Department of Spatial Sciences

Joker's Tunnel

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ABSTRACT

There has been rapid growth of Terrestrial Laser Scanners (TLS) in the surveying industry. Their purpose and use are now becoming wide and varied with applications in the mining industry becoming attractive for firms. This report will address some of the common errors that will occur whilst using a scanner in an underground mining environment.

A TLS is a useful piece of surveying instrumentation, however its' limitations in an adverse environment like an underground mine must be tested. The errors in such an environment can be caused by random, instrumental, surface material, geometry related and control configuration effects.

Different control configurations were tested to show the effect on the registration process with the TLS. A systematic angular error was found which caused the TLS to deviate from its true position. An error in the distance component was also found during the registration process. A traditional '3 peg test', usually observed with a total station, was conducted and found a systematic error caused by a discrepancy in the targets.

Due to the narrow nature of the tunnel the effect of a large incident angle is unavoidable. The irregular surface of the tunnel walls means this effect goes unnoticed. A controlled test was conducted on a flat wall which revealed as the incident angle increased the residual from the actual wall positioned increased. The errors are within the manufactures stated ± 4mm distance accuracy (Leica Geosystems, 2012), however they can still be quantified and modelled.

This report will hopefully allow for better understanding of the potential errors whilst using a TLS in an adverse environment, specifically underground mining. The recommendations are aimed to provide a guide for the best use of the TLS with regards to its limitations which will maximise the quality of data.

ACKNOWLEDGEMENTS

I would like to acknowledge all the mentors who attended the 2014 Murchison region expedition whose experience and guidance was extremely helpful. The expedition would not have been possible without the many sponsors of the expedition in particular Curtin University and Landgate.

Many thanks also goes to David Belton, the supervisor of this project, for his help with terrestrial laser scanning and a special mention to Sabrina Paes Leme for completing the scans of the test wall.

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1. INTRODUCTION

A Terrestrial Laser Scanner (TLS) is increasing becoming a viable tool in many aspects of surveying. Their use has become an affordable option for many surveying firms in completing such tasks as topographic surveys, dimensional control surveys, construction quality assurance and historical modelling. The mining industry has also recognized the potential benefits of TLS surveys over traditional methods. Like any new techniques being adopted there needs to be proof of its accuracy and viability.

The environment in an underground mine tunnel poses issues for surveying accuracy. The two main issues of underground surveying are; the restricted space and narrow nature of the tunnels, and the potential drift of a traverse where a closing connection cannot be made to a fixed station.

For TLS to become a useful tool its errors in such an environment must be quantified and the resulting limitations appreciated. Jokers Tunnel is being used as a case study to test the feasibility of using the TLS in an underground mining environment.

1. 1 Objectives

The primary objectives of this project are to first examine the control layout required to accurately position a survey in an underground mining tunnel with a terrestrial laser scanner. The second is to study the point cloud properties which are affected by the scanner geometry, such as the systematic errors caused by having a small incidence angle between the scanner and the walls of the tunnel.

2 BACKGROUND

The awareness of the errors associated with the terrestrial laser scanning are becoming more well-known with the publication of many studies. For the TLS to become a sustainable tool the errors and their resulting limitations need to be understood and appreciated.

When the angle of the laser beam from the TLS is non normal to the object surafce there can be bias in the position of the point. This bias is due to the low signal strength from an elongated return demonstated in Figure 1.

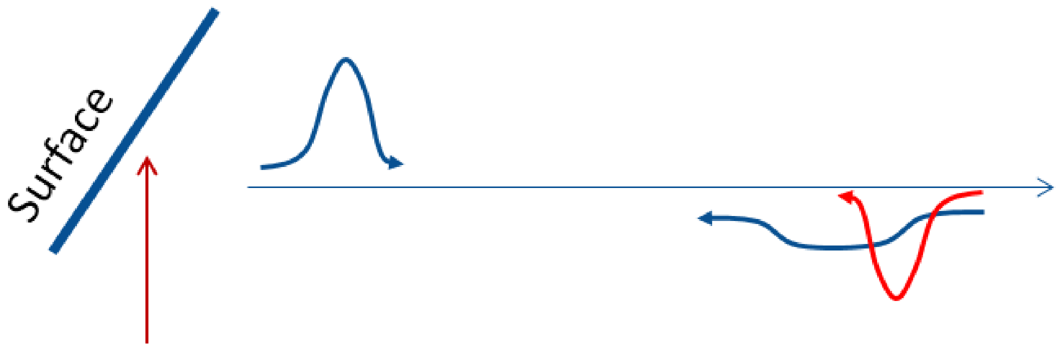

Figure 1: Bias Return from a High Incident Angle (Jones et al, 2014)

The errors in the point cloud properties in relation to the incidence angle have been previously documented. An earlier study, *"Error Models and Propagation in Directly Georeferenced Terrestrial Laser Scanner Networks"* (Lichti, Gordon, and Tipdecho, 2005) examined numerous data artifact errors unique to laser scanners and presented real data examples. The analysis of shape distortion from angular displacement errors caused by the non normal incidence angle of the laser beam are issutrated in Figure 2. The figure pictures the discrepancies between the scanned surface of a 400mm cycliner with the actually surface.

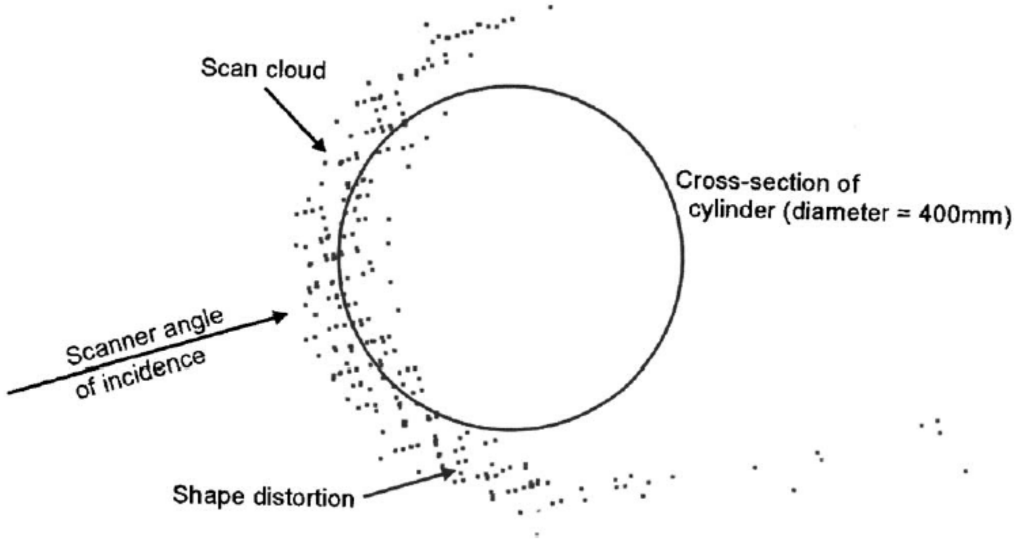

Figure 2: Shape distortion of TLS point cloud.

The effect of the incident angle can be modelled however the material of the surface can disrupt the analysis making finding the error difficult. These complications were found in a study completed at the Finnish Geodetic Institute; *"Analysis of Incidence Angle and Distance Effects on Terrestrial Laser Scanner Intensity: Search for Correction Methods"* (S. Kaasalainen, Jaakkola, M. Kaasalainen, Krooks and Kukko, 2011). Kaasalainen et al, (2011) found that analysing the effect of the incident angle was difficult with different target surface properties. As the walls of the tunnel are extremely irregular the demonstration of the incident angle effects could be jeopardised.

Further documentation was found in a study completed at Curtin University, "*3-Dimensional Boundary Connections*" (Buswell, 2012), where it was concluded that poor scanner geometry created significant errors in the point cloud due to the low incident angle the laser beam makes with the surface of an object. Bad geometry resulting in poor incidence angles is an unavoidable problem facing underground mining.

2. 1 Test Site

Every two years the Department of Spatial Sciences at Curtin University, in conjunction with industry partners, organizes an expedition for a group of surveying students. The expedition provides an opportunity for the students to explore remote parts of Western Australia with an interesting and usually historical surveying aspect.

The 2014 expedition took the students and their mentors through the Murchison Region. The sites identified for interesting projects included; Payne’s Find gold battery, Jokers tunnel, Austin town site, Walga Rock, Big Bell town site, Rabbit Proof Fence intersection and historic trig marks surveyed by John Forrest shown in Figure 3. Each site has different and diverse surveying tasks to be carried out with each student appointed in charge of one particular site.

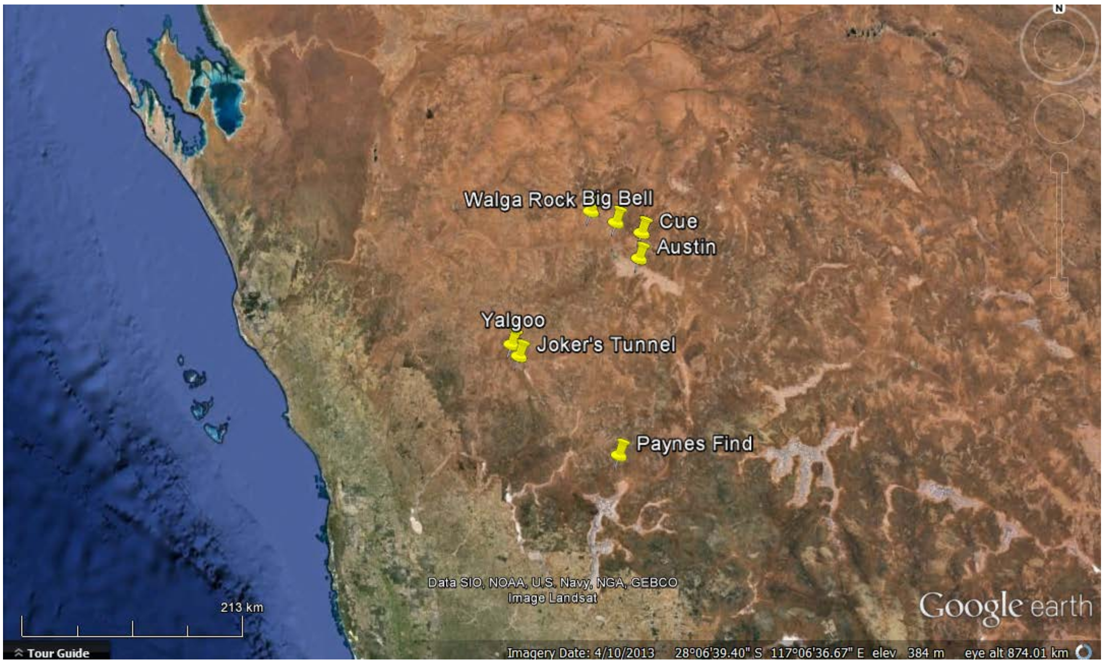

Figure 3: Project Sites on 2104 Murchison Region Expedition

Jokers tunnel is an old gold mining tunnel dug by early prospectors in the 1890's. It is situated approximately twelve kilometres south of Yalgoo, down Paynes Find Yalgoo road. The tunnel replicates an underground situation with dimensions of approximately 130 metres in length, rarely more than 2 metres in width and a varying height from the ground of 1 to 2 metres. Figure 4 pictures the TLS in the tunnel with the limited space available.

Figure 4: TLS in operation in the Tunnel

3 FIELD WORK PROCEDURE

The field work was broken into two stages of establishing the reference control followed by the scanning of the tunnel. The reference control is to be observed using the total station and GNSS receivers and will act as the ‘reference’ or ‘true’ position of each station. The scanning will be completed using the Lecia C10 terrestrial laser scanner and be compared to the reference control.

3. 1 Establishment of Control

The TLS operates in a plane grid with a scale factor of 1, thus the reference station coordinates must also be produced on a plane grid to allow for accurate comparisons. An arbitrary system was created with initial coordinates given to Stn 2 and an arbitrary north direction to Stn 1, shown in Figure 5.

The GNSS receivers were used to create three stations outside the tunnel which will be used for geo-referencing of the final model. The reference control through the tunnel was observed using the total station from the previously observed GNSS stations.

The total station observations were adopted for the reference stations over the GNSS data as it was observed with a scale factor of 1. The GNSS observations were made in a projection (MGA zone 50), therefore are distorted compared to the TLS observations

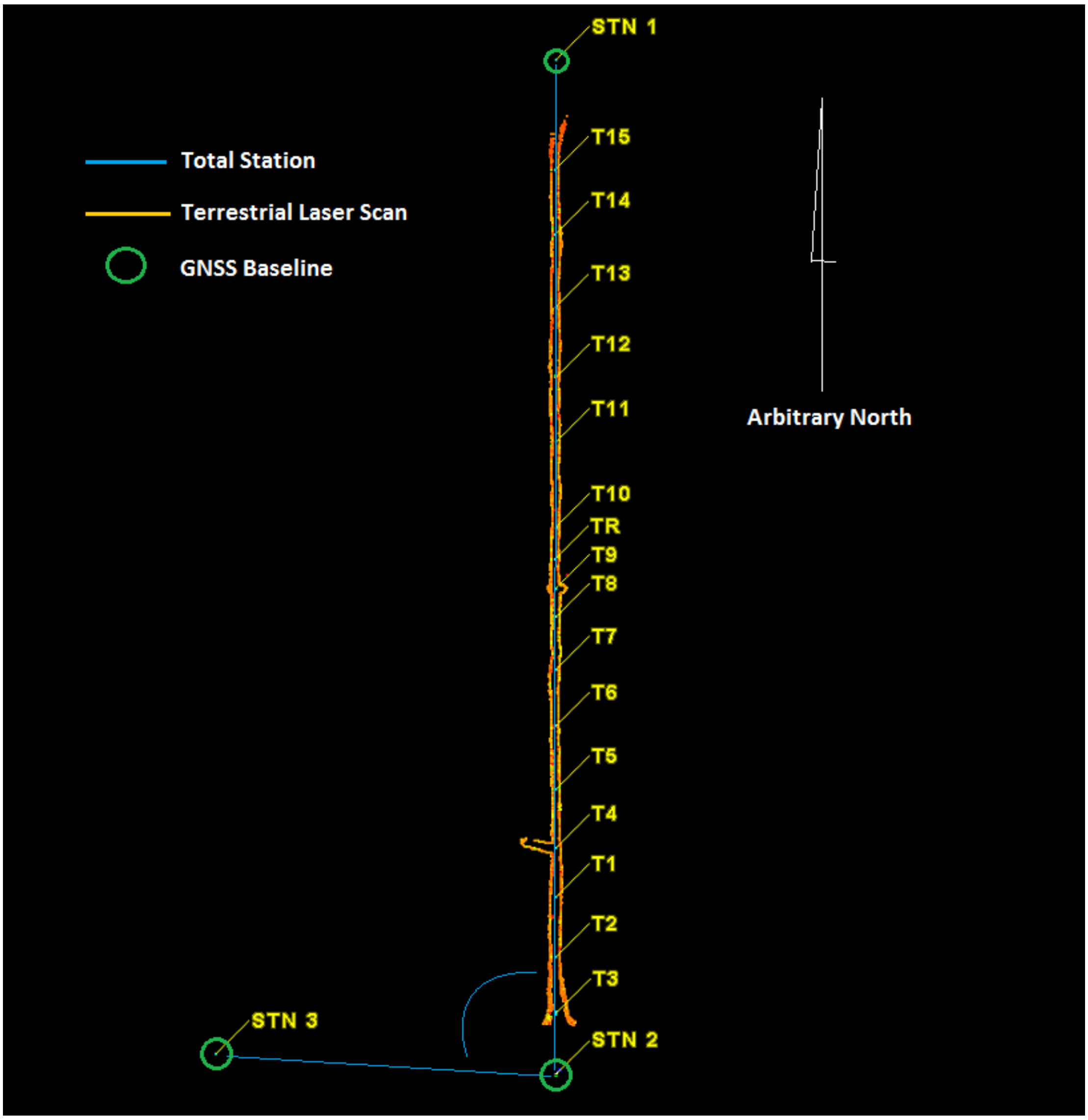

Figure 5: Control Layout

3.1.1 GNSS

<u>Equipment:</u>

- 6 x Trimble R10 Receivers
- Miscellaneous survey equipment
- Trimble Business Centre (version 3.21)

The Trimble R10 has a stated accuracy of ± 3mm for position and ± 5mm for vertical when using static mode.

