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Final report on APMP regional key comparison APMP.L-K6: Calibration of ball plate and hole plate

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Asia-Pacific Metrology Programme

APMP Regional Comparison (APMP.L-K6)

Calibration of ball plate and hole plate

Final Report

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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: toshiyaaki.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 Measurement Institute of Australia (NMI) 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
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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
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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, $\alpha = (11.5 \pm 1.0) \times 10^{-6} \text{ K}^{-1}$ at 20 °C.

Dimensions (mm):

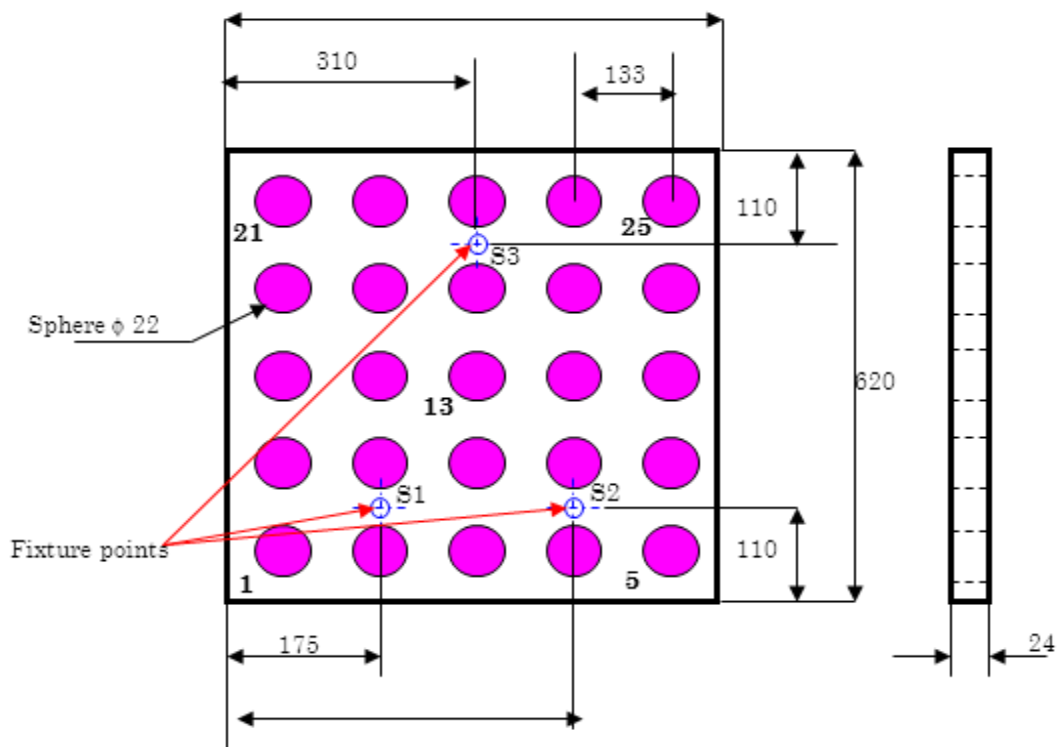


Fig. 3-1 Ball plate description

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: $\alpha = (0 \pm 0.5) \times 10^{-6} \text{ K}^{-1}$ 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):

