National Metrology Institute of South Africa

Korea Research Institute of Standards and Science

Report on APMP Key Comparison

Calibration of angle standards

APMP.L-K3

Final Report

O. Kruger (NMISA), C.-S. Kang (KRISS),

P. Cox (NMIA), Z. Xue (NIM), P. Liou (CMS/ITRI), S. Y. Wong (SCL), K. P. Chaudhary (NPLI), N. Alfiyati (RCM-LIPI), T. Watanabe (NMIJ/AIST), T. Eom (KRISS), R. M. Halim (NMIM), S. L. Tan (NMC/A*STAR), A. Tonmueanwai (NIMT), M. Dibo (NSCL)

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Contents

1 Introduction

1.1 The metrological equivalence of national measurement standards and of calibration certificates issued by National Metrology Institutes is becoming more and more important. This is established by key comparisons set out by the CIPM. Specific key comparisons are decided upon and organised by the Consultative Committee for a specific field, which, in this case is the Consultative Committee for Length (CCL).

1.2 A CCL intercomparison on calibration of angle standards (CCL-K3) was held, where-after a regional comparison will be held. Both the CCL and the regional comparisons will demonstrate the degree of equivalence of national measurement standards and of calibration certificates issued by National Metrology Institutes throughout the world. The participating countries for CCL-K3 MUST participate in the regional comparison.

1.3 This technical protocol has been drawn up by a small working group comprising of members from the NMISA (South Africa), NRC (Canada), METAS (Switzerland) and the PTB (Germany), which was used for CCL-K3 [1]. The procedure, which follows the guidelines established by the BIPM [2], is also based on the existing technical protocol document for the key comparison on gauge blocks [3] and the EUROMET comparison No. 371 for angle calibration on a precision polygon [4]. The protocol for the APMP regional comparison for angle standards was drawn up from these existing protocols.

1.4 The goal of the regional comparison for topics in dimensional metrology is to demonstrate the equivalence of routine calibration services offered by NMIs to clients, as listed in Appendix C of the BIPM Mutual Recognition Arrangement (MRA). To this end, participants in this comparison agree to use the same apparatus and methods as is routinely applied when calibrating client artefacts.

2 Organisation

2.1 Participants

This key comparison was piloted by Mr. Oelof Kruger of NMISA and co-piloted by Dr. Chu-Shik Kang of KRISS. The list of participant laboratories and their contacts are given in Table 1.

Table 1. List of participant laboratories and their contacts.

Lab code	Contact person, Laboratory address	Phone, Fax, email
NMISA	Mr. O. Kruger National Metrology Institute of South Africa CSIR campus Meiring Naude road, Pretoria, 0001 SOUTH AFRICA	Tel: + 27 12 841 4340 Fax + 27 12 841 4458 e-mail: oakruger@nmisa.org
NMIA	Mr. P. Cox National Measurement Institute 71 Normanby Road, Clayton VIC 3168 AUSTRALIA	Tel: 61 3 9542 4006 Fax: 61 3 9542 4001 e-mail: peter.cox@measurement.gov.au
NIM	Prof Zi Xue Length Division, National Institute of Metrology Beisanhuandonglu 18 100013 Beijing CHINA	Tel: 86-10-64524909 Fax: 86-10-64524902 e-mail: xuez@nim.ac.cn
CMS/ITRI	Mr. P Liou Center for Measurement Standards/ITRI E600, Bldg 16, 321 Kuang Fu Road Sec. 2, Hsinchu 300 TAIWAN	Tel: 886-3-574 3762 Fax: 886-3-572 6445 e-mail: Pascal_Liou@itri.org.tw
SCL	Dr. S. Y. Wong Standards and calibration laboratory.	Tel: 852-28294805 Fax: 852-28294865

	36/F Immigration Tower 7 Gloucester Road, Wanchai HONG KONG	e-mail: sywong@itc.gov.hk
NPLI	Dr. K. P. Chaudhary Length and Dimension Standard National Physical Laboratory Dr. K.S. Krishnan Road, New Delhi, 110 012 INDIA	Tel: 91-11-25732965 Fax: 91-11-25732965 e-mail: kpc@mail.nplindia.org
RCM-LIPI [1]	Ms. Nurul Alfiyati RCM-LIPI Kawasan Puspiptek, Cisauk, Tangerang INDONESIA, 15314	Tel: 62-21-7560533 Fax: 62-21-7560568 e-mail:nurul@kim.lipi.go.id, nurul.alfi@gmail.com
NMIJ/AIST	Dr. T. Watanabe Dimensional Standards Section, Lengths and Dimensions Division National Metrology Institute of Japan / National Institute of Advanced Industrial Science and Technology (AIST) Tsukuba Central 3, 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8563 JAPAN	Tel: 81-29-861-4041 Fax: 81-29-861-4042 e-mail: t.watanabe@aist.go.jp
KRISS	Dr. T. Eom KRISS 267 Gajeong-ro, Yuseong-gu, Daejeon, 34113 Republic of KOREA	Tel: 82-42-8685100 Fax: 82-42-8685608 e-mail: tbeom@kriss.re.kr
NMIM [2]	Mr. R. M. Halim National Metrology Institute of Malaysia Lot Pt 4803 Bandar Baru Salak Tinggi 43900 Sepang, Selangor MALAYSIA	Tel: 60 387 781 600 Fax: 60 387 781 616 e-mail: razmannh@sirim.my
NMC/ A*STAR [3]	Ms. S. L. Tan NMC/A*STAR 1 Science Park Drive SINGAPORE, 118221	Tel: 65-6279 1938 Fax: 65-6279 1993 e-mail: tan_siew_leng@nmc.a-star.edu.sg
NIMT	Mr. A. Tonmueanwai NIMT 75/7 Rama 6 Road, Rajthevi, Bangkok THAILAND 10400	Tel: 662-02-2482181 Fax: 662-02-2484484 e-mail: anusorn@nimt.or.th
NSCL	Ms M Dibo National standards & Calibration Laboratory PO Box 30116, Damascus, Syria	Tel: 963 11 2216 760 Fax: 963 11 5117 539 e-mail: nscl@rd.gov.sy

2.2 Time Schedule

2.2.1 The comparison commenced with the NMISA as the pilot laboratory followed by a number of participants, the artefacts then were sent back to NMISA, and again to a number of participants. This was arranged depending on the number of laboratories taking part. On completion of the

[1] At the time of measurement, RCM-LIPI was known as KIM-LIPI.

[2] At the time of measurement, NMIM was known as SIRIM Berhad.

[3] At the time of measurement, NMC/A*STAR was known as NMC/SPRING.

comparison the artefacts were returned to the pilot laboratory for verification of either drift or damage to the artefacts.

2.2.2 Each laboratory had one month (4 weeks) to perform the calibration and a further 2 weeks to pass it on to the next laboratory. Unfortunately due to a wide variety of problems at customs, there were some huge delays in the intercomparison.

2.2.3 NMIM (Malaysia) has requested to re-measure the artefact. The artefacts were sent back to Malaysia after the other participants completed the measurement. After the re-measurement NMIM decided not to submit any results and withdrew from the comparison.

2.2.4 Final Time Schedule is shown in Table 2.

Table 2. Schedule of the comparison.

Laboratory	Start Date
NMISA (Pilot Laboratory)	April 2005
NMIA (Australia)	May 2005
KRISS (Korea)	June 2005
NMIJ/AIST (Japan)	August 2005
NMISA (Pilot Laboratory)	October 2005
NMIM (Malaysia)	November 2005
NMC/A*STAR (Singapore)	January 2006
NIMT (Thailand)	March 2006
SCL (Hong Kong)	May 2006
NMISA (Pilot Laboratory)	July 2006
CMS/ITRI (Taiwan)	September 2006
NMISA (Pilot Laboratory)	November 2006
RCM-LIPI (Indonesia)	January 2007
NMISA (Pilot Laboratory)	March 2007
NPLI (India)	April 2007
NMISA (Pilot Laboratory)	May 2007
NIM (China)	June 2007
NMISA (Pilot Laboratory)	August 2007
NSCL (Syria)	October 2007
NMISA (Pilot Laboratory)	December 2007

3 Artefacts

3.1 The artefacts consisted of a 12 sided polygon and 4 angle blocks.

3.2 Four angle blocks, 5"; 30'; 5' and 5° were used to test the calibration capabilities of the laboratory which are the extremes of their calibration range. The angle blocks are manufactured by Starrett with a material of chrome carbide and having a serial number UVF5. The angle blocks have a measuring face of 26 mm × 51 mm.

3.3 The polygon with serial number 72704.1 is also manufactured by Starrett and is made of steel; with 12 measuring faces of 19 mm × 19.5 mm each. The polygon has a centre hole of 25.4 mm for mounting purposes and a thickness of 19 mm.

3.4 The angle blocks were measured using an aperture, which is 1 mm less (on the edge) than the overall face.

3.5 Drawing:

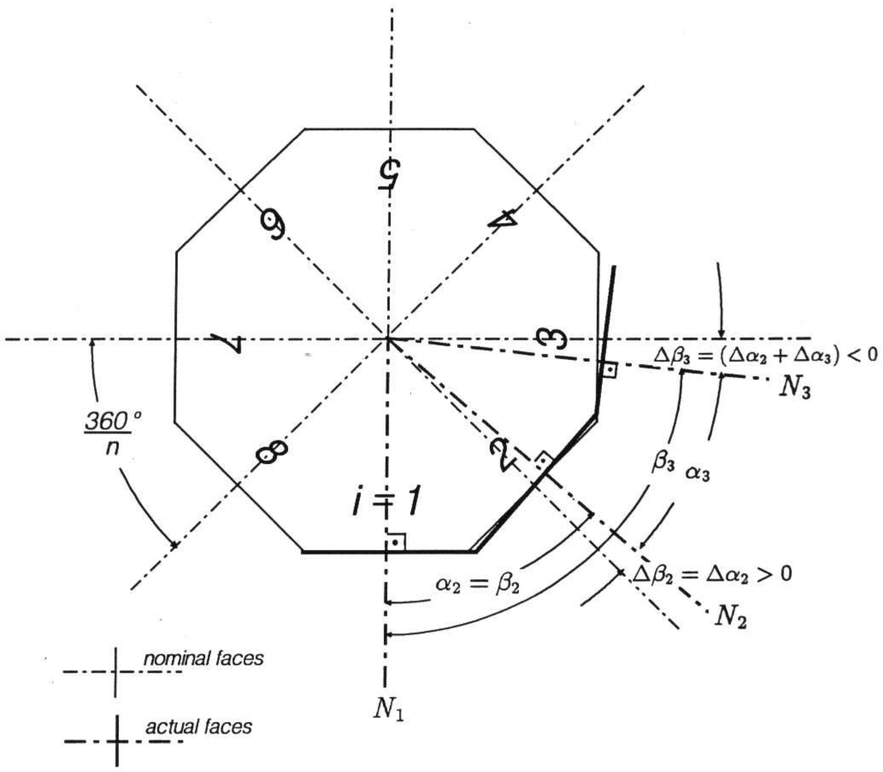

Figure 1. Schematic drawing of the polygon. The pitch angles α_i are the angles between the projections of two adjacent normals N_{i-1} and N_i in the measuring plane with the counting index (i=1,2,...,12). The deviations of the pitch angles from their nominal values of 360°/12 are referred to as pitch angle deviations.

