Key Comparison

CCL-K3

Calibration of angle standards

Report - Final

NMISA August 2007

Contents

1 Introduction

The metrological equivalence of national measurement standards and calibration certificates issued by national metrology institutes is established by a set of key comparisons chosen and organised by the Consultative Committees of the CIPM or by the regional metrology organisations in collaboration with the Consultative Committees.

At the meeting in September 1997, the Consultative Committee for Length, CCL, decided on a key comparison of angle standards, numbered CCL-K3, which started in 2000 with the National Metrology Laboratory (CSIR-NML), changed to NMISA in 2007, as the pilot laboratory.

The result of this international comparison contributes to the Mutual Recognition Arrangement (MRA) between the national metrology institutes of the Metre Convention. This CIPM key comparison is linked with regional comparisons (RMO key comparisons) following exactly the same protocol. Laboratories participating in both the CIPM and the RMO comparisons establish the link between these and ensure equivalence of national metrology institutes according to the MRA between NMis.

2 Organisation

According to the rules set up by the CIPM [1] a small group from the list of participating laboratories drafted the detailed technical protocol. The group was comprised of Jim Pekelsky from the NRC- Canada, Rudi Thalmann from METAS- Switzerland, Reinhard Probst from the PTB and Oelof Kruger from the pilot laboratory, CSIR-NML. The protocol and this report have been based on the corresponding documents for key comparison CCL-K1 [2] and CCL-K2 [3]. The protocol document was issued to all participants at the start of the comparison.

2.1 Participants

All members of the CCL were invited to participate subject to meeting certain technical requirements as laid out in the draft protocol document. In order to further reduce the number of participants to an acceptable level, each RMO was asked to limit the number of participants in their region by its own decision process. This prevented the comparison from taking too long with the commensurate risk of excessive damage to the artefacts. The participants were organised into regional groups to assist in the transportation of the artefacts. The list of participants is given in Table 1 below.

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SIM		
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Dr Theodore D. Doiron	**National Institute of Standards and Technology** Metrology (220) Room B118, 100 Bureau Drive, Stop 8211 Gaithersburg, MD, 20899-8211 USA	Tel: 1 301 975 3472 Fax: 1 301 869 0822 e-mail theodore.doiron@nist.gov
Dr Jim Pekelsky	**Institute for National Measuring Standards** National Research Council Canada Ottawa K1A OR6 CANADA	Tel: + 1 613 993 7578 Fax: + 1 613 952 1394 e-mail: jim.pekelsky@nrc.ca

Table 1 Participating laboratories.

2.2 Schedule

The comparison has been carried out in a mixed form, circulation and star-type. After the standards had been circulated in a region, they went back to the pilot laboratory before moving on to the next region. Re-scheduling of the COOMET region was necessary due to problems with customs during the proposed circulation of the artefacts in the area.

Each laboratory was allocated four weeks to make all necessary measurements and one week for transportation to the next participant. The schedule was set up to suit the laboratories to ensure enough time for measurement. It was found, however, that the four weeks and one week allocated for transportation to the next laboratory was not sufficient. This necessitated changes to the schedule and thus made it more difficult for the laboratories that were last on the schedule. The final circulation schedule is in table 2 below.

Region	**Laboratory**	**Start Date**
Pilot laboratory		**July 2000**
APMP	NIM KRISS NMIJ	21 August 2000 2 October 2000 13 November 2000
Pilot laboratory		20 January 2001
COOMET	SMU	15 March 2001
EUROMET	PTB METAS LNE IMGC	28 May 2001 9 July 2001 20 August 2001 1 October 2001
Pilot laboratory		12 December 2001
SIM	NIST NRC CENAM	28 January 2002 11 March 2002 22 April 2002
Pilot laboratory		3 June 2002
COOMET	VNIIM	24 June 2002
Pilot laboratory		August 2002

Table 2 Time schedule of the comparison.

3 Standards

3.1 The artefacts to be measured consisted of a 12-sided polygon and 4 angle blocks.

3.2 Four angle blocks, 5"; 5'; 30' and 5° were to be used to test the Calibration and Measurement Capabilities (CMC) of the laboratory to demonstrate the extreme of their calibration range. The angle blocks were Webber blocks made from a material known as chrome carbide. All the angle blocks had the serial number OGU6. The blocks had a measuring face of 50*25 mm.

3.3 The polygon with a serial number of 9.387OP7, which was also manufactured by Webber and consisted of the material chrome carbide, had a measuring faces of 16*14 mm. The polygon had a centre hole of 25.4 mm for mounting purposes and a thickness of 18.5 mm. The polygon was used to test the Best Measurement Capability (BMC) of the laboratories.

3.4 The angle blocks had to be measured using an aperture, which was 1mm less (on the edge) than the overall face.

3.5 Drawing:

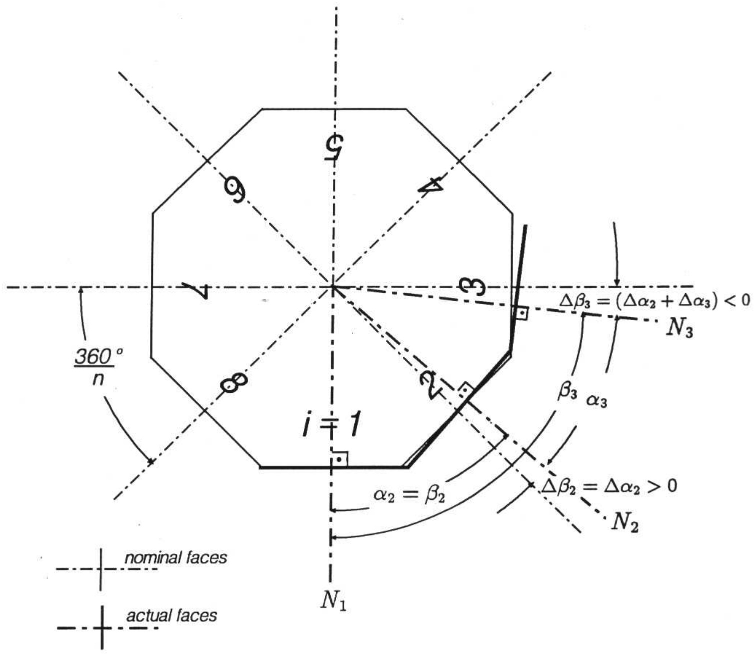


Figure 1: Schematic drawing of the polygon. The pitch angles α_i are the angles between the projections of two adjacent normals N_{i-1} and N_i in the measuring plane with the counting index (i=1,2,...,n). The deviations of the pitch angles from their nominal values of 360°/n are referred to as pitch angle devi ations.

The standards were supplied in a custom-made case in which it was transported. It was manufactured from aluminium, lined with high-density foam and sculpted for a tight fit for each individual gauge in order to prevent any motion thereof.

Even with these precautions in place, the polygon was damaged during transport from the APMP region to the pilot laboratory. A loose holding bolt that was not clamped down and just placed in the polygon's individual container caused the damage. This probably happened at customs during inspection.

4 Measurement instructions and reporting of results

Before calibration, the gauges had to be inspected for damage on the measurement surfaces. Any scratches, rusty spots or other damage had to be documented using forms appended to the protocol and returned to the pilot laboratory.

5 Measurement methods and instruments used by the participants

A wide variety of instruments and techniques were used to make measurements. The details of these instruments and techniques are recorded in Table 3 with the uncertainties of the equipment appearing in brackets. Participants were selected on their knowledge and ability to measure at an uncertainty of better than 0,2".

For the movement of the polygon/angle block, the majority of the participants used index tables, Moore and Heidenhain, with a few exceptions where laboratories use other devices such as a ring laser or in-house designed systems. For the measuring of the deviation from nominal, most laboratories used autocollimators with only two using laser interferometers.

