European Association of National Metrology Institutes

EURAMET Key Comparison L - K6

CMM 2-D Artifact: Ball Plate

Final Report

1 Introduction

The metrological equivalence of national measurement standards will be 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 RMOs are asked to organize Regional Key Comparisons to link the CCL KC to those NMIs that did not participate in the CCL KC.

At its meeting in 2002, the EURAMET TC Length committee decided to run such a Regional Key Comparison as a link to the KC CCL-K6. In 2003, PTB was identified as pilot and organizer.

The procedures outlined in this document cover the technical procedure to be followed during measurement of the artifacts. The procedure, which follows the guidelines established by the BIPM[1], is based on the existing technical protocol document for the key comparison on small gauge blocks[2], long gauge blocks[3], CMM 1-D artifacts[4], and CMM 2-D artifacts[5]. Some part of the text of this report is based on the APMP.L-K6 report, written by Toshiyuki Takatsuji (NMIJ).

I like to thank Toshiyuki Takatsuji and his NMIJ colleague Osamu Sato for providing me their MATLAB scripts, which originally were developed for analyzing APMP.L-K6.

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

[1] T.J. Quinn, Guidelines for key comparisons carried out by Consultative Committees, BIPM, Paris

[2] R. Thalmann, Calibration, of gauge blocks by interferometry - Instructions and technical protocols, OFMET, Wabern.

[3] A. Lewis, Calibration of long artefacts - Technical Protocol, NPL, Teddington.

[4] O. Jusko, Calibration of Ball Bars and a Step Gauge - Technical Protocol, PTB, Germany.

[5] M. Vielisid, Calibration of Coordinate Measuring Machine (CMM), Two-dimensional (2-D) Artifacts (Ball Plates & Bore Plates), Final report of KC CCL.L-K6

2 Organization

2.1 Participation

A first list of National Metrology Institutes (NMIs) considering participation was compiled in the EURAMET TC.

The participating laboratories should:

- Be able to calibrate a 420 mm steel ball plate (outer gauge), with 5x5 ceramic 22 mm in diameter balls and 83 mm pitch between ball centers. The centers span a 332 mm x 332 mm grid.

- Be able to demonstrate independent traceability to the realization of the meter.

After agreeing on a final version of this protocol, each nominated participant had to reconfirm its participation and approval of 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 and, eventually invite other possible participants.

By their declared intention to participate in this key comparison, the laboratories accepted the general instructions and the technical protocols written down in this document and to follow the procedures strictly.

Once the protocol and list of participants had been agreed, no change to the protocol or list of participants was allowed without prior agreement of all participants.

2.2 Participant addresses

No.	COUNTRY	CONTACT PERSON / ADDRESS
1	CZECH REPUBLIC CMI	Vit Zeleny Czech Metrology Institute (CMI) V botanice 4 150 72 Praha 5 Czech Republic tel. +420 257 288 387 fax. +420 257 328 077 vzeleny@cmi.cz
2	DENMARK CGM / IPL / DTU	Prof. Leonardo de Chiffre Manufacturing Engineering and Management Produktionstorvet DTU – Building 424 2800 Kgs. Lyngby Denmark tel. +45 4525 4760 fax. +45 4525 0190 ldc@ipl.dtu.dk
3	FINLAND TUT	Prof. Heikki Tikka Tampere University of Technology Institute of Production Engineering Korkeakoulunkatu 6 33720 Tampere Finland tel. +358-3-3115 2719 fax. heikki.tikka@pe.tut.fi
4	GERMANY (Pilot) PTB	Otto Jusko Department Coordinate Metrology Physikalisch-Technische Bundesanstalt (PTB) Bundesallee 100 38116 Braunschweig Germany Fon +49-531-592-5310 Fax +49-531-592-695310 Otto.Jusko@ptb.de
5	HUNGARY OMH	Edit Banreti National Office of Measures(OMH) Németvölgyi út 37-39 H-1124 Budapest XII Hungary tel. +36 1 458 59 97 fax. +36 1 458 59 27 banretie@mkeh.hu

6	IRELAND NML	Paul Turner National Metrology Laboratory Glasnevin IE-Dublin 9 Ireland paul.turner@nsai.ie
7	NETHERLANDS VSL	Rob Bergmans VSL Dutch Metrology Thisseweg 11 P.O. Box 654 2600 AR Delft The Netherlands Tel.: 31 15 269 15 00 Fax: 31 15 261 29 71 rbergmans@nmi.nl
8	POLAND GUM	Central Office of Measures (GUM) ul. Elektoralna 2 P.O. Box 10 PL-00 950 Warszawa Poland Tel: + 48 22 620 54 38 Fax: + 48 22 620 83 78 length@gum.gov.pl
9	PORTUGAL IPQ	Fernanda Saraiva Instituto Português da Qualidade Laboratório de Metrologia Rua António Gião, 2 PT-2829-513 Caparica Portugal Tel : +351 21 294 81 60 Fax :+351 21 264 81 88 fsaraiva@mail.ipq.pt
10	UNITED KINGDOM NPL	Andrew Lewis Centre for Basic, Thermal and Length Metrology National Physical Laboratory (NPL) Teddington ,Middlesex, TW11 0LW United Kingdom Tel: +44 20 8943 6124 Fax: +44 20 8943 2945 andrew.lewis@npl.co.uk

11	SWITZERLAND METAS	Dr. Ruedi Thalmann Federal Office of Metrology (METAS) Lindenweg 50 CH-3003 Bern-Wabern Switzerland Tel: + 41 31 32 33 385 Fax:+ 41 31 32 33 210 rudolf.thalmann@metas.ch
12	ITALY IMGC (INRIM)	Dr. Gian Bartolo Picotto Istituto Nazionale di Recerca Metrologica Strada delle Cacce, 91 10135 Torino Italy g.picotto@inrim.it

2.3 Form of comparison

The calibration suitability of the artifact was assessed by measurements at PTB prior to the start of the circulation of the artifacts. PTB acted as the pilot laboratory.

In the following section the timetable of the comparison is presented.

Each laboratory received the artifacts according to the pre-agreed timetable.

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

Each laboratory had six weeks for customs clearance (if applicable), measurement and shipment to the following participant from the moment it is received at customs in his country till the following participant receives it at customs. With its confirmation to participate, each laboratory had confirmed that it is capable to perform the measurements in the time allocated to it. It guaranteed that the standards arrived in the country of the next participant at the beginning of the next 6 week period.

If for some reasons, the measurement facility was not ready, the laboratory had 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. If possible the laboratory had be sent the artifacts at the end of the comparison.

2.4 Timetable

The timetable below shows the measurement schedule.

PTB additionally checked and measured the ball plate before and after the schedule.

Part.-#	NMI	Country	Period
1	TUT	Finland	May 2004
2	METAS	Switzerland	July 2004
3	CMI	Czech Republic	November 2004
4	OMH	Hungary	March 2005
5	CGM	Denmark	April 2005
6	NPL	United Kingdom	May 2005
7	EI	Ireland	July 2005
8	VSL	Netherlands	Sept 2005
9	PTB	Germany	October 2005
10	IPQ	Portugal	November 2005
11	IMGC (INRIM)	Italy	December 2005
12	GUM	Poland	January 2006

2.5 Handling of Artifacts

Upon reception, the laboratory had to confirm it to the pilot laboratory as well as to the sender laboratory by sending the form of Appendix A1. The artifact had to be examined immediately upon receipt. The condition of the artifact had to be noted in the form.

The artifact had be handled by authorized persons and stored in such a way as to prevent damage.

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

Before and after the measurements, the artifact had to be cleaned. It had to be ensured that the content of the package was complete before shipment.