The standards were supplied in a custom-made case in which they were 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.

4 Measurement instructions

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.

4.1 Measurands

The measurands for the polygon are the 12 pitch angle deviations from nominal angle, $\Delta\alpha_i = \alpha_i - 30^\circ$ (i=1,2,…,12).

For the angle blocks, the measurand of each angle block is the deviation angle from nominal angle, $\Delta\theta = \theta - \theta_o$, where θ is the measured angle of the angle block and θ_o is its nominal angle.

5 Measurement results

5.1 Polygon: Results and standard uncertainties as reported by participants

Table 3. Tabular presentation of the measurement values for the polygon in arc seconds

Face	NMISA	NMIA	KRISS	NMIJ/ AIST	NMC/ A*STAR	NIMT	SCL	CMS/ ITRI	NPLI	RCM-LIPI	NIM	NSCL
1-2	0.096	0.04	0.050	0.08	0.2	0.00	0.03	0.10	0.00	-0.03	0.05	0.0
2-3	0.095	0.17	0.185	0.17	0.1	0.07	0.17	0.17	0.11	0.21	0.18	0.1
3-4	0.444	0.42	0.428	0.43	0.2	0.36	0.39	0.48	0.41	0.24	0.45	0.4
4-5	-0.192	-0.08	-0.101	-0.11	0.0	-0.16	-0.08	-0.13	0.09	-0.04	-0.11	-0.2
5-6	-0.532	-0.53	-0.511	-0.50	-0.4	-0.47	-0.47	-0.50	-0.53	-0.34	-0.53	-0.4
6-7	-0.202	-0.30	-0.271	-0.28	-0.3	-0.16	-0.30	-0.26	-0.28	-0.13	-0.30	-0.2
7-8	0.048	0.02	0.033	0.07	0.0	0.14	0.03	0.05	-0.06	0.05	0.04	0.1
8-9	-0.664	-0.88	-0.890	-0.81	-0.4	-0.73	-0.90	-0.73	-0.65	-0.54	-0.84	-0.5
9-10	1.434	1.56	1.581	1.52	0.9	1.60	1.48	1.42	1.46	0.97	1.53	1.2
10-11	-0.546	-0.63	-0.655	-0.63	-0.3	-0.53	-0.62	-0.59	-0.43	-0.39	-0.61	-0.5
11-12	0.422	0.58	0.597	0.53	0.2	0.46	0.62	0.44	0.23	0.27	0.56	0.4
12-1	-0.481	-0.38	-0.446	-0.46	-0.3	-0.56	-0.35	-0.45	-0.49	-0.25	-0.44	-0.4

Table 4. Tabular presentation of the standard uncertainty values for the polygon in arc seconds

Face	NMISA	NMIA	KRIS S	NMIJ/ AIST	NMC/ A*STAR	NIMT	SCL	CMS / ITRI	NPLI	RCM-LIPI	NIM	NSCL
1-2	0.08	0.101	0.064	0.067	0.3	0.17	0.055	0.08	0.39	0.26	0.043	0.18
2-3	0.08	0.101	0.064	0.067	0.3	0.17	0.055	0.08	0.39	0.26	0.043	0.28
3-4	0.08	0.101	0.064	0.067	0.3	0.17	0.055	0.08	0.39	0.26	0.043	0.2
4-5	0.08	0.101	0.064	0.067	0.3	0.17	0.055	0.08	0.39	0.26	0.043	0.18
5-6	0.08	0.101	0.064	0.067	0.3	0.17	0.055	0.08	0.39	0.26	0.043	0.16
6-7	0.08	0.101	0.064	0.067	0.3	0.17	0.055	0.08	0.39	0.26	0.043	0.18
7-8	0.08	0.101	0.064	0.067	0.3	0.17	0.055	0.08	0.39	0.26	0.043	0.3
8-9	0.08	0.101	0.064	0.067	0.3	0.17	0.055	0.08	0.39	0.26	0.063	0.19
9-10	0.08	0.101	0.064	0.067	0.3	0.17	0.055	0.08	0.39	0.26	0.063	0.83
10-11	0.08	0.101	0.064	0.067	0.3	0.17	0.055	0.08	0.39	0.26	0.043	0.39
11-12	0.08	0.101	0.064	0.067	0.3	0.17	0.055	0.08	0.39	0.26	0.043	0.19
12-1	0.08	0.101	0.064	0.067	0.3	0.17	0.055	0.08	0.39	0.26	0.043	0.15

In figures 2(a) through to 2(l) all measurement results from the polygon reporting the deviation from the nominal angle in arc seconds are given along with their combined standard uncertainties as reported by the participants. NIM, China reported a different uncertainty (0,63″ compared to 0,43″) for face 9 measurements due to damage of the face. However, only this reported uncertainty, 0,43″ was used throughout all the calculations.

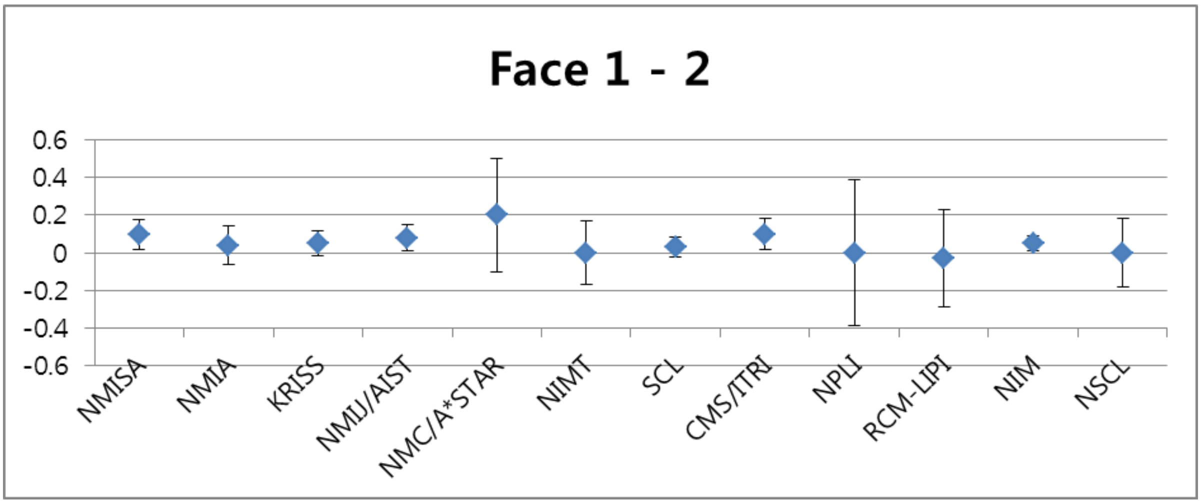

Figure 2(a). Results for the polygon, face 1 to 2, in arc seconds (standard uncertainty bars shown).

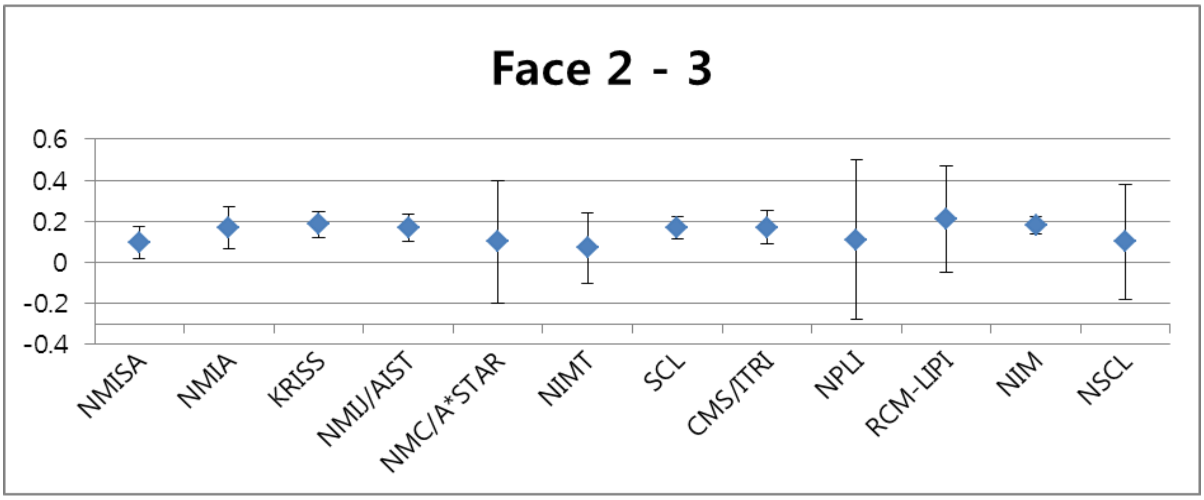

Figure *2*(b). Results for the polygon, face 2 to 3*, in arc seconds* (standard uncertainty bars shown).

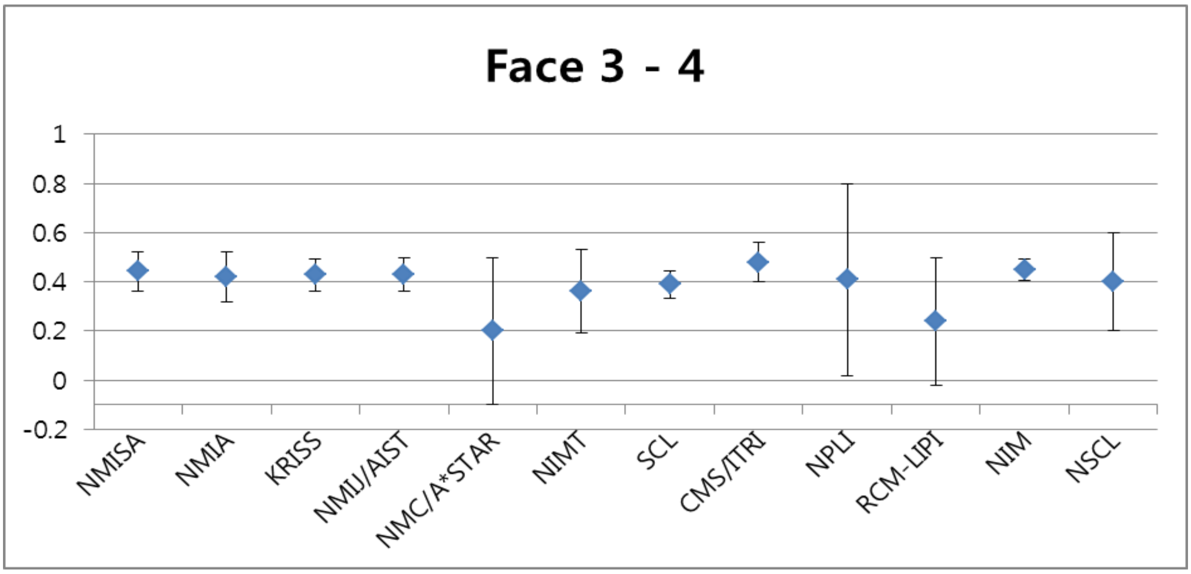

Figure 2(c). Results for the polygon, face 3 to 4*, in arc seconds* (standard uncertainty bars shown).

