

Small Angle Generator Final Traceability Report

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**NMS Programme for Length 1997 - 1999
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**David R Flack
Dimensional Metrology Section
Centre for Basic, Thermal and Length Metrology
National Physical Laboratory
Queens Road
Teddington
Middlesex
United Kingdom
TW11 0LW**

Abstract

The aim of the Small Angle Generator project was to develop and commission a small angle measurement facility to provide a traceable measurement service of angles over a range of 60 seconds of arc with an uncertainty of ± 0.01 second of arc. The Small Angle Generator was designed, built and installed at NPL by Renishaw Plc. This document is the Final Traceability Report that forms part of WP4 of the Small Angle Generator Project. It describes work at NPL to verify the encoder system against calibrated angle standards. It covers the use of the standards to calibrate the encoder and the calibration of the standards themselves. The use of the standards with a calibrated system is also described and the report also summarises the main achievements of the project. This document demonstrates that the target specification has been met.

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National Physical Laboratory
Queens Road, Teddington, Middlesex, United Kingdom, TW11 0LW

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A handwritten signature in blue ink, consisting of a series of loops and a trailing line, representing the signature of Dr David Robinson.

Approved on behalf of the Managing Director
by Dr David Robinson, Head of Centre for Basic, Thermal and Length Metrology

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1. INTRODUCTION

1.1 THE SMALL ANGLE GENERATOR PROJECT

In the latter part of 1996 a consortium comprising Renishaw Plc and NPL began work on a Project to develop a Small Angle Generator. The Small Angle Generator was to be designed and built by Renishaw Plc. It was installed at NPL in June 1999. NPL's role in the project was to prove the system and demonstrate traceability.

The Small Angle Generator project was split into four work packages. Work package one involved a feasibility study. Work package two involved developing the first prototype system. Report DS/9901A/009/01A covered work package three, the evaluation of the prototype system.

Report DS/9901A/009/01A is Restricted Commercial but its conclusions can be summarised as follows:

- The ability to successfully interface the Small Angle Generator software with an external instrument was demonstrated.

The automatic calibration of an autocollimator was successfully demonstrated. Results showed that the combined error of the autocollimator and the small angle generator was less than 0.03 second of arc.

The Small Angle Generator was compared with the NPL angular interferometer over a range of ± 140 seconds of arc. Over a six hour test the drift in the zero position reading was typically less than 0.2 second of arc. When grouping the data, the differences from the mean value were generally less than 0.05 second of arc. With a cubic used to correct the NPL interferometer fringe counts to seconds of arc the differences were centred on zero with a spread of ± 0.06 second of arc. If the mean value at each position is calculated and a cubic used to correct the NPL interferometer fringe counts to seconds of arc the differences between the two instruments are less than 0.03 second of arc. Over the sets of data taken on three days the mean differences between the NPL interferometer and the Small Angle Generator were less than 0.01 second of arc over the central ± 30 seconds of arc.

This report covers work package four and in particular the establishment of traceability.

1.2 THE SMALL ANGLE GENERATOR

The Small Angle generator is shown in Figure 1. The main measurement system of the Small Angle Generator is an angular interferometer. The design of the interferometer system is such that a one second of arc rotation results in one full Lissajous count of the sine and cosine signals. The type of interferometer used is based on the principle that as a glass block rotates the optical path length of a beam passing through it changes. In the Small Angle Generator two glass blocks are used to improve the linearity of the system and to make the system more-or-less equally sensitive at both ends of its angular range.

The angular interferometer is precise but not accurate. As pointed out above the interferometer is non-linear and also its calibration is dependent on the ambient temperature, pressure and humidity.

To make the Small Angle Generator accurate its interferometer system is regularly calibrated against its own internal encoder system. The accuracy of the encoder system is specified as ± 1 second of arc. The interferometer is calibrated over a range of 30° to achieve a scale factor accuracy of 0.001 second of arc in 30 seconds of arc. Software routines were provided by Renishaw to perform this calibration.

If one can demonstrate that the encoder is traceable one can easily show that the whole system is traceable.



Figure 1 The Small Angle Generator

2. METHODS CONSIDERED

Work reported on in Report DS/9901A/009/01A showed that the mean differences between an NPL designed angular interferometer and the calibrated interferometer in the Small Angle Generator were less than 0.01 second of arc. However at the time that this exercise was performed traceability of the Small Angle Generator encoder had not been demonstrated. Both the NPL interferometer and the Small Angle Generator's interferometer had scale factors derived from the Small Angle Generator's built in encoder. Therefore although both interferometers agreed to better than 0.01 second of arc it had not been demonstrated that the Small Angle Generator was traceable. Establishing that the Small Angle Generator was traceable therefore basically involved calibrating the in-built encoder.

Three basic methods were considered for making the system traceable. They were

- (1) calibration of the encoder against a Moore Precision Index or AA Gage Ultradex[®],
- (2) calibration of the encoder against a polygon,
- (3) calibration of the encoder using several optical wedges and
- (4) calibration of the encoder against angle gauge combinations.

At the start of the project method (1) was considered the best route to obtain traceability. However it transpired that the Moore Precision Index was too heavy for the servo control system. A lighter Ultradex table was a possible alternative. However since no Ultradex tables are available at NPL this option was not considered further although the best route to traceability in the long run may be via an Ultradex table.

Method (2) was quickly rejected because the smallest angle between faces obtainable is 5 degrees which would allow only five calibration points (-10, -5, 0, 5, 10 degrees).

Method (3) was also considered. However this method was rejected as suitable optical wedges could not be procured in time.

In the end method (4) was used. Method (4) involved wringing pairs of angle gauges to a glass block. The glass block was wrung in such a way that the weight of the combination was taken by the bottom angle gauge. Each combination was measured on the Small Angle Generator using a

to-electric illuminator to the other is fed precision Index.

IGN CONVENTION

When radiating this document the following should be borne in mind

() A POSITIVE total of the Small Angle Generator is ANTICLOCKWISE

AN CLOCKWISE NEGATIVE total of the Small Angle Generator to INCREASE the firing of collimator 10 87

An ANTICLOCKWISE rotation of the Precision Index results in INCREASE in total

An ANTICLOCKWISE total of the total of the Precision Index results in

DECREASE in the firing of collimator T806

() An increase in the total of the LARGE total of the Precision Index said to have PLU:

4. PROCEDURE FOR DETERMINING TRACEABILITY

4.1 OUTLINE OF METHOD

The combinations of angle gauges given in Table 1 were used to calibrate the encoder of the Small Angle Generator. A list of equipment used follows:

- (1) Hilger and Watts 100 second of arc range photo-electric autocollimator type TA9057 (inventory number ST806) Calibration certificate 08B071/99012/NPL10/1 dated 4 March 1999.
- (2) Moore Precision Index 8-1440-28 Calibration certificate C2/66 dated 19 December 1997
- (3) Combination Angle Gauges (British patent 5307/40) made by Coventry gauge and Tool Co. Limited Set No. 171. Calibrated for these tests in wrung combinations.
- (4) Hilger and Watts Microptic Autocollimator No. 98462 NPL inventory number MO(1)1873. Calibration certificate LD08/000001/NPL11/44 dated 8 February 2000

To create an angle standard, a pair of combination angle gauges was wrung to a glass block. The glass block was wrung in such a way that the weight of the combination was taken by the bottom angle gauge. Each combination was measured on the Small Angle Generator using photo-electric autocollimator MO(1)1873 to view the faces.

The wrung combination was placed nominally at the centre of the Small Angle Generator work table. Rotations were generated, using the encoder calibration routine in the software, equal to the nominal angle of the wrung combination and the change in autocollimator reading noted over several rotations.

The angle combination was then checked against a Moore Precision Index and photoelectric autocollimator ST806.

Ideally autocollimator ST806 would have been used both on the Small Angle Generator and with the Moore Precision Index used to calibrate the combinations but this was not practicable. The only other autocollimator that gave a suitable image and had a photo-electric detector was MO(1)1873. This autocollimator's resolution (0.1 second) is not as good as the resolution of ST806 (0.01 second) but was adequate for this task.

Table 1 Combinations of angle gauges used in the tests

Angle Gauges Used	Angle Generated (Degrees)	Angle Generated (Seconds)
$9^{\circ}+3^{\circ}$	12	43200
$9^{\circ}-3^{\circ}$	6	21600
$3^{\circ}-1^{\circ}$	2	7200
$3^{\circ}+1^{\circ}$	4	14400
$3^{\circ}-0.1'$	≈ 3	10794
$9^{\circ}-0.1'$	≈ 9	32394
$1^{\circ}-0.1'$	≈ 1	3594

Section 4.2 gives an example calibration at the 12° positions.

4.2 EXAMPLE CALIBRATION AT 12 DEGREES

The procedure used is described below using the 12° degree case as an example. The data was collected using the software's encoder calibration routine.

First the Small Angle Generator table was rotated to 0.00 seconds and the autocollimator reading noted. The table was then rotated to -43200 seconds (-12°), i.e. an absolute move of -43200. This was repeated a further two times and finally a zero reading recorded. The angle standard was then repositioned on the worktable to allow the calibration of the +12° interval. Examples from the 12° calibration are given below at 4.2.1 and 4.2.2.

4.2.1 Measurements at -12 degrees

Filename n12a.edr

Table 2 12 degree encoder calibration (negative)

Rotation entered	Actual Position	Autocollimator reading	Autocollimator (Seconds)	Difference (Seconds)
0	-0.19	5'06.9"	306.9	2.2
-43200	-43199.8	5'09.1"	309.1	
0	-0.22	5'06.95"	306.95	2.1
-43200	-43199.8	5'09.05"	309.05	
0	-0.22	5'07.0"	307.0	2.2
-43200	-43199.9	5'09.2"	309.2	
0	-0.22	5'07.0"	307.0	
Mean				2.17

The data content of the file is shown below

7

```

-8.80      -151410      -2552.45      -137.49      -0.19853  0.00029  306.9000
-43090.43  -741293288      -71590969.87  -71576103.64  -43199.83876  0.00038  309.1000
-8.80      -151460      -2677.17      -83.96      -0.22001  0.00029  306.9500
-43090.43  -741293251      -71590967.04  -71576128.87  -43199.84552  0.00037  309.0500
-8.81      -151649      -2680.69      -84.73      -0.22131  0.00034  307.0000
-43090.44  -741293484      -71590985.04  -71576134.66  -43199.85270  0.00029  309.2000
-8.81      -151554      -2676.63      -82.92      -0.21954  0.00034  307.0000

```

If we look at the two important columns (column 5 the encoder average and column 7 the autocollimator reading) we have

Table 3 Summary of data at -12 degrees

Encoder Average (seconds)	Difference (seconds)	Autocollimator Reading (seconds)	Difference (seconds)
-0.19853	43199.64023	306.9	2.2
-43199.83876		309.1	
-0.22001	43199.62551	306.95	2.1
-43199.84552		309.05	
-0.22131	43199.63139	307.0	2.2
-43199.85270		309.2	
-0.21954		307.0	
Mean	-43199.63238	Mean	2.17
Std. Dev.	0.0074	Std Dev.	0.058

The mean angle generated is: -43199.63 seconds and the mean difference in autocollimator readings is 2.17 seconds. However the encoder did not rotate through 43200 seconds falling short by 0.37 seconds. To reach 43200 seconds we would have had to rotate a further -0.37 second. This would have increased the autocollimator reading by 0.37 second resulting in a bigger difference. The error in the angle gauge combination measured by the Small Angle Generator is therefore $2.17 + 0.37 = 2.54$ seconds.

4.2.2 Measurements at +12 degrees

Filename p12.edr

Table 4 12 degree encoder calibration (positive side)

Rotation entered	Actual Position	Autocollimator reading	Autocollimator (Seconds)	Difference (Seconds)
0	-0.22	4'56.1"	296.1	-2.5
43200	43199.9	4'53.6"	293.6	
0	-0.22	4'56.05"	296.05	-2.45
43200	43199.9	4'53.6"	293.6	
0	-0.19	4'56.0"	296.0	-2.4
43200	43199.9	4'53.6"	293.6	
0	-0.19	4'56.05"	296.05	
Mean				-2.45

-8.84	-152007	-2601.54	-149.74	-0.21704	0.00032	296.1000	1
43073.72	741005827	71582732.39	71580463.91	43199.89512	0.00027	293.6000	1
-8.82	-151658	-2483.05	-186.92	-0.19251	0.00027	296.0500	1
43073.71	741005708	71582721.33	71580457.30	43199.88979	0.00030	293.6000	1
-8.81	-151482	-2451.13	-180.39	-0.18091	0.00042	296.0000	1
43073.72	741005848	71582726.96	71580464.28	43199.89360	0.00046	293.6000	1
-8.80	-151378	-2447.05	-181.42	-0.17998	0.00035	296.0500	1

If we look at the two important columns we have

Table 5 Summary of data at +12 degrees

Encoder Average (seconds)	Difference (seconds)	Autocollimator Reading (seconds)	Difference (seconds)
-0.21704	43200.11216	296.1	-2.5
43199.89512		293.6	
-0.19251	43200.0823	296.05	-2.45
43199.88979		293.6	
-0.18091	43200.07451	296.0	-2.4
43199.89360		293.6	
-0.17998		296.05	
Mean	43200.089657	Mean	2.45
Std. Dev.	0.0199	Std. Dev.	0.05

The mean angle generated is: 43200.09 seconds and the mean difference in autocollimator readings is -2.45 seconds. However the encoder rotated through more than 43200 seconds by 0.09 second. To reach 43200 seconds we would have had to rotate -0.09 second. This would have increased the second autocollimator reading by 0.09 seconds resulting in a smaller difference. The error in the angle gauge combination measured by the Small Angle Generator is therefore $2.45 - 0.09 = 2.34$ seconds.

