Asia-Pacific Metrology Programme

APMP Regional Comparison (APMP.L-K6)

Calibration of ball plate and hole plate

Final Report

Toshiyuki TAKATSUJI, NMIJ, 10 Sep 2012

Contents

1 Introduction

The metrological equivalence of national measurement standards is determined by a set of key comparisons chosen and organized by the Consultative Committees of the CIPM working closely with the Regional Metrology Organizations (RMOs).

The CCL inter-comparison for ball plate and hole plate (CCL-K6) has been conducted. During the inter-comparison, the APMP/TCL decided to carry out an APMP regional comparison (APMP.L.K6) to establish equivalence of National Metrology Institutes in APMP region to the world.

In September 2003, CCL 11 decided to introduce some changes in future Key Comparisons by having inter-regional participation organized through the Regional Technical Committees for Length (RTCLs) and the WGDM, so leaving the regions in charge of their comparisons but bringing the CCL/WGDM into the loop to be able to monitor and negotiate any difficulties.

Hence, participants should look at other regional KC with a view to finding a) a better time to do the comparison, b) a better uncertainty range or c) a more appropriate technique or method.

The technical protocol for APMP.L.K6 comparison was made based on the previous protocol for CCL-K6 drawn by the Centro Nacional de Metrologia (CENAM), Mexico. The procedures outlined in the protocol cover the technical procedure to be followed during measurement of the ball-plate and hole plate. The procedure follows the guidelines established by the BIPM1.

The first pilot measurement by NMIJ was performed in April 2006, then the gauges were circulated among the participating laboratories, and the final pilot measurement was done in October 2008. Although there was a little delay from the initial schedule, the comparison was finished successfully.

This document has been compiled to report the result of APMP.L.K6 comparison and is considered to be a supporting evidence of participants' calibration capabilities for two dimensional CMM gauges.

2 **Organization**

2.1 Participants

On 2005/Oct/7th the pilot laboratory distributed an e-mail to call for participation in the APMP.L.K6 inter-regional comparison. The participating laboratories should:

1) Be able to calibrate a 620 mm steel ball plate, with 5x5 ceramic 22 mm in diameter balls and 133 mm pitch between ball centers.
2) Be able to calibrate a 600 mm hole plate made of a low thermal expansion glass, with 44 holes, 20 mm in diameter holes and 50 mm pitch between hole centers.
3) Be able to demonstrate independent traceability to the realization of the meter.

There is an additional requirement to measure the artifacts at a temperature sufficiently close to 20 °C that the uncertainty in the measured expansion coefficient does not dominate the overall measurement uncertainty. The temperature inside the measuring volume of the CMM should have a mean inside the range 19.7 °C to 20.3 °C with variations in time and volume under 0.3 °C.

After agreeing on the final version of this protocol, each nominated participant must reconfirm its participation and approval of the protocol. If for any of the above technical reasons a nominated laboratory is not able to participate, it must notify the pilot laboratory as soon as possible to reschedule the comparison.

By their declared intention to participate in this inter-regional key comparison, the laboratories accept the general instructions and the technical protocols written down in this document and commit themselves to follow the procedures strictly.

Once the protocol and list of participants has been agreed, no change to the protocol or list of participants may be made without prior agreement of all participants.

2.2 Participants list

No.	Country	Region	Contact person/address
1	Japan (Pilot)	APMP	Toshiyuki TAKATSUJI Dimensional Standards Section, Lengths and Dimensions Division National Metrology Institute of Japan (NMIJ/AIST) AIST Central 3, 1-1-1, Umezono, Tsukuba, Ibaraki 305-8563 Japan e-mail: toshiyuki.takatsuji@aist.go.jp
2	Korea	APMP	Taebong EOM Length Group Korean Research Institute of Standards and Science (KRISS) 1 Doryung-Dong, Yuseong-Gu, Daejeon 305-600], Rep of Korea e-mail: tbeom@kriss.re.kr
3	Thailand	APMP	Anusorn Tonmueanwai National Institute of Metrology (Thailand) (NIMT) Department of Dimensional Metrology 3/5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120, Thailand e-mail: anusorn@nimt.or.th
4	Australia	APMP	Ruimin Yin National Measurment Institute of Australia (NMIA) Bradfield Road, West Lindfield NSW2070, Australia e-mail: Ruimin.Yin@measurement.gov.au
5	South Africa	APMP	Floris van der Walt CSIR NML P O Box 395, Pretoria, 0001, South Africa e-mail: FvdWalt@csir.co.za
6	China	APMP	Sitian Gao Deputy Director of Length Division National Institute of Metrology (NIM) Beisanhuandonglu 18, 100013 Beijing China e-mail: gaost@nim.ac.cn
7	Vietnam	APMP	Bui Quoc Thu Laboratory of Length, Vietnam Metrology Institute (VMI) No 8 Hoang Quoc Viet Road, Cau Giay District, Hanoi, Vietnam e-mail: vmi@fpt.vn
8	India	APMP	R P Singhal National Physical Laboratory, India (NPLI) Dr. K S Krishnan Marg, New Delhi- 110 012, India e-mail: singhal@mail.nplindia.ernet.in
9	New Zealand	APMP	Eleanor Howick Measurement Standards Laboratory of New Zealand (MSLNZ) PO BOX 31-310, Gracefield Road, Lower Hutt, New Zealand e-mail: e.howick@irl.cri.nz
10	Canada	SIM	Kostadin Doytchinov Dimensional Metrology Institute for National Measurement Standards National Research Council of Canada (NRC) 1200 Montreal Road, Bldg M36, Rm134 Ottawa, Canada K1A 0R6 email: Kostadin.Doytchinov@nrc-cnrc.gc.ca
11	Brazil	SIM	José Carlos Valente de Oliveira Mechanical Division Dimensional Metrology Laboratory National Institute of Metrology, Standardization and Industrial

			Quality (INMETRO) Av. N. Sra. das Graças, 50 - Vila Operária - Xerém - Duque de Caxias, 25250-133 , Duque de Caxias, R.J., Brazil e-mail: jcoliveira@inmetro.gov.br
12	Finland	EUROMET	Antti Lassila Group manager, Length, MIKES P.O. box 9 (Tekniikantie 1) FIN-02151 Espoo, Finland e-mail: Antti.Lassila@mikes.fi
13	Ireland	EUROMET	Jim O Donnell National Metrology Laboratory Enterprise Ireland campus Glasnevin, Dublin 9 Ireland e-mail: Jim.ODonnell@enterprise-ireland.com
14	Italy	EUROMET	Alessandro Balsamo Istituto Nazionale di Ricerca Metrologica (INRiM) str. delle cacce, 73 - 10135 Torino – Italy e-mail: a.balsamo@inrim.it

2.3 Form of comparison

The calibration suitability of the gauges has been assessed by measurements at NMIJ prior to the start of the circulation of the gauges. NMIJ acted as the pilot laboratory.

Each laboratory received the gauges according to the pre-agreed timetable. Three loops were carried out in succession. The first loop comprises of five APMP countries, and in all the countries an ATA carnet is acceptable. In the second loop, three APMP countries will participate, and no ATA carnet will be used in this loop. In the third loop six countries from APMP, SIM, and EUROMET participated, and an ATA carnet was used except Brazil. At the beginning and the end of each loop, the gauges were sent to NMIJ/AIST (the pilot laboratory) for control measurements to check the stability of the gauges. Because of time constraints, it was impossible to arrange for a ‘star-shaped’ circulation.

All results were supposed to be sent directly to the pilot laboratory as soon as possible and certainly within 4 weeks of completion of the measurements by each laboratory.

Each laboratory has one month for customs clearance, measurement and shipment to the following participant. With its confirmation to participate, each laboratory has confirmed that it is capable to perform the measurements in the time allocated to it. It guarantees that the standards arrive in the country of the next participant at the beginning of the next one month period.

If for some reasons, the measurement facility is not ready or customs clearance takes too much time in a country, the laboratory has to contact the pilot laboratory immediately and – according to the arrangement made – eventually to send the standards directly to the next participant before finishing the measurements or even without doing any measurements. Just in case this kind of situation happens, the next chance for the measurement will never be given. The participant is encouraged to participate in the next interregional key-comparison. The concept of interregional key-comparison was invented to overcome this situation and to give opportunities for all NMIs to the maximum.

All participants shall strictly abide by the agreed time schedule. Being not able to complete the measurement by some reasons is not embarrassing as it is often the case with everyone. All participants, however, should keep it in mind that to delay the comparison will deteriorate your reputation.

2.4 Timetable

As is often the case with intercomparisons, the circulation was delayed with respect to the plan. The circulation was supposed to terminate within one and half years, but actually it took two and half years. The third loop took more than one year which is longer than the term of validity of the ATA carnet. To avoid the expiry and issue a new carnet, the artifacts returned to the pilot in the middle of the third circulation, but no measurement was done at the pilot lab.

Table 2.4.1 Planned and actual timetable of the comparison.

Region	NMI	Country	Planned	Actual (DD/MM/YYYY)
Pilot1	NMIJ	Japan		
APMP	CRISS	Korea	May 2006	02/05/2006-29/05/2009
	NIMT	Thailand	Jun 2006	06/06/2006-28/06/2006
	NMIA	Australia	Jul 2006	19/07/2006-01/09/2006
	CSIR	South Africa	Sep 2006	14/09/2006-01/10/2006
Pilot2	NMIJ	Japan	Oct 2006	04/10/2006-01/11/2006
APMP	NIM	China	Nov 2006	03/11/2006-04/01/2007
	VMI	Vietnam	Jan 2007	24/01/2007-07/03/2007
	NPL	India	Feb 2007	09/04/2007-19/06/2007
Pilot3	NMIJ	Japan	Mar 2007	28/06/2007-27/07/2007
SIM	NRC	Canada	Apr 2007	08/08/2007-22/09/2007
EUROMET	MIKES	Finland	May 2007	27/09/2007-25/10/2007
	NML	Ireland	Jun 2007	29/10/2007-28/11/2007
	INRiM	Italy	Jul 2007	30/11/2007-15/01/2008
SIM	INMETRO	Brazil	Aug 2007	14/03/2008-28/04/2008
Pilot4	NMIJ	Japan		
APMP	MSLNZ	New Zealand	Sep 2007	07/08/2008-15/10/2008
Pilot5	NMIJ	Japan	Oct 2007	23/10/2008

2.5 Handling and transport of the artefact

Upon reception, the laboratory should confirm it to the pilot laboratory as well as to the sender laboratory. The artifacts should be examined immediately upon receipt. The condition of the gauges should also be noted in the form.

The gauges should only be handled by authorized persons and stored in such a way as to prevent damage. The artifacts should not be touched with bare hands.

The gauges should be examined before dispatch and any change in condition during the measurement at each laboratory should be communicated to the pilot laboratory.

The participants must inform the pilot laboratory and the next laboratory via fax or e-mail when the gauges are about to be sent to the next recipient.

Before and after the measurements, the gauges must be cleaned. Ensure that the content of the package is complete before shipment. Always use the original packaging.

The gauges shouldn’t be lent to anyone other than the participants or used for any other purposes.

The gauges should be kept under 20 °C temperature and 50 % humidity condition as close as possible no matter if they are stored in the carriage container or not.

In order to monitor the temperature and humidity during the circulation, a small data logger is packed in each carriage box of the ball plate and hole plate. The data logger should be placed near the gauges at all time, i.e. it should be taken out from the carriage box when the gauge is taken out. The recorded data is analyzed by the pilot after the whole comparison schedule is completed.

3 Description of the gauges

3.1 Gauges

The gauges used for the comparison are the following:

Ball Plate

Manufacturer: KOBA

Serial Number: 20040216

Material: Steel frame with ceramic balls.

Thermal expansion coefficient of steel, $\alpha = (11.5 \pm 1.0) \times 10^{-6}\ K^{-1}$ at 20 °C.

Dimensions (mm):

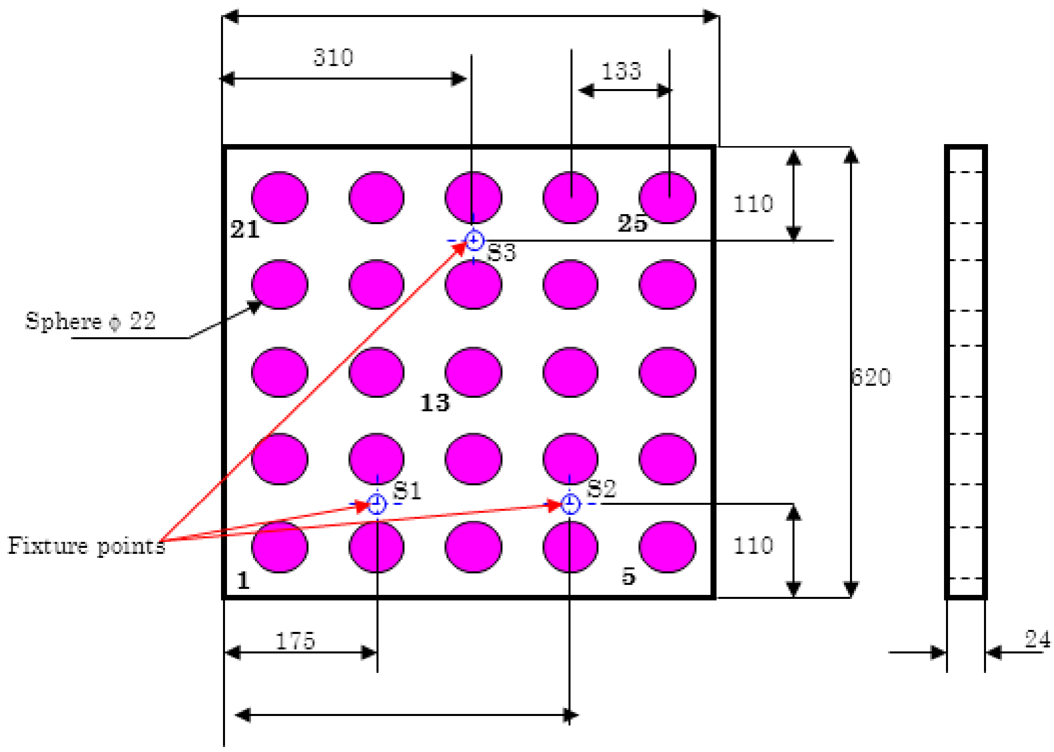

Fig. 3-1 Ball plate description

Hole Plate

Manufacturer: Unimetrik

Serial Number: UMTK1628

Material: Mail body: Zero expansion glass (Schott Robax)

Ring: Ceramic

Frame: Carbon fiber

Thermal expansion coefficient of Robax: $\alpha = (0 \pm 0.5) \times 10^{-6}$ K^{-1} at 20 °C.

The detail of Robax can be seen in the following web site.
http://www.schott.com/hometech/english/download/schott_brosch_robax_e.pdf

Dimensions (mm):

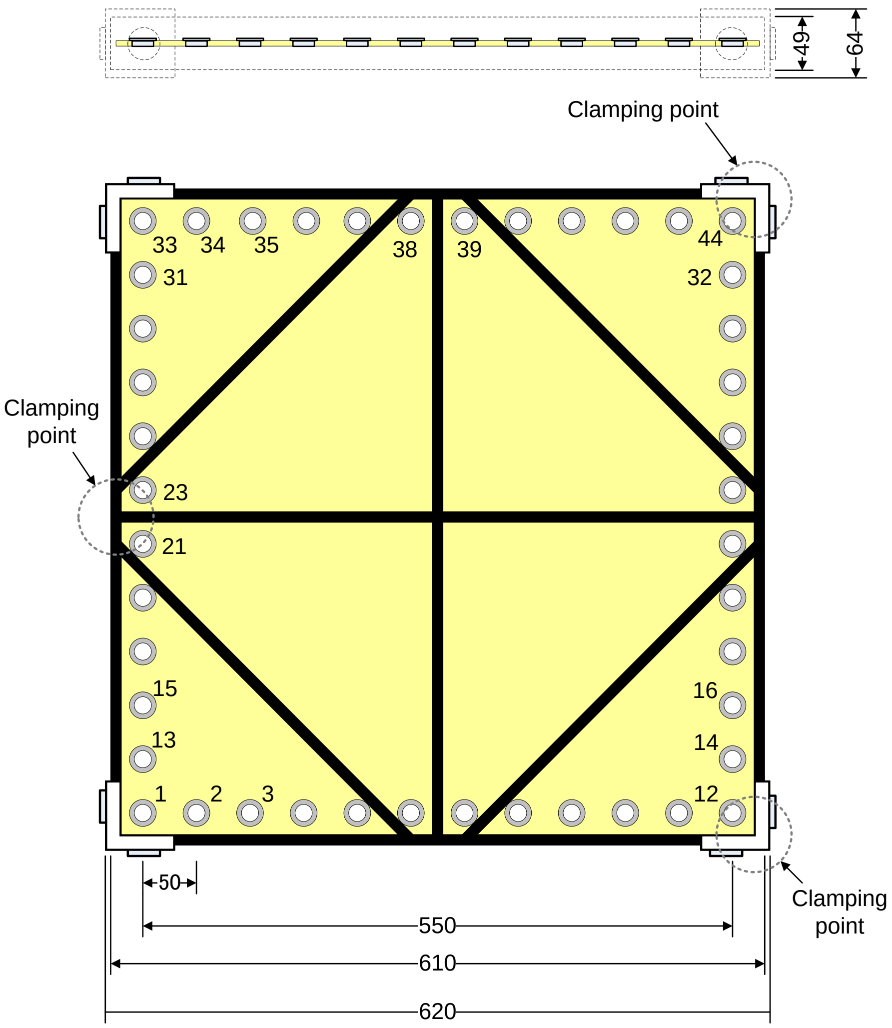

Fig. 3-2 Hole plate description

Fig. 3-3 The ball plate in the carrying case

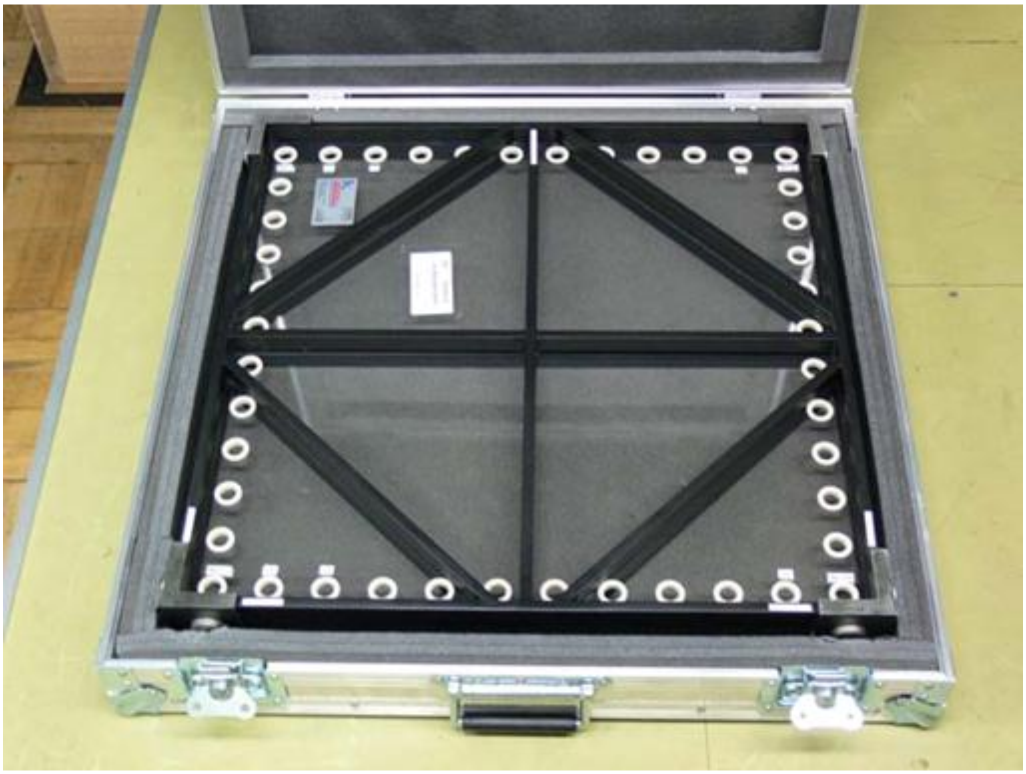

Fig. 3-4 The hole plate in the carrying case

3.2 Damage

During the circulation, no damage was found on the artifacts.