2.6 Transport of Artifacts

It was of utmost importance that the artifact was transported in a manner in which they were not going to be lost, damaged or handled by unauthorized persons.

Packaging for the artifact was made suitably robust to protect the artifacts from being deformed or damaged during transit. Notices in the boxes stated handling instructions in case the boxes had to be opened at customs.

The artifact had to be sent via courier or delivery company and marked as ‘Fragile’.

The artifact had to be sent with enough time in advance as to have the following laboratory receive them at the nearest port or airport on the date that their period starts.

Until the first return of the ball plate to PTB (December 2004), the artifact was accompanied by an ATA – Carnet. Although this only was needed by non EU participants, its presence should be checked.

Transportation and insurance to the following participant was each laboratory’s responsibility and cost. Each participating laboratory had to cover the costs for its own measurements, transportation and any customs charges upon receipt as well as for any damages that may have occurred within its country. The overall costs for the organization and for the devices were covered by the organizing pilot laboratory. The pilot laboratory had no insurance for any loss or damage of the standards during transportation.

3 Description of the Standard

3.1 Artifacts

The measurement artifact was the following:

Ball Plate

Make: KOBA

Serial Number:

Material: Steel frame with ceramic balls.

Nominal thermal expansion coefficient (as stated by the manufacturer):

$\alpha = 11.5 \times 10^{-6}\ K^{-1}$ at 20 °C.

Dimensions (mm):

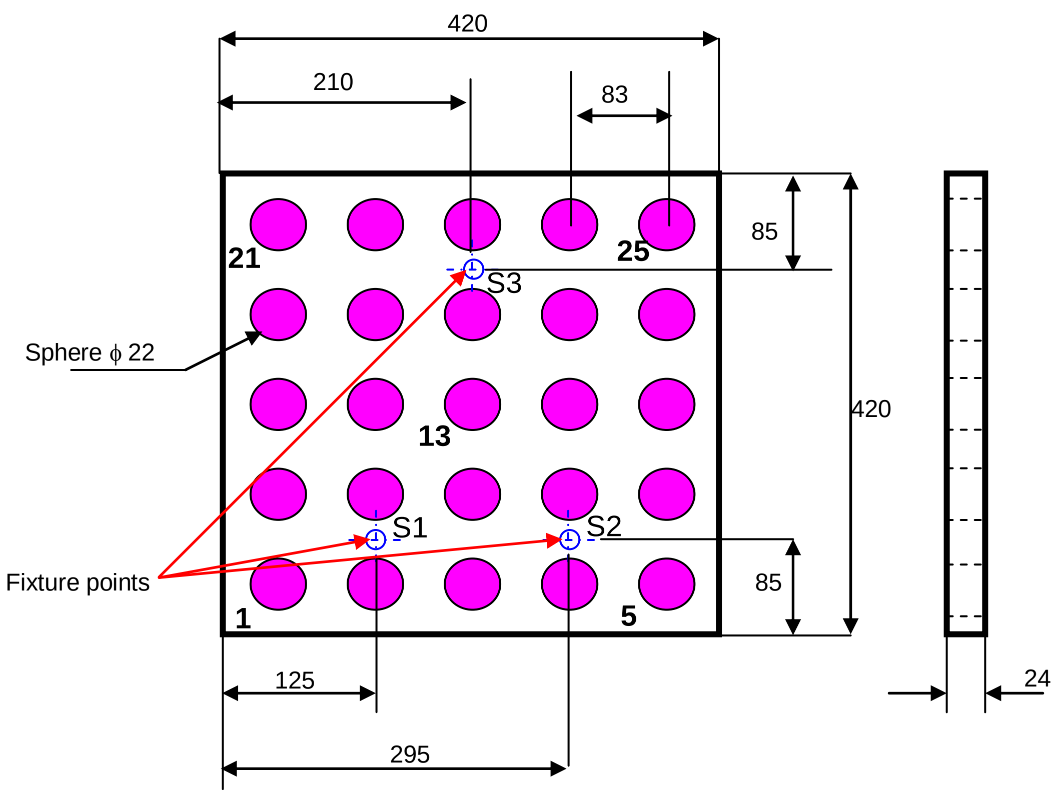

Figure 3-1. Ball plate description

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 had to be transferred to the ball and bore 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

4.2.1 *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 was 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-Y-co-ordinates of each ball center with respect to the origin of object coordinate system (Figure2) with the plate lying horizontally and fixed as described in section 4.3. Optionally the Z-coordinates could be reported, but they were not intended be the base of MRA/CMC – relevant analysis.

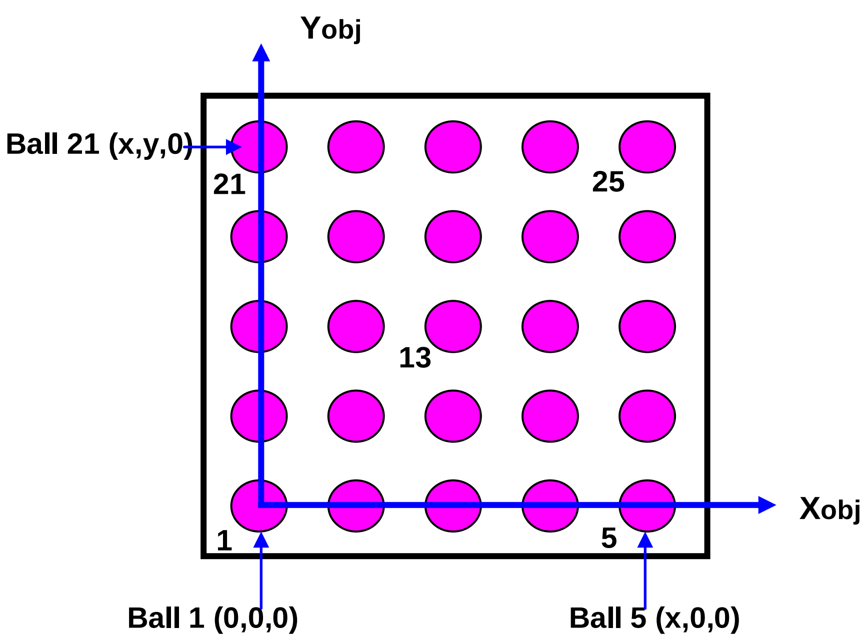

Figure 4-1. Ball plate coordinate system

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.

4.3 Measurement instructions

Each laboratory was 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 artifacts had to be inspected for damage. Special attention should have been paid to the measurement surfaces and balls. Any scratches or damages had to be documented.

Before measurement, the plate and support had to be cleaned. The balls had 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 were three hemispherical supports which could be screwed to tapped holes in the plate. The proposed holes were marked by pilot.

No other measurements had to be attempted by the participants and the artifacts had not be used for any purpose other than described in this document.

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

5 Measurement uncertainty

The uncertainty of measurement had to be estimated according to the *ISO Guide to the Expression of Uncertainty in Measurement*. The following table quotes the usual measurement uncertainty sources for ball plates. Additional sources could be added at the end of the table according to each laboratory's set-up, equipment, procedures and uncertainty estimation method, but it was expected that these additional sources would not dominate the uncertainty budget.

Measurement uncertainty sources if employing *gauge blocks,* step gauges or laser interferometer for the length comparison on *calibration plates*

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 had to 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 results had to be reported with forms circulated with the Technical Protocol.

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

$$u_c(l) = (a^2 + b^2 \cdot l^2)^{1/2} \quad ,$$

where *a* and *b* are real numbers, *l* is the length in mm and $u_c(l)$ is in μm.