The two files relating to the example above are given in full in section 11

4.3 EXAMPLE CALIBRATION OF THE STANDARD (12°)

The standard was then placed on a Moore Precision Index (8-1440-28) and calibrated against the appropriate index on the table. The faces were viewed using autocollimator ST806. The angle was measured eight times in total and a mean value calculated. The results are summarised for the 12° case in Table 6.

Table 6 Calibration of 12 degree angle standard

Number	0°	12°	Difference (seconds)
1	29.20	26.75	-2.45
2	29.25	26.76	-2.49
3	29.21	26.76	-2.45
4	29.28	26.76	-2.52
5	29.25	26.76	-2.49
6	29.24	26.75	-2.49
7	29.26	26.77	-2.49
8	29.25	26.76	-2.49
		Mean	-2.48

4.4 DETERMINING THE ENCODER ERRORS AT 12°

For the two examples given in section 4.2 we have

-12 degrees

The calibrated angle of the angle gauge is -2.48 seconds of arc. The error in the Small Angle Generator is therefore $2.54 - 2.48 = 0.06$ second of arc. The table has therefore rotated too far and so the error is -0.06 second of arc.

+ 12 degrees

The calibrated angle of the angle gauge is -2.48 seconds of arc. The error in the Small Angle Generator is therefore $2.34 - 2.48 = -0.14$ second of arc. The table has therefore rotated too far and so the error is -0.14 second of arc.

4.5 UNCERTAINTY IN CALIBRATION OF ANGLE STANDARD

The calibration of the angle gauge combination provides the reference value for the calibration of the Small Angle Generator. However, there is an uncertainty associated with these reference values.

4.5.1 Type A

A spread sheet summarising the measured angles of each angle gauge combination is given below

	12	6	4	2	3		9
	-2.45	-0.75	+1.69	-1.19	-4.07	-5.72	-4.15
2	-2.49	-0.80	+1.72	-1.15	-4.06	-5.74	-4.08
3	-2.45	-0.81	+1.71	-1.18	-4.09	-5.69	-4.10
4	-2.52	-0.83	+1.70	-1.16	-4.08	-5.74	-4.10
5	-2.49	-0.79	+1.74	-1.13	-4.06	-5.72	-4.11
6	-2.49	-0.83	+1.75	-1.14	-4.07	-5.68	-4.09
7	-2.49	-0.81	+1.75	-1.17	-4.04	-5.71	-4.10
8	-2.49	-0.81	+1.68	-1.18	-4.01	-5.73	-4.13
mean	-2.48	-0.80	+1.72	-1.16	-4.06	-5.72	-4.11
standard deviation	0.023	0.026	0.027	0.021	0.025	0.022	0.023
experimental	0.008	0.009	0.010	0.008	0.009	0.008	0.008

As can be seen the maximum experimental standard deviation is 0.01 second of arc (A1).

4.5.2 Type B

(1) Autocollimator calibration

The autocollimator used had an error of up to 0.36 second of arc over its 100 second range and a error of up to 0.08 second of arc over half a revolution of the micrometer drum (5 seconds of arc). The uncertainty associated with this calibration was ± 0.02 second of arc ($k = 2$). However over any 10 second interval of the progressive calibration the error in the autocollimator is less than 0.10 second of arc. No attempt was made to correct for these errors. This introduces an uncertainty of

0.10 second of arc. It will be assumed that this error has a rectangular *a priori* probability distribution. Its contribution is therefore:

$$\frac{0.10''}{\sqrt{3}} + \frac{0.02''}{2} = 0.07'' \quad (\text{B1})$$

This value is known with a high degree of confidence and the number of degrees of freedom to associate with it is infinite.

(2) Pyramidal error

The autocollimator was set up so as to minimise pyramidal errors. It was estimated that the residual pyramidal error was approximately 0.05 second of arc for a displacement normal to the measurement axis of 200 seconds of arc. Since it is difficult to judge the exact vertical movement of the cross wire we will assume this uncertainty to be 0.10 second of arc and to have a rectangular *a priori* probability distribution. Its contribution is therefore:

$$\frac{0.10''}{\sqrt{3}} = 0.06'' \quad (\text{B2})$$

It is judged that this value of $u(x_i)$ is reliable to about 20% therefore the number of degrees of freedom to assign is $\nu_i = (0.20)^{-2} / 2 = 12.5$

Note:

$$\nu_i = \frac{1}{2} \frac{u^2(x_i)}{\sigma^2[u(x_i)]} \approx \frac{1}{2} \left[\frac{\Delta u(x_i)}{u(x_i)} \right]^{-2}$$

(3) Centrality of beam

The estimated uncertainty due to the autocollimator axis not coinciding with the centre of the gauge face is 0.10 second of arc. It will be assumed that this error has a rectangular *a priori* probability distribution. Its contribution is therefore:

$$\frac{0.10''}{\sqrt{3}} = 0.06''$$

It is judged that this value of $u(x_i)$ is reliable to about 20% therefore the number of degrees of freedom to assign is $\nu_i = (0.20)^{-2}/2 = 12.5$

(4) Moore Precision Index

In the measurement of the standard it has been assumed that there is no error in the intervals of the Moore Precision Index. Past calibrations of this table at thirty degree intervals have revealed errors of up to 0.15 second of arc. These errors have been ignored for this exercise. It will be assumed that this error has a rectangular *a priori* probability distribution. Its contribution is therefore:

$$\frac{0.15''}{\sqrt{3}} = 0.09''$$

This value is known with a high degree of confidence and the number of degrees of freedom to associate with it is infinite.

(5) Wavefront

Since each angle gauge is subtended by different parts of the autocollimator the wavefront errors in the autocollimator optics will add an additional source of uncertainty. It is estimated that this contribution is of the order of 0.1 second of arc. It will be assumed that this error has a rectangular *a priori* probability distribution. Its contribution is therefore:

$$\frac{0.10''}{\sqrt{3}} = 0.06''$$

It is judged that this value of $u(x_i)$ is reliable to about 20% therefore the number of degrees of freedom to assign is $\nu_i = (0.20)^{-2}/2 = 12.5$

4.5.3 Combined and expanded uncertainty

The combined standard uncertainty of the calibration of the standard angle gauge combination is

$$\sqrt{0.01^2 + 0.07^2 + 0.06^2 + 0.06^2 + 0.09^2 + 0.06^2} = 0.155''$$

The expanded uncertainty of the calibration ($k = 2$) is therefore 0.31 second of arc. The total number of degrees of freedom is calculated using the Welch-Satterthwaite formula

$$v_{eff} = \frac{u_c^4}{\frac{1}{N} \sum \frac{u_i^4}{v_i}}$$

This equals

$$v_{eff} = \frac{0.155^4}{\frac{0.01^4}{7} + \frac{0.06^4}{12.5} + \frac{0.06^4}{12.5} + \frac{0.06^4}{12.5}} \quad \text{i.e. 185}$$

effective degrees of freedom justifying the use of $k = 2$ (if v_{eff} is >30 then k_p is less than 2.09 and can be approximated by $k = 2$). Values of k used in this document have been taken from the table in Appendix B of UKAS document M3003 *Uncertainty and Confidence in Measurement*. The values that appear in this table actually relate to a level of confidence of 95.45%.

4.5.4 Summary of angle standard uncertainties

Component	Value sec.	Probability distribution	Divisor	u_i sec	v_i or v_{eff}
A1	0.01	normal	1.0	0.01	7
B1 (a)	0.10	rectangular	$\sqrt{3}$	0.07	∞
B1 (b)	0.02	normal	2.0	0.01	∞
B2	0.10	rectangular	$\sqrt{3}$	0.06	12.5
B3	0.10	rectangular	$\sqrt{3}$	0.06	12.5
B4	0.15	rectangular	$\sqrt{3}$	0.09	∞
B5	0.10	rectangular	$\sqrt{3}$	0.06	12.5
u_c		normal		0.155	185
U		normal ($k = 2$)		0.310	185

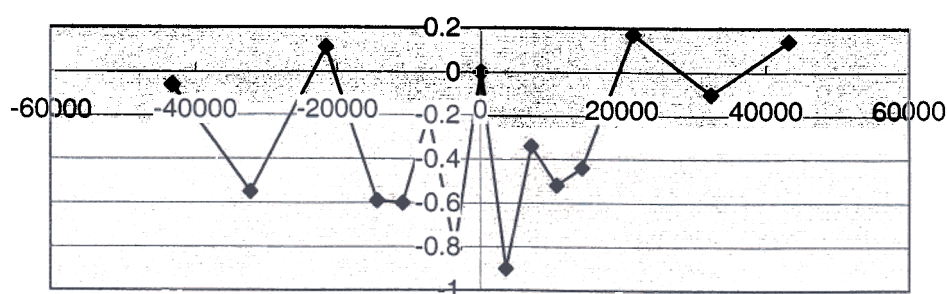
5. RESULTS

The following table is a summary of the measurements at each position. As can be seen from the table the encoder errors are no greater than 0.9 second of arc. Strictly the column labelled encoder error contains some error due to the uncertainty in determining the error in the angle standard.

Table 7 Summary at all encoder positions, (all values in seconds)

Nominal Rotation	Actual Rotation	Measured error of angle gauge	Corrected error of angle gauge	Calibrated error of angle gauge	Encoder error
-43200	-43199.63	-2.17	-2.54	-2.48	-0.06
43200	43200.09	-2.45	-2.34	-2.48	0.14
-21600	-21599.79	-0.48	-0.69	-0.80	0.11
21600	21600.19	-0.82	-0.63	-0.80	0.17
-14400	-14400.73	+0.40	1.13	1.72	-0.59
14400	14400.05	+1.23	1.28	1.72	-0.44
-7200	-7200.02	-1.72	-1.36	-1.16	-0.2
7200	7200.22	-1.38	-1.50	-1.16	-0.34
-10800	-10800.19	-4.85	-4.66	-4.06	-0.6
10800	10800.60	-5.18	-4.58	-4.06	-0.52
-3600	-3599.82	-6.35	-6.53	-5.72	-0.81
3600	3600.20	-6.82	-6.62	-5.72	-0.9
-32400	-32400.02	-4.68	-4.66	-4.11	-0.55
32400	32400.19	-4.40	-4.21	-4.11	-0.1

Encoder errors



Note on 1, 9 and 3 degree standards

The 3, 9 and 1 degree standards are actually nominally $2^{\circ} 59' 54''$, $8^{\circ} 59' 54''$ and $0^{\circ} 59' 54''$. However when generating the nominal rotations and when calibrating them they are treated as 3, 9 and 1 degree standards, hence the errors of approximately 6 seconds in column 5 of Table 7.

Note on signs of encoder error.

If the indicated rotation is 43200.1 and the actual rotation 43200 the encoder is said to have an error of 0.1 second of arc. If the indicated rotation is -43200.1 and the actual rotation -43200 the encoder is said to have an error of -0.1 second of arc.

Table 7 shows that the largest error occurs at the 1 degree position (the smallest rotation). An error of 0.9 second of arc in 1 degree is equivalent to an error of 0.015 second of arc in a 60 second of arc rotation. However, larger angular rotations show a proportionally smaller error. Since a calibration of the system is made at 120 positions over a rotation of ± 54000 seconds of arc ($\pm 15^{\circ}$) in 900 seconds of arc (15') steps the error over any 60 seconds of arc will be less than 0.01 second of arc.

6. UNCERTAINTY OF ENCODER CALIBRATION

This section derives the total uncertainty associated with the calibration of the encoder within the Small Angle Generator. The various contributions are listed below.

6.1 TYPE A

The maximum standard deviation of the measurements on the angle standard was 0.28 second of arc. Three measurements were made and this contribution equates to

$$\frac{0.28}{\sqrt{3}} = 0.17''$$

6.2 TYPE B

6.2.1 Autocollimator calibration

The autocollimator used had an error of up to 0.40 seconds of arc over its 10 minute range and a error of up to 0.15 second of arc over a revolution of the micrometer drum (30 seconds of arc). However the autocollimator was only used between 4 and 6 minutes of arc and the largest difference measured was 6 seconds of arc. Over this two minute interval of the progressive calibration the error in the autocollimator is less than 0.10 second of arc. No attempt was made to correct for these errors. This introduces an uncertainty of 0.25 second of arc. It will be assumed that this error has a rectangular *a priori* probability distribution. Its contribution is therefore:

$$\frac{0.25''}{\sqrt{3}} = 0.15''$$

In addition the uncertainty in this calibration is 0.13 second of arc ($k=2.5$). Six degrees of freedom have been associated with this uncertainty. This contribution is therefore 0.06 second of arc (B2).