Table 1: Accuracy Specifications of Trimble R10 (Trimble, 2014)

Static and Fast Static

Horizontal..+/-3 mm + 0.5 ppm RMS

Vertical..+/-5 mm + 0.5 ppm RMS

Three stations were established around the tunnel using static methods with the Trimble R10 receivers. These stations were connected to the existing geodetic network using Standard Survey Marks (SSM's) in the town of Yalgoo, namely Yalgoo 1, Yalgoo 26 and Yalgoo 144, shown in Figure 6. The reference marks of each SSM were located and used to verify the position and height of the primary mark. All marks were determined to be stable with the exception of the height at Yalgoo 1. The verification reports are shown on the SSM summary sheets in Appendix A.

The GNSS baselines were observed following the *'Guideline for GNSS Geodetic Surveys'* outlined by Landgate. The guidelines dictate, among other things, the minimum observing time and antenna orientation. The minimum observing time for each session is based on the distance between receivers and should be no less than 50 minutes plus 2 minutes per kilometre. The baselines were approximately 12 kilometres in length and therefore were set logging for a minimum of 1 hour and 14 minutes. While the antenna was orientated within 5 degrees of true north using a compass.

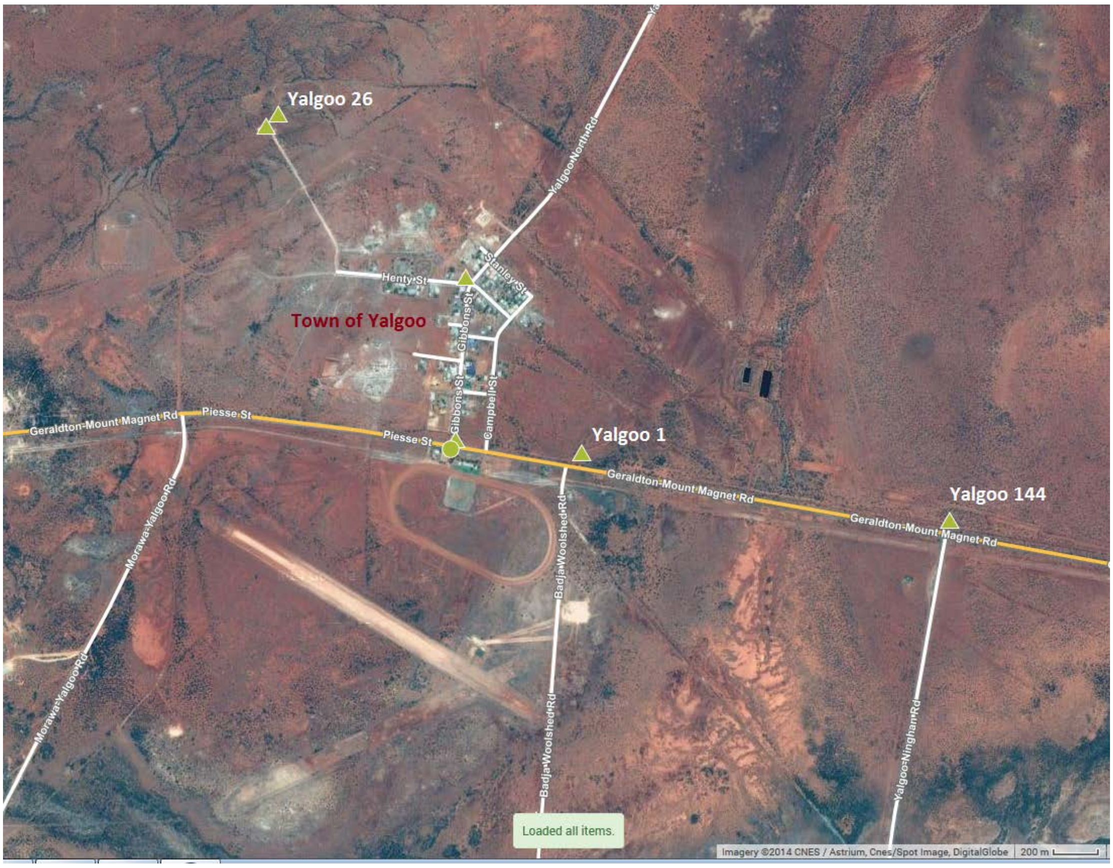

Figure 6: SSM locations around the town of Yalgoo

3.1.2 Total Station

Equipment:

- Leica TCR1103 Total Station (SN: 624706)
- Sokkia Prism Set
- Matlab R2013a (version 2001.9.20.0)

Reference stations (T1 – T15) were established on line between Stn 1 and Stn 2 approximately every 10 -15 metres through the tunnel. These stations were observed digitally using the Leica TCR1103 total station. Each of these reference stations will be occupied by the terrestrial laser scanner.

The stations were observed using the points on line technique due to time constraints and the narrow nature of the tunnel. Conducting a traditional traverse with the total station would require sets of angles to be observed at each station which would take significantly longer to observe and not necessarily provide any better results.

Table 2 demonstrates the angular and EDM accuracy of the Leica 1103 total station. Further checks of the EDM were completed to ensure its good working order as it was used to establish the reference stations.

Table 2: Accuracy Specifications of Leica TCR 1103 (Leica Geosystems, 2003)

Types	Accuracy Hz, V (ISO 17123-3)	Display (least count)
1101	1.5" (0.5 mgon)	1" (0.1 mgon
1102	2" (0.6 mgon)	1" (0.1 mgon)
1103	3" (1.0 mgon)	1" (0.5 mgon)
1105	5" (1.5 mgon)	1" (0.5 mgon)

EDM measuring programm	Accuracy **	Time per measurement
Standard measurement	2 mm + 2 ppm	1.0 sec.
Fast measurement	5 mm + 2 ppm	0.5 sec.
Normal tracking	5 mm + 2 ppm	0.3 sec.
Rapid tracking	10 mm + 2 ppm	< 0.15 sec.
Averaging	2 mm + 2 ppm	-----

** Beam interruptions, severe heat shimmer and moving objects within the beam path can result in deviations of the specified accuracy.)

The Landgate EDM baseline located at Curtin University was used to calibrate the EDM of the total station. The baseline is designed to quantify the three most dominant systematic errors in an EDM being; zero constant, scale error and cyclic error. Landgate is responsible for the maintenance and calibration of the baseline which was last completed in February 2014 (Landgate, 2014).

The results of the calibration dictate an instrument correction to be applied to each reading calculated as:

$$IC = -0.44 + 0.00288L$$

Where IC = instrument correction in millimetres and L = distance of the reading in metres. The '*EDM Calibrate Certificate*', shown in Appendix B, deems this correction insignificant and states the instrument satisfies the National Measurement institute standards.

3. 2 Scanning

Equipment:

- Leica C10 Laser Scanner
- Sokkia Prism Set with 3 inch scanning targets
- Cyclone (version 8.1.3)
- Matlab R2013a (version 2001.9.20.0)

The manufactures specifications are displayed in Table 3. The main values of interest are the ± 4mm distance and ± 6mm position accuracy.

Table 3: Accuracy Specifications of Leica C10 (Leica Geosystems, 2012)

System Performance	
Accuracy of single measurement	
Position*	6 mm
Distance*	4 mm
Angle (horizontal/vertical)	60 µrad / 60 µrad (12" / 12")
Modeled surface precision/noise**	2 mm
Target acquisition***	2 mm std. deviation
Dual-axis compensator	Selectable on/off, resolution 1", dynamic range +/- 5', accuracy 1.5"

All specifications are subject to change without notice.
All ± accuracy specifications are one sigma unless otherwise noted.
* At 1 m – 50 m range, one sigma
** Subject to modeling methodology for modeled surface
*** Algorithmic fit to planar HDS targets

A traverse with the scanner commenced from Stn 2 with a back sight at Stn 3. The traverse only occupied stations T1, T6, T9, T11, T13 and concluded at Stn 1. Resections were observed on the remaining stations using the traversed stations either side to orientate its position.

4 PROCESSING

4. 1 GNSS Control

The GNSS baselines are processed using Trimble Business Centre. The coordinate system was set to the MGA Zone 50 projection of the GDA94 datum with AusGeoid09 defined as the geoid.

The geometry of the network is bad with numerous elongated triangles. This situation could not be avoided as Jokers tunnel is remotely located and good quality control is sparse in the area.

A least squares adjustment was ran on the network in the TBC software. The adjustment was successful with the Chi Squared test passing at the 95% confidence level. Table 4 displays the adjusted coordinates of the three stations and their respective precisions. The precision of each station is slightly higher than the manufactures specification, this is due to the bad network geometry.

These coordinates will not be used during the analysis of the TLS data, rather to create a final geo-referenced model of the tunnel.

Table 4: GNSS Coordinates of Control Stations

Map Grid of Australia (MGA94) Zone 50 Coordinates			AHD
Station Name	**Easting (m)**	**Northing (m)**	**Height (m)**
Stn 1	475580.106	6853937.909	346.109
Standard Deviation (m)	0.015	0.015	0.008
Stn 2	475699.823	6854065.734	346.111
Standard Deviation (m)	0.015	0.015	0.009
Stn 3	475740.050	6854022.977	346.737
Standard Deviation (m)	0.015	0.015	0.009

4. 2 Reference Control

Matlab R2103a was used to calculate the coordinates of reference stations T1 – T15. The GSI file produced by the total station (Appendix C) was edited and imported into Matlab where the horizontal angle, zenith angle and distance observations were used to produce three dimensional coordinates of each reference station.

A list of the coordinates of the reference stations is shown in Table 5 below. With the exception of T4 at -0.003 metres each station is within 0.002 metres of the line between Stn 1 and Stn 2. The coordinates of the reference stations produced by the TLS will be examined against these coordinates to analyse any trends apparent.

Table 5: Reference Station Coordinates

Station	**Easting (m)**	**Northing (m)**	**Height (m)**	**Deviation from line (m)**
Stn 3	941.386	1003.713	100.625	
Stn 2	1000.000	1000.000	100.000	
T3	1000.000	1175.208	99.993	0.000
T2	999.999	1010.259	100.128	-0.001
T1	1000.000	1020.359	100.496	0.000
T4	999.997	1030.513	100.131	-0.003
T5	999.998	1039.153	100.209	-0.002
T6	999.998	1049.126	100.032	-0.002
T7	1000.001	1060.117	100.164	0.001
T8	1000.002	1069.928	100.177	0.002
T9	999.998	1078.926	100.326	-0.002
T10	999.999	1083.835	100.440	-0.001
T11	1000.000	1094.380	100.436	0.000
T12	1000.001	1109.085	100.760	0.001
T13	1000.001	1120.24	100.568	0.001
T14	999.999	1132.320	100.562	-0.001
T15	999.999	1144.904	100.670	-0.001
Stn 1	1000.000	1175.208	99.993	

4. 3 Cyclone

4.3.1 Registration Method

The processing of the TLS data was undertaken in the cyclone software. Each individual scan needs to be registered together for further analysis to take place.

The accuracy of the registration is a direct result of the constraints used to join the scanworlds together. The registration of scanworlds can be completed by either Target (tie point) constraints or Cloud to Cloud constraints. A successful registration needs to constrain the scanworld in all 6 degrees of freedom (Translation in X, Y and Z directions and rotation around the X, Y and Z axis). The six degrees of freedom are shown in Figure 7.

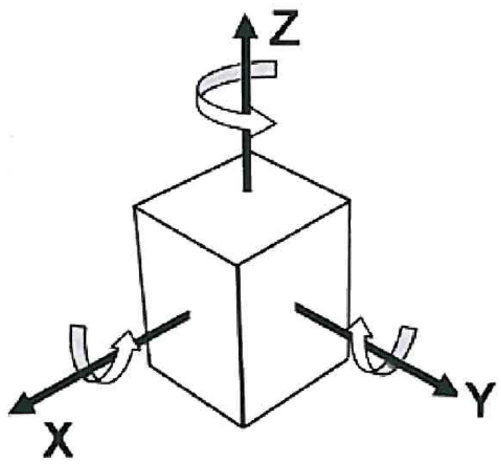

Figure 7: Six Degrees of Freedom (Leica Geosystems, 2008)

The target registration used the *'Auto – Add Constraints (Target ID – Only)'* function in cyclone. This function is used "When two ScanWorlds' ControlSpaces contain objects with the same Registration label, a constraint is automatically created, relating each of these object pairs" (Leica Geosystems, 2008, pp. 14). The 'Registration label' refers to the Target ID's given to each control station. Each scanworld contained at least one target which overlapped with another scanworld.

Cloud to Cloud registration works similar to the principle of target registration where there must be common 'objects' in the two scanworlds. The registration is possible when the point cloud of one scanworld overlaps with the point cloud of another scanworld.

The cloud to cloud registration can be conducted automatically using '*Auto – Add Cloud Constraints'* function. However this function can only be carried out after the initial alignment has been created via the target registration. The cloud to cloud constraints are used to enhance the target registration results. The registration of two scanworlds can be made by only the Cloud to Cloud constraints but only if all 6 degrees of freedom are defined. This is done by disabling all the target constraints leaving only the cloud to cloud constraints enabled.

4.3.2 Geo – Referencing

In an underground mining environment it is rare that you have the ability to close a traverse. This situation can be replicated by only making available certain reference control point to constrain the registration. The coordinates of the reference stations shown in Table 5 are imported as a scanworld into cyclone. This scanworld is set as the home scanworld and will constrain any scanworld which have the same 'Registration label', or in other words Target ID, as the imported coordinates.

Three different control situations have been created to test the coordinates produced by the TLS. The first is 'Full Control' which contains all calculated reference stations. 'First and Last' has the coordinates of Stn 1 and Stn 2 at either end of the tunnel only. Finally 'First and Bearing' has the coordinates of Stn 2 and Stn 3 both of which are located at the southern end of the tunnel.

Table 6 below shows the different registration methods used in conjunction with each control set out and the resulting RMS error and corresponding residual plot. As you can see the RMS values of the 'Full Control' situation are considerably lower than those from the 'First and Bearing' scenario. There is also a trend which shows that the Cloud to Cloud registration method has a better RMS than using the target constriants.