3.3 Temperature and humidity monitored by the data logger

Figure 3-5 shows the temperature and humidity monitored by the data logger placed near the ball plate during the comparison. The temperature during the measurements is around 20 °C but the temperature changed from 10 to 40 °C during the transportation. The humidity changed from below 30 to over 90 %. In spite of the large environmental change, the ball plate was stable throughout the comparison as can be seen later.

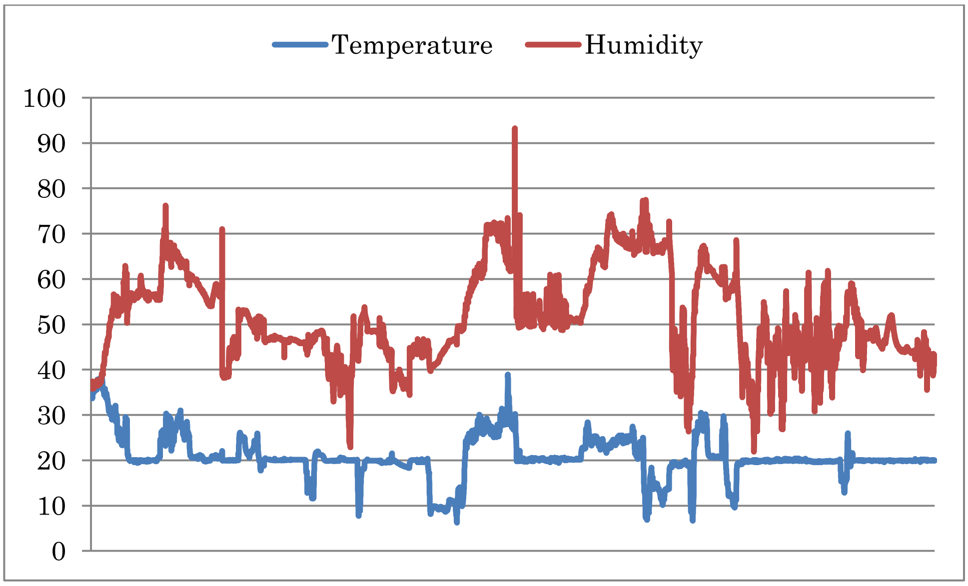

Fig. 3-5 The environmental condition of the ball plate during the comparison

Figure 3-6 shows the environmental condition monitored by the data logger placed near the hole plate during the comparison. The temperature and humidity bands are similar to those of the ball plate in Fig. 3.3.1. The hole plate was also stable throughout the comparison.

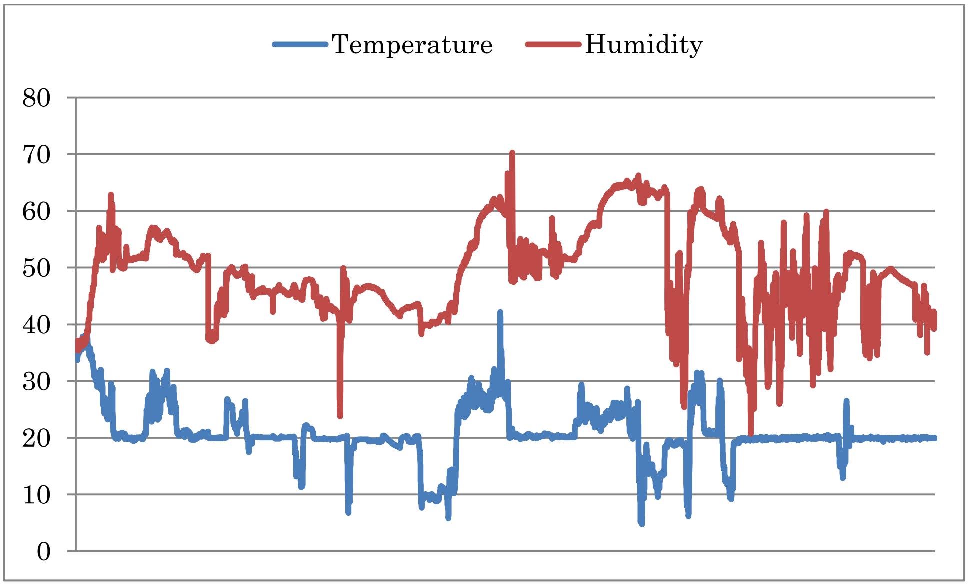

Fig. 3-6 The environment condition of the hole plate during the comparison

4 **Measurement instructions**

4.1 Traceability

Length measurements should be independently traceable to the latest realization of the *mètre* as set out in the current "*Mise en Pratique*". This means that the length unit is transferred to the ball and hole plates with the CMM by one of the following methods: laser interferometer, gauge blocks, ball beams, ball bar or step gauges. Whatever the instrument or standard used, it should be traceable to the definition of the length unit through calibrations performed in house. Temperature measurements should be made using the International Temperature Scale of 1990 (ITS-90).

4.2 Measurands

Ball Plate: The object reference plane is defined by the center of balls number 1, 5 and 21. The origin of object coordinate system is the center of ball number 1. The X-axis of the object reference system is defined by the line that passes through the center of ball number 1 and the center of ball number 5. The direction from the origin to ball number 5 defines the positive X-axis direction. The Y-axis is defined as the orthogonal line that passes through the center of ball number 1. The positive direction is from ball number 1 to ball number 21. The measurands of the ball plate are the X and Y coordinates of each ball center with respect to the origin of object coordinate system (Fig.4-1) with the plate lying horizontally and fixed as described in section 4.3.3. It is recommended to report Z coordinates of each ball as well, however it is not in the scope of this comparison and will be used just as a reference.

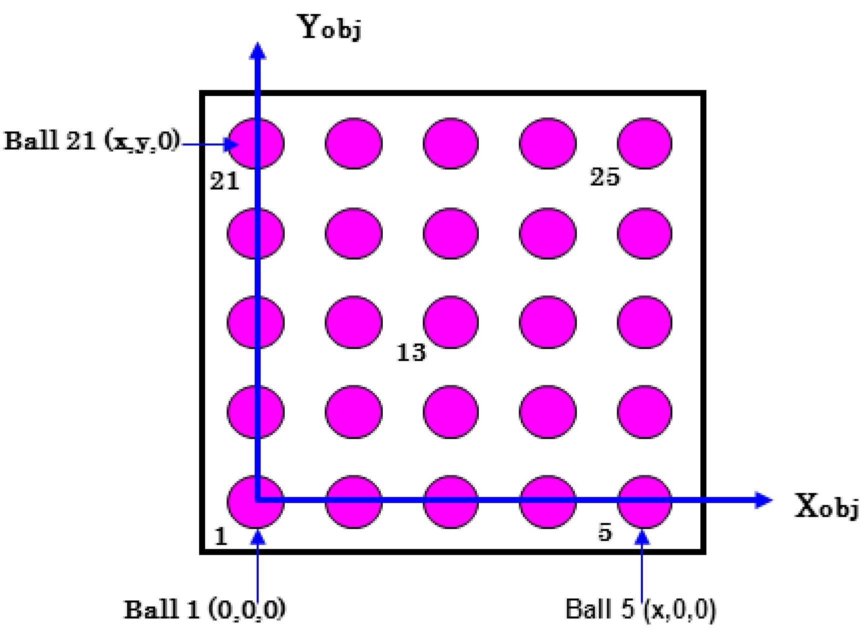

Fig. 4-1. Ball plate coordinate system

Hole Plate: As the hole plate is ultra-light-weight, some additional care should be taken in the calibration, as compared to the normal solid type hole plate. Ring elements are not symmetrical in the Z direction, as shown in Fig.4-3: the nominal thickness of the glass plate is 5 mm, and the ring element has a 2 mm nominal thickness flange on its top. Therefore the centerline of the glass is approximately 4.5 mm from the flange top surface, and approximately 2.5 mm from the bottom of the ring element. Because the bottom of the ring element is very narrow (2 mm width ring), the alignment procedure should be performed meticulously. The measurement procedure is as follows. An exaggerated image is shown in Fig.4-4 to explain the measurement procedure.

[Build the symmetry plane]

a) Measure the 4 corner elements, (1,12,33,44), namely four points on the top surface of each element, 90° apart to each other.

b) Calculate the best fit plane through these 16 points.

c) Shift the best fit plane 4.5 mm below when the plate is measured from the “top” and 2.5 mm above when the plate is measured from the “bottom”. The shifted plane is used as a symmetry plane. Refer to Fig. 4-3.

[Measure the ring elements; the following applies to each element]

d) Measure the inner cylinder in 8 points: 4 points 0.25 mm above and 4 points 0.25 mm below the symmetry plane.

e) measure the upper plane in four points, 90° apart each other (similarly to a)).

f) translate the plane nominally onto the symmetry plane, i.e. 4.5 mm when the flange top surface is measured, and 2.5 mm when the bottom ring surface is measured.

g) Calculate the intersection between the cylinder axis and this translated plane.

h) Project this point onto the symmetry plane. This is called the “center point” of the element. Now all center points lie in the symmetry plane.

[Build the hole plate coordinate system]

i) The XY plane is the symmetry plane. The origin is the center point of element 1. The X-axis passes through the center point of element 12. The Y-axis is positive in the direction towards element 33.

[Measurands]

The measurands are the (X,Y) coordinates of each center point with respect to the object coordinate system, when the plate rests horizontally and is fixed as described in section 4-4.

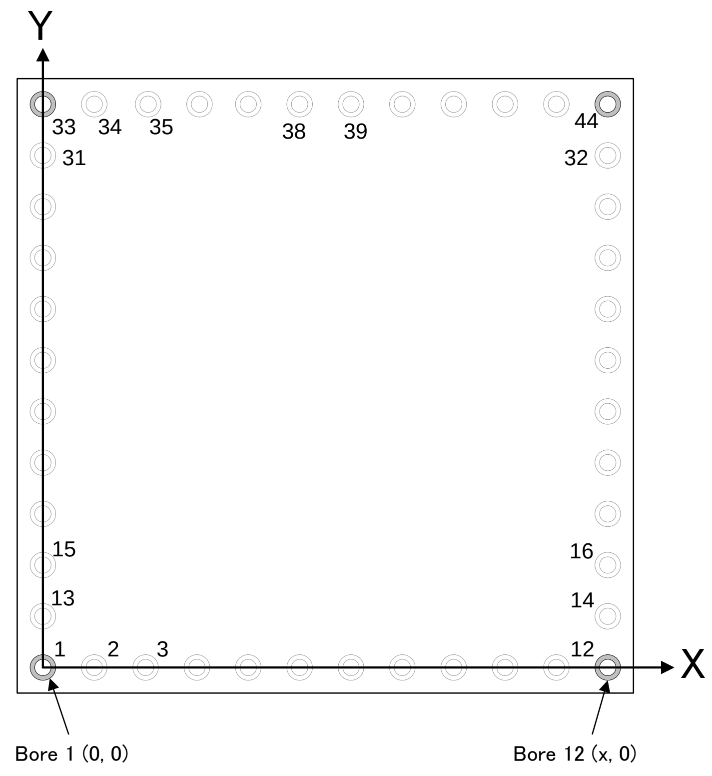

Fig. 4-2 Hole plate coordinate system

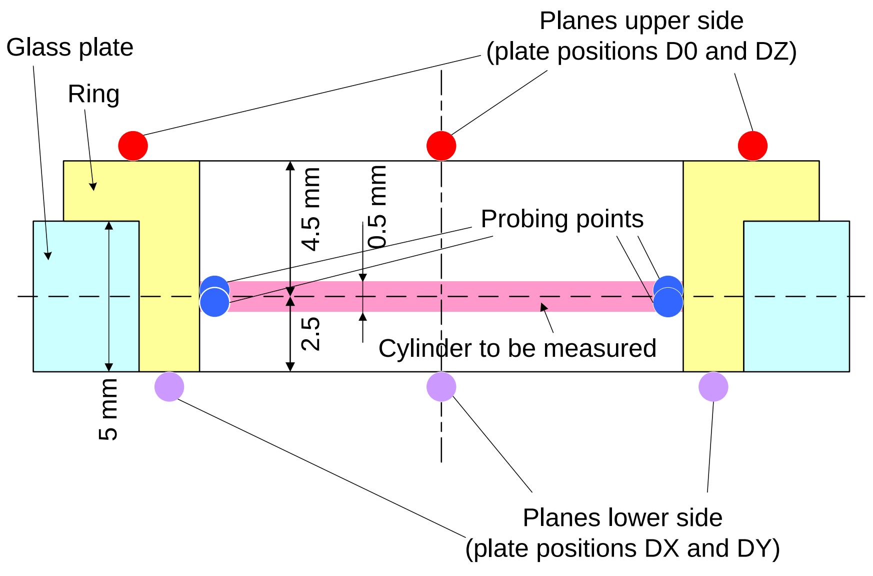

Fig. 4-3 Ring element of the hole plate

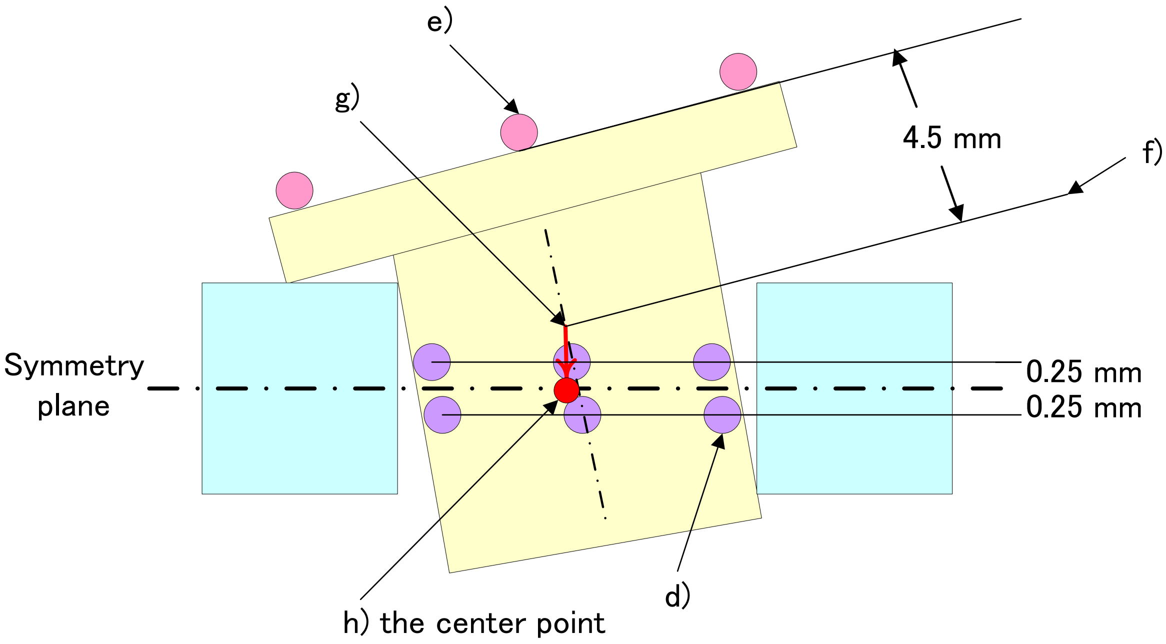

Fig. 4-4 An exaggerated image to explain the measurement procedure

The thermal expansion coefficient used should be the quoted values for each plate. Laboratories should report the temperatures at which the length measurements were made. Laboratories should only measure the artifacts at a temperature of (20 ± 0.3) °C.

For both the ball plate and the hole plate, the center coordinates should be reported with 10 nm resolution. In case the resolution is worse, the rounding error should be carefully taken into account in the uncertainty estimation.

4.3 Measurement instructions

Each laboratory is free to use its own measuring method. However, measurements should be reported in the object reference coordinate system described in 4.2. Before measurement, the gauges must be inspected for damage. Special attention should be paid to the measurement surfaces and form elements (balls or holes). Any scratches, rusty spots or other damages have to be documented. An inspection report should be sent to the pilot upon reception quoting the state of the gauge as received.

Before measurement, the plates and supports must be cleaned. The form elements have to be cleaned with special care individually as well as the measuring surfaces in the vicinity of all probing points.

Included with the ball plate there is a fixture to mount it in horizontal position which has three elements to support the ball plate: one conical, one with a V-grove and a flat one. See figure 4-5 to 4-8. Three hemispherical supports are screwed to the ball plate (points S1, S2 and S3). The three supports must be fixed to the CMM table as to support each of the hemispheres in the following order. Firstly, the cone base should be attached to the support point S1. Secondly, the V-grove base should be attached to point S3, with the grove aligned towards the cone. Finally, the plane base should be attached to point S2.

Fig. 4-5 Ball plate support

Fig. 4-6 Ball plate support (cone)

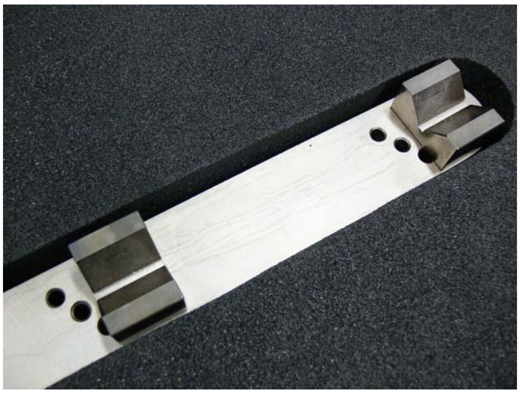

Fig. 4-8 Ball plate support (V-grove)

Fig. 4-7 Ball plate support (flat)

Included with the hole plate there are 7 mm and 7.5 mm gauge blocks. The hole plate is placed on the stage of the CMM directly without any support. The corner points on the frame near hole 12 (figure 4-9) and hole 44 (figure 4-10) are clamped firmly. The clamping points are clearly marked on the hole plate and thin steel plates are fixed on the corners to strengthen the surface. In addition, one point on the frame between hole 21 and 23 (figure 4-11) is clamped with a gauge block sandwiched between the frame and the CMM table. No steel plate is fixed on this points, so extra care should be exercised to avoid damages. The 7 mm gauge block is used for the position D0 and DZ, and the 7.5 mm one is used when the hole plate is upside down (i.e. for the position DX and DY).

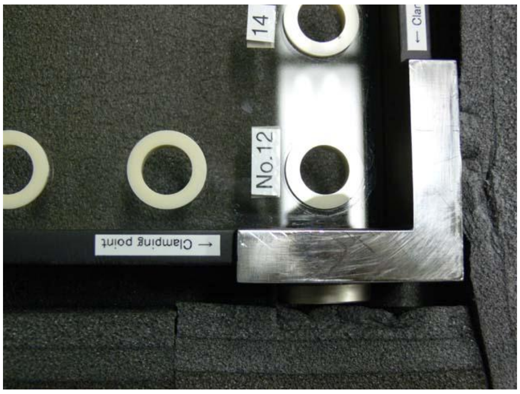

Fig. 4-9 Clamping point near hole 12

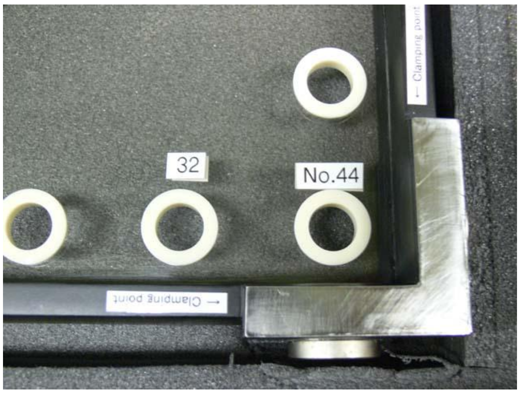

Fig. 4-10 Clamping point near hole 44

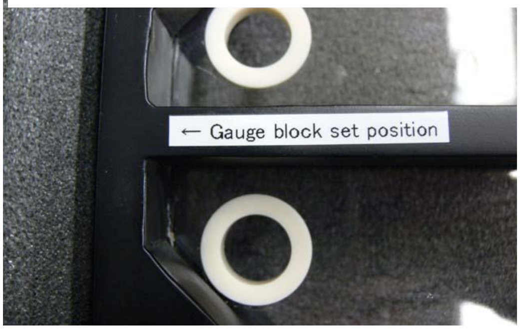

Fig. 4-11 Clamping point between hole 21 and 23

The measurement results should be corrected to the reference temperature of 20 °C using the values of the thermal expansion coefficient provided by the pilot laboratory.