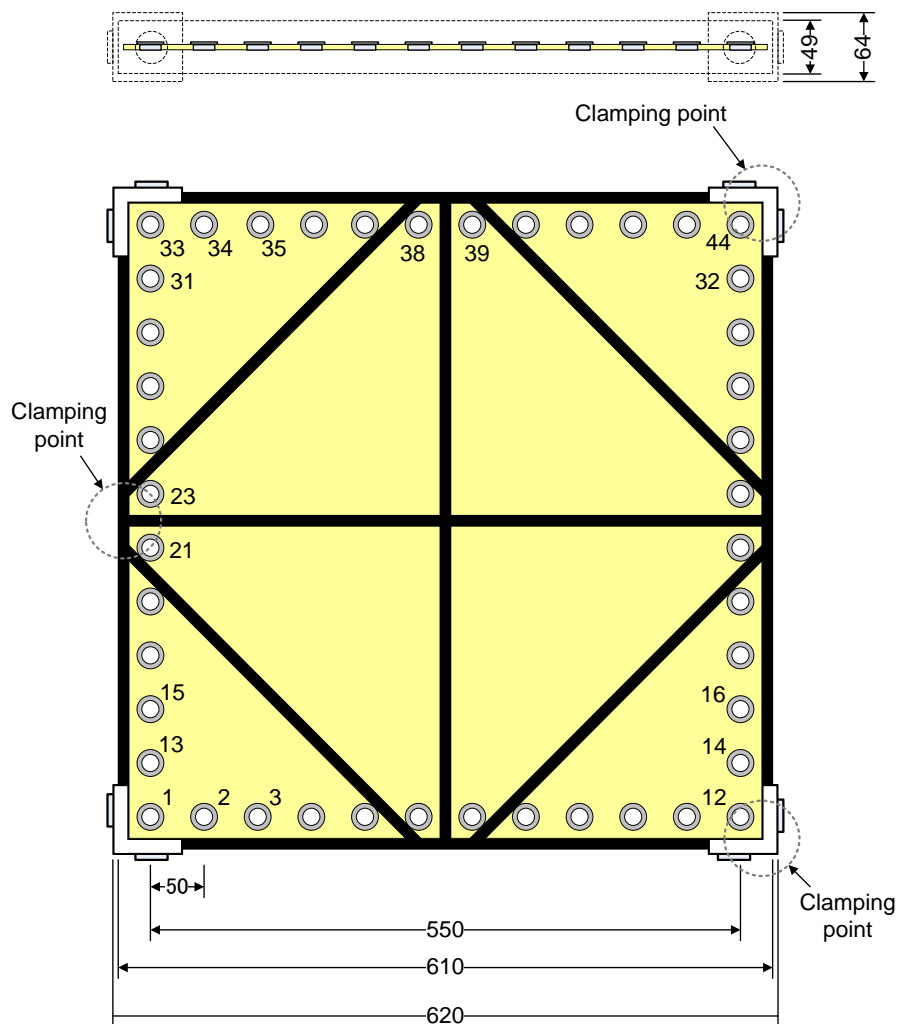


Fig. 3-2 Hole plate description



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

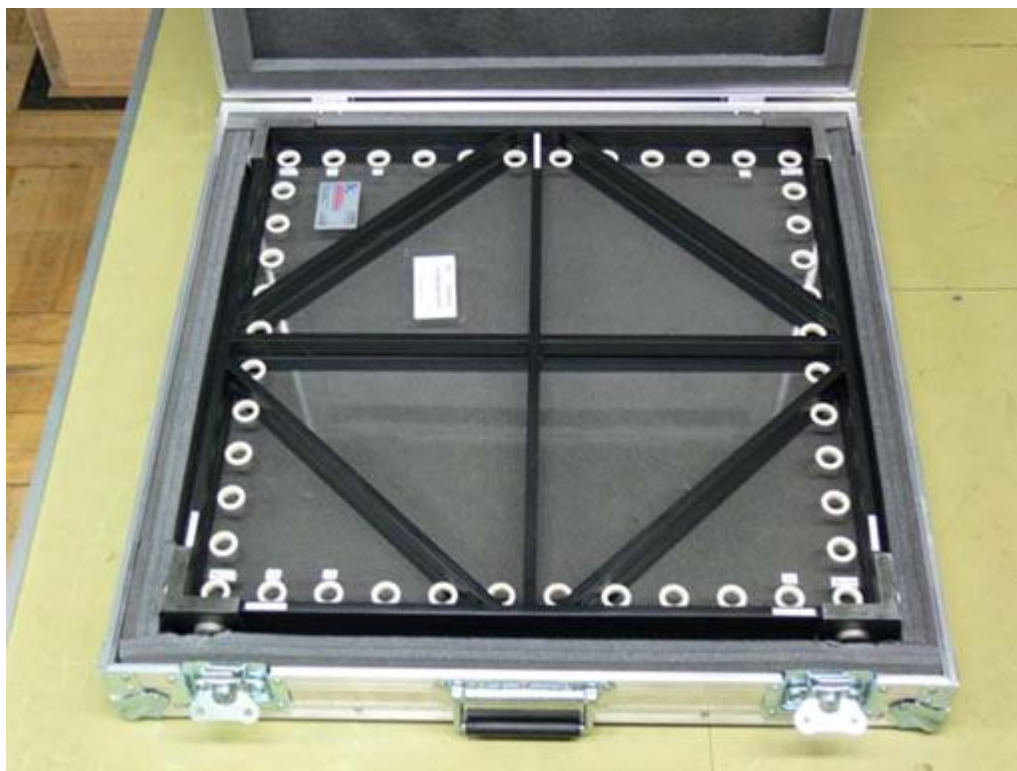


Fig. 3-4 The hole plate in the carrying case

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.

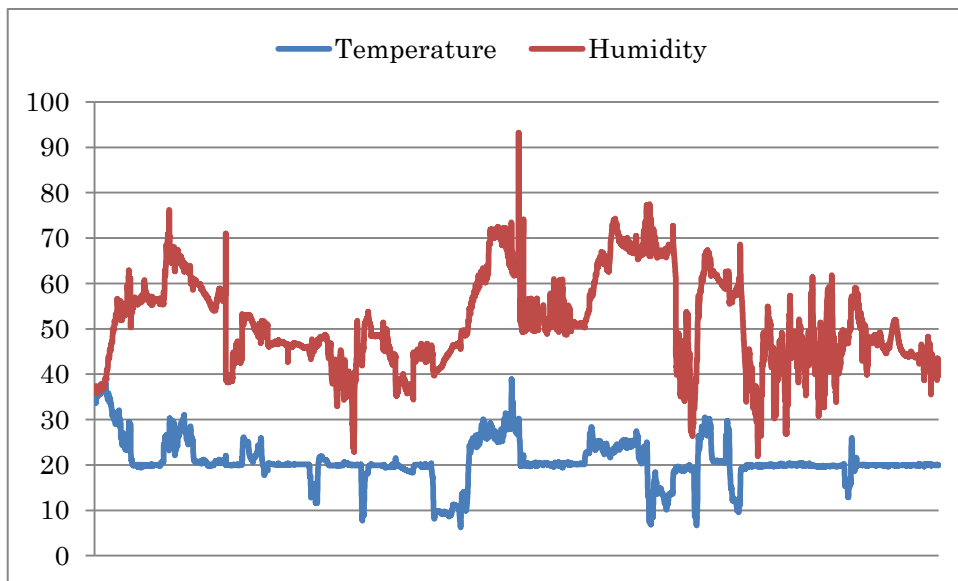


Fig. 3-5 The environmental condition of the ball plate during the comparison

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.

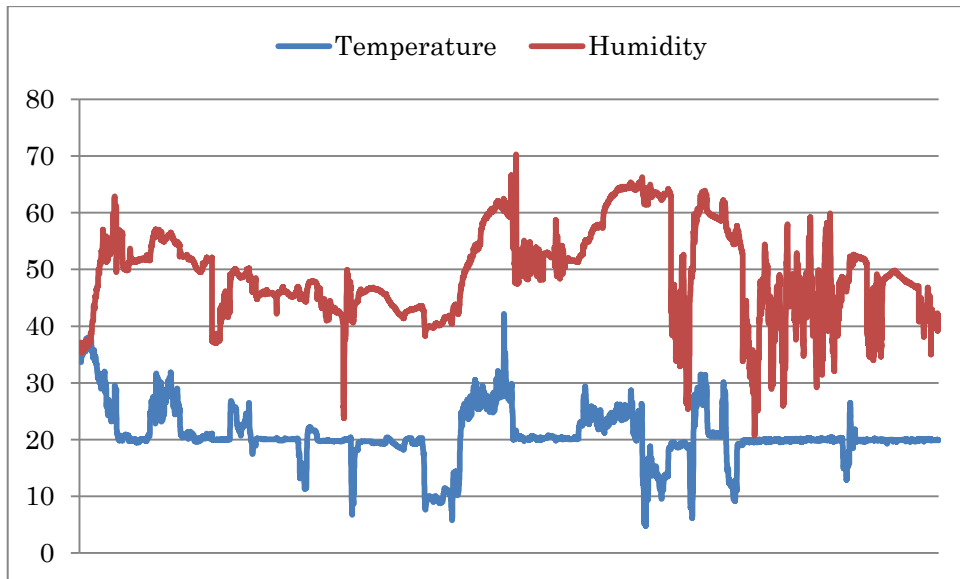


Fig. 3-6 The environment condition of the hole plate during the comparison

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.