Table 6: Registration Method and Control Layout used with associated RMS Value.

RMS value (m)	Registration Method		Control Used		
Corresponding Figure	**Targets**	**Cloud to Cloud**	**First and Bearing**	**First and Last**	**Full Control**
0.0050	X				X
0.0042		X			X
0.0053	X	X			X
0.0087	X			X	
0.0065		X		X	
0.0071	X	X		X	
0.0445	X		X		
0.0374		X	X		
0.0480	X	X	X		

5 ANALYSIS OF ERRORS

Understanding and taking into consideration the limitations and accuracies of each instrument, any errors present in the survey can be analysed accordingly. The analysis of errors can be modelled even if they do not exceed the accuracies quoted form the manufactures specifications. The different control layout situations are analysed for any systematic errors while the instrument and geometry related errors are also examined.

5. 1 Comparison of Techniques

The total station observations are similar to the GNSS observations indicating no gross errors and present in the observations. When comparing the TLS observations it is evident that there is errors in the distance and angular components of the survey. The source of these errors (gross or systematic) will be investigated. Table 7 shows the comparison of the three methods.

Table 7: Comparison of Techniques

Observation	**Total Station**	**GNSS**	**TLS**
Distance from Stn 2 – Stn 1	175.208	175.201	175.181
Difference in Height Stn 2 – Stn 1	-0.007	-0.006	-0.122
Distance from Stn 2 – Stn 3	58.732	58.728	58.724
Difference in Height Stn 2 – Stn 3		0.625	0.595
Angle at Stn 2	86° 22’ 32”	86° 22’ 33”	86° 24’ 44”

5. 2 Control Layout Errors

5.2.1 Full Control

The plot of the residuals visually represents the variation in coordinates of the adjusted TLS position relative to the reference station. Figure 8 represents the residuals from a registration with ‘Full Control’ using only targets. The direction and size of the residuals is random with no trend visible. This indicates the source of the error is not systematic and is most likely to be random. Set up errors and general noise errors are the likely cause of the residuals.

Using ‘Full Control’ with targets produces a RMS value of 0.0050 metres.

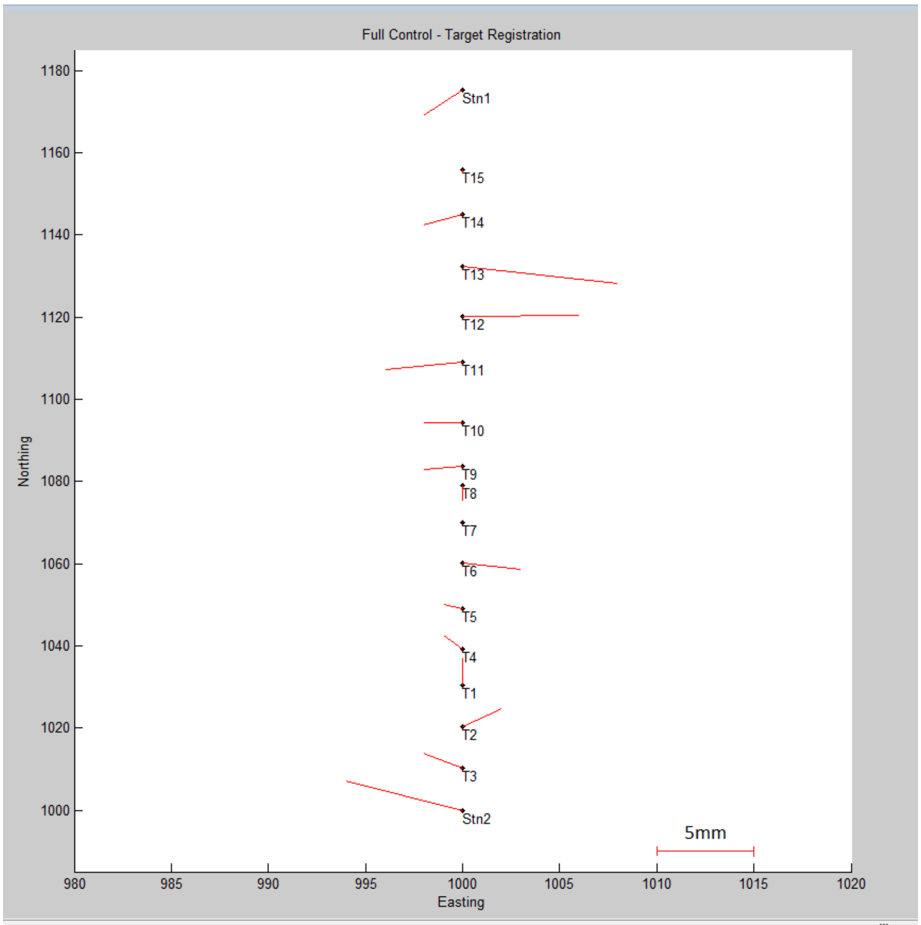

Figure 8: Residuals of Full Control Layout with Target Registration

5.2.2 First and Last

Figure 9 depicts the residuals when using the 'First and Last' registration method using targets only. The shape of the residuals seem to draw towards the middle of the tunnel while bowing towards the east. The end stations (Stn 1 and Stn 2) residuals pull directly towards each other. This indicates that there is an error in the distance component of the measurements.

The size of the residuals appear to be smaller at the beginnings of the tunnel and get larger towards the middle. This drifting trend is to be expected as the constraints fixing the registration are at either end of the tunnel. The RMS value of 0.0087 metres is larger than using 'Full Control'. Again this is to be expected as there is fewer constraints fixing the registration allowing drift to occur.

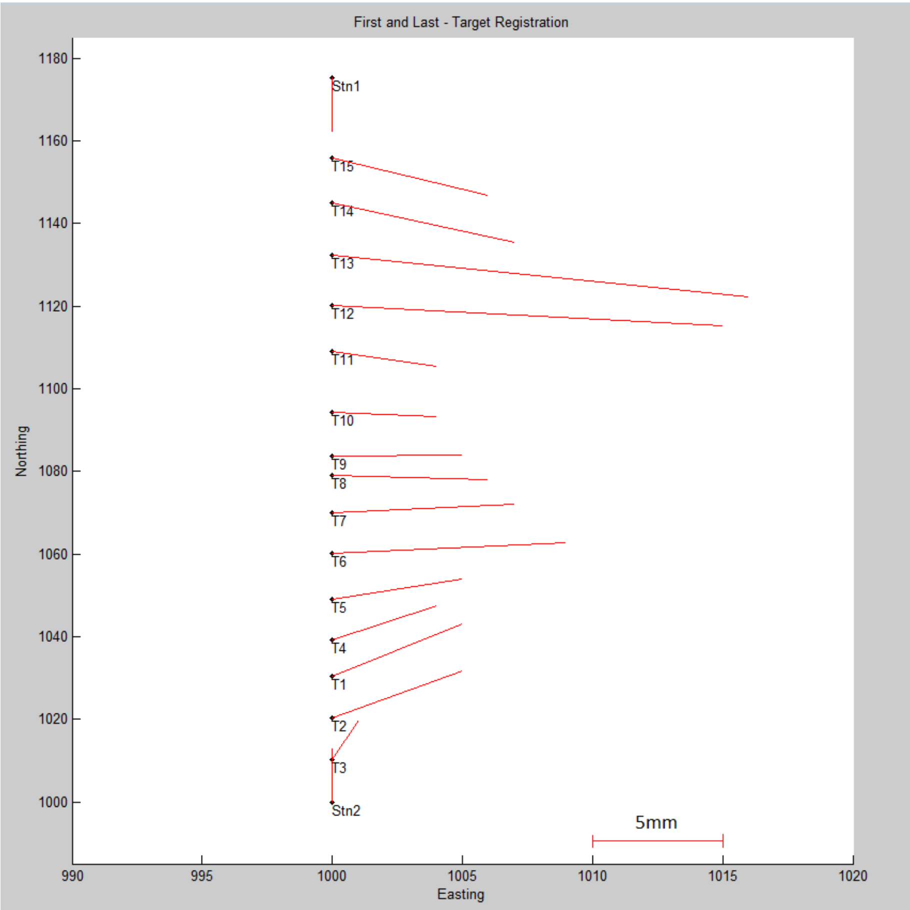

Figure 9: Residuals of First and Last Layout with Target Registration

5.2.3 First and Bearing

The ‘First and Bearing’ registration method using targets produced the residuals shown in Figure 10. These results are of most interest as it simulates the situation in an underground mine where a closing connection cannot be made to a fixed station.

The shape of the residuals shows a definitely trend increasing to the east indicating a systematic angular error. There is still evidence of error in the distance component as each residual pulls towards the constraint. The size of the residuals consistently increases the further away from the station used to constrain the registration.

This shows that an open ended traverse contains systematic errors which will lead the TLS to deviate from its actual position. There is a direct relationship between the distance of the traverse and the size of the error from its actual position. An RMS value of 0.0445 metres confirms the indication of significant errors.

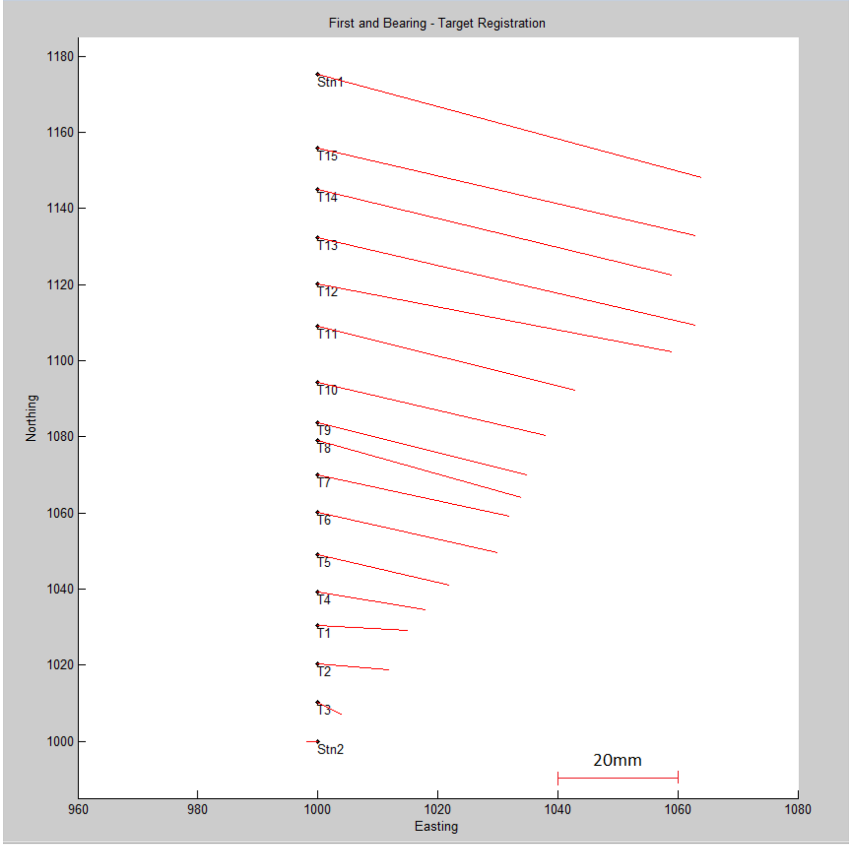

Figure 10: Residuals of First and Bearing Layout with Target Registration

5. 3 Offset Errors

The errors in the distance component were not expected before the survey was conducted. During the comparison of techniques it was discovered that the total station and GNSS observations agreed while the TLS observations did not. The error in the distance was examined by conducting a simple three station test. The benefit of having all reference points in a line means this test can be completed.

The three station test is typically used to test the prism constant applied in total stations. The test requires 3 stations in a straight line any distance apart, depicted in Figure 11. The instrument, in this case the TLS, is used to measure the distances A, B and C with a target. Assuming there are no errors present the distance B plus C should equal the total distance A.

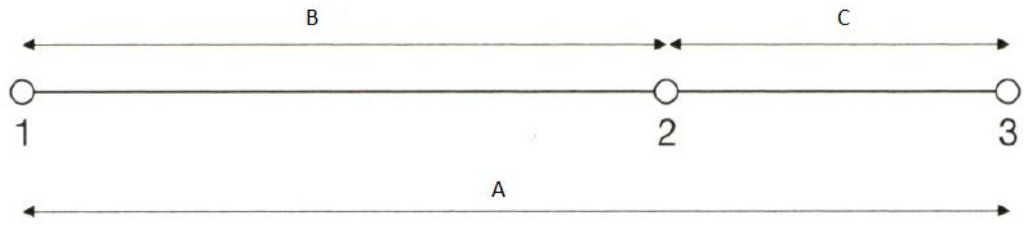

Figure 11: Three Peg Test Example (Caulfield, 2010)

In this situation the distance between the traverse stations (foresight or back sight) should equal the sum of the distances of one of the resection stations in between. Looking at the results of the three stations tests it showed there was an error in the same direction for each test. This error is always negative indicating it is systematic and results in the distance observed by the TLS being smaller than the actual distance. Examples of the three station test results are shown in Table 8.

Table 8: Partial Results of Three Peg Test

Station		Distance	A-B-C
From	To	(m)	
T3	T6	29.5935	
T3	T5	18.6069	-0.0038
T5	T6	10.9904	
T9	T6	23.7169	
T6	T8	18.8083	-0.0027
T8	T9	4.9113	
T13	T11	23.2303	
T11	T12	11.1558	-0.0030
T12	T13	12.0775	

The sum of all the three peg test errors is -0.026m, seen in Appendix D. This error was most likely caused by an error in the targets. When looking at the residuals from the registration using ‘First and Bearing’ with targets, Stn 1 has an error in the distance direction of -0.027m. Both errors are of similar magnitude confirming that there is indeed a systematic error in the targets.

5. 4 Incident Angle Errors

5.4.1 Analysis of Test Surface

In order to analyse the effect of the incident angle a local plane surface is created over the entire object surface. When creating this plane over the walls of the tunnel there is a large amount of noise due to the irregular surface. As a result the residuals from different scans will be drowned out and the effect of the incident angle less noticeable. For this reason a test was completed on a flat wall on the Curtin University campus with the Lecia C10 Scanner.

A local surface plane of 0.5 metre radius was created from the point cloud of Scan 4 to be used as a reference. This scan is the furthest from the wall and will have the least effect from the incident angle. Figure 12 shows the locations of each scan in relation to the flat wall.