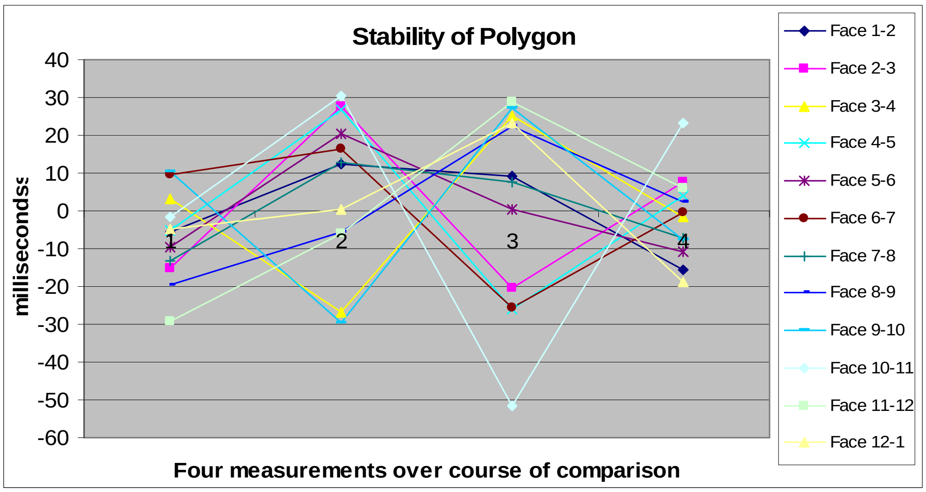
Laboratory	**Autocollimator/ Interferometer (uncertainty in milliseconds)**	**Table (uncertainty in milliseconds)**
NIM (China)	TA 80 Hilger Watts (29)	CDFT 720A Chinese table (17)
KRISS (Korea)	Möller-Wedel (30)	Moore 1440 (40)
NMIJ (Japan)	Möller-Wedel (12)	Canon Index Table (8.6)
SMU (Slovakia)	Photoelectric	Ring laser
PTB (Germany)	Möller-Wedel Elcomat (10)	Heidenhain (2.4)
METAS (Switzerland)	Möller-Wedel Elcomat (10)	Heidenhain air bearing rotary table with RON 905 encoder (20)
LNE (France)	Möller-Wedel Elcomat (10)	In-house designed (15)
IMGC (Italy)	TA 5 Hilger Watts (10)	Moore 1440 (6)
NIST (USA)	Möller-Wedel /interferometer (13)	AG Davis AAMACS (0)
CENAM (Mexico)	DA 20 RTH (35)	Moore 1440 (0)
NRC (Canada)	Möller-Wedel (30)	Moore 1440 (20)
VNIIM (Russia)	In-house (20)	In-house (30)
CSIR-NML (South Africa)	Interferometer (25)	Moore 2160 (50)

Table 3 Measurement instruments and their uncertainties (k=1) as reported by the participating laboratories.

6 Stability and condition of the gauges

6.1 Stability of the gauges

The CSIR-NML made measurements before the start of the comparison. The laboratory made a further two measurements during the comparison and one at the end of the comparison, all using the same equipment as those used to perform the first measurements. The system, phase shifting interferometer used, had to be calibrated before every set of the measurements, as the same calibration data for the interferometer could not be used over such a long period of time, however, the same method was used. This unfortunately widens the uncertainty of the stability measurements.



Graph 1: Stability of the polygon.

The results obtained by the pilot laboratory are in good agreement as illustrated by graph 1 and it can be concluded that the nominal angles of the polygon did not change substantially. The graph shows the deviation from the mean for each face-to-face reading. A standard deviation on each of the sets of four readings was calculated with the worst being 37 milliseconds for face 11-12 with an average of 20 milliseconds. The uncertainty in these measurements is the same as for the results given by the pilot laboratory, ± 0,15 ".

The stability of the angle blocks was measured by the pilot laboratory as the uncertainty in the calibration was quite large and it was felt that the results from these were not conclusive. This will be discussed later when looking at the results form all the laboratories.

6.2 Condition of the gauges

The protocol was written so that only optical measurements were allowed and so that there was no touching of the faces. It was not expected that any damage to the gauge would be incurred. Unfortunately, the polygon was damaged during transportation from the APMP region back to the pilot laboratory. It is suspected that the polygon was not properly fastened after inspection at customs, causing the loose bolt to damage the face of the polygon. After this incident, extra protection was fitted to the polygon holder to prevent any further damage. The damage to the polygon faces did not influence the results and will be discussed later.

The angle blocks were in separate boxes and were not damaged during this incident.

It appears that there was no damage to any of the gauges, except for the incident during transportation and the laboratories did in fact handle the gauges with great care.

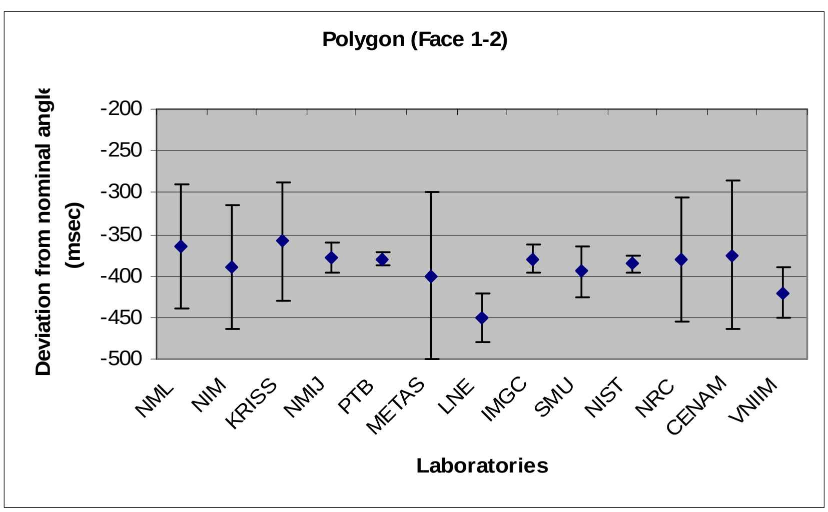
7 Measurement results, as reported by participants

7.1 Polygon; Deviation from nominal angle

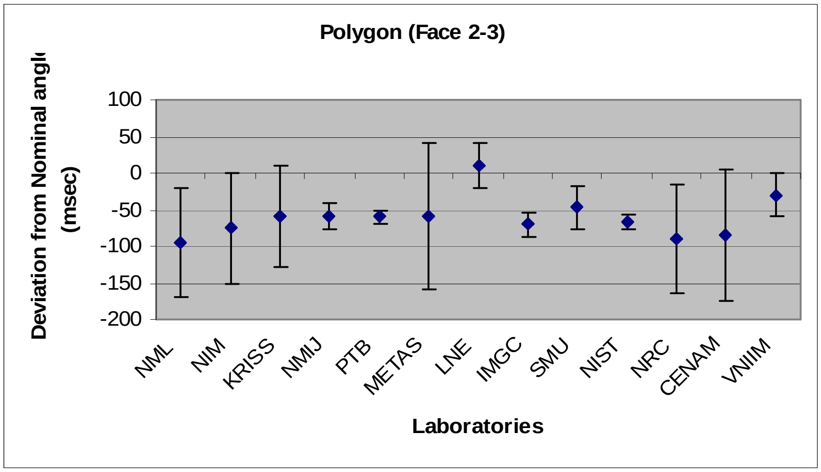
Face	NML	NIM	KRISS	NMIJ	PTB	METAS	LNE	IMGC	SMU	NIST	NRC	CENAM	VNIIM
1-2	-365	-389	-359	-379	-380	-400	-450	-380	-395	-386	-380	-375	-420
2-3	-95	-75	-59	-58	-60	-60	10	-70	-47	-66	-90	-84	-30
3-4	397	375	337	371	380	400	370	340	377	423	410	346	390
4-5	249	247	245	226	230	220	240	280	252	224	260	227	260
5-6	-092	-75	-68	-78	-80	-70	-110	-90	-94	-74	-70	-6	-100
6-7	-625	-572	-559	-571	-580	-570	-580	-560	-601	-590	-590	-589	-620
7-8	-189	-202	-173	-178	-160	-160	-190	-210	-189	-179	-200	-161	-210
8-9	-58	-59	-59	-42	-50	-50	20	-60	-28	-37	-10	-64	-10
9-10	337	337	309	345	320	310	260	340	345	329	340	295	370
10-11	390	384	361	350	360	360	400	390	377	354	330	343	390
11-12	-242	-214	-244	-256	-230	-240	-220	-170	-239	-227	-250	-382	-190
12-1	308	244	269	271	250	270	250	180	265	256	250	442	170

Table 4 Tabular presentation of the results for the polygon in milliseconds.

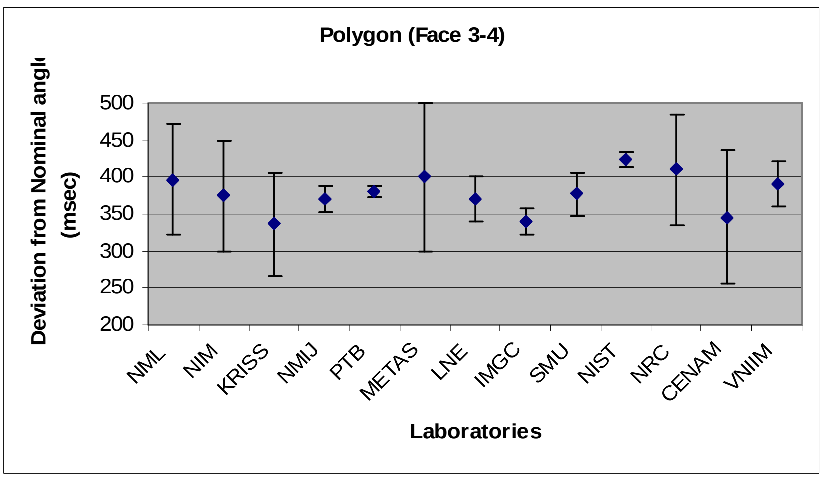
Graphs 2(a) through to 2(l) are all measurement results from the polygon reporting the deviation from the nominal angle are given along with their combined standard uncertainties as reported by the participants.