6.2.2 Pyramidal error

The autocollimator was set up so as to minimise pyramidal errors. It was estimated that the residual pyramidal error was approximately 0.05 second of arc for a displacement normal to the measurement axis of 200 seconds of arc. Since it is difficult to judge the exact vertical movement of the cross wire we will assume this uncertainty to be 0.10 second of arc and to have a rectangular *a priori* probability distribution. Its contribution is therefore:

$$\frac{0.10''}{\sqrt{3}} = 0.06''$$

It is judged that this value of $u(x_i)$ is reliable to about 20% therefore the number of degrees of freedom to assign is $\nu_i = (0.20)^{-2}/2 = 12.5$

6.2.3 Centrality of beam

The estimated uncertainty due to the autocollimator axis not coinciding with the centre of the gauge face is 0.10 second of arc. It will be assumed that this error has a rectangular *a priori* probability distribution. Its contribution is therefore:

$$\frac{0.10''}{\sqrt{3}} = 0.06''$$

It is judged that this value of $u(x_i)$ is reliable to about 20% therefore the number of degrees of freedom to assign is $\nu_i = (0.20)^{-2}/2 = 12.5$

6.2.4 Wavefront

Since each angle gauge is subtended by different parts of the autocollimator the wavefront errors in the autocollimator optics will add an additional source of uncertainty. It is estimated that this contribution is of the order of 0.1 second of arc. It will be assumed that this error has a rectangular *a priori* probability distribution. Its contribution is therefore:

$$\frac{0.10''}{\sqrt{3}} = 0.06''$$

It is judged that this value of $u(x_i)$ is reliable to about 20% therefore the number of degrees of freedom to assign is $\nu_i = (0.20)^{-2}/2 = 12.5$

6.2.5 Uncertainty in the calibration of the angle gauge

The derivation of this term is given in section 4.5. This contribution is equal to 0.155 seconds of arc (B6)

6.3 COMBINED STANDARD UNCERTAINTY

The combined standard uncertainty of the calibration of the encoder calibration is

$$\sqrt{0.17^2 + 0.15^2 + 0.06^2 + 0.06^2 + 0.06^2 + 0.06^2 + 0.155^2} = 0.300''$$

The expanded uncertainty of the calibration, $k = 2.14$, (see below) is therefore 0.641 seconds of arc.

The total number of degrees of freedom is calculated using the Welch-Satterthwaite formula

$$v_{eff} = \frac{0.300^4}{\frac{0.06^4}{6} + \frac{0.06^4}{12.5} + \frac{0.06^4}{12.5} + \frac{0.06^4}{12.5} + \frac{0.17^4}{2}} = 19$$

The correct value of k to use is $k = 2.14$ (Taken from Appendix B of M3003).

6.4 SUMMARY

Component	Value sec.	Probability distribution	Divisor	u_i sec	v_i or v_{eff}
A1	0.17	normal	1.0	0.17	2
B1	0.25	rectangular	$\sqrt{3}$	0.15	∞
B2	0.13	normal	2.5	0.06	6
B3	0.10	rectangular	$\sqrt{3}$	0.06	12.5
B4	0.10	rectangular	$\sqrt{3}$	0.06	12.5
B5	0.10	rectangular	$\sqrt{3}$	0.06	12.5
B6	0.31	normal	2	0.155	∞
u_c		normal		0.300	19.2
U		normal ($k = 2.14$)		0.642	19.2

7. UNCERTAINTY OF ANGLES GENERATED BY THE SMALL ANGLE GENERATOR

The uncertainty achievable when using the Small Angle Generator will be considered in two cases. The first case is the uncertainty that can be achieved when calibrating a typical high accuracy autocollimator. This uncertainty will have terms that relate to the autocollimator being tested. The second case is the Best Measurement Capability where only those terms relating to the Small Angle Generator will be considered.

7.1 TYPE A UNCERTAINTIES

This uncertainty is associated with the modulation of the interferometer optical path length. The main sources for this uncertainty are air turbulence, mechanical vibration and the response time of the servo-control loop. Shielding the optical path lengths has reduced the effect of air turbulence on the interferometer system. Air turbulence will also affect the autocollimator under test.

Mechanical vibration will alter the optical path length of the interferometer by vibrating the optical components and disturbing the position of the air bearing. Anti vibration mounting the system reduces this effect. In addition the frequency response of the servo-control loop has been set as high as possible so as not to cause mechanical resonance problems.

The measurement cycle is at least fifty times longer than the servo control loop response time to reduce the effect of small control loop oscillations on the measurement, and this also helps to reduce the effect that mechanical vibration has on the readings.

The net result of these effects on the readings is averaged out and will contribute to the type A term. It will affect the reproducibility of both the difference in Small Angle Generator readings and the difference in autocollimator readings.

The reproducibility of making several determinations of the error at each position is determined experimentally, e.g. for three measurements at -5 seconds of arc:

-4.998 seconds of arc (mean of ten determinations)

-4.998 seconds of arc (mean of ten determinations)

-4.957 seconds of arc (mean of ten determinations)

the standard deviation $\sigma_{n-1} = 0.0237$ second of arc. Since three determinations of the mean error are made the contribution is 0.0137 second of arc (A1). The number of degrees of freedom to associate with this contribution is 29.

7.2 TYPE B UNCERTAINTIES

7.2.1 Calibration of the interferometer against the encoder.

The interferometer system is calibrated against the encoder at intervals of 900 seconds of arc over a range of ± 54000 seconds of arc.

The uncertainty in the angular encoder's calibration is ± 0.300 second of arc (19.2 degrees of freedom). That is to say we have an uncertainty of 0.3 seconds of arc in $\pm 12^\circ$. The angular errors of the encoder are of the order of 1 second of arc (measured over $\pm 12^\circ$) and are ignored. This gives

$$\frac{1}{\sqrt{3}} + 0.3 = 0.9 \text{ second of arc}$$

If we assume we could have a total error of 0.9 second of arc in 43200 seconds of arc the total contribution (assuming the system is linear) is:

$$\frac{0.9}{43200} \times 60 = 0.0012 \text{ seconds of arc (B1)}$$

It is judged that this value of $u(x_i)$ is reliable to about 20% therefore the number of degrees of freedom to assign is $v_i = (0.20)^{-2} / 2 = 12.5$

This term is probably pessimistic as it does not take into account the fact that the interferometer is calibrated against the encoder at several positions and therefore averaging occurs. This term will be derived more rigorously when producing the measurement procedure relating to the measurement service.

7.2.2 Encoder repeatability.

The repeatability of the encoder was measured in situ against the laser interferometer system. This experimental term is a combination of electrical, optical and mechanical noise. Renishaw obtained a repeatability of 0.1 second of arc with the system anti vibration mounted. This figure along with the encoder accuracy determines the angular range needed to calibrate the laser interferometer system to achieve an accuracy of 0.01 second of arc over the central 60 seconds. If a repeatability of 0.1 second of arc can be achieved against the encoder then, in theory and ignoring other errors with a 24° calibration band an accuracy of 0.01 second of arc over 2° can be obtained. The encoder repeatability is less than the errors in the encoder and will be ignored. Its effect in any case is negligible over 60 seconds of arc.

7.2.3 Drift.

The interferometer is of a balanced design so the drift results from how well arms of the interferometer were matched during manufacture. If the interferometer could be held thermally stable there would be no drift. Glass, steel, and granite control the differential physical path lengths. The linear coefficients of expansion of these materials are about +7, +11 and +4 ppm K⁻¹ respectively. The optical path lengths are in glass and air. The thermal coefficients of refractive index for these materials are +1.2 and -0.9 ppm K⁻¹ respectively. A differential optical path length change of 0.63 microns corresponds to about 1 arc second. Thus a 1 mm physical path length difference in glass, steel and granite would produce a drift in readings for +1 Kelvin change in temperature of +11, +17 and +6 milli-arc-seconds respectively. The contribution to the drift from the thermal refractive effect is for 1 mm of glass and air are 1.9 and -1.4 milli-arc-seconds respectively. Although these two figure have opposite sign in practice the effect will add, because an increase in glass displaces an air path.

The Small Angle Generator is designed so that the physical path lengths in glass are matched to within 1 mm. The same precision cannot be claimed for the path lengths controlled by the steel and granite.

Drift also results from instability between the detector and beam. The detector is centrally mounted in the horizontal plane on a circuit board. Here a movement of 0.040 mm corresponds to

a drift in readings of 1 second of arc. Renishaw did not evaluate the positional stability of the detector in the horizontal plane.

The only way to measure this drift is to alter the Small Angle Generator's temperature and measure its drift. This test has not been performed in a controlled manner. Stability of better than 0.01 second of arc over an hour were achieved at Renishaw, in a poorly temperature controlled room. At NPL the Small Angle Generator was compared against an existing NPL interferometer. The combined drift of the two systems over eight hours was less than 0.15 second of arc i.e. approximately 0.02 second per hour. Some of this drift will have been in the NPL interferometer system. A typical autocollimator calibration takes about three hours. However the normal practice of returning to zero between measurements removes this term. It also hides the drift in the instrument to be calibrated.

Setting up of interferometer signals

The Small Angle Generator uncertainties depend partly on how well the interferometer signals have been set up. Ideally if the Lissajous figure is a perfectly centred circle there will be no error. If the figure is any other shape or is not perfectly centred there will be errors in sub-division. The manual states in appendix 3 that the Lissajous should be set up to have a DC offset of no greater than 1% of the diameter and that the circularity should be no greater than 1% of the diameter.

DC Offset

A DC Offset of 1% results in a maximum error around the Lissajous of 0.8 degrees

It is calculated by comparing θ with $\tan^{-1} \frac{0.01 + \sin \theta}{0.01 + \cos \theta}$

The equivalent error in angle measured is $\frac{0.8}{360} \times 1.05 = 0.0023$ seconds of arc

Circularity

A circularity of 1% results in a maximum error around the Lissajous of 0.3 degrees

It is calculated by comparing θ with $\tan^{-1} \frac{1.01 \sin \theta}{\cos \theta}$

The equivalent error in angle measured is $\frac{0.3}{360} \times 1.05 = 0.0009$ seconds of arc

Assuming the interferometer has been set up correctly the actual error could lie anywhere between these bounds. We will assume a rectangular *a priori* probability distribution, although arguments could be made for a U-shaped distribution.

Total contribution from interferometer set up is 0.0015 seconds of arc and is calculated from:

$$\frac{\sqrt{0.0023^2 + 0.0009^2}}{\sqrt{3}} \quad (\text{B2})$$

It is judged that this value of $u(x_i)$ is reliable to about 20% therefore the number of degrees of freedom to assign is $v_i = (0.20)^{-2} / 2 = 12.5$

7.2.5 Resolution

12 bit analogue to digital converters are used to digitise the sine and cosine signals from the interferometer. The instrument resolution is therefore 1/8192 of a fringe. This component of uncertainty is estimated to be distributed with a symmetric, rectangular *a priori* probability distribution

$$u = \frac{0.00012}{\sqrt{12}} = 0.0001 \text{ second of arc (rounding to 4dp and rounding up)} \quad (\text{B3})$$

The value is known with a high degree of confidence so the number of degrees of freedom to associate with it is infinite.

7.2.6 Resolution of DSP

The DSP has a 16 bit resolution i.e. 1/65536 of a fringe. This component of uncertainty is estimated to be distributed with a symmetric, rectangular *a priori* probability distribution

$$u = \frac{0.15 \times 10^{-4}}{\sqrt{12}} = 4.4 \times 10^{-6} \text{ seconds} \quad (\text{B5})$$

The value is known with a high degree of confidence so the number of degrees of freedom to associate with it is infinite.

Scale factor

The following affect the scale factor of the instrument.

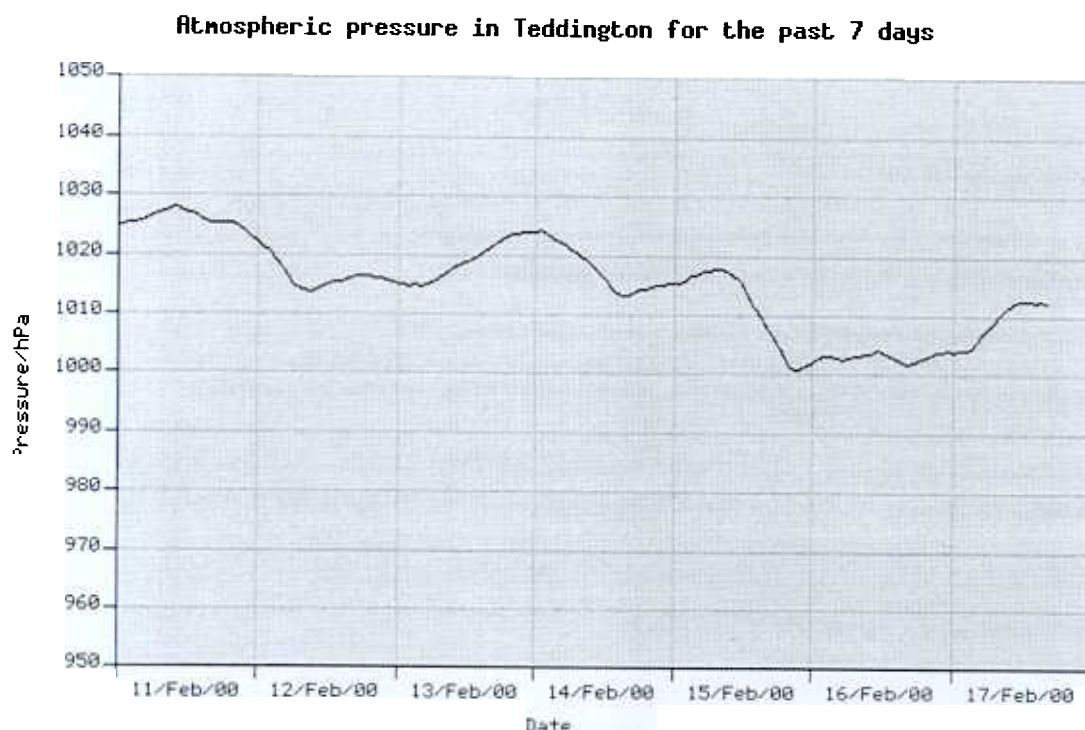
- the frequency stability of the laser (better than 0.5 ppm)
- the physical thickness of the sensing glass blocks
- the refractive index of the sensing glass blocks
- the refractive index of air

The stability of the fringe detection optics will alter the DC value and the fringe contrast and not the scale factor.

The thermal stability of the scale factor is 9.9 ppm K^{-1} This value was derived by Renishaw using knowledge of the interferometer design. Renishaw Mathematica file SAGThermalb.nb refers.

The room the Small Angle Generator is housed in currently is temperature controlled to $20 \pm 0.25 \text{ }^{\circ}\text{C}$. The total error introduced by this term is therefore 3 ppm.