No other measurements are to be attempted by the participants and the artifacts should not be used for any purpose other than described in this document. The artifacts may not be given to any party other than the participants in the comparison.

Special attention should be paid to the numbering sequence of the elements. It is not a spiral manner as can be observed in Fig 4-2.

If for any reason a laboratory is not able to make all the measurements of one or both gauges, it is still encouraged to report the rest of the results.

5 Measurement uncertainty

The uncertainty of measurement shall be estimated according to the *ISO Guide to the Expression of Uncertainty in Measurement*. Due to differences of equipment, methods and procedures applied between laboratories, a complete list of uncertainty sources to be taken in account may not be drawn. However, the following table quotes the usual measurement uncertainty sources. Additional sources may be added at the end of the table according to each laboratory's set-up, equipment, procedures and uncertainty estimation method, but it is expected that this additional source will not dominate the uncertainty budget.

Table 5.1 Usual measurement uncertainty sources if employing gauge blocks, step gauges or laser interferometer for the length comparison

Uncertainty Source	Uncertainty value	Uncertainty in Length
short term reproducibility	μm	μm
drift of temperature in the plate	K	μm*L/m
drift of temperature in CMM	K	μm*L/m
deviation from linearity of the CMM's errors of position	μm	μm
uncertainty of the gauge block or step gauge length or laser interferometer	μm*L/m	μm*L/m
uncertainty of the length comparison (probing uncertainty)	μm	μm
uncertainty of the temperature difference during the length comparison	K	μm*L/m
uncertainty of the thermal expansion coefficient	K^{-1}	μm*L/m
Other contributions	μm	μm

6 Reporting of results

Results should be communicated to the pilot laboratory as soon as possible and within four weeks after the end of the corresponding laboratory allocated time period.

The reports should include the state of the measurement surfaces of the artifacts; description of the measurement instrument, measuring technique, traceability chain, temperature variation and temperature measurement method.

Finally the uncertainty budget must be stated. The uncertainty shall be stated as combined standard uncertainty with no coverage factor applied at the end. Length dependent terms should be left in terms of l (length), and the combined standard uncertainty should be expressed as a quadratic sum of the form:

$$u_C(l) = \sqrt{a^2 + b^2 \times l^2}$$

Where a and b are real numbers, l is the length in mm and $u_C(l)$ is in μm.

The report should be sent by courier service as well as by electronic mail to the pilot laboratory. The later means is to allow the pilot laboratory to collect the results as soon as possible. In any case, the signed report must also be sent in paper form. In case of any differences between the two messages, the paper forms are the ones considered to be valid.

Following receipt of all measurement reports from the participating laboratories, the pilot laboratory will analyze the results and prepare a first draft report on the comparison. This will be circulated to the participants for comments, additions and corrections. Subsequently, the procedure outlined in the BIPM Key Comparison Guidelines will be followed.

For comparison of the measurement results a reference value will be needed. As there is at present a lot of discussion about the calculation of reference values, the method for the calculation of the reference value will be fixed after the completion of the measurements.

7 Stability of the gauges

Four measurements were performed by the pilot laboratory, the first one at the beginning of the comparison, two at intermediate, and the last one at the end of the comparison. The average values of four measurements are calculated by using the best fit algorithm and the deviation of each measurement from the average is shown in Figure 7-1 to Figure 7-4.

Ball plate: Figure 7-1 and figure 7-2 show the stability of the ball plate in X direction and Y direction respectively. The red lines indicate the measurement uncertainty of the pilot. The largest deviation is approximately 0.15 μm which is much smaller than the measurement uncertainty of the pilot. It means significant change was not observed during the comparison. If any time-varying phenomena occur in the gauges, it can be observed as a unidirectional length variation over time. No such obvious tendency cannot be found.

Hole plate: Figure 7-3 and figure 7-4 show the stability of the hole plate in X direction and Y direction respectively. The largest deviation is almost equal to the measurement uncertainty of the pilot. Two reasons can be considered for this. The first is the pilot underestimated the measurement uncertainty, and the second is the hole plate is not stable enough to use for the purpose of international comparisons. Anyway at least the validity of the comparison has been confirmed. Similar to the ball plate, time-varying phenomena cannot be seen in the hole plate.

Although four measurements are performed by the pilot, only the first result is used as a reporting result of the pilot.

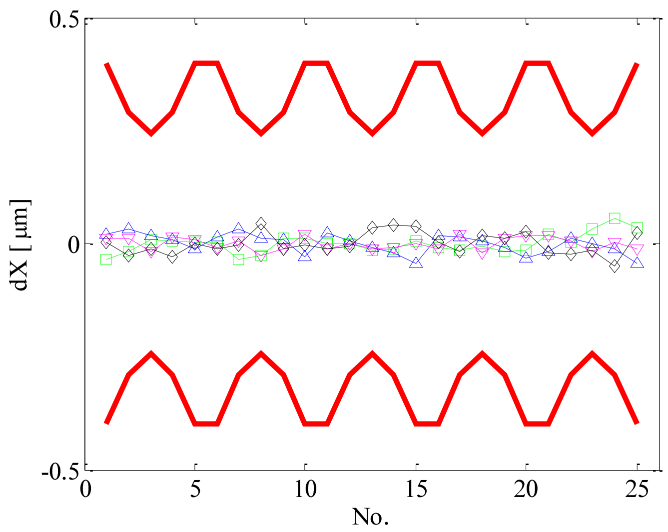

Fig. 7-1 Stability of the ball plate observed by the pilot (X direction)

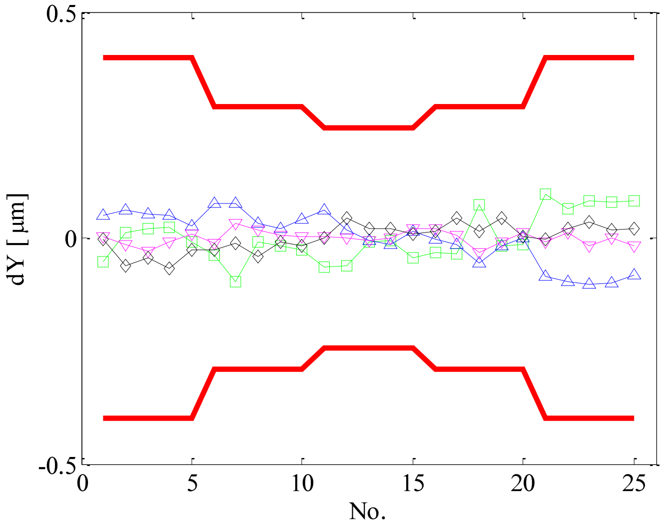

Fig. 7-2 Stability of the ball plate observed by the pilot (Y direction)

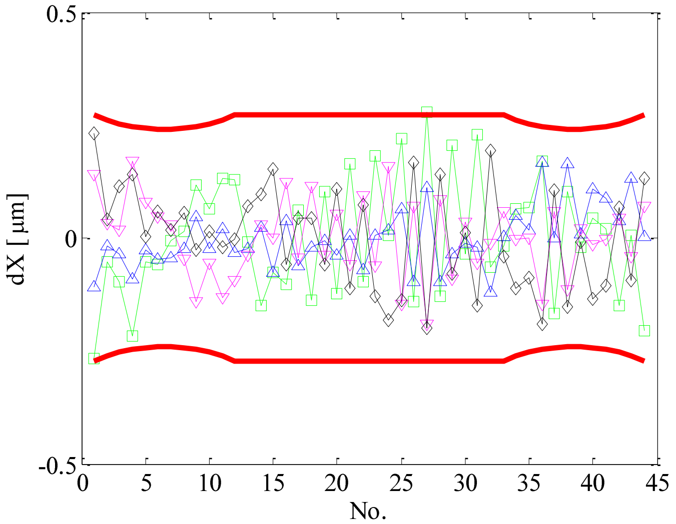

Fig. 7-3 Stability of the hole plate observed by the pilot (X direction)

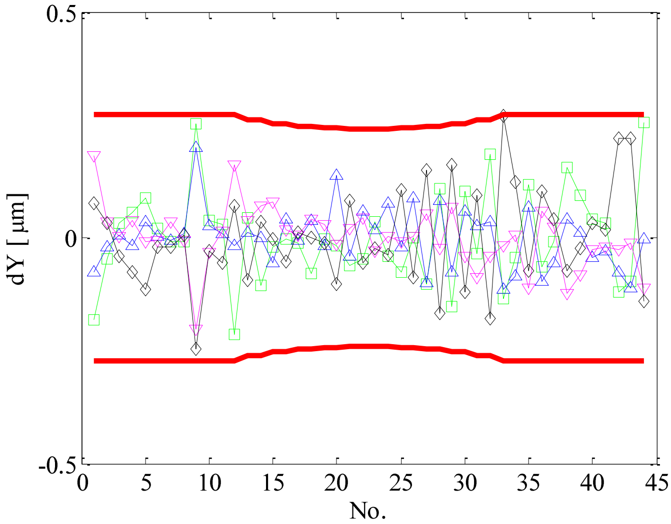

Fig. 7-4 Stability of the hole plate observed by the pilot (Y direction)

8 Measurement results

Some participants submitted their reports within four weeks after the measurements and some others not.

The gauges were actually delivered to Vietman Metrology Institute (VMI) and then forwarded to the next participant, however they didn't submit their report within four weeks after their gauges dispatch. The pilot does not know whether they have actually made measurements or not. After sending some notification to VMI, APMP.TCL decided at its 2008 meeting that a deadline is set for VMI to submit their report and that failure to do so is regarded as withdrawal from the comparison. VMI didn't submit their report to the pilot by the deadline. Consequently VMI was excluded from this report.

Without VMI, there are thirteen participants. While all of them were able to measure the ball plate, four participants, NIM, NPLI, NML, and INRiM, didn't measure the hole plate mainly due to limited CMM measurement volume. As a result, there are nine participants for the hole plate.

After receiving all reports, the pilot calculated a preliminary key comparison reference values (KCRV) and deviation of each participant from KCRV. Then according to the international comparison guideline by CIPM the pilot made a contact to those participants having anomalous results and informed them of the possibility of anomalousness. At that time, only the possibility was taught to the participant but not sign or amount of the anomalous results. On receiving this information, some participants revised their results.

Measurement results finally reported by the participants for the ball plate are shown in Table 8-1 and those for the hole plate are in Table 8-2.

KRISS didn't report the hole No. 26 of the hole plate, so this cell of Table 8-2 is left blank.

Table 8-1 Reported measurement results by the participants for the ball plate

	Nominal		NMIJ (B1)		KRISS (B2)		NIMT (B3)		NMIA (B4)		CSIR (B5)		NIM (B6)		NPLI (B7)	
No	*X*	*Y*	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]
1	0	0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2	133	0	132.99544	0.00064	132.99563	0.00063	132.99537	0.00061	132.99552	0.00061	132.99530	0.00080	132.99552	0.00057	132.99940	0.00070
3	266	0	265.99464	-0.00041	265.99487	-0.00033	265.99455	-0.00044	265.99484	-0.00042	265.99240	-0.00030	265.99476	-0.00052	266.00270	0.00040
4	399	0	398.99765	-0.00022	398.99808	-0.00012	398.99775	-0.00029	398.99779	-0.00022	398.99350	-0.00030	398.99797	-0.00024	399.00980	0.00030
5	532	0	532.00074	0.00000	532.00119	0.00000	532.00081	0.00000	531.99998	0.00000	531.99640	0.00000	532.00112	0.00000	532.01690	0.00040
6	0	133	-0.01893	133.01012	-0.01893	133.01034	-0.01892	133.01032	-0.01900	133.00996	-0.01900	133.00960	-0.01900	133.01029	0.01970	133.01000
7	133	133	132.97898	133.01135	132.97913	133.01167	132.97897	133.01158	132.97907	133.01129	132.97890	133.01100	132.97904	133.01155	132.98230	133.01180
8	266	133	265.98069	133.00876	265.98089	133.00900	265.98069	133.00892	265.98091	133.00857	265.97830	133.00810	265.98081	133.00880	265.98810	133.00900
9	399	133	398.98005	133.01047	398.98040	133.01075	398.98015	133.01025	398.98014	133.01028	398.97540	133.00990	398.98038	133.01059	398.99150	133.01100
10	532	133	531.98216	133.01178	531.98249	133.01198	531.98218	133.01185	531.98141	133.01174	531.97800	133.01110	531.98252	133.01195	531.99760	133.01200
11	0	266	-0.02493	266.01824	-0.02491	266.01855	-0.02484	266.01834	-0.02495	266.01787	-0.02500	266.01760	-0.02496	266.01858	0.02630	266.01840
12	133	266	132.97277	266.01851	132.97289	266.01879	132.97279	266.01859	132.97289	266.01811	132.97300	266.01820	132.97279	266.01876	132.97560	266.01870
13	266	266	265.97195	266.01798	265.97214	266.01828	265.97197	266.01808	265.97222	266.01753	265.96970	266.01760	265.97208	266.01815	265.97880	266.01800
14	399	266	398.97607	266.01834	398.97643	266.01865	398.97617	266.01824	398.97620	266.01793	398.97180	266.01780	398.97642	266.01857	398.98700	266.01860
15	532	266	531.97802	266.01915	531.97834	266.01946	531.97807	266.01908	531.97728	266.01884	531.97410	266.01840	531.97838	266.01944	531.99280	266.01930
16	0	399	-0.04657	399.02948	-0.04655	399.02993	-0.04646	399.02947	-0.04660	399.02875	-0.04650	399.02890	-0.04660	399.03004	0.04860	399.02960
17	133	399	132.95213	399.03246	132.95224	399.03287	132.95217	399.03237	132.95227	399.03180	132.95260	399.03210	132.95217	399.03298	132.95430	399.03230
18	266	399	265.95323	399.03078	265.95341	399.03111	265.95330	399.03057	265.95348	399.02998	265.95120	399.03000	265.95336	399.03110	265.95950	399.03070
19	399	399	398.95389	399.03125	398.95426	399.03171	398.95405	399.03108	398.95405	399.03057	398.94950	399.03060	398.95426	399.03174	398.96420	399.03120
20	532	399	531.95261	399.03227	531.95294	399.03271	531.95268	399.03210	531.95188	399.03165	531.94880	399.03150	531.95299	399.03282	531.96680	399.03230
21	0	532	-0.05261	532.04015	-0.05265	532.04075	-0.05254	532.04023	-0.05274	532.03884	-0.05240	532.03890	-0.05270	532.04103	0.05530	532.04040
22	133	532	132.94336	532.03935	132.94342	532.03995	132.94338	532.03953	132.94337	532.03806	132.94360	532.03830	132.94334	532.04017	132.94480	532.03960
23	266	532	265.94210	532.03930	265.94226	532.03995	265.94211	532.03950	265.94224	532.03804	265.94020	532.03820	265.94218	532.04005	265.94770	532.03980
24	399	532	398.94430	532.03706	398.94464	532.03772	398.94444	532.03719	398.94437	532.03582	398.94000	532.03580	398.94459	532.03788	398.95390	532.03730
25	532	532	531.94664	532.03776	531.94692	532.03836	531.94668	532.03784	531.94582	532.03654	531.94240	532.03640	531.94691	532.03866	531.96030	532.03780

	Nominal		NRC (B8)		MIKES (B9)		NML (B10)		INRiM (B11)		INMETRO (B12)		MSLNZ (B13)	
No	*X*	*Y*	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]
1	0	0	0.00000	0.00000	0.00000	0.00000	-0.00010	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2	133	0	132.99541	0.00055	132.99541	0.00062	132.99470	0.00070	132.99535	0.00057	132.99560	0.00060	132.99549	0.00059
3	266	0	265.99456	-0.00036	265.99452	-0.00041	265.99370	-0.00080	265.99458	-0.00042	265.99470	-0.00040	265.99471	-0.00044
4	399	0	398.99770	-0.00011	398.99761	-0.00021	398.99640	-0.00050	398.99782	-0.00026	398.99790	-0.00030	398.99790	-0.00027
5	532	0	532.00068	0.00000	532.00062	0.00000	531.99900	-0.00040	532.00076	0.00000	532.00090	0.00000	532.00095	0.00000
6	0	133	-0.01903	133.01017	-0.01904	133.01023	-0.01890	133.00930	-0.01902	133.01002	-0.01900	133.01020	-0.01894	133.01017
7	133	133	132.97894	133.01145	132.97892	133.01158	132.97850	133.01060	132.97893	133.01146	132.97920	133.01160	132.97915	133.01155
8	266	133	265.98063	133.00888	265.98058	133.00890	265.97970	133.00780	265.98070	133.00879	265.98080	133.00890	265.98088	133.00886
9	399	133	398.98007	133.01064	398.98001	133.01061	398.97880	133.00960	398.98020	133.01033	398.98020	133.01060	398.98032	133.01063
10	532	133	531.98206	133.01185	531.98200	133.01194	531.98030	133.01100	531.98215	133.01174	531.98220	133.01190	531.98235	133.01197
11	0	266	-0.02504	266.01826	-0.02500	266.01841	-0.02500	266.01730	-0.02495	266.01826	-0.02500	266.01840	-0.02500	266.01838
12	133	266	132.97263	266.01849	132.97266	266.01868	132.97210	266.01770	132.97264	266.01798	132.97290	266.01870	132.97278	266.01868
13	266	266	265.97188	266.01804	265.97188	266.01810	265.97100	266.01720	265.97191	266.01800	265.97200	266.01810	265.97204	266.01812
14	399	266	398.97609	266.01842	398.97606	266.01846	398.97480	266.01730	398.97616	266.01842	398.97620	266.01840	398.97635	266.01851
15	532	266	531.97791	266.01918	531.97785	266.01933	531.97630	266.01820	531.97792	266.01937	531.97810	266.01930	531.97822	266.01940
16	0	399	-0.04674	399.02946	-0.04668	399.02967	-0.04660	399.02850	-0.04663	399.02968	-0.04670	399.02950	-0.04666	399.02972
17	133	399	132.95197	399.03243	132.95201	399.03269	132.95150	399.03160	132.95203	399.03265	132.95230	399.03250	132.95213	399.03275
18	266	399	265.95310	399.03074	265.95310	399.03091	265.95230	399.02960	265.95318	399.03086	265.95330	399.03070	265.95331	399.03091
19	399	399	398.95390	399.03136	398.95391	399.03146	398.95270	399.03010	398.95402	399.03148	398.95410	399.03130	398.95420	399.03154
20	532	399	531.95249	399.03229	531.95247	399.03249	531.95100	399.03110	531.95258	399.03201	531.95280	399.03230	531.95281	399.03262
21	0	532	-0.05286	532.04024	-0.05282	532.04053	-0.05250	532.03890	-0.05279	532.04042	-0.05280	532.04020	-0.05279	532.04064
22	133	532	132.94314	532.03941	132.94316	532.03975	132.94280	532.03820	132.94312	532.03967	132.94340	532.03950	132.94327	532.03987
23	266	532	265.94186	532.03942	265.94187	532.03968	265.94120	532.03820	265.94196	532.03969	265.94210	532.03950	265.94203	532.03982
24	399	532	398.94418	532.03725	398.94416	532.03747	398.94310	532.03580	398.94429	532.03739	398.94450	532.03720	398.94443	532.03758
25	532	532	531.94644	532.03793	531.94646	532.03819	531.94490	532.03650	531.94649	532.03813	531.94680	532.03790	531.94677	532.03830