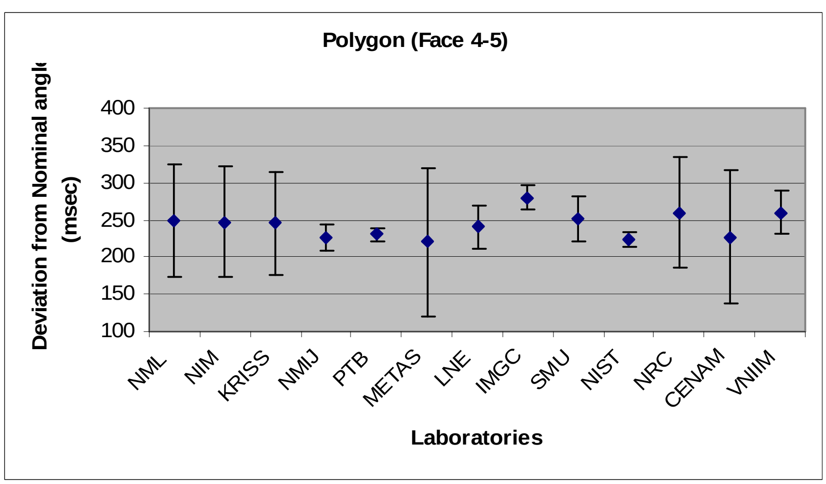
Graph 2(a) Results for the polygon, face 1 to 2 (standard uncertainty bars shown). LNE and VNIIM have measurement errors on face2, as can be seen from the opposite deviation directions in graph 2(a) and (b).



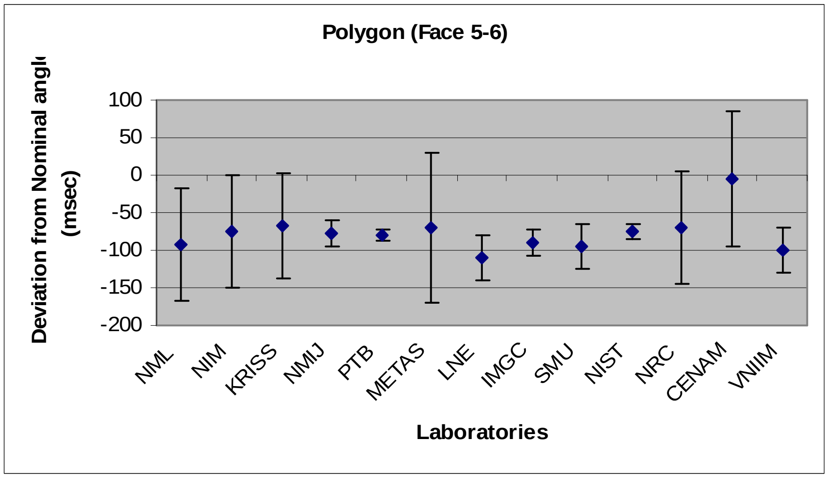
Graph 2(b) Results for the polygon, face 2 to 3 (standard uncertainty bars shown).



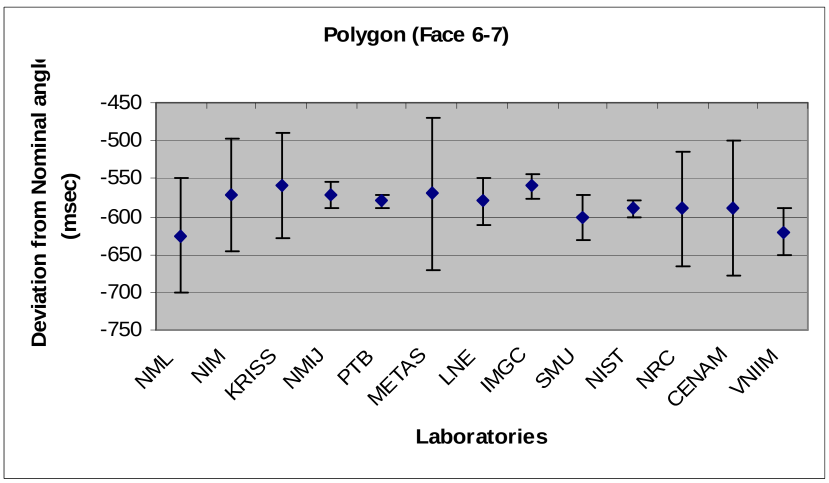
Graph 2(c) Results for the polygon, face 3 to 4 (standard uncertainty bars shown).



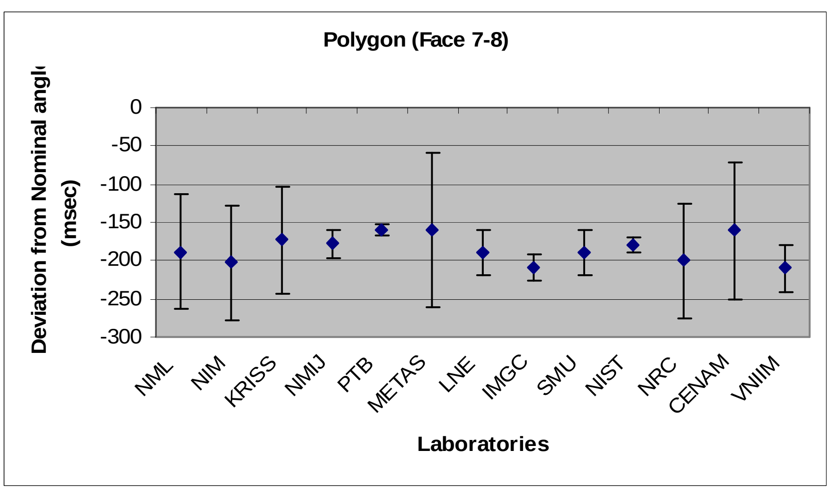
Graph 2 (d) *Results for the polygon, face 4 to 5 (standard uncertainty bars shown).*



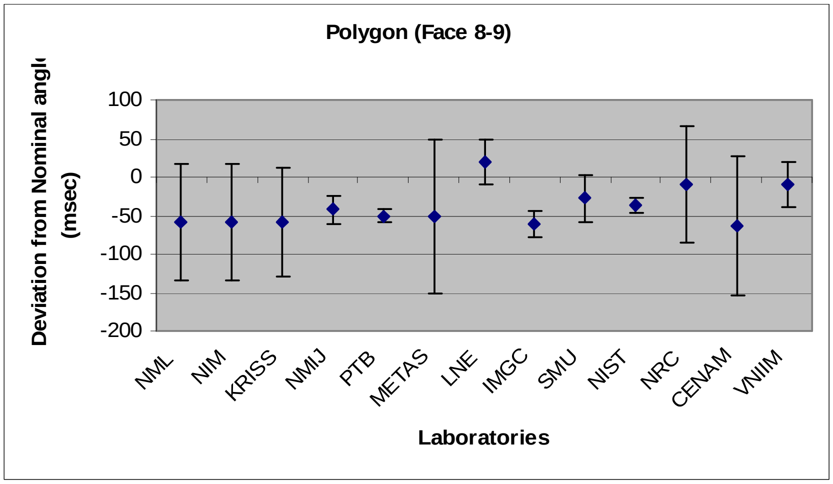
Graph 2(e) *Results for the polygon, face 5 to 6 (standard uncertainty bars shown).*



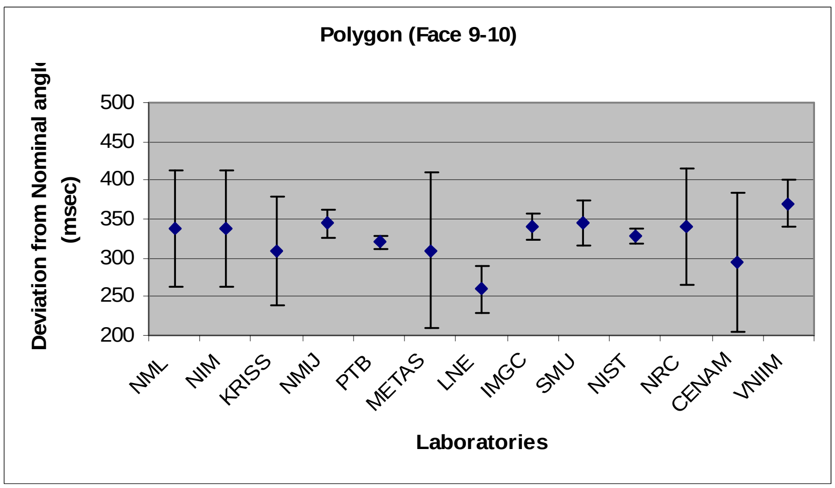
Graph 2(f) *Results for the polygon, face 6 to 7 (standard uncertainty bars shown).*