The scale factor is also dependent upon atmospheric pressure, directly and indirectly. The refractive index of air is proportional to atmospheric pressure. At room temperature and pressure this dependence is approximately $0.031 \text{ ppm Pa}^{-1}$. The graph below shows the air pressure over a typical seven days in the Teddington area. A typical change over a day is 10 hPa. (1000 Pa) i.e. 31 ppm.



Change in air pressure also affects the refractive index of the glass via the stress coefficient. The effect is small; a 10% change in atmospheric pressure would alter the scale factor by 0.03 ppm. This is negligible compared to the direct term.

The main two terms are the direct pressure and temperature terms. Summing these gives a total scale factor term of 32 ppm i.e. 0.002 seconds of arc in 60 seconds of arc. It is estimated that this term is known with a high degree of confidence (infinite degrees of freedom). Therefore its contribution to the uncertainty is

$$\frac{0.002}{\sqrt{3}} = 0.0012 \text{ seconds of arc} \quad (\text{B4})$$

7.2.8 Resolution of autocollimator

The contribution from the autocollimator will depend on the item under test. For a 0.005 second of arc resolution autocollimator this contribution will be

$$\frac{0.005}{\sqrt{12}} = 0.0014 \text{ second of arc} \quad (\text{B5})$$

The value is known with a high degree of confidence so the number of degrees of freedom to associate with it is infinite.

7.2.9 Combined standard uncertainty

Taking an example where the angle measured is 60 seconds of arc

$$u_c = \sqrt{0.0137^2 + 0.0012^2 + 0.0015^2 + 0.0001^2 + 0.0012^2 + 0.0014^2} = 0.014$$

The expanded uncertainty U at $k = 2$ is therefore 0.028 seconds of arc which would be quoted as 0.03 seconds of arc.

7.2.10 Best Measurement Capability

The best measurement capability is the uncertainty that results when all terms relating to the instrument under test tend to zero i.e. it is the uncertainty associated with the generation of the angles.

$$u_c = \sqrt{0.0012^2 + 0.0015^2 + 0.0001^2 + 0.0012^2} = 0.0023 \text{ second of arc}$$

The expanded uncertainty U at $k = 2$ is therefore 0.0042 seconds of arc which would be quoted as 0.005 second of arc.

7.3 SUMMARY

Component	Value sec.	Probability distribution	Divisor	u_i sec	v_i or v_{eff}
A1	0.0137	normal	1.0	0.0137	29
B1	0.0012	normal	1.0	0.0012	12.5
B2	0.0025	rectangular	$\sqrt{3}$	0.0015	12.5
B3	0.00012	rectangular	$\sqrt{12}$	0.0001	∞
B4	0.0020	rectangular	$\sqrt{3}$	0.0012	∞
B5	0.0050	rectangular	$\sqrt{12}$	0.0014	∞
u_c		normal		0.0140	32
U		normal ($k = 2$)		0.0280	32

The total number of degrees of freedom is calculated using the Welch-Satterthwaite formula
This equals

$$v_{eff} = \frac{0.0140^4}{\frac{0.0137^4}{29} + \frac{0.0012^4}{12.5} + \frac{0.0015^4}{12.5}} \quad \text{i.e. 32}$$

effective degrees of freedom justifying the use of $k = 2$, as $k_{95} = 2.08$ (if v_{eff} is >30 then k_p is less than 2.09 and can be approximated by $k = 2$)

8. CHECKS USING A CALIBRATED SYSTEM

The system was also checked using angle gauges at two positions after a calibration had been performed on the Small Angle Generator. The checks were made at the 30 minute and 1 degree positions. The procedure was similar to that described in Section 4 except that the autocollimator calibration routine was used instead of the encoder calibration routine.

8.1 MEASUREMENTS AT 30 MINUTE POSITION

8.1.1 Measurements at -30 minutes

Filename n30min.dat

Table 8 System calibration at -30 minute position

Rotation entered	Actual position	Autocollimator reading	Autocollimator (seconds)	Difference (seconds)
0	0.00	6'32.3"	392.3	+1.45
-1800	-1800.00	6'33.75"	393.75	
0	-0.00	6'32.25"	392.25	+1.45
-1800	-1800.00	6'33.7"	393.7	
0	0.00	6'32.2"	392.2	+1.50
-1800	-1800.00	6'33.7"	393.7	
0	0.00	6'32.4"	392.4	
			Mean	+1.47

The data content of the file is shown below:

7

```

0.0000      -49677      0.0000      0.00080      0.009      392.3000 1
-1800.0000   -30470020  -1800.0000      0.00039     -1800.052   393.7500 1
0.0000      -49680      -0.0002      0.00028      0.011      392.2500 1
-1800.0000   -30470020  -1800.0000      0.00034     -1800.057   393.7000 1
0.0000      -49681      -0.0002      0.00026      0.009      392.2000 1
-1800.0000   -30470020  -1800.0000      0.00020     -1800.059   393.7000 1
0.0000      -49681      -0.0002      0.00039      0.011      392.4000 1

```

8.1.2 Measurements at +30 minutes

Filename p30min.dat

Table 9 System calibration at +30 minute position

Rotation entered	Actual position	Autocollimator reading	Autocollimator (seconds)	Difference (seconds)
0	0.00	5'38.7"	338.7	-1.50
1800	1800.00	5'37.2"	337.2	
0	0.00	5'38.75"	338.75	-1.45
1800	1800.00	5'37.3"	337.3	
0	0.00	5'38.7"	338.7	-1.45
1800	1800.00	5'37.25"	337.25	
0	0.00	5'38.75"	338.75	
Mean				-1.47

The data content of the file is shown below:

7

```

0.0000      -49677      0.0000      0.00076      0.000      338.7000  1
1800.0000    30370719    1799.9997    0.00025    1799.919    337.2000  1
0.0000      -49683      -0.0003     0.00026      0.012      338.7500  1
1800.0000    30370717    1799.9996    0.00034    1799.921    337.3000  1
0.0000      -49680      -0.0002     0.00018      0.013      338.7000  1
1800.0000    30370719    1799.9997    0.00029    1799.920    337.2500  1
0.0000      -49679      -0.0001     0.00040      0.017      338.7500  1

```

8.1.3 Calibration of 30 minute angle gauge combination

Table 10 calibration of 30 minute angle gauge

Number	0°	30'	Difference (seconds)
1	20.35	19.13	-1.22
2	20.32	19.14	-1.18
3	20.30	19.12	-1.18
4	20.30	19.13	-1.17
5	20.30	19.15	-1.15
6	20.30	19.15	-1.15
7	20.30	19.14	-1.16
8	20.32	19.15	-1.17
		Mean	-1.17

8.1.4 Evaluation at 30 minute positions

The angle generated was 1800.00 seconds of arc and the error in the angle gauge combination measured as 1.47 seconds of arc for both positive and negative rotations. The error in the angle gauge combination as measured on the Moore Precision Index table was 1.17 seconds of arc. The 'error' in the Small Angle Generator is 0.30 second of arc. However some of this error can be attributed to the uncertainty in measuring the angle using the Moore Precision Index table. However, assuming all the error was in the Small Angle generator (worst case) leads to an error of 0.3 second of arc in 1800 seconds of arc. This is equivalent to 0.01 second of arc in 60 seconds.

8.2 MEASUREMENTS AT 1 DEGREE POSITION

8.2.1 Measurements at -1 degree

Filename n1deg.dat

Table 11 System calibration at -1 degree position

Rotation entered	Actual Position	Autocollimator reading	Autocollimator (Seconds)	Difference (Seconds)
0	0.00	4'44.2"	284.2	+6.5
-3600	-3600.00	4'50.7"	290.7	
0	-0.00	4'44.15"	284.15	+6.55
-3600	-3600.00	4'50.7"	290.7	
0	0.00	4'44.1"	284.1	+6.55
-3600	-3600.00	4'50.65"	290.65	
0	0.00	4'44.1"	284.1	
			Mean	+6.53

The data content of the file is shown below:

7

```

0.0000      -49677      0.0000      0.00080      0.033      284.2000 1
-3600.0000  -60895142  -3599.9999  0.00035  -3600.005  290.7000 1
0.0000      -49680      -0.0002      0.00033      0.044      284.1500 1
-3600.0000  -60895141  -3599.9999  0.00025  -3600.010  290.7000 1
0.0000      -49681      -0.0003      0.00020      0.035      284.1000 1
-3600.0000  -60895142  -3599.9999  0.00033  -3600.011  290.6500 1
0.0000      -49680      -0.0002      0.00027      0.041      284.1000 1

```

8.2.2 Measurements at + 1 degree

1 degree calibrationFilename p1deg.dat**Table 12 System calibration at +1 degree position**

Rotation entered	Actual Position	Autocollimator reading	Autocollimator (Seconds)	Difference (Seconds)
0	0.00	5'28.4"	328.4	-6.3
3600	3600.00	5'22.1"	322.1	
0	0.00	5'28.5"	328.5	-6.5
3600	3600.00	5'22.0"	322.0	
0	0.00	5'28.5"	328.5	-6.5
3600	3600.00	5'22.0"	322.0	
0	0.00	5'28.4"	328.4	
Mean				-6.43

The data content of the file is shown below:

```

0.0000      -49676      0.0000      0.00073      0.051      328.4000 1
3600.0000    60796018    3599.9997    -0.00010    3600.042      0.0000 1
0.0000      -49681      -0.0002      0.00022      0.045      328.5000 1
3600.0000    60796013    3599.9994      0.00017    3600.035      322.0000 1
0.0000      -49682      -0.0003      0.00034      0.043      328.5000 1
3600.0000    60796012    3599.9993      0.00042    3600.036      0.0000 1
0.0000      -49680      -0.0002      0.00024      0.043      328.4000 1

```

8.2.3 Calibration of 1 degree angle standard

The results of the calibration of the 1° standard are given in Table 13 below

Table 13 Calibration of 1 degree angle gauge combination

Number	0°	1°	Difference
1	19.35	13.26	-6.09
2	19.32	13.21	-6.11
3	19.31	13.24	-6.07
4	19.35	13.26	-6.09
5	19.34	13.25	-6.09
6	19.34	13.23	-6.11
7	19.34	13.24	-6.10
8	19.36	13.24	-6.12
		Mean	-6.10

8.2.4 Evaluation at 1 degree positions

The angle generated was 3600.00 seconds of arc and the error in the angle gauge combination measured as -6.5 seconds of arc for the negative rotation and -6.4 seconds of arc for the positive rotation. The error in the angle gauge combination as measured on the Moore index table was -6.10 seconds of arc. The 'error' in the Small Angle Generator is 0.40 seconds of arc. However some of this error can be attributed to the uncertainty in measuring the angle using the Moore table. However, assuming all the error was in the Small Angle Generator (worst case) leads to an error of 0.4 seconds of arc in 3600 seconds of arc. This is equivalent to 0.007 seconds of arc in 60 seconds.

9. CALIBRATION AGAINST AN AUTOCOLLIMATOR

9.1 METHOD

Autocollimator MO(1)1873 was calibrated by the Small Angle Generator in its calibrated state. Whilst this is a fairly low resolution autocollimator (0.1 second of arc) it does have a range 10 times that specified for the accuracy of the Small Angle Generator. For the Small Angle Generator to be accurate to 0.01 second in 60 seconds we would expect an accuracy of 0.1 second of arc in 600 seconds.

9.2 RESULTS

Table 14 Autocollimator calibration: Run 1

Angle Generated seconds	Autocollimator Reading	Autocollimator reading seconds	Difference from zero seconds	Error seconds
0.00	0' 04.1"	4.1	0.0	0.0
-60.00	1' 04.2"	64.2	60.10	0.1
-120.00	2' 04.05"	124.05	119.95	-0.05
-180.00	3' 04.1"	184.1	180.00	0.0
-240.00	4' 04.15"	244.15	240.05	0.05
-300.00	5' 04.15"	304.15	300.05	0.05
-360.00	6' 04.05"	364.05	359.95	-0.05
-420.00	7' 04.05"	424.05	419.95	-0.05
-480.00	8' 04.10"	484.10	480.00	0.0
-540.00	9' 04.2"	544.2	540.10	0.1
-600.00	10' 04.4"	604.4	600.30	0.3

Table 15 Autocollimator calibration: Run 2

Angle Generated seconds	Autocollimator Reading	Autocollimator reading seconds	Difference from zero seconds	Error seconds
0.00	0' 04.0"	4.0	0.0	0.0
-60.00	1' 04.05"	64.05	60.05	0.05
-120.00	2' 04.05"	124.05	120.05	0.05
-180.00	3' 04.0"	184.0	180.00	0.0
-240.00	4' 04.0"	244.0	240.00	0.0
-300.00	5' 04.0"	304.0	300.00	0.0
-360.00	6' 04.15"	364.15	360.15	0.15
-420.00	7' 04.15"	424.15	420.15	0.15
-480.00	8' 04.1"	484.10	480.10	0.1
-540.00	9' 04.2"	544.20	540.20	0.2
-600.00	10' 04.3"	604.30	600.30	0.3

Combining the above two tables we get table 16. Column 5 of table 16 is the error in the autocollimator as determined by the Small Angle Generator. Column 6 contains data from the most recent calibration of this autocollimator.