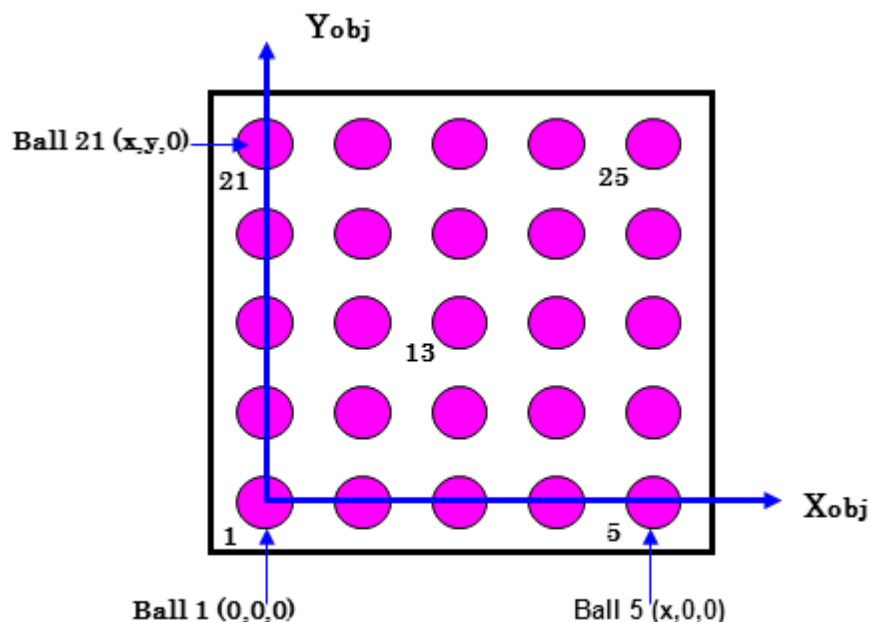


Fig. 4-1. Ball plate coordinate system

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.

