Measuring Critical Speed Marks

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Impact *Spring 2012 Vol.20 No. 1*

Abstract

A comparison is made between the various methods used to measure critical speed tyre marks (yaw marks) created at road traffic collision scenes to determine the method likely to produce the most accurate results. The traditional manual method of measuring the chord and mid-ordinate using tapes was compared to the electronic methods now available using Total Station and GPS technology. Four arcs of varying radii where created and subsequently measured. A total of 48 manual measurements were made including 16 using sight boards. Electronically 44 measurements were taken using a TPS pole; 40 using a GPS pole; 34 using a TPS mini-prism and 8 reflectorless. The electronic surveying methods examined were shown to provide significantly more accurate results than the traditional manual measurements with the mini-prism providing the most accurate results. Although the electronic methods examined provided superior results to the manual measurements the results also highlighted the importance of using sight-boards to obtain acceptable results when using manual techniques. It is also apparent that obtaining electronic measurements at frequent intervals inherently allows for a certain amount of data redundancy and self-checking to be performed when establishing the radius. With a point frequency of approximately one metre erroneously surveyed points are readily identified and can be discounted from subsequent radii calculations. This further enhances the accuracy and reliability of the electronic methods when compared with manual measurements.

Introduction

An essential tool in any collision investigator's toolkit is the ability to investigate and determine a vehicle's speed by measuring curved 'striated' tyre mark evidence in order to obtain their radius. This measurement is then used with the tyre/road coefficient of friction value to calculate the speed of a vehicle. The basic techniques (and limitations) are described by Lambourn [**1**] and Neades [**2**]. The majority of investigators in the English speaking world will have been taught to determine this radius by measuring the tyre marks using tape measures and the manual method of physically measuring the chord and mid-ordinate at a live collision scene – the 'manual method'. Lambourn [**1**] describes a series of guidelines to assist in the measurement process.

Over recent years, even with the advent of developments in electronic surveying methods and plan drawing software packages the approach by many is to defer to the manual method or conduct both manual and electronic measurements to compare with one another. Many have access to total stations and global positioning (GPS) technology yet many will still use 'the old, tried and trusted method'.

A series of tests were devised to compare the accuracy between the chord/mid ordinate manual method, with various electronic methods such as ordinary survey pole, mini-prism, GPS pole and reflectorless. These tests were intended to specifically consider the comparisons of the various measuring methods to determine the radius of critical speed 'striated' tyre marks and not to provide comment on the principles concerning the behaviour of a vehicle as they are created.

Methodology

A Leica TCRP1205 total station was used to set out a series of 4 arcs of approximately 20m in length using 15 - 20 individual points. These arcs were marked individually on a smooth level concrete surface of a disused airfield using permanent white spray paint and black marker pen to ensure a defined and clear edge for reference. Figure 1 shows the survey points being set out for one of the arcs. A continuous line was similarly marked near the centre of each arc to allow for the mid ordinate measurements to be taken. The radius of each mark was chosen at random to represent a wide range of measurements and to provide a more realistic assessment. The actual radii were: #1 - 35.85m; #2 - 58.2m; #3 - 76.66m and #4 - 141.8m. A considerable amount of care was taken to ensure the arcs were drawn as accurately as possible.

Figure 1. Photograph showing the layout of the arc

Members from many of the collision investigation units in the North West police region of the UK and Mr Christopher Gibbons representing Leica Geosystems were invited to attend. Prior to the testing none of the participants knew the radii of the arcs. Their brief was to measure the marks ‘as they would normally do’ at a live collision scene to determine the radii for use in a critical speed calculation. Over the course of the tests the weather was predominantly warm and dry with sunny intervals. There was a prevailing light wind which did create some issues when setting out the tape measures, otherwise the conditions were favourable.

Chord/Mid Ordinate Manual Method

Individual teams measured each mark twice using a chord length in excess of 15m and a chord length below 10m. This was in order to compare the levels of accuracy obtained between both. The latter was expected to produce results that were less accurate. In the text that follows the term +15m is used to denote results where the chord length greater than 15 metres and -10m is used to denote chord lengths of less than 10m.

In total 24 measurements were recorded for each chord length of +15m and -10m. Sightboards were used for 16 of the test measurements. Fibre tapes (30m long) were used for the chord measurements with shorter metal tapes being used for the mid-ordinate measurements. Without exception all the measurements were recorded using as much care as possible. All personnel were conscious that the accuracy of the mid-ordinate measurement was crucial to the final accuracy of the radii obtained. It was also evident that all those taking part were working in a sterile environment with none of the pressures associated with working at some live scenes.