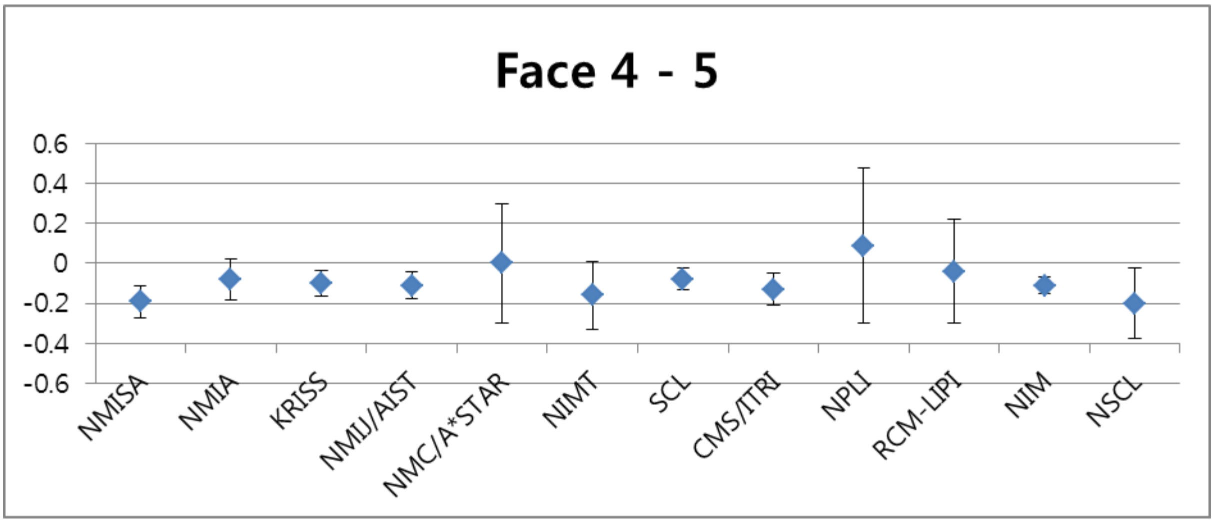

Figure 2(d). Results for the polygon, face 4 to 5, in arc seconds (standard uncertainty bars shown).

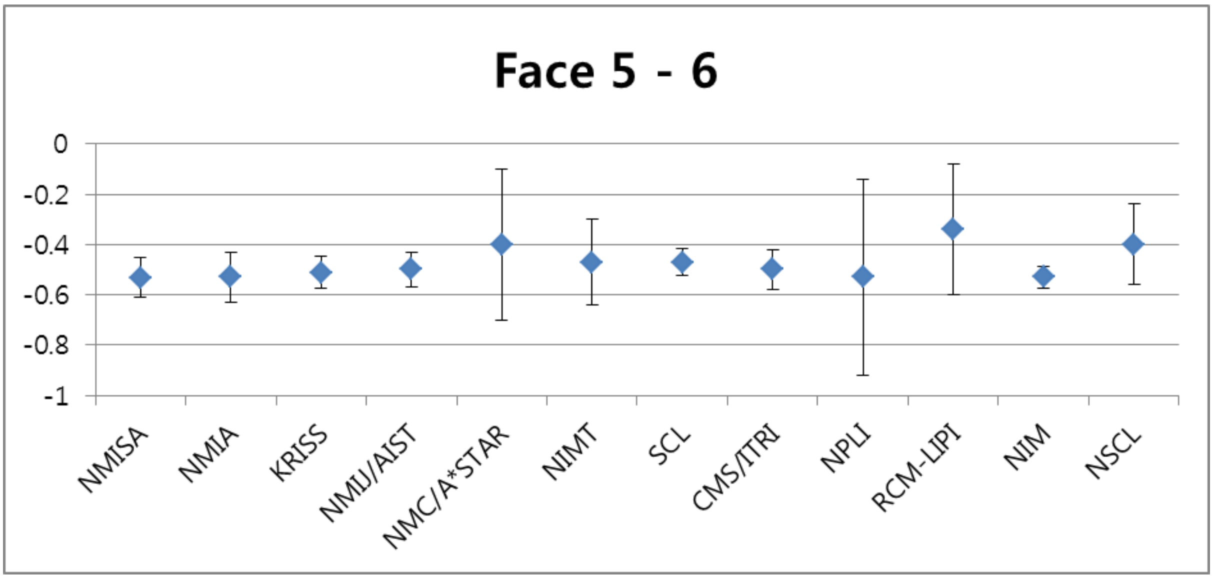

Figure 2(e). Results for the polygon, face 5 to 6*, in arc seconds* (standard uncertainty bars shown).

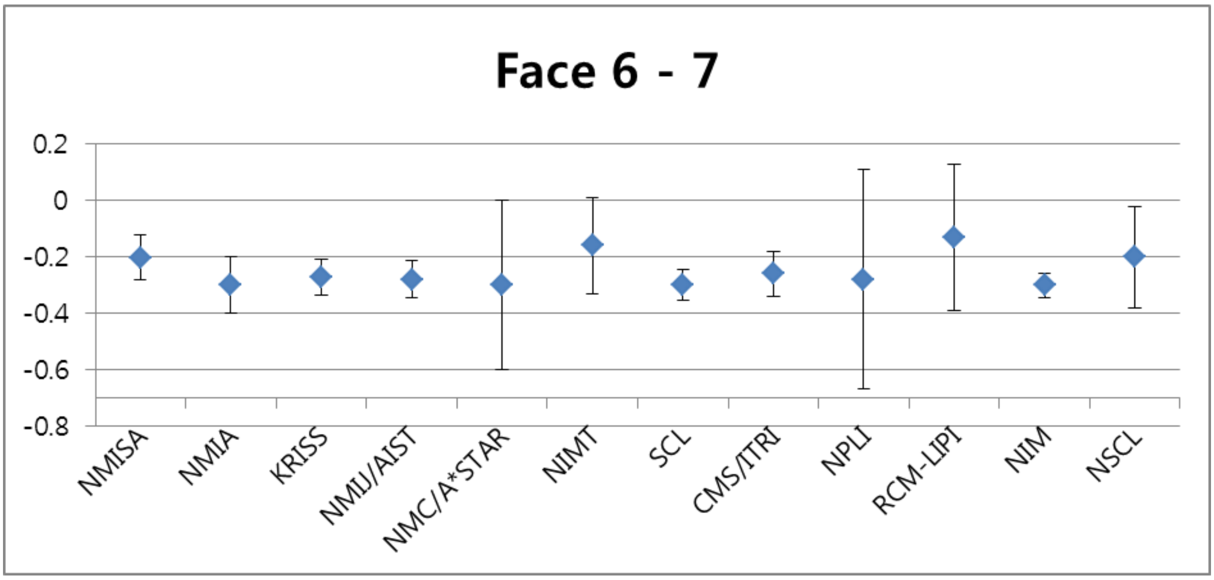

Figure 2(f). Results for the polygon, face 6 to 7, in arc seconds (standard uncertainty bars shown).

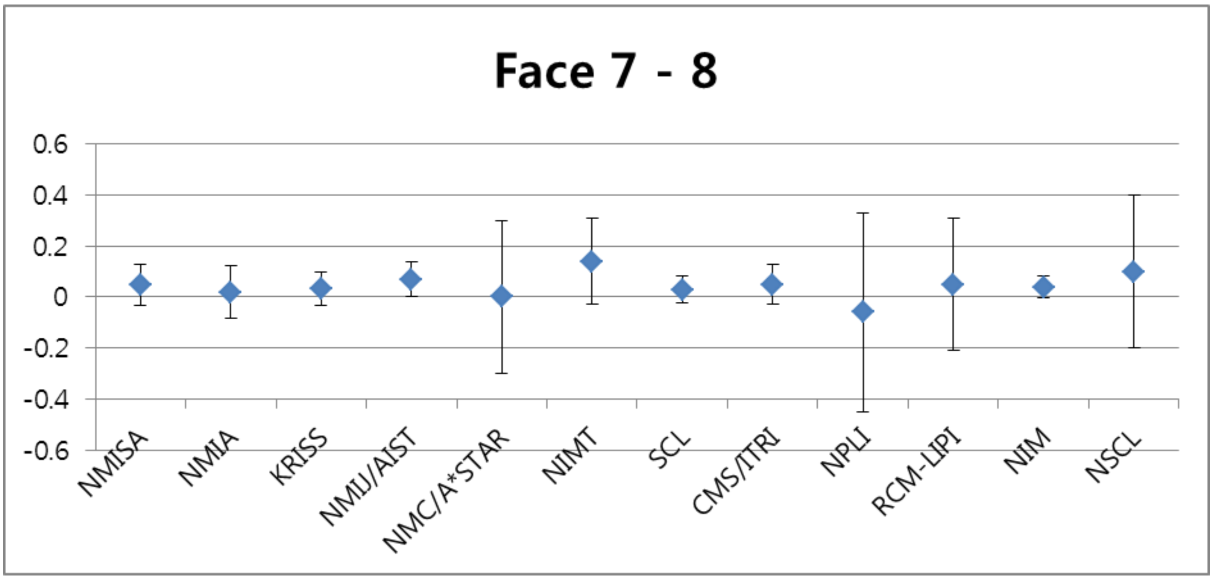

Figure 2(g). Results for the polygon, face 7 to 8, in arc seconds (standard uncertainty bars shown).