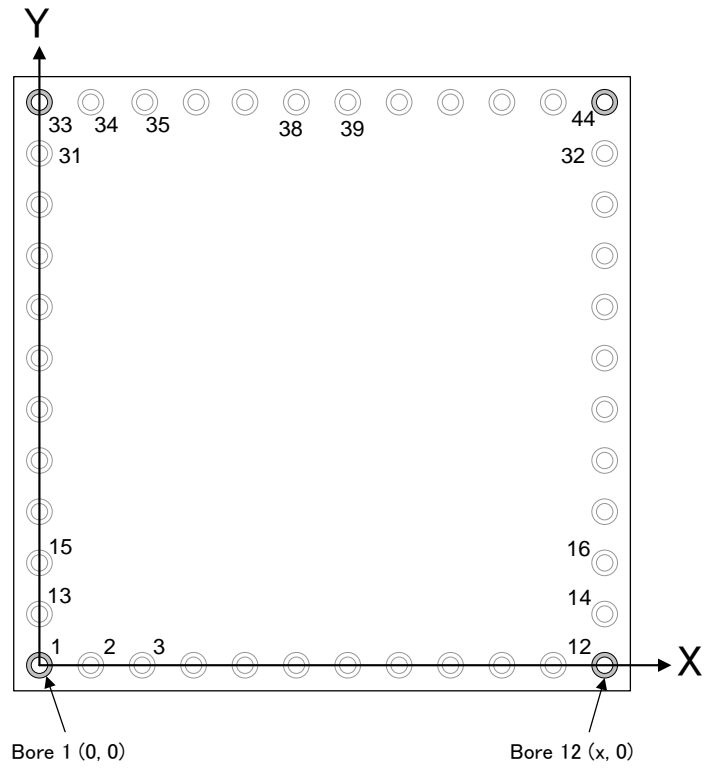


Fig. 4-2 Hole plate coordinate system

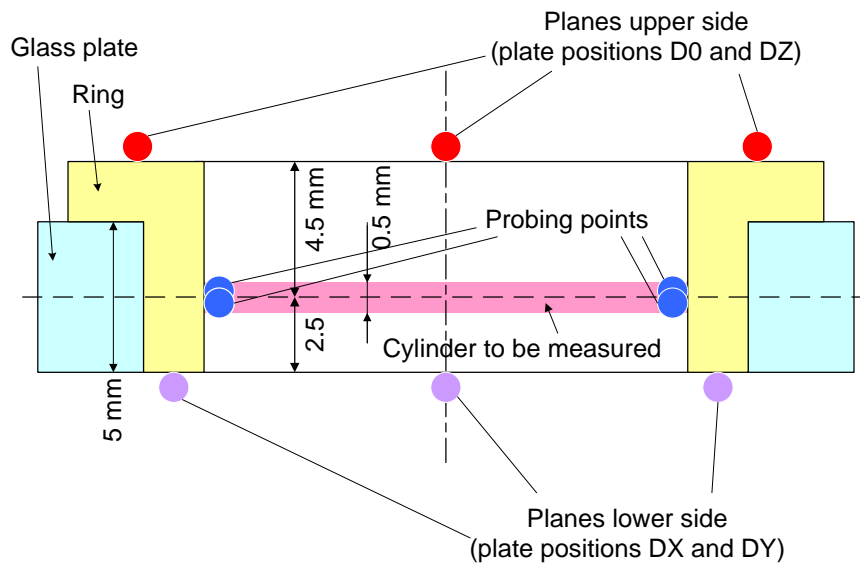


Fig. 4-3 Ring element of the hole plate

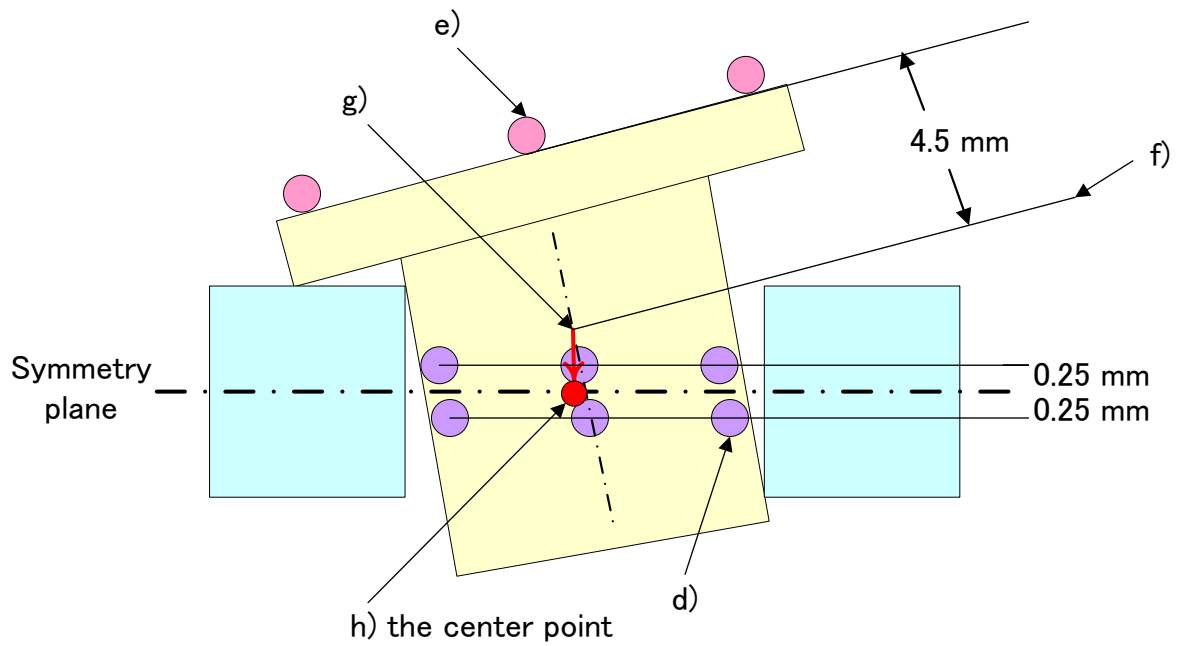


Fig. 4-4 An exaggerated image to explain the measurement procedure

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 $(20 \pm 0.3) ^\circ\text{C}$.

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-groove 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-groove base should be attached to point S3, with the groove 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)

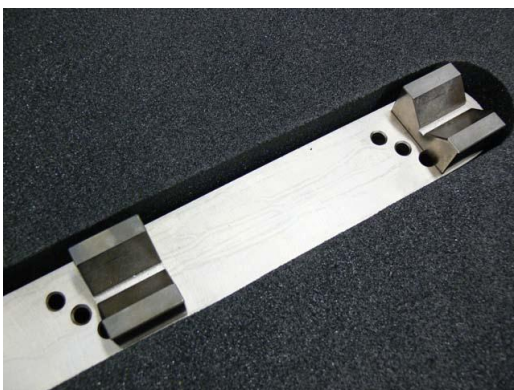


Fig. 4-8 Ball plate support (V-groove)



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).

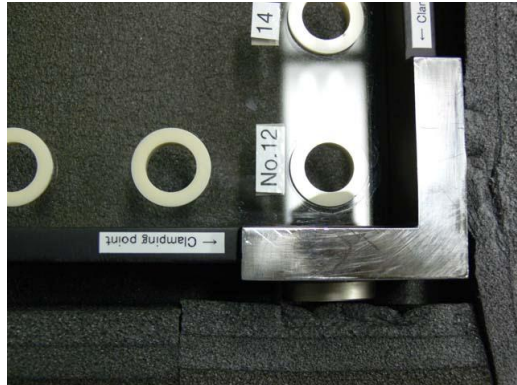


Fig. 4-9 Clamping point near hole 12

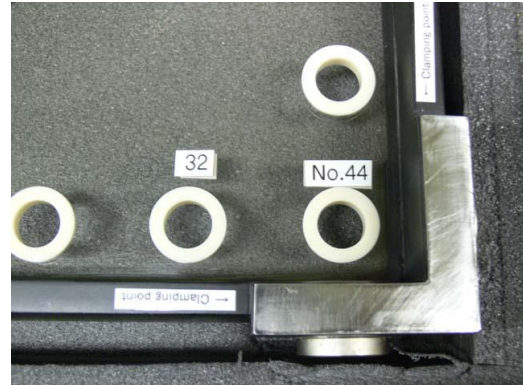


Fig. 4-10 Clamping point near hole 44

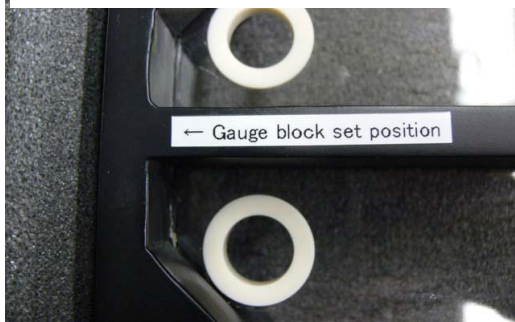


Fig. 4-11 Clamping point between hole 21 and 23

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	$\mu\text{m}^*\text{L}/\text{m}$
drift of temperature in CMM	K	$\mu\text{m}^*\text{L}/\text{m}$
deviation from linearity of the CMM's errors of position	μm	μm
uncertainty of the gauge block or step gauge length or laser interferometer	$\mu\text{m}^*\text{L}/\text{m}$	$\mu\text{m}^*\text{L}/\text{m}$
uncertainty of the length comparison (probing uncertainty)	μm	μm
uncertainty of the temperature difference during the length comparison	K	$\mu\text{m}^*\text{L}/\text{m}$
uncertainty of the thermal expansion coefficient	K^{-1}	$\mu\text{m}^*\text{L}/\text{m}$
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 $0.15\ \mu\text{m}$ 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.

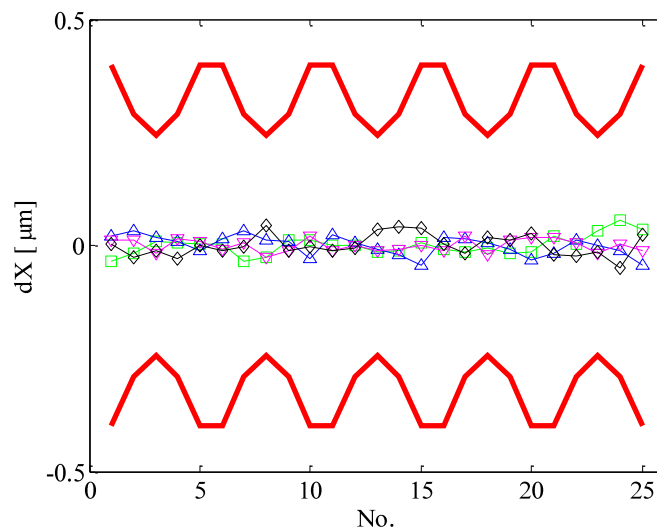


Fig. 7-1 Stability of the ball plate observed by the pilot (X direction)