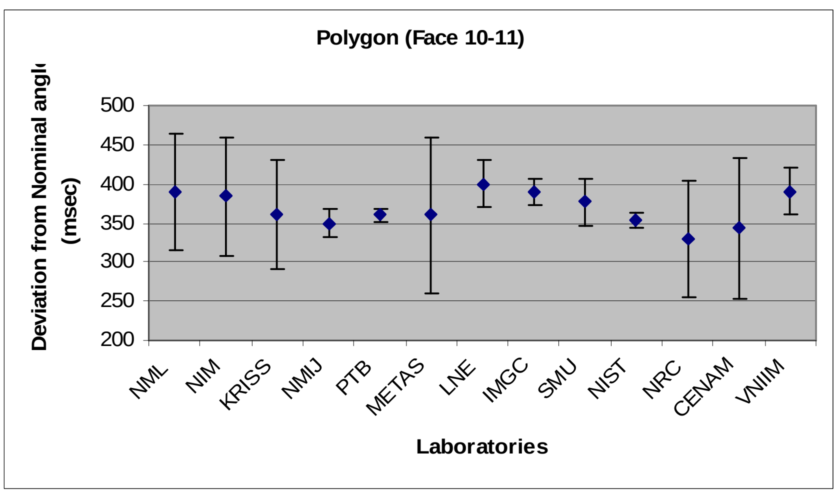
Graph 2(g) *Results for the polygon, face 7 to 8 (standard uncertainty bars shown).*



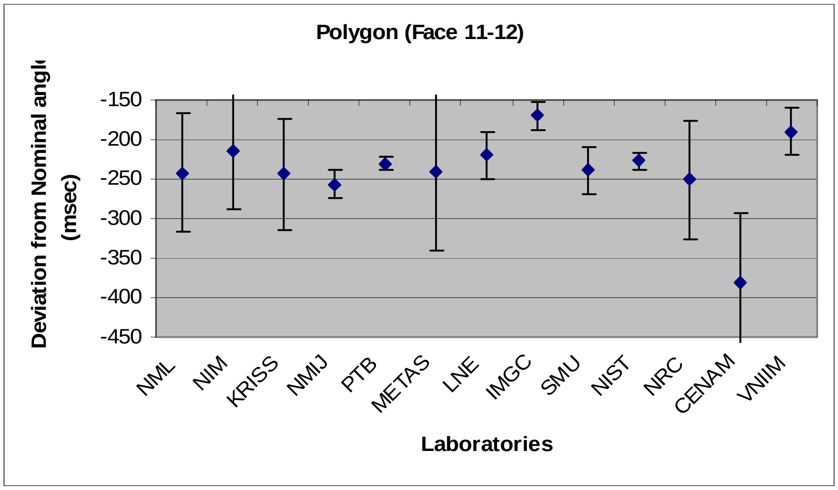
Graph 2(h) *Results for the polygon, face 8 to 9 (standard uncertainty bars shown). LNE has measurement errors on face 9, as can be seen from the opposite directions in graphs 2(h) and (i).*



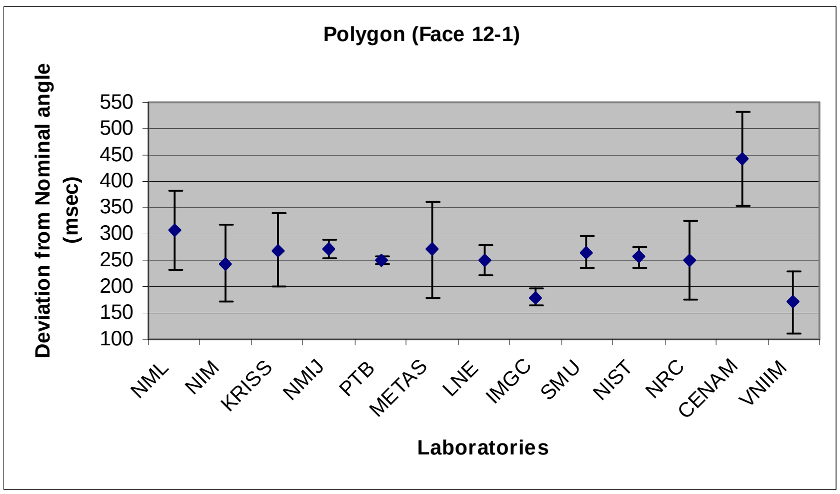
Graph 2(i) *Results for the polygon, face 9 to 10 (standard uncertainty bars shown).*



Graph 2(j) *Results for the polygon, face 10 to 11 (standard uncertainty bars shown).*



Graph 2(k) Results for the polygon, face 11 to 12 (standard uncertainty bars shown). VNIIM, CENAM and IMGC have measurement errors on face 12, as can be seen from the opposite directions in graphs 2(k) and (l).



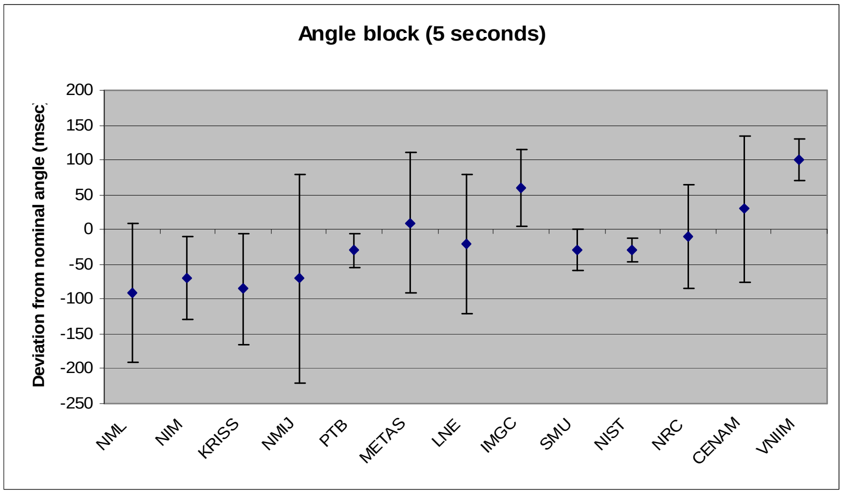
Graph 2(l) Results for the polygon, face 12 to 1 (standard uncertainty bars shown).

7.2 Angle blocks; Deviation from nominal angle

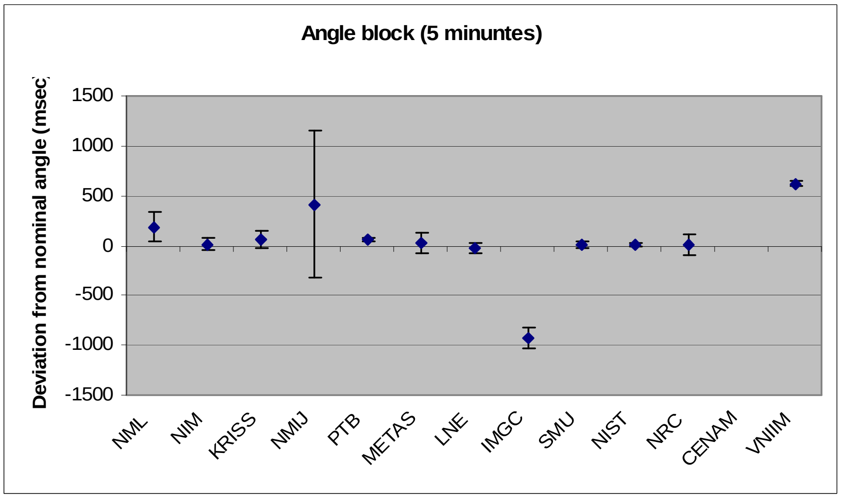
Graphs 3(a) through to 3(d), are all measurement results for the four angle blocks reporting the deviation from nominal angle and are given along with their combined standard uncertainties as reported by the participants. The stability of the gauge blocks were not discussed under section 6, where only results on the stability of the polygon were discussed. When looking at the results from all the laboratories, it seems to be drift in the 5" angle block. However, PTB, SMU and NIST, the three laboratories with the small uncertainties, do agree very well. Two of these laboratories measurements were made 8 months apart. This drift was therefore not taken into account when calculating the Key comparison reference value, KCRV. The other three blocks did not show any amount of drift.