7 Measurement results

This chapter shows the reported measurement results as reported by the participants. Only X and Y coordinates are displayed and further analyzed.

For each ball the average coordinate of all results was calculated. From these the center of gravity of the coordinates was calculated by summing up all xmean- and ymean-coordinate values and dividing by the number of spheres 25. This was done in order to align the format of the data to the MATLAB script used for subsequent evaluation (see section 9.1).

Table 7-1 shows the reported results.

Ball-#	PTB (D)		METAS (CH)		CMI (CZ)		TUT (FIN)		GUM (PL)		EI (IRL)		VSL (NL)	
	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
1	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
2	83,0034	0,0018	83,0036	0,0016	83,0033	0,0016	83,0033	0,0016	83,0032	0,0017	83,0038	0,0016	83,0036	0,0017
3	166,0050	0,0028	166,0050	0,0026	166,0048	0,0027	166,0047	0,0026	166,0043	0,0027	166,0052	0,0026	166,0049	0,0028
4	249,0059	0,0019	249,0057	0,0019	249,0053	0,0020	249,0056	0,0016	249,0049	0,0020	249,0057	0,0019	249,0055	0,0020
5	332,0061	0,0000	332,0060	0,0000	332,0054	0,0000	332,0058	0,0000	332,0047	0,0000	332,0063	0,0000	332,0058	0,0000
6	0,0062	83,0025	0,0064	83,0025	0,0061	83,0025	0,0062	83,0028	0,0062	83,0026	0,0062	83,0027	0,0062	83,0028
7	83,0057	83,0017	83,0061	83,0017	83,0056	83,0017	83,0057	83,0021	83,0055	83,0018	83,0062	83,0019	83,0059	83,0021
8	166,0074	83,0015	166,0076	83,0015	166,0070	83,0015	166,0073	83,0018	166,0068	83,0017	166,0078	83,0017	166,0073	83,0018
9	249,0101	83,0003	249,0102	83,0003	249,0096	83,0004	249,0099	83,0005	249,0092	83,0006	249,0102	83,0006	249,0098	83,0007
10	332,0094	83,0007	332,0095	83,0007	332,0090	83,0007	332,0092	83,0007	332,0082	83,0008	332,0098	83,0010	332,0092	83,0009
11	0,0080	166,0032	0,0082	166,0030	0,0078	166,0031	0,0079	166,0033	0,0080	166,0032	0,0082	166,0034	0,0080	166,0033
12	83,0083	166,0023	83,0084	166,0025	83,0080	166,0026	83,0081	166,0028	83,0079	166,0024	83,0086	166,0029	83,0084	166,0027
13	166,0088	166,0015	166,0090	166,0015	166,0085	166,0016	166,0087	166,0017	166,0082	166,0016	166,0091	166,0018	166,0088	166,0017
14	249,0113	166,0013	249,0115	166,0012	249,0107	166,0014	249,0111	166,0012	249,0104	166,0013	249,0116	166,0016	249,0111	166,0015
15	332,0102	166,0017	332,0104	166,0015	332,0097	166,0015	332,0100	166,0015	332,0090	166,0016	332,0108	166,0019	332,0101	166,0016
16	0,0083	249,0047	0,0085	249,0046	0,0082	249,0046	0,0083	249,0048	0,0083	249,0046	0,0085	249,0051	0,0084	249,0047
17	83,0103	249,0036	83,0105	249,0037	83,0101	249,0039	83,0102	249,0039	83,0100	249,0036	83,0107	249,0040	83,0105	249,0037
18	166,0106	249,0026	166,0108	249,0026	166,0102	249,0027	166,0106	249,0027	166,0100	249,0025	166,0110	249,0030	166,0107	249,0027
19	249,0122	249,0022	249,0124	249,0022	249,0116	249,0024	249,0120	249,0023	249,0113	249,0022	249,0124	249,0027	249,0121	249,0023
20	332,0117	249,0024	332,0119	249,0023	332,0110	249,0024	332,0116	249,0023	332,0105	249,0025	332,0122	249,0029	332,0116	249,0024
21	0,0101	332,0037	0,0104	332,0037	0,0101	332,0037	0,0101	332,0039	0,0102	332,0036	0,0103	332,0042	0,0102	332,0038
22	83,0126	332,0018	83,0129	332,0017	83,0124	332,0018	83,0125	332,0018	83,0121	332,0016	83,0130	332,0023	83,0128	332,0019
23	166,0123	332,0011	166,0125	332,0010	166,0119	332,0011	166,0121	332,0011	166,0115	332,0010	166,0125	332,0015	166,0123	332,0012
24	249,0120	332,0005	249,0122	332,0003	249,0115	332,0003	249,0118	332,0003	249,0113	332,0003	249,0123	332,0009	249,0120	332,0004
25	332,0119	332,0009	332,0121	332,0007	332,0114	332,0008	332,0117	332,0006	332,0106	332,0009	332,0124	332,0013	332,0118	332,0009

OMH (H)		CGM (DK)		IPQ (P)		NPL (UK)			
X	Y	X	Y	X	Y	X	Y	xmean	ymean
0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
83,0041	0,0016	83,0035	0,0017	83,0035	0,0017	83,0034	0,0016	83,0035	0,0017
166,0047	0,0027	166,0047	0,0027	166,0049	0,0027	166,0048	0,0027	166,0048	0,0027
249,0048	0,0019	249,0054	0,0027	249,0057	0,0019	249,0056	0,0020	249,0055	0,0020
332,0056	0,0000	332,0054	0,0000	332,0060	0,0000	332,0057	0,0000	332,0057	0,0000
0,0062	83,0026	0,0062	83,0025	0,0061	83,0024	0,0064	83,0025	0,0062	83,0026
83,0064	83,0018	83,0058	83,0018	83,0058	83,0017	83,0059	83,0018	83,0059	83,0018
166,0072	83,0016	166,0072	83,0017	166,0073	83,0015	166,0074	83,0015	166,0073	83,0016
249,0091	83,0005	249,0097	83,0005	249,0099	83,0004	249,0100	83,0004	249,0098	83,0005
332,0091	83,0009	332,0090	83,0008	332,0095	83,0007	332,0094	83,0007	332,0092	83,0008
0,0080	166,0026	0,0080	166,0030	0,0079	166,0031	0,0082	166,0031	0,0080	166,0031
83,0088	166,0020	83,0081	166,0025	83,0082	166,0027	83,0084	166,0024	83,0083	166,0025
166,0086	166,0011	166,0086	166,0016	166,0087	166,0018	166,0089	166,0015	166,0087	166,0016
249,0104	166,0008	249,0109	166,0013	249,0112	166,0015	249,0114	166,0012	249,0110	166,0013
332,0098	166,0011	332,0098	166,0015	332,0103	166,0017	332,0102	166,0014	332,0100	166,0015
0,0083	249,0036	0,0082	249,0045	0,0081	249,0050	0,0086	249,0045	0,0083	249,0046
83,0109	249,0027	83,0101	249,0035	83,0103	249,0041	83,0105	249,0035	83,0104	249,0037
166,0104	249,0016	166,0103	249,0025	166,0105	249,0031	166,0108	249,0025	166,0105	249,0026
249,0112	249,0012	249,0118	249,0022	249,0121	249,0027	249,0123	249,0021	249,0119	249,0022
332,0114	249,0013	332,0113	249,0023	332,0118	249,0028	332,0117	249,0022	332,0115	249,0023
0,0101	332,0028	0,0100	332,0035	0,0100	332,0039	0,0104	332,0036	0,0102	332,0037
83,0132	332,0009	83,0124	332,0015	83,0125	332,0020	83,0127	332,0016	83,0126	332,0017
166,0121	332,0001	166,0119	332,0008	166,0121	332,0013	166,0123	332,0008	166,0121	332,0010
249,0111	331,9994	249,0117	332,0003	249,0119	332,0007	249,0120	332,0002	249,0118	332,0003
332,0115	331,9999	332,0115	332,0007	332,0118	332,0011	332,0120	332,0005	332,0117	332,0007

center of gravity = 166,0086 166,0019

Table 7-1 : Results as reported by the participants and calculated mean coordinates and center of gravity

8 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 had to be stated as combined standard uncertainty with no coverage factor applied (1 σ). 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. Six participants reported their uncertainties in this form, while four participants reported in a linear combination form.