Table 8-2 Reported measurement results by the participants for the hole plate

	Nominal		NMIJ (H1)		KRISS (H2)		NIMT (H3)		NMIA (H4)		CSIR (H5)		NRC (H6)		MIKESI (H7)		INMETRO (H8)		MSLNZ (H9)	
No	X	Y	X [mm]	Y [mm]	X [mm]	Y [mm]	X [mm]	Y [mm]	X [mm]	Y [mm]	X [mm]	Y [mm]	X [mm]	Y [mm]	X [mm]	Y [mm]	X [mm]	Y [mm]	X [mm]	Y [mm]
1	0	0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2	50	0	50.03385	0.03544	50.03400	0.03549	50.03364	0.03548	50.03399	0.03539	50.03410	0.03590	50.03339	0.03523	50.03367	0.03522	50.03350	0.03530	50.03343	0.03527
3	100	0	100.03297	0.02031	100.03323	0.02051	100.03268	0.02009	100.03295	0.02031	100.03300	0.02080	100.03268	0.01998	100.03295	0.02000	100.03300	0.02010	100.03249	0.02003
4	150	0	150.02981	-0.02548	150.03014	-0.02556	150.02939	-0.02593	150.02984	-0.02574	150.02980	-0.02520	150.02953	-0.02582	150.02980	-0.02580	150.03010	-0.02590	150.02911	-0.02581
5	200	0	200.03641	-0.07128	200.03683	-0.07110	200.03610	-0.07163	200.03646	-0.07129	200.03540	-0.07110	200.03611	-0.07170	200.03636	-0.07171	200.03590	-0.07160	200.03566	-0.07170
6	250	0	250.04137	0.04331	250.04186	0.04367	250.04092	0.04298	250.04116	0.04344	250.03940	0.04350	250.04091	0.04302	250.04114	0.04298	250.04090	0.04330	250.04042	0.04306
7	300	0	300.03631	0.08253	300.03700	0.08270	300.03585	0.08223	300.03593	0.08244	300.03500	0.08280	300.03578	0.08228	300.03605	0.08225	300.03590	0.08230	300.03520	0.08233
8	350	0	350.03458	0.12852	350.03546	0.12857	350.03421	0.12811	350.03436	0.12840	350.03250	0.12870	350.03409	0.12830	350.03416	0.12824	350.03400	0.12820	350.03346	0.12834
9	400	0	400.00581	-0.01816	400.00668	-0.01793	400.00540	-0.01849	400.00540	-0.01813	400.00280	-0.01830	400.00512	-0.01886	400.00542	-0.01894	400.00500	-0.01880	400.00461	-0.01885
10	450	0	450.02306	0.05689	450.02396	0.05711	450.02257	0.05654	450.02272	0.05679	450.01980	0.05670	450.02244	0.05656	450.02272	0.05651	450.02230	0.05670	450.02162	0.05659
11	500	0	500.01271	-0.02264	500.01373	-0.02268	500.01218	-0.02296	500.01153	-0.02299	500.00920	-0.02270	500.01199	-0.02289	500.01227	-0.02299	500.01450	-0.02320	500.01099	-0.02300
12	550	0	550.04997	0.00000	550.05109	0.00000	550.04933	0.00000	550.04861	0.00000	550.04750	0.00000	550.04913	0.00000	550.04941	0.00000	550.04960	0.00000	550.04831	0.00000
13	0	50	0.00597	50.07021	0.00596	50.07020	0.00591	50.07005	0.00581	50.06990	0.00500	50.07910	0.00563	50.06974	0.00582	50.06982	0.00560	50.06940	0.00554	50.06975
14	550	50	550.03047	50.01985	550.03139	50.01975	550.02982	50.01924	550.02916	50.01960	550.02820	50.02800	550.02993	50.01953	550.03038	50.01947	550.03030	50.01940	550.02917	50.01953
15	0	100	-0.02905	99.89044	-0.02904	99.89059	-0.02907	99.89051	-0.02919	99.89013	-0.02980	99.90730	-0.02927	99.88999	-0.02905	99.88995	-0.02920	99.88990	-0.02936	99.88986
16	550	100	550.01878	100.00993	550.01960	100.00987	550.01819	100.00873	550.01732	100.00948	550.01670	100.02560	550.01824	100.00910	550.01866	100.00896	550.01850	100.00940	550.01741	100.00890
17	0	150	-0.01540	149.97063	-0.01539	149.97086	-0.01546	149.97079	-0.01550	149.97025	-0.01750	149.99520	-0.01579	149.97017	-0.01559	149.97031	-0.01570	149.97020	-0.01592	149.96988
18	550	150	550.06317	150.11161	550.06424	150.11164	550.06260	150.11093	550.06194	150.11110	550.06120	150.13530	550.06270	150.11121	550.06311	150.11128	550.06300	150.11140	550.06185	150.11095
19	0	200	-0.05455	199.92656	-0.05446	199.92688	-0.05455	199.92645	-0.05473	199.92598	-0.05530	199.95890	-0.05502	199.92612	-0.05481	199.92617	-0.05510	199.92630	-0.05528	199.92578
20	550	200	550.04713	199.97598	550.04783	199.97616	550.04657	199.97525	550.04552	199.97529	550.04520	200.00770	550.04659	199.97549	550.04698	199.97548	550.04670	199.97590	550.04571	199.97522
21	0	250	-0.01786	250.01437	-0.01741	250.01480	-0.01787	250.01393	-0.01895	250.01367	-0.01780	250.05470	-0.01799	250.01381	-0.01795	250.01388	-0.01880	250.01390	-0.01826	250.01346
22	550	250	549.99965	250.12122	550.00071	250.12142	549.99903	250.12071	549.99841	250.12041	549.99800	250.16110	549.99910	250.12115	549.99951	250.12113	549.99950	250.12100	549.99821	250.12086
23	0	300	-0.07592	299.80331	-0.07579	299.80387	-0.07593	299.80278	-0.07625	299.80211	-0.07660	299.85270	-0.07660	299.80249	-0.07632	299.80268	-0.07660	299.80230	-0.07682	299.80203
24	550	300	549.98511	300.13521	549.98603	300.13562	549.98455	300.13446	549.98366	300.13396	549.98340	300.18420	549.98451	300.13479	549.98490	300.13489	549.98480	300.13470	549.98358	300.13444
25	0	350	-0.06047	349.96903	-0.06044	349.96984	-0.06039	349.96884	-0.06073	349.96811	-0.06100	350.02670	-0.06119	349.96865	-0.06093	349.96882	-0.06130	349.96850	-0.06140	349.96816
26	550	350	550.24709	350.10607	--------	--------	550.24661	350.10513	550.24547	350.10513	550.24520	350.16290	550.24653	350.10546	550.24701	350.10575	550.24670	350.10560	550.24564	350.10521
27	0	400	-0.09555	399.88148	-0.09558	399.88223	-0.09558	399.88102	-0.09594	399.88016	-0.09600	399.94700	-0.09640	399.88121	-0.09611	399.88131	-0.09650	399.88100	-0.09661	399.88072
28	550	400	549.99019	400.03756	549.99110	400.03812	549.98973	400.03690	549.98879	400.03620	549.98860	400.10280	549.98964	400.03732	549.99004	400.03742	549.99000	400.03770	549.98870	400.03697
29	0	450	-0.14291	449.88693	-0.14304	449.88774	-0.14294	449.88665	-0.14334	449.88572	-0.14340	449.95970	-0.14357	449.88649	-0.14330	449.88680	-0.14370	449.88660	-0.14378	449.88579
30	550	450	549.93769	450.11836	549.93862	450.11882	549.93729	450.11742	549.93630	450.11692	549.93610	450.19070	549.93703	450.11775	549.93746	450.11802	549.93750	450.11810	549.93608	450.11723
31	0	500	-0.12957	499.94576	-0.12959	499.94672	-0.12955	499.94558	-0.12986	499.94402	-0.13010	500.02700	-0.13026	499.94512	-0.13001	499.94537	-0.13050	499.94520	-0.13052	499.94433
32	550	500	549.90403	500.03459	549.90499	500.03518	549.90361	500.03365	549.90269	500.03254	549.90230	500.11500	549.90334	500.03380	549.90380	500.03401	549.90410	500.03470	549.90247	500.03316
33	0	550	-0.17945	549.94002	-0.17937	549.94099	-0.17922	549.93982	-0.17949	549.93813	-0.17970	550.02960	-0.17979	549.93952	-0.17956	549.93982	-0.18000	549.93950	-0.18006	549.93877
34	50	550	49.88589	550.05633	49.88600	550.05704	49.88584	550.05578	49.88593	550.05429	49.88650	550.14590	49.88523	550.05572	49.88560	550.05603	49.88500	550.05600	49.88498	550.05508
35	100	550	99.82679	549.86029	99.82701	549.86109	99.82670	549.85940	99.82663	549.85817	99.82740	549.94980	99.82615	549.85940	99.82653	549.85965	99.82640	549.85930	99.82581	549.85864
36	150	550	149.81517	549.94687	149.81551	549.94750	149.81487	549.94610	149.81496	549.94458	149.81570	550.03620	149.81414	549.94626	149.81450	549.94656	149.81460	549.94640	149.81353	549.94556
37	200	550	199.83016	549.96871	199.83065	549.96935	199.83011	549.96783	199.83029	549.96635	199.82980	550.05790	199.82979	549.96800	199.83016	549.96829	199.82960	549.96830	199.82933	549.96729
38	250	550	249.82813	549.92718	249.82863	549.92789	249.82791	549.92621	249.82786	549.92480	249.82670	550.01640	249.82716	549.92621	249.82750	549.92649	249.82710	549.92630	249.82659	549.92549
39	300	550	299.82023	549.88758	299.82090	549.88827	299.82007	549.88660	299.82018	549.88522	299.81970	549.97680	299.81965	549.88672	299.82003	549.88696	299.81970	549.88680	299.81906	549.88598
40	350	550	349.85628	549.89913	349.85716	549.89967	349.85639	549.89814	349.85589	549.89672	349.85500	549.98880	349.85573	549.89834	349.85615	549.89871	349.85560	549.89850	349.85500	549.89764
41	400	550	399.86302	549.93086	399.86386	549.93137	399.86303	549.92985	399.86261	549.92845	399.86060	550.02000	399.86245	549.93011	399.86282	549.93041	399.86230	549.93060	399.86184	549.92941
42	450	550	450.15988	550.12105	450.16076	550.12174	450.15978	550.12015	450.15973	550.11889	450.15750	550.21040	450.15942	550.12057	450.15978	550.12084	450.15940	550.12120	450.15860	550.11999
43	500	550	499.85204	550.13783	499.85294	550.13846	499.85172	550.13695	499.85079	550.13572	499.84930	550.22680	499.85125	550.13732	499.85160	550.13764	499.85360	550.13780	499.85020	550.13678
44	550	550	549.87308	550.03789	549.87412	550.03843	549.87266	550.03704	549.87184	550.03550	549.89390	550.14200	549.87255	550.03682	549.87302	550.03711	549.87370	550.03750	549.87166	550.03628

9 Measurement uncertainty

The technical protocol specified that the uncertainty of measurement should be estimated according to the ISO Guide to Expression of Uncertainty in Measurement (GUM). The uncertainty shall be stated as combined standard uncertainty with no coverage factor applied (1σ). Length dependent terms should be left in terms of l (length), and the combined standard uncertainty should be expressed as a quadratic sum of the form:

$$u_C(l) = \sqrt{a^2 + b^2 \times l^2} = \mathrm{Q}[a\ \mu\mathrm{m}, b \times l]$$

The value a and l is expressed in length unit, while the value b is a coefficient without unit. All participants except one reported their uncertainties in this form, while one participant reported in a linear combination form.

Measurement uncertainties for the ball plate and the hole plate reported by the participants are listed in Table 9-1. Measurement uncertainties calculated for the corresponding measurement length are also listed in Table 9-2 for the ball plate and in Table 9-3 for the hole plate.

Table 9-1 Combined standard uncertainties reported by the participants.

NMI, Country	Ball plate	Hole plate
NMIJ, Japan	$\mathrm{Q}[0.122\ \mu\mathrm{m}, 0.593 \times 10^{-6} \times l]$	$\mathrm{Q}[0.120\ \mu\mathrm{m}, 0.234 \times 10^{-6} \times l]$
KRISS, Korea	$\mathrm{Q}[0.27\ \mu\mathrm{m}, 0.72 \times 10^{-6} \times l]$	$\mathrm{Q}[0.34\ \mu\mathrm{m}, 0.62 \times 10^{-6} \times l]$
NIMT, Thailand	$\mathrm{Q}[0.30\ \mu\mathrm{m}, 0.948 \times 10^{-6} \times l]$	$\mathrm{Q}[0.30\ \mu\mathrm{m}, 0.948 \times 10^{-6} \times l]$
NMIA, Australia	$\mathrm{Q}[0.42\ \mu\mathrm{m}, 1.83 \times 10^{-6} \times l]$	$\mathrm{Q}[0.42\ \mu\mathrm{m}, 1.67 \times 10^{-6} \times l]$
CSIR, South Africa	$\mathrm{Q}[2.9\ \mu\mathrm{m}, 3 \times 10^{-6} \times l]$	$\mathrm{Q}[2.9\ \mu\mathrm{m}, 3 \times 10^{-6} \times l]$
NIM, China	$\mathrm{Q}[0.10\ \mu\mathrm{m}, 0.40 \times 10^{-6} \times l]$	N/A
NPLI, India	$0.43\ \mu\mathrm{m} + 1.1 \times 10^{-6} \times l$	N/A
MSLNZ, New Zealand	$\mathrm{Q}[0.450\ \mu\mathrm{m}, 0.67 \times 10^{-6} \times l]$	$\mathrm{Q}[0.450\ \mu\mathrm{m}, 1.2 \times 10^{-6} \times l]$
NRC, Canada	$\mathrm{Q}[0.15\ \mu\mathrm{m}, 0.34 \times 10^{-6} \times l]$	$\mathrm{Q}[0.15\ \mu\mathrm{m}, 0.34 \times 10^{-6} \times l]$
INMETRO, Brazil	$\mathrm{Q}[0.318\ \mu\mathrm{m}, 1.16 \times 10^{-6} \times l]$	$\mathrm{Q}[0.749\ \mu\mathrm{m}, 1.90 \times 10^{-6} \times l]$
MIKES, Finland	$\mathrm{Q}[0.065\ \mu\mathrm{m}, 0.350 \times 10^{-6} \times l]$	$\mathrm{Q}[0.151\ \mu\mathrm{m}, 0.437 \times 10^{-6} \times l]$
NML, Ireland	$\mathrm{Q}[0.400\ \mu\mathrm{m}, 0.700 \times 10^{-6} \times l]$	N/A
INRiM, Italy	$\mathrm{Q}[0.344\ \mu\mathrm{m}, 0.594 \times 10^{-6} \times l]$	N/A

Table 9-2 Measurement uncertainties calculated for the corresponding measurement length for the ball plate

	Nominal		NMIJ (B1)		KRISS (B2)		NIMT (B3)		NMIA (B4)		CSIR (B5)		NIM (B6)		NPLI (B7)		NRC (B8)		MIKES (B9)		NML (B10)		INRiM (B11)		INMETRO (B12)		MSLNZ (B13)	
No	*X*	*Y*	*X* [μm]	*Y* [μm]	*X* [μm]	*Y* [μm]	*X* [μm]	*Y* [μm]	*X* [μm]	*Y* [μm]	*X* [μm]	*Y* [μm]	*X* [μm]	*Y* [μm]	*X* [μm]	*Y* [μm]	*X* [μm]	*Y* [μm]	*X* [μm]	*Y* [μm]	*X* [μm]	*Y* [μm]	*X* [μm]	*Y* [μm]	*X* [μm]	*Y* [μm]	*X* [μm]	*Y* [μm]
1	0	0	0.12	0.12	0.27	0.27	0.30	0.30	0.42	0.42	2.90	2.90	0.10	0.10	0.43	0.43	0.15	0.15	0.07	0.07	0.40	0.40	0.34	0.34	0.32	0.32	0.45	0.45
2	133	0	0.15	0.12	0.29	0.27	0.33	0.30	0.49	0.42	2.93	2.90	0.11	0.10	0.58	0.43	0.16	0.15	0.08	0.07	0.41	0.40	0.35	0.34	0.35	0.32	0.46	0.45
3	266	0	0.20	0.12	0.33	0.27	0.39	0.30	0.64	0.42	3.01	2.90	0.15	0.10	0.72	0.43	0.18	0.15	0.11	0.07	0.44	0.40	0.38	0.34	0.44	0.32	0.48	0.45
4	399	0	0.27	0.12	0.39	0.27	0.48	0.30	0.84	0.42	3.14	2.90	0.19	0.10	0.87	0.43	0.20	0.15	0.15	0.07	0.49	0.40	0.42	0.34	0.56	0.32	0.52	0.45
5	532	0	0.34	0.12	0.47	0.27	0.59	0.30	1.06	0.42	3.31	2.90	0.24	0.10	1.02	0.43	0.23	0.15	0.20	0.07	0.55	0.40	0.47	0.34	0.69	0.32	0.57	0.45
6	0	133	0.12	0.15	0.27	0.29	0.30	0.33	0.42	0.49	2.90	2.93	0.10	0.11	0.43	0.58	0.15	0.16	0.07	0.08	0.40	0.41	0.34	0.35	0.32	0.35	0.45	0.46
7	133	133	0.15	0.15	0.29	0.29	0.33	0.33	0.49	0.49	2.93	2.93	0.11	0.11	0.58	0.58	0.16	0.16	0.08	0.08	0.41	0.41	0.35	0.35	0.35	0.35	0.46	0.46
8	266	133	0.20	0.15	0.33	0.29	0.39	0.33	0.64	0.49	3.01	2.93	0.15	0.11	0.72	0.58	0.18	0.16	0.11	0.08	0.44	0.41	0.38	0.35	0.44	0.35	0.48	0.46
9	399	133	0.27	0.15	0.39	0.29	0.48	0.33	0.84	0.49	3.14	2.93	0.19	0.11	0.87	0.58	0.20	0.16	0.15	0.08	0.49	0.41	0.42	0.35	0.56	0.35	0.52	0.46
10	532	133	0.34	0.15	0.47	0.29	0.59	0.33	1.06	0.49	3.31	2.93	0.24	0.11	1.02	0.58	0.23	0.16	0.20	0.08	0.55	0.41	0.47	0.35	0.69	0.35	0.57	0.46
11	0	266	0.12	0.20	0.27	0.33	0.30	0.39	0.42	0.64	2.90	3.01	0.10	0.15	0.43	0.72	0.15	0.18	0.07	0.11	0.40	0.44	0.34	0.38	0.32	0.44	0.45	0.48
12	133	266	0.15	0.20	0.29	0.33	0.33	0.39	0.49	0.64	2.93	3.01	0.11	0.15	0.58	0.72	0.16	0.18	0.08	0.11	0.41	0.44	0.35	0.38	0.35	0.44	0.46	0.48
13	266	266	0.20	0.20	0.33	0.33	0.39	0.39	0.64	0.64	3.01	3.01	0.15	0.15	0.72	0.72	0.18	0.18	0.11	0.11	0.44	0.44	0.38	0.38	0.44	0.44	0.48	0.48
14	399	266	0.27	0.20	0.39	0.33	0.48	0.39	0.84	0.64	3.14	3.01	0.19	0.15	0.87	0.72	0.20	0.18	0.15	0.11	0.49	0.44	0.42	0.38	0.56	0.44	0.52	0.48
15	532	266	0.34	0.20	0.47	0.33	0.59	0.39	1.06	0.64	3.31	3.01	0.24	0.15	1.02	0.72	0.23	0.18	0.20	0.11	0.55	0.44	0.47	0.38	0.69	0.44	0.57	0.48
16	0	399	0.12	0.27	0.27	0.39	0.30	0.48	0.42	0.84	2.90	3.14	0.10	0.19	0.43	0.87	0.15	0.20	0.07	0.15	0.40	0.49	0.34	0.42	0.32	0.56	0.45	0.52
17	133	399	0.15	0.27	0.29	0.39	0.33	0.48	0.49	0.84	2.93	3.14	0.11	0.19	0.58	0.87	0.16	0.20	0.08	0.15	0.41	0.49	0.35	0.42	0.35	0.56	0.46	0.52
18	266	399	0.20	0.27	0.33	0.39	0.39	0.48	0.64	0.84	3.01	3.14	0.15	0.19	0.72	0.87	0.18	0.20	0.11	0.15	0.44	0.49	0.38	0.42	0.44	0.56	0.48	0.52
19	399	399	0.27	0.27	0.39	0.39	0.48	0.48	0.84	0.84	3.14	3.14	0.19	0.19	0.87	0.87	0.20	0.20	0.15	0.15	0.49	0.49	0.42	0.42	0.56	0.56	0.52	0.52
20	532	399	0.34	0.27	0.47	0.39	0.59	0.48	1.06	0.84	3.31	3.14	0.24	0.19	1.02	0.87	0.23	0.20	0.20	0.15	0.55	0.49	0.47	0.42	0.69	0.56	0.57	0.52
21	0	532	0.12	0.34	0.27	0.47	0.30	0.59	0.42	1.06	2.90	3.31	0.10	0.24	0.43	1.02	0.15	0.23	0.07	0.20	0.40	0.55	0.34	0.47	0.32	0.69	0.45	0.57
22	133	532	0.15	0.34	0.29	0.47	0.33	0.59	0.49	1.06	2.93	3.31	0.11	0.24	0.58	1.02	0.16	0.23	0.08	0.20	0.41	0.55	0.35	0.47	0.35	0.69	0.46	0.57
23	266	532	0.20	0.34	0.33	0.47	0.39	0.59	0.64	1.06	3.01	3.31	0.15	0.24	0.72	1.02	0.18	0.23	0.11	0.20	0.44	0.55	0.38	0.47	0.44	0.69	0.48	0.57
24	399	532	0.27	0.34	0.39	0.47	0.48	0.59	0.84	1.06	3.14	3.31	0.19	0.24	0.87	1.02	0.20	0.23	0.15	0.20	0.49	0.55	0.42	0.47	0.56	0.69	0.52	0.57
25	532	532	0.34	0.34	0.47	0.47	0.59	0.59	1.06	1.06	3.31	3.31	0.24	0.24	1.02	1.02	0.23	0.23	0.20	0.20	0.55	0.55	0.47	0.47	0.69	0.69	0.57	0.57