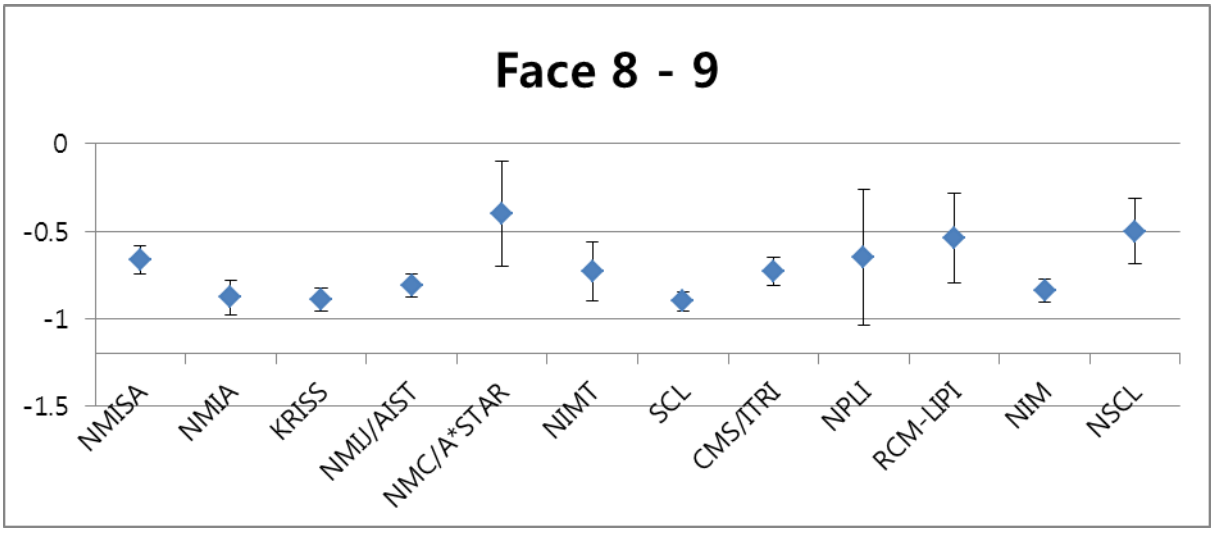

Figure 2(h). Results for the polygon, face 8 to 9, in arc seconds (standard uncertainty bars shown).

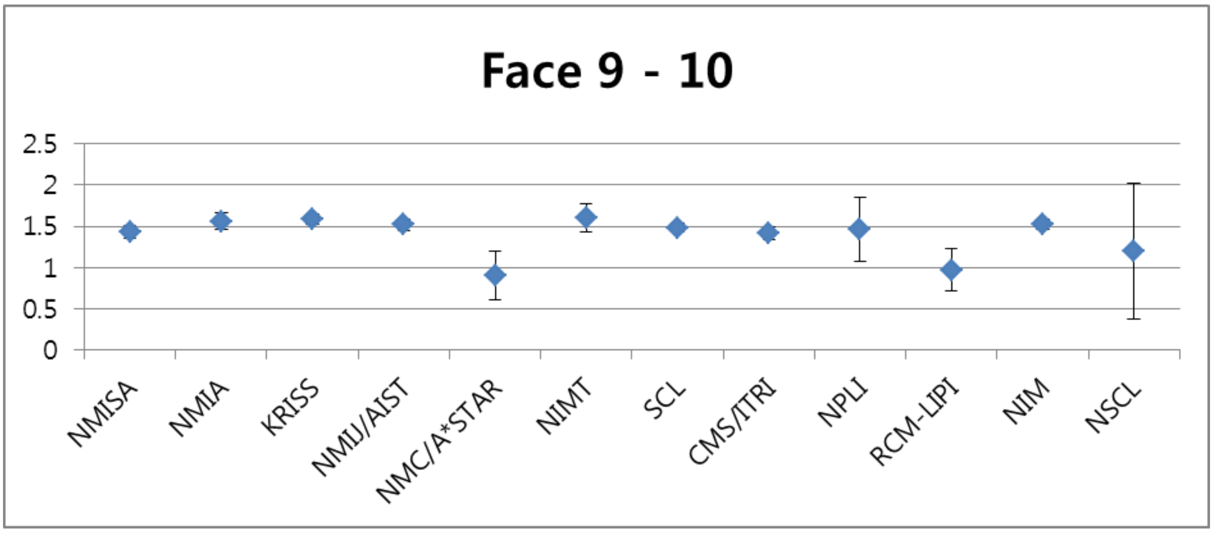

Figure 2(i). Results for the polygon, face 9 to 10, in arc seconds (standard uncertainty bars shown).

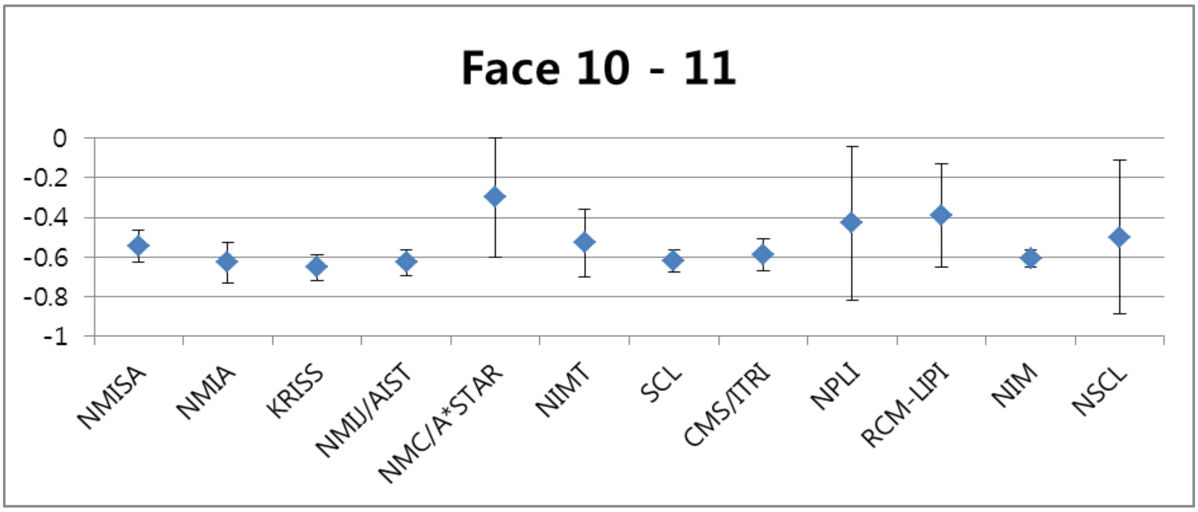

Figure 2(j). Results for the polygon, face 10 to 11, in arc seconds (standard uncertainty bars shown).

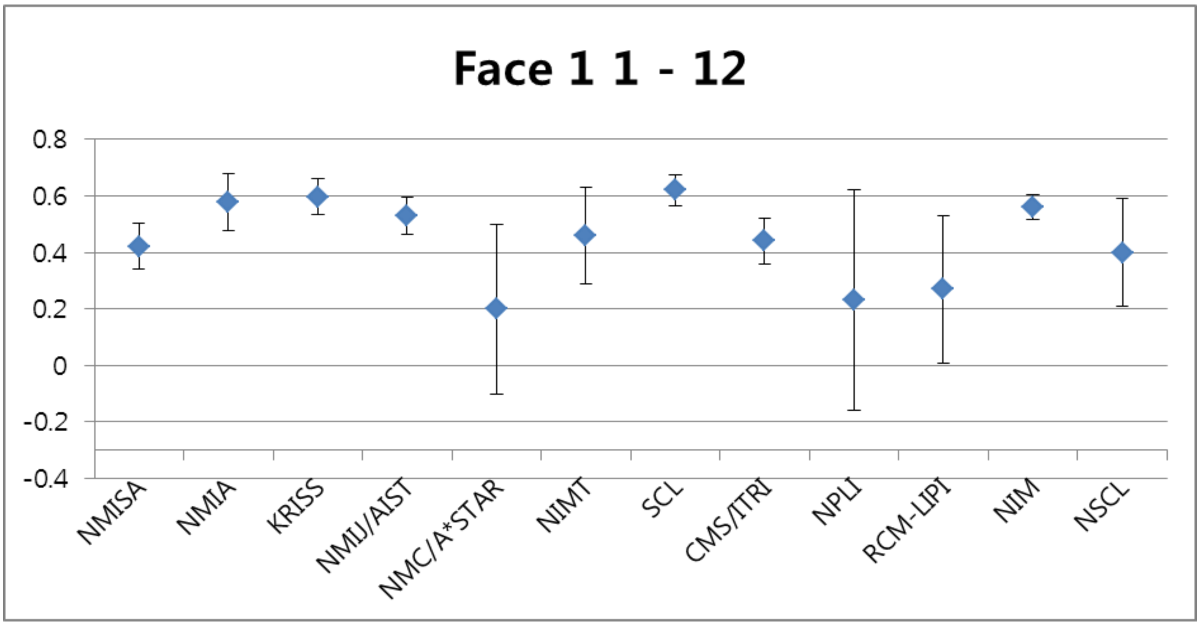

Figure 2(k). Results for the polygon, face 11 to 12, in arc seconds (standard uncertainty bars shown).

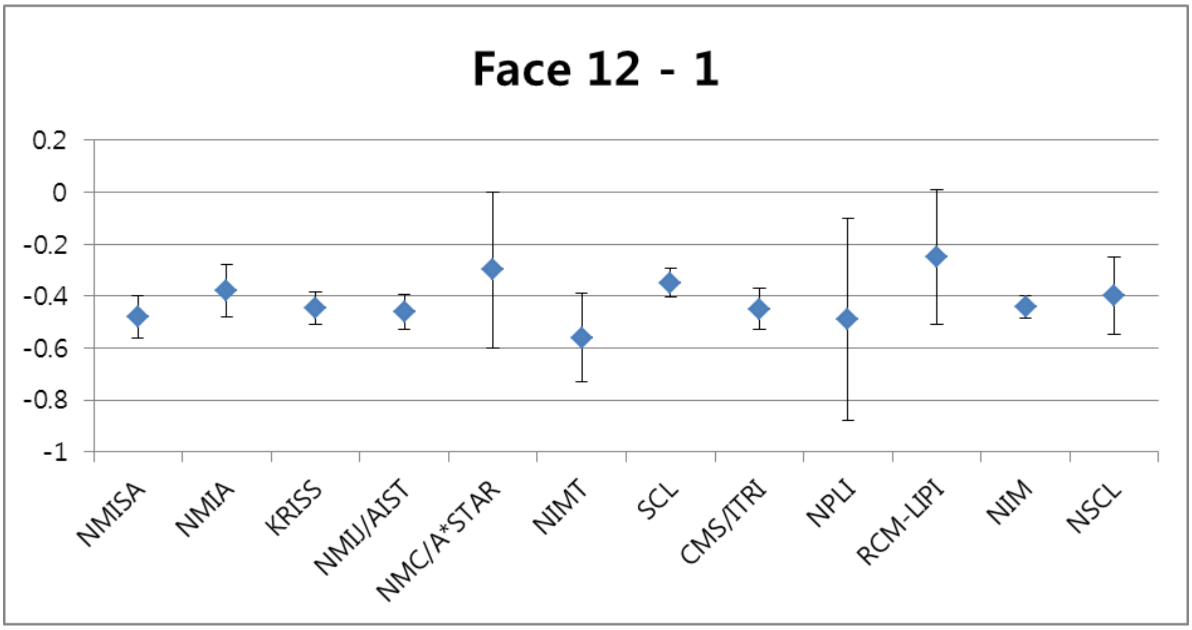

Figure 2(l). Results for the polygon, face 12 to 1, in arc seconds (standard uncertainty bars shown).

