Topcon, etc. have not been tested.

The author recommends that further research on the similar topic; i.e. Testing of RTS for dynamic tracking using other instruments, should be undertaken in order to obtain a more accurate results.

The Kalman Filter, which is able to refine the measured solution, also determines up-to-date uncertainties of the estimates for real-time quality assessments. Since the author discovered the process of implementing the tests results into Kalman Filter nearly at the end of this project, only the basic calculations were carried out using the stated filter. There is still various information on Kalman Filter, which was not fully utilised due to time constraints and therefore, the author recommends that some efforts be taken to discover more on the stated filter.

In my opinion, my work on this project has proven that the speed and the accuracy of results were highly and closely related to the pointing accuracy of the RTS to the reflective prism. Furthermore, speeds level can be increased with longer measured distances. It has been recommended by *Geodimeter (2004)*, that the minimum distance to the survey instrument should be at least 100m for a moving speed of less than 5m/sec. From the circular path testing, the rotation speed for Pillar 4 and Pillar 5 were less than the stated speed however the RTS seemed to still lose lock at these ranges.

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APPENDIX A

Project Specification

**University of Southern Queensland
Faculty of Engineering and Surveying**

ENG 4111 / 4112 Research Project

PROJECT SPECIFICATION

FOR: CHUN SIONG CHUA

TOPIC: TESTING ROBOTIC TOTAL STATIONS FOR DYNAMIC TRACKING

SUPERVISOR: Mr. Kevin McDougal

SPONSORSHIP: Faculty of Engineering and Surveying

PROJECT AIM: This project aims to test a number of Robotic Systems to evaluate their dynamic accuracy. Robotic Total Stations have been used for dynamic measurement applications for sometime but little information is available on their accuracy and reliability

PROGRAMME: Issue A, 16th March 2004

1. Research information on manufacturers' specification for various types of Robotic Total Stations.
2. Design a simple field measurement programme and collect information on the accuracy of Robotic Total Stations.
3. Analyse field data obtained and provide relevant adjustments for the preliminary report.
4. Further design of field measurement programme for testing of different types of Robotic Total Stations in dynamic tracking.
5. Analyse field data with an aid from relevant surveying software such as LisCAD or Terramodel.
6. Combine the obtained field data from (2) and (4) above and compared with relevant manufacturers' specification.

AGREED: _____ (Student) _____ (Supervisor)

Dated: ____ / ____ / ____

APPENDIX B

Kalman Filter Programs

Part A – Kalman Filter (kalman_filter.m)

Part B – Kalman Smoother (kalman_smoother.m)

Part A – Kalman Filter Program

/* Name: Gordon C.S.Chua
 Student ID: D11374001
 Purpose: Transforming Tests Results to Kalman Filter Format

```
function [x, V, VV, loglik] = kalman_filter(y, A, C, Q, R, init_x, init_V, varargin)
% Kalman filter.
% [x, V, VV, loglik] = kalman_filter(y, A, C, Q, R, init_x, init_V, ...)
%
% INPUTS:
% y(:,t) - the observation at time t
% A - the system matrix
% C - the observation matrix
% Q - the system covariance
% R - the observation covariance
% init_x - the initial state (column) vector
% init_V - the initial state covariance
%
% OPTIONAL INPUTS (string/value pairs [default in brackets])
% 'model' - model(t)=m means use params from model m at time t [ones(1,T) ]
%   In this case, all the above matrices take an additional final dimension,
%   i.e., A(:, :, m), C(:, :, m), Q(:, :, m), R(:, :, m).
%   However, init_x and init_V are independent of model(1).
% 'u' - u(:,t) the control signal at time t [ [] ]
% 'B' - B(:, :, m) the input regression matrix for model m
%
% OUTPUTS (where X is the hidden state being estimated)
% x(:,t) = E[X(:,t) | y(:,1:t)]
% V(:, :, t) = Cov[X(:,t) | y(:,1:t)]
% VV(:, :, t) = Cov[X(:,t), X(:,t-1) | y(:,1:t)] t >= 2
% loglik = sum{t=1}^T log P(y(:,t))
%
% If an input signal is specified, we also condition on it:
% e.g., x(:,t) = E[X(:,t) | y(:,1:t), u(:, 1:t)]
% If a model sequence is specified, we also condition on it:
% e.g., x(:,t) = E[X(:,t) | y(:,1:t), u(:, 1:t), m(1:t)]

[os T] = size(y);
ss = size(A,1); % size of state space

% set default params
model = ones(1,T);
u = [];
B = [];
```

```

ndx = [];

args = varargin;
nargs = length(args);
for i=1:2:nargs
    switch args{i}
        case 'model', model = args{i+1};
        case 'u', u = args{i+1};
        case 'B', B = args{i+1};
        case 'ndx', ndx = args{i+1};
        otherwise, error(['unrecognized argument ' args{i}'])
    end
end

x = zeros(ss, T);
V = zeros(ss, ss, T);
VV = zeros(ss, ss, T);

loglik = 0;
for t=1:T
    m = model(t);
    if t==1
        %prevx = init_x(:,m);
        %prevV = init_V(:,:,m);
        prevx = init_x;
        prevV = init_V;
        initial = 1;
    else
        prevx = x(:,t-1);
        prevV = V(:,:,t-1);
        initial = 0;
    end
    if isempty(u)
        [x(:,t), V(:,:,t), LL, VV(:,:,t)] = ...
            kalman_update(A(:,:,m), C(:,:,m), Q(:,:,m), R(:,:,m), y(:,t), prevx, prevV, 'initial',
initial);
    else
        if isempty(ndx)
            [x(:,t), V(:,:,t), LL, VV(:,:,t)] = ...
                kalman_update(A(:,:,m), C(:,:,m), Q(:,:,m), R(:,:,m), y(:,t), prevx, prevV, ...
                    'initial', initial, 'u', u(:,t), 'B', B(:,:,m));
        else
            i = ndx{t};
            % copy over all elements; only some will get updated
            x(:,t) = prevx;
            prevP = inv(prevV);

```

```
    prevPsmall = prevP(i,i);
    prevVsmall = inv(prevPsmall);
    [x(i,t), smallV, LL, VV(i,i,t)] = ...
        kalman_update(A(i,i,m), C(:,i,m), Q(i,i,m), R(:,i,m), y(:,t), prevx(i),
prevVsmall, ...
                    'initial', initial, 'u', u(:,t), 'B', B(i,:,m));
    smallP = inv(smallV);
    prevP(i,i) = smallP;
    V(:,i,t) = inv(prevP);
end
end
loglik = loglik + LL;
end
```