Angle block	NML	NIM	KRISS	NMIJ	PTB	METAS	LNE	IMGC	SMU	NIST	NRC	CENAM	VNIIM
5"	-90	-70	-85	-70	-30	10	-20	60	-30	-29	-10	30	100
Uncertainty	100	57	82	145	50	70	50	55	60	23	75	105	60
5'	190	10	62	410	60	30	-30	-930	10	10	10	X	520
Uncertainty	150	57	82	692	50	70	50	105	60	23	100	X	60
30'	600	530	520	-210	560	560	60	530	540	561	590	510	620
Uncertainty	100	64	82	360	50	80	50	55	60	23	75	105	60
5°	370	250	287	150	360	340	250	280	280	274	340	300	170
Uncertainty	100	64	82	624	50	70	50	68	60	23	75	105	60

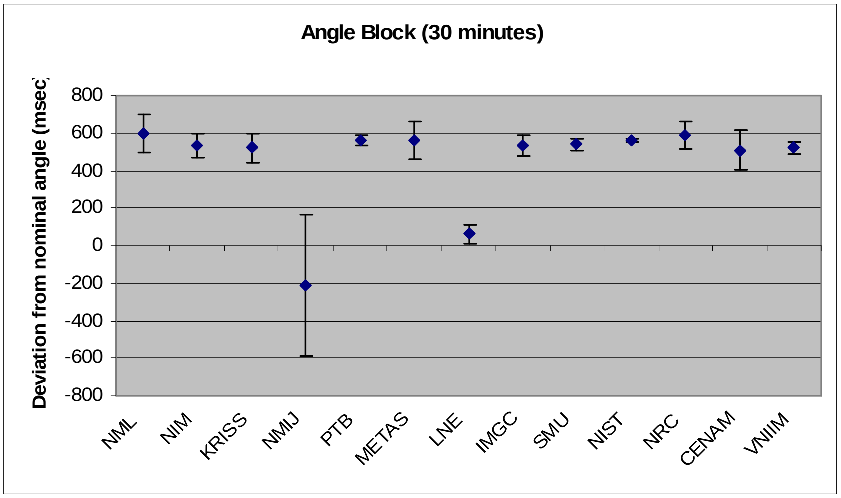
Table 5 Tabular presentation of the results for the four angle blocks in milliseconds.



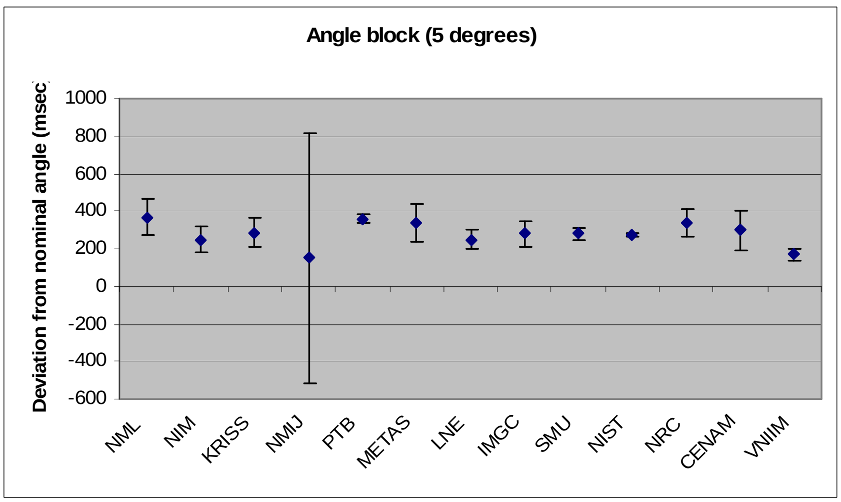
Graph 3(a) Results for the angle block, 5 seconds (standard uncertainty bars shown).



Graph 3(b) Results for the angle block, 5 minutes (standard uncertainty bars shown).



Graph 3(c) *Results for the angle block, 30 minutes (standard uncertainty bars shown).*



Graph 3(d) *Results for the angle block, 5 degrees (standard uncertainty bars shown).*

8 Measurement uncertainties

8.1 Model equations

The participants were asked (in the technical protocol of the comparison) to estimate the uncertainty of measurement according to the *ISO Guide for the Expression of Uncertainty in Measurement*. An example of a mathematical model [3] was given but participants were encouraged to use their own. This was due to a variety of measurement techniques and equipment being used and angle uncertainties in general not being well defined as in some other dimensional fields.

The majority of participants took the following contributions to the combined uncertainty into account:

The pitch angle deviations are described by:

$$\Delta\alpha_i = \alpha_i - \frac{360°}{n} + \delta A_F + \delta A_P + \delta A_E \qquad (i = 2,3\ldots12) \qquad (1)$$

$$\alpha_i = Ç - §$$

Where:

α_i the pitch angle
δA_F correction for flatness deviations of measuring face
δA_P correction for pyramidal errors of measuring face
δA_E correction for eccentricity errors in setup of polygon/angle block
§ autocollimator / interferometer reading
Ç index table reading
i measuring face index

In Table 6 the uncertainty contributions are summarised for all laboratories for the polygon. The uncertainties are given in milliseconds.

Laboratory	**§**	**Ç**	**δA_F**	**δA_P**	**δA_E**	**Repeat.**	**Combined uncertainty**
NIM (China)	29	17	47	0.4	47	2.4	73
KRISS (Korea)	30	40	15	36	9	25	69
NMIJ (Japan)	12	8.6				10	18
SMU (Slovakia)	10	60	20		1		60
PTB (Germany)	10	2.4	4	9		3	15
METAS (Switzerland)	10	20	80	30		20	90
LNE (France)	10	15	4.7	4.7	4.7	28+4.7 Auto+ Table	30
IMGC (Italy)	10	6	10			5	16
NIST (USA)	13		9	4	4	10	20
CENAM (Mexico)	35		31	80	4	7	82
NRC (Canada)	30	20	50	25	25	25	75
VNIIM (Russia)	20	30	20	30	10	30	60
CSIR-NML (South Africa)	25	50	28	25	10	30	75

Table 6 Standard uncertainties (in milliseconds) for the polygon quoted by the different laboratories for the different uncertainty contributions, and combined standard uncertainty calculated from these values.

In Table 7, the uncertainty contributions are summarised for all laboratories for the angle blocks. The uncertainties are given in milliseconds.

Laboratory	§	Ç	δA_F	δA_P	δA_E	Repeat.	Combined uncertainty
NIM (China)	29	33	30	0.8	31	14	130
KRISS (Korea)	50	40	24	30		35	80
NMIJ (Japan)	20	20				692	735
SMU (Slovakia)	100	60	10		1		
PTB (Germany)	24	36	8	11		22	50
METAS (Switzerland)	10	20	80	30		20	90
LNE (France)	10	15	4.7	4.7	4.7	28+ 4.7 Auto+ Table	50
IMGC (Italy)	100	40	10			105	110
NIST (USA)	5	10	9	4	4	17	23
CENAM (Mexico)	35	60	31	69	10	20	105
NRC (Canada)	30	20	50	25	25	25	75
VNIIM (Russia)	20	30	20	30	10	30	60
CSIR-NML (South Africa)	25	100	28	25	10	30	110

Table 7 Standard uncertainties (in milliseconds) for the 5 ' angle block (largest uncertainty) quoted by the different laboratories for the different uncertainty contributions, and combined standard uncertainty calculated from these values.

The examination of Table 6 and 7 shows that uncertainties contributions are well specified in general, with all the laboratories stating uncertainty contributions for the table, the autocollimator/interferometer and repeatability.

9 Analysis of the reported results

The reported measurement results should be analysed by simple statistical means to allow identification of any significant bias or outliers, as well as to investigate the statistical distribution of the results.

At the 12th WGDM meeting it was decided that the weighted mean will be used as the reference value for all intercomparisons. The discussions around the calculation of the KCRV is explained in appendix A.

9.1 Internal and external uncertainties and the Birge ratio test

The uncertainty of the reference value for the KCRV is calculated as the internal standard deviation. The internal standard deviation is based on the estimated uncertainties as reported by the laboratories and is calculated from equation 3 as follows:

$$\mathrm{u}_{\mathrm{int}}\left(\bar{x}_{\mathrm{w}}\right)=\sqrt{\frac{1}{\sum_{i=1}^{I}\left(\frac{1}{u(x_i)}\right)^2}} \qquad (3)$$

The external standard deviation is calculated, with I the number of participants:

$$\mathrm{u}_{\mathrm{ext}}\left(\bar{x}_{\mathrm{w}}\right)=\sqrt{\frac{1}{(I-1)}\cdot\frac{\sum_{i=1}^{I}\frac{1}{[u(x_i)]^2}\left(x_i-\bar{x}_w\right)^2}{\sum_{i=1}^{I}\frac{1}{[u(x_1)]^2}}} \qquad (4)$$

The Birge ratio has an expectation value of 1(for a large number of *I*) where the Birge ratio is calculated [6]:

$$R_B=\frac{u_{ext}\left(\bar{x}_w\right)}{u_{\mathrm{int}}\left(\bar{x}_w\right)} \qquad (5)$$

The Birge ratio has an expectation value of R_B=1, when considering standard uncertainties. For a coverage factor of *k=2*, the expectation value is increased and the data in a comparison are consistent provided that:

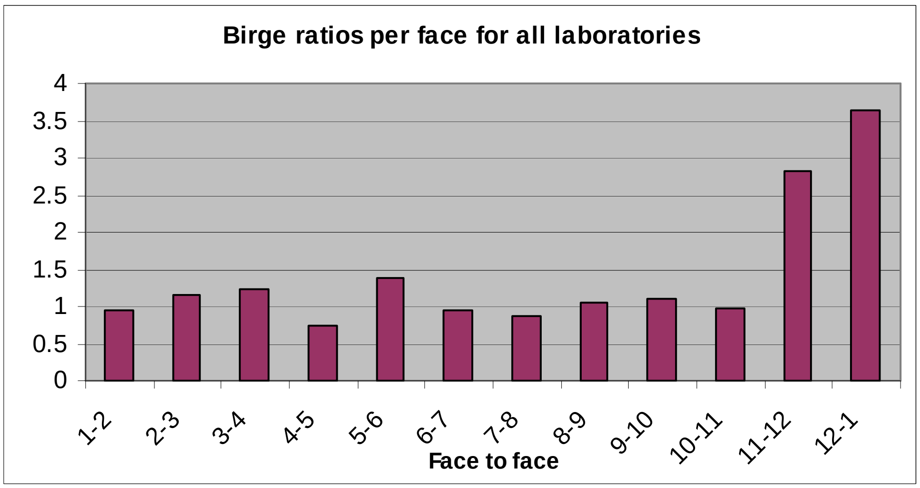
$$R_B<\sqrt{1+\sqrt{8/(I-1)}} \qquad (6)$$

where I is the number of laboratories. For I = 13, a value of R_B< 1,35 indicates consistency.