5.2 Angle blocks: Results and standard uncertainties as reported by participants

Table 5 shows the measurement results for the four angle blocks reporting the deviation from nominal angle in arc seconds, and are given along with their combined standard uncertainties as reported by the participants. These are also plotted in Figures 3(a) through to 3(d).

Table 5. Tabular presentation of the measurement results for the four angle blocks in arc seconds.

Angle block	NMISA	NMIA	KRISS	NMIJ/ AIST	NMC/ A*STAR	NIMT	SCL	CMS/ ITRI	NPLI	RCM-LIPI	NIM	NSCL
5"	1.00	0.71	0.882	0.82	0.6	0.79	0.58	0.74	0.80	1.32	0.800	0.70
u (*k*=1)	0.10	0.13	0.082	0.07	0.4	0.27	0.10	0.09	0.21	0.32	0.059	0.42
5'	-0.64	-0.39	-0.455	-0.44	1.8	-0.45	-0.38	-0.51	-0.75	-0.69	-0.390	-0.50
u (*k*=1)	0.15	0.16	0.082	0.08	0.4	0.27	0.14	0.09	0.21	0.32	0.073	0.20
30'	-0.88	-0.98	-0.857	-0.87	-0.9	-0.79	-0.98	-0.92	0.69	-0.31	-0.900	1.00
u (*k*=1)	0.10	0.12	0.082	0.08	0.4	0.27	0.13	0.09	0.21	0.32	0.059	0.18
5°	0.40	0.35	0.370	0.45	0.5	-0.51	0.31	0.50	-0.95	0.56	0.440	-0.20
u (*k*=1)	0.10	0.12	0.082	0.07	0.4	0.27	0.13	0.09	0.21	0.32	0.059	0.23

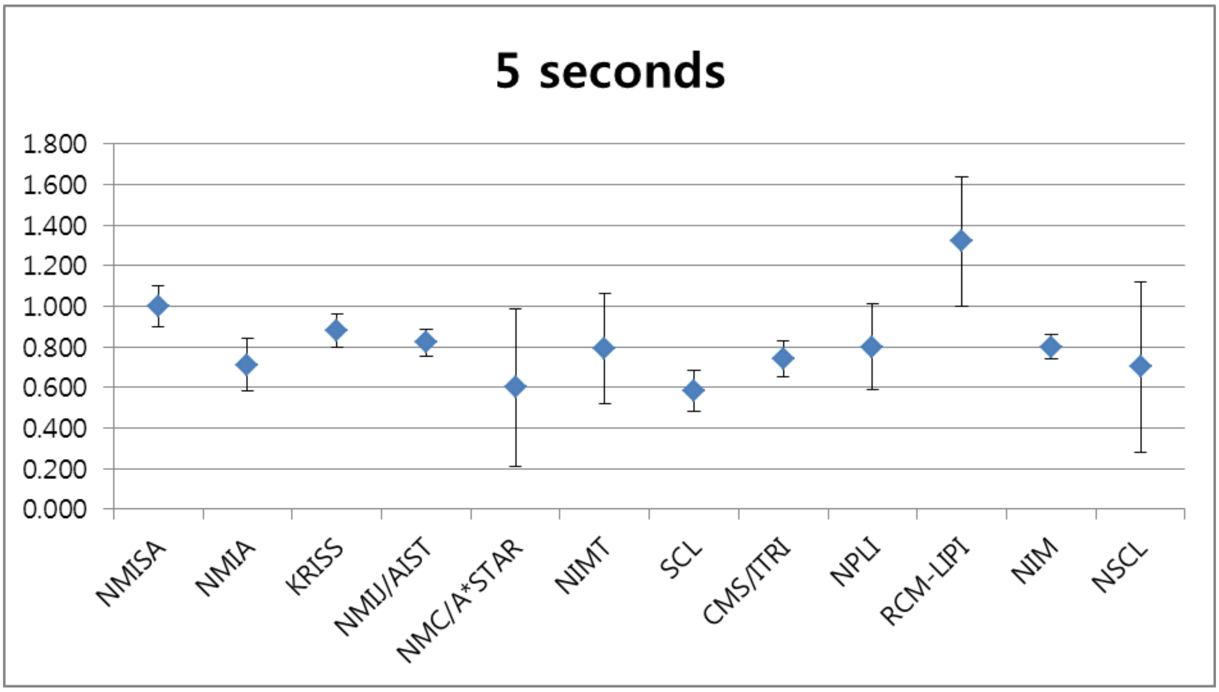

Figure 3(a). Results for the 5″ angle block in arc seconds (standard uncertainty bars shown).

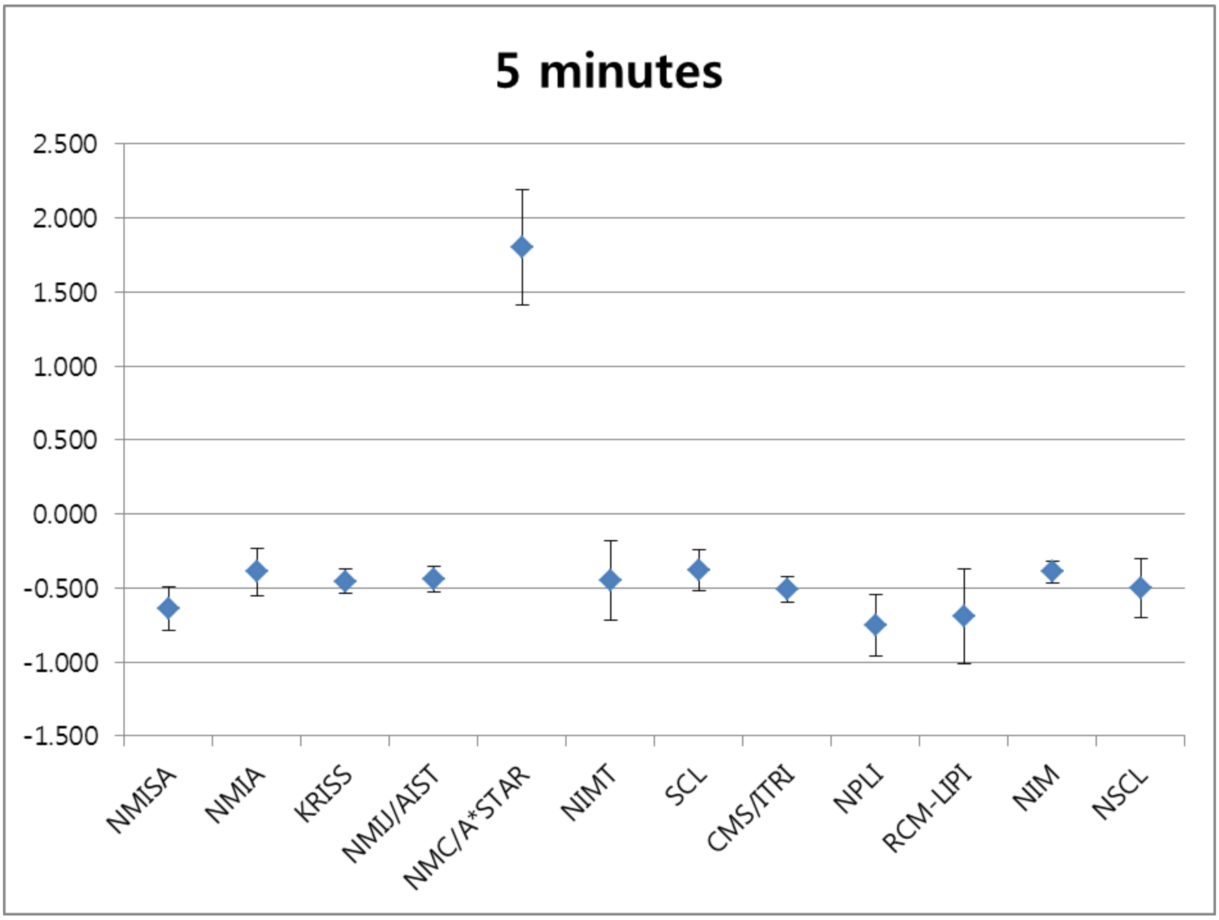

Figure 3(b). Results for the 5′ angle block in arc seconds (standard uncertainty bars shown).

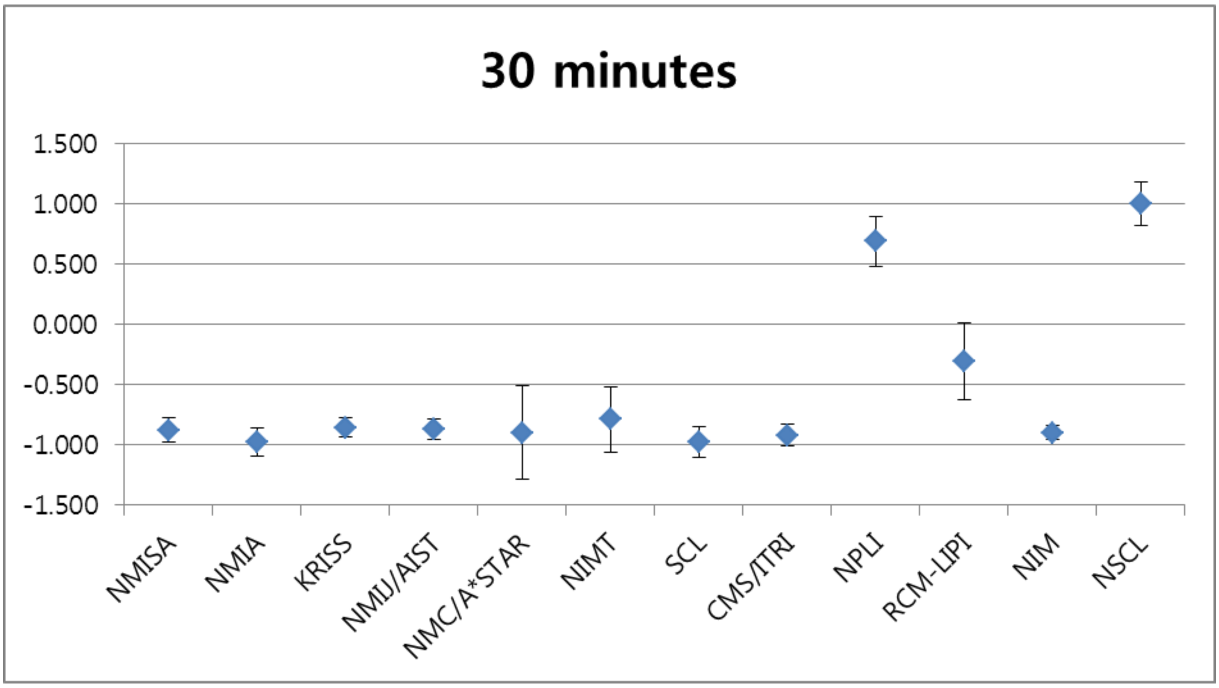

Figure 3(c). Results for the 30′ angle block in arc seconds (standard uncertainty bars shown).