Part B – Kalman Smoother Program

```
/* Name:      Gordon C.S.Chua
Student ID:   D11374001
Purpose:     Smoothing Tests Results
*/

function [xsmooth, Vsmooth, VVsmooth, loglik] = kalman_smoother(y, A, C, Q, R,
init_x, init_V, varargin)
% Kalman/RTS smoother.
% [xsmooth, Vsmooth, VVsmooth, loglik] = kalman_smoother(y, A, C, Q, R, init_x,
init_V, ...)
%
% The inputs are the same as for kalman_filter.
% The outputs are almost the same, except we condition on y(:, 1:T) (and u(:, 1:T) if
specified),
% instead of on y(:, 1:t).

[os T] = size(y);
ss = length(A);

% set default params
model = ones(1,T);
u = [];
B = [];

args = varargin;
nargs = length(args);
for i=1:2:nargs
    switch args{i}
        case 'model', model = args{i+1};
        case 'u', u = args{i+1};
        case 'B', B = args{i+1};
        otherwise, error(['unrecognized argument ' args{i}])
    end
end

xsmooth = zeros(ss, T);
Vsmooth = zeros(ss, ss, T);
VVsmooth = zeros(ss, ss, T);

% Forward pass
[xfilt, Vfilt, VVfilt, loglik] = kalman_filter(y, A, C, Q, R, init_x, init_V, ...
'model', model, 'u', u, 'B', B);

% Backward pass
```

```
xsmooth(:,T) = xfilt(:,T);
Vsmooth(:,:,T) = Vfilt(:,:,T);
%VVsmooth(:,:,T) = VVfilt(:,:,T);

for t=T-1:-1:1
    m = model(t+1);
    if isempty(B)
        [xsmooth(:,t), Vsmooth(:,t), VVsmooth(:,t+1)] = ...
            smooth_update(xsmooth(:,t+1), Vsmooth(:,t+1), xfilt(:,t), Vfilt(:,t), ...
                Vfilt(:,t+1), VVfilt(:,t+1), A(:,m), Q(:,m), [], []);
    else
        [xsmooth(:,t), Vsmooth(:,t), VVsmooth(:,t+1)] = ...
            smooth_update(xsmooth(:,t+1), Vsmooth(:,t+1), xfilt(:,t), Vfilt(:,t), ...
                Vfilt(:,t+1), VVfilt(:,t+1), A(:,m), Q(:,m), B(:,m), u(:,t+1)));
    end
end

VVsmooth(:,1) = zeros(ss,ss);
```

APPENDIX C

Tests Results (Frequency Figures)

Part A – Circular Path Tests

Part B – Straight Line Tests

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Part A – Circular Path Tests