Table 9-3 Measurement uncertainties calculated for the corresponding measurement length for the hole plate

	Nominal		NMIJ (H1)		KRISS (H2)		NIMT (H3)		NMIA (H4)		CSIR (H5)		NRC (H6)		MIKES (H7)		INMETRO (H8)		MSLNZ (H9)	
No	*X*	*Y*	*X* [µm]	*Y* [µm]	*X* [µm]	*Y* [µm]	*X* [µm]	*Y* [µm]	*X* [µm]	*Y* [µm]	*X* [µm]	*Y* [µm]	*X* [µm]	*Y* [µm]	*X* [µm]	*Y* [µm]	*X* [µm]	*Y* [µm]	*X* [µm]	*Y* [µm]
1	0	0	0.12	0.12	0.34	0.34	0.30	0.30	0.42	0.42	2.90	2.90	0.15	0.15	0.15	0.15	0.75	0.75	0.45	0.45
2	50	0	0.12	0.12	0.34	0.34	0.30	0.30	0.43	0.42	2.90	2.90	0.15	0.15	0.15	0.15	0.76	0.75	0.45	0.45
3	100	0	0.12	0.12	0.35	0.34	0.31	0.30	0.45	0.42	2.92	2.90	0.15	0.15	0.16	0.15	0.77	0.75	0.47	0.45
4	150	0	0.13	0.12	0.35	0.34	0.33	0.30	0.49	0.42	2.93	2.90	0.16	0.15	0.16	0.15	0.80	0.75	0.48	0.45
5	200	0	0.13	0.12	0.36	0.34	0.35	0.30	0.54	0.42	2.96	2.90	0.16	0.15	0.17	0.15	0.84	0.75	0.51	0.45
6	250	0	0.13	0.12	0.37	0.34	0.38	0.30	0.59	0.42	3.00	2.90	0.17	0.15	0.19	0.15	0.89	0.75	0.54	0.45
7	300	0	0.14	0.12	0.39	0.34	0.41	0.30	0.65	0.42	3.04	2.90	0.18	0.15	0.20	0.15	0.94	0.75	0.58	0.45
8	350	0	0.15	0.12	0.40	0.34	0.45	0.30	0.72	0.42	3.08	2.90	0.19	0.15	0.21	0.15	1.00	0.75	0.62	0.45
9	400	0	0.15	0.12	0.42	0.34	0.48	0.30	0.79	0.42	3.14	2.90	0.20	0.15	0.23	0.15	1.07	0.75	0.66	0.45
10	450	0	0.16	0.12	0.44	0.34	0.52	0.30	0.86	0.42	3.20	2.90	0.21	0.15	0.25	0.15	1.14	0.75	0.70	0.45
11	500	0	0.17	0.12	0.46	0.34	0.56	0.30	0.93	0.42	3.26	2.90	0.23	0.15	0.27	0.15	1.21	0.75	0.75	0.45
12	550	0	0.18	0.12	0.48	0.34	0.60	0.30	1.01	0.42	3.34	2.90	0.24	0.15	0.28	0.15	1.28	0.75	0.80	0.45
13	0	50	0.12	0.12	0.34	0.34	0.30	0.30	0.42	0.43	2.90	2.90	0.15	0.15	0.15	0.15	0.75	0.76	0.45	0.45
14	550	50	0.18	0.12	0.48	0.34	0.60	0.30	1.01	0.43	3.34	2.90	0.24	0.15	0.28	0.15	1.28	0.76	0.80	0.45
15	0	100	0.12	0.12	0.34	0.35	0.30	0.31	0.42	0.45	2.90	2.92	0.15	0.15	0.15	0.16	0.75	0.77	0.45	0.47
16	550	100	0.18	0.12	0.48	0.35	0.60	0.31	1.01	0.45	3.34	2.92	0.24	0.15	0.28	0.16	1.28	0.77	0.80	0.47
17	0	150	0.12	0.13	0.34	0.35	0.30	0.33	0.42	0.49	2.90	2.93	0.15	0.16	0.15	0.16	0.75	0.80	0.45	0.48
18	550	150	0.18	0.13	0.48	0.35	0.60	0.33	1.01	0.49	3.34	2.93	0.24	0.16	0.28	0.16	1.28	0.80	0.80	0.48
19	0	200	0.12	0.13	0.34	0.36	0.30	0.35	0.42	0.54	2.90	2.96	0.15	0.16	0.15	0.17	0.75	0.84	0.45	0.51
20	550	200	0.18	0.13	0.48	0.36	0.60	0.35	1.01	0.54	3.34	2.96	0.24	0.16	0.28	0.17	1.28	0.84	0.80	0.51
21	0	250	0.12	0.13	0.34	0.37	0.30	0.38	0.42	0.59	2.90	3.00	0.15	0.17	0.15	0.19	0.75	0.89	0.45	0.54
22	550	250	0.18	0.13	0.48	0.37	0.60	0.38	1.01	0.59	3.34	3.00	0.24	0.17	0.28	0.19	1.28	0.89	0.80	0.54
23	0	300	0.12	0.14	0.34	0.39	0.30	0.41	0.42	0.65	2.90	3.04	0.15	0.18	0.15	0.20	0.75	0.94	0.45	0.58
24	550	300	0.18	0.14	0.48	0.39	0.60	0.41	1.01	0.65	3.34	3.04	0.24	0.18	0.28	0.20	1.28	0.94	0.80	0.58
25	0	350	0.12	0.15	0.34	0.40	0.30	0.45	0.42	0.72	2.90	3.08	0.15	0.19	0.15	0.21	0.75	1.00	0.45	0.62
26	550	350	0.18	0.15	--------	--------	0.60	0.45	1.01	0.72	3.34	3.08	0.24	0.19	0.28	0.21	1.28	1.00	0.80	0.62
27	0	400	0.12	0.15	0.34	0.42	0.30	0.48	0.42	0.79	2.90	3.14	0.15	0.20	0.15	0.23	0.75	1.07	0.45	0.66
28	550	400	0.18	0.15	0.48	0.42	0.60	0.48	1.01	0.79	3.34	3.14	0.24	0.20	0.28	0.23	1.28	1.07	0.80	0.66
29	0	450	0.12	0.16	0.34	0.44	0.30	0.52	0.42	0.86	2.90	3.20	0.15	0.21	0.15	0.25	0.75	1.14	0.45	0.70
30	550	450	0.18	0.16	0.48	0.44	0.60	0.52	1.01	0.86	3.34	3.20	0.24	0.21	0.28	0.25	1.28	1.14	0.80	0.70
31	0	500	0.12	0.17	0.34	0.46	0.30	0.56	0.42	0.93	2.90	3.27	0.15	0.23	0.15	0.27	0.75	1.21	0.45	0.75
32	550	500	0.18	0.17	0.48	0.46	0.60	0.56	1.01	0.93	3.34	3.27	0.24	0.23	0.28	0.27	1.28	1.21	0.80	0.75
33	0	550	0.12	0.18	0.34	0.48	0.30	0.60	0.42	1.01	2.90	3.34	0.15	0.24	0.15	0.28	0.75	1.28	0.45	0.80
34	50	550	0.12	0.18	0.34	0.48	0.30	0.60	0.43	1.01	2.90	3.34	0.15	0.24	0.15	0.28	0.76	1.28	0.45	0.80
35	100	550	0.12	0.18	0.35	0.48	0.31	0.60	0.45	1.01	2.92	3.34	0.15	0.24	0.16	0.28	0.77	1.28	0.47	0.80
36	150	550	0.13	0.18	0.35	0.48	0.33	0.60	0.49	1.01	2.93	3.34	0.16	0.24	0.16	0.28	0.80	1.28	0.48	0.80
37	200	550	0.13	0.18	0.36	0.48	0.35	0.60	0.54	1.01	2.96	3.34	0.16	0.24	0.17	0.28	0.84	1.28	0.51	0.80
38	250	550	0.13	0.18	0.37	0.48	0.38	0.60	0.59	1.01	3.00	3.34	0.17	0.24	0.19	0.28	0.89	1.28	0.54	0.80
39	300	550	0.14	0.18	0.39	0.48	0.41	0.60	0.65	1.01	3.04	3.34	0.18	0.24	0.20	0.28	0.94	1.28	0.58	0.80
40	350	550	0.15	0.18	0.40	0.48	0.45	0.60	0.72	1.01	3.08	3.34	0.19	0.24	0.21	0.28	1.00	1.28	0.62	0.80
41	400	550	0.15	0.18	0.42	0.48	0.48	0.60	0.79	1.01	3.14	3.34	0.20	0.24	0.23	0.28	1.07	1.28	0.66	0.80
42	450	550	0.16	0.18	0.44	0.48	0.52	0.60	0.86	1.01	3.20	3.34	0.21	0.24	0.25	0.28	1.14	1.28	0.70	0.80
43	500	550	0.17	0.18	0.46	0.48	0.56	0.60	0.93	1.01	3.26	3.34	0.23	0.24	0.27	0.28	1.21	1.28	0.75	0.80
44	550	550	0.18	0.18	0.48	0.48	0.60	0.60	1.01	1.01	3.34	3.34	0.24	0.24	0.28	0.28	1.28	1.28	0.80	0.80

10 **Analysis of the reported results**

10.1 Two dimensional analysis

Ball/hole plates are two dimensional gauges, therefore when they are used to calibrate CMMs, two dimensional coordinate of the gauges are used. Nevertheless in the previous CCL-K6 comparison, the distance from the ball/hole No.1 (i.e. the origin of the workpiece coordinate) to the respective balls/holes was defined as a measurand. There might be several reasons to have done so; the largest reason was the method to compare two dimensional coordinate have not been scientifically and meaningfully developed, and another reason was that the largest length, i.e. the diagonal length of the gauges, can be assessed.

In spite of these reasons, two dimensional coordinate will be used as measurands in this comparison report as the pilot thinks ‘two dimensional’ is the most important inherent nature of the ball and hole plates.

The next question is how to compare two or more two-dimensional data. Two methods can be considered. One method is matching the origins and axes of the two coordinates, so that the ball/hole No. 1 of both data become (0, 0) and the *Y* coordinate of the furthest ball/hole in the *X* axis from the origin become zero. Another method is using the best fit method, where the gravity centres of two coordinates coincide and either data is rotated with respect to the other.

The former method has an advantage that two-dimensional coordinate is used as it is normally used to calibrate CMMs. However a disadvantage is that No.1 ball/hole has too much significance than other balls/holes although No. 1 ball/hole has the same amount of measurement uncertainty as other balls.

The disadvantage of the former method can be overcome by the latter method, but the latter one is different from the normal usage of the ball/hole plate. In addition, the maximum evaluation length becomes shorter because the origin of the coordinate moves from the ball/hole No. 1 to the gravity center.

10.2 Calculation of KCRV

All measurement results except outliers are used to calculate the two dimensional KCRV by the best fit algorithm with considering participants measurement uncertainties, i.e. weighted best fit.

Let us define $\boldsymbol{x}_{ij}$ as the position of the *j*-th ball/hole reported by the *i*-th participant. The coordinate system of the *i*-th participant result is rotated and then shifted. The amount and direction of the rotation and shift are calculated using the least square method.

The observation equation of the least square method is defined as follows

$$\boldsymbol{O} = \left[\boldsymbol{R}_i x_{ij} + \boldsymbol{t}_i - \boldsymbol{x}_{0j}\right],$$

where $\hat{\boldsymbol{x}}_{ij}$ is the coordinate of the *j*-th ball/hole reported by the *i*-th participants after transformation and $\boldsymbol{x}_{0j}$ are those KCRV. The rotation matrix $\boldsymbol{R}_i$ and the translation vector $\boldsymbol{t}_i$ are written as

$\boldsymbol{R}_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix}$, and

$\boldsymbol{t}_i = \begin{bmatrix} t_{x_i} \\ t_{y_i} \end{bmatrix}$.

The KCRV are calculated as the weighted mean with the following equation.

$$\boldsymbol{x}_{0j} = \frac{1}{\sum_{i=1}^{n} \frac{1}{{U_{\hat{x}_{ij}}}^2}} \sum_{i=1}^{n} \frac{\hat{\boldsymbol{x}}_{ij}}{{U_{\hat{x}_{ij}}}^2} \ .$$

$U_{\hat{x}_{ij}}$ is the expanded uncertainty ($k = 2$) of the *j*-th ball/hole of the *i*-th participant after transformation. Since the rotation matrix $\boldsymbol{R}_i$ and the translation matrix $\boldsymbol{t}_i$ are very small, the expanded uncertainty $U_{x_{ij}}$ before transformation are used instead of $U_{\hat{x}_{ij}}$.

After the iterative calculation, the residue of the observation equation becomes negligibly small, so that the KCRV $\boldsymbol{x}_{0j}$ and its uncertainty $\boldsymbol{U}_{0j}$ are derived as follows

$$\boldsymbol{U}_{0j} = \sqrt{\frac{1}{\sum_{i=1}^{n} \frac{1}{{U_{x_{ij}}}^2}}} .$$

10.3 Elimination of outliers

Each participant has the same number of E_n numbers as that of the balls/holes. Once KCRV is determined, the participant which has the most E_n numbers which are larger than unity will be eliminated from the group of participants whose results are used for the calculation of KCRV (so called the KCRV data group hereafter). Then a new KCRV is calculated again and this procedure is repeated until all E_n numbers of all participants are smaller than unity.

In one dimensional case, E_n number can be defined as

$$E_n = \frac{x_i - x_0}{u(x_i - x_0)}$$

$$u(x_i - x_0) = \sqrt{u(x_i)^2 + u(x_0)^2 - 2\mathrm{cov}(x_i, x_0)}$$

Since the measurand of the comparison is two dimensional coordinate, the definition of E_n should be extended to a two dimensional case.

$$E_\mathrm{n} = \frac{\|\boldsymbol{x}_i - \boldsymbol{x}_0\|}{u(\|\boldsymbol{x}_i - \boldsymbol{x}_0\|)}$$

$$u(\|x_i - x_0\|) = \sqrt{\boldsymbol{n}^\mathrm{T}\boldsymbol{\Psi}_i\boldsymbol{n} + \boldsymbol{n}^\mathrm{T}\boldsymbol{\Psi}_0\boldsymbol{n} - 2\boldsymbol{n}^\mathrm{T}\boldsymbol{\Psi}_{i,0}\boldsymbol{n}}$$

$$\boldsymbol{n} = \frac{\boldsymbol{x}_i - \boldsymbol{x}_0}{\|\boldsymbol{x}_i - \boldsymbol{x}_0\|}$$

As the KCRV is derived from the participants results, they are correlated each other. To simplify the calculation, we assumed the transformation was sufficiently small, i.e.

$$\boldsymbol{\Psi}_0 = \begin{bmatrix} {U_{x_{0j}}}^2 & 0 \\ 0 & {U_{y_{0j}}}^2 \end{bmatrix}$$

$$\boldsymbol{\Psi}_i = \begin{bmatrix} {U_{x_{ij}}}^2 & 0 \\ 0 & {U_{y_{ij}}}^2 \end{bmatrix}$$

$$\boldsymbol{\Psi}_{i,0} = \begin{bmatrix} {U_{x_{0j}}}^2 & 0 \\ 0 & {U_{y_{0j}}}^2 \end{bmatrix}$$ (in the case the *i*-th participant's affects the KCRV)

$$\boldsymbol{\Psi}_{i,0} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$ (in the case the *i*-th participant's doesn't affect the KCRV)

If this rule is strictly applied, for the hole plate comparison, only a few participants can stay in the KCRV data group to the end of the iterative outlier elimination procedure. The coverage factor $k = 2$ means the true value lies in the uncertainty band with 95 % probability, in turn, it implies that 5 % of measurement results may lie outside the uncertainty band.

Considering this fact, a new rule was agreed in the CIPM/TCL/WG meeting held in Singapore in 2010.

There are 25 balls and 40 holes and their 5 % is approximately 1 and 2. In case the participant who has the most outlier results has only one outlier for the ball plate and one or two outliers for the hole plate, only the outlier data will be eliminated from the KCRV data set and the participant may stay in the KCRV data group. Applying the basic rule and the new rule, the participants to be removed from the KCRV data group are determined.

10.4 Calculation of KCRV and outlier elimination for the ball plate comparison

Figure 10-1 shows the E_n numbers of reported results of all 13 participants. A weighted mean is used as the KCRV.

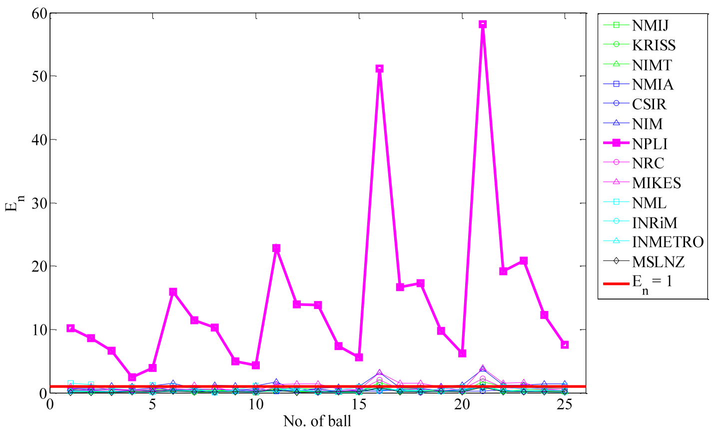

Fig. 10-1 $\boldsymbol{E_n}$ numbers calculated from all participants results

The E_n = 1 line is drawn in red and it is at the bottom of the figure. The largest outlier is NPLI and some of their E_n numbers are more than 50. It is decided NPLI will be eliminated from the KCRV data group. All the other participants also look outliers, but this situation happened because the KCRV was shifted by the largest outlier.