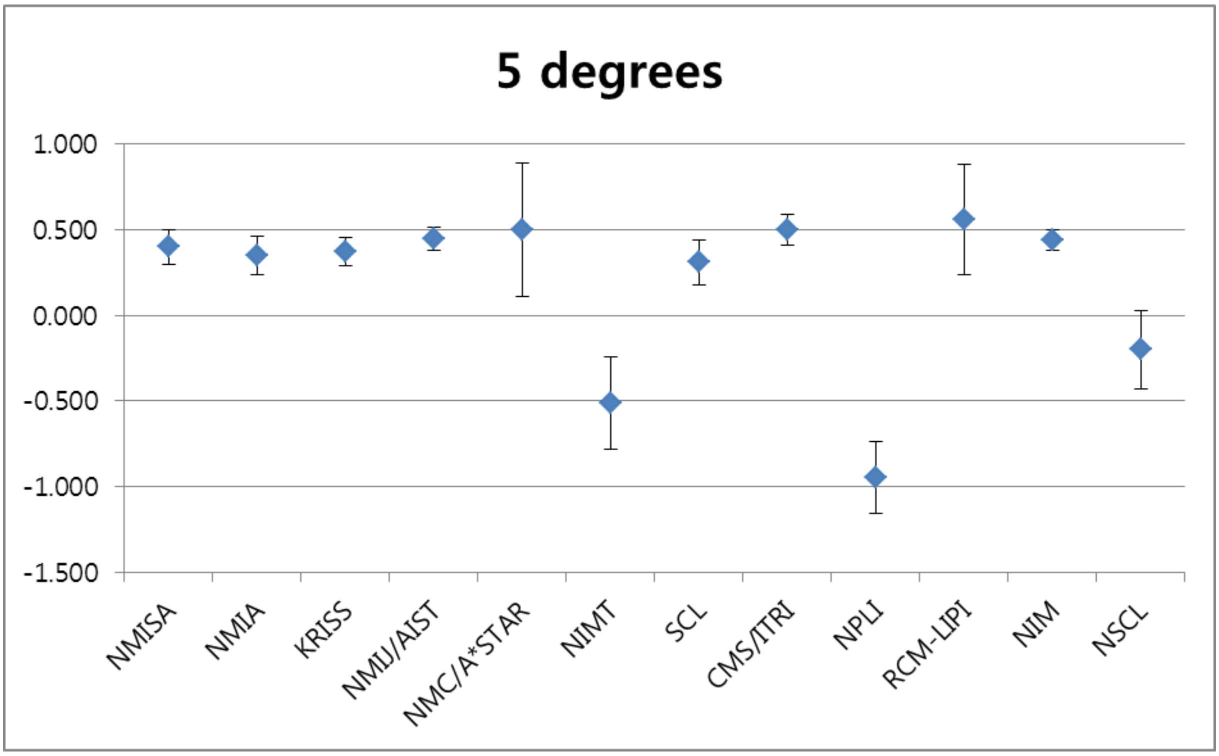

Figure 3(d). Results for the 5° angle block in arc seconds (standard uncertainty bars shown).

5.3 Measurement uncertainties

5.3.1 Model equations

The participants were asked (in the technical protocol of the comparison) to evaluate the uncertainty of measurement according to the *ISO Guide for the Expression of Uncertainty in Measurement*. An example of a mathematical model 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 pitch angle deviations of a polygon are described by:

$$\begin{aligned}\Delta\alpha_{\mathrm{i}} &= \alpha_{\mathrm{i}} - \frac{360^{\circ}}{12} + \delta A_{\mathrm{F}} + \delta A_{\mathrm{P}} + \delta A_{\mathrm{E}} \\ &= (\theta_{T,\mathrm{i}} - \theta_{R,\mathrm{i}}) - \frac{360^{\circ}}{12} + \delta A_{\mathrm{F}} + \delta A_{\mathrm{P}} + \delta A_{\mathrm{E}}\end{aligned} \qquad (\mathrm{i} = 1,2,3,\ldots,12) \qquad (1)$$

where:

α_{i} is the pitch angle,
δA_{F} is the correction for flatness deviations of measuring face,
δA_{P} is the correction for pyramidal errors of measuring face,
δA_{E} is the correction for eccentricity errors in setup of polygon/angle block,
$\theta_{\mathrm{R,i}}$ is the autocollimator / interferometer reading
$\theta_{\mathrm{T,i}}$ is the index table reading
i is the measuring face index.

6 Analysis

The weighted mean calculated from the consistent data set is used as the key comparison reference value (KCRV) of each measurand. For this, the Birge ratio tests were performed iteratively to find out the consistent data set. Finally, E_{n} values are calculated to find out the consistency of each measurement results with the KCRV.

6.1 Calculation of the KCRV

The KCRV was calculated as the weighted mean of the consistent data set using equation (2)

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

where I denotes the total number of laboratories included in the calculation of KCRV, x_i and $u(x_i)$ denote the measurement value of the i-th laboratory, and its standard uncertainty, respectively.

6.2 Internal and external uncertainties and the Birge ratio test

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

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

The external standard deviation is calculated as

$$\mathrm{u}_{\mathrm{ext}}(\bar{x}_{\mathrm{w}}) = \sqrt{\frac{1}{I-1} \cdot \frac{\sum_{i=1}^{I} \frac{1}{u^2(x_i)} (x_i - \bar{x}_w)^2}{\sum_{i=1}^{I} \frac{1}{u^2(x_i)}}} \tag{4}$$

The Birge ratio is defined as the ratio of the external standard deviation to the internal standard deviation of the KCRV, i.e., it is calculated as [5]:

$$R_B = \frac{u_{ext}(\bar{x}_w)}{u_{\mathrm{int}}(\bar{x}_w)} \ . \tag{5}$$

The Birge ratio has an expectation value of R_B=1 *(for a large number of* I*)*, 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:

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

where I is the number of laboratories included in calculation of the KCRV. For I = 12, a value of R_B< 1,36 indicates consistency.

6.3 Calculation of Degrees of Equivalence

The Degrees of Equivalence (DoE) of each measurement value is defined as $x_i - \overline{x}_{\mathrm{w}}$. Thus the standard uncertainty of DoE is given by equation (7) where a minus sign is used to take into account the correlation between the two uncertainties.

$$u(x_i - \overline{x}_w) = \sqrt{[u(x_i)]^2 - [u_{int}(\overline{x}_w)]^2} \tag{7}$$

For uncorrelated uncertainties, the minus sign would be replaced by a plus sign as equation (8).

$$u(x_i - \overline{x}_w) = \sqrt{[u(x_i)]^2 + [u_{\mathrm{int}}(\overline{x}_w)]^2} \tag{8}$$

A check for statistical consistency of the results with their associated uncertainties can be made by calculating the E_n value for each laboratory's result, where E_n is defined as the deviation of the measured value from the weighted mean, divided by the expanded uncertainty of this deviation. Thus for the laboratories whose measurement results are used in the calculation of the weighted mean, the E_n is calculated as

$$E_n = \frac{x_i - \overline{x}_w}{2\sqrt{[u(x_i)]^2 - [u_{\mathrm{int}}(\overline{x}_w)]^2}}, \tag{9}$$

whereas for the outliers whose measurement values are not included in the calculation of the weighted mean, E_{n} is calculated as

$$E_n = \frac{x_i - \overline{x}_w}{2\sqrt{[u(x_i)]^2 + [u_{\mathrm{int}}(\overline{x}_w)]^2}}. \tag{10}$$

6.4 Polygon calculations

Weighted mean ($\overline{x}_w$) values of the deviation from nominal angle are shown in Table 6, and the corresponding Birge ratios are plotted as Figure 4.

Table 6. Weighted mean and its standard uncertainty values for the polygon measurements

Measured angle position	$\overline{x}_{\mathrm{w}}$ / ″	$u(\overline{x}_{\mathrm{w}})$ / ″
Face 1 – 2	0.056	0.023
Face 2 – 3	0.166	0.023
Face 3 – 4	0.429	0.023
Face 4 – 5	-0.111	0.023
Face 5 – 6	-0.505	0.023
Face 6 – 7	-0.276	0.023
Face 7 - 8	0.043	0.023
Face 8 - 9	-0.815	0.025
Face 9 - 10	1.498	0.026
Face 10 - 11	-0.608	0.023
Face 11 - 12	0.541	0.023
Face 12 - 1	-0.427	0.023

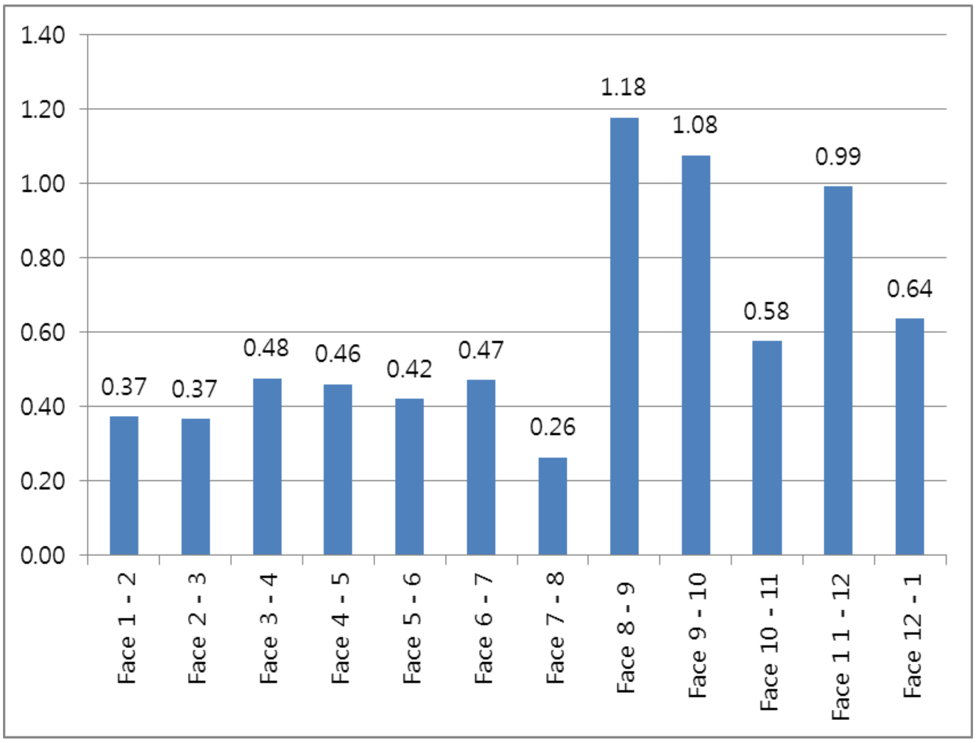

Figure 4. Birge ratios calculated for all the face to face readings on the polygon.