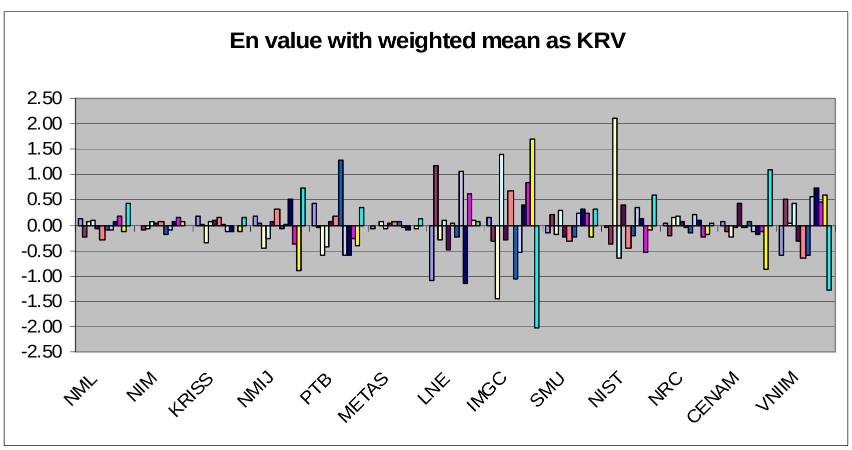
Calculating the E_n value for each reading of each laboratory can make a check for statistical consistency of the laboratories' results with their uncertainties as used in other intercomparisons, CCL-K1 and CCL-K2. The E_n value is calculated according to (7); minus sign in denominator is due to correlation between single measurement results and the KCRV.

$$E_n = \frac{x_i - \overline{x_w}}{\sqrt{\left[u(x_i)\right]^2 - \left[u_{\text{int}}\left(\overline{x_w}\right)\right]^2}} \qquad (7)$$

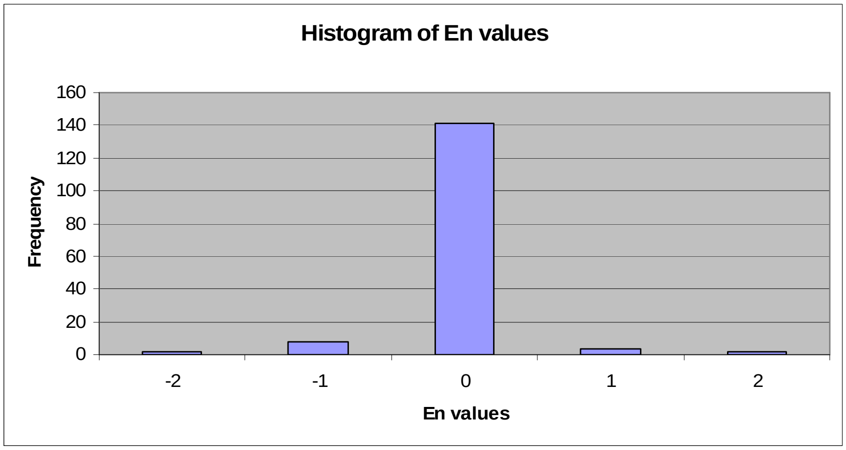
9.2 Polygon calculations and discussions



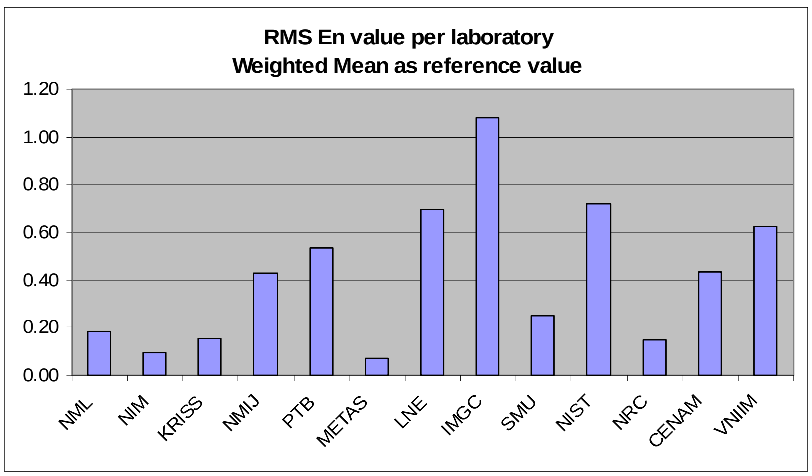
Graph 4 *R_B calculated for all the face to face readings on the polygon.*



Graph 5 *E_n values from the weighted mean result for ALL the readings on the polygon and ALL laboratories (laboratory result for a face to face reading – weighted mean result for that face to face reading).*



Graph 6 *Histogram of the E_n values from the KCRV calculated from the mean result for all the readings on the polygon as in figure 5.*

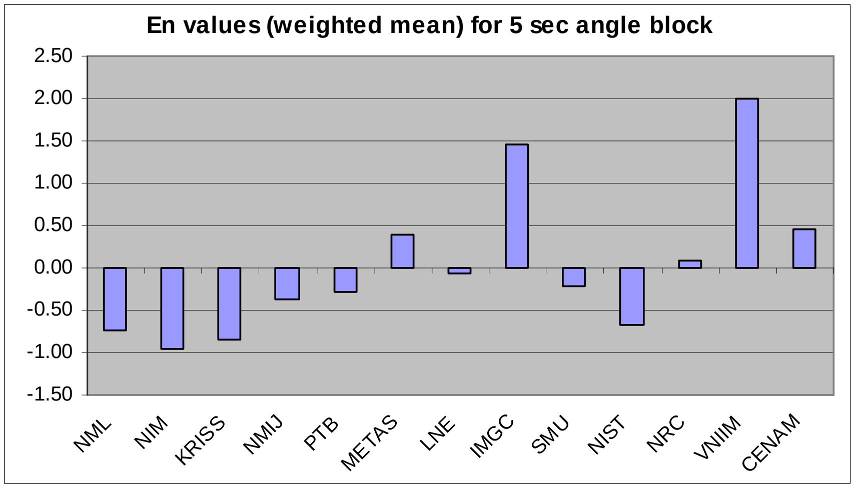


Graph 7 *RMS (Root mean Square) of the E_n values for all the laboratories from the KCRV calculated from the weighted mean result for all the readings on the polygon as in figure 5.*

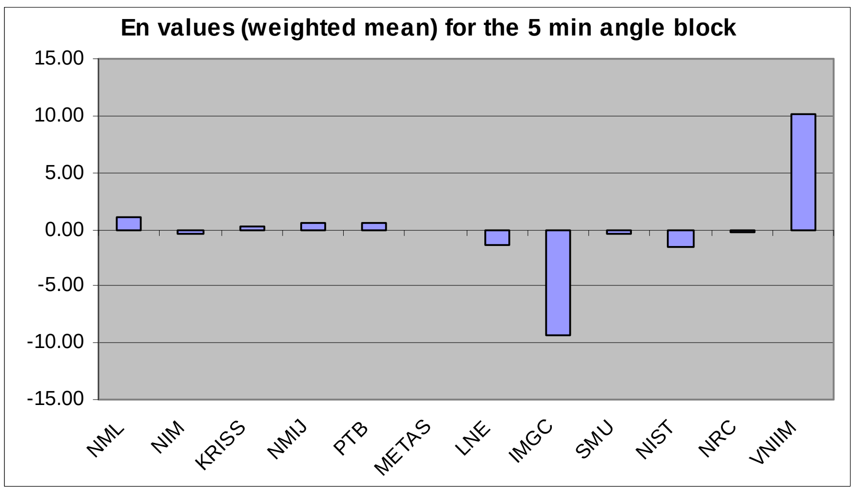
From the polygon graph 5, it can be seen that 15 readings out of a total of 156 readings (13 participants and 12 readings on the polygon) have E_n values larger than 1. It must be remembered that k=1 is used. The comparisons of the Birge ratio, graph 4, shows good ratios, for all the faces except for the last two faces that have ratios of 2,8 and even 3,6 respectively.