The following formula was used to calculate the radius for each set of measurements

$$r = \frac{C^2}{8m} + \frac{m}{2}$$

where *r* is the radius, *C* is the chord and *m* is the mid-ordinate.

TPS/GPS Method

The equipment of three manufacturers were used in these tests, those manufactured by Trimble, Leica Geosystems and Topcon. The Trimble equipment consisted of the TPS S6 and the GPS R8. The Leica Geosystems' equipment consisted of the TPS TCRP1205 and the GPS GS15. The Topcon equipment consisted of the TPS GPT9003A and GPS GR3.

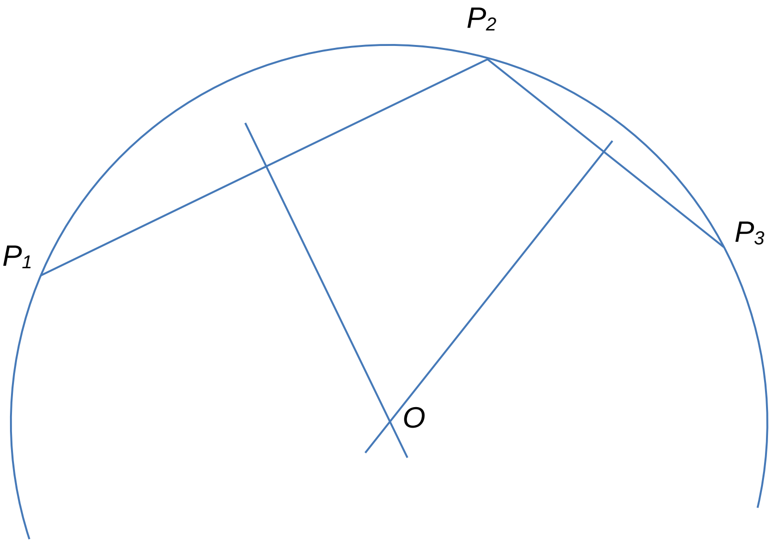
All equipment was calibrated and in everyday use with each respective unit. In practice there was no significant difference with the equipment in the operation or methods used to accurately record the measurements required. Four basic methods were used to survey the marks electronically, a standard TPS pole with a 360˚ prism set at a height of 1.8m to 2m; a standard GPS receiver pole at 1.8m in height, a 0.1m mini prism and a series of reflectorless measurements.

Figure 2. Photograph of the measurements being recorded.

Each team was then asked interrogate the raw data that had been logged to determine the radius of each mark surveyed using their normal commercially available plan drawing software. Software used included, LSS by McCarthy Taylor; Terramodel and Geosite 5.1 Professional by Trimble; SurveyMaster by Topcon and Fastcad 32 by Evolution Computing. The radius for each mark was calculated within each of these programs by generating arcs of best fit using three known points of those surveyed. This is a function common to most surveying/plan drawing software packages.

To calculate the radius from three points on an arc the software uses the fact that the bisector of any chord passes through the centre of the circle. Using three points lying on the circumference of a circle, two chords are defined and the centre of the circle *O* can be found as the intersection of the two bisectors. This is illustrated in Figure 3 below. An explanation of one of the methods used to determine the coordinates of the centre and radius of the circle is given in Appendix A.

Figure 3. Calculation of radius from three points on an arc.



In relation to these tests, it was appreciated that the radius for each mark would be constant, unlike a real world critical speed mark that would invariably alter along its length as the speed of the vehicle changes. This was not a concern as the objective of the testing was to compare the electronic methods to the manual measurements taken. By recording each surveyed point with a minimum interval in the region of 1m, sufficient data was recorded to be able to accurately determine the radii of the test marks or indeed any real world marks.

Results

A summary of the results are shown in Table 1 with graphs showing the full results provided in Appendix B. The raw data is provided in Appendix C for further analysis if required. In Table 1 the maximum and mean percentage differences are displayed for each method used together with the actual radii and the total number of recordings made for that method.