Table 16 Summary of runs 1 and 2

Angle Generated seconds	Run 1 seconds	Run 2 seconds	Mean seconds	Autocollimator error Seconds	Calibrated error seconds 1/2000	Calibrated error seconds 1983
0.00	0.00	0.00	0.0	0.00	0	0
-60.00	60.10	60.05	60.08	+ 0.08	+0.25	+ 0.12
-120.00	119.95	120.05	120.0	0.00	+0.30	+ 0.15
-180.00	180.00	180.00	180.0	0.00	+0.25	+ 0.10
-240.00	240.05	240.00	240.03	+ 0.02	+0.40	+ 0.20
-300.00	300.05	300.00	300.02	+ 0.02	+0.35	+ 0.16
-360.00	359.95	360.15	360.05	+ 0.05	+0.30	+ 0.10
-420.00	419.95	420.15	420.05	+ 0.05	+0.30	+ 0.06
-480.00	480.00	480.10	480.05	+ 0.05	+0.25	+ 0.08
-540.00	540.10	540.20	540.15	+ 0.15	+0.30	+ 0.16
-600.00	600.30	600.30	600.3	+ 0.30	+0.40	+ 0.34

At the six hundred second position the calibration of the autocollimator agrees with a previous calibration using the existing NPL Small Angle Generator (a sine-bar based device) to better than 0.1 arc second. This again is equivalent to 0.01 second of arc in 60 seconds of arc.

It should be borne in mind that the autocollimator's resolution is at best 0.05 second of arc and the calibration of the autocollimator by traditional means will also have an uncertainty approaching 0.15 second of arc ($k = 2$).

10. CONCLUSION

The encoder of the Small Angle Generator was calibrated against known angles. The results indicate that the errors in the encoder system from which the interferometer gains its calibration are no greater than 0.9 second of arc. It was shown that the effect of these errors on the performance of the Small Angle Generator is less than 0.01 second of arc for rotations of ± 60 seconds of arc. The uncertainty in the encoder calibration was also calculated.

The uncertainty in the angles generated by the Small angle Generator and the total uncertainty when calibrating a typical high accuracy autocollimator were also presented.

Further tests were carried out using the Small Angle Generator in its calibrated mode. The Small Angle Generator was calibrated against its internal encoder. The calibrated system was then used to measure two angle standards. The results indicate that the errors in the system are commensurate with errors of less than 0.01 second of arc in 60 seconds of arc.

A further calibration of a 10 minute range autocollimator with a 0.1 second of arc resolution over its full range confirmed the above.

These results combined with those in document DS/9901A/009/01A (see figure 2) where it was shown that the Small Angle Generator agreed to better than 0.01 seconds of arc with the NPL angular interferometer (both instruments being calibrated against the Small Angle generator's internal encoder) show that the instruments scaling is traceable and that the fringe sub-division is functioning within specification.

At the time that the work described in DS/9901A/009/01A was performed traceability of the Small Angle Generator encoder had not been demonstrated. Both the NPL interferometer and the

Small Angle Generators interferometers had their scale factors determined from the Small Angle Generator's built in encoder. Therefore although both interferometers agreed, it had not been demonstrated that the Small Angle Generator was traceable. By showing that the encoder is traceable at the 1 second of arc level we have demonstrated that both interferometers are traceable. Although the NPL interferometer had a range of only about ± 3600 seconds it was compared against, and gained its calibration from, the interferometer in the Small Angle Generator that was calibrated over a much wider range. By making the encoder traceable, both interferometer's scale factors were then determined traceably.

The results of the comparisons with the NPL interferometer over the sub 1.0 second of arc range that were performed to highlight any non-linearity could also then be considered to be traceable.

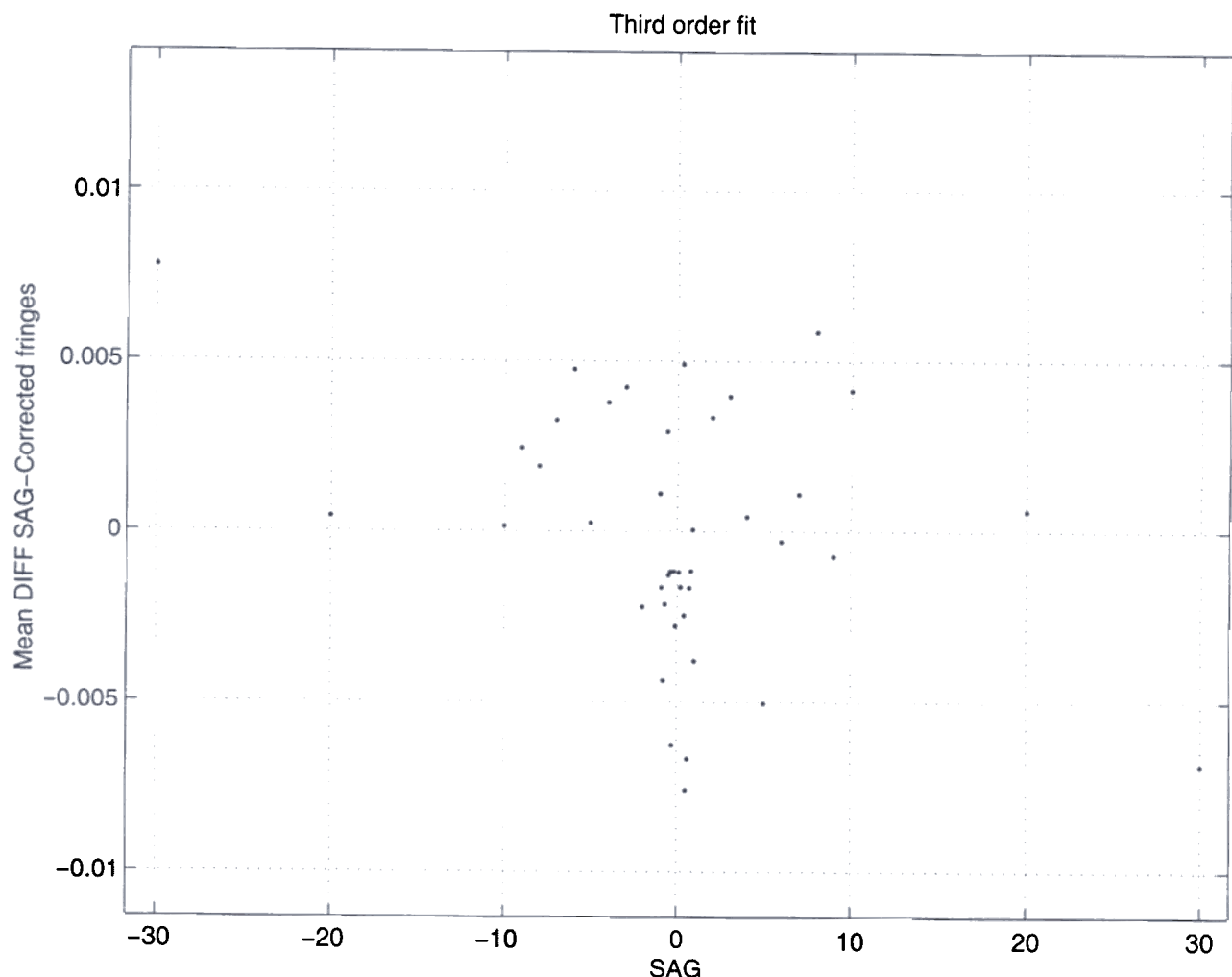


Figure 2 Central 60 seconds comparison with NPL interferometer

The tests described in this document show that the Small Angle Generator is capable of traceably generating rotations over a 60 seconds of arc of arc range centred on zero to 0.01 second of arc. The

method chosen to demonstrate traceability is not ideal and could be improved by procuring an Ultradex table. An Ultradex table could be calibrated more easily and would enable the encoder to be checked at every 1 degree over its range. Since the use of an Ultradex would not involve wringing of angle gauges its calibration would not need to be checked every time it was used. In addition the encoder intervals could be checked in quick succession rather than over several days as is the case with the technique described in this document.

11. SUMMARY OF THE MAIN PROJECT ACHIEVEMENTS

The main project achievements are:

A Small Angle Generator capable of producing rotation accurate to 0.01 second of arc over a range of ± 60 seconds of arc has been designed and built by Renishaw. Software has been developed by Renishaw to calibrate the system and to rotate the table to user-defined positions. Routines to allow automatic instrument calibration via a dll call have also been developed. Renishaw have produced all the appropriate design documentation and a user manual. The Small Angle Generator has been installed and set up at NPL by Renishaw.

NPL have developed a routine to automatically collect data from a Möller Wedel high accuracy autocollimator and have integrated that routine with the Small Angle Generator Software. The automatic calibration of an autocollimator has been demonstrated. NPL have compared the rotations generated by the Small Angle Generator against an existing angular interferometer at NPL. Results agreed over ± 30 seconds of arc to better than 0.01 second of arc. At this stage since both the Small Angle Generator and the NPL interferometer had their scale factors derived from the Small Angle Generator's in-built encoder, traceability had not been demonstrated

Further work was then carried out to demonstrate traceability. This work is described in this document. This work showed that the Small Angle Generator is capable of generating angles traceably over ± 30 seconds of arc to better than 0.01 second of arc. Uncertainties have been derived from first principles that confirm this

The Small Angle Generator is now ready to be used in measurement services at NPL. Initially NPL calibration certificates will be issued. When the instrument moves to the new building in May 2000, UKAS permission for this system to replace the existing UKAS accredited method will be sought.

Some of the work carried out at NPL during assessment of the Small Angle Generator will feed into the project in the new programme to reduce turn-around times of angle measurements by 10%. In particular the software routines developed for reading the Moller Wedel autocollimator from Microsoft Windows 95 will be used to automate some angle measuring tasks. Now that the Small Angle Generator is traceable it will be used to calibrate the Moller Wedel Elcomat high accuracy autocollimator allowing its use for measurement service work.

The project has had problems during its duration but the final result is that the UK now has a facility for the calibration of high accuracy autocollimators manufactured by Taylor Hobson, Newport, Möller Wedel, Micro-Radian and others. The service has several advantages over existing methods at NPL in that it has a smaller uncertainty and allows for autocollimators to be calibrated at any customer-specified intervals and not just those specified by NPL.

12. REFERENCES

Report DS/9901A/009/01A *Final System Performance Hardware report*

Small Angle Generator User manual DS/9901/0006/01B

Ultradex - manufactured by A.G. Davis/ AA Gage, Sterling Heights, MI 48313, USA
(www.agdavis.com)

Knogle, C.H. NPL Combination Angle Gauges Methods of Production and Size Generation Machinery, August 31, 1950

British Patent 569,002 (1945)

BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML *Guide to the Expression of Uncertainty in Measurement*. International Organisation for Standardisation, Geneva, Switzerland. ISBN 92-67-10188-9, First Edition 1993

M3003, *The Expression of Uncertainty and Confidence in Measurement*, United Kingdom Accreditation Service, Edition 1 December 1997

13. DATA FILES

The following pages have been included at Renishaws request. They contain the raw data relating to the tests described in this document.

File n12a.dat

7

-8.80	-1 1410	-25 2.45	-137	-0.19853	0.00029	306.9000	1
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-8.80	-1 1460	-26 7.17	-83	-0.22001	0.00029	306.9500	1
43090.43	7412 3251	715909 7.04	-71576128	-43199.84552	0.00037	309.0500	1
-8.81	-1 1649	-26 0.69	-84	-0.22131	0.00034	307.0000	1
43090.44	7412 3484	715909 5.04	-71576134	-43199.85270	0.00029	309.2000	1
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% (arc secs)	(count)	(count)	(count)	(arc secs)	(arc secs)	(arc secs)	Code

%

%

%Each data point reading is the average of two sets of 8000 readings, each set being taken over a 1.0 second period. One set of readings is taken prior to user data entry, the second set after data entry.

%The hold error is the average of the second set of interferometer readings minus the average of the first set of interferometer readings.

%

%Instrument Name	Autocollimator and Angle Gauges
%Manufacturer	Hilger and Watts/Coventry Gauge
%Instrument Type / Model Number	Photoelectric Autocollimator
%Instrument Serial / Identification Number	MO(1)1873 and Set 171

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%Quartic error term                 0.000000
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%Operator Name                      David Flack
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%                                   3 degree top - apex right
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%Automatic Access Routine Used       ****
%Target Position File Used           ****
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%Program version number               Version 1.001
%
%Hardware details                     Small Angle Generator Table
%Hardware serial number               001
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File n12a.dat

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43073.71	741005708	71582721.33	71580457.30	43199.88979	0.00030	293.6000	1
-8.81	-151482	-2451.13	-180.39	-0.18091	0.00042	296.0000	1
43073.72	741005848	71582726.96	71580464.28	43199.89360	0.00046	293.6000	1
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% Table	Actual	Encoder	Encoder	Encoder	Hold	Reading	Data%
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% (arc secs)	(count)	(count)	(count)	(arc secs)	(arc secs)	(arc secs)	Code

%

%

%Each data point reading is the average of two sets of 8000 readings, each set being taken over a 1.0 second period. One set of readings is taken prior to user data entry, the second set after data entry.

%The hold error is the average of the second set of interferometer readings minus the average of the first set of interferometer readings.

%

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%Manufacturer	Hilger and Watts/Coventry Gauge
%Instrument Type / Model Number	Photoelectric Autocollimator
%Instrument Serial / Identification Number	MO(1)1873 and Set 171

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%Quartic error term              0.000000
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%Operator Name                    David Flack
%Additional Information            9 degree bottom - apex left
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%Target Position File Used         ****
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File n6.edr

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% Table	Actual	Encoder	Encoder	Encoder	Hold	Reading	Data%
% Position	Position	1	2	Average	Error	1	Valid%
% (arc secs)	(count)	(count)	(count)	(arc secs)	(arc secs)	(arc secs)	Code

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%

%Each data point reading is the average of two sets of 8000 readings, each set being taken over a 1.0 second period. One set of readings is taken prior to user data entry, the second set after data entry.

%The hold error is the average of the second set of interferometer readings minus the average of the first set of interferometer readings.