Measurement uncertainties for the ball plate reported by the participants are listed in Table 8-1. Not all participants reported the uncertainty Q[a, b] format. VSL reported the uncertainty as a table with uncertainties on the coordinates of each ball. Due to the VSL measuring method, which is based on multilateration, the uncertainty does not only depend on the length l but also on the amount of neighbours for a given ball.

NMI	**Standard uncertainty**
PTB	Q[0.2 , 0.35 × 10^{-6} × l]
METAS	0.25 + 0.398 × 10^{-6} × l
CMI	Q[0.35, 0.5 × 10^{-6} × l]
TUT	0.412 + 0.633 × 10^{-6} × l
GUM	Q[0.4, 0.8 × 10^{-6} × l]
EI	Q[0.38, 0.92 × 10^{-6} × l]
NMI-VSL	Tabulated (*)
OMH	Q[0.45, 1 × 10^{-6} × l]
CGM	0.8 µm + 1.1 × 10^{-6} × l
IPQ	0.7 µm + 0.25 × 10^{-6} × l
NPL	Q[0.22, 0.46 × 10^{-6} × l]

Table 8-1 : Measurement uncertainty as reported by the participants. (*) For VSL see next Table and note section 9.2.

	VSL (NL)	
Ball-#	X	Y
1	0.000	0.000
2	0.099	0.071
3	0.118	0.095
4	0.138	0.111
5	0.169	0.000
6	0.071	0.129
7	0.087	0.089
8	0.108	0.078
9	0.128	0.081
10	0.157	0.088
11	0.095	0.101
12	0.092	0.094
13	0.102	0.085
14	0.123	0.079
15	0.152	0.082
16	0.111	0.094
17	0.100	0.089
18	0.106	0.078
19	0.124	0.081
20	0.155	0.088
21	0.129	0.101
22	0.114	0.071
23	0.118	0.095
24	0.134	0.111
25	0.166	0.129

Table 8-2 : Reported measurement uncertainty of VSL in µm

9 Harmonization of the results

9.1 Shift to the centre of gravity

Although it originally was agreed to report the results with reference to ball #1, it was decided to shift all reported coordinates to the centre of gravity (see Table 7-1). The shifted coordinates are shown in Table 9-1. This step was needed for the application of Osamu Sato's MATLAB routine.

9.2 Rotation and final shifting

As explained in 10.2 all results were corrected for rotation and re-shifted to the centre of gravity. The resulting data is shown in Table 10-1. There are only small differences to Table 9-1.

9.3 Re-calculation of the uncertainty

To prepare the uncertainty declarations for application of Osamu Sato's MATLAB routine, all uncertainties were transformed to the form:

$$u_{l_i} = \sqrt{\left(a^2 + b^2 \times \ l_i{}^2\right)} \text{ where: } l_i = \sqrt{x_i^2 + y_i^2}$$

These are the uncertainties of the x and y-coordinates of the i-th ball and a,b are the parameters of uncertainty declaration of the form Q[a,b]. This procedure differs slightly from the APMP analysis, where the x and y coordinates were treated separately for the uncertainty calculation.

Table 9-2 shows the harmonized uncertainties for each participant and for the shifted coordinates.

Please note that the shifting process may lead to a light over-estimation of all uncertainties.

For VSL the reported uncertainty was replaced by the formula from the CCL.K-6 report:

$u_c(l) = \sqrt{(0.16^2 + (0.00047 \times l)^2} \,\mu\text{m}$, l: measurement length in metre

because the MATLAB routines do not run with zero uncertainties.

This simplification of VSL's uncertainties by a fitted quadratic term leads to significant over-estimation of the real uncertainty.

So this would raise the En values, but they would still remain below 1. Also the reference value will be a bit closer to the VSL value when calculated with the 30% lower uncertainty.

	PTB (D)		METAS (CH)		CMI (CZ)		TUT (FIN)		GUM (PL)		EI (IRL)	
Ball-#	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
1	-166.0086	-166.0019	-166.0086	-166.0019	-166.0086	-166.0019	-166.0086	-166.0019	-166.0086	-166.0019	-166.0086	-166.0019
2	-83.0052	-166.0001	-83.0050	-166.0003	-83.0053	-166.0003	-83.0053	-166.0003	-83.0054	-166.0002	-83.0048	-166.0003
3	-0.0036	-165.9991	-0.0036	-165.9993	-0.0038	-165.9992	-0.0039	-165.9993	-0.0043	-165.9992	-0.0034	-165.9993
4	82.9973	-166.0000	82.9971	-166.0000	82.9967	-165.9999	82.9969	-166.0003	82.9963	-165.9999	82.9971	-166.0000
5	165.9975	-166.0019	165.9974	-166.0019	165.9968	-166.0019	165.9971	-166.0019	165.9961	-166.0019	165.9977	-166.0019
6	-166.0024	-82.9994	-166.0022	-82.9994	-166.0025	-82.9994	-166.0025	-82.9991	-166.0024	-82.9993	-166.0024	-82.9992
7	-83.0029	-83.0002	-83.0025	-83.0002	-83.0030	-83.0002	-83.0029	-82.9998	-83.0031	-83.0001	-83.0024	-83.0000
8	-0.0012	-83.0004	-0.0010	-83.0004	-0.0016	-83.0004	-0.0013	-83.0001	-0.0018	-83.0002	-0.0008	-83.0002
9	83.0015	-83.0016	83.0016	-83.0016	83.0010	-83.0015	83.0013	-83.0014	83.0006	-83.0013	83.0016	-83.0013
10	166.0008	-83.0012	166.0009	-83.0012	166.0004	-83.0012	166.0006	-83.0012	165.9996	-83.0011	166.0012	-83.0009
11	-166.0006	0.0013	-166.0004	0.0011	-166.0008	0.0012	-166.0007	0.0014	-166.0006	0.0013	-166.0004	0.0015
12	-83.0003	0.0004	-83.0002	0.0006	-83.0006	0.0007	-83.0006	0.0009	-83.0007	0.0005	-83.0000	0.0010
13	0.0002	-0.0004	0.0004	-0.0004	-0.0001	-0.0003	0.0001	-0.0002	-0.0004	-0.0003	0.0005	-0.0001
14	83.0027	-0.0006	83.0029	-0.0007	83.0021	-0.0005	83.0024	-0.0007	83.0018	-0.0006	83.0030	-0.0003
15	166.0016	-0.0002	166.0018	-0.0004	166.0011	-0.0004	166.0014	-0.0004	166.0004	-0.0003	166.0022	0.0000
16	-166.0003	83.0028	-166.0001	83.0027	-166.0004	83.0027	-166.0003	83.0029	-166.0003	83.0027	-166.0001	83.0032
17	-82.9983	83.0017	-82.9981	83.0018	-82.9985	83.0020	-82.9984	83.0020	-82.9986	83.0017	-82.9979	83.0021
18	0.0020	83.0007	0.0022	83.0007	0.0016	83.0008	0.0019	83.0008	0.0014	83.0006	0.0024	83.0011
19	83.0036	83.0003	83.0038	83.0003	83.0030	83.0005	83.0033	83.0004	83.0027	83.0003	83.0038	83.0008
20	166.0031	83.0005	166.0033	83.0004	166.0024	83.0005	166.0029	83.0004	166.0019	83.0006	166.0036	83.0010
21	-165.9985	166.0018	-165.9982	166.0018	-165.9985	166.0018	-165.9985	166.0020	-165.9984	166.0017	-165.9983	166.0023
22	-82.9960	165.9999	-82.9957	165.9998	-82.9962	165.9999	-82.9962	165.9999	-82.9965	165.9997	-82.9956	166.0004
23	0.0037	165.9992	0.0039	165.9991	0.0033	165.9992	0.0034	165.9992	0.0029	165.9991	0.0039	165.9996
24	83.0034	165.9986	83.0036	165.9984	83.0029	165.9984	83.0032	165.9984	83.0027	165.9984	83.0037	165.9990
25	166.0033	165.9990	166.0035	165.9988	166.0028	165.9989	166.0030	165.9987	166.0020	165.9990	166.0038	165.9994