Figure C.1: Pillar Z120 Frequency Graph – Before Filtering

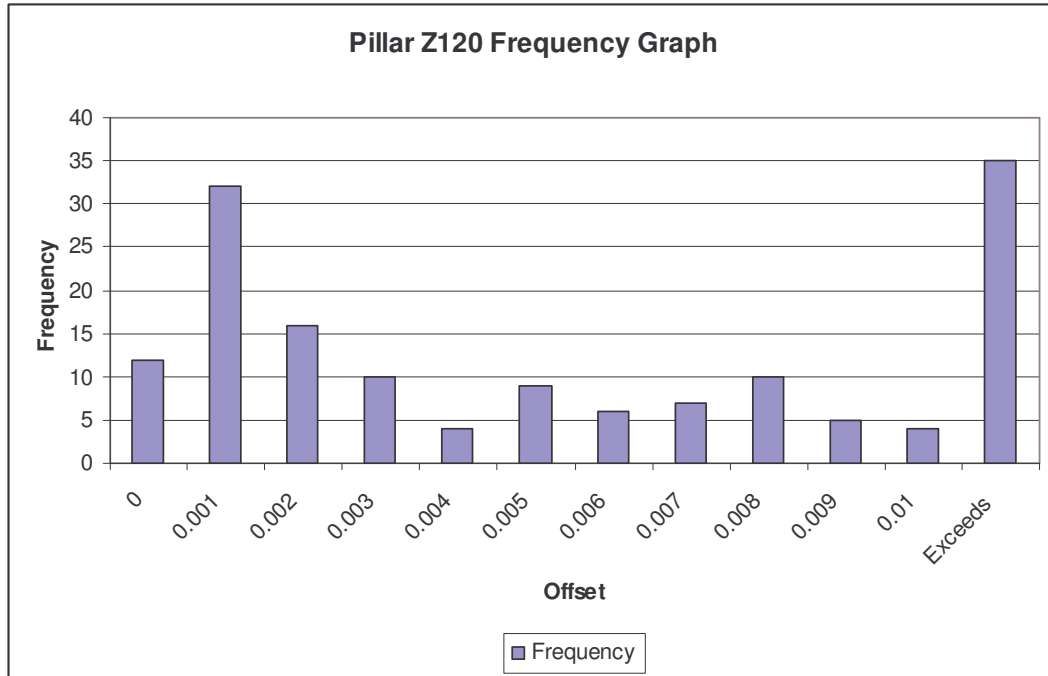


Figure C.1: Frequency of Measurements Obtained from Pillar Z120

Figure C.2: Pillar Z120 Frequency Graph – Filtered

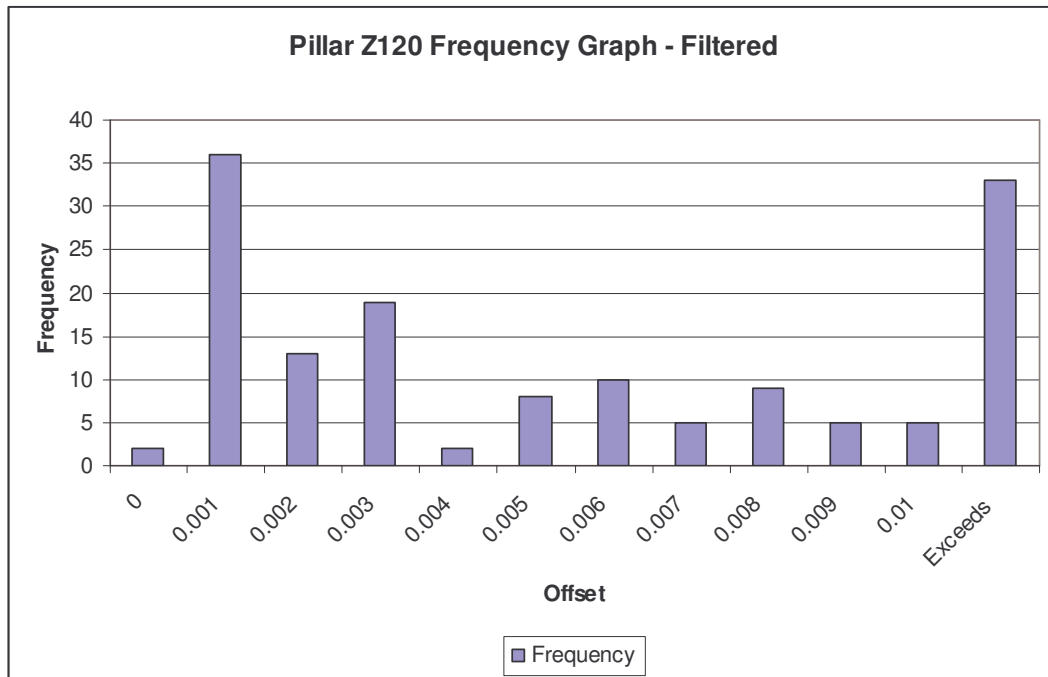


Figure C.2: Frequency of Measurements Obtained from Pillar Z120 (Filtered)

Figure C.3: Pillar 2 Frequency Graph – Before Filtering

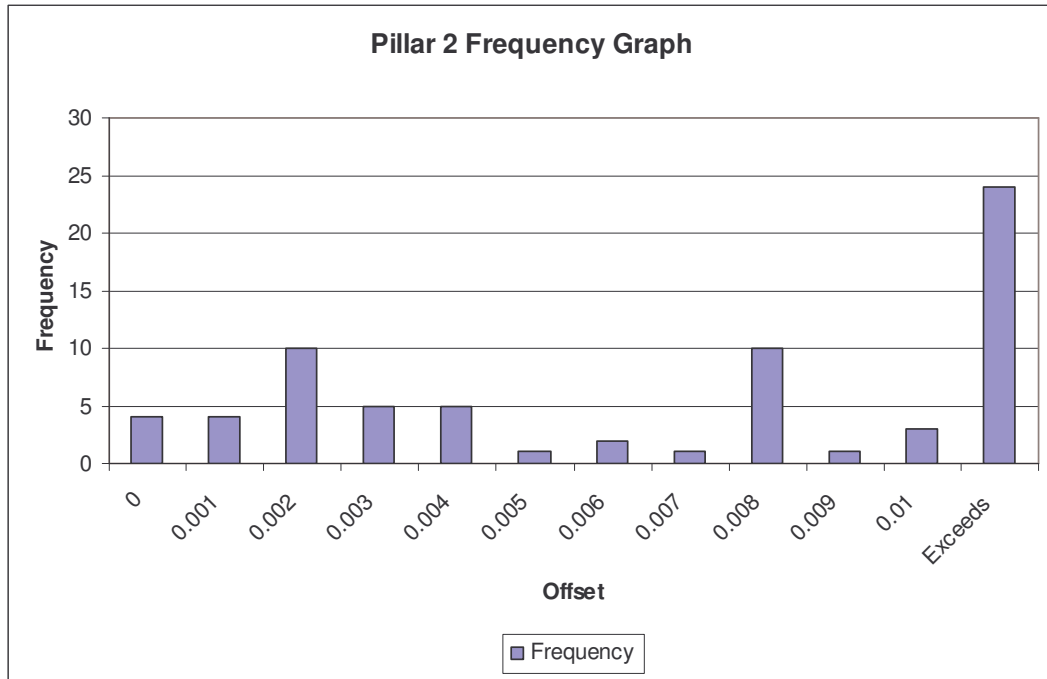


Figure C.3: Frequency of Measurements Obtained from Pillar 2

Figure C.4: Pillar 2 Frequency Graph – Filtered

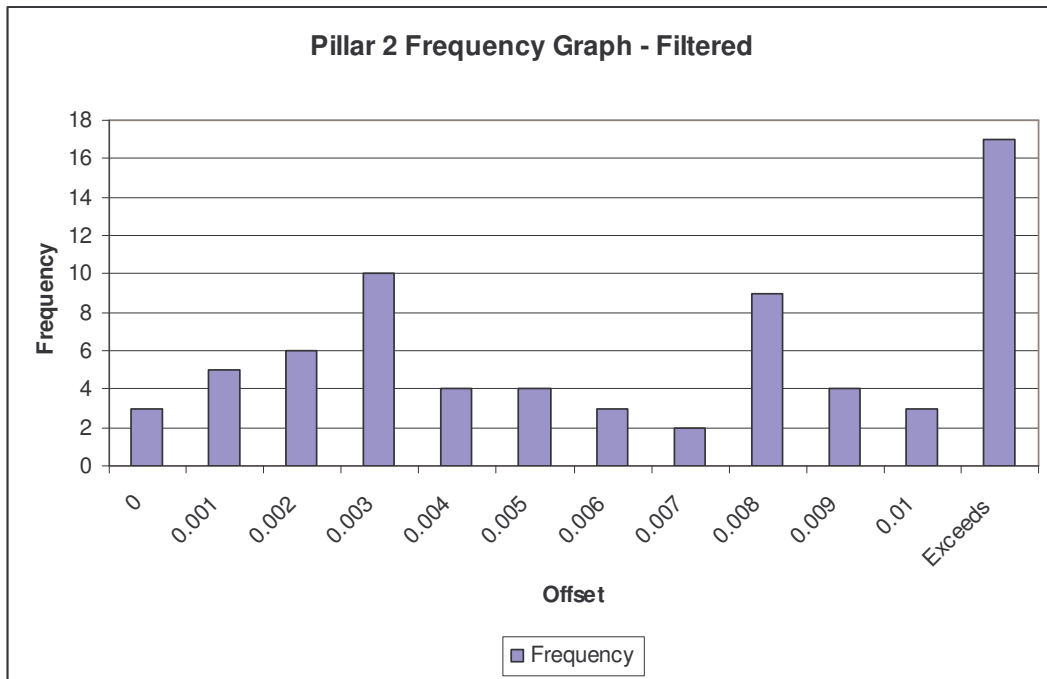


Figure C.4: Frequency of Measurements Obtained from Pillar 2 (Filtered)