%

%Instrument Name	Autocollimator and Angle Gauges
%Manufacturer	Hilger and Watts/Coventry Gauge
%Instrument Type / Model Number	Photoelectric Autocollimator
%Instrument Serial / Identification Number	MO(1)1873 and Set 171

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%Calibration Certificate Number	****
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%	Position	Position	1	2	Average	Error	1	Valid%
%	(arc secs)	(count)	(count)	(count)	(arc secs)	(arc secs)	(arc secs)	Code

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%Each data point reading is the average of two sets of 8000 readings, each set being taken
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%The hold error is the average of the second set of interferometer readings minus the average of
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%

%Instrument Name Autocollimator and Angle Gauges

%Manufacturer Hilger and Watts/Coventry Gauge

%Instrument Type / Model Number Photoelectric Autocollimator

%Instrument Serial / Identification Number MO(1)1873 and Set 171

%

%Calibration Certificate Number ****

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%Finish Time of Encoder Calibration Cycle 11 : 33

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File n4.edr

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% Position	Position	1	2	Average	Error	1	Valid%
% (arc secs)	(count)	(count)	(count)	(arc secs)	(arc secs)	(arc secs)	Code

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%Each data point reading is the average of two sets of 8000 readings, each set being taken over a 1.0 second period. One set of readings is taken prior to user data entry, the second set after data entry.

%The hold error is the average of the second set of interferometer readings minus the average of the first set of interferometer readings.

%

%Instrument Name	Autocollimator and Angle Gauges
%Manufacturer	Hilger and Watts/Coventry Gauge
%Instrument Type / Model Number	Photoelectric Autocollimator
%Instrument Serial / Identification Number	MO(1)1873 and Set 171

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Filename p4.edr

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0.00	-51444	-329.55	-2386.73	-0.11656	0.00986	331.7000
14167.09	243719255	23861716.59	23857625.16	14399.94361	0.00045	332.8000
0.00	-51184	-318.75	-2362.42	-0.10596	0.00985	331.7000
14167.09	243719211	23861703.15	23857618.03	14399.93740	0.00043	333.2500
0.00	-51237	-325.36	-2365.75	-0.10896	0.00989	332.1000

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% Position	Position	1	2	Average	Error	1	Valid%
% (arc secs)	(count)	(count)	(count)	(arc secs)	(arc secs)	(arc secs)	Code

%

%

%Each data point reading is the average of two sets of 8000 readings, each set being taken over a 1.0 second period. One set of readings is taken prior to user data entry, the second set after data entry.

%The hold error is the average of the second set of interferometer readings minus the average of the first set of interferometer readings.

%

%Instrument Name	Autocollimator and Angle Gauges
%Manufacturer	Hilger and Watts/Coventry Gauge
%Instrument Type / Model Number	Photoelectric Autocollimator
%Instrument Serial / Identification Number	MO(1)1873 and Set 171

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%Calibration Certificate Number	****
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%Quartic error term              0.000000
%
%Operator Name                    David Flack
%Additional Information           9 degree bottom - apex left
%                                3 degree top - apex right
%
%Readings Per Calibration Point   1
%Manual or Automatic Test        Manual
%Automatic Access Routine Used   ****
%Target Position File Used       ****
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File n2.edr

7

-3.20	-55105	-3950.60	-1810.09	-0.13750	0.00035	331.9500	1
-7079.14	-121783888	-11935456.73	-11931297.08	7200.15676	0.00034	333.3000	1
0.00	-55122	-4050.10	-1730.73	-0.14358	0.01064	331.9000	1
-7079.15	-121784018	-11935481.29	-11931303.96	7200.16624	0.00031	333.3500	1
0.00	-55001	-4045.40	-1716.44	-0.13785	0.01052	331.9000	1
-7079.14	-121783916	-11935467.41	-11931287.19	7200.15700	0.00029	333.2500	1
0.00	-55266	-4055.49	-1736.71	-0.14701	0.01053	331.9500	1

%

% Table	Actual	Encoder	Encoder	Encoder	Hold	Reading	Data%
% Position	Position	1	2	Average	Error	1	Valid%
% (arc secs)	(count)	(count)	(count)	(arc secs)	(arc secs)	(arc secs)	Code

%

%

%Each data point reading is the average of two sets of 8000 readings, each set being taken over a 1.0 second period. One set of readings is taken prior to user data entry, the second set after data entry.

%The hold error is the average of the second set of interferometer readings minus the average of the first set of interferometer readings.

%

%Instrument Name	Autocollimator and Angle Gauges
%Manufacturer	Hilger and Watts/Coventry Gauge
%Instrument Type / Model Number	Photoelectric Autocollimator
%Instrument Serial / Identification Number	MO(1)1873 and Set 171

%

%Calibration Certificate Number	****
---------------------------------	------

%

%Start Time of Encoder Calibration Cycle	13 : 13
%Start Date of Encoder Calibration	17 / 1 / 2000
%Finish Time of Encoder Calibration Cycle	13 : 26
%Finish Date of Encoder Calibration Cycle	17 / 1 / 2000

%

%Number of valid data point readings taken during encoder calibration	7
---	---

```

%Number of invalid data point readings taken during encoder calibration  0
%
%Encoder polynomial used :-
%Offset error term                0.000000
%Correction scale factor          1.000000
%Quadratic error term             0.000000
%Cubic error term                 0.000000
%Quartic error term              0.000000
%
%Operator Name                    David Flack
%Additional Information           3 degree bottom - apex left
%                                1 degree top - apex left
%
%Readings Per Calibration Point   1
%Manual or Automatic Test        Manual
%Automatic Access Routine Used   ****
%Target Position File Used       ****
%
%
%Program name                    Small Angle Generator Software
%Program version number          Version 1.001
%
%Hardware details                Small Angle Generator Table
%Hardware serial number          001
%End of File

```

File p2.edr

7

0.00	-55194	-3996.59	-1783.73	-0.14343	-0.01062	335.3000	1
7073.03	121678698	11927470.60	11928407.10	7200.07646	0.00044	333.5000	1
0.00	-55419	-3974.98	-1812.30	-0.14553	-0.01073	335.2000	1
7073.02	121678570	11927481.51	11928414.88	7200.08210	0.00039	333.5500	1
0.00	-55228	-3956.70	-1809.45	-0.13915	-0.01030	335.2000	1
7073.03	121678680	11927485.72	11928424.42	7200.08625	0.00038	333.5000	1
0.00	-55164	-3954.01	-1796.97	-0.13457	-0.01081	335.1500	1

%

% Table	Actual	Encoder	Encoder	Encoder	Hold	Reading	Data%
% Position	Position	1	2	Average	Error	1	Valid%
% (arc secs)	(count)	(count)	(count)	(arc secs)	(arc secs)	(arc secs)	Code

%

%

%Each data point reading is the average of two sets of 8000 readings, each set being taken over a 1.0 second period. One set of readings is taken prior to user data entry, the second set after data entry.

%The hold error is the average of the second set of interferometer readings minus the average of the first set of interferometer readings.

%

%Instrument Name	Autocollimator and Angle Gauges
%Manufacturer	Hilger and Watts/Coventry Gauge
%Instrument Type / Model Number	Photoelectric Autocollimator
%Instrument Serial / Identification Number	MO(1)1873 and Set 171

%

%Calibration Certificate Number	****
---------------------------------	------

%

%Start Time of Encoder Calibration Cycle	12 : 57
%Start Date of Encoder Calibration	17 / 1 / 2000
%Finish Time of Encoder Calibration Cycle	13 : 10
%Finish Date of Encoder Calibration Cycle	17 / 1 / 2000

%

%Number of valid data point readings taken during encoder calibration	7
---	---

```

%Number of invalid data point readings taken during encoder calibration  0
%
%Encoder polynomial used :-
%Offset error term                0.000000
%Correction scale factor          1.000000
%Quadratic error term             0.000000
%Cubic error term                 0.000000
%Quartic error term              0.000000
%
%Operator Name                    David Flack
%Additional Information            3 degree bottom - apex left
%                                1 degree top - apex left
%
%Readings Per Calibration Point   1
%Manual or Automatic Test        Manual
%Automatic Access Routine Used    ****
%Target Position File Used       ****
%
%
%Program name                    Small Angle Generator Software
%Program version number          Version 1.001
%
%Hardware details                 Small Angle Generator Table
%Hardware serial number          001
%End of File

```

File n3.edr

7

0.00	-55182	-3865.4	.76	-0.13554	-0.01042	279.7500	1
-10622.90	-182747807	-17901359.2	.67	-10800.32587	0.00031	284.5000	1
0.00	-55173	-3928.7	.56	-0.14977	-0.01047	279.6000	1
-10622.88	-182747609	-17901353.2	.89	-10800.32172	0.00031	284.5000	1
0.00	-55099	-3923.5	.87	-0.14466	-0.01058	279.6000	1
-10622.92	-182748158	-17901398.3	.63	-10800.34913	0.00031	284.5000	1
0.00	-55322	-3935.9	.40	-0.15067	-0.01111	279.6000	1

%

% Table	Actual	Encoder	Encoder	Encoder	Hold	Reading	Data%
% Position	Position	1	2	Average	Error		Valid%
% (arc secs)	(count)	(count)	(count)	(arc secs)	(arc secs)	(arc secs)	Code

%

%

%Each data point reading is the average of two sets of 8000 readings, each set being taken over a 1.0 second period. One set of readings is taken prior to user data entry, the second set after data entry.

%The hold error is the average of the second set of interferometer readings minus the average of the first set of interferometer readings.

%

%Instrument Name Autocollimator and Angle Gauges

%Manufacturer Hilger and Watts/Coventry Gauge

%Instrument Type / Model Number Photoelectric Autocollimator

%Instrument Serial / Identification Number MO(1)1873 and Set 171

%

%Calibration Certificate Number ****

%

%Start Time of Encoder Calibration Cycle 14 : 23

%Start Date of Encoder Calibration 17 / 1 / 2000

%Finish Time of Encoder Calibration Cycle 14 : 36

%Finish Date of Encoder Calibration Cycle 17 / 1 / 2000

%

```

%Number of valid data point readings taken during encoder calibration    7
%
%Number of invalid data point readings taken during encoder calibration  0
%
%Encoder polynomial used :-
%Offset error term              0.000000
%Correction scale factor        1.000000
%Quadratic error term           0.000000
%Cubic error term               0.000000
%Quartic error term            0.000000
%
%Operator Name                  David Flack
%Additional Information         3 degree bottom - apex left
%                               0.1 minute top - apex left
%
%Readings Per Calibration Point  1
%Manual or Automatic Test       Manual
%Automatic Access Routine Used  ****
%Target Position File Used      ****
%
%
%Program name                   Small Angle Generator Software
%Program version number         Version 1.001
%
%Hardware details               Small Angle Generator Table
%Hardware serial number         001
%End of File

```

File P3.edr

7

0.00	-54892	-3846.75	-1877.03	-0.12637	-0.01054	349.8000	1
10617.00	182646310	17893558.28	17894055.28	10800.46004	0.00040	344.5500	1
0.00	-55169	-3853.74	-1906.45	-0.13735	-0.01048	349.6500	1
10616.99	182646219	17893570.42	17894057.44	10800.46436	0.00022	344.5000	1
0.00	-55292	-3856.14	-1926.30	-0.14407	-0.01068	349.6000	1
10616.98	182646077	17893559.96	17894051.28	10800.45934	0.00029	344.4500	1
0.00	-55342	-3853.94	-1925.11	-0.14304	-0.01079	349.5500	1

%

% Table	Actual	Encoder	Encoder	Encoder	Hold	Reading	Data%
% Position	Position	1	2	Average	Error	1	Valid%
% (arc secs)	(count)	(count)	(count)	(arc secs)	(arc secs)	(arc secs)	Code

%

%

%Each data point reading is the average of two sets of 8000 readings, each set being taken over a 1.0 second period. One set of readings is taken prior to user data entry, the second set after data entry.

%The hold error is the average of the second set of interferometer readings minus the average of the first set of interferometer readings.

%

%Instrument Name Autocollimator and Angle Gauges

%Manufacturer Hilger and Watts/Coventry Gauge

%Instrument Type / Model Number Photoelectric Autocollimator

%Instrument Serial / Identification Number MO(1)1873 and Set 171

%

%Calibration Certificate Number ****

%

%Start Time of Encoder Calibration Cycle 14 : 04

%Start Date of Encoder Calibration 17 / 1 / 2000

%Finish Time of Encoder Calibration Cycle 14 : 17

%Finish Date of Encoder Calibration Cycle 17 / 1 / 2000

%

%Number of valid data point readings taken during encoder calibration 7

```

%
%Number of invalid data point readings taken during encoder calibration  0
%
%Encoder polynomial used :-
%Offset error term                0.000000
%Correction scale factor          1.000000
%Quadratic error term             0.000000
%Cubic error term                 0.000000
%Quartic error term              0.000000
%
%Operator Name                    David Flack
%Additional Information           3 degree bottom - apex left
%                                0.1 minute top - apex left
%
%Readings Per Calibration Point   1
%Manual or Automatic Test        Manual
%Automatic Access Routine Used   ****
%Target Position File Used       ****
%
%
%Program name                    Small Angle Generator Software
%Program version number          Version 1.001
%
%Hardware details                Small Angle Generator Table
%Hardware serial number          001
%End of File

```

File n1.edr

7

0.00	-55190	-3856.26	-1906.75	-0.13820	-0.01059	260 6000	1
-3539.85	-60896685	-5969238.36	5966321.91	3599.93682	0.00015	267 0000	1
0.00	-55012	-3939.74	-1805.03	-0.13270	-0.01051	260 7000	1
-3539.87	-60897131	-5969296.29	5966361.47	3599.96624	0.00028	266 9500	1
0.00	-55043	-3952.51	-1824.87	-0.14254	-0.01053	260 8000	1
-3539.87	-60897017	-5969297.03	5966361.03	3599.96633	0.00044	267 2000	1
0.00	-54975	-3945.34	-1806.65	-0.13488	-0.01047	260 4500	1

%

% Table	Actual	Encoder	Encoder	Encoder	Hold	Reading	Data%
% Position	Position	1	2	Average	Error	1	Valid%
% (arc secs)	(count)	(count)	(count)	(arc secs)	(arc secs)	(arc secs)	Code

%

%

%Each data point reading is the average of two sets of 8000 readings, each set being taken over a 1.0 second period. One set of readings is taken prior to user data entry, the second set after data entry.