VSL (NL)		OMH (H)		CGM (DK)		IPQ (P)		NPL (UK)	
X	Y	X	Y	X	Y	X	Y	X	Y
-166.0086	-166.0019	-166.0086	-166.0019	-166.0086	-166.0019	-166.0086	-166.0019	-166.0086	-166.0019
-83.0050	-166.0002	-83.0045	-166.0003	-83.0051	-166.0002	-83.0051	-166.0002	-83.0052	-166.0003
-0.0037	-165.9991	-0.0039	-165.9992	-0.0039	-165.9992	-0.0037	-165.9992	-0.0038	-165.9992
82.9969	-165.9999	82.9962	-166.0000	82.9968	-165.9992	82.9971	-166.0000	82.9969	-165.9999
165.9972	-166.0019	165.9970	-166.0019	165.9968	-166.0019	165.9974	-166.0019	165.9971	-166.0019
-166.0024	-82.9991	-166.0024	-82.9993	-166.0024	-82.9994	-166.0025	-82.9995	-166.0022	-82.9993
-83.0027	-82.9997	-83.0022	-83.0001	-83.0028	-83.0001	-83.0028	-83.0002	-83.0027	-83.0001
-0.0013	-83.0001	-0.0014	-83.0003	-0.0014	-83.0002	-0.0013	-83.0004	-0.0012	-83.0003
83.0012	-83.0012	83.0005	-83.0014	83.0011	-83.0014	83.0013	-83.0015	83.0014	-83.0015
166.0006	-83.0010	166.0005	-83.0010	166.0004	-83.0011	166.0009	-83.0012	166.0007	-83.0012
-166.0006	0.0014	-166.0006	0.0007	-166.0006	0.0011	-166.0007	0.0012	-166.0004	0.0012
-83.0002	0.0008	-82.9998	0.0001	-83.0005	0.0006	-83.0004	0.0008	-83.0002	0.0006
0.0002	-0.0002	0.0000	-0.0008	0.0000	-0.0003	0.0001	-0.0001	0.0003	-0.0003
83.0025	-0.0004	83.0018	-0.0011	83.0023	-0.0006	83.0026	-0.0004	83.0028	-0.0007
166.0015	-0.0002	166.0012	-0.0008	166.0012	-0.0004	166.0017	-0.0002	166.0016	-0.0005
-166.0002	83.0029	-166.0003	83.0017	-166.0004	83.0026	-166.0005	83.0031	-166.0000	83.0027
-82.9981	83.0019	-82.9977	83.0008	-82.9985	83.0016	-82.9983	83.0022	-82.9981	83.0016
0.0021	83.0008	0.0018	82.9997	0.0017	83.0006	0.0019	83.0012	0.0022	83.0006
83.0035	83.0004	83.0026	82.9993	83.0032	83.0003	83.0035	83.0008	83.0037	83.0002
166.0030	83.0005	166.0028	82.9994	166.0027	83.0004	166.0032	83.0009	166.0031	83.0003
-165.9984	166.0020	-165.9985	166.0009	-165.9986	166.0016	-165.9986	166.0020	-165.9982	166.0018
-82.9958	166.0001	-82.9954	165.9990	-82.9962	165.9996	-82.9961	166.0001	-82.9959	165.9997
0.0037	165.9993	0.0035	165.9982	0.0033	165.9989	0.0035	165.9994	0.0037	165.9990
83.0034	165.9986	83.0025	165.9975	83.0031	165.9984	83.0033	165.9988	83.0034	165.9983
166.0032	165.9991	166.0029	165.9980	166.0029	165.9988	166.0032	165.9992	166.0034	165.9986

Table 9-1 : Results after shifting to the center of gravity

Ball-#	PTB	METAS	CMI	TUT	GUM	EI	VSL	OMH	CGM	IPQ	NPL
1	0.22	0.27	0.37	0.44	0.44	0.44	0.19	0.45	0.84	0.70	0.25
2	0.21	0.26	0.36	0.43	0.43	0.42	0.18	0.45	0.83	0.70	0.24
3	0.21	0.26	0.36	0.43	0.42	0.41	0.18	0.45	0.82	0.70	0.23
4	0.21	0.26	0.36	0.43	0.43	0.42	0.18	0.45	0.83	0.70	0.24
5	0.22	0.27	0.37	0.44	0.44	0.44	0.19	0.45	0.84	0.70	0.25
6	0.21	0.26	0.36	0.43	0.43	0.42	0.18	0.45	0.83	0.70	0.24
7	0.20	0.25	0.35	0.42	0.41	0.40	0.17	0.45	0.81	0.70	0.23
8	0.20	0.25	0.35	0.42	0.41	0.39	0.16	0.45	0.81	0.70	0.22
9	0.20	0.25	0.35	0.42	0.41	0.40	0.17	0.45	0.81	0.70	0.23
10	0.21	0.26	0.36	0.43	0.43	0.42	0.18	0.45	0.83	0.70	0.24
11	0.21	0.26	0.36	0.43	0.42	0.41	0.18	0.45	0.82	0.70	0.23
12	0.20	0.25	0.35	0.42	0.41	0.39	0.16	0.45	0.81	0.70	0.22
13	0.20	0.25	0.35	0.41	0.40	0.38	0.16	0.45	0.80	0.70	0.22
14	0.20	0.25	0.35	0.42	0.41	0.39	0.16	0.45	0.81	0.70	0.22
15	0.21	0.26	0.36	0.43	0.42	0.41	0.18	0.45	0.82	0.70	0.23
16	0.21	0.26	0.36	0.43	0.43	0.42	0.18	0.45	0.83	0.70	0.24
17	0.20	0.25	0.35	0.42	0.41	0.40	0.17	0.45	0.81	0.70	0.23
18	0.20	0.25	0.35	0.42	0.41	0.39	0.16	0.45	0.81	0.70	0.22
19	0.20	0.25	0.35	0.42	0.41	0.40	0.17	0.45	0.81	0.70	0.23
20	0.21	0.26	0.36	0.43	0.43	0.42	0.18	0.45	0.83	0.70	0.24
21	0.22	0.27	0.37	0.44	0.44	0.44	0.19	0.45	0.84	0.70	0.25
22	0.21	0.26	0.36	0.43	0.43	0.42	0.18	0.45	0.83	0.70	0.24
23	0.21	0.26	0.36	0.43	0.42	0.41	0.18	0.45	0.82	0.70	0.23
24	0.21	0.26	0.36	0.43	0.43	0.42	0.18	0.45	0.83	0.70	0.24
25	0.22	0.27	0.37	0.44	0.44	0.44	0.19	0.45	0.84	0.70	0.25

Table 9-2: Uncertainties in µm after harmonization

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 were 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 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

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

where $\hat{\boldsymbol{x}}_{ij} = \boldsymbol{R}_i \boldsymbol{x}_{ij} + \boldsymbol{t}_i$ is the coordinate of the *j*-th ball 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

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

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

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 $U_{\hat{x}_{ij}}$.