Figure C.5: Pillar 4 Frequency Graph – Before Filtering

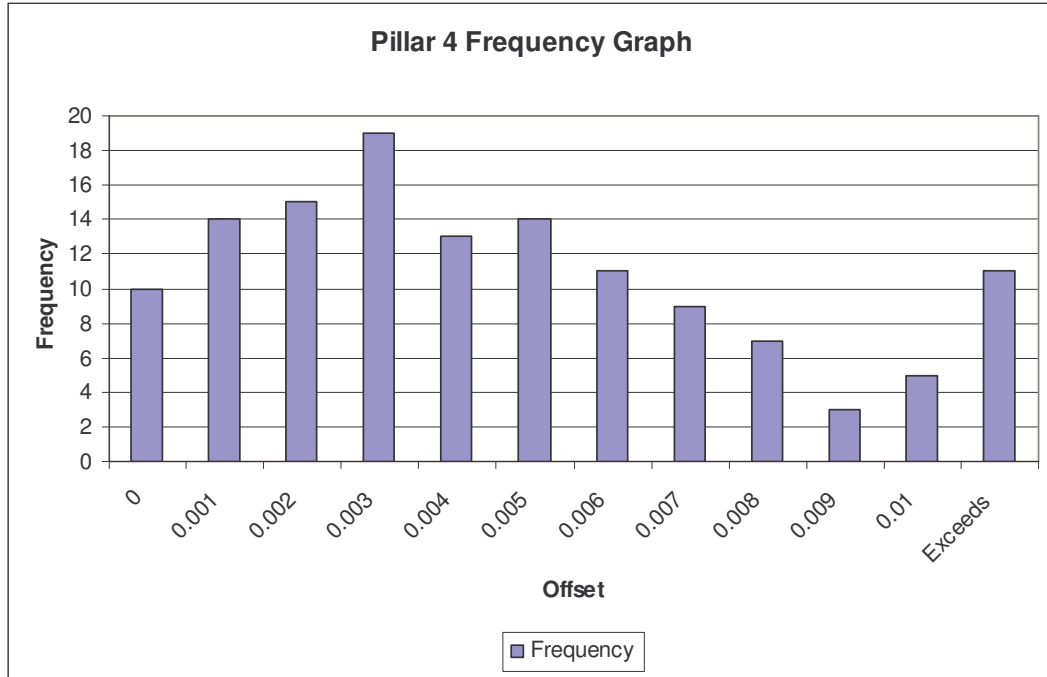


Figure C.5: Frequency of Measurements Obtained from Pillar 4

Figure C.6: Pillar 4 Frequency Graph – Filtered

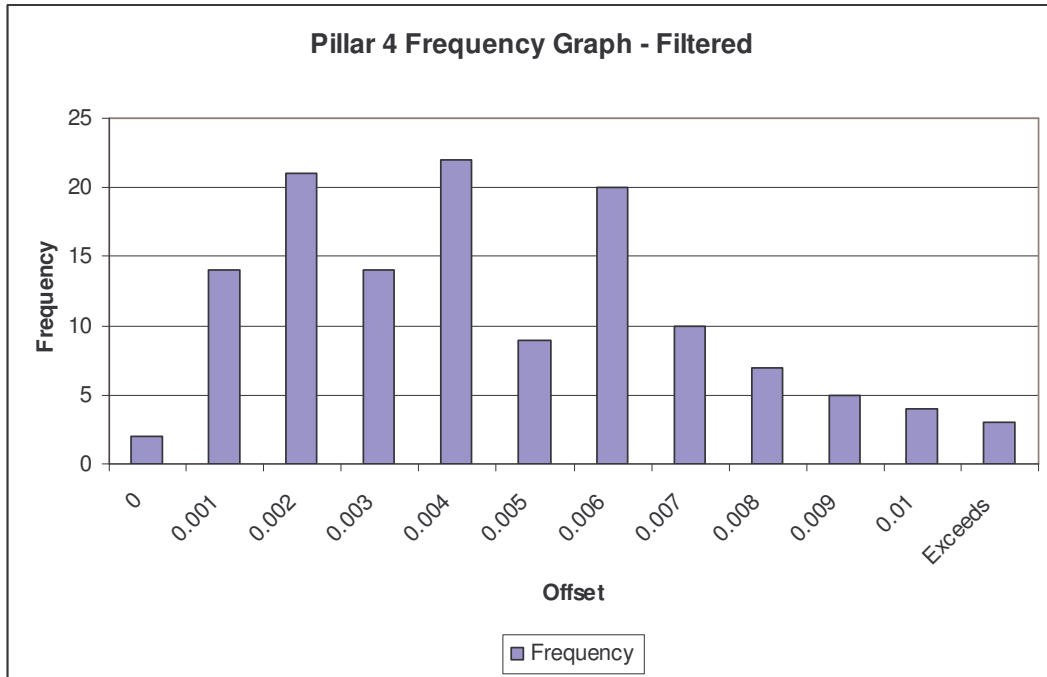


Figure C.6: Frequency of Measurements Obtained from Pillar 4 (Filtered)