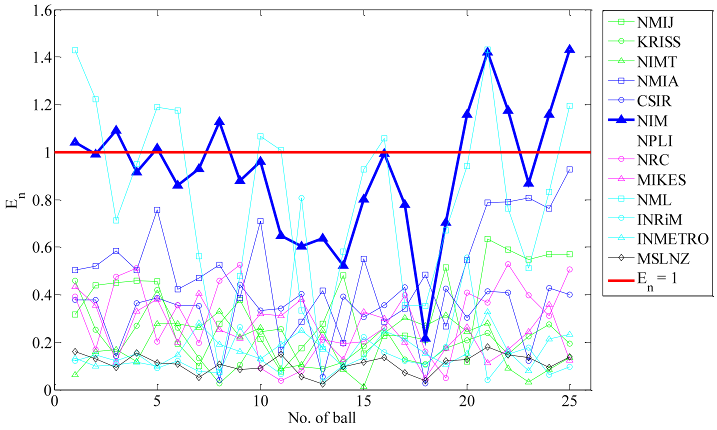

Fig. 10-2 ***E*$_n$** numbers calculated except NPLI

Figure 10-2 shows E_n numbers after eliminating NPLI. There are two laboratories having $E_n > 1$ results, i.e. NIM and NML. Both laboratories have almost as much and large anomalous results, but NIM's result has larger RMS value; therefore NIM is eliminated from the KCRV data group.

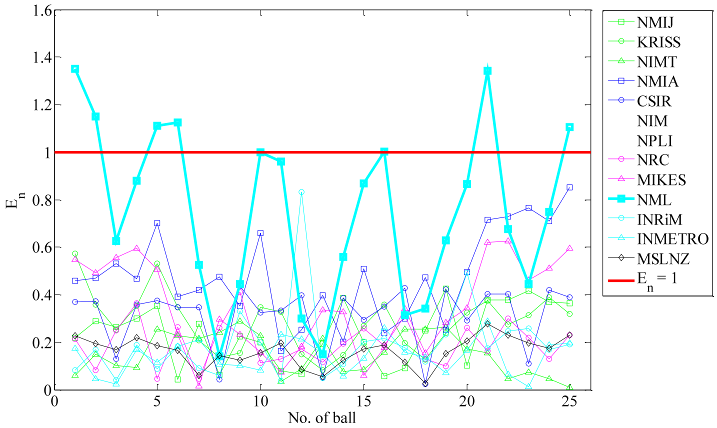

Fig. 10-3 ***E*$_n$** numbers calculated except NPLI and NIM

Figure 10-3 shows E_n numbers after eliminating NPLI and NIM. NML has $E_n > 1$ results; therefore NIM is eliminated from the KCRV data group.

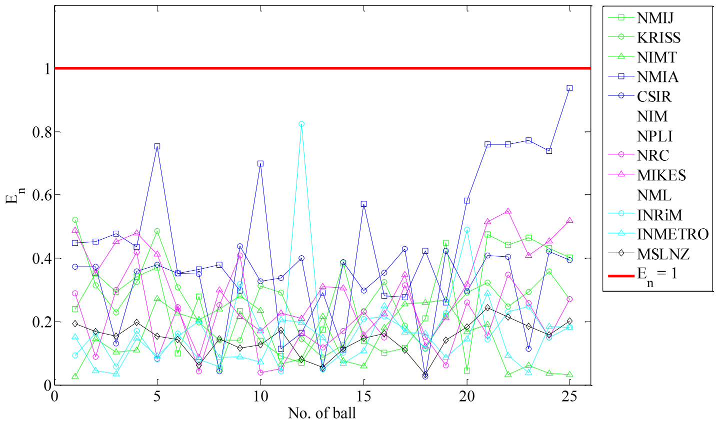

Fig. 10-4 $\boldsymbol{E_n}$ numbers calculated except NPLI, NIM, and NML

Figure 10-4 shows E_n numbers after eliminating NPLI, NIM, and NML. Now all measurement results are within $E_n < 1$ band. The outlier elimination procedure terminates here and it is decided the KCRV is calculated by the weighted mean from all participants except NPLI, NIM, and NML.

The measurement uncertainty of the KCRV is written as follows.

$$u_c = \sqrt{0.0505^2 + 0.2175^2 \times l^2} \text{ [µm]}, \quad l : \text{measurement length in metre}$$

KCRV and its uncertainty for the ball plate comparison are shown in Table 10-1.

Reported measurement results by the participants for the ball plate after transformation are shown in Table 10-2.

E_n numbers of all participants for the ball plate comparison are listed in Table 10-3. Those results not used for KCRV calculation are written in parentheses ().$E_n > 1$ results are written in red.

Table 10-1 The KCRV and its uncertainty for the ball plate comparison

	Nominal		KCRV		Uncertainty	
No	*X*	*Y*	*X* [mm]	*Y* [mm]	u_x [µm]	u_Y [µm]
1	0	0	0.0000	0.0000	0.08	0.08
2	133	0	132.9954	0.0006	0.06	0.08
3	266	0	265.9946	-0.0004	0.05	0.08
4	399	0	398.9977	-0.0002	0.06	0.08
5	532	0	532.0007	0.0000	0.08	0.08
6	0	133	-0.0190	133.0102	0.08	0.06
7	133	133	132.9790	133.0115	0.06	0.06
8	266	133	265.9806	133.0089	0.05	0.06
9	399	133	398.9801	133.0106	0.06	0.06
10	532	133	531.9821	133.0119	0.08	0.06
11	0	266	-0.0250	266.0183	0.08	0.05
12	133	266	132.9727	266.0186	0.06	0.05
13	266	266	265.9719	266.0181	0.05	0.05
14	399	266	398.9761	266.0184	0.06	0.05
15	532	266	531.9779	266.0193	0.08	0.05
16	0	399	-0.0467	399.0296	0.08	0.06
17	133	399	132.9521	399.0326	0.06	0.06
18	266	399	265.9532	399.0308	0.05	0.06
19	399	399	398.9539	399.0314	0.06	0.06
20	532	399	531.9525	399.0324	0.08	0.06
21	0	532	-0.0528	532.0404	0.08	0.08
22	133	532	132.9432	532.0396	0.06	0.08
23	266	532	265.9419	532.0396	0.05	0.08
24	399	532	398.9442	532.0373	0.06	0.08
25	532	532	531.9465	532.0380	0.08	0.08

Table 10-2 Reported measurement results by the participants for the ball plate after transformation

	Nominal		NMIJ (B1)		KRISS (B2)		NIMT (B3)		NMIA (B4)		CSIR (B5)		NIM (B6)		NPLI (B7)	
No	*X*	*Y*	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]
1	0	0	-0.00002	0.00008	-0.00026	-0.00022	-0.00001	0.00002	-0.00005	0.00057	0.00218	0.00055	-0.00019	-0.00024	-0.01397	-0.00496
2	133	0	132.99542	0.00073	132.99537	0.00042	132.99536	0.00067	132.99547	0.00118	132.99748	0.00142	132.99533	0.00034	132.98543	-0.00183
3	266	0	265.99462	-0.00030	265.99461	-0.00054	265.99454	-0.00034	265.99479	0.00015	265.99458	0.00039	265.99457	-0.00075	265.98873	0.00031
4	399	0	398.99762	-0.00009	398.99782	-0.00033	398.99774	-0.00015	398.99774	0.00036	398.99568	0.00046	398.99778	-0.00046	398.99583	0.00264
5	532	0	532.00072	0.00014	532.00093	-0.00021	532.00080	0.00018	531.99993	0.00058	531.99858	0.00083	532.00093	-0.00021	532.00293	0.00518
6	0	133	-0.01897	133.01020	-0.01919	133.01012	-0.01897	133.01034	-0.01906	133.01053	-0.01689	133.01015	-0.01920	133.01005	0.00330	133.00504
7	133	133	132.97894	133.01144	132.97887	133.01146	132.97892	133.01164	132.97901	133.01186	132.98101	133.01162	132.97884	133.01132	132.96590	133.00927
8	266	133	265.98065	133.00887	265.98063	133.00879	265.98064	133.00902	265.98085	133.00914	265.98041	133.00879	265.98061	133.00857	265.97170	133.00891
9	399	133	398.98001	133.01059	398.98014	133.01054	398.98010	133.01039	398.98008	133.01086	398.97751	133.01066	398.98018	133.01037	398.97510	133.01334
10	532	133	531.98212	133.01191	531.98223	133.01177	531.98213	133.01203	531.98135	133.01232	531.98011	133.01193	531.98232	133.01174	531.98120	133.01678
11	0	266	-0.02498	266.01833	-0.02517	266.01833	-0.02493	266.01836	-0.02501	266.01844	-0.02297	266.01815	-0.02517	266.01834	0.00747	266.01344
12	133	266	132.97272	266.01861	132.97263	266.01858	132.97270	266.01865	132.97283	266.01868	132.97503	266.01882	132.97258	266.01853	132.95677	266.01617
13	266	266	265.97190	266.01809	265.97188	266.01807	265.97188	266.01818	265.97216	266.01810	265.97173	266.01829	265.97187	266.01792	265.95997	266.01791
14	399	266	398.97601	266.01847	398.97617	266.01844	398.97608	266.01838	398.97614	266.01851	398.97383	266.01856	398.97621	266.01835	398.96817	266.02094
15	532	266	531.97797	266.01929	531.97808	266.01925	531.97798	266.01926	531.97722	266.01942	531.97613	266.01923	531.97817	266.01923	531.97397	266.02408
16	0	399	-0.04663	399.02957	-0.04681	399.02971	-0.04660	399.02949	-0.04666	399.02932	-0.04454	399.02945	-0.04682	399.02980	0.02733	399.02464
17	133	399	132.95206	399.03256	132.95198	399.03266	132.95203	399.03243	132.95221	399.03237	132.95456	399.03272	132.95195	399.03275	132.93303	399.02977
18	266	399	265.95317	399.03089	265.95315	399.03090	265.95316	399.03067	265.95342	399.03055	265.95316	399.03069	265.95314	399.03087	265.93823	399.03061
19	399	399	398.95382	399.03137	398.95400	399.03150	398.95391	399.03122	398.95399	399.03115	398.95146	399.03136	398.95404	399.03152	398.94293	399.03354
20	532	399	531.95254	399.03240	531.95268	399.03250	531.95254	399.03228	531.95182	399.03223	531.95076	399.03233	531.95277	399.03261	531.94553	399.03707
21	0	532	-0.05269	532.04023	-0.05292	532.04053	-0.05272	532.04025	-0.05280	532.03941	-0.05051	532.03945	-0.05293	532.04079	0.03160	532.03544
22	133	532	132.94328	532.03945	132.94315	532.03974	132.94320	532.03959	132.94331	532.03863	132.94549	532.03892	132.94311	532.03994	132.92110	532.03707
23	266	532	265.94202	532.03941	265.94199	532.03974	265.94193	532.03960	265.94218	532.03861	265.94209	532.03889	265.94195	532.03982	265.92400	532.03971
24	399	532	398.94423	532.03718	398.94437	532.03751	398.94426	532.03733	398.94431	532.03640	398.94189	532.03656	398.94436	532.03766	398.93020	532.03964
25	532	532	531.94656	532.03790	531.94665	532.03815	531.94650	532.03802	531.94576	532.03712	531.94429	532.03723	531.94668	532.03845	531.93660	532.04257

	Nominal		NRC (B8)		MIKES (B9)		NML (B10)		INRiM (B11)		INMETRO (B12)		MSLNZ (B13)	
No	*X*	*Y*	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]
1	0	0	0.00001	0.00009	0.00005	-0.00006	0.00085	0.00086	-0.00003	0.00006	-0.00013	0.00001	-0.00017	-0.00008
2	133	0	132.99542	0.00063	132.99546	0.00056	132.99565	0.00160	132.99532	0.00063	132.99547	0.00062	132.99532	0.00050
3	266	0	265.99457	-0.00030	265.99457	-0.00047	265.99465	0.00015	265.99456	-0.00036	265.99457	-0.00038	265.99454	-0.00054
4	399	0	398.99771	-0.00007	398.99766	-0.00027	398.99735	0.00050	398.99780	-0.00021	398.99777	-0.00027	398.99773	-0.00038
5	532	0	532.00069	0.00002	532.00067	-0.00006	531.99995	0.00064	532.00074	0.00004	532.00077	0.00004	532.00079	-0.00012
6	0	133	-0.01900	133.01026	-0.01899	133.01017	-0.01800	133.01016	-0.01904	133.01008	-0.01914	133.01021	-0.01909	133.01009
7	133	133	132.97897	133.01153	132.97897	133.01152	132.97940	133.01150	132.97891	133.01152	132.97906	133.01162	132.97899	133.01147
8	266	133	265.98065	133.00894	265.98063	133.00884	265.98060	133.00875	265.98067	133.00884	265.98066	133.00892	265.98072	133.00876
9	399	133	398.98009	133.01069	398.98006	133.01055	398.97970	133.01060	398.98017	133.01037	398.98006	133.01063	398.98016	133.01052
10	532	133	531.98208	133.01188	531.98205	133.01188	531.98120	133.01204	531.98213	133.01178	531.98206	133.01194	531.98219	133.01185
11	0	266	-0.02500	266.01835	-0.02495	266.01835	-0.02414	266.01816	-0.02496	266.01832	-0.02515	266.01841	-0.02514	266.01831
12	133	266	132.97268	266.01856	132.97271	266.01862	132.97296	266.01860	132.97263	266.01804	132.97275	266.01872	132.97263	266.01859
13	266	266	265.97192	266.01809	265.97193	266.01804	265.97186	266.01815	265.97189	266.01805	265.97185	266.01812	265.97190	266.01802
14	399	266	398.97613	266.01846	398.97611	266.01840	398.97566	266.01830	398.97615	266.01847	398.97605	266.01843	398.97620	266.01840
15	532	266	531.97795	266.01921	531.97790	266.01927	531.97716	266.01924	531.97791	266.01941	531.97795	266.01934	531.97807	266.01929
16	0	399	-0.04668	399.02955	-0.04663	399.02961	-0.04579	399.02936	-0.04664	399.02974	-0.04685	399.02951	-0.04680	399.02965
17	133	399	132.95203	399.03250	132.95206	399.03263	132.95231	399.03250	132.95202	399.03271	132.95215	399.03252	132.95199	399.03267
18	266	399	265.95316	399.03079	265.95315	399.03085	265.95311	399.03055	265.95317	399.03092	265.95315	399.03072	265.95317	399.03081
19	399	399	398.95396	399.03140	398.95396	399.03140	398.95351	399.03110	398.95401	399.03153	398.95395	399.03133	398.95406	399.03144
20	532	399	531.95254	399.03232	531.95252	399.03243	531.95181	399.03214	531.95257	399.03205	531.95265	399.03234	531.95267	399.03250
21	0	532	-0.05279	532.04033	-0.05276	532.04047	-0.05174	532.03976	-0.05280	532.04049	-0.05296	532.04021	-0.05292	532.04057
22	133	532	132.94322	532.03949	132.94322	532.03969	132.94356	532.03910	132.94312	532.03973	132.94324	532.03952	132.94314	532.03978
23	266	532	265.94193	532.03948	265.94193	532.03962	265.94196	532.03915	265.94195	532.03974	265.94194	532.03952	265.94191	532.03973
24	399	532	398.94426	532.03729	398.94422	532.03741	398.94386	532.03680	398.94428	532.03744	398.94434	532.03723	398.94430	532.03747
25	532	532	531.94651	532.03795	531.94652	532.03813	531.94566	532.03754	531.94648	532.03817	531.94664	532.03794	531.94665	532.03819

Table 10-3 E_n numbers of all participants for the ball plate comparison

No	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13
1	0.25	0.52	0.04	0.48	0.37	(0.93)	(10.16)	0.29	0.49	(1.35)	0.09	0.15	0.19
2	0.36	0.31	0.16	0.49	0.37	(0.90)	(8.68)	0.09	0.35	(1.15)	0.16	0.06	0.17
3	0.30	0.23	0.11	0.54	0.13	(1.04)	(6.62)	0.30	0.47	(0.63)	0.05	0.04	0.15
4	0.36	0.32	0.09	0.48	0.36	(0.85)	(2.45)	0.42	0.50	(0.88)	0.17	0.15	0.20
5	0.39	0.49	0.26	0.73	0.38	(0.92)	(3.96)	0.08	0.43	(1.11)	0.08	0.10	0.15
6	0.10	0.31	0.23	0.39	0.35	(0.79)	(15.94)	0.25	0.25	(1.12)	0.17	0.15	0.14
7	0.27	0.19	0.21	0.42	0.35	(0.91)	(11.41)	0.04	0.07	(0.53)	0.08	0.22	0.06
8	0.05	0.14	0.24	0.47	0.04	(1.14)	(10.29)	0.25	0.33	(0.14)	0.06	0.10	0.15
9	0.25	0.14	0.29	0.35	0.44	(0.86)	(4.90)	0.41	0.24	(0.44)	0.33	0.10	0.12
10	0.15	0.31	0.22	0.67	0.33	(0.89)	(4.32)	0.04	0.19	(1.00)	0.18	0.09	0.13
11	0.08	0.29	0.06	0.16	0.34	(0.57)	(22.76)	0.05	0.22	(0.96)	0.05	0.21	0.17
12	0.07	0.14	0.08	0.26	0.40	(0.59)	(13.99)	0.16	0.18	(0.30)	0.83	0.22	0.08
13	0.20	0.08	0.22	0.40	0.05	(0.64)	(13.81)	0.12	0.32	(0.15)	0.05	0.15	0.06
14	0.41	0.13	0.09	0.19	0.39	(0.50)	(7.36)	0.17	0.33	(0.56)	0.10	0.07	0.12
15	0.15	0.23	0.06	0.52	0.30	(0.73)	(5.55)	0.23	0.17	(0.87)	0.20	0.12	0.15
16	0.09	0.32	0.18	0.24	0.35	(0.93)	(51.05)	0.15	0.21	(1.00)	0.21	0.24	0.16
17	0.10	0.19	0.26	0.31	0.43	(0.76)	(16.64)	0.31	0.33	(0.31)	0.17	0.17	0.11
18	0.23	0.12	0.26	0.48	0.03	(0.20)	(17.29)	0.15	0.13	(0.34)	0.11	0.15	0.03
19	0.46	0.22	0.27	0.25	0.42	(0.66)	(9.73)	0.06	0.19	(0.63)	0.22	0.07	0.14
20	0.07	0.29	0.18	0.51	0.30	(1.10)	(6.22)	0.26	0.30	(0.87)	0.50	0.15	0.18
21	0.46	0.32	0.19	0.73	0.41	(1.33)	(58.11)	0.15	0.50	(1.34)	0.14	0.28	0.24
22	0.42	0.25	0.04	0.74	0.40	(1.12)	(19.22)	0.35	0.54	(0.67)	0.23	0.09	0.21
23	0.44	0.30	0.06	0.77	0.11	(0.83)	(20.83)	0.26	0.41	(0.44)	0.24	0.03	0.18
24	0.42	0.36	0.04	0.72	0.42	(1.10)	(12.26)	0.15	0.45	(0.75)	0.14	0.19	0.16
25	0.38	0.27	0.04	0.87	0.39	(1.36)	(7.58)	0.27	0.51	(1.11)	0.18	0.18	0.20

Lab No 1: NMIJ, 2: KRISS, 3: NIMT, 4:NMIA, 5:CSIR, 6:NIM, 7: NPLI, 8: NRC, 9: MIKES, 10: NML, 11: INRiM, 12: INMETRO, 13: MSLNZ

E_n numbers of each participant is illustrated in the following figures. E_n = 1 line is drawn in red.