Table 10-1 shows the results after shifting and rotating.

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

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

The KCRV and its uncertainty are shown in Table 10-2.

The standard uncertainty of the KCRV can be approximated as:

$u_0(l) = \sqrt{(0.084^2 + (0.00028 \times l)^2}\,\mu\text{m}$, l : measurement length in metre

10.3 Calculation of E_n values

E_n numbers were calculated as follows (see report of APMP.L-K6)

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

Figure 10-1 shows the E_n numbers of reported results of all participants. The En = 1 line is drawn in red. No participant crosses the line. However, one result of OMH nearly touches the line. Such, there is no need to eliminate any participants results from KCRV calculation.

En numbers of all participants for the ball plate comparison are listed in Table 10-3 and visualized in Figure 10-1. En graphs are also shown individually per participant from Figure 10-2 to 10-12.

The deviation from the KCRV is shown per participant in Figures 10-13 to 10-23.

This simplification of VSL's uncertainties by a fitted quadratic term leads to significant over-estimation of the real uncertainty. Therefore, this raises the corresponding En values, but they still remain below 1. Also the reference value gets slightly shifted.

	PTB (D)		**METAS (CH)**		**CMI (CZ)**		**TUT (FIN)**		**GUM (PL)**		**EI (IRL)**	
Ball-#	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
1	-166.0086	-166.0019	-166.0087	-166.0019	-166.0083	-166.0019	-166.0084	-166.0020	-166.0080	-166.0019	-166.0088	-166.0022
2	-83.0052	-166.0001	-83.0051	-166.0002	-83.0050	-166.0003	-83.0051	-166.0003	-83.0048	-166.0002	-83.0050	-166.0005
3	-0.0036	-165.9991	-0.0037	-165.9992	-0.0035	-165.9992	-0.0037	-165.9993	-0.0037	-165.9992	-0.0036	-165.9995
4	82.9973	-166.0000	82.9970	-165.9999	82.9970	-165.9999	82.9972	-166.0003	82.9969	-165.9999	82.9969	-166.0002
5	165.9975	-166.0019	165.9973	-166.0017	165.9971	-166.0019	165.9974	-166.0018	165.9967	-166.0019	165.9975	-166.0021
6	-166.0024	-82.9994	-166.0023	-82.9994	-166.0022	-82.9994	-166.0023	-82.9992	-166.0018	-82.9993	-166.0027	-82.9995
7	-83.0029	-83.0002	-83.0026	-83.0001	-83.0027	-83.0002	-83.0027	-82.9999	-83.0025	-83.0001	-83.0027	-83.0002
8	-0.0012	-83.0004	-0.0011	-83.0003	-0.0013	-83.0004	-0.0011	-83.0001	-0.0012	-83.0002	-0.0011	-83.0004
9	83.0015	-83.0016	83.0015	-83.0015	83.0013	-83.0015	83.0015	-83.0014	83.0012	-83.0013	83.0013	-83.0015
10	166.0008	-83.0012	166.0008	-83.0010	166.0007	-83.0012	166.0008	-83.0011	166.0002	-83.0011	166.0009	-83.0011
11	-166.0006	0.0013	-166.0006	0.0011	-166.0005	0.0012	-166.0005	0.0013	-166.0000	0.0013	-166.0007	0.0012
12	-83.0003	0.0004	-83.0004	0.0007	-83.0003	0.0007	-83.0004	0.0009	-83.0001	0.0005	-83.0003	0.0008
13	0.0002	-0.0004	0.0002	-0.0003	0.0002	-0.0003	0.0003	-0.0002	0.0002	-0.0003	0.0002	-0.0003
14	83.0027	-0.0006	83.0027	-0.0006	83.0024	-0.0005	83.0026	-0.0006	83.0024	-0.0006	83.0027	-0.0005
15	166.0016	-0.0002	166.0016	-0.0002	166.0014	-0.0004	166.0016	-0.0003	166.0010	-0.0003	166.0019	-0.0002
16	-166.0003	83.0028	-166.0003	83.0027	-166.0001	83.0027	-166.0002	83.0028	-165.9997	83.0027	-166.0004	83.0029
17	-82.9983	83.0017	-82.9983	83.0019	-82.9982	83.0020	-82.9983	83.0020	-82.9980	83.0017	-82.9982	83.0019
18	0.0020	83.0007	0.0020	83.0008	0.0019	83.0008	0.0021	83.0008	0.0020	83.0006	0.0021	83.0009
19	83.0036	83.0003	83.0036	83.0004	83.0033	83.0005	83.0035	83.0004	83.0033	83.0003	83.0035	83.0006
20	166.0031	83.0005	166.0031	83.0006	166.0027	83.0005	166.0031	83.0005	166.0025	83.0006	166.0033	83.0008
21	-165.9985	166.0018	-165.9984	166.0018	-165.9982	166.0018	-165.9984	166.0019	-165.9978	166.0017	-165.9986	166.0020
22	-82.9960	165.9999	-82.9959	165.9999	-82.9959	165.9999	-82.9961	165.9998	-82.9959	165.9997	-82.9959	166.0002
23	0.0037	165.9992	0.0037	165.9992	0.0036	165.9992	0.0035	165.9992	0.0035	165.9991	0.0036	165.9994
24	83.0034	165.9986	83.0034	165.9985	83.0032	165.9984	83.0033	165.9985	83.0033	165.9984	83.0034	165.9988
25	166.0033	165.9990	166.0033	165.9990	166.0031	165.9989	166.0031	165.9988	166.0026	165.9990	166.0035	165.9992