Table 1: Summary of results

	Total Measurements	Maximum % Difference	Mean % Difference	% Standard Deviation
Manual -10m Overall	24	+33.65	-0.12	8.31
Manual -10m Sightboards	8	-9.74	-1.06	2.59
Manual -10m No Sightboards	16	+33.65	+1.12	9.69
Manual +15m Overall	24	+18.8	+1.60	4.51
Manual +15m Sightboards	8	3.71	+0.62	1.57
Manual +15m No Sightboards	16	+18.8	+2.10	5.31
GPS Pole	40	+3.4	+0.17	1.14
TPS Pole	44	+2.74	+0.15	0.78
TPS Mini	34	+1.34	+0.13	0.38
Reflectorless	8	+0.56	+0.23	0.08

The most obvious result from these tests is that the electronic methods of measuring are significantly more accurate than manual measurements using a chord and mid-ordinate. The largest individual errors and the largest mean errors both occurred with the manual measurements with the measurements of the larger radii being more prone to error than the smaller radii. This loss of accuracy with the larger manual radii calculation would appear to be due to the difficulty in measuring small mid-ordinate measurements. Considering the manual methods in isolation, the benefit of using sightboards also became apparent. There was an appreciable increase in accuracy when they were used. The largest percentage errors occurred mainly when they were not used and the spread of the results was also more variable as shown by the large standard deviations in the percentage differences.

Of the electronic methods, the most accurate method would appear to be the reflectorless measurements followed closely by the mini-prism measurements. It is emphasised however that only two measurements were taken of each of the marks using the reflectorless system. More importantly, in these tests the marks were of white paint which forms an ideal reflective surface. In reality, striated tyre marks are not anything like as reflective so this level of accuracy is unlikely to be maintained in real-world scenarios. In practice therefore the mini-prism is likely to provide the most accurate method followed by the ordinary detail pole and then GPS.

Discussion

The radii measurement is obtained to calculate the speed of a vehicle whilst in a critical speed state, using the formula

$$V = \sqrt{\mu g r}$$

where V is the speed of the vehicle, μ is the coefficient of friction and g is the acceleration due to gravity. Since the speed of the vehicle is a function of the square root of the radius a significant difference in the calculated speed is only possible with relatively large differences in the radius. For example a 10% increase in the radius will increase the calculated speed by just under 5% It follows that minor differences in the calculated radius will not produce large changes in the final calculated speed.

In these tests the largest percentage differences obtained were recorded measuring the largest arc with a radius of 141.8m as might be expected since in these tests the mid-ordinate length is minimised so that any errors in this measurement are critical. With a chord of 10m the mid-ordinate measurement was less than 9 cm and in this case the largest result was 189.52m (+33.65%). Using a chord of 15m the mid-ordinate measurement is around 20 cm and in this case the largest result was 168.46m (+18.8%). Note that sightboards were not used for either of these results.

Using the previous calculation with theoretical coefficient of friction of 0.7g would indicate a calculated vehicle speed of 69.8mph (±10%). If the incorrect radius calculated as above was used this would change the calculated speed of the vehicle up to 80.7mph (±10%). This would indicate that it is possible using the manual method to create an undetectable error with the potential to significantly alter the final calculated speed of the vehicle.

It is possible to use statistical methods to estimate uncertainty in the final result from an estimate of the uncertainty in the source data, which in this situation is the chord and mid-ordinate measurements. However a 2 cm uncertainty in a 9 cm mid-ordinate measurement when coupled with a chord of 10 m, produces the very wide range of 115 to 183 metres. This finding supports strongly Lambourn's [**1**] suggestion of a minimum mid-ordinate measurement of 30 cm in order to minimise the effect of errors in this measurement. It is also noted that this effect is alleviated somewhat by the use of a longer chord length which results in a larger and therefore less critical mid-ordinate measurement.

With manual measurements, typically only one set of measurements will be made. As shown here, that one set of measurements may be in error but crucially the investigator will not know since there is no way of verifying that single result. A significant advantage of the electronic measurements is that by surveying a number of points, a variety of choices were available from which it is possible in the software to calculate the radius. This has the effect of providing a way of self-checking the data using a succession of point combinations.

Although is appreciated that the arcs used for the purposes of these tests were all of constant radii, the same methodology can obviously be applied when analysing real world critical speed 'striated' tyre marks. The radius will vary depending upon the behaviour of the vehicle at any given point when the marks were generated. Providing sufficient points are recorded accurate comparisons can be made and safeguards maintained. It is suggested that one point is surveyed every 1 metre. This provides sufficient numbers of points from which to choose combinations of points to determine the radius and also allows erroneous points to be readily identified.