Figure C.7: Pillar 5 Frequency Graph – Before Filtering

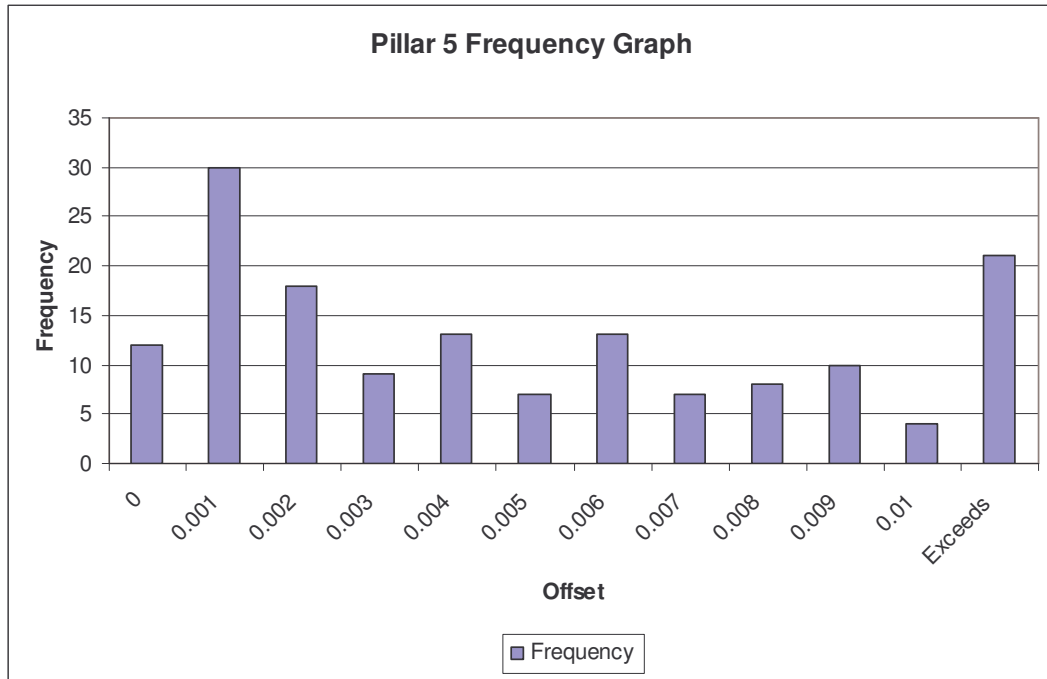


Figure C.7: Frequency of Measurements Obtained from Pillar 5

Figure C.8: Pillar 5 Frequency Graph – Filtered

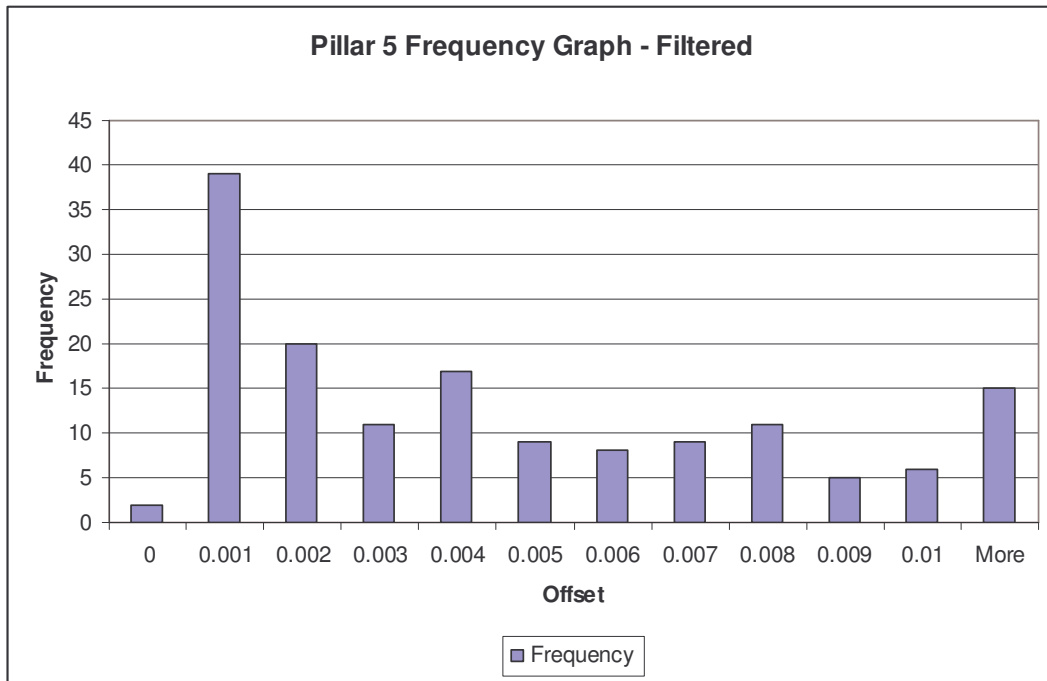


Figure C.8: Frequency of Measurements Obtained from Pillar 5 (Filtered)