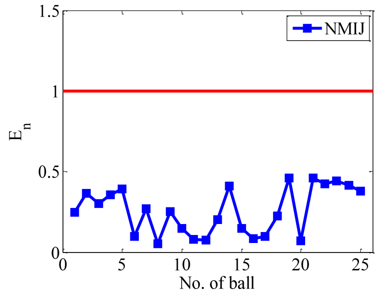

Fig. 10-5 ***E*$_n$** of NMIJ (Lab B1)

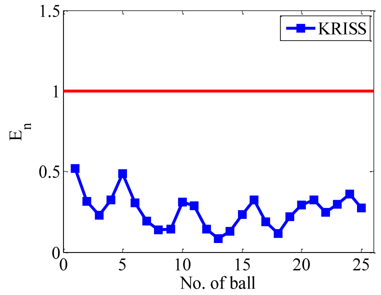

Fig. 10-6 ***E*$_n$** of KRISS (Lab B2)

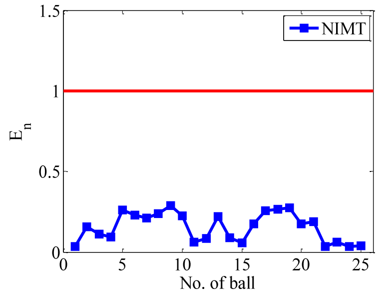

Fig. 10-7 ***E*$_n$** of NIMT (Lab B3)

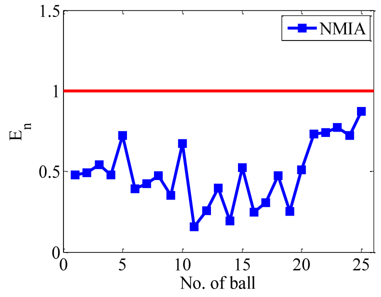

Fig. 10-8 ***E*$_n$** of NMIA (Lab B4)

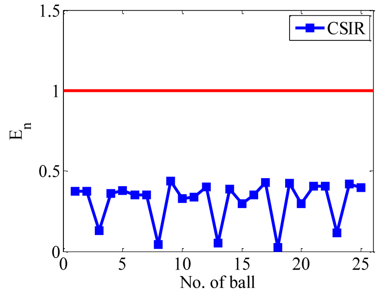

Fig. 10-9 ***E*$_n$** of CSIR (Lab B5)

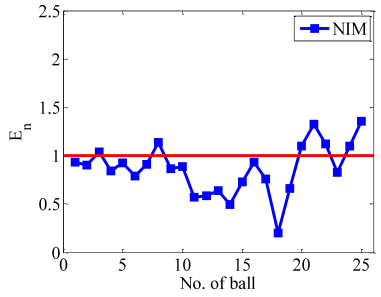

Fig. 10-10 ***E*$_n$** of NIM (Lab B6)

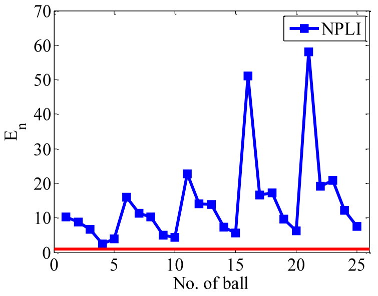

Fig. 10-11 $\boldsymbol{E_n}$ of NPLI (Lab B7)

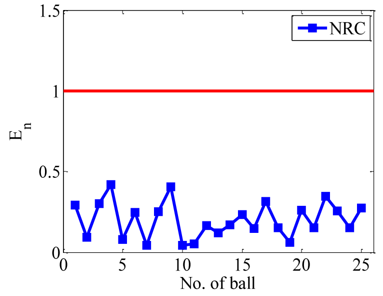

Fig. 10-12 $\boldsymbol{E_n}$ of NRC (Lab B8)

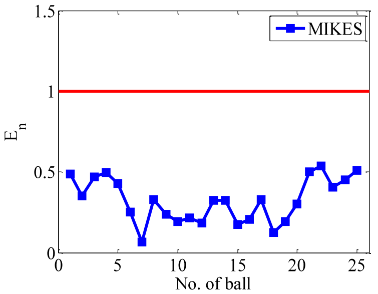

Fig. 10-13 $\boldsymbol{E_n}$ of MIKES (Lab B9)

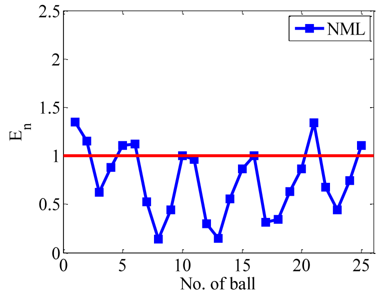

Fig. 10-14 $\boldsymbol{E_n}$ of NML (Lab B10)

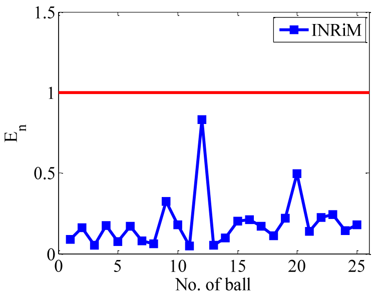

Fig. 10-15 $\boldsymbol{E_n}$ of INRiM (Lab B11)

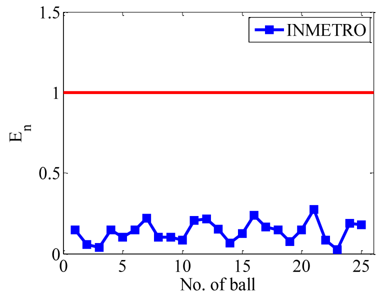

Fig. 10-16 $\boldsymbol{E_n}$ of INMETRO (Lab B12)

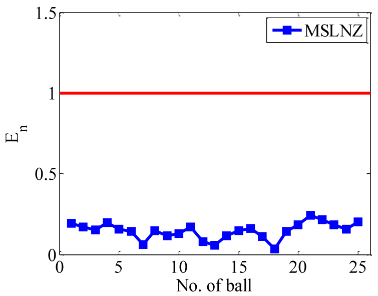

Fig. 10-17 $\boldsymbol{E_n}$ of MSLNZ (Lab B13)

Although some participants were not able to demonstrate their measurement competence, overall results look reasonable. We can conclude this comparison is valid and it can be a supporting evidence for participants' CMC claims.

10.5 Calculation of KCRV and outlier elimination for the hole plate comparison

Figure 10-18 shows E_n numbers of the reported results of all 9 participants. The weighted mean is used as KCRV.

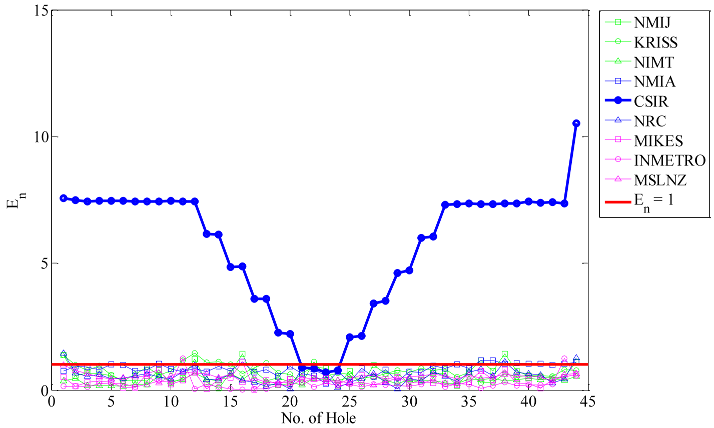

Fig. 10-18 $\boldsymbol{E_n}$ numbers calculated from all participants results

CSIR result can be easily recognized as an outlier. Most E_n numbers are larger than 5 and the largest E_n number is more than 10. We decided to eliminate CSIR from the KCRV data group.

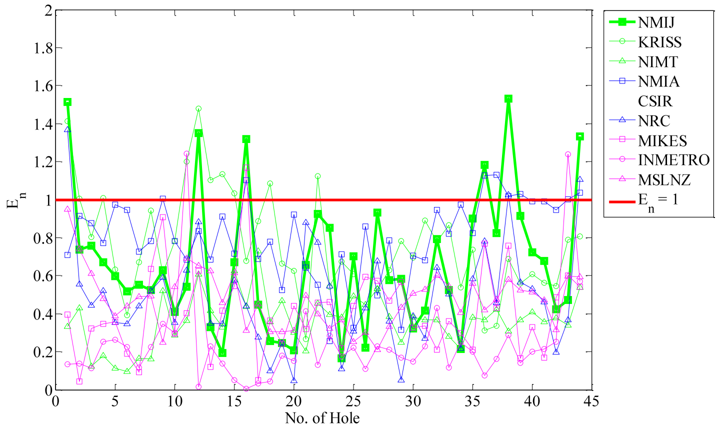

Fig. 10-19 $\boldsymbol{E_n}$ numbers calculated except CSIR

Figure 10-19 shows E_n numbers after eliminating CSIR from the KCRV data group. NMIJ has more than 2 and the largest outlier so that it will be eliminated from the KCRV data group.

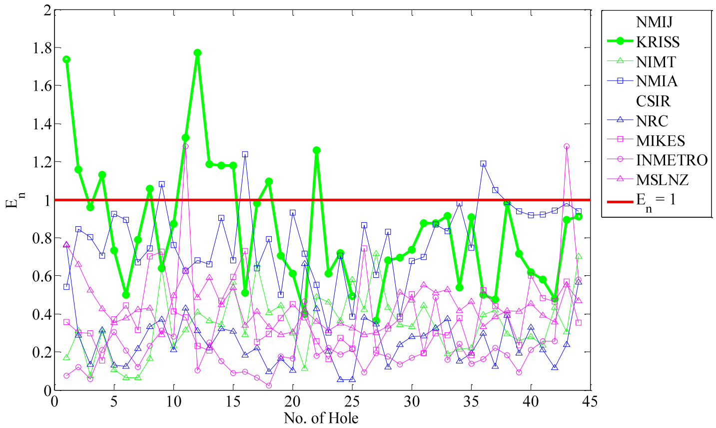

Fig. 10-20 $\boldsymbol{E_n}$ numbers calculated except CSIR and NMIJ

Figure 10-20 shows E_n numbers after eliminating CSIR and NMIJ. KRISS has more than 2 and the largest outlier so that it will be eliminated from the KCRV data group.

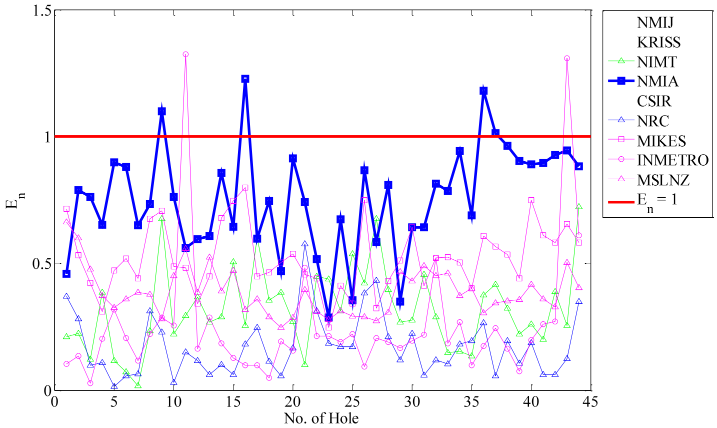

Fig. 10-21 $\boldsymbol{E_n}$ numbers calculated except CSIR, NMIJ and KRISS

Figure 10-21 shows E_n numbers after eliminating CSIR, NMIJ and KRISS. Although the largest outlier is made by INMETRO, they have only two outliers which are less than 5 % of the measurement results. Contrarily NMIA has five $E_n > 1$ results which is more than 5 % of the measurement results. Therefore NMIA is deleted from the KCRV data group.

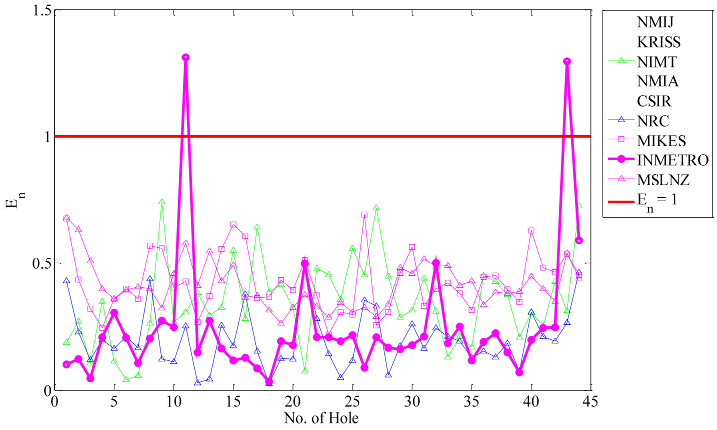

Fig. 10-22 ***E*$_n$** numbers calculated except CSIR, NMIJ, KRISS, and NMIA

Figure 10-22 shows E_n numbers after eliminating CSIR, NMIJ, KRISS, and NMIA. INMETRO have two $E_n > 1$ results. Two is less than 5 % of 44 measurements. According to the decision by CIPM/TCL/ WG the laboratory doesn't have to leave from the KCRV data group. Only two outlier data of the laboratory should be eliminated from the KCRV data set.

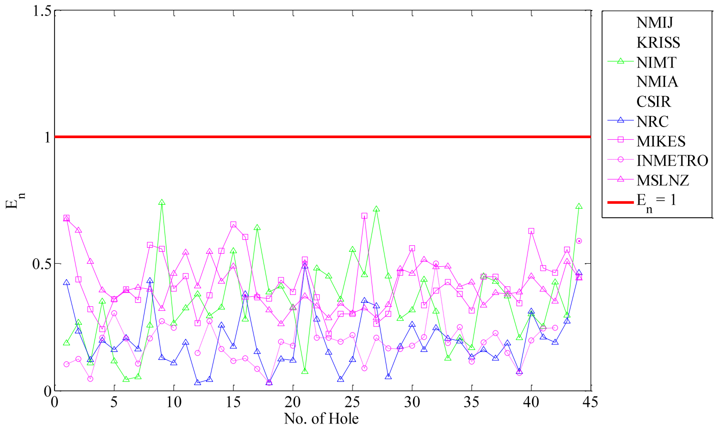

Fig. 10-23 ***E*$_n$** numbers calculated except CSIR, NMIJ, KRISS, NMIA, and No. 11 and 43 of INMETRO

The outlier elimination procedure terminates here. All data are within $E_n < 1$ band. The measurement uncertainty of the KCRV is written as follows.

$$u_c = \sqrt{0.0971^2 + 0.2558^2 \times l^2} \ [\mu\text{m}], \quad l : \text{measurement length in metre}$$

The KCRV and its uncertainty of the hole plate comparison are shown in Table 10-4.

Reported measurement results by the participants for the hole plate after transformation are shown in Table 10-5.

E_n numbers of all participants for the hole plate comparison are listed in Table 10-6. Those results not used for KCRV calculation are written in parentheses ().E_n > 1 results are written in red.

Table 10-4 KCRV and its uncertainty of the hole plate comparison

	Nominal		KCRV		Uncertainty	
No	*X*	*Y*	*X* [mm]	*Y* [mm]	u_X [μm]	u_Y [μm]
1	0	0	0.0000	0.0000	0.12	0.12
2	50	0	50.0335	0.0353	0.11	0.12
3	100	0	100.0328	0.0200	0.11	0.12
4	150	0	150.0296	-0.0258	0.10	0.12
5	200	0	200.0362	-0.0717	0.10	0.12
6	250	0	250.0410	0.0430	0.10	0.12
7	300	0	300.0359	0.0823	0.10	0.12
8	350	0	350.0341	0.1283	0.10	0.12
9	400	0	400.0052	-0.0189	0.10	0.12
10	450	0	450.0225	0.0565	0.11	0.12
11	500	0	500.0121	-0.0229	0.11	0.12
12	550	0	550.0492	0.0000	0.12	0.12
13	0	50	0.0057	50.0698	0.12	0.11
14	550	50	550.0301	50.0195	0.12	0.11
15	0	100	-0.0292	99.8900	0.12	0.11
16	550	100	550.0184	100.0090	0.12	0.11
17	0	150	-0.0157	149.9703	0.12	0.10
18	550	150	550.0628	150.1112	0.12	0.10
19	0	200	-0.0549	199.9262	0.12	0.10
20	550	200	550.0467	199.9755	0.12	0.10
21	0	250	-0.0180	250.0138	0.12	0.10
22	550	250	549.9992	250.1211	0.12	0.10
23	0	300	-0.0764	299.8026	0.12	0.10
24	550	300	549.9846	300.1348	0.12	0.10
25	0	350	-0.0610	349.9687	0.12	0.10
26	550	350	550.2467	350.1055	0.12	0.10
27	0	400	-0.0962	399.8812	0.12	0.10
28	550	400	549.9898	400.0373	0.12	0.10
29	0	450	-0.1434	449.8866	0.12	0.11
30	550	450	549.9372	450.1178	0.12	0.11
31	0	500	-0.1301	499.9452	0.12	0.11
32	550	500	549.9035	500.0339	0.12	0.11
33	0	550	-0.1797	549.9396	0.12	0.12
34	50	550	49.8854	550.0558	0.11	0.12
35	100	550	99.8263	549.8595	0.11	0.12
36	150	550	149.8143	549.9463	0.10	0.12
37	200	550	199.8299	549.9681	0.10	0.12
38	250	550	249.8273	549.9263	0.10	0.12
39	300	550	299.8198	549.8868	0.10	0.12
40	350	550	349.8559	549.8984	0.10	0.12
41	400	550	399.8626	549.9302	0.10	0.12
42	450	550	450.1595	550.1206	0.11	0.12
43	500	550	499.8514	550.1374	0.11	0.12
44	550	550	549.8727	550.0369	0.12	0.12

Table 10-5 Reported measurement results by the participants for the hole plate after transformation