Considering now the electronic methods the largest percentage differences obtained were again recorded measuring the largest arc with a radius of 141.8m. With the GPS pole this was 146.61m (+3.4%) and using the TPS pole 145.68m (+2.74%). Compared to the theoretical calculated speed of 69.8mph as above, these differences would increase the calculated speed of a vehicle by about 1 mph only. The difference is minimal with the added safeguard of being able to identify any errors prior to performing any calculations.

The largest percentage difference in the TPS mini prism results was noted as being 58.98m for the radius of 58.2m (+1.34%). This minor difference of around 80 cm has a negligible effect on any calculated speed.

Conclusions

Overall all the electronic surveying methods examined were shown to provide more accurate results than the manual alternative. Any of the electronic methods examined were acceptable but in order of accuracy the preference would be to use TPS mini prism, TPS pole and finally GPS pole. This ranking of results was not unexpected.

The results indicate the importance of using a minimum chord length of 15m for manual measurements and using sightboards as there is a significant increase in the accuracy of the calculated radii when so doing. Lambourn's [**1**] suggestion to take great care if measuring a smaller than 30cm mid-ordinate would also seem to be justified. Of the results with the greatest difference from the true values it is noted that seven out of eight were obtained where no sightboards were used.

Not only were the electronic results shown to be more accurate overall, it was also possible to evaluate all the individual surveyed points to allow comparisons and to immediately identify if an erroneous point had been recorded. If using an electronic system, it is recommended that all points are surveyed with a minimum interval of 1m. This will allow accurate comparisons of the recorded points to ensure their integrity and the changing radii to be plotted.

If an error occurs whilst recording the manual measurements there is no means to identify the tolerance or percentage error margin possibly applicable. Even when extreme care is taken significant errors can occur with no means or other data with which to make a comparison or alert the investigator.

The results indicate that it is not necessary to measure striated critical speed tyre marks using manual methods. Indeed to do so may be less accurate and expose the investigator to making unknown errors. All the electronic methods coupled with appropriate computer software provided more accurate results than manual measurements. Electronic methods of measuring is also beneficial as the evidence gathering process and data obtained would be completely transparent and fully auditable.

Acknowledgements

Our thanks are due to Mr Christopher Gibbons of Leica Geosystems and the members of the following Collision Investigation Units whom we are grateful to for participating in the evidence gathering and analysis processes: Cheshire Constabulary, Merseyside Police, Greater Manchester Police, North Wales Police and Cumbria Police.

References

[**1**] Lambourn, R.F. *The calculation of motor car speeds from curved tyre marks*. (1989) Journal of the Forensic Science Society Vol. 29 No. 6

[**2**] Neades, J. *Determining the maximum speed at which a bend can be negotiated* (2007) Impact Vol. 16 No. 1

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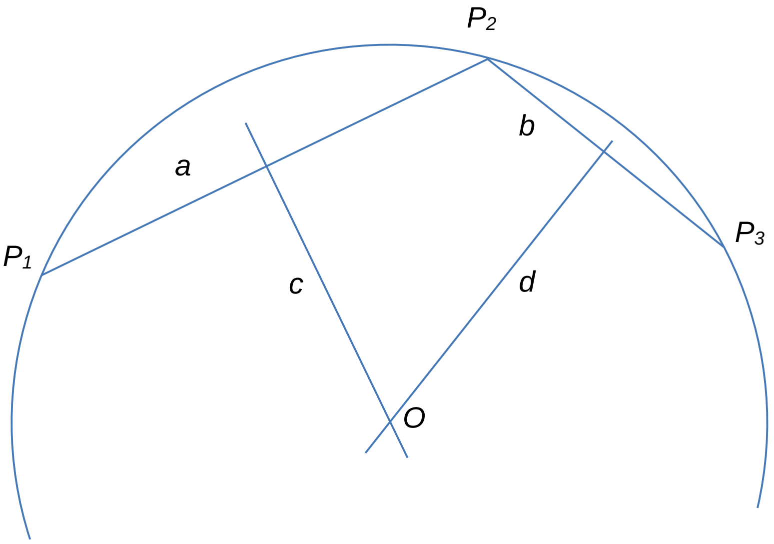
Appendix A: Method to find the centre coordinates and radius of a circle

A method is presented here which allows the coordinates of the centre of a circle to be calculated from three arbitrary points lying on the circumference and is the method by which RelMo calculates the centre of the circle. Other software packages probably use similar methods although other techniques do exist. In the diagram below point P_1 has coordinates (x_1, y_1), point P_2 has coordinates (x_2, y_2) and P_3 has coordinates (x_3, y_3).