Part B – Straight Line Tests

Figure C.9: Straight Line Test 1 Frequency Graph – Before Filtering

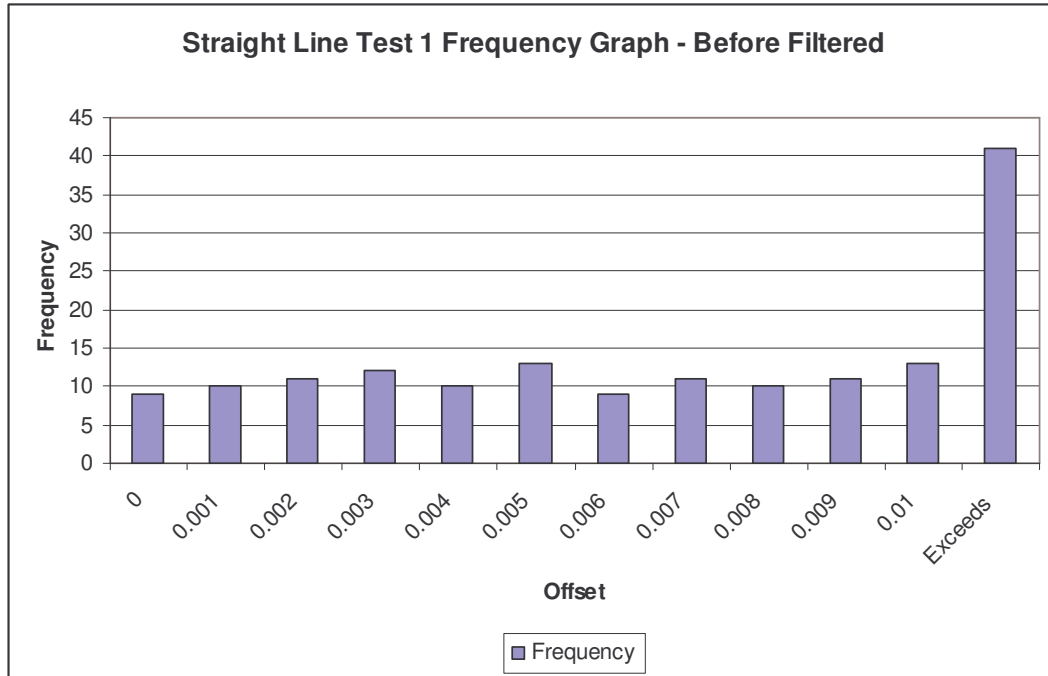


Figure C.9: Frequency of Measurements Obtained from Straight Line Test 1

Figure C.10: Straight Line Test 1 Frequency Graph – Filtered

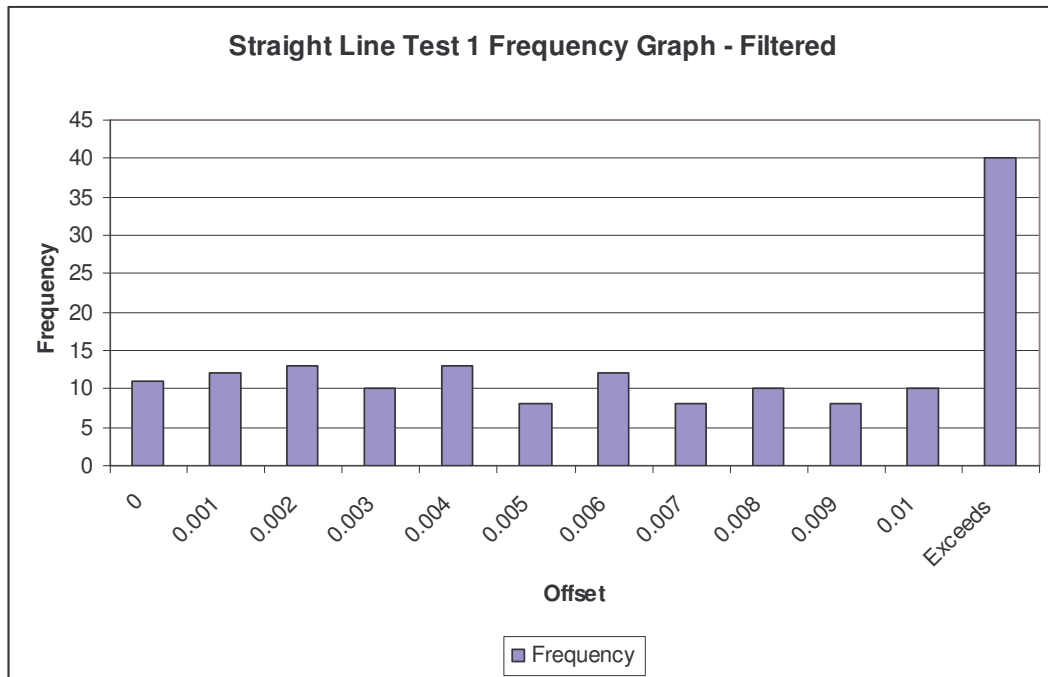


Figure C.10: Frequency of Measurements Obtained from Straight Line Test 1 (Filtered)