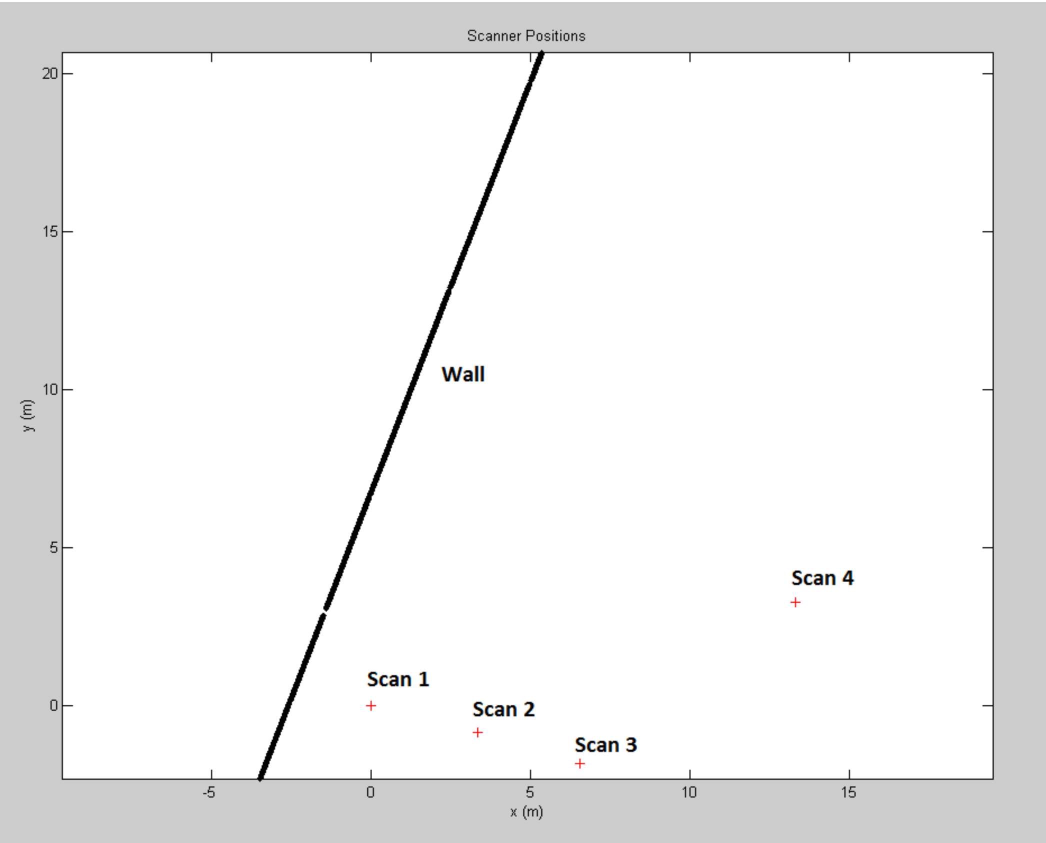

Figure 12: Location of Scans of the Flat Wall

The point cloud of the three other scans were compared to the plane surface created from Scan 4. The residuals are the distance the individual point is from the locally interpolated surface. The incident angle is the difference between the interpolated surface normal vector (V_1) and the vector toward the position of the scanner (V_2) calculated by:

$$cos^{-1}(\theta) = \frac{dot(V_1, V_2)}{\|V_1\|\|V_2\|}$$

Where θ = incident angle.

The plot of Scan 1 against the reference scan is displayed in Figure 13. A quadratic line of best fit has been plot to show the trend. The trend line indicates that as the incident angle increases there is an increase in the size of the residual.

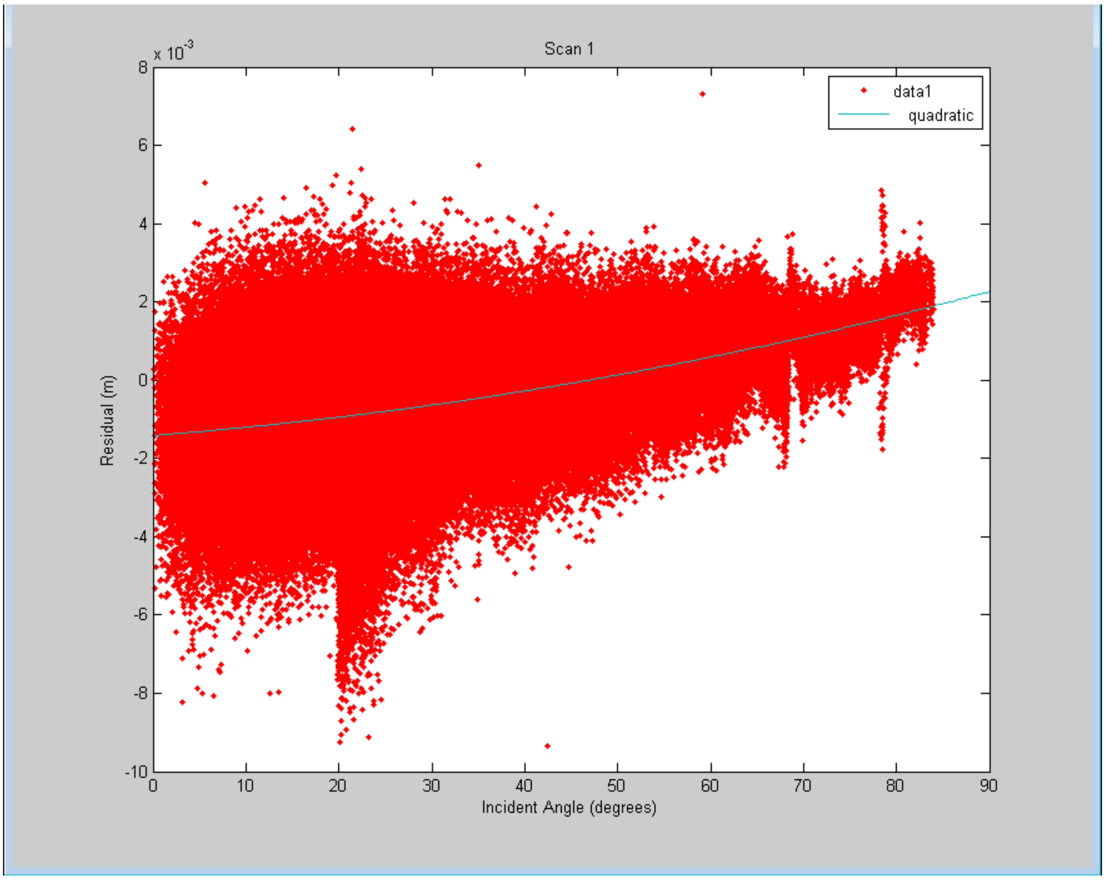

Figure 13: Plot of the Residuals against Incident Angles for Scan 1

The same trend where the residuals increase as the incident angle increases is evident in Scans 2 and 3 shown in Figures Figure 14 and Figure 15. The accuracies of the scanner previously mentioned in Table 3 quote a distance accuracy of ± 0.004 metres at range of 1 – 50 metres. This is why the residual values range from approximately -0.004 to 0.004 metres at each incident angle.

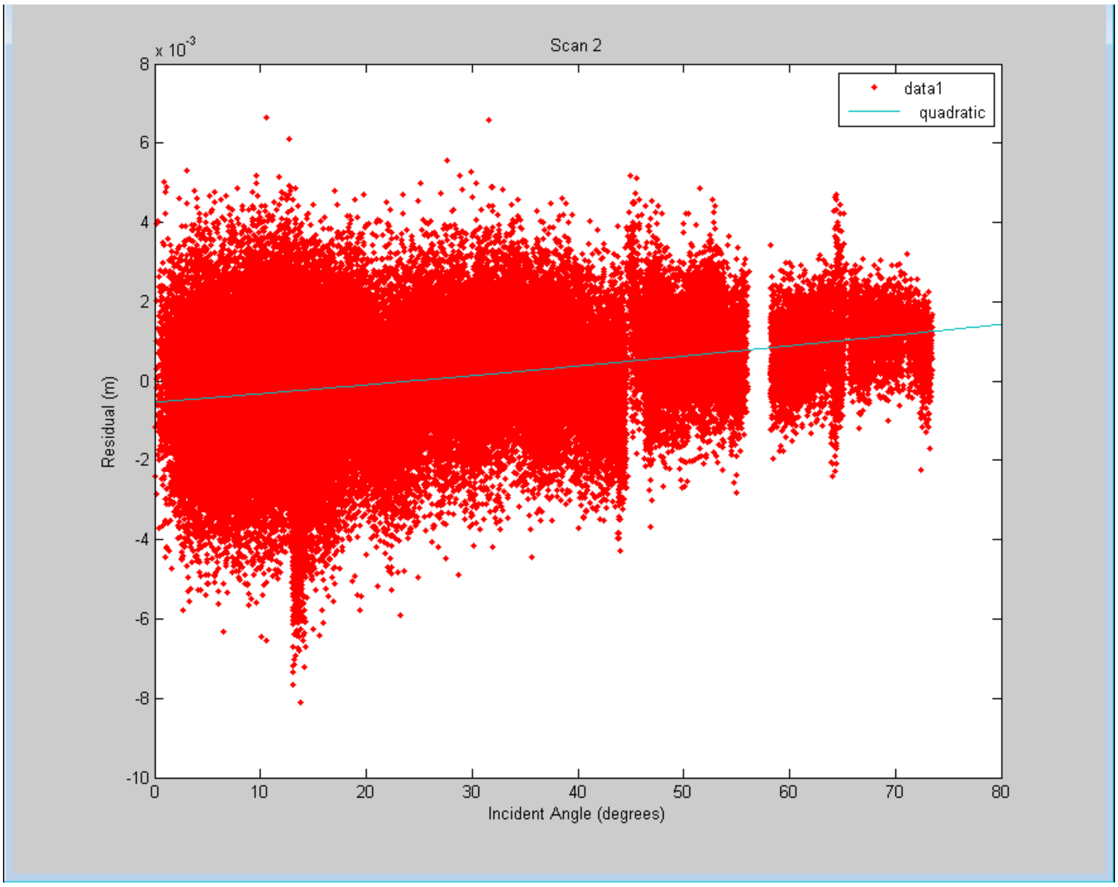

Figure 14: Plot of the Residuals against Incident Angles for Scan 2

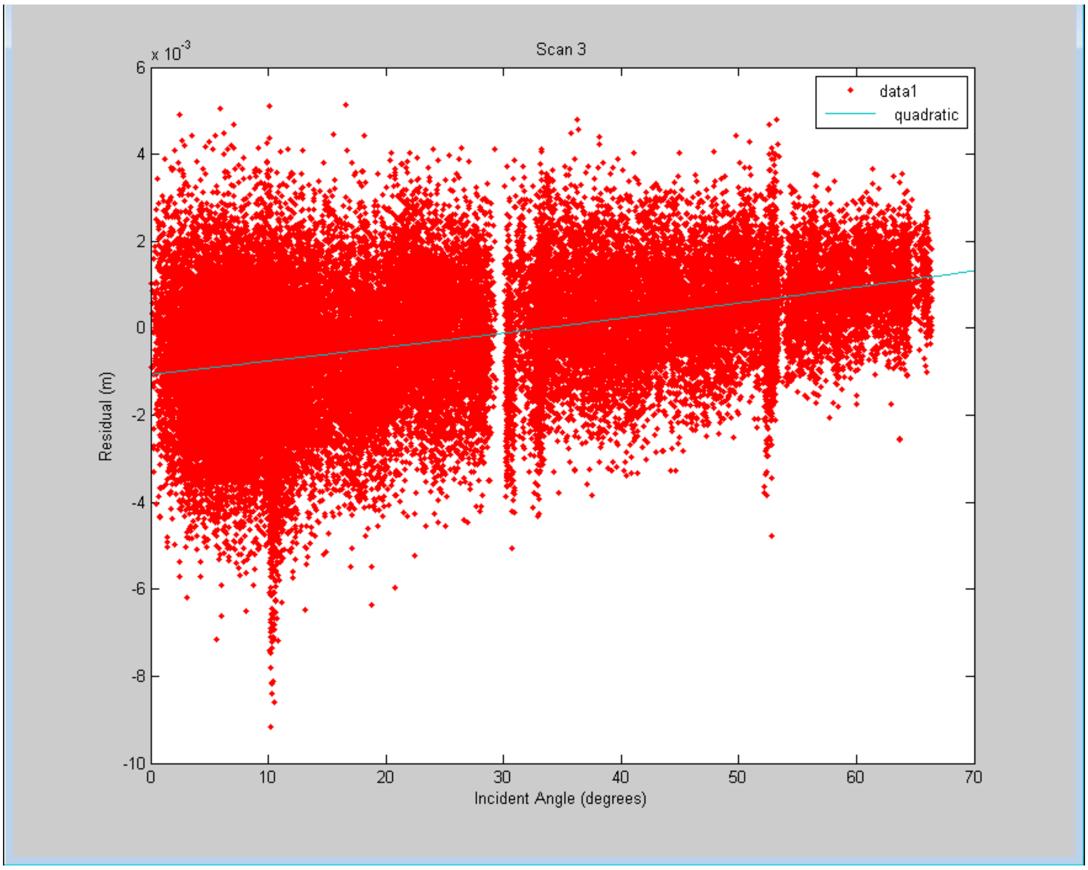

Figure 15: Plot of the Residuals against Incident Angles for Scan 3

The intensity values of each point in the scanner have been replaced with the residual values. The residuals range from -0.004 metres to 0.004 metres shown in the colour bar of each figure. The effect of the error is obvious with the residuals changing in colour from green to yellow / orange indicating they are increasing as the incident angle increases. The residuals in Scan 1 are larger due to the position of the scanner being the closest to the wall.