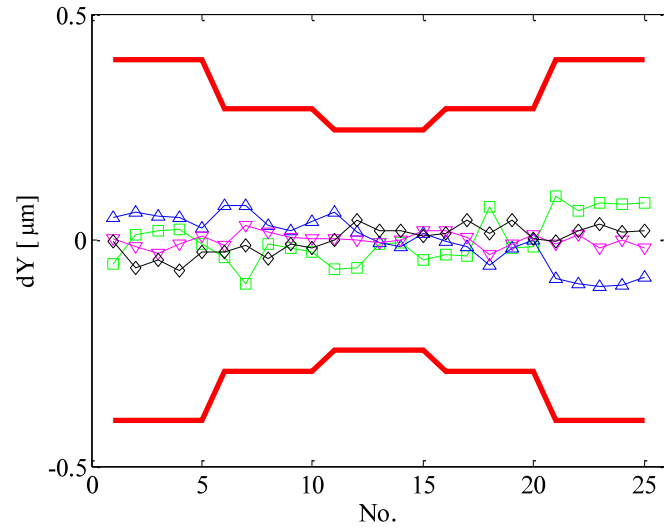


Fig. 7-2 Stability of the ball plate observed by the pilot (Y direction)

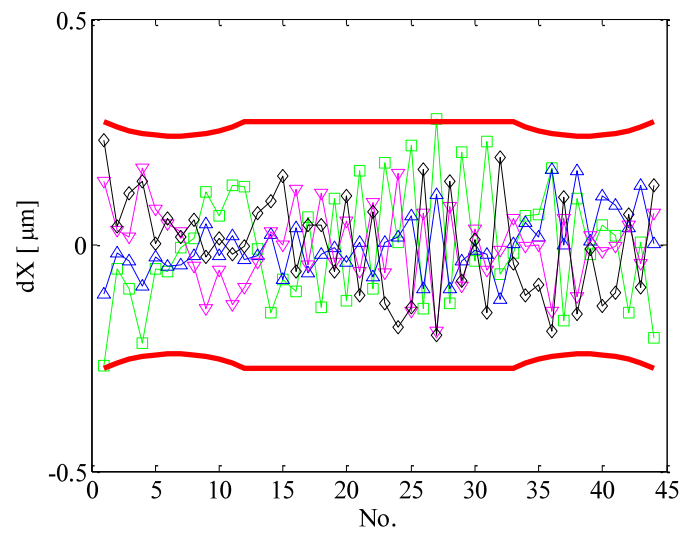


Fig. 7-3 Stability of the hole plate observed by the pilot (X direction)

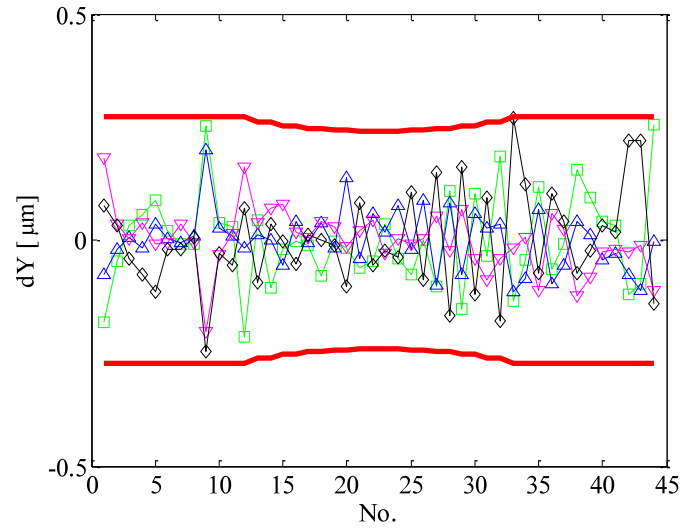


Fig. 7-4 Stability of the hole plate observed by the pilot (Y direction)

8 Measurement results

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

The gauges were actually delivered to Vietnam 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.

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:

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

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

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

No	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)	
	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

No	Nominal		NMIJ (H1)		KRISS (H2)		NIMT (H3)		NMIA (H4)		CSIR (H5)		NRC (H6)		MIKES (H7)		INMETRO (H8)		MSLNZ (H9)	
	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 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

$$\mathbf{O} = [\mathbf{R}_i x_{ij} + \mathbf{t}_i - x_{0j}],$$

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

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

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

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

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

$U_{\hat{x}_{ij}}$ is the expanded uncertainty ($k = 2$) of the j -th ball/hole of the i -th participant after transformation. Since the rotation matrix \mathbf{R}_i and the translation matrix \mathbf{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 \mathbf{x}_{0j} and its uncertainty \mathbf{U}_{0j} are derived as follows

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

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

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

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

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

$$E_n = \frac{\|\mathbf{x}_i - \mathbf{x}_0\|}{u(\|\mathbf{x}_i - \mathbf{x}_0\|)}$$

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

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

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.

$$\Psi_0 = \begin{bmatrix} U_{x_{0j}}^2 & 0 \\ 0 & U_{y_{0j}}^2 \end{bmatrix}$$

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

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

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

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.

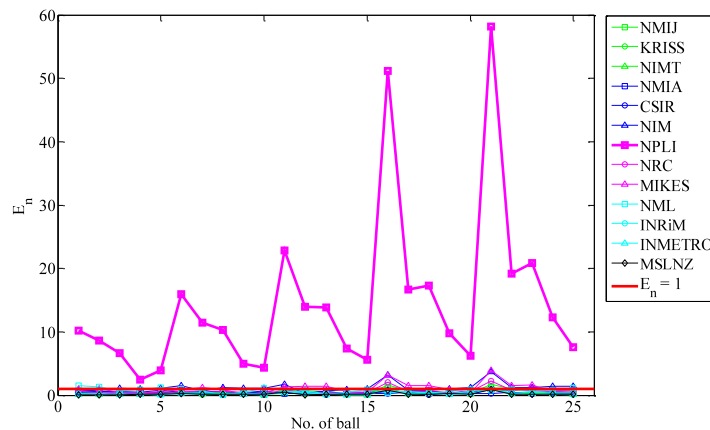


Fig. 10-1 E_n numbers calculated from all participants results

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.

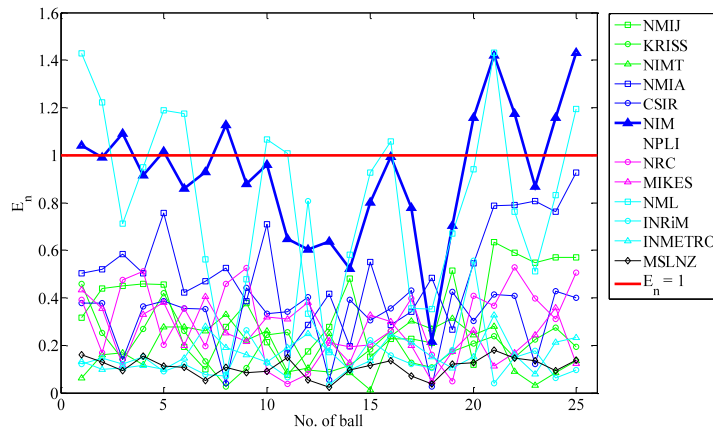


Fig. 10-2 E_n numbers calculated except NPLI

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.