The equation of the line joining points, P_1, and P_2 (line *a*) can be expressed as $y_a = m_a(x - x_1) + y_1$ and the equation joining the points P_1, and P_3 (line *b*) as $y_b = m_b(x - x_2) + y_2$ where

$$m_a = \frac{y_2 - y_1}{x_2 - x_1}, \qquad m_b = \frac{y_3 - y_2}{x_3 - x_2}.$$

A line perpendicular to line *a* will have a slope equal to $-\frac{1}{m_a}$ so the equation of the perpendicular to line *a* which passes through its midpoint (line *c*) will have the equation

$$y_c = -\frac{1}{m_a}\left(x - \frac{x_1 + x_2}{2}\right) + \frac{y_1 + y_2}{2}.$$

Similarly a line perpendicular to line *b* passing through the midpoint (line *d*) will have the equation

$$y_d = -\frac{1}{m_b}\left(x - \frac{x_2 + x_3}{2}\right) + \frac{y_2 + y_3}{2}.$$

As already noted, the two bisectors meet at the centre of the circle so equating y_c and y_d produces

$$\frac{1}{m_a}\left(x - \frac{x_1 + x_2}{2}\right) + \frac{y_1 + y_2}{2} = \frac{1}{m_b}\left(x - \frac{x_2 + x_3}{2}\right) + \frac{y_2 + y_3}{2}.$$

This can be solved for *x* to give

$$x = \frac{m_a m_b \left(y_1 - y_3\right) + m_b \left(x_1 + x_2\right) - m_a \left(x_2 + x_3\right)}{2\left(m_b - m_a\right)}.$$

The *y* coordinate can be found by substitution into either of the equations for the perpendiculars.

Once the coordinates of the centre of the circle are known, the radius can be found easily from any of the points , P_1, P_2 or P_3 Using P_1, the radius *r* is given by

$$r = \sqrt{\left(x - x_1\right)^2 + \left(y - y_1\right)^2}$$

There are other methods to find the radius of a circle from three points but this method has the advantage of also determining the coordinates of the circle. This allows the survey software to draw circles based on these points.

Appendix B: Results

Chart 1.