Table 10-1(a) : Results after shifting and rotating

VSL (NL)		**OMH (H)**		**CGM (DK)**		**IPQ (P)**		**NPL (UK)**	
X	Y	X	Y	X	Y	X	Y	X	Y
-166.0085	-166.0020	-166.0084	-166.0014	-166.0084	-166.0018	-166.0086	-166.0020	-166.0086	-166.0019
-83.0049	-166.0003	-83.0043	-165.9998	-83.0049	-166.0001	-83.0051	-166.0003	-83.0051	-166.0002
-0.0036	-165.9992	-0.0037	-165.9987	-0.0037	-165.9991	-0.0037	-165.9993	-0.0038	-165.9991
82.9970	-166.0000	82.9964	-165.9995	82.9970	-165.9992	82.9971	-166.0001	82.9970	-165.9998
165.9973	-166.0019	165.9972	-166.0014	165.9970	-166.0019	165.9974	-166.0020	165.9971	-166.0017
-166.0024	-82.9993	-166.0022	-82.9988	-166.0022	-82.9993	-166.0025	-82.9996	-166.0022	-82.9993
-83.0026	-82.9999	-83.0020	-82.9996	-83.0026	-83.0000	-83.0028	-83.0003	-83.0027	-83.0000
-0.0012	-83.0002	-0.0012	-82.9998	-0.0012	-83.0001	-0.0013	-83.0005	-0.0012	-83.0002
83.0012	-83.0013	83.0007	-83.0009	83.0013	-83.0014	83.0013	-83.0016	83.0014	-83.0013
166.0007	-83.0010	166.0007	-83.0005	166.0006	-83.0011	166.0009	-83.0013	166.0007	-83.0010
-166.0005	0.0012	-166.0004	0.0012	-166.0004	0.0012	-166.0006	0.0011	-166.0004	0.0012
-83.0002	0.0007	-82.9996	0.0006	-83.0003	0.0007	-83.0003	0.0007	-83.0003	0.0006
0.0002	-0.0003	0.0002	-0.0003	0.0002	-0.0002	0.0002	-0.0002	0.0002	-0.0002
83.0025	-0.0005	83.0020	-0.0006	83.0025	-0.0006	83.0027	-0.0005	83.0027	-0.0005
166.0015	-0.0003	166.0014	-0.0003	166.0014	-0.0004	166.0018	-0.0003	166.0015	-0.0003
-166.0002	83.0027	-166.0001	83.0022	-166.0001	83.0027	-166.0004	83.0030	-166.0001	83.0027
-82.9981	83.0017	-82.9975	83.0013	-82.9982	83.0017	-82.9982	83.0021	-82.9982	83.0017
0.0021	83.0007	0.0020	83.0002	0.0020	83.0007	0.0020	83.0011	0.0021	83.0007
83.0035	83.0004	83.0028	82.9998	83.0035	83.0003	83.0036	83.0007	83.0036	83.0004
166.0030	83.0005	166.0030	82.9999	166.0030	83.0004	166.0033	83.0008	166.0030	83.0005
-165.9984	166.0018	-165.9983	166.0014	-165.9983	166.0017	-165.9985	166.0019	-165.9984	166.0018
-82.9958	165.9999	-82.9952	165.9995	-82.9959	165.9997	-82.9960	166.0000	-82.9960	165.9998
0.0036	165.9992	0.0037	165.9987	0.0036	165.9990	0.0036	165.9993	0.0036	165.9991
83.0033	165.9985	83.0027	165.9980	83.0034	165.9984	83.0034	165.9987	83.0033	165.9985
166.0032	165.9990	166.0031	165.9985	166.0032	165.9988	166.0033	165.9991	166.0033	165.9988

Table 10-1(b) : Results after shifting and rotating

Ball-#	X	Y	u_l
1	-166.0085	-166.0019	0.095
2	-83.0050	-166.0002	0.092
3	-0.0037	-165.9992	0.091
4	82.9970	-165.9999	0.092
5	165.9973	-166.0018	0.095
6	-166.0023	-82.9993	0.092
7	-83.0027	-83.0000	0.088
8	-0.0012	-83.0002	0.087
9	83.0013	-83.0014	0.088
10	166.0007	-83.0011	0.092
11	-166.0005	0.0012	0.091
12	-83.0002	0.0006	0.087
13	0.0002	-0.0003	0.086
14	83.0026	-0.0005	0.087
15	166.0015	-0.0003	0.091
16	-166.0002	83.0027	0.092
17	-82.9982	83.0018	0.088
18	0.0020	83.0007	0.087
19	83.0035	83.0004	0.088
20	166.0030	83.0005	0.092
21	-165.9984	166.0018	0.095
22	-82.9959	165.9999	0.092
23	0.0036	165.9992	0.091
24	83.0033	165.9985	0.092
25	166.0032	165.9989	0.095

Table 10-2: KCRV for the ball plate (coordinates X and Y in mm, uncertainty u_l in µm)

Ball-#	PTB	METAS	CMI	TUT	GUM	EI	VSL	OMH	CGM	IPQ	NPL
1	0.20	0.32	0.34	0.19	0.57	0.46	0.32	0.56	0.10	0.06	0.12
2	0.53	0.15	0.10	0.13	0.25	0.39	0.31	0.91	0.10	0.06	0.23
3	0.25	0.11	0.26	0.14	0.06	0.44	0.18	0.51	0.02	0.11	0.30
4	0.56	0.10	0.05	0.46	0.18	0.41	0.15	0.84	0.46	0.16	0.32
5	0.45	0.14	0.22	0.12	0.66	0.36	0.23	0.49	0.17	0.19	0.42
6	0.24	0.12	0.21	0.12	0.58	0.46	0.16	0.56	0.08	0.22	0.19
7	0.62	0.22	0.20	0.18	0.19	0.28	0.43	0.85	0.05	0.20	0.04
8	0.25	0.16	0.20	0.17	0.10	0.28	0.22	0.50	0.07	0.19	0.03
9	0.54	0.30	0.14	0.18	0.21	0.16	0.41	0.89	0.01	0.18	0.15
10	0.27	0.08	0.17	0.13	0.61	0.25	0.12	0.63	0.06	0.25	0.09
11	0.31	0.23	0.05	0.11	0.60	0.21	0.05	0.11	0.09	0.13	0.19
12	0.45	0.23	0.14	0.34	0.21	0.16	0.16	0.69	0.03	0.08	0.04
13	0.17	0.06	0.04	0.08	0.03	0.05	0.08	0.03	0.04	0.07	0.11
14	0.23	0.27	0.24	0.13	0.24	0.15	0.20	0.67	0.04	0.04	0.22
15	0.26	0.18	0.21	0.04	0.62	0.46	0.13	0.17	0.09	0.17	0.02
16	0.32	0.16	0.19	0.06	0.59	0.33	0.11	0.59	0.04	0.25	0.17
17	0.28	0.28	0.36	0.28	0.23	0.11	0.14	0.88	0.06	0.24	0.18
18	0.11	0.15	0.20	0.06	0.11	0.20	0.11	0.56	0.06	0.26	0.16
19	0.22	0.22	0.31	0.07	0.23	0.27	0.06	1.00	0.03	0.22	0.17
20	0.18	0.17	0.38	0.05	0.60	0.48	0.10	0.64	0.06	0.25	0.03
21	0.27	0.10	0.30	0.11	0.67	0.37	0.07	0.44	0.07	0.12	0.06
22	0.27	0.04	0.10	0.21	0.15	0.33	0.22	0.83	0.11	0.12	0.33
23	0.22	0.09	0.08	0.13	0.13	0.25	0.05	0.50	0.13	0.09	0.20
24	0.33	0.11	0.16	0.08	0.10	0.33	0.08	0.88	0.06	0.12	0.07
25	0.28	0.12	0.09	0.24	0.66	0.43	0.16	0.48	0.07	0.10	0.31