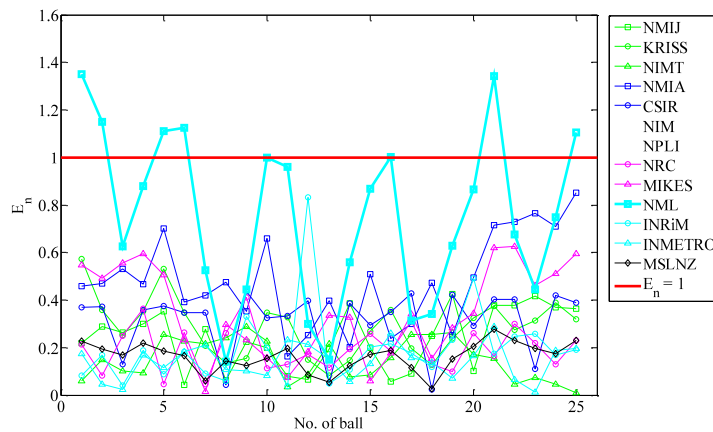


Fig. 10-3 E_n numbers calculated except NPLI and NIM

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.

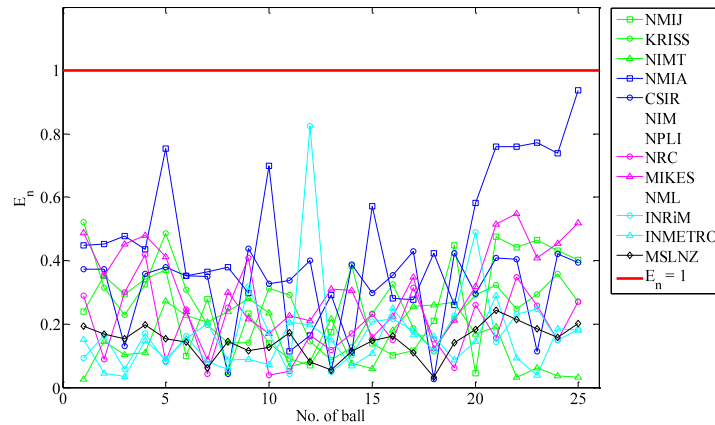


Fig. 10-4 E_n numbers calculated except NPLI, NIM, and NML

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.

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

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

No	Nominal		KCRV		Uncertainty	
	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 10-3 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: KRIS, 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.

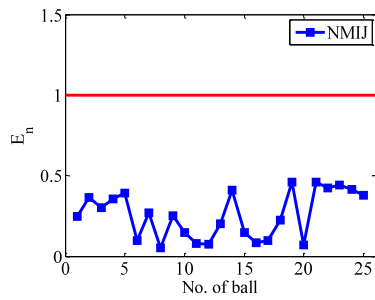


Fig. 10-5 E_n of NMIJ (Lab B1)

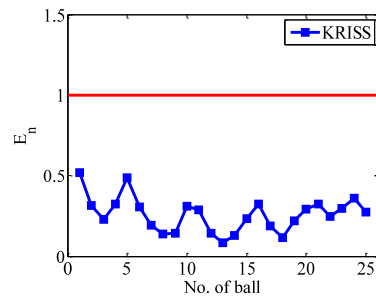


Fig. 10-6 E_n of KRISS (Lab B2)

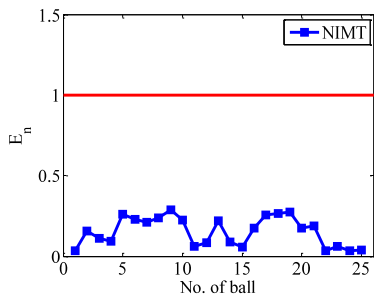


Fig. 10-7 E_n of NIMT (Lab B3)

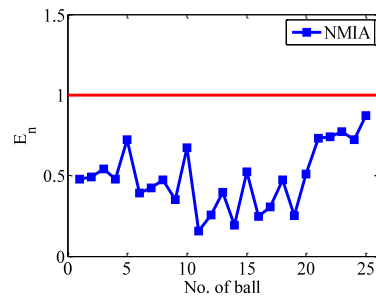


Fig. 10-8 E_n of NMIA (Lab B4)

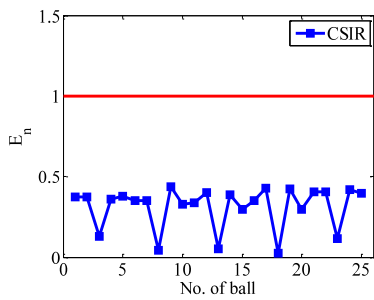


Fig. 10-9 E_n of CSIR (Lab B5)

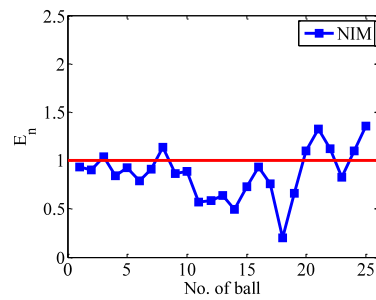


Fig. 10-10 E_n of NIM (Lab B6)

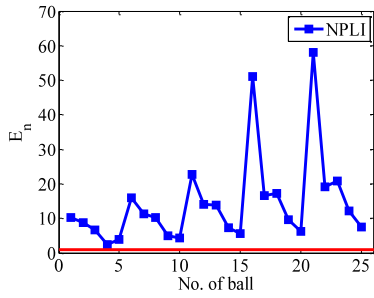


Fig. 10-11 E_n of NPLI (Lab B7)

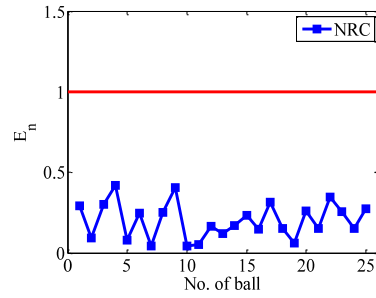


Fig. 10-12 E_n of NRC (Lab B8)

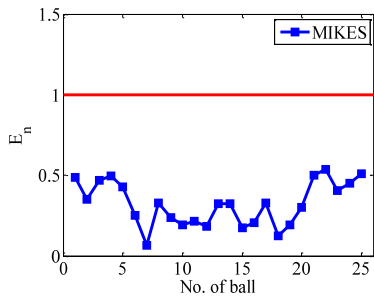


Fig. 10-13 E_n of MIKES (Lab B9)