%The hold error is the average of the second set of interferometer readings minus the average of the first set of interferometer readings.

%

%Instrument Name Autocollimator and Angle Gauges

%Manufacturer Hilger and Watts/Coventry Gauge

%Instrument Type / Model Number Photoelectric Autocollimator

%Instrument Serial / Identification Number MO(1)1873 and Set 171

%

%Calibration Certificate Number ****

%

%Start Time of Encoder Calibration Cycle 16 : 23

%Start Date of Encoder Calibration 17 / 1 / 2000

%Finish Time of Encoder Calibration Cycle 10 : 22

%Finish Date of Encoder Calibration Cycle 18 / 1 / 2000

%

```

%Number of valid data point readings taken during encoder calibration    7
%
%Number of invalid data point readings taken during encoder calibration  0
%
%Encoder polynomial used :-
%Offset error term              0.000000
%Correction scale factor        1.000000
%Quadratic error term           0.000000
%Cubic error term               0.000000
%Quartic error term            0.000000
%
%Operator Name                  David Flack
%Additional Information          1 degree bottom - apex left
                                0.1 minute top - apex left
%
%Readings Per Calibration Point  1
%Manual or Automatic Test        Manual
%Automatic Access Routine Used   ****
%Target Position File Used       ****
%
%
%Program name                   Small Angle Generator Software
%Program version number          Version 1.001
%
%Hardware details                Small Angle Generator Table
%Hardware serial number          001
%End of File

```

File p1.edr

7

0.00	-50339	-3882.33	-1855.21	-0.13052	0.01045	293.7500	1
3533.89	60794263	5962008.23	5963398.26	3600.07448	0.00049	286.8000	1
0.00	-50316	-3858.22	-1889.25	-0.13351	0.01082	293.7500	1
3533.88	60794007	5961981.60	5963378.54	3600.06050	0.00031	286.8000	1
0.00	-50310	-3862.20	-1897.04	-0.13707	0.01089	293.6500	1
3533.88	60794093	5961996.78	5963393.44	3600.06957	0.00020	287.1000	1
0.00	-50314	-3859.17	-1896.42	-0.13596	0.01026	293.7500	1

%

% Table	Actual	Encoder	Encoder	Encoder	Hold	Reading	Data%
% Position	Position	1	2	Average	Error	1	Valid%
% (arc secs)	(count)	(count)	(count)	(arc secs)	(arc secs)	(arc secs)	Code

%

%

%Each data point reading is the average of two sets of 8000 readings, each set being taken over a 1.0 second period. One set of readings is taken prior to user data entry, the second set after data entry.

%The hold error is the average of the second set of interferometer readings minus the average of the first set of interferometer readings.

%

%Instrument Name	Autocollimator and Angle Gauges
%Manufacturer	Hilger and Watts/Coventry Gauge
%Instrument Type / Model Number	Photoelectric Autocollimator
%Instrument Serial / Identification Number	MO(1)1873 and Set 171

%

%Calibration Certificate Number	****
---------------------------------	------

%

%Start Time of Encoder Calibration Cycle	16 : 07
%Start Date of Encoder Calibration	17 / 1 / 2000
%Finish Time of Encoder Calibration Cycle	16 : 19
%Finish Date of Encoder Calibration Cycle	17 / 1 / 2000

%

%Number of valid data point readings taken during encoder calibration	7
---	---

```

%
%Number of invalid data point readings taken during encoder calibration  0
%
%Encoder polynomial used :-
%Offset error term                0.000000
%Correction scale factor          1.000000
%Quadratic error term             0.000000
%Cubic error term                 0.000000
%Quartic error term              0.000000
%
%Operator Name                    David Flack
%Additional Information            1 degree bottom - apex left
%                                0.1 minute top - apex left
%
%Readings Per Calibration Point    1
%Manual or Automatic Test          Manual
%Automatic Access Routine Used     ****
%Target Position File Used         ****
%
%
%Program name                     Small Angle Generator Software
%Program version number            Version 1.001
%
%Hardware details                  Small Angle Generator Table
%Hardware serial number            001
%End of File

```

File n9.edr

0.00	-54263	-4146.15	-1632.47	-0.14291	0.01026	240.9000	1
-32103.69	-552286245	-53695665.12	53684381.98	32400.16904	0.00034	245.6000	1
-3.15	-54228	-4193.63	-1609.25	-0.15024	0.00035	240.9000	1
-32103.70	-552286310	-53695674.90	53684389.14	32400.17415	0.00039	245.6500	1
0.00	-54273	-4202.44	-1614.75	-0.15455	0.01039	241.0000	1
-32103.69	-552286209	-53695677.17	53684384.86	32400.17355	0.00045	245.6000	1
-3.16	-54348	-4186.68	-1597.32	-0.14454	0.00040	240.9000	1

%

% Table	Actual	Encoder	Encoder	Encoder	Hold	Reading	Data%
% Position	Position	1	2	Average	Error		Valid%
% (arc secs)	(count)	(count)	(count)	(arc secs)	(arc secs)	(arc ecs)	Code
%							
%							

%Each data point reading is the average of two sets of 8000 readings, each set being taken
 %over a 1.0 second period. One set of readings is taken prior to user data entry, the second
 %set after data entry.

%The hold error is the average of the second set of interferometer readings minus the average f
 %the first set of interferometer readings.

%

%Instrument Name	Autocollimator and Angle Gauges
%Manufacturer	Hilger and Watts/Coventry Gauge
%Instrument Type / Model Number	Photoelectric Autocollimator
%Instrument Serial / Identification Number	MO(1)1873 and Set 171
%	
%Calibration Certificate Number	****
%	
%Start Time of Encoder Calibration Cycle	11 : 12
%Start Date of Encoder Calibration	18 / 1 / 2000
%Finish Time of Encoder Calibration Cycle	11 : 30
%Finish Date of Encoder Calibration Cycle	18 / 1 / 2000

```

%
%Number of valid data point readings taken during encoder calibration    7
%
%Number of invalid data point readings taken during encoder calibration  0
%
%Encoder polynomial used :-
%Offset error term                0.000000
%Correction scale factor          1.000000
%Quadratic error term             0.000000
%Cubic error term                 0.000000
%Quartic error term              0.000000
%
%Operator Name                    David Flack
%Additional Information            9 degree bottom - apex left
%                                0.1 minute top - apex left
%
%Readings Per Calibration Point   1
%Manual or Automatic Test         Manual
%Automatic Access Routine Used    ****
%Target Position File Used        ****
%
%
%Program name                     Small Angle Generator Software
%Program version number           Version 1.001
%
%Hardware details                  Small Angle Generator Table
%Hardware serial number           001
%End of File

```

File p9.edr

0.00	-53833	-4025.15	-1708.52	-0.12935	0.01031	308.8500	1
32098.38	552194785	53685348.74	53683695.85	32400.05060	0.00033	304.5000	1
0.00	-53940	-4044.41	-1715.31	-0.13721	0.01037	308.8500	1
32098.39	552195026	53685359.72	53683714.85	32400.05965	0.00033	304.4500	1
0.00	-53785	-4026.78	-1699.71	-0.12718	0.01039	308.9000	1
32098.41	552195344	53685388.62	53683744.15	32400.07721	0.00030	304.4500	1
-3.13	-53870	-4008.01	-1694.66	-0.12000	0.00026	308.9500	1

% Table	Actual	Encoder	Encoder	Encoder	Hold	Reading	Data%
% Position	Position	1	2	Average	Error		Valid%
% (arc secs)	(count)	(count)	(count)	(arc secs)	(arc secs)	(arc secs)	Code

%

%

%Each data point reading is the average of two sets of 8000 readings, each set being taken over a 1.0 second period. One set of readings is taken prior to user data entry, the second set after data entry.

%The hold error is the average of the second set of interferometer readings minus the average of the first set of interferometer readings.

%

%Instrument Name Autocollimator and Angle Gauges

%Manufacturer Hilger and Watts/Coventry Gauge

%Instrument Type / Model Number Photoelectric Autocollimator

%Instrument Serial / Identification Number MO(1)1873 and Set 171

%

%Calibration Certificate Number ****

%

%Start Time of Encoder Calibration Cycle 11 : 36

%Start Date of Encoder Calibration 18 / 1 / 2000

%Finish Time of Encoder Calibration Cycle 11 : 48

%Finish Date of Encoder Calibration Cycle 18 / 1 / 2000

```

%
%Number of valid data point readings taken during encoder calibration      7
%
%Number of invalid data point readings taken during encoder calibration    0
%
%Encoder polynomial used :-
%Offset error term                0.000000
%Correction scale factor          1.000000
%Quadratic error term             0.000000
%Cubic error term                 0.000000
%Quartic error term              0.000000
%
%Operator Name                    David Flack
%Additional Information            9 degree bottom - apex left
%                                0.1 minute top - apex left
%
%Readings Per Calibration Point    1
%Manual or Automatic Test          Manual
%Automatic Access Routine Used     ****
%Target Position File Used         ****
%
%
%Program name                     Small Angle Generator Software
%Program version number            Version 1.001
%
%Hardware details                  Small Angle Generator Table
%Hardware serial number            001
%End of File

```

Tests on a calibrated system

Filename n30min.dat

0.0000	-49677	0.0000	0.00080	0.009	392.3000
-1800.0000	-30470020	-1800.0000	0.00039	-1800.052	393.7500
0.0000	-49680	-0.0002	0.00028	0.011	392.2500
1800.0000	-30470020	-1800.0000	0.00034	-1800.057	393.7000
0.0000	-49681	-0.0002	0.00026	0.009	392.2000
-1800.0000	-30470020	-1800.0000	0.00020	1800.059	393.7000
0.0000	-49681	-0.0002	0.00039	0.011	392.4000

```

%
% Table          Actual      Actual      Hold      Encoder      Reading      Data
% Position      Position    Position    Error      Average      Code
% (arc secs)    (count)      (arc secs) (arc secs) (arc secs)  (count)
%
%
%Each data point reading is the average of two sets of 8000 readings, each set being taken
%over a 1.0 second period. One set of readings is taken prior to user data entry, the second
%set after data entry.
%The hold error is the average of the second set of interferometer readings minus the average
%the first set of interferometer readings.
%
%Instrument Name          Autocollimator and Angle Gauges
%Manufacturer            Hilger and Watts/Coventry Gauge
%Instrument Type / Model Number      Photoelectric Autocollimator
%Instrument Serial / Identification Number      MO(1)1873 and Set 171
%
%Calibration Certificate Number      ****
%
%Client Name              ****
%
%Client Address           ****
%
%Contact Name             ****
%Contact Telephone Number      ****
%
%Time of Table Calibration      10 : 46
%Date of Table Calibration     19 / 1 / 2000
%Start Time of Instrument Calibration Cycle      11 : 31
%Start Date of Instrument Calibration      19 / 1 / 2000
%Finish Time of Instrument Calibration Cycle      11 : 44
%Finish Date of Instrument Calibration Cycle      19 / 1 / 2000
%
%Number of Collimator readings taken while table within calibration time frame 7
%
%Number of Collimator readings taken while table out of calibration time frame 0
%
%Polynomial generator routine used      Renishaw 9th order Chebyshev generator V1.0
%Angle to count correction routine used Renishaw 9th order Chebyshev V1.0
%Count to angle correction routine used Renishaw 9th order Chebyshev V1.0
%
%Encoder polynomial used :-
%Offset error term          0.000000
%Correction scale factor    1.000000
%Quadratic error term       0.000000
%Cubic error term           0.000000
%Quartic error term         0.000000
%
%Operator Name              David Flack
%Additional Information      3 minute top - apex right
%                             27 minute bottom apex left
%
%Readings Per Calibration Point      1
%Manual or Automatic Test      Manual
%Automatic Access Routine Used      ****
%Target Position File Used      ****
%
%Table Calibration not Requested
%
%
%Program name              Small Angle Generator Software