Graph 7 shows a histogram of the RMS E_n per laboratory which shows all laboratories, except IMGC, having an RMS E_n value smaller than one.

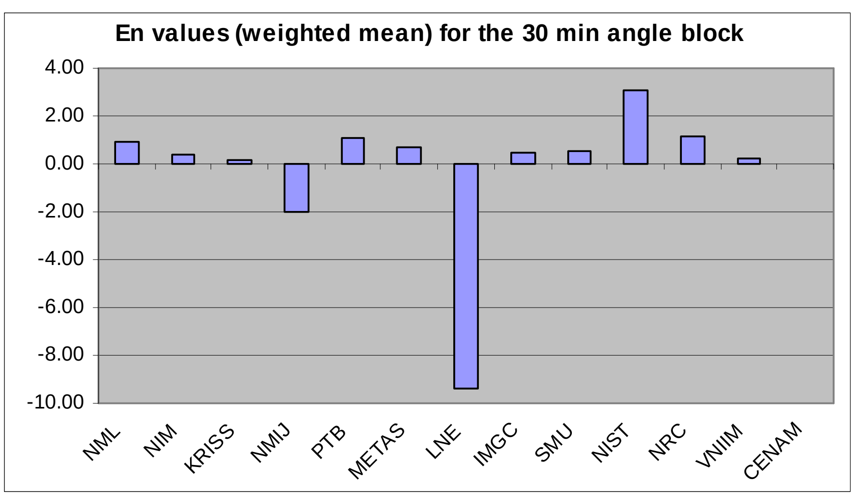
9.3 Angle blocks calculations and discussions



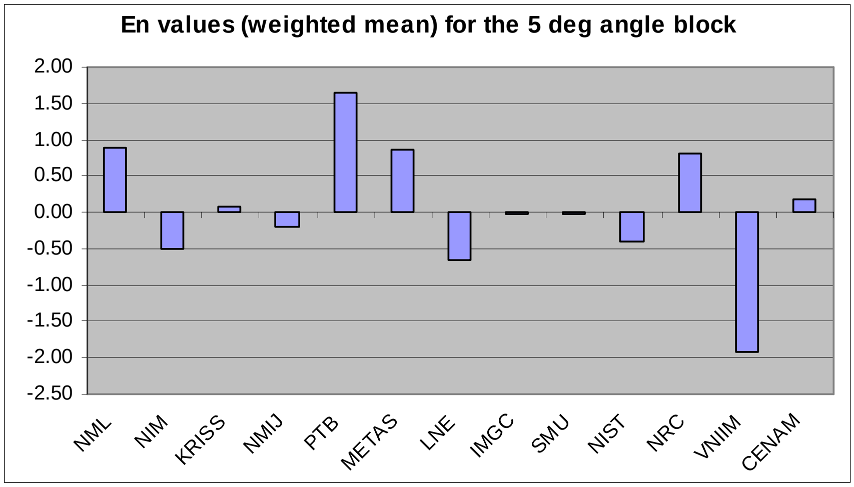
Graph 8 *E_n values from the weighted mean for all the readings on the 5" angle block.*



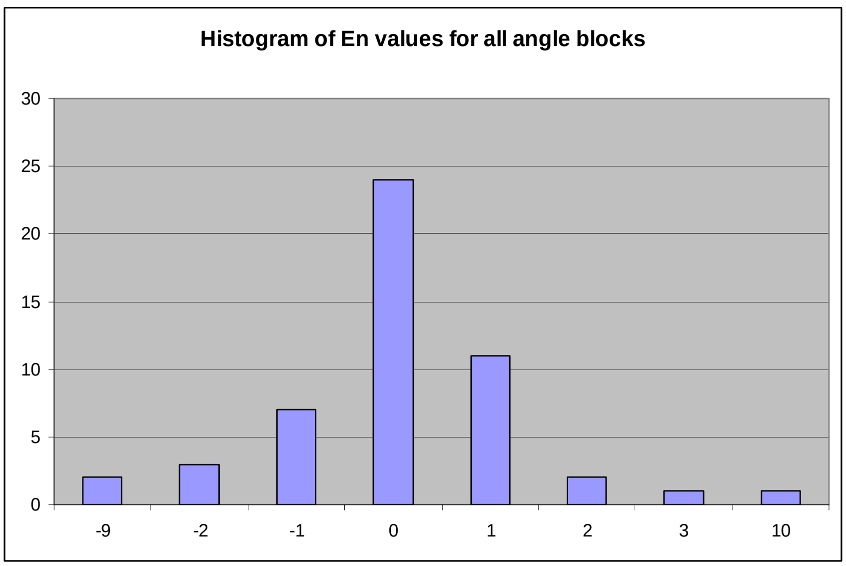
Graph 9 *E_n values from the weighted mean for all the readings on the 5'angle block.*



Graph 10 *E_n values from the weighted mean for all the readings on the 30' angle block.*



Graph 11 E_n values from the weighted mean for all the readings on the 5° angle block.



Graph 12 Histogram of the E_n values from weighted mean result for all angle blocks and all laboratories.

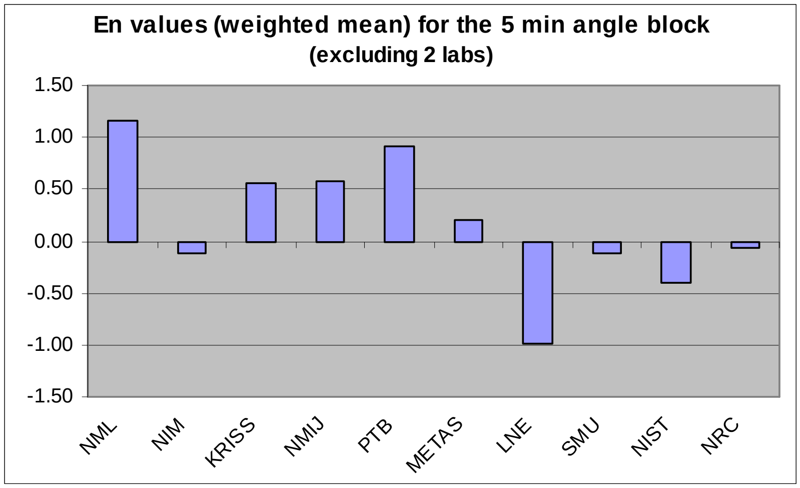
From the angle block graphs (figures 8 to 11) it can be seen that 9 readings out of a total of 51 (13 participants and four angle blocks with one laboratory only measuring three of the four angle blocks) have E_n values larger than 1.

Graph 12 shows a histogram of all the E_n values calculated for all the angle blocks.

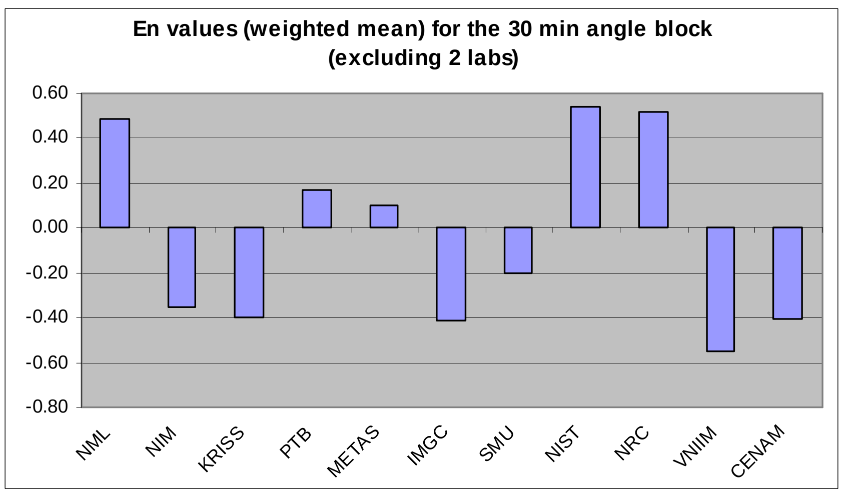
9.4 Angle blocks calculations and discussions, excluding outliers

After feedback from some of the laboratories it was decided to exclude four laboratories, two laboratories (IMGC and VNIIM) on the 5' angle block and two laboratories (NMIJ and LNE) on the 30' angle block in the calculation of the KCRV. It was decided to exclude these from the results as shown in graphs 9 and 10 in the calculation of the E_n value.

The following two graphs show the newly calculated E_n values for the two angle blocks. The graphs are only calculated using the weighted mean as the reference as in the previous chapter, 9.4. The graphs, compared to graphs 9 and 10, shows significant improvement to the E_n value for all the participants.