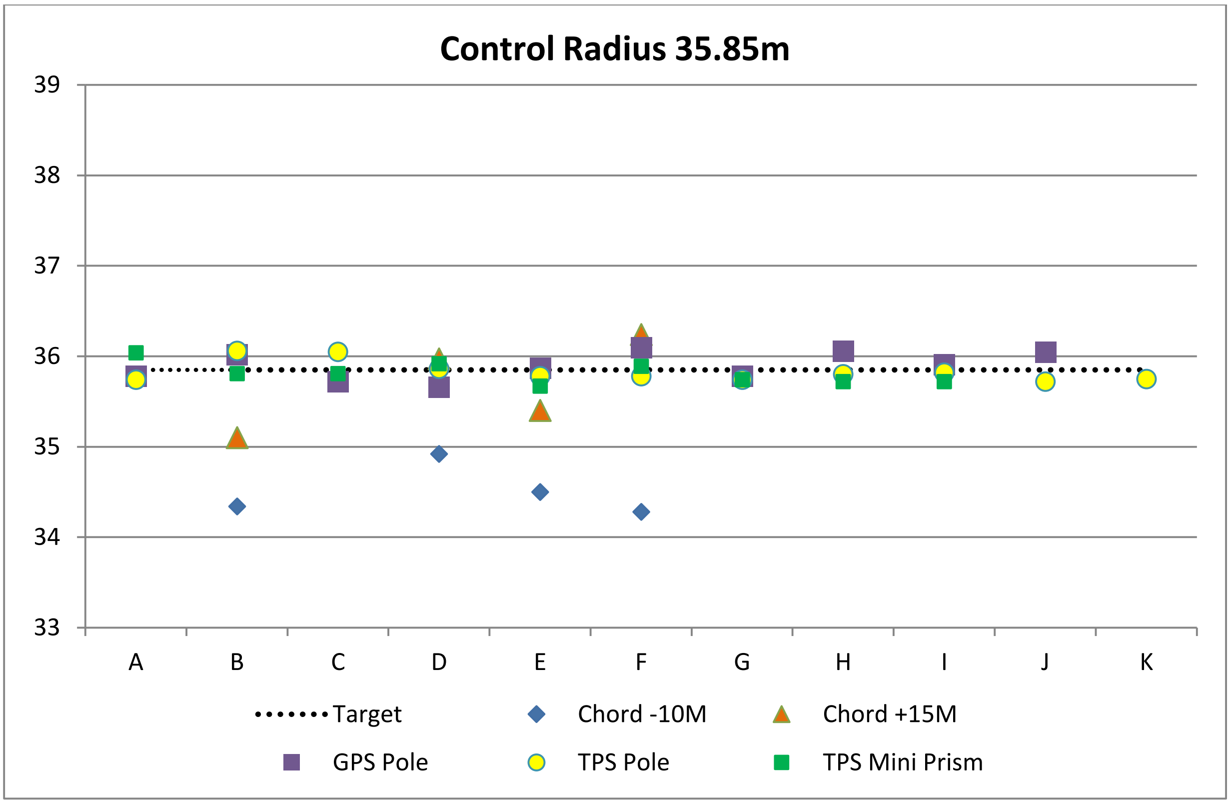


Figure 2

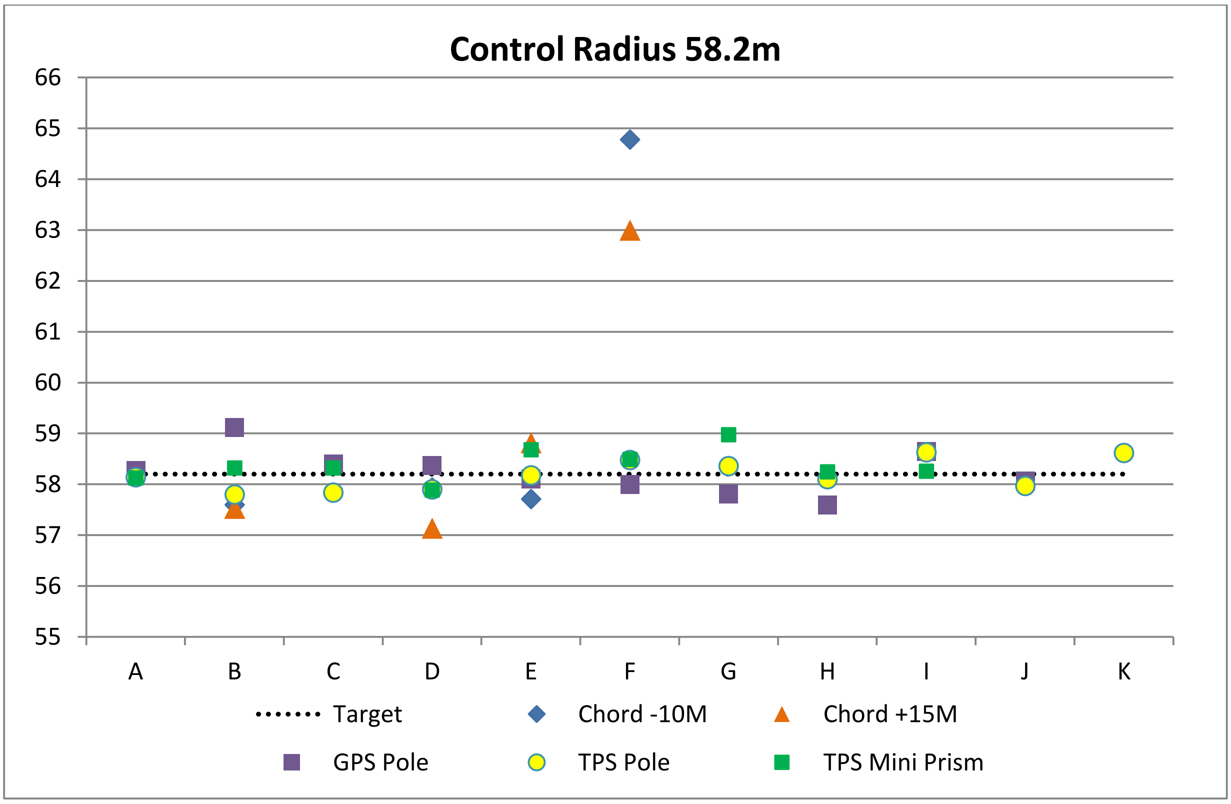