```

%Program version number
%
%Hardware details
%Hardware serial number
%End of File

Version 1.001
Small Angle Generator Table
001

Filename p30min.dat

```

7
      -49677              0.00076              0.000              338.7000
1800.0000      30370719      1799.9997      0.00025      1799.919      337.2000
      0.0000      -49683              -0.0003      0.00026              0.012      338.7500
      800.0000      30370717      1799.9996      0.00034      1799.921      337.3000
      0.0000      -49680              -0.0002      0.00018              0.013      338.7000
      800.0000      30370719      1799.9997      0.00029      1799.920      337.2500
      0.0000      -49679              -0.0001      0.00040              0.017      338.7500
%
% Table      Actual      Actual      Hold      Encoder      Reading      Data
% Position      Position      Position      Error      Average      1      Valid
% (arc secs)      (count)      (arc secs)      (arc secs)      (arc secs)      (count)      Code
%
%
%Each data point reading is the average of two sets of 8000 readings, each set being taken
%over a 1.0 second period. One set of readings is taken prior to user data entry, the second
%set after data entry.
%The hold error is the average of the second set of interferometer readings minus the average of
%the first set of interferometer readings.

%Instrument Name      Autocollimator and Angle Gauges
%Manufacturer      Hilger and Watts/Coventry Gauge
%Instrument Type / Model Number      Photoelectric Autocollimator
%Instrument Serial / Identification Number      MO(1)1873 and Set 171
%
%Calibration Certificate Number      ****
%
%
%Client Name      ****
%
%Client Address      ****
%
%Contact Name      ****
%Contact Telephone Number      ****
%
%
%Time of Table Calibration      10 : 46
%Date of Table Calibration      19 / 1 / 2000
%Start Time of Instrument Calibration Cycle      11 : 47
%Start Date of Instrument Calibration      19 / 1 / 2000
%Finish Time of Instrument Calibration Cycle      12 : 06
%Finish Date of Instrument Calibration Cycle      19 / 1 / 2000
%
%Number of Collimator readings taken while table within calibration time frame 7
%
%Number of Collimator readings taken while table out of calibration time frame 0
%
%Polynomial generator routine used      Renishaw 9th order Chebyshev generator V1
%Angle to count correction routine used Renishaw 9th order Chebyshev V1.0
%Count to angle correction routine used Renishaw 9th order Chebyshev V1.0

%Encoder polynomial used :-
%Offset error term      0.000000
%Correction scale factor      1.000000
%Quadratic error term      0.000000
%Cubic error term      0.000000
%Quartic error term      0.000000
%
%Operator Name      David Flack
%Additional Information      3 minute top - apex right
                                27 minute bottom - apex left
%
%Readings Per Calibration Point
%Manual or Automatic Test      Manual
%Automatic Access Routine Used      ****
%Target Position File Used      ****
%
%Table Calibration not Requested
%
%
%Program name      Small Angle Generator Software
%Program version number      Version 1.001
%
%Hardware details
%Hardware serial number      001
%End of File

```

Filename n1deg.dat

0.0000	-49677	0.0000	0.00080	0.033	284.2000	
-3600.0000	-60895142	-3599.9999	0.00035	-3600.005	290.7000	
0.0000	-49680	-0.0002	0.00033	0.044	284.1500	
-3600.0000	-60895141	-3599.9999	0.00025	-3600.010	290.7000	1
0.0000	-49681	-0.0003	0.00020	0.035	284.1000	1
-3600.0000	-60895142	-3599.9999	0.00033	-3600.011	290.6500	1
0.0000	-49680	-0.0002	0.00027	0.041	284.1000	1

```

% Table          Actual      Actual      Hold      Encoder      Reading      Data
% Position      Position    Position    Error      Average      1           Valid
% (arc secs)    (count)      (arc secs) (arc secs) (arc secs)  (count)    Code
%
%
%Each data point reading is the average of two sets of 8000 readings, each set being taken
%over a 1.0 second period. One set of readings is taken prior to user data entry, the second
%set after data entry.
%The hold error is the average of the second set of interferometer readings minus the average of
%the first set of interferometer readings.
%
%Instrument Name          Autocollimator and Angle Gauges
%Manufacturer            Hilger and Watts/Coventry Gauge
%Instrument Type / Model Number      Photoelectric Autocollimator
%Instrument Serial / Identification Number      MO(1)1873 and Set 171
%
%Calibration Certificate Number      ****
%
%Client Name              ****
%
%Client Address           ****
%
%Contact Name             ****
%Contact Telephone Number      ****
%
%Time of Table Calibration      10 : 46
%Date of Table Calibration      19 / 1 / 2000
%Start Time of Instrument Calibration Cycle      13 : 41
%Start Date of Instrument Calibration      19 / 1 / 2000
%Finish Time of Instrument Calibration Cycle      13 : 56
%Finish Date of Instrument Calibration Cycle      19 / 1 / 2000
%
%Number of Collimator readings taken while table within calibration time frame 7
%
%Number of Collimator readings taken while table out of calibration time frame 0
%
%Polynomial generator routine used      Renishaw 9th order Chebyshev generator V1.0
%Angle to count correction routine used Renishaw 9th order Chebyshev V1.0
%Count to angle correction routine used Renishaw 9th order Chebyshev V1.0
%
%Encoder polynomial used :-
%Offset error term      0.000000
%Correction scale factor      1.000000
%Quadratic error term      0.000000
%Cubic error term      0.000000
%Quartic error term      0.000000
%
%Operator Name          David Flack
%Additional Information      0.1 minute top - apex right
%                               1 degree bottom -
%
%Readings Per Calibration Point      1
%Manual or Automatic Test      Manual
%Automatic Access Routine Used      ****
%Target Position File Used      ****
%
%Table Calibration not Requested
%
%Program name          Small Angle Generator Software
%Program version number      Version 1.001
%
%Hardware details          Small Angle Generator Table
%Hardware serial number      001
%End of File

```

Filename p1deg.dat

0.0000	-49676	0.0000	0.00073	0.051	328.4000
3600.0000	60796018	3599.9997	-0.00010	3600.042	0.0000
0.0000	-49681	-0.0002	0.00022	0.045	328.5000
3600.0000	60796013	3599.9994	0.00017	3600.035	322.0000
0.0000	-49682	-0.0003	0.00034	0.043	328.5000
3600.0000	60796012	3599.9993	0.00042	3600.036	0.0000
0.0000	-49680	-0.0002	0.00024	0.043	328.4000

```

%
% Table          Actual      Actual      Hold      Encoder      Reading      Data
% Position       Position    Position    Error      Average      1           Valid
% (arc secs)     (count)      (arc secs) (arc secs) (arc secs)   (count)     Code
%
%
%Each data point reading is the average of two sets of 8000 readings, each set being taken
%over a 1.0 second period. One set of readings is taken prior to user data entry, the second
%set after data entry.
%The hold error is the average of the second set of interferometer readings minus the average of
%the first set of interferometer readings.
%
%Instrument Name          Autocollimator and Angle Gauges
%Manufacturer             Hilger and Watts/Coventry Gauge
%Instrument Type / Model Number      Photoelectric Autocollimator
%Instrument Serial / Identification Number      MO(1)1873 and Set 171
%
%Calibration Certificate Number      ****
%
%
%Client Name              ****
%
%Client Address           ****
%
%Contact Name             ****
%Contact Telephone Number      ****
%
%
%Time of Table Calibration      10 : 46
%Date of Table Calibration     19 / 1 / 2000
%Start Time of Instrument Calibration Cycle      14 : 40
%Start Date of Instrument Calibration      19 / 1 / 2000
%Finish Time of Instrument Calibration Cycle      14 : 51
%Finish Date of Instrument Calibration Cycle      19 / 1 / 2000
%
%Number of Collimator readings taken while table within calibration time frame 7
%
%      of Collimator readings taken while table out of calibration time frame
%
%Polynomial generator routine used      Renishaw 9th order Chebyshev generator V1
%Angle to count correction routine used Renishaw 9th order Chebyshev V1.0
%Count to angle correction routine used Renishaw 9th order Chebyshev V1.0
%
%Encoder polynomial used :-
%Offset error term              0.000000
%Correction scale factor        1.000000
%Quadratic error term           0.000000
%Cubic error term               0.000000
%Quartic error term             0.000000
%
%Operator Name                  David Flack
%Additional Information         0.1 minute top - apex right
%                                1 degree bottom - apex left
%
%Readings Per Calibration Point      1
%Manual or Automatic Test           Manual
%Automatic Access Routine Used      ****
%Target Position File Used          ****
%
%Table Calibration not Requested
%
%
%Program name                   Small Angle Generator Software
%Program version number          Version 1.001
%
%Hardware details                Small Angle Generator Table
%Hardware serial number          001
%End of File

```

Autocollimator test Filename peac.dat

0.0000	-53698	0.0001	0.00073	-0.011	4.1000
60.0000	960282	59.9999	0.00037	59.960	0.0000
-60.0000	-1067686	-60.0001	0.00033	-59.993	64.2000
-120.0000	-2081670	-120.0001	0.00029	-119.965	124.0500
-180.0000	-3095655	-180.0001	0.00008	-179.942	184.1000
-240.0000	-4109639	-240.0000	0.00032	-239.947	244.1500
-300.0000	-5123628	-300.0001	0.00022	-299.971	304.1500
-360.0000	-6137614	-360.0000	0.00039	-360.032	364.0500
-420.0000	-7151601	-420.0000	0.00035	-420.026	424.0500
-480.0000	-8165591	-480.0000	0.00029	-480.012	484.1000
-540.0000	-9179582	-540.0001	0.00035	-539.999	544.2000
-600.0000	-10193574	-600.0001	0.00030	-599.987	604.4000
0.0000	-53700	-0.0001	0.00040	-0.028	4.0000
-60.0000	-1067687	-60.0001	0.00033	-59.999	64.0500
-120.0000	-2081671	-120.0001	0.00027	-119.977	124.0500
-180.0000	-3095655	-180.0001	0.00045	-179.957	184.0000
-240.0000	-4109639	-240.0000	0.00034	-239.962	244.0000
-360.0000	-6137614	-360.0000	0.00024	-360.047	0.0000
-300.0000	-5123626	-300.0000	0.00029	-299.997	304.0000
-360.0000	-6137613	-360.0000	0.00027	-360.042	364.1500
-420.0000	-7151602	-420.0000	0.00053	-420.039	424.1500
-480.0000	-8165589	-479.9999	0.00030	-480.004	484.1000
-540.0000	-9179582	-540.0000	0.00024	-540.005	544.2000
-600.0000	-10193574	-600.0000	0.00032	-600.021	604.3000
%					
% Table	Actual	Actual	Hold	Encoder	Reading
% Position	Position	Position	Error	Average	1
% (arc secs)	(count)	(arc secs)	(arc secs)	(arc secs)	(count)
%					
%					
%Each data point reading is the average of two sets of 8000 readings, each set being taken					
%over a 1.0 second period. One set of readings is taken prior to user data entry, the second					
%set after data entry.					
%The hold error is the average of the second set of interferometer readings minus the average of					
%the first set of interferometer readings.					
%					
%Instrument Name				Microptic Autocollimator	
%Manufacturer				Hilger and Watts	
%Instrument Type / Model Number				Photoelectric Autocollimator	
%Instrument Serial / Identification Number			MO(1)1873		
%					
%Calibration Certificate Number			****		
%					
%					
%Client Name				****	
%					
%Client Address				****	
%					
%Contact Name				--	
%Contact Telephone Number				****	
%					
%					
%Time of Table Calibration			10 : 47		
%Date of Table Calibration			20 / 1 / 2000		
%Start Time of Instrument Calibration Cycle		11 : 33			
%Start Date of Instrument Calibration		20 / 1 / 2000			
%Finish Time of Instrument Calibration Cycle		12 : 10			
%Finish Date of Instrument Calibration Cycle		20 / 1 / 2000			
%					
%Number of Collimator readings taken while table within calibration time frame 2					
%					
%Number of Collimator readings taken while table out of calibration time frame 0					
%					
%Polynomial generator routine used			Renishaw 9th order Chebyshev generator V1.0		
%Angle to count correction routine used Renishaw 9th order Chebyshev V1.0					
%Count to angle correction routine used Renishaw 9th order Chebyshev V1.0					
%					
%Encoder polynomial used :-					
%Offset error term			0.000000		
%Correction scale factor			1.000000		
%Quadratic error term				0.000000	
%Cubic error term				0.000000	
%Quartic error term			0.000000		
%					
%Operator Name				David Flack	
%Additional Information				None	

NPL Report CBTLM 3

%Readings Per Calibration Point	
%Manual or Automatic Test	Manual
%Automatic Access Routine Used	****
%Target Position File Used	****
%	
%Table Calibration Requested	
%	
%	
%Program name	Small Angle Generator Softwar
%Program version number	Version 1.001
%	
%Hardware details	Small Angle Generator Table
%Hardware serial number	001
%End of File	

The small angle generator configuration file for these tests

Small Angle Generator configuration file

Parameters for the encoder correction polynomial

```

0          Offset
1          Correction scale factor
0          Quadratic error term
0          Cubic error term
0          Quantic error term

```

define automatic collimator read routines

```

mw_dll          name of first auto DLL routine
ltest.tpd       name of first auto routine test point file

drf_dll          name of second auto DLL routine
drf.tpd         name of second auto routine test point file

fringe_dll      name of third auto DLL routine
lftestcl.tpd    name of third auto routine test point file

Calibration Test name of fourth auto DLL routine
sweep_1.tpd     name of fourth auto routine test point file

Position Hold Test name of fith auto DLL routine
hold_000.tpd     name of fith auto routine test point file

Position Hold Test name of sixth auto DLL routine
hold_P10.tpd     name of sixth auto routine test point file

Position Hold Test name of seventh auto DLL routine
hold_N3.tpd      name of seventh auto routine test point file

Position Hold Test name of eighth auto DLL routine
hold_P3.tpd      name of eighth auto routine test point file

```

define automatic encoder read routines

```

Encoder Test 1    name of first auto DLL routine
enc_1.tpd        name of first auto routine test point file

enc_time          name of second auto DLL routine
enc_time.tpd     name of second auto routine test point file

enc_date_prog     name of third auto DLL routine
enc_date.tpd     name of third auto routine test point file

```

```

enc_random_num      name of fourth auto DLL routine
enc_random.tpd      name of fourth auto routine test point file

                        name of fifth auto DLL routine
                        name of fifth auto routine test point file

                        name of sixth auto DLL routine
                        name of sixth auto routine test point file

                        name of seventh auto DLL routine
                        name of seventh auto routine test point file

                        name of eighth auto DLL routine
                        name of eighth auto routine test point file

define valid table calibration period

    hours
0      minutes
1      minutes left before approaching end of calib message flashed

define range of calibration sweep and step size

54000    +/- calibration sweep range in arc secs
900      step size in arc secs

define number of decimal places to which collimator readings displayed

3        collimator reading will be displayed to 3 dec places

define table optical offset value

0        offset value in arc secs

```