Since all the Birge ratios are less than 1.36, the data can be regarded as consistent.

The degrees of equivalence, $x_i - \bar{x}_w$, and its expanded uncertainty (k=2) calculated by using equation (7), are shown in Table 7 and 8, respectively.

Table 7. DoE in arc seconds for the polygon calibration

	NMISA	NMIA	KRISS	NMIJ/ AIST	NMC/ A*STAR	NIMT	SCL	CMS/ ITRI	NPLI	RCM-LIPI	NIM	NSCL
Face 1 - 2	0.040	-0.016	-0.006	0.024	0.144	-0.056	-0.026	0.044	-0.056	-0.086	-0.006	-0.056
Face 2 - 3	-0.071	0.004	0.019	0.004	-0.066	-0.096	0.004	0.004	-0.056	0.044	0.014	-0.066
Face 3 - 4	0.015	-0.009	-0.001	0.001	-0.229	-0.069	-0.039	0.051	-0.019	-0.189	0.021	-0.029
Face 4 - 5	-0.081	0.031	0.010	0.001	0.111	-0.049	0.031	-0.019	0.201	0.071	0.001	-0.089
Face 5 - 6	-0.027	-0.025	-0.006	0.005	0.105	0.035	0.035	0.005	-0.025	0.165	-0.025	0.105
Face 6 - 7	0.074	-0.024	0.005	-0.004	-0.024	0.116	-0.024	0.016	-0.004	0.146	-0.024	0.076
Face 7 - 8	0.005	-0.023	-0.010	0.027	-0.043	0.097	-0.013	0.007	-0.103	0.007	-0.003	0.057
Face 8 - 9	0.151	-0.065	-0.075	0.005	0.415	0.085	-0.085	0.085	0.165	0.275	-0.025	0.315
Face 9 - 10	-0.064	0.062	0.083	0.022	-0.598	0.102	-0.018	-0.078	-0.038	-0.528	0.032	-0.298
Face 10 - 11	0.062	-0.022	-0.047	-0.022	0.308	0.078	-0.012	0.018	0.178	0.218	-0.002	0.108
Face 11 - 12	-0.119	0.039	0.056	-0.011	-0.341	-0.081	0.079	-0.101	-0.311	-0.271	0.019	-0.141
Face 12 - 1	-0.054	0.047	-0.019	-0.033	0.127	-0.133	0.077	-0.023	-0.063	0.177	-0.013	0.027

Table 8. Expanded uncertainty of DoE in arc seconds for the polygon calibration

	NMISA	**NMIA**	**KRISS**	**NMIJ/ AIST**	**NMC/ A*STAR**	**NIMT**	**SCL**	**CMS/ ITRI**	**NPLI**	**RCM-LIPI**	**NIM**	**NSCL**
Face 1 - 2	0.153	0.197	0.119	0.126	0.598	0.337	0.100	0.153	0.779	0.518	0.072	0.357
Face 2 - 3	0.153	0.197	0.119	0.126	0.598	0.337	0.100	0.153	0.779	0.518	0.072	0.558
Face 3 - 4	0.153	0.197	0.119	0.126	0.598	0.337	0.100	0.153	0.779	0.518	0.072	0.397
Face 4 - 5	0.153	0.197	0.119	0.126	0.598	0.337	0.100	0.153	0.779	0.518	0.072	0.357
Face 5 - 6	0.153	0.197	0.119	0.126	0.598	0.337	0.100	0.153	0.779	0.518	0.072	0.317
Face 6 - 7	0.153	0.197	0.119	0.126	0.598	0.337	0.100	0.153	0.779	0.518	0.072	0.357
Face 7 - 8	0.153	0.197	0.119	0.126	0.598	0.337	0.100	0.153	0.779	0.518	0.072	0.598
Face 8 - 9	0.152	0.196	0.118	0.124	0.598	0.336	0.098	0.152	0.778	0.518	0.115	0.377
Face 9 - 10	0.152	0.195	0.117	0.124	0.598	0.336	0.097	0.152	0.778	0.517	0.115	1.659
Face 10 - 11	0.153	0.196	0.119	0.126	0.598	0.337	0.100	0.153	0.779	0.518	0.072	0.779
Face 11 - 12	0.153	0.197	0.119	0.126	0.598	0.337	0.100	0.153	0.779	0.518	0.072	0.377
Face 12 - 1	0.153	0.197	0.119	0.126	0.598	0.337	0.100	0.153	0.779	0.518	0.072	0.296

Thus, the E_n values for the polygon are as follows:

Table 9. E_n values of the results for the polygon measurements.

	NMISA	NMIA	KRISS	NMIJ/ AIST	NMC/ A*STAR	NIMT	SCL	CMS/ ITRI	NPLI	RCM-LIPI	NIM	NSCL
Face 1 - 2	0.262	-0.081	-0.050	0.191	0.241	-0.166	-0.260	0.288	-0.072	-0.166	-0.082	-0.157
Face 2 - 3	-0.463	0.021	0.161	0.033	-0.110	-0.285	0.042	0.027	-0.072	0.085	0.196	-0.118
Face 3 - 4	0.100	-0.044	-0.005	0.011	-0.382	-0.204	-0.388	0.336	-0.024	-0.364	0.296	-0.072
Face 4 - 5	-0.529	0.158	0.084	0.008	0.186	-0.146	0.311	-0.124	0.258	0.137	0.014	-0.249
Face 5 - 6	-0.178	-0.129	-0.053	0.037	0.175	0.103	0.348	0.031	-0.033	0.318	-0.350	0.331
Face 6 - 7	0.486	-0.120	0.045	-0.029	-0.040	0.345	-0.237	0.107	-0.005	0.283	-0.327	0.214
Face 7 - 8	0.032	-0.118	-0.085	0.214	-0.072	0.288	-0.132	0.045	-0.132	0.013	-0.043	0.095
Face 8 - 9	0.994	-0.334	-0.640	0.039	0.694	0.252	-0.873	0.559	0.212	0.531	-0.219	0.836
Face 9 - 10	-0.420	0.319	0.710	0.180	-1.000	0.304	-0.182	-0.513	-0.048	**-1.020**	0.280	-0.179
Face 10 - 11	0.405	-0.112	-0.395	-0.176	0.515	0.231	-0.121	0.117	0.229	0.421	-0.029	0.139
Face 11 - 12	-0.779	0.197	0.467	-0.090	-0.571	-0.241	0.790	-0.662	-0.400	-0.524	0.259	-0.375
Face 12 - 1	-0.350	0.241	-0.156	-0.259	0.213	-0.394	0.776	-0.147	-0.080	0.343	-0.174	0.093

As can be seen from Table 9, there is only 1 E_n value whose magnitude exceeds 1.
The average of the $|E_n|$ numbers of each laboratory is depicted in Figure 5.
From the Figures 4 and 5 and Table 9, it can be concluded that for the polygon, all the laboratories have shown consistent measurement results.

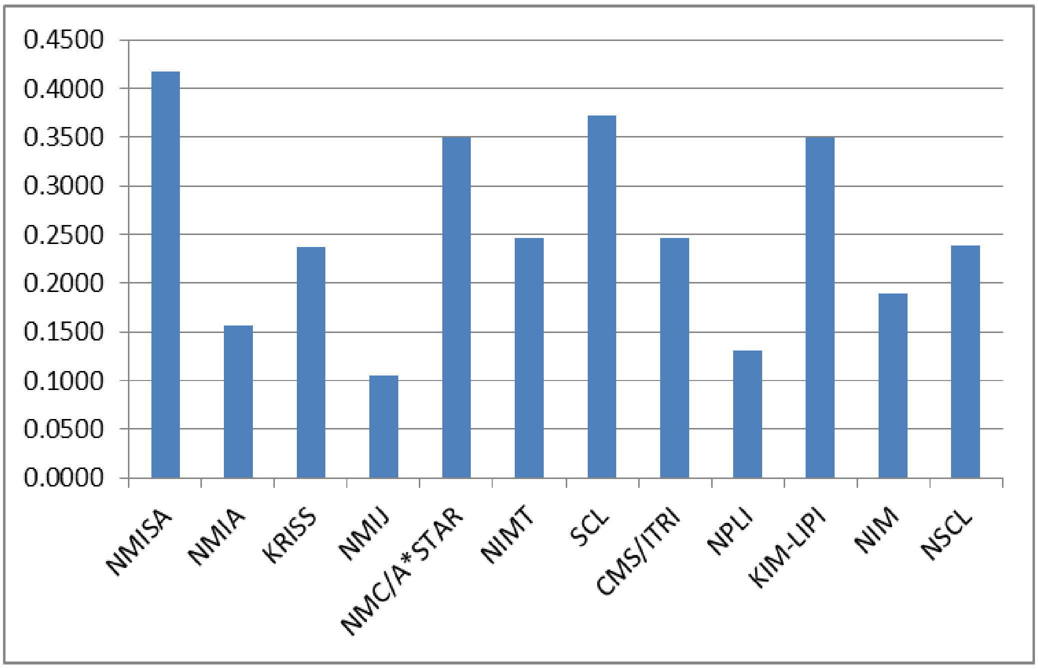

Figure 5. Average of | E_n| values of the participants for the polygon calibration

6.5 Angle blocks calculations

Table 10 shows the weighted mean values of the measured deviation from nominal angle of the angle blocks calculated by equation (2) using the measurement results from all participants, and Table 11 and Figure 6 show the corresponding E_n values and Birge ratios, respectively.
.