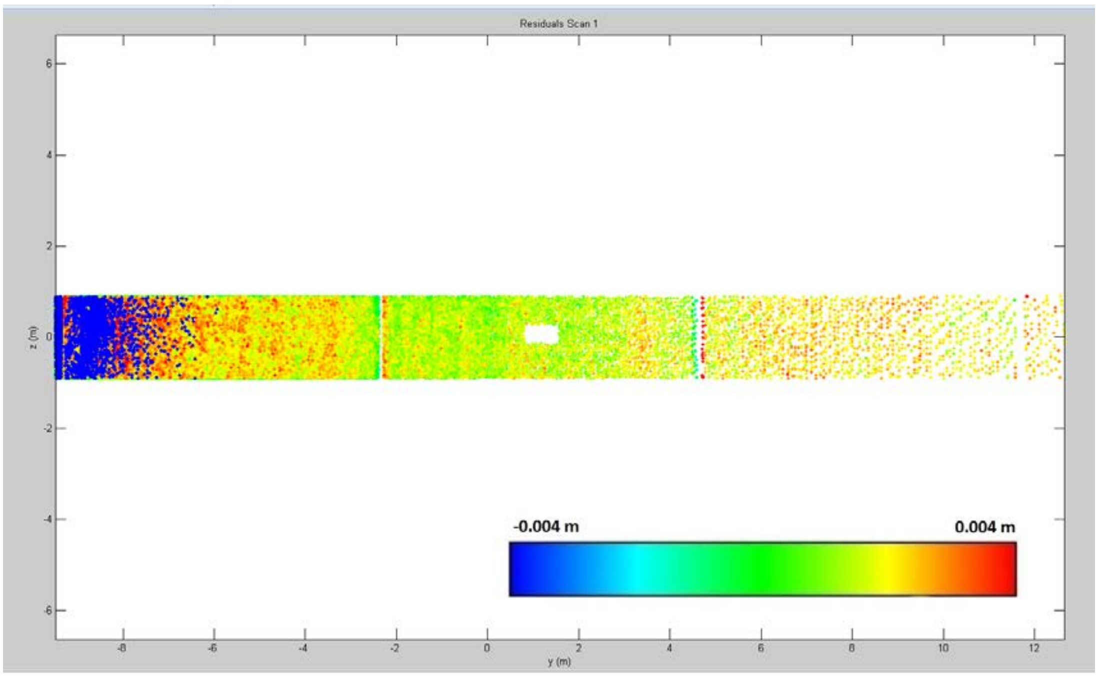

Figure 16: Residual Plot of Scan 1

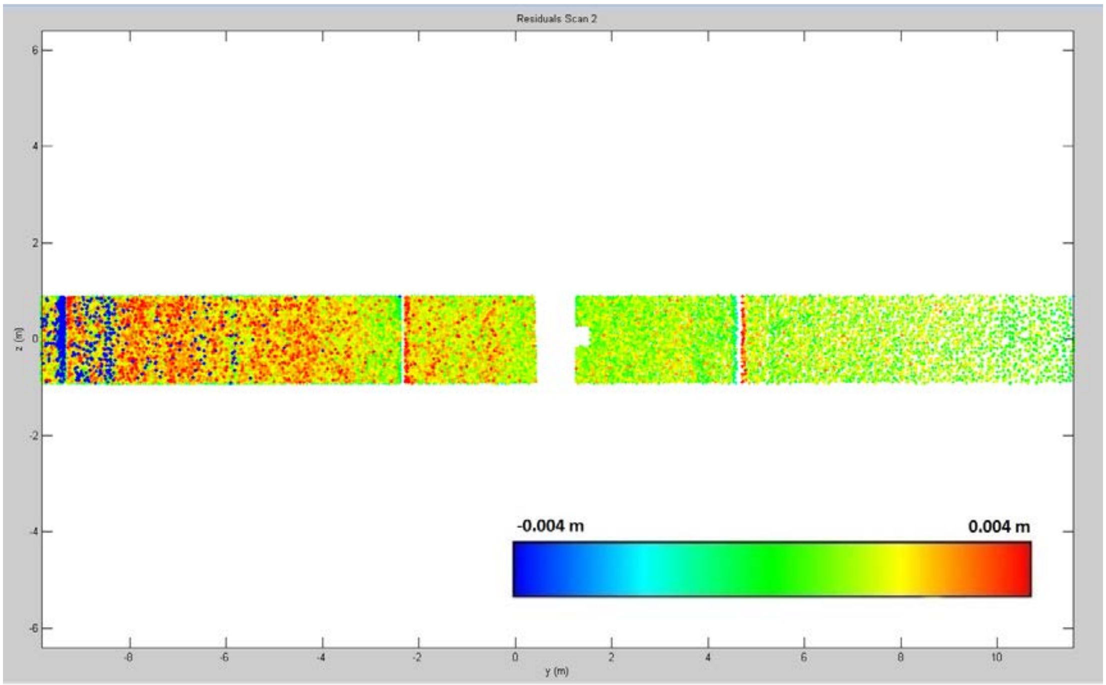

Figure 17: Residual Plot of Scan 2

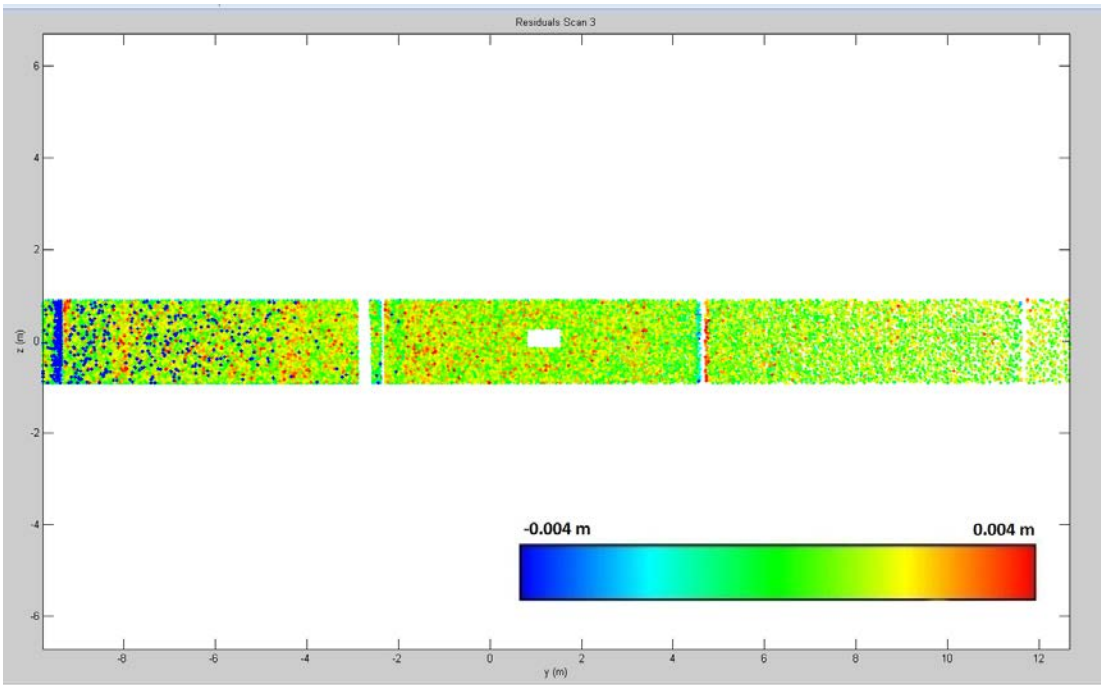

Figure 18: Residual Plot of Scan 3

5.4.2 Analysis of Tunnel

The irregualr surface of the tunnel made it hard to model the effect of the high incidnet angle. In the figures of the screen captures below there is a slight pattern showing smaller resisuals (blue) near the scanner postion and higher residuals (red) in between scanning postions. The effect is not consistent however, therefore a result cannot be confidently concluded.

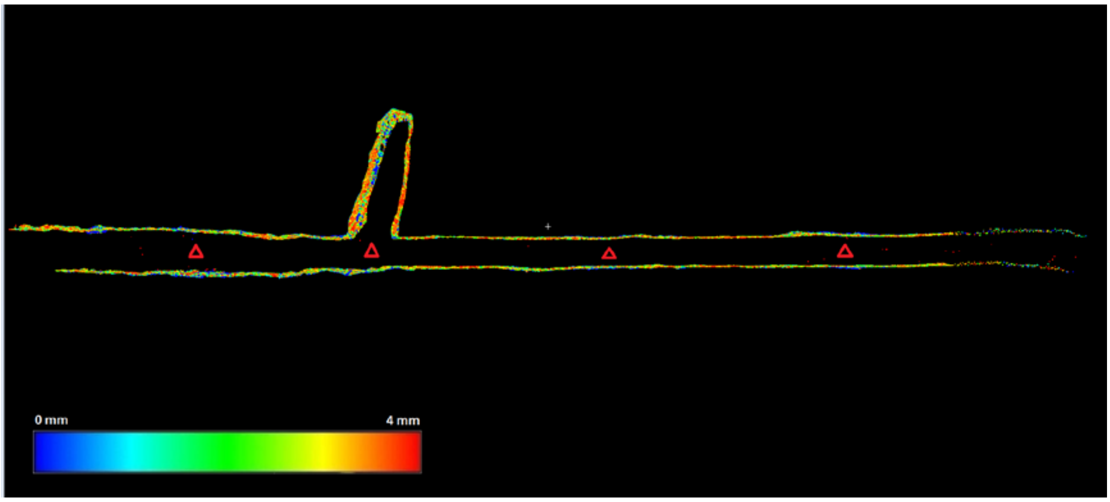

Figure 19: Residuals of Tunnel Wall - Screen Capture 1

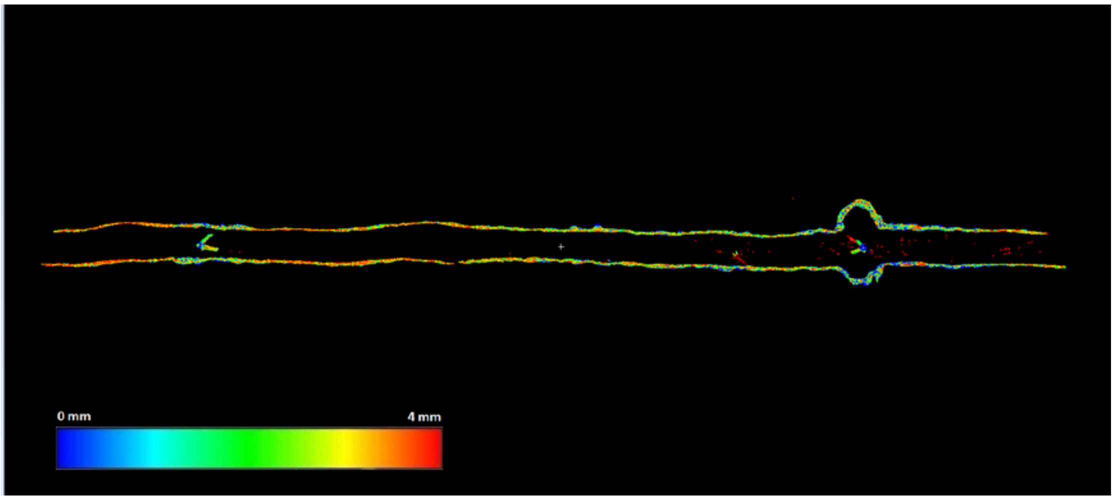

Figure 20: Residuals of Tunnel Wall - Screen Capture 2

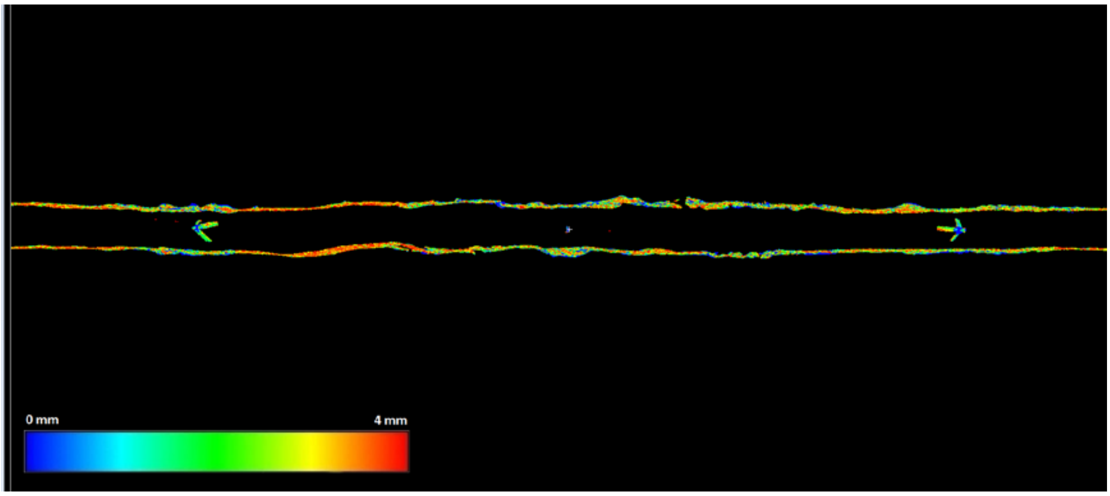

Figure 21: Residuals of Tunnel Wall - Screen Capture 3

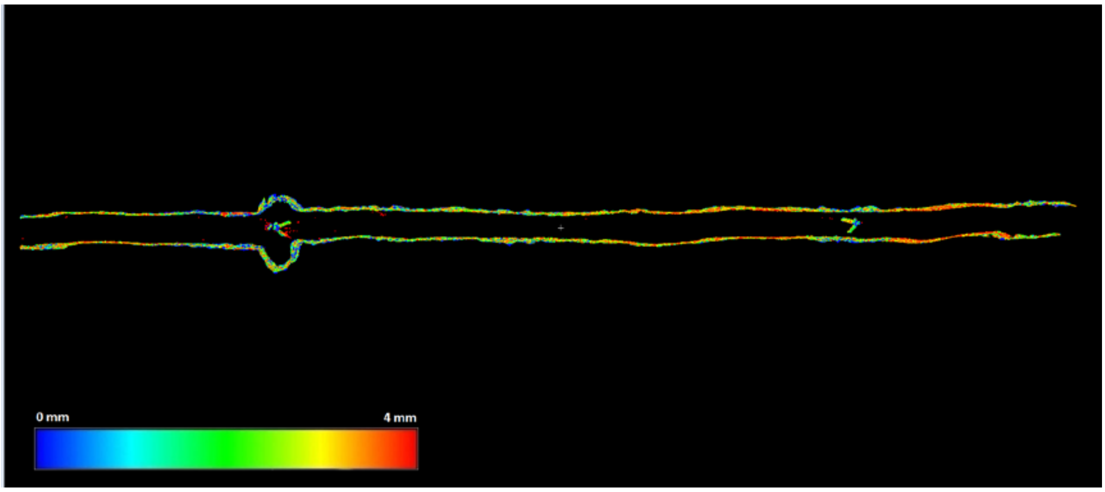

Figure 22: Residuals of Tunnel Wall - Screen Capture 4

6 CONCLUSION

The findings have demonstrated errors caused by instrumental, control configuration, geometry and registration methods.

The instrumental errors produced a discrepancy in distance of -0.026 metres over with a mean error of -0.0029 metres. This error was the main contribution to the difference in the reference station coordinates and scanner coordinates at Stn 1 with an open ended traverse.

The high the incident angle the laser beam makes with the object caused an error in the point cloud. The error was an increased divergence in the position of the wall from its true position the greater the incident angle. This effect was difficult to detect using the tunnel due to the undulation surface of the wall. The test scan on the flat wall revealed the error clearly with the residuals visibly increasing the higher the incident angle.

The systematic distance and angular errors were counteracted when implementing more constrains to the traverse. When fixing more control stations the magnitude of the errors decreased. The optimal situation was constraining every control point which left only the effects of random errors.

The registration method also played a part in the quality of the survey. When using the Cloud-to-Cloud registration method the RMS value of the registration decreased. This was evident in each different control layout showing that this was independent of the amount of constraints rather the type of constraints used.

6. 1 Recommendations

From the findings of this report it can be seen that although the amount of data collected by the TLS far exceeds traditional methods, the quality and accuracy of that data can be inconsistent. Without the proper controls and methodology the quality of the survey can be significantly diminished.

The calibration of the Lecia C10 scanner was not completed as part of this report. Further testing should be conducted to confirm the working order of the scanner before and sustainable recommendations can be made.

From this study some preliminary recommendations can be made about the use of the TLS in an underground mining situation. When using a TLS in such a situation a connection to a fixed station at either end of a traverse should be a minimum requirement. The errors created from an opened ended traverse were too significant to be overlooked. For tunnels of extremely small nature (less than 3m wide) the distance between scanner positions should be no less than 6 metres apart to avoid the effects of the high incident angle.

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APPENDIX A – SSM VERIFICATION SUMMARY

APPENDIX B – CURTIN BASELINE CALIBRATION - OBSERVATIONS AND CERTIFICATIES

APPENDIX C – TOTAL STATION GSI FILE

APPENDIX D – CALCULATION OF OFFSET ERRORS

APPENDIX E – GNSS BOOKING SHEETS

APPENDIX F – MATLAB CODE

22141

STANDARD SURVEY MARKS ACT, 1924

DB Number 114319

S.S.M. No. YALGOO 1

Department of
LAND ADMINISTRATION W.A.

DESCRIPTION OF MARK

☐ Standard Survey Mark set in concrete with steel / concrete hatch cover.

☒ Other MRD Brass Plaque set in concrete.