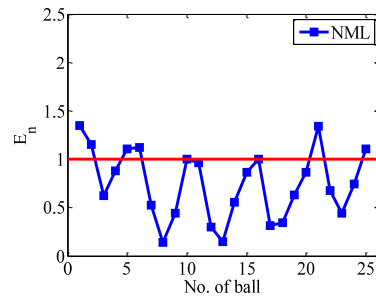


Fig. 10-14 E_n of NML (Lab B10)

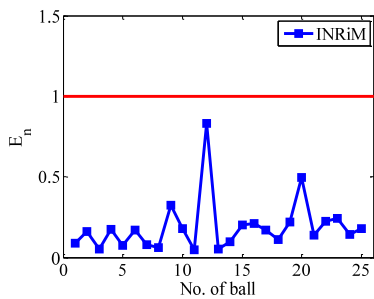


Fig. 10-15 E_n of INRiM (Lab B11)

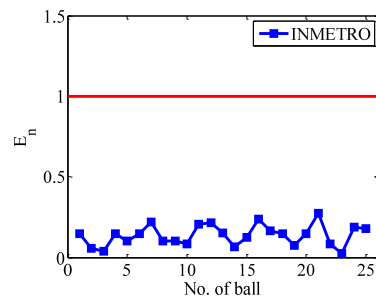


Fig. 10-16 E_n of INMETRO (Lab B12)

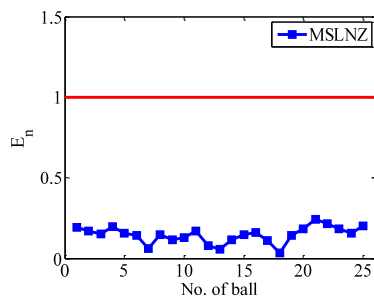


Fig. 10-17 E_n of MSLNZ (Lab B13)

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.

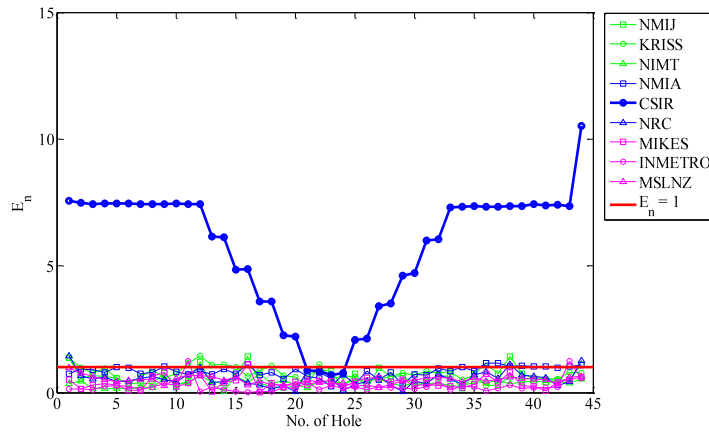


Fig. 10-18 E_n numbers calculated from all participants results

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.

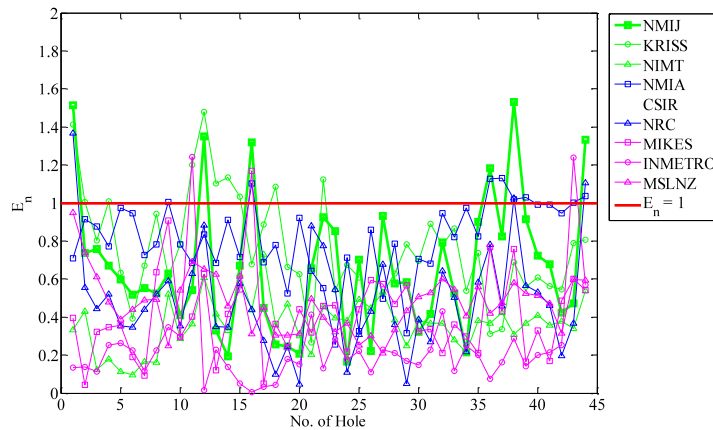


Fig. 10-19 E_n numbers calculated except CSIR

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.

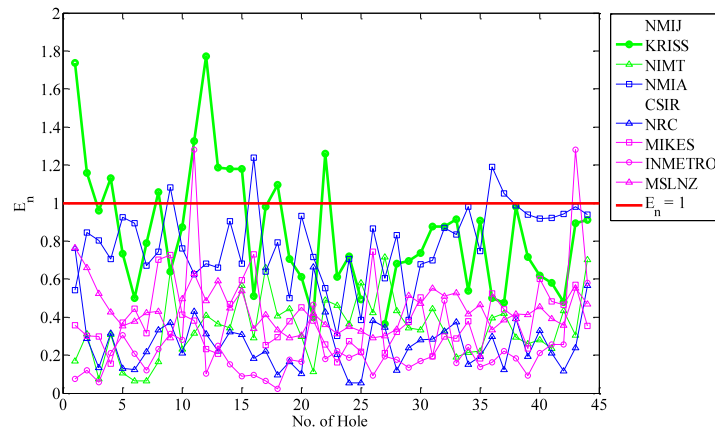


Fig. 10-20 E_n numbers calculated except CSIR and NMIJ

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.

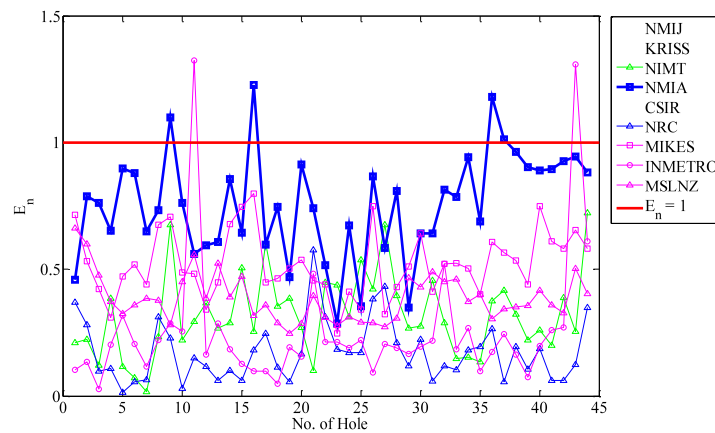


Fig. 10-21 E_n numbers calculated except CSIR, NMIJ and KRISS

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.