	Nominal		NMIJ (H1)		KRISS (H2)		NIMT (H3)		NMIA (H4)		CSIR (H5)		NRC (H6)		MIKESI (H7)		INMETRO (H8)		MSLNZ (H9)	
No	*X*	*Y*	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]	*X* [mm]	*Y* [mm]
1	0	0	-0.02355	0.02826	0.00461	-0.00093	0.00004	-0.00014	0.00578	0.00056	0.00636	-0.04594	0.00010	0.00006	-0.00017	-0.00010	-0.00053	0.00002	0.00059	0.00046
2	50	0	50.01029	0.05848	50.03861	0.03455	50.03368	0.03537	50.03977	0.03595	50.04046	-0.00996	50.03348	0.03529	50.03350	0.03513	50.03297	0.03530	50.03402	0.03571
3	100	0	100.00941	0.03813	100.03784	0.01956	100.03272	0.02002	100.03873	0.02088	100.03936	-0.02498	100.03277	0.02003	100.03278	0.01991	100.03247	0.02008	100.03307	0.02046
4	150	0	150.00626	-0.01289	150.03475	-0.02652	150.02943	-0.02596	150.03562	-0.02517	150.03616	-0.07089	150.02962	-0.02577	150.02963	-0.02589	150.02957	-0.02594	150.02970	-0.02540
5	200	0	200.01285	-0.06391	200.04144	-0.07207	200.03614	-0.07163	200.04224	-0.07071	200.04176	-0.11671	200.03620	-0.07166	200.03619	-0.07180	200.03537	-0.07166	200.03625	-0.07130
6	250	0	250.01782	0.04546	250.04647	0.04269	250.04096	0.04302	250.04694	0.04403	250.04576	-0.00203	250.04101	0.04306	250.04097	0.04289	250.04037	0.04322	250.04101	0.04344
7	300	0	300.01276	0.07945	300.04161	0.08171	300.03589	0.08231	300.04171	0.08303	300.04136	0.03735	300.03588	0.08231	300.03588	0.08216	300.03537	0.08220	300.03578	0.08270
8	350	0	350.01104	0.12022	350.04007	0.12757	350.03425	0.12822	350.04014	0.12900	350.03886	0.08334	350.03418	0.12832	350.03399	0.12815	350.03347	0.12808	350.03405	0.12869
9	400	0	399.98225	-0.03168	400.01129	-0.01894	400.00544	-0.01834	400.01118	-0.01753	400.00916	-0.06358	400.00521	-0.01885	400.00525	-0.01902	400.00447	-0.01893	400.00520	-0.01851
10	450	0	449.99951	0.03814	450.02857	0.05608	450.02261	0.05673	450.02850	0.05740	450.02616	0.01150	450.02253	0.05657	450.02255	0.05643	450.02177	0.05655	450.02221	0.05691
11	500	0	499.98915	-0.04660	500.01834	-0.02372	500.01222	-0.02274	500.01731	-0.02237	500.01556	-0.06782	500.01208	-0.02289	500.01210	-0.02307	500.01397	-0.02337	500.01157	-0.02269
12	550	0	550.02641	-0.02919	550.05570	-0.00105	550.04937	0.00026	550.05439	0.00062	550.05386	-0.04503	550.04923	-0.00001	550.04924	-0.00008	550.04907	-0.00019	550.04889	0.00029
13	0	50	-0.01235	50.09847	0.01058	50.06927	0.00591	50.06991	0.01158	50.07046	0.01128	50.03316	0.00573	50.06981	0.00564	50.06972	0.00509	50.06942	0.00614	50.07020
14	550	50	550.01213	49.99066	550.03601	50.01870	550.02982	50.01950	550.03493	50.02022	550.03448	49.98297	550.03003	50.01953	550.03020	50.01939	550.02979	50.01921	550.02977	50.01982
15	0	100	-0.04217	99.91870	-0.02441	99.88966	-0.02911	99.89037	-0.02342	99.89069	-0.02360	99.86136	-0.02916	99.89006	-0.02923	99.88985	-0.02969	99.88992	-0.02874	99.89032
16	550	100	550.00567	99.98074	550.02423	100.00882	550.01815	100.00899	550.02309	100.01010	550.02290	99.98057	550.01835	100.00909	550.01848	100.00888	550.01801	100.00921	550.01803	100.00920
17	0	150	-0.02329	149.99889	-0.01075	149.96993	-0.01553	149.97065	-0.00974	149.97081	-0.01139	149.94926	-0.01568	149.97024	-0.01577	149.97021	-0.01617	149.97022	-0.01528	149.97034
18	550	150	550.05529	150.08242	550.06888	150.11059	550.06253	150.11119	550.06770	150.11172	550.06731	150.09027	550.06282	150.11121	550.06293	150.11120	550.06253	150.11121	550.06248	150.11124
19	0	200	-0.05722	199.95483	-0.04981	199.92595	-0.05466	199.92631	-0.04898	199.92654	-0.04927	199.91296	-0.05490	199.92618	-0.05499	199.92607	-0.05555	199.92632	-0.05464	199.92624
20	550	200	550.04446	199.94679	550.05248	199.97511	550.04646	199.97551	550.05127	199.97591	550.05123	199.96267	550.04671	199.97548	550.04680	199.97540	550.04625	199.97571	550.04636	199.97551
21	0	250	-0.01530	250.04263	-0.01275	250.01387	-0.01802	250.01379	-0.01320	250.01423	-0.01185	250.00876	-0.01787	250.01387	-0.01813	250.01378	-0.01923	250.01392	-0.01759	250.01392
22	550	250	550.00221	250.09203	550.00537	250.12037	549.99888	250.12097	550.00416	250.12103	550.00395	250.11607	549.99923	250.12115	549.99933	250.12105	549.99907	250.12081	549.99887	250.12115
23	0	300	-0.06816	299.83158	-0.07112	299.80294	-0.07611	299.80264	-0.07051	299.80267	-0.07073	299.80676	-0.07647	299.80255	-0.07650	299.80258	-0.07702	299.80232	-0.07614	299.80249
24	550	300	549.99290	300.10602	549.99070	300.13457	549.98437	300.13472	549.98940	300.13458	549.98927	300.13917	549.98464	300.13479	549.98472	300.13481	549.98438	300.13451	549.98426	300.13474
25	0	350	-0.04747	349.99730	-0.05576	349.96891	-0.06061	349.96870	-0.05500	349.96867	-0.05522	349.98076	-0.06106	349.96871	-0.06111	349.96872	-0.06170	349.96852	-0.06071	349.96862
26	550	350	550.26010	350.07685	----------	----------	550.24639	350.10539	550.25120	350.10575	550.25098	350.11787	550.24666	350.10546	550.24683	350.10567	550.24630	350.10541	550.24634	350.10550
27	0	400	-0.07734	399.90975	-0.09089	399.88130	-0.09584	399.88088	-0.09021	399.88072	-0.09030	399.90106	-0.09625	399.88127	-0.09629	399.88121	-0.09688	399.88102	-0.09591	399.88118
28	550	400	550.00842	400.00838	549.99579	400.03707	549.98947	400.03716	549.99452	400.03682	549.99430	400.05777	549.98978	400.03732	549.98986	400.03734	549.98962	400.03751	549.98940	400.03726
29	0	450	-0.11948	449.91520	-0.13834	449.88681	-0.14323	449.88651	-0.13762	449.88628	-0.13778	449.91376	-0.14342	449.88655	-0.14349	449.88670	-0.14406	449.88662	-0.14306	449.88625
30	550	450	549.96114	450.08917	549.94332	450.11777	549.93700	450.11768	549.94202	450.11754	549.94172	450.14567	549.93718	450.11775	549.93727	450.11794	549.93714	450.11791	549.93681	450.11752
31	0	500	-0.10091	499.97403	-0.12488	499.94579	-0.12988	499.94544	-0.12414	499.94458	-0.12456	499.98106	-0.13010	499.94519	-0.13020	499.94527	-0.13084	499.94522	-0.12979	499.94479
32	550	500	549.93270	500.00541	549.90970	500.03413	549.90328	500.03391	549.90841	500.03316	549.90784	500.06997	549.90350	500.03380	549.90361	500.03393	549.90376	500.03451	549.90320	500.03346
33	0	550	-0.14556	549.96830	-0.17465	549.94006	-0.17959	549.93968	-0.17378	549.93869	-0.17425	549.98366	-0.17962	549.93959	-0.17975	549.93972	-0.18032	549.93952	-0.17931	549.93923
34	50	550	49.91979	550.07938	49.89072	550.05610	49.88547	550.05567	49.89164	550.05485	49.89195	550.10004	49.88540	550.05578	49.88541	550.05594	49.88468	550.05600	49.88573	550.05552
35	100	550	99.86067	549.87812	99.83173	549.86014	99.82633	549.85933	99.83234	549.85874	99.83285	549.90402	99.82631	549.85945	99.82634	549.85956	99.82608	549.85928	99.82656	549.85906
36	150	550	149.84905	549.95948	149.82023	549.94654	149.81450	549.94607	149.82067	549.94515	149.82115	549.99051	149.81430	549.94631	149.81431	549.94647	149.81428	549.94636	149.81428	549.94597
37	200	550	199.86405	549.97609	199.83537	549.96838	199.82974	549.96783	199.83600	549.96693	199.83525	550.01229	199.82995	549.96804	199.82997	549.96820	199.82928	549.96824	199.83009	549.96768
38	250	550	249.86202	549.92935	249.83335	549.92691	249.82754	549.92625	249.83357	549.92539	249.83215	549.97087	249.82733	549.92624	249.82731	549.92640	249.82678	549.92622	249.82734	549.92587
39	300	550	299.85411	549.88452	299.82562	549.88728	299.81970	549.88668	299.82589	549.88581	299.82515	549.93135	299.81981	549.88675	299.81984	549.88687	299.81938	549.88670	299.81981	549.88635
40	350	550	349.89016	549.89084	349.86188	549.89867	349.85602	549.89825	349.86160	549.89732	349.86045	549.94344	349.85589	549.89837	349.85596	549.89862	349.85528	549.89838	349.85575	549.89799
41	400	550	399.89690	549.91736	399.86858	549.93036	399.86266	549.93000	399.86832	549.92905	399.86605	549.97472	399.86261	549.93012	399.86263	549.93033	399.86198	549.93047	399.86259	549.92975
42	450	550	450.19378	550.10229	450.16548	550.12071	450.15941	550.12034	450.16544	550.11950	450.16295	550.16520	450.15958	550.12058	450.15959	550.12076	450.15908	550.12105	450.15935	550.12031
43	500	550	499.88594	550.11388	499.85766	550.13742	499.85135	550.13717	499.85650	550.13634	499.85475	550.18168	499.85142	550.13733	499.85141	550.13756	499.85328	550.13763	499.85096	550.13708
44	550	550	549.90698	550.00872	549.87884	550.03738	549.87229	550.03730	549.87755	550.03612	549.89935	550.09697	549.87271	550.03682	549.87283	550.03703	549.87338	550.03731	549.87242	550.03658

Table 10-6 E_n numbers of all participants for the hole plate comparison

No	H1	H2	H3	H4	H5	H6	H7	H8	H9
1	(1.74)	(1.70)	0.19	(0.46)	(7.61)	0.43	0.68	0.10	0.68
2	(0.82)	(1.10)	0.27	(0.79)	(7.49)	0.24	0.44	0.12	0.63
3	(0.81)	(0.91)	0.11	(0.76)	(7.45)	0.12	0.32	0.05	0.51
4	(0.73)	(1.08)	0.35	(0.65)	(7.47)	0.20	0.24	0.21	0.40
5	(0.58)	(0.66)	0.12	(0.90)	(7.46)	0.16	0.36	0.31	0.36
6	(0.46)	(0.43)	0.04	(0.88)	(7.46)	0.21	0.40	0.21	0.39
7	(0.58)	(0.74)	0.05	(0.65)	(7.44)	0.16	0.36	0.11	0.41
8	(0.62)	(1.02)	0.26	(0.73)	(7.45)	0.43	0.57	0.20	0.40
9	(0.82)	(0.64)	0.74	(1.10)	(7.42)	0.13	0.56	0.27	0.32
10	(0.49)	(0.85)	0.27	(0.76)	(7.47)	0.11	0.40	0.25	0.46
11	(0.77)	(1.31)	0.33	(0.54)	(7.45)	0.19	0.45	(1.31)	0.54
12	(1.53)	(1.72)	0.38	(0.60)	(7.46)	0.03	0.27	0.15	0.41
13	(0.48)	(1.15)	0.29	(0.61)	(6.15)	0.04	0.37	0.27	0.55
14	(0.23)	(1.11)	0.33	(0.86)	(6.13)	0.26	0.55	0.16	0.43
15	(0.83)	(1.15)	0.55	(0.64)	(4.86)	0.17	0.65	0.12	0.49
16	(1.43)	(0.42)	0.28	(1.23)	(4.83)	0.38	0.60	0.13	0.37
17	(0.52)	(0.95)	0.64	(0.60)	(3.60)	0.15	0.37	0.09	0.37
18	(0.22)	(1.03)	0.39	(0.75)	(3.58)	0.03	0.36	0.03	0.32
19	(0.27)	(0.68)	0.41	(0.47)	(2.27)	0.12	0.44	0.19	0.26
20	(0.23)	(0.54)	0.33	(0.92)	(2.20)	0.12	0.39	0.18	0.33
21	(0.82)	(0.44)	0.07	(0.74)	(0.88)	0.49	0.52	0.50	0.37
22	(1.02)	(1.22)	0.48	(0.52)	(0.88)	0.28	0.37	0.21	0.33
23	(0.91)	(0.61)	0.45	(0.28)	(0.72)	0.15	0.22	0.21	0.28
24	(0.20)	(0.67)	0.36	(0.67)	(0.77)	0.04	0.30	0.19	0.34
25	(0.61)	(0.48)	0.56	(0.35)	(2.07)	0.12	0.30	0.22	0.30
26	(0.25)	------	0.46	(0.87)	(2.13)	0.35	0.69	0.09	0.33
27	(0.89)	(0.35)	0.71	(0.59)	(3.39)	0.33	0.26	0.21	0.29
28	(0.63)	(0.64)	0.45	(0.81)	(3.50)	0.05	0.30	0.17	0.34
29	(0.48)	(0.69)	0.28	(0.35)	(4.61)	0.17	0.46	0.16	0.48
30	(0.34)	(0.68)	0.32	(0.64)	(4.73)	0.26	0.56	0.18	0.46
31	(0.35)	(0.85)	0.44	(0.64)	(6.01)	0.16	0.34	0.21	0.52
32	(0.83)	(0.83)	0.31	(0.82)	(6.06)	0.25	0.39	0.50	0.49
33	(0.64)	(0.89)	0.13	(0.78)	(7.30)	0.21	0.43	0.19	0.49
34	(0.17)	(0.50)	0.21	(0.94)	(7.33)	0.20	0.38	0.25	0.41
35	(0.98)	(0.88)	0.17	(0.69)	(7.39)	0.13	0.32	0.11	0.43
36	(1.28)	(0.50)	0.45	(1.18)	(7.32)	0.16	0.45	0.19	0.34
37	(0.81)	(0.44)	0.43	(1.01)	(7.33)	0.13	0.45	0.22	0.39
38	(1.65)	(0.97)	0.37	(0.96)	(7.39)	0.19	0.40	0.15	0.38
39	(0.95)	(0.70)	0.21	(0.90)	(7.39)	0.07	0.34	0.07	0.39
40	(0.67)	(0.59)	0.30	(0.89)	(7.46)	0.31	0.63	0.20	0.45
41	(0.63)	(0.56)	0.25	(0.90)	(7.39)	0.21	0.48	0.24	0.40
42	(0.35)	(0.47)	0.43	(0.93)	(7.40)	0.19	0.46	0.25	0.35
43	(0.63)	(0.89)	0.30	(0.93)	(7.35)	0.27	0.56	(1.29)	0.51
44	(1.38)	(0.86)	0.73	(0.88)	(10.54)	0.46	0.45	0.59	0.44

Lab No 1: NMIJ, 2: KRISS, 3: NIMT, 4:NMIA, 5:CSIR, 6:NRC, 7: MIKES, 8: INMETRO, 9: MSLNZ

E_n numbers of each participant is illustrated in the following figures. E_n = 1 line is drawn in red.

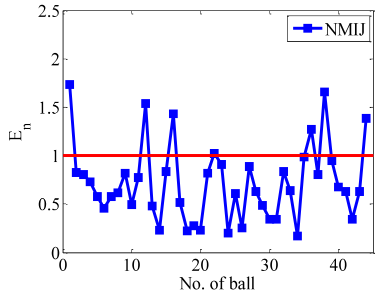

Fig. 10-24 $\boldsymbol{E_n}$ of NMIJ (Lab H1)

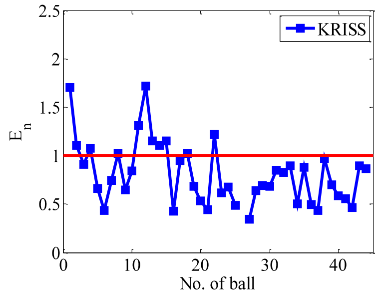

Fig. 10-25 $\boldsymbol{E_n}$ of KRISS (Lab H2)

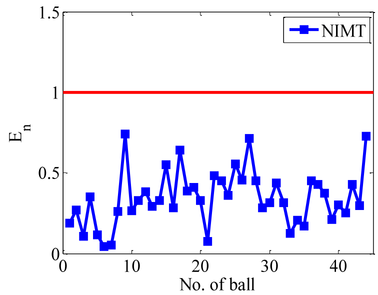

Fig. 10-26 $\boldsymbol{E_n}$ of NIMT (Lab H3)

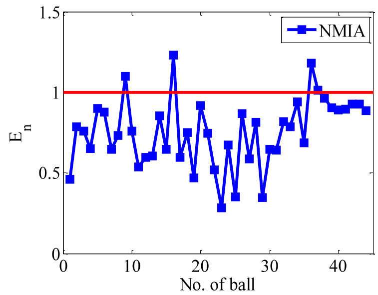

Fig. 10-27 $\boldsymbol{E_n}$ of NMIA (Lab H4)

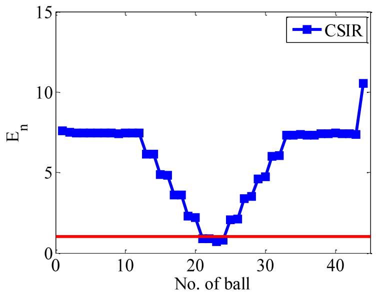

Fig. 10-28 $\boldsymbol{E_n}$ of CSIR (Lab H5)

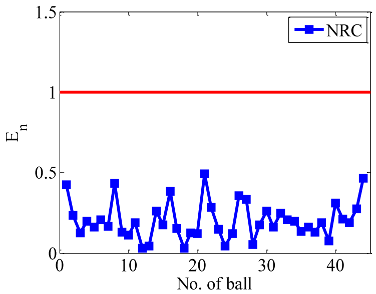

Fig. 10-29 $\boldsymbol{E_n}$ of NRC (Lab H6)

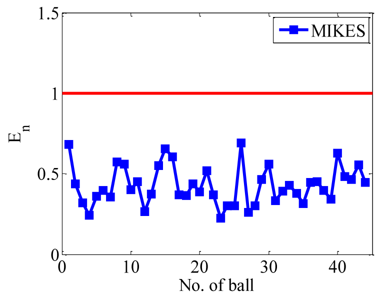

Fig. 10-30 $\boldsymbol{E}_n$ of MIKES (Lab H7)

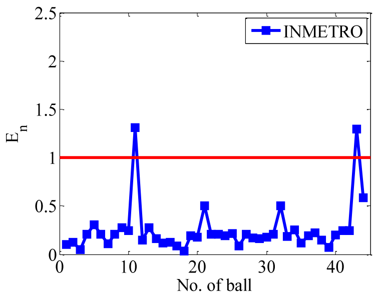

Fig. 10-30 $\boldsymbol{E}_n$ of INMETRO (Lab H8)

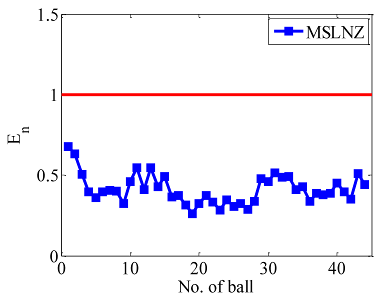

Fig. 10-31 $\boldsymbol{E}_n$ of MSLNZ (Lab H9)

Four out of nine participants (44 %) were excluded from the KCRV data group. In addition two results of a participant were excluded from the KCRV data set. This fact implies the hole plate contains unseen unstable nature. The pilot measurements done by the pilot multiple times show its long time stability is good.

Two possibilities can be considered to explain this fact.

The first is that the hole plate is not sturdy enough and deforms when clamped.

The second is that different positions have been measured by different participants due to its imperfect dimensions. The hole plate was specialy designed for light weight and reducing the cost. The cylinders are inserted to the glass plate. If perpendicularity between the cylinder axis and the glass plate surface is not perfect, the calibration results may shift as the perpendicularity is getting worse. If all participants measure the center position of the cylinders in the exactly same plane, the calibration results don't shift no matter if the perpendicularity is good or bad.

To avoid these two possibilities, the protocol was carefully made, i.e. the clamping position was clearly defined and the workpiece coordinate was clearly defined. In spite of these cautions, the comparison was not so successful.

These two possibilities were difficult to find by each participant because as far as it is measured by a single laboratory the result looks stable. These two factors are categorized in the uncertainty sources made by the device under test (DUT). Anyway it is true that some participants underestimated the measurement uncertainties caused by DUT. It is a lesson we learned by this comparison. We should pay more attention to DUT when performing calibration services.

11 Conclusion

This comparison involved 14 laboratories from 3 different metrological regions.

The comparison lasted more than 2 years from May 2006 to Oct. 2008.

Damage in the gauges was not observed and the gauges were stable during the comparison.

VMI (Vietnam) withdrew from the comparison. All other (13) laboratories measured the ball plate and nine laboratories did the hole plate.

Ball plate: Three laboratories, NIM (China), NPLI (India) and NML (Ireland), failed to demonstrate their calibration capabilities.

After submitting the final report to CCL-WG-MRA, NML, Ireland found that they had reported incorrect measurement uncertainty. It should be noted that if their measurement uncertainty registered in KCDB Appendix C was used, their En numbers were much smaller than unity and their measurement capability could be confirmed.

NIM, China also reported incorrect uncertainty. It was caused by the bad temperature environment when the gauge was measured. If their measurement uncertainty registered in KCDB Appendix C was used, their En numbers much smaller than unity and their measurement capability could be confirmed.

Hole plate: Four laboratories, NMIJ(Japan), KRISS (Korea), NMIA (Australia) and CSIR (South Africa), failed to demonstrate their calibration capabilities.

The results of the hole plate was worse than those of the ball plate. Reasons for this fact is not clear but gauge‘s insturdyness and imperfect dimension may be possible reasons. Some participants underestimated their measurement uncertainties by underestimating the effect of DUT.

We would like to express our sincere gratitude for the participants and all people who have supported this comparison.

End of the report