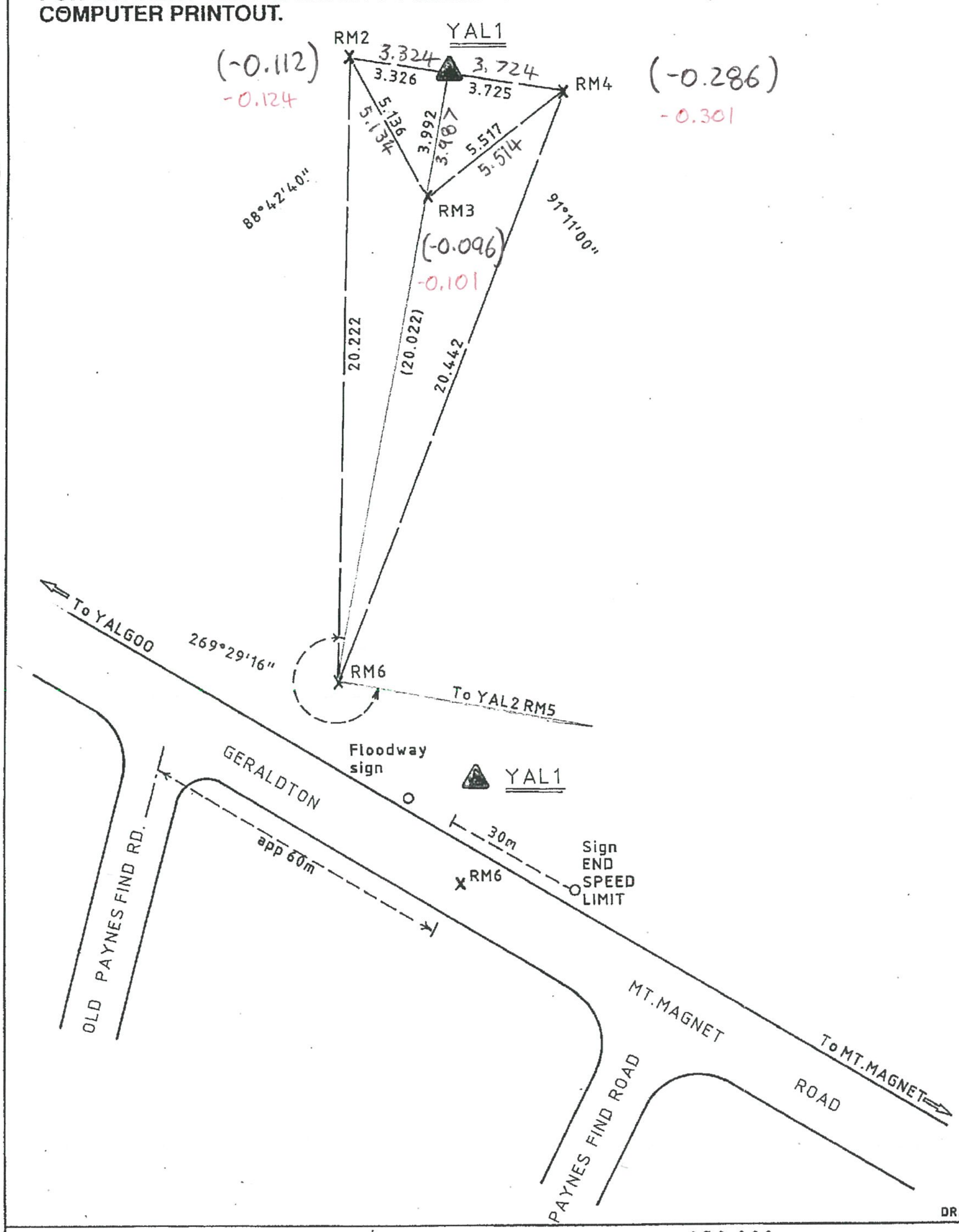
Stamped YAL1

Spike set in concrete R.M. 2,3,4

S.I.P. set in concrete R.M.

S.H.N. ~~Spike~~ in bitumen R.M. 6

FOR CURRENT VALUES REFER TO GESMAR COMPUTER PRINTOUT.



12.6.95

DRAWN: I.DIXON

Map Sheet: YALGOO H50/2 Scale 1: 250,000

18171

STANDARD SURVEY MARKS ACT,1924 | D.B.NUMBER | 109497

S.S.M. No. YALGOO 26

MULLYAKKO

Department of
LAND ADMINISTRATION W.A.

DESCRIPTION OF MARK

☐ Standard Survey Mark set in concrete with steel / concrete hatch cover. Stamped YAL 26

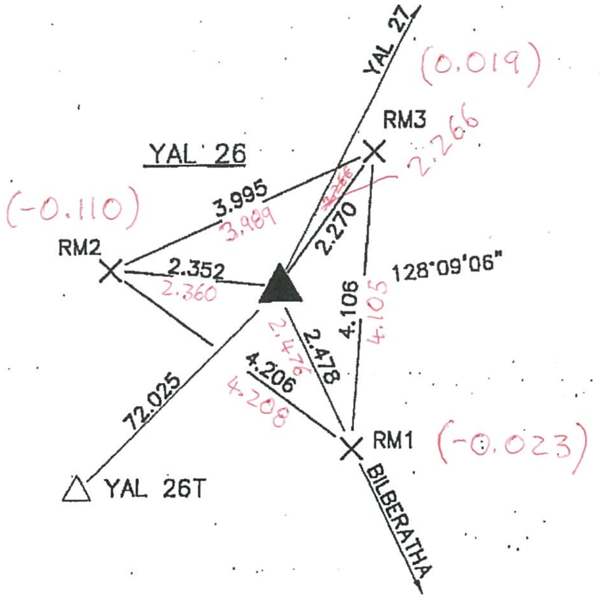
☒ Other Mines Dept. Brass Plaque set in concrete

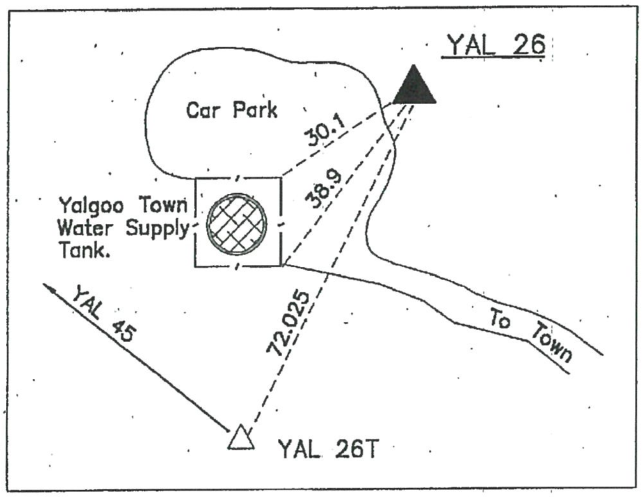
Spike set in concrete R.M. 1,2,3.

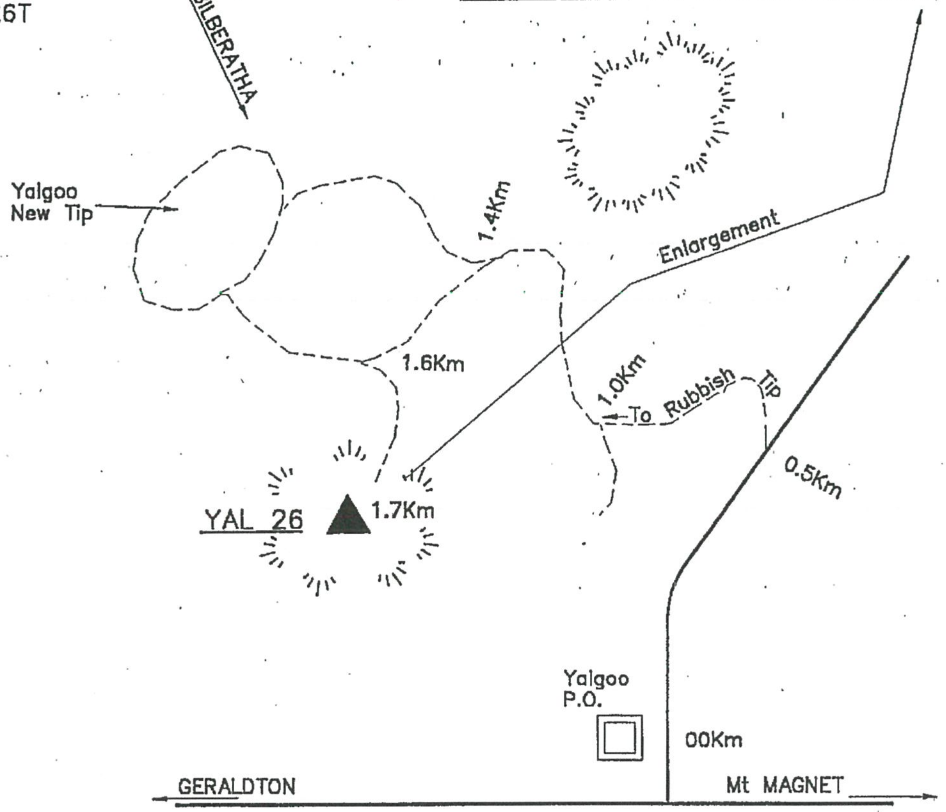
R.M.

Spike in bitumen R.M.

FOR CURRENT VALUES REFER TO GESMAR COMPUTER PRINTOUT







Provision of this access Summary by DOLA does not imply automatic right of entry onto Lands. The onus remains with the user to confirm entry requirements prior to use.

Drawn by: B.MAYNE

CKD Map Sheet : YALGOO H50-2 Scale : 1 : 250,000 Disk No.35

STANDARD SURVEY MARKS ACT,1924

DB NUMBER	13173219

Landgate

Western Australian Land Information Authority

Standard Survey Mark No. YALGOO 144

[X] Brass plaque set in concrete ~~with~~ ~~concrete~~ steel ~~hatch cover~~.

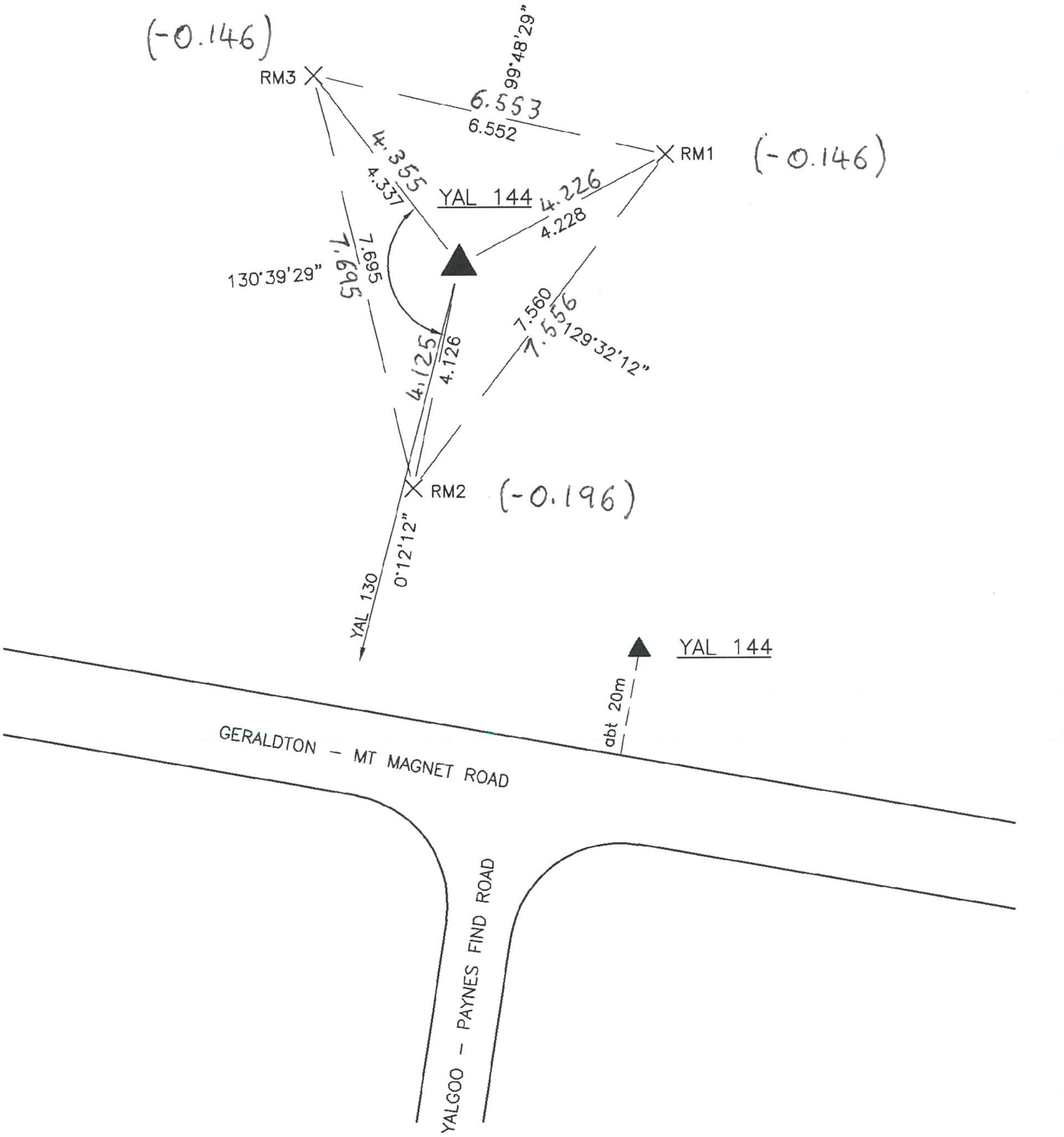
[ ] Other.

Stamped YAL 144

Spike set in concrete. RM 1,2,3

RM

RM



Provision of this access summary by LANDGATE does not imply automatic right of entry onto Lands. The onus remains with the user to confirm entry requirements prior to use.

Map Sheet YALGOO H50-2 Scale : 1:250 000

Job Identification: PhilExpedition

EDM Calibration Certificate

This report has been generated by program Baseline Version 6.1.0.3, developed by the Western Australian Land Information Authority.

Use of this application elsewhere should rely on baseline distances certified by the relevant authority.

Observation Date: 26/06/2014
Instrument Operator: Phil

Computation Date: 26/06/2014
Computation Time: 5:01:49 PM

Equipment Details

Instrument Owner: McMullen Nolan Group
Owner Address:
EDM Instrument Make: Leica
EDM Instrument Model: TCR1103
EDM Serial Number: 624706

Reflector Make: Leica
Reflector Model: GRZ4
Serial Number: 99999
Reflector Constant: 0 mm

Baseline Details

Name Curtin B 2013
Authority: Landgate
Authority Address: Midland WA

Location: Curtin University
Last calibration Date: 18/10/2013

This baseline consists of known lengths, which are the certified distances between the pillars of the baseline. All certified distances are on the same horizontal plane and on the same vertical plane running through the first and last stations.

The baseline has been calibrated in accordance with the NATA requirements which include the requirements of ISO/IEC 17025 and are traceable to the Australian National Standards of Measurement in accordance with Section 10 of the National Measurement Act.