Graph 13 E_n values from the weighted mean for all the readings on the 5‘angle block excluding IMGC and VNIIM.



Graph 14 E_n values from the weighted mean for all the readings on the 30‘angle block excluding LNE and NMIJ.

The following table show the improvement in the Birge ratio compared to the ratio before the four laboratories were excluded.

Angle block	Birge ratio for weighted mean with all participants included	Birge ratio for weighted mean with two participants per block excluded
5’	4,1	0,6
30’	2,8	0,4

Table 8 Comparison of the Birge ratio for the weighted mean between all the participants and the ratio with “outliers” excluded.

For the 5’ angle block it was decided to further evaluate the comparison for consistency with the use of the En tool builder as describe by Steele and Douglas ”Chi-squared statistics for KCRV candidates”. This was to determine if only two laboratories must be excluded for the calculation of the KCRV or maybe a third laboratory, NMISA (NML) which’s En value was larger than 1. After running the En tool builder it was decided that the comparison for the 5’ angle block passes the 5% level and that only the two laboratories have to be excluded to prove consistency.

10 Conclusion

From the CCL-K3 angle standard key comparison, the following conclusions can be drawn:

- It took two years from the time the decision was made to carry out this comparison until the protocol document was finally issued. This reflected the degree of discussion necessary to agree on the technical basis of the comparison, the likely timetable and list of participants. There were also long discussions on which artefacts to use and whether to check for BMCs or CMCs.

- The polygon was damaged during transport when the locking bolt was not tightened, probably during inspection at customs. Luckily this damage did not influence the reading as it was on the edge of 2 faces of the polygon. Protective material was inserted to prevent this from happening again.

- VNIIM was moved to the end of the schedule after problems with customs were experienced during their normal slot.

- The comparison of the polygon shows good agreement between the laboratories for all the faces except for the last two faces. The RMS E_n value for all the laboratories (except IMGC) is smaller than one. The Birge ratio is for 10 faces close to 1, but the last 2 faces have a larger ratio and must be investigated.

- The angle blocks did not agree on the same level as the polygon. This can be due to the fact that some of the laboratories claimed similar uncertainties, as for the polygon.

- The aim of this angle intercomparison was to determine the level at which laboratories can be equivalent with/to their calibration services. The artefacts were chosen to verify both the laboratories' best measurement capabilities (BMC), using the polygon and its calibration and measurement capabilities (CMC) by using the angle blocks. The BMC demonstration of equivalence was very impressive as the results of measurements of the polygon demonstrated but some further investigation with regards to the CMC demonstration, angle block measurements, is required.

11 Acknowledgements

The pilot laboratory would like to acknowledge all our colleagues in the participating laboratories for their assistance in the smooth running of this comparison.

We would like to thank in particular the NRC for kindly donating the polygon that was used for this comparison.

Thank you to Jim Pekelsky (NRC), Reinhard Probst (PTB), Jack Stone (NIST) and Ruedi Thalmann (METAS) for assistance in the preparation of the protocol document and discussions surrounding the calculations of Key comparison Reference Value (KCRV). Also thank you to Jennifer Decker for the help in using the En tool builder in the calculation for the 5' angle block and Jack Stone for verification of the final spread sheet.

The protocol document and report of the key comparison CCL-K2, written by Ruedi Thalmann (METAS), were also extremely useful in the preparation of the corresponding documents for comparison CCL-K3.

12 References

[1] T. J. Quinn, Guidelines for key comparisons carried out by Consultative Committees, draft of 21 November 1997, BIPM, Paris.

[2] R. Thalmann, Swiss Federal Office of Metrology (METAS), Technical Protocol document, CCL-K1

[3] A. Lewis, National Physical Laboratory (NPL), Final report, CCL-K2

[4] R Probst, Euromet angle comparison. Final report, Euromet project 371

[5] Cox, The total median and its uncertainty, Mathematical & Computational Tools in Metrology V.

[6] http://www.npl.co.uk/ssfm/download/documents/sss_m_00_173.pdf

[7] Steele AG and Douglas RJ, 2005, Chi-squared statistics for KCRV candidates, Metrologia 42

Appendix A: Determination of the Key Comparison Reference values

In the intercomparison the polygon was used to validate the BMC (best measurement capability) of the laboratory and the angle blocks that were used to verify the laboratory's CMC (calibration and measurement capability). At the 12^{th} WGDM meeting it was decided that the weighted mean will be used as the reference value for all intercomparisons. Different methods for calculating the KCRV were calculated before this decision was taken and is included in this report.

A1.1 Mean, weighted mean and modified weighted mean

Different methods for calculating the KCRV were investigated to compare the values, although the final KCRV will be the weighted mean. A comparison between these methods is described.

For the polygon readings, face-to-face, and the angle blocks, the mean *x* value was calculated:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N}(x_i) \quad (1)$$

Where x_i is the result for the individual reading (face-to-face) *i*. N = 13 is the number of laboratories that participated in the polygon calibration.

In the same way the weighted mean value was calculated for the use of the angle blocks:

$$\bar{x}_{\mathrm{w}} = \frac{\sum_{i=1}^{n} u^{-2}(x_i)\cdot x_i}{\sum_{i=1}^{n} u^{-2}(x_i)} \quad (2)$$

At the CCL-WGDM held in China in 2004, Dr Brown made a presentation on a possible technique (modified weighted mean) which could be used for analysis of key comparison results. This modified weighted mean value was also calculated. It differs from the normal weighted mean value as in (2) in the following manner. The weights are not determined on the uncertainties quoted by the laboratories but by the average deviation of each laboratory's results from the tentative reference value. Such an average deviation can be evaluated in cases for all the different faces of a polygon. In practice, for each laboratory E_n value are calculated given by the average deviation from the weighted mean divided by the square root of the weight. In an iterative process the weights are varied until all E_n values equal 0,5. For the final E_n value calculation, the original uncertainty claimed will be used.

For the angle blocks the total median, as described by Cox [4], was also calculated.

A1.2 Polygon discussions

Face	Mean (msec)	Modified Weighted mean (msec)	Weighted mean (msec)
1-2	- 389	-384	-386
2-3	-60	-62	-58
3-4	378	385	375
4-5	243	233	243
5-6	-77	-78	-83
6-7	-585	-580	-576
7-8	-185	-172	-183
8-9	-39	-45	-43
9-10	326	326	328
10-11	368	361	368
11-12	-239	-234	-220
12-1	263	258	238

Table A1.1 Face to face KRV values for the polygon to show difference between mean, weighted mean and modified weighted mean.

Table A1.1 shows three different methods to calculate the KCRV for the polygon. One disadvantage of using the modified weighted mean is that the weight for the modified weighted mean is calculated per laboratory and not for face-to-face reading. The result is that, for example, VNIIM that has an E_n value larger than 1 for last face-to-face reading should in theory carry less weight. Unfortunately the weight is calculated on the average of all the readings for the polygon so one "bad" reading will not affect the weight of the laboratory.

For the polygon, from table 3, it is clear that there is not a significant difference (uncertainties) in the equipment used by the laboratories. All of these, as well as the different methods and the uncertainties associated with this equipment, are also similar. If however, one looks at the uncertainties from table 4 there are a few large contributions for systematic effects that are not consistent across all the laboratories. There is a factor of 12.5 times for the difference in the uncertainties for the "best" laboratory which claimed 8 msec to the "worst" laboratory which claimed 100 msec

Angle block	Mean (milliseconds)	Modified Weighted mean (milliseconds)	Weighted mean (milliseconds)	Total Median (milliseconds)
5”	-18	-2	-11	-11
5’	38	124	64	64
30’	452	537	538	538
5°	281	267	278	287

Table A1.2 Face to face KCRV values for the angle blocks to show difference between mean, weighted mean, total median and modified weighted mean.

The table A1.2 for the angle blocks that used four methods for calculating the KCRV shows large differences in the KCRVs for all the blocks, with two angle blocks showing 0,086” difference between the maximum and minimum calculated KCRV. This is much larger than the internal uncertainty calculated, which is at worst 10 msec compared to an external uncertainty of as high as 140 msec. Table A1.2 shows very good agreement between the weighted mean and the total median for three of the four angle blocks.

These blocks, the 5” and 5’ blocks especially, were chosen since they are more problematical than the polygon to measure, and it was expected that a larger uncertainty would be claimed by the laboratories. It was, however, not true in all cases and a few laboratories claimed the same uncertainty for the angle blocks as the polygon, with one laboratory claiming a smaller uncertainty. This might be the reason for the bad agreement and large Birge ratios, and must be investigated further.

For the angle blocks the same equipment is used as for the polygon, but because of the large angle away from nominal the autocollimators and index tables used have a greater effect on the uncertainty contribution than is the case with the polygon. There is a difference between the “best” laboratory, which claimed an uncertainty of ± 25 msec, and the “worst” laboratory which claimed ± 735 msec, with a factor of 30, compared to a factor of 12,5 of the polygon.