Figure C.11: Straight Line Test 2 Frequency Graph – Before Filtering

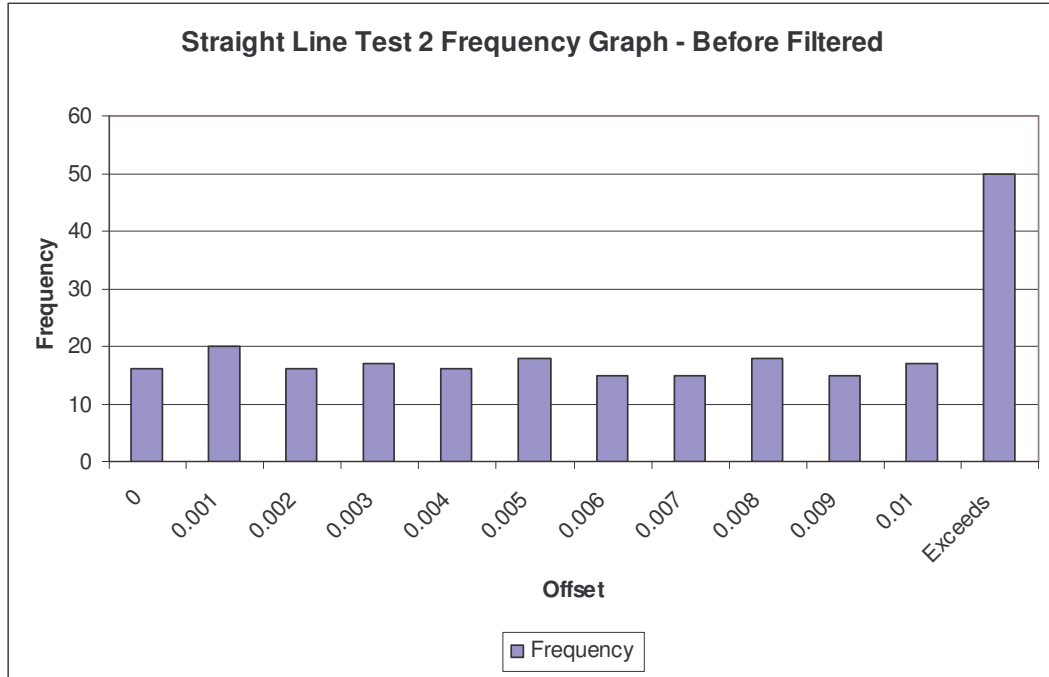


Figure C.11: Frequency of Measurements Obtained from Straight Line Test 2

Figure C.12: Straight Line Test 2 Frequency Graph – Filtered

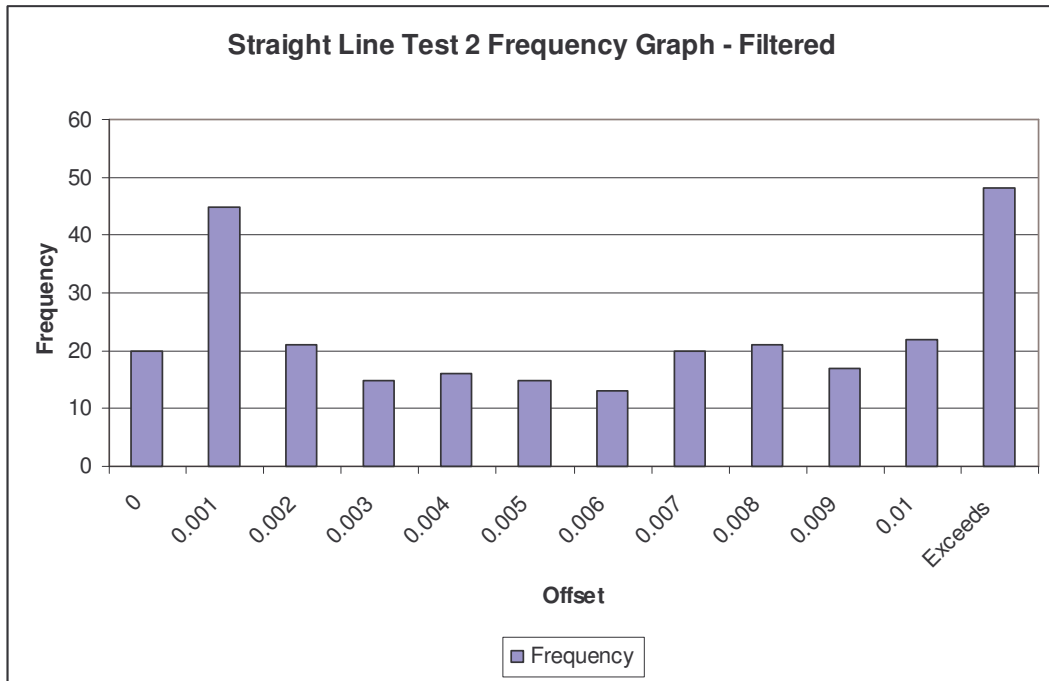


Figure C.12: Frequency of Measurements Obtained from Straight Line Test 2 (Filtered)

APPENDIX D

Tests Results (Frequency Tables)

Part A – Circular Path Tests

Part B – Straight Line Tests

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D.3	Percentage Associated with Manufacturer's Specification (Straight Line Tests) – Before Smoothing	100
D.4	Percentage Associated with Manufacturer's Specification (Straight Line Tests) – After Smoothing	100

Part A – Circular Path Tests

**Table D.1: Percentage Associated with Manufacturer’s Specification (Circular Path Tests)
– Before Smoothing**

Circular Path Tests	Within Manufacturer’s Specification	Exceeds Manufacturer’s Specification
Pillar Z120	77%	23%
Pillar 2	66%	34%
Pillar 4	92%	8%
Pillar 5	86%	14%

**Table D.2: Percentage Associated with Manufacturer’s Specification (Circular Path Tests)
– After Smoothing**

Circular Path Tests	Within Manufacturer’s Specification	Exceeds Manufacturer’s Specification
Pillar Z120	80%	20%
Pillar 2	74%	26%
Pillar 4	98%	2%
Pillar 5	90%	10%

Part B – Straight Line Tests

**Table D.3: Percentage Associated with Manufacturer’s Specification (Straight Line Tests)
– Before Smoothing**

Circular Path Tests	Within Manufacturer’s Specification	Exceeds Manufacturer’s Specification
Straight Line Test 1	74%	26%
Straight Line Test 2	79%	21%

**Table D.4: Percentage Associated with Manufacturer’s Specification (Straight Line Tests)
– After Smoothing**

Circular Path Tests	Within Manufacturer’s Specification	Exceeds Manufacturer’s Specification
Straight Line Test 1	74%	26%
Straight Line Test 2	82%	18%

APPENDIX E

Tests Results (Graphical Form)

Part A – Circular Path Tests

Part B – Straight Line Tests

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E.5	Observation of Straight Line Test 1	105
E.6	Observation of Straight Line Test 2	105