Instrument Correction (IC) in mm (to be added to the instrument reading)

IC = -0.44 + 0.00288 L

Where L = distance in metres

The reflector constant has been entered into the instrument

CYCLIC ERRORS ARE INSIGNIFICANT

Calibration Parameters	Value	Uncertainty(95%)
Index	-0.44 mm	± 0.80 mm
Scale	(2.88×10^{-3} L) mm	±(1.94×10^{-3} L) mm
	where L = length in metres	

The instrument correction has been determined from measurements in the range of 143 to 540 metres

Job Identification: PhilExpedition

EDM Calibration Certificate

This report has been generated by program Baseline Version 6.1.0.3, developed by the Western Australian Land Information Authority.

Use of this application elsewhere should rely on baseline distances certified by the relevant authority.

Uncertainty of the Instrument Correction

Minimum standard for the uncertainty of calibration of an EDM instrument is ±(4.00 + 20.00 x 10^{-3} L) mm as described in terms of Recommendation No.8 of the Working Party of the National Standards Commision on the calibration of EDM Equipment of 1 February, 1983. All uncertainties are specified at the 95 % confidence level. A coverage factor of 2 has been used for the uncertainty computations.

Uncertainty of instrument correction: ±(0.80 + 1.94 x 10^{-3} L) mm where L = length in metres

Distance (metres)	Instrument Uncertainty (mm)	Minimum Standard (mm)	Comparison Test
50	±0.90	±5.00	PASS
100	±0.99	±6.00	PASS
200	±1.19	±8.00	PASS
300	±1.38	±10.00	PASS
400	±1.58	±12.00	PASS
600	±1.96	±16.00	PASS

This instrument satisfies the National Measurement Institute standards.

First Velocity Correction (Atmospheric Correction)

The atmospheric correction dial of the EDM instrument was set for all observations. Therefore the observed distances have already been corrected for atmospheric effects.

To obtain a regulation 13 Certificate for the purpose of legal traceability to the Australian standard of length contact the Verifying Authority responsible for length measurements in your State or Territory.

Data entry by: ....

Results checked by: ....

Position: ....

Position: ....

Signature: ....

Approved Signatory: ....

Date: ....

Date: ....

Instrument Pillar, Target Pillar, Slope Distance, Instrument Height, Target Height

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Jokers Tunnel GSI File

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006 359.59590 89.57010 230.394 00999.999 005230.394 10.229 1.629 1.616

Calculation of Offset Errors

From	To	Distance (m)		A-B-C (m)
T3	Stn 2	30.5109		
Stn 2	T1	10.2597		-0.0058
T1	T3	20.257		
T3	T6	29.5935		
T3	T4	8.6369		-0.0038
T4	T6	20.9604		
T3	T6	29.5935		
T3	T5	18.6069		-0.0038
T5	T6	10.9904		
T9	T6	23.7169		
T6	T7	9.8112		-0.0010
T7	T9	13.9067		
T9	T6	23.7169		
T6	T8	18.8083		-0.0027
T8	T9	4.9113		
T9	T11	25.2483		
T9	TR	5.1242		-0.0055
TR	T11	20.1296		
T9	T11	25.2483		
T9	T10	10.5451		-0.0003
T10	T11	14.7035		
T13	T11	23.2303		
T11	T12	11.1558		-0.0030
T12	T13	12.0775		
T13	Stn1	42.885		
T13	T14	12.5847		-0.0001
T14	Stn1	30.3004		
			Sum	-0.0260
			Avg	-0.0029

GNSS LOG SHEET

Job No. : Jokers Tunnel **Location:** Jokers Tunnel

Site Name Entered in Receiver: ____________ Ground Mark Description: S.I.P

Full Station Name: Station 1

Day / Date : Mon 30th June UT Day : 181 Session/s : 1

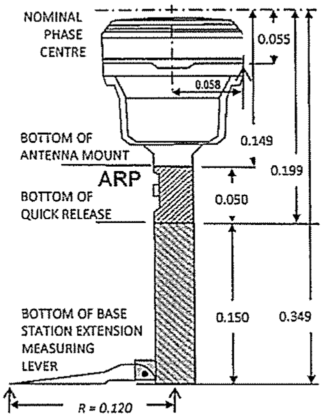
UT Start : 12:32 pm UT Finish : 2:50pm Session Length : ________ Minutes

Epochs set to: ________ Seconds. Antenna orientated to North? Y / N

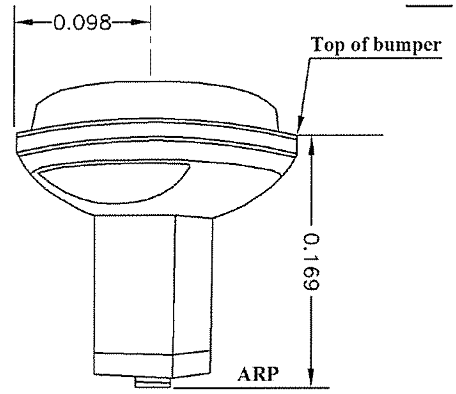
File Name: 85061810.T02 Operator Name: Phil Jones

EQUIPMENT DETAILS

Trimble TRMR10 ☑

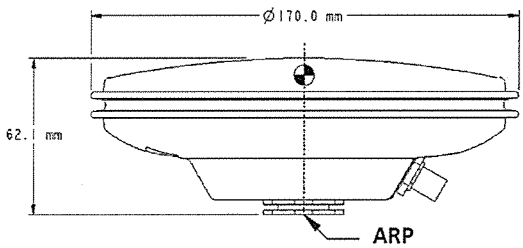


Leica LEIGS15 ☐

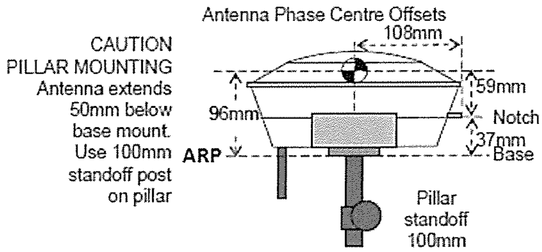


Skyhook + 0.2545 = ARP

Leica LEIAX1202GG ☐



Sokkia SOK_GSR2700ISX ☐



Antenna / Receiver Serial Number ______________ / 8506

MEASURING SKYHOOK / OFFSET TAPE

Measurement (Slant): 1.481 m ________ m

Radius: 0.120 m

Calc Vertical Ht : 1.476 m

SKYHOOK: ________ m

Offset to A.R.P: 0.200 m

Measured Height: 1.676 m ARP.

△ A.R.P. Heights: ________ mm

ARP (Enter into Receiver): ________ m

Entered in Receiver: Y / N

(Tick If) Antenna occupied main mark and site clear above 15 Deg. ☑
Show GNSS Network with Observing Sessions or Site Obstructions

Nil

Comments/Problems:

GNSS LOG SHEET

Job No. : Jokers Tunnel **Location:** Jokers Tunnel

Site Name Entered in Receiver: ________ Ground Mark Description: S.I.P

Full Station Name: Station 2

Day / Date : Mon 30th June UT Day : 181 Session/s : 1

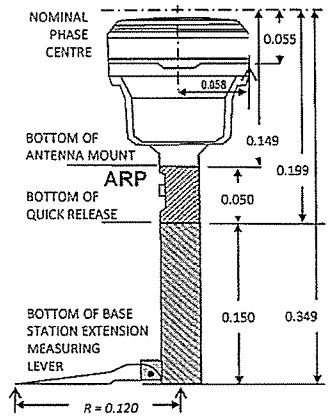
UT Start : 12:45pm UT Finish : 2:40pm Session Length : ________ Minutes

Epochs set to: ________ Seconds. Antenna orientated to North? Y / N

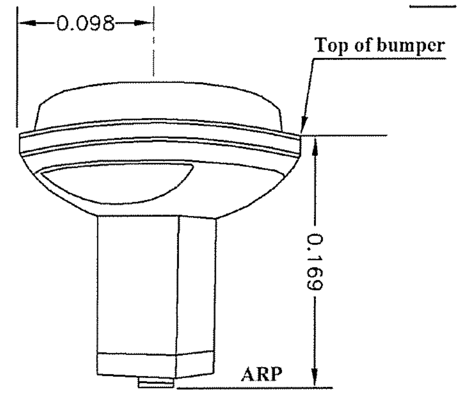
File Name: 4499181 Operator Name: Phil Jones

EQUIPMENT DETAILS

Trimble TRMR10 ☑

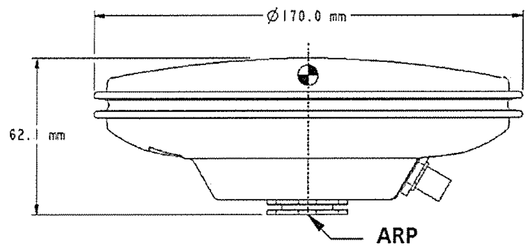


Leica LEIGS15 ☐

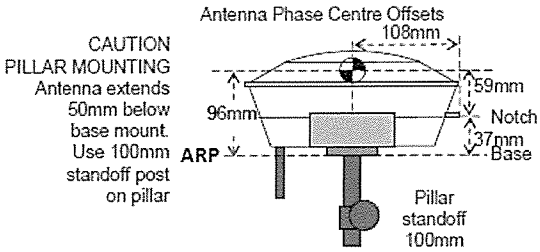


Skyhook + 0.2545 = ARP

Leica LEIAX1202GG ☐



Sokkia SOK_GSR2700ISX ☐



Antenna / Receiver Serial Number ________ / 4499

MEASURING SKYHOOK / OFFSET TAPE

Measurement (Slant): 1.620 m ________ m

Radius: 0.120 m

Calc Vertical Ht : 1.615 m

SKYHOOK: ________ m

Offset to A.R.P: 0.200 m

Measured Height: 1.815 m ARP.

△ A.R.P. Heights: ________ mm

ARP (Enter into Receiver): ________ m

Entered in Receiver: Y / N

(Tick If) Antenna occupied main mark and site clear above 15 Deg. ☑
Show GNSS Network with Observing Sessions or Site Obstructions

Nil

Comments/Problems:

GNSS LOG SHEET

Job No. : Jokers Tunnel Location: Jokers Tunnel

Site Name Entered in Receiver: ____________ Ground Mark Description: Spike

Full Station Name: Station 3

Day / Date : Mon 30th June UT Day : 181 Session/s : 1

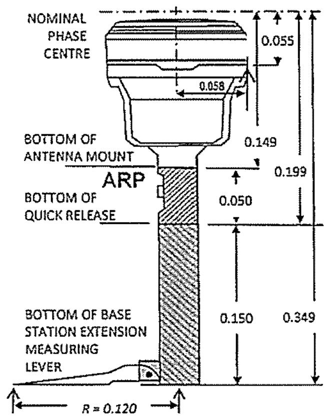
UT Start : 12:56pm UT Finish : 2:33pm Session Length : ________Minutes

Epochs set to: ________Seconds. Antenna orientated to North? (Y) / N

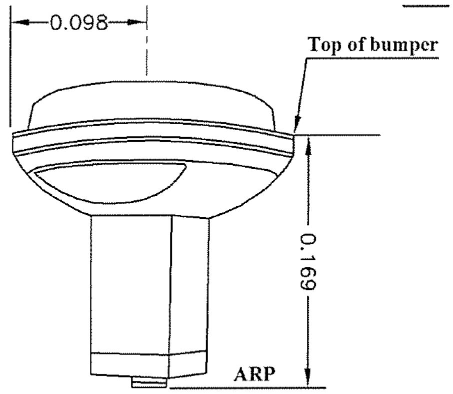
File Name: 55231810.T02 Operator Name: Phil Jones

EQUIPMENT DETAILS

Trimble TRMR10 ☑

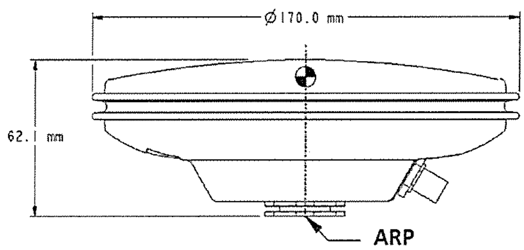


Leica LEIGS15 ☐

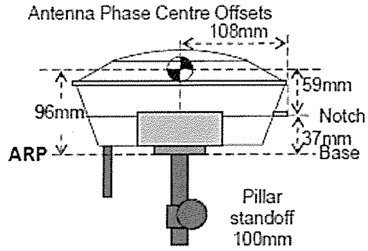


Skyhook + 0.2545 = ARP

Leica LEIAX1202GG ☐



Sokkia SOK_GSR2700ISX ☐



Antenna / Receiver Serial Number ____________ / 5523

MEASURING SKYHOOK / OFFSET TAPE

Measurement (Slant): 1.494 m ________ m

Radius: 0.120 m

Calc Vertical Ht : 1.489 m

SKYHOOK: ________ m

Offset to A.R.P: 0.200 m

Measured Height: 1.689 m ARP.

△ A.R.P. Heights: ________ mm

ARP (Enter into Receiver):________ m

Entered in Receiver: Y (N)

(Tick If) Antenna occupied main mark and site clear above 15 Deg. ☐
Show GNSS Network with Observing Sessions or Site Obstructions

Nil

Comments/Problems:

GNSS LOG SHEET

Job No. : Jokers Tunnel **Location:** Yalgoo

Site Name Entered in Receiver: ____________ Ground Mark Description: SSM - BRASS IN CONCRETE

Full Station Name: YALGOO 26 MULLYAKKO

Day / Date : 30/6/14 → MONDAY UT Day : 181 Session/s : ____________

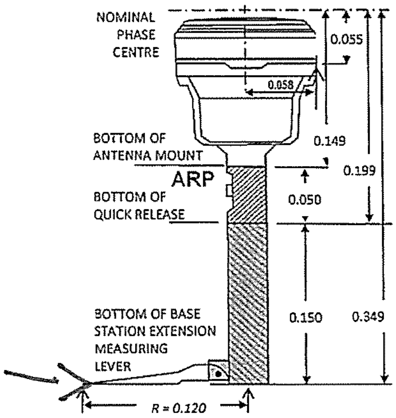
UT Start : ~~4:15~~ 4.20 UT Finish : 6.58 Session Length : 158 Minutes

Epochs set to: 15 Seconds. Antenna orientated to North? Y / N

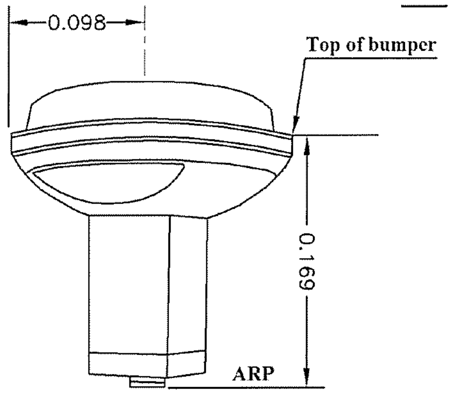
File Name: 79431810O Operator Name: Shane

EQUIPMENT DETAILS

Trimble TRMR10 ☒

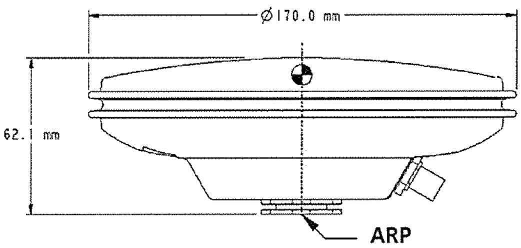


Leica LEIGS15 ☐

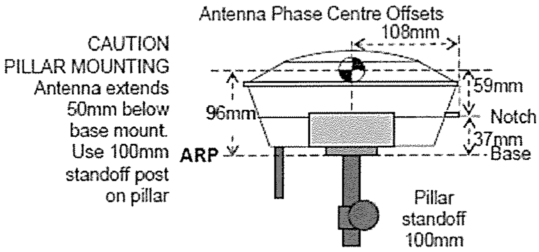


Skyhook + 0.2545 = ARP

Leica LEIAX1202GG ☐



Sokkia SOK_GSR2700ISX ☐



Antenna / Receiver Serial Number 5322437 / 943

MEASURING SKYHOOK / OFFSET TAPE

Measurement (Slant): ~~1.147~~ 1.417 m 1.417 m

Radius: __________ m

Calc Vertical Ht : ~~1.447~~ 1.442 m

SKYHOOK: __________ m

Offset to A.R.P: 0.2 m

Measured Height: __________ m ARP.