Figure 3

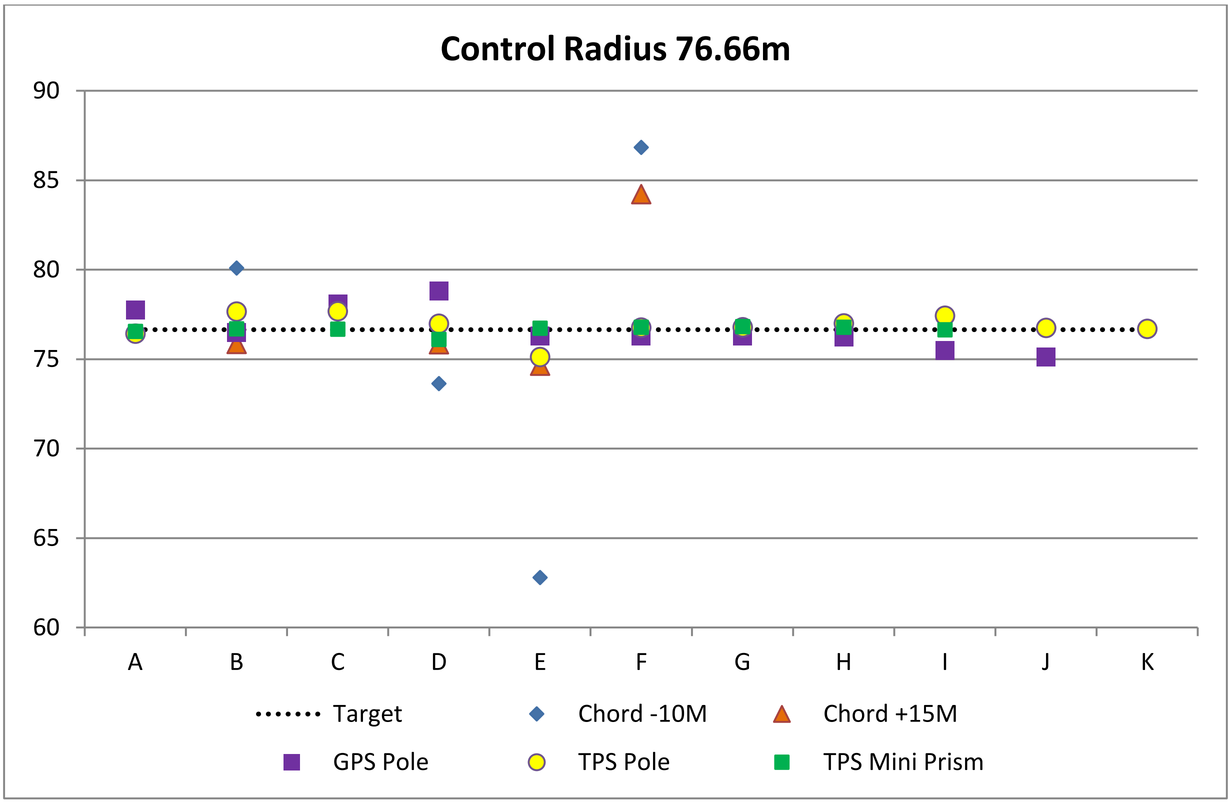
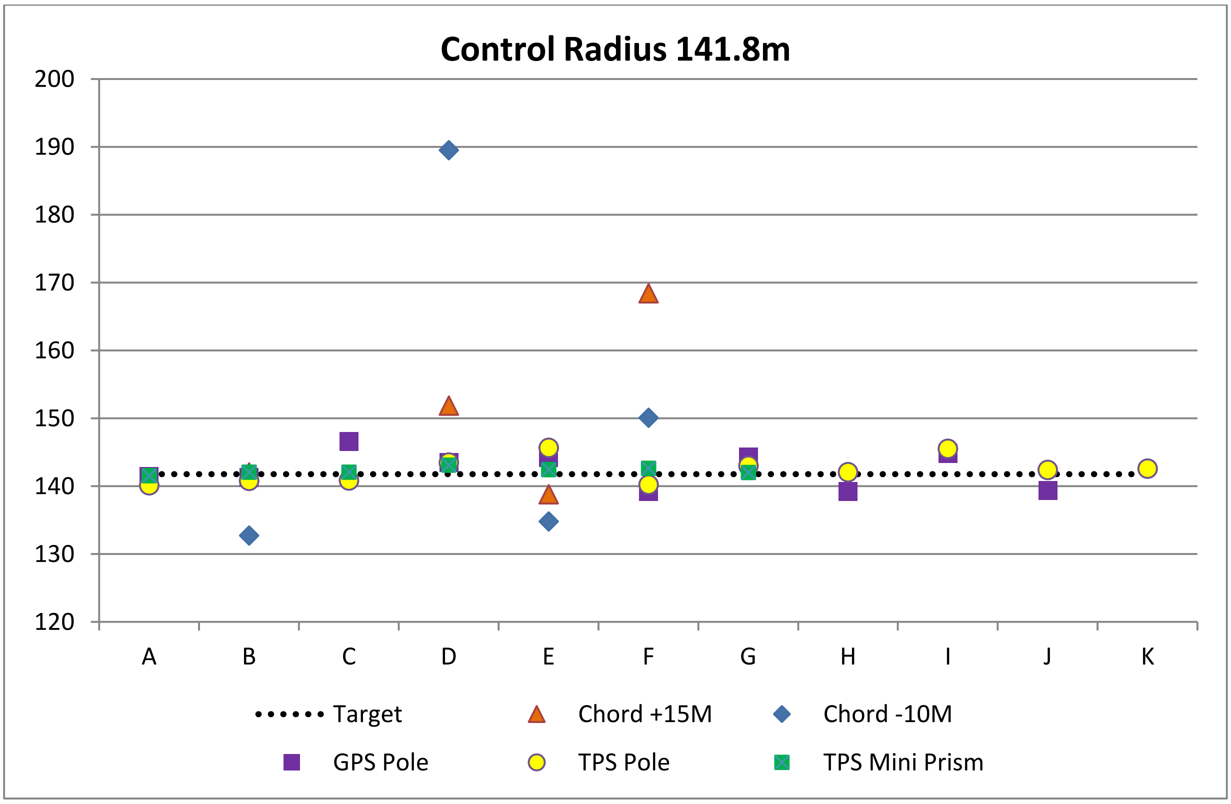