Table 10. Weighted mean and its standard uncertainty of the deviation from nominal angle

Nominal angle	$\bar{x}_w$	$u(\bar{x}_w)$
5″	0.805″	0.030″
30′	-0.800″	0.031″
5′	-0.442″	0.035″
5°	0.372″	0.030″

Table 11. E_n values of angle block measurement results when all data are used in the calculation of the weighted mean. The coloured cells with bold font are those with $|E_n| > 1$.

	NMISA	NMIA	KRISS	NMIJ/ AIST	NMC/ A*STAR	NIMT	SCL	CMS/ ITRI	NPLI	RCM-LIPI	NIM	NSCL
5″	1.023	-0.375	0.505	0.126	-0.264	-0.028	-1.167	-0.383	-0.012	0.808	-0.049	-0.125
30′	-0.422	-0.784	-0.377	-0.459	-0.129	0.018	-0.708	-0.712	3.588	0.769	-1.001	5.077
5′	-0.678	0.166	-0.086	0.015	2.886	-0.015	0.228	-0.409	-0.743	-0.389	0.407	-0.147
5°	0.148	-0.098	-0.011	0.655	0.165	-1.643	-0.242	0.757	-3.180	0.295	0.674	-1.254

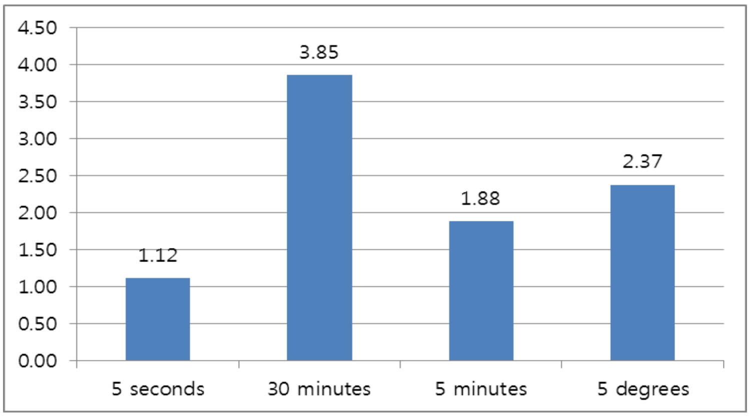

Figure 6. Birge ratio (R_B) calculated for each angle block

It can be seen from Figure 6 that Birge ratios of 3 angle blocks exceed the consistency limit of 1.36. Thus, the farthest outlier was excluded one by one in the calculation of the weighted mean until the Birge ratio became less than the value calculated by equation (6) with I being the number of participants included in the calculation of the weighted mean.

For the 30′ block, NPLI and NSCL had to be excluded to let the Birge ratio become less than the threshold value of 1.39 which was calculated from equation (6) using I=10. For the 5′ block, NMC/A*STAR was excluded and for the 5° block, NIMT and NPLI were excluded in calculating the KCRV.
Figure 7 shows the final Birge ratios when the outliers are excluded.

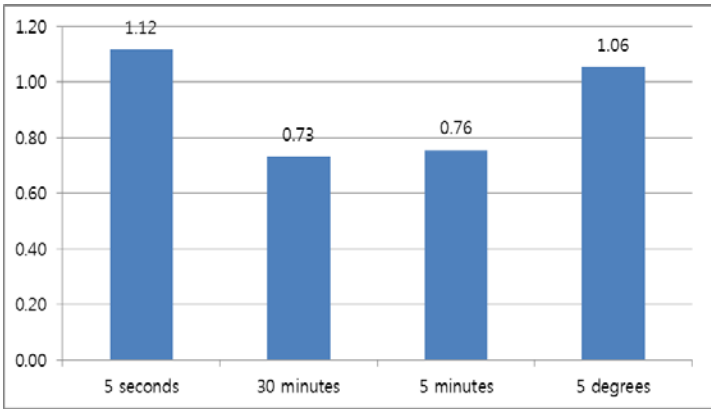

Figure 7. Birge ratio calculated for each angle block when the outliers are excluded

.
The weighted mean values obtained with the outliers excluded are shown in Table 12.

Table 12. Weighted mean values of the deviation from nominal angle of each angle block in arc seconds with outliers excluded in the calculation. These values were taken as the KCRVs.

Nominal angle	$\bar{x}_w$	$u(\bar{x}_w)$
5″	0.805	0.030
30′	-0.892	0.032
5′	-0.460	0.035
5°	0.412	0.031

The degrees of equivalence and its expanded uncertainty are shown in Table 13 and 14, respectively.

Table 13. DoE values of angle block measurement results in arc seconds when the outliers are excluded in the calculation of the KCRVs. The coloured cells are the ones whose data were excluded in the Birge ratio and KCRV (weighted mean) calculations.

	NMISA	NMIA	KRISS	NMIJ/ AIST	NMC/ A*STAR	NIMT	SCL	CMS/ ITRI	NPLI	RCM-LIPI	NIM	NSCL
5″	0.195	-0.095	0.077	0.015	-0.205	-0.015	-0.225	-0.065	-0.005	0.515	-0.005	-0.105
30′	0.012	-0.088	0.035	0.022	-0.008	0.102	-0.088	-0.028	1.582	0.582	-0.008	1.892
5′	-0.180	0.070	0.005	0.020	2.260	0.010	0.080	-0.050	-0.290	-0.230	0.070	-0.040
5°	-0.012	-0.062	-0.042	0.038	0.088	-0.922	-0.102	0.088	-1.362	0.148	0.028	-0.612

Table 14. Expanded uncertainty of DoE values in arc seconds when the outliers are excluded in the calculation of the KCRVs. For the coloured cells, the uncertainties were calculated using equation (8) and then multiplied by 2.

	NMISA	NMIA	KRISS	NMIJ/ AIST	NMC/ A*STAR	NIMT	SCL	CMS/ ITRI	NPLI	RCM-LIPI	NIM	NSCL
5″	0.191	0.253	0.152	0.120	0.778	0.537	0.193	0.170	0.416	0.637	0.101	0.838
30′	0.189	0.229	0.151	0.152	0.777	0.536	0.254	0.168	0.425	0.637	0.099	0.366
5′	0.292	0.314	0.148	0.149	0.783	0.535	0.273	0.166	0.414	0.636	0.128	0.394
5°	0.190	0.222	0.152	0.119	0.778	0.544	0.255	0.169	0.425	0.637	0.101	0.456

The E_n values of the angle block calibration are given in Table 15.

Table 15. E_n values of the measurement results for the angle blocks. The cells with $|E_n| > 1$ are shown in bold. The coloured cells' measurement results were excluded in the calculation of KCRVs.

	NMISA	NMIA	KRISS	NMIJ/ AIST	NMC/ A*STAR	NIMT	SCL	CMS/ ITRI	NPLI	RCM-LIPI	NIM	NSCL
5″	**1.023**	-0.375	0.505	0.126	-0.264	-0.028	**-1.167**	-0.383	-0.012	0.808	-0.049	-0.125
30′	0.066	-0.382	0.235	0.148	-0.010	0.191	-0.345	-0.164	**3.724**	0.915	-0.076	**5.175**
5′	-0.616	0.224	0.036	0.137	**2.886**	0.019	0.294	-0.299	-0.699	-0.361	0.550	-0.101
5°	-0.062	-0.279	-0.275	0.321	0.113	**-1.696**	-0.400	0.522	**-3.208**	0.233	0.281	**-1.342**

7 Conclusion

From the APMP.L-K3 angle standard key comparison, the following conclusions can be drawn:

- The comparison of the polygon shows good agreement between the laboratories for all the faces. The Birge ratio of the measurement results of each face is less than the consistency test ratio of 1.36. The average $|E_n|$ value for all the laboratories is smaller than one.

- The angle blocks did not agree to the same level as the polygon. Measurement result of the participant with largest $|E_n|$ value was excluded one by one until the Birge ratio became smaller than the consistency test value, and the KCRV was calculated using the remaining consistent data set. The non-agreement of the measurement results can come from 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 respect to their calibration services. The artefacts were chosen to verify both the laboratories' calibration and measurement capabilities, using the polygon and more routine calibrations using the angle blocks. The demonstration of equivalence was very impressive as the results of measurements of the polygon demonstrated but some further investigation with regards to the angle block measurements, is required.

8 Acknowledgement

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

9 References

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

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Appendix A. Measurement methods and instruments used by the participants

A wide variety of instruments and techniques were used to make the measurements. The details of these instruments are recorded in Table A1 with the uncertainties of the equipment appearing in brackets.

For the measurement of the polygon/angle blocks, the majority of the participants used index tables with a few exceptions where laboratories used an in-house designed system. For the measuring of the deviation from nominal, most laboratories used autocollimators with only one using a laser interferometer.

Table A1. Measurement instruments and their uncertainties (k=1) as reported by the participants

Laboratory	**Autocollimator/Interferometer (standard uncertainty in milliseconds)**	**Table (standard uncertainty in milliseconds)**
NMISA (South Africa)	Interferometer (25)	Moore 2160 (50)
NMIA (Australia)	Taylor Hobson DA20 (61) Hilger & Watts (117) Heidenhain type 129.3 (60)	Moore 1440 (82)
KRISS (Korea)	Möller-Wedel Elcomat (40 up to 5', 50 over 5')	Moore 1440 (40)
NMIJ/AIST (Japan)	Möller-Wedel Elcomat HR (15) Möller-Wedel Elcomat 3000 (15 up to 100", 50 over 100")	SSOKU PSID-720A (50) Self calibratable Canon X-1M rotary encoders (5)
NMC/A*STAR (Singapore)	Hilger & Watts (150)	AA Gage Inc (250)
NIMT (Thailand)	Möller-Wedel Elcomat 2000 (50 (SN 167), 100 (SN 168))	Dai-Ichi Sokuhan Works, SPID 720A (100)
SCL (Hong Kong)	Taylor Hobson DA20 (15)	Moore 1440 (55)
CMS/ITRI (Taiwan)	Möller-Wedel Elcomat 2000 (12)	Rotary Table (0)
NPLI (India)	Möller-Wedel Elcomat 2000 (50)	Moore 1440 (15)
RCM-LIPI (Indonesia)	Hilger & Watts (100)	Moore 1440 (250)
NIM (China)	Möller-Wedel Elcomat HR (10 for ±10" range, 50 for ±150" range)	6354th Institute of CSSC, DFT 720 (100)
NSCL (Syria)	Nikon (80)	ISSOKU, SPID-720A (130)