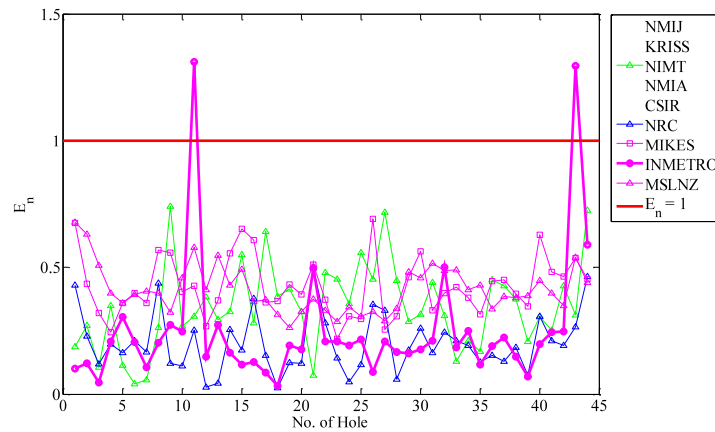


Fig. 10-22 E_n numbers calculated except CSIR, NMIJ, KRISS, and NMIA

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.

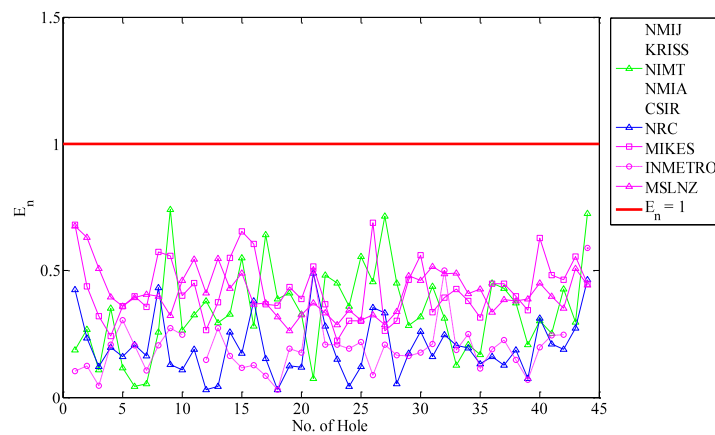


Fig. 10-23 E_n numbers calculated except CSIR, NMIJ, KRISS, NMIA, and No. 11 and 43 of INMETRO

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

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

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

No	Nominal		KCRV		Uncertainty	
	X	Y	X [mm]	Y [mm]	u_x [μ m]	u_y [μ m]
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 10-6 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: KRIS, 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.

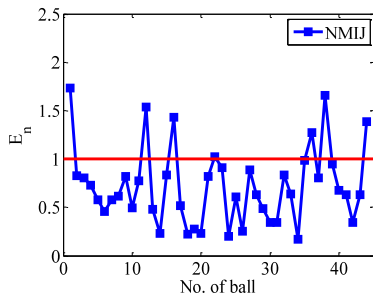


Fig. 10-24 E_n of NMIJ (Lab H1)

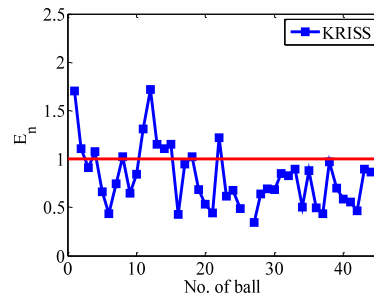


Fig. 10-25 E_n of KRISS (Lab H2)

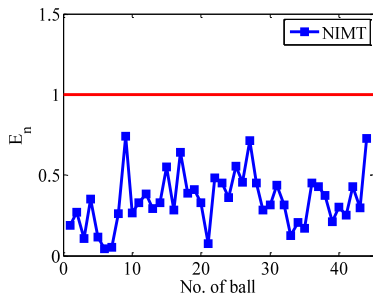


Fig. 10-26 E_n of NIMT (Lab H3)

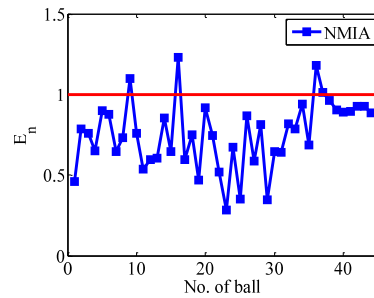


Fig. 10-27 E_n of NMIA (Lab H4)

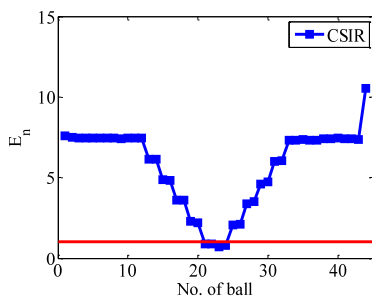


Fig. 10-28 E_n of CSIR (Lab H5)

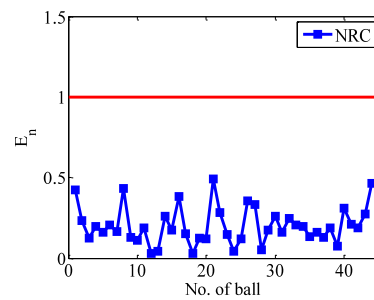


Fig. 10-29 E_n of NRC (Lab H6)

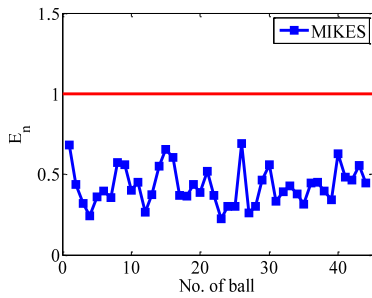


Fig. 10-30 E_n of MIKES (Lab H7)

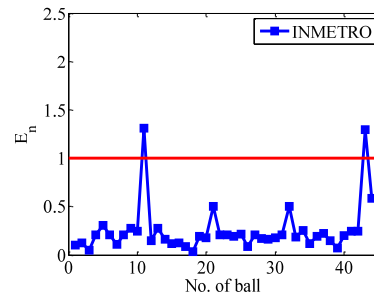


Fig. 10-30 E_n of INMETRO (Lab H8)

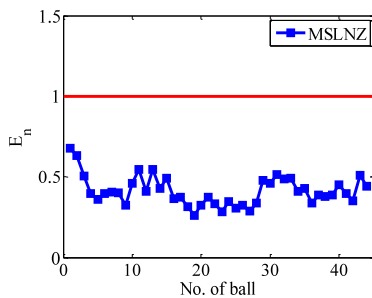


Fig. 10-31 E_n of MSLNZ (Lab H9)

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 specially 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