Part A: Circular Path Tests

Pillar Z120

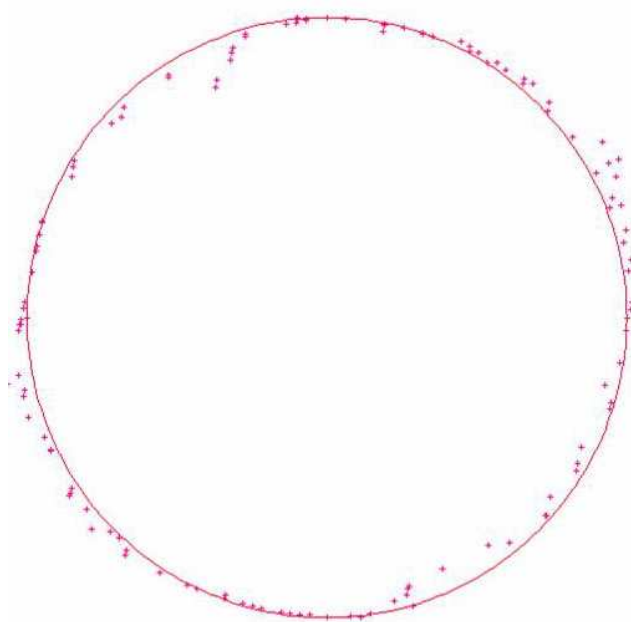


Figure E.1: Observation to Pillar Z120

Pillar 2

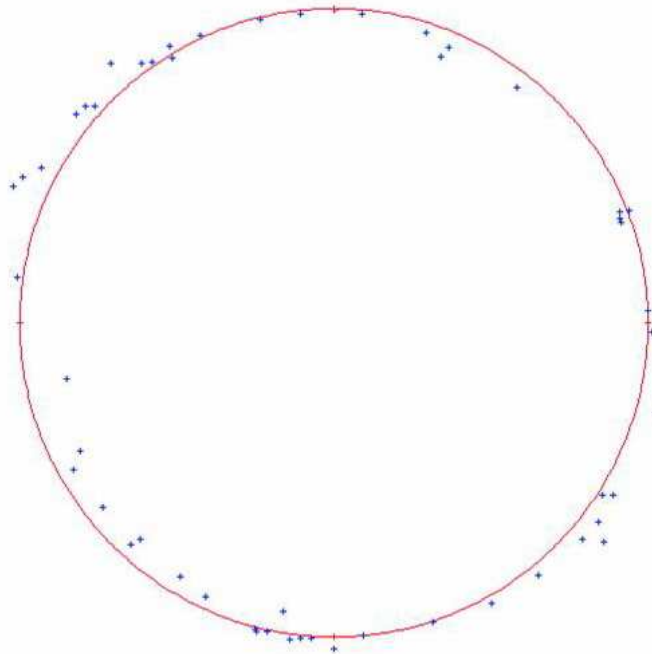


Figure E.2: Observation to Pillar 2

Pillar 4

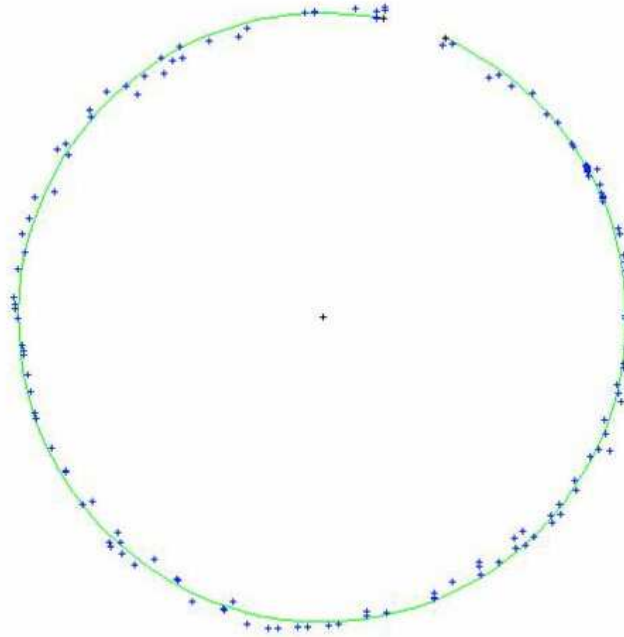


Figure E.3: Observation to Pillar 4

Pillar 5

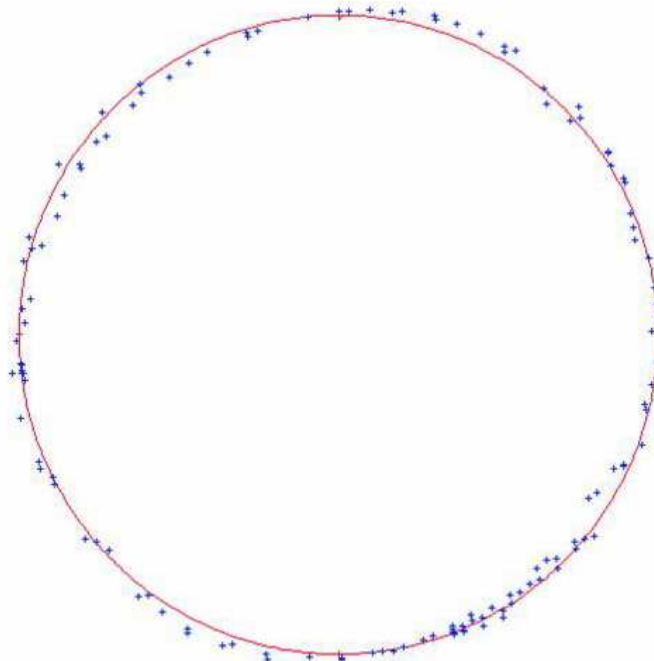


Figure E.4: Observation to Pillar 5

Part B: Straight Line Tests

Straight Line Test 1

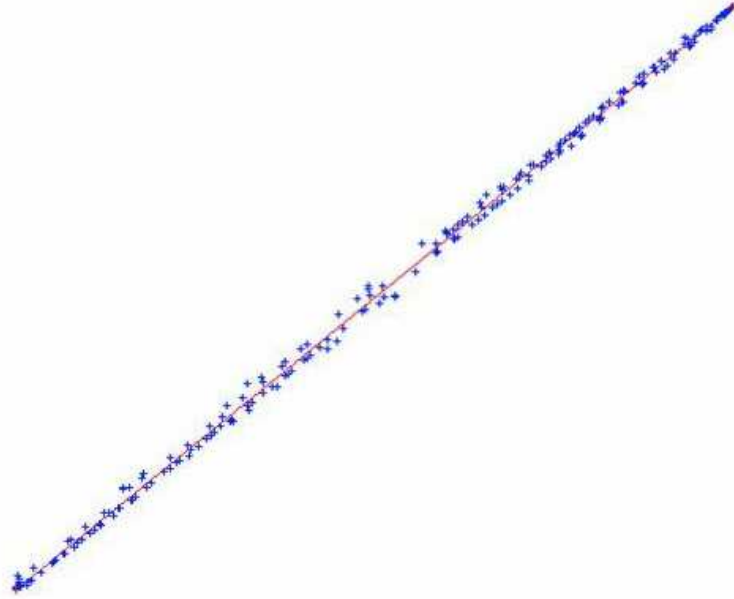


Figure E.5: Observation of Straight Line Test 1

Straight Line Test 2

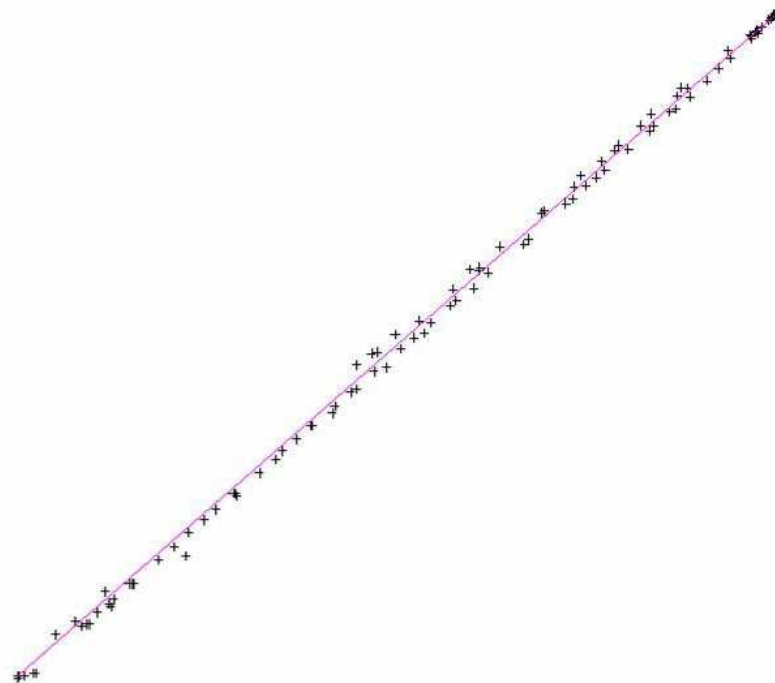


Figure E.6: Observation of Straight Line Test 2