Figure 4



Appendix C: Raw Data

Table C.1 Chord and mid-ordinate. Chord length -10m.

Target (m)	Measurements (metres)					
35.85	35.61*	34.34	35.05*	34.92	34.5	34.28
58.20	59.24*	57.6	56.19*	57.94	57.71	64.78
76.66	75.21*	80.1	69.19*	73.63	62.79	86.84
141.8	147.3*	132.76	147.3*	189.52	134.82	150.1

*Indicates use of sightboards

Table C.2 Chord and mid-ordinate. Chord length +15m.

Target (m)	Measurements (metres)					
35.85	37.18*	35.1	35.74*	35.97	35.4	36.24
58.20	58.57*	57.53	57.91*	57.14	58.82	63
76.66	76.93*	75.85	74.96*	75.83	74.64	84.23
141.8	144.92*	142.03	143.31*	151.91	138.84	168.46

*Indicates use of sightboards

Table C.3 Surveyed using GPS pole.

Target (m)	Measurements (metres)					
35.85	35.78	36.02	35.72	35.66	35.87	36.1
	35.78	36.06	35.91	36.05		
58.20	58.28	59.12	58.4	58.37	58.11	58
	57.81	57.6	58.65	58.07		
76.66	77.75	76.49	78.1	78.81	76.28	76.3
	76.28	76.24	75.48	75.13		
141.8	141.43	141.35	146.61	143.58	144.28	139.24
	144.31	139.24	144.83	139.35		

Table C.4 Surveyed using TPS pole.

Target (m)	**Measurements (metres)**					
35.85	35.74	36.06	36.05	35.86	35.78	35.78
	35.74	35.8	35.82	35.72	35.75	
58.20	58.14	57.8	57.84	57.9	58.18	58.48
	58.36	58.1	58.63	57.97	58.62	
76.66	76.42	77.66	77.68	76.99	75.12	76.77
	76.79	77.01	77.43	76.75	76.69	
141.8	140.16	140.82	140.85	143.51	145.68	140.24
	143.04	142.08	145.54	142.44	142.59	

Table C.5 Surveyed using mini-prism.

Target (m)	**Measurements (metres)**					
35.85	36.04	35.81	35.81	35.92	35.67	35.89
	35.74	35.72	35.72			
58.20	58.13	58.32	58.32	57.89	58.68	58.49
	58.98	58.25	58.26			
76.66	76.56	76.7	76.68	76.11	76.73	76.79
	76.82	76.79	76.65			
141.8	141.58	142.1	142.1	143.11	142.49	142.67
	142.06					

Table C.6 Reflectorless.

Target (m)	**Measurements (m)**	
35.85	35.65	35.72
58.20	58.2	58.2
76.66	76.62	76.34
141.8	141.53	141.46