$\triangle$ A.R.P. Heights: __________ mm

ARP (Enter into Receiver): __________ m

Entered in Receiver: Y / N

(Tick If) Antenna occupied main mark and site clear above 15 Deg. ☐
Show GNSS Network with Observing Sessions or Site Obstructions

NIL

Comments/Problems:

GNSS LOG SHEET

Job No. : – Jokers Tunnel Location: Yalgoo

Site Name Entered in Receiver: – Ground Mark Description: Brass plaque

Full Station Name: Yalgoo 144

Day / Date : 30/06/14 UT Day : 181 Session/s : 1

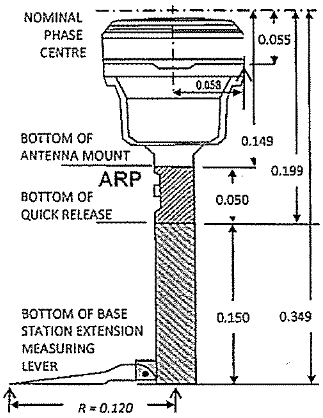
UT Start : 12:15 local UT Finish : 15:04 local Session Length : ________ Minutes

Epochs set to: - ________ Seconds. Antenna orientated to North? Y / N

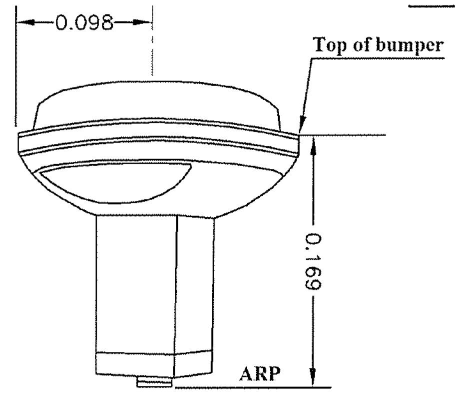
File Name: – Operator Name: Bjorn Skoog

EQUIPMENT DETAILS

Trimble TRMR10 ☑

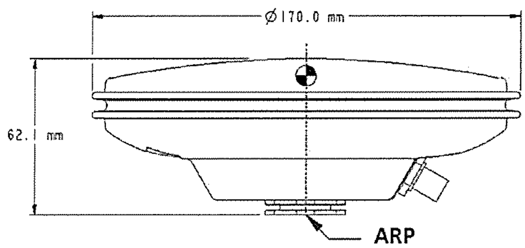


Leica LEIGS15 ☐

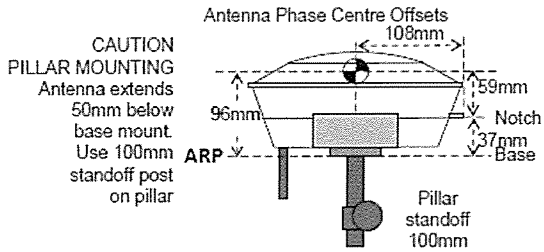


Skyhook + 0.2545 = ARP

Leica LEIAX1202GG ☐



Sokkia SOK_GSR2700ISX ☐



Antenna / Receiver Serial Number 13-03 / 5249419349

MEASURING SKYHOOK / OFFSET TAPE

Measurement (Slant): 1.307 m 1.308 m

Radius: 0.120 m

Calc Vertical Ht : ________ m

SKYHOOK: – m

Offset to A.R.P: 0.200 m

Measured Height: ________ m ARP.

△ A.R.P. Heights: ________ mm

ARP (Enter into Receiver): ________ m

Entered in Receiver: Y / N

(Tick If) Antenna occupied main mark and site clear above 15 Deg. ☑
Show GNSS Network with Observing Sessions or Site Obstructions

height measured to extension lever

Nil

Comments/Problems:

GNSS LOG SHEET

Job No.: Jokers Tunnel Location: Yalgoo

Site Name Entered in Receiver: ~ Ground Mark Description: Brass plaque

Full Station Name: Yalgoo 1

Day / Date: 30/06/2014 UT Day: 181 Session/s: 1

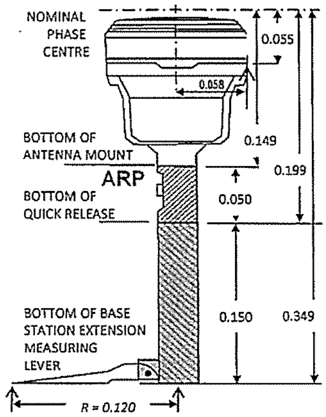
UT Start: 13:00 local UT Finish: 14:52 local Session Length: 112 Minutes

Epochs set to: ________ Seconds. Antenna orientated to North? Y / N

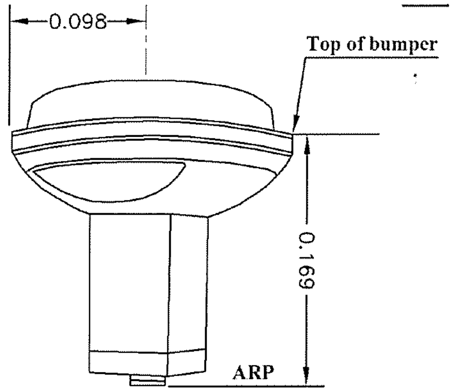
File Name: - Operator Name: Geoff Robb

EQUIPMENT DETAILS

Trimble TRMR10 ☐

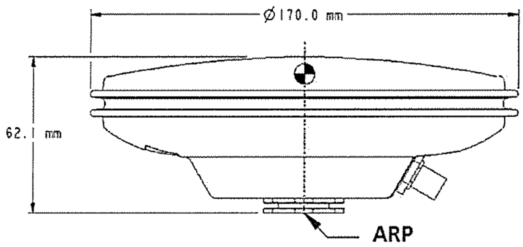


Leica LEIGS15 ☐

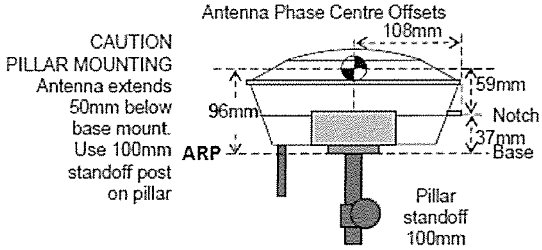


Skyhook + 0.2545 = ARP

Leica LEIAX1202GG ☑



Sokkia SOK_GSR2700ISX ☐



Antenna / Receiver Serial Number 06210050 / 1351337

MEASURING SKYHOOK / OFFSET TAPE

Measurement (Slant): - m - m

Radius: - m

Calc Vertical Ht: ~~1.546~~ m

SKYHOOK: 1.186 m

Offset to A.R.P: 0.360 m

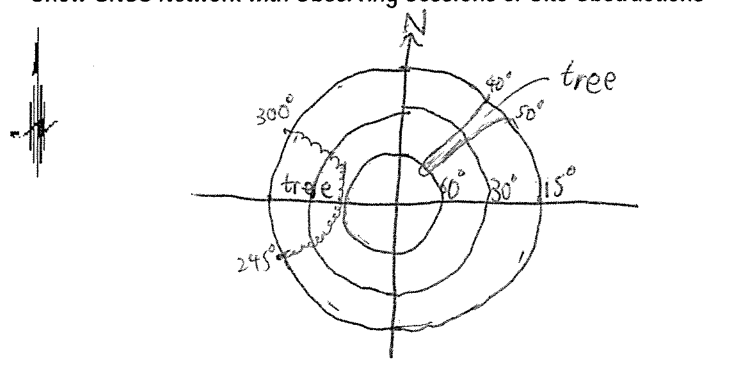
Measured Height: 1.546 m ARP.

△ A.R.P. Heights: ________ mm

ARP (Enter into Receiver): ________ m

Entered in Receiver: Y / N

(Tick If) Antenna occupied main mark and site clear above 15 Deg. ☑
Show GNSS Network with Observing Sessions or Site Obstructions



Comments/Problems:

Matlab Code

```
clear

pts_1 = load('E:\Uni\Year 4 Sem 1\Expedition\GSI Jokers\Wall\Scan1.pts');
pts_2 = load('E:\Uni\Year 4 Sem 1\Expedition\GSI Jokers\Wall\Scan2.pts');
pts_3 = load('E:\Uni\Year 4 Sem 1\Expedition\GSI Jokers\Wall\Scan3.pts');
pts_4 = load('E:\Uni\Year 4 Sem 1\Expedition\GSI Jokers\Wall\Scan4.pts');

s1 = [0,0,0];
s2 = [3.326, -0.842, 0.071];
s3 = [6.547, -1.818, 0.131];
s4 = [13.311, 3.288, 0.077];



cov_m = cov(pts_4(:,1:3));
[vi,ei] = eig(cov_m);
[v,e] = pc(vi,ei);
translation = mean(pts_4(:,1:3));
rotation = [v(:,1)';v(:,3)';v(:,2)'];

%create tree
[tmp, tmp, TreeRoot] = kdtree(pts_4(:,1:3), []);

nn_rad = 0.25;
fprintf(1,'First run through:\n');
per = 0;
fprintf(1,'\t%3d',per);
pts_1 = pts_1(1:20:size(pts_1,1),:);
res_1 = zeros(size(pts_1,1),1);
for idx=1:size(pts_1,1)

    if(floor(idx*100/size(pts_1,1)) > per)
        per = floor(idx*100/size(pts_1,1));
        fprintf(1,'\b\b\b%3d',per);
    end

    clear nn_pts
    clear nn_dist
    clear nn_idx
    [nn_pts, nn_dist, nn_idx] = kdrangequery(TreeRoot, pts_1(idx,1:3), nn_rad);
    if(size(nn_pts,1) > 30)
        cov_m = cov(nn_pts);
        mea_v = mean(nn_pts);
        [vi,ei] = eig(cov_m);
        [v,e] = pc(vi,ei);
        if(v(2,1) > 0)
            v(:,1) = -v(:,1);
        end
        res_1(idx,1) = (pts_1(idx,1:3) - mea_v)*v(:,1);
        res_1(idx,2) = acos(-((pts_1(idx,1:3)-s1)/norm(pts_1(idx,1:3)-s1))*v(:,1));
    end

end
```

```
fprintf(1,'\n');

pts_1_t = pts_1;
for i=1:size(pts_1,1)
    pts_1_t(i,1:3) = (rotation*(pts_1(i,1:3) - translation)')';
end

nn_rad = 0.25;
fprintf(1,'First run through:\n');
per = 0;
fprintf(1,'\t%3d',per);
pts_2 = pts_2(1:20:size(pts_2,1),:);
res_2 = zeros(size(pts_2,1),1);
for idx=1:size(pts_2,1)

    if(floor(idx*100/size(pts_2,1)) > per)
        per = floor(idx*100/size(pts_2,1));
        fprintf(1,'\b\b\b%3d',per);
    end

    clear nn_pts
    clear nn_dist
    clear nn_idx
    [nn_pts, nn_dist, nn_idx] = kdrangequery(TreeRoot, pts_2(idx,1:3), nn_rad);
    if(size(nn_pts,1) > 30)
        cov_m = cov(nn_pts);
        mea_v = mean(nn_pts);
        [vi,ei] = eig(cov_m);
        [v,e] = pc(vi,ei);
        if(v(2,1) > 0)
            v(:,1) = -v(:,1);
        end
        res_2(idx,1) = (pts_2(idx,1:3) - mea_v)*v(:,1);
        res_2(idx,2) = acos(-((pts_2(idx,1:3)-s2)/norm(pts_2(idx,1:3)-s2))*v(:,1));
    end

end
fprintf(1,'\n');

pts_2_t = pts_2;
for i=1:size(pts_2,1)
    pts_2_t(i,1:3) = (rotation*(pts_2(i,1:3) - translation)')';
end

nn_rad = 0.25;
fprintf(1,'First run through:\n');
per = 0;
fprintf(1,'\t%3d',per);
pts_3 = pts_3(1:20:size(pts_3,1),:);
res_3 = zeros(size(pts_3,1),1);
for idx=1:size(pts_3,1)

    if(floor(idx*100/size(pts_3,1)) > per)
        per = floor(idx*100/size(pts_3,1));
```

```
        fprintf(1,'\b\b\b%3d',per);
    end

    clear nn_pts
    clear nn_dist
    clear nn_idx
    [nn_pts, nn_dist, nn_idx] = kdrangequery(TreeRoot, pts_3(idx,1:3), nn_rad);
    if(size(nn_pts,1) > 30)
        cov_m = cov(nn_pts);
        mea_v = mean(nn_pts);
        [vi,ei] = eig(cov_m);
        [v,e] = pc(vi,ei);
        if(v(2,1) > 0)
            v(:,1) = -v(:,1);
        end
        res_3(idx,1) = (pts_3(idx,1:3) - mea_v)*v(:,1);
        res_3(idx,2) = acos(-((pts_3(idx,1:3)-s3)/norm(pts_3(idx,1:3)-s3))*v(:,1));
    end

end
fprintf(1,'\n');

pts_3_t = pts_3;
for i=1:size(pts_3,1)
    pts_3_t(i,1:3) = (rotation*(pts_3(i,1:3) - translation)')';
end

kdtree([],[],TreeRoot);

figure(1)
plot(pts_4(:,1),pts_4(:,2),'.k');
hold on
plot(s1(1),s1(2),'+r');
plot(s2(1),s2(2),'+r');
plot(s3(1),s3(2),'+r');
plot(s4(1),s4(2),'+r');
hold off
axis equal

figure(2)
plot(res_1(:,2)*180/pi,res_1(:,1),'.r');

figure(3)
plot(res_2(:,2)*180/pi,res_2(:,1),'.r');

figure(4)
plot(res_3(:,2)*180/pi,res_3(:,1),'.r');

%plot_colour(pts,dim,col,fig_num,no_layers,min_val,max_val,axis_equal)
plot_colour([pts_1(:,1:3),res_1(:,1)],3,4,5,100,-0.004,0.004,1)
title('residuals cloud 1')

plot_colour([pts_2(:,1:3),res_2(:,1)],3,4,6,100,-0.004,0.004,1)
title('residuals cloud 2')
```

```
plot_colour([pts_3(:,1:3),res_3(:,1)],3,4,7,100,-0.004,0.004,1)
title('residuals cloud 3')
```