Table 10-3: E_n numbers calculated from all participants results

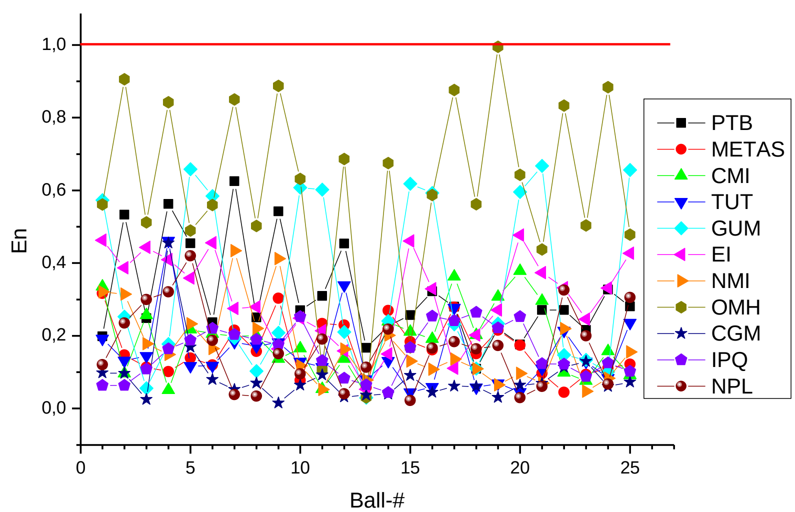

Figure 10-1 E_n numbers calculated from all participants results

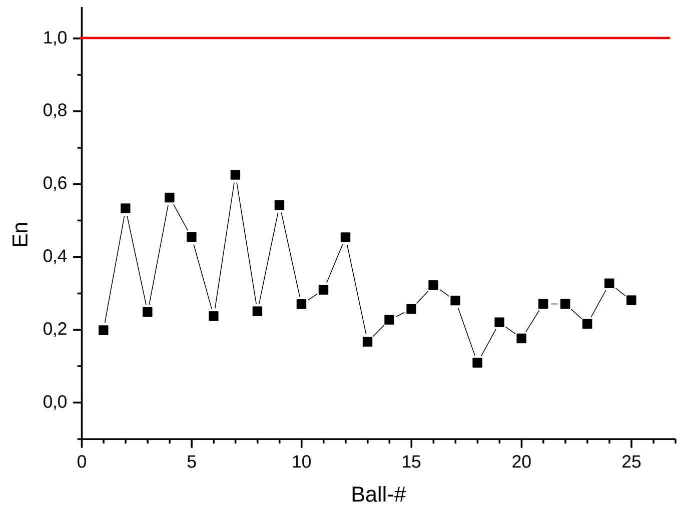

Figure 10-2 E_n numbers for PTB

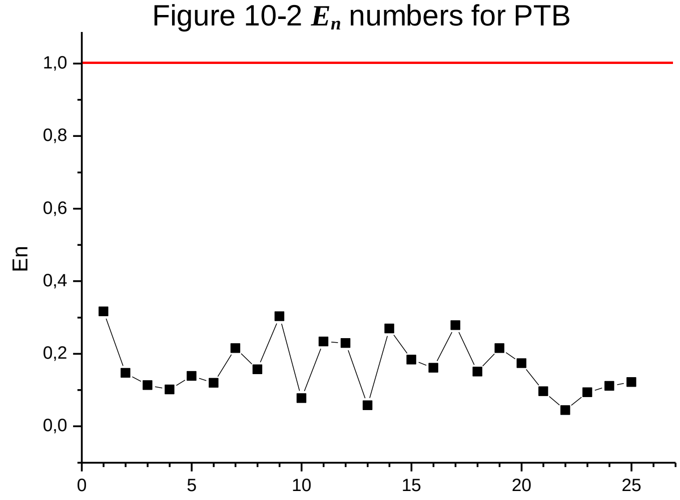

Figure 10-3 E_n numbers for METAS

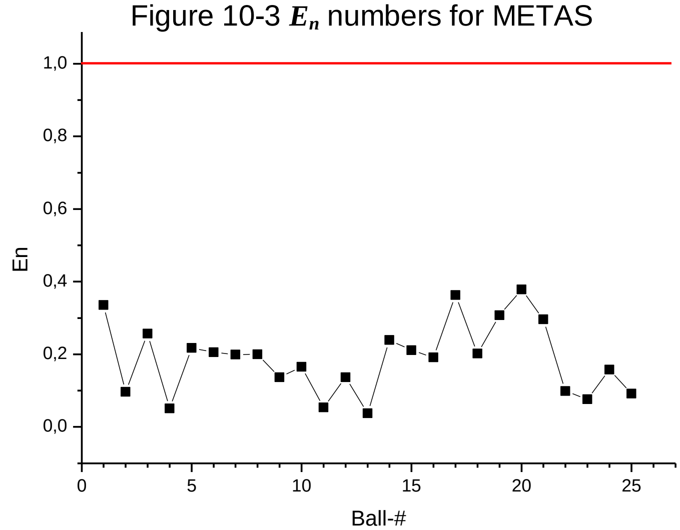

Figure 10-4 E_n numbers for CMI

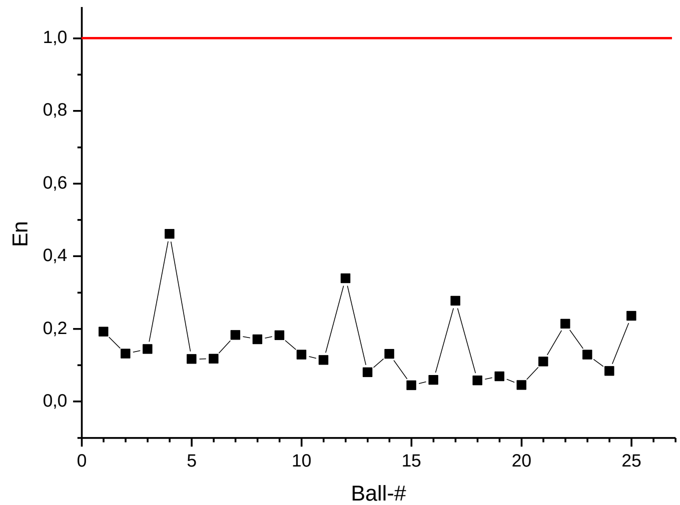

Figure 10-5 E_n numbers for TUT

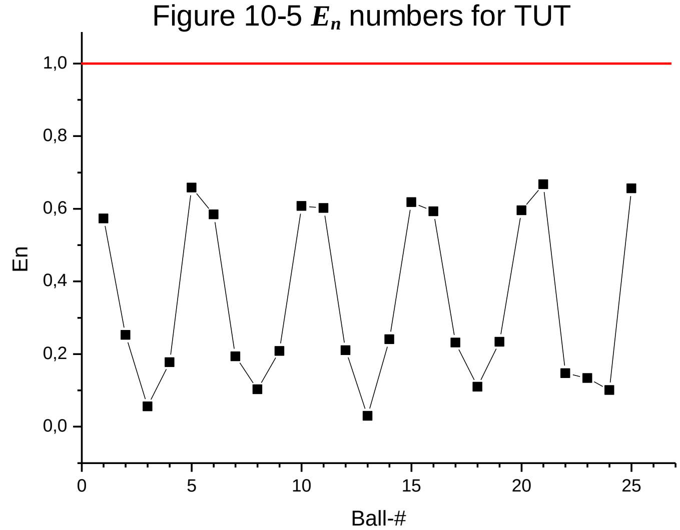

Figure 10-6 E_n numbers for GUM

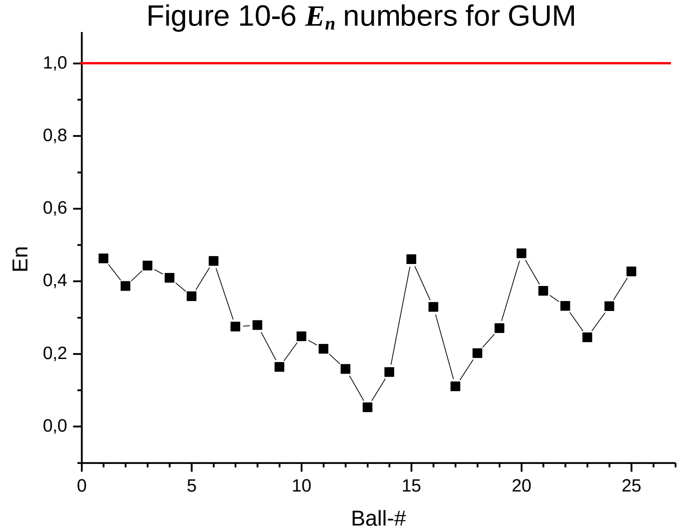

Figure 10-7 E_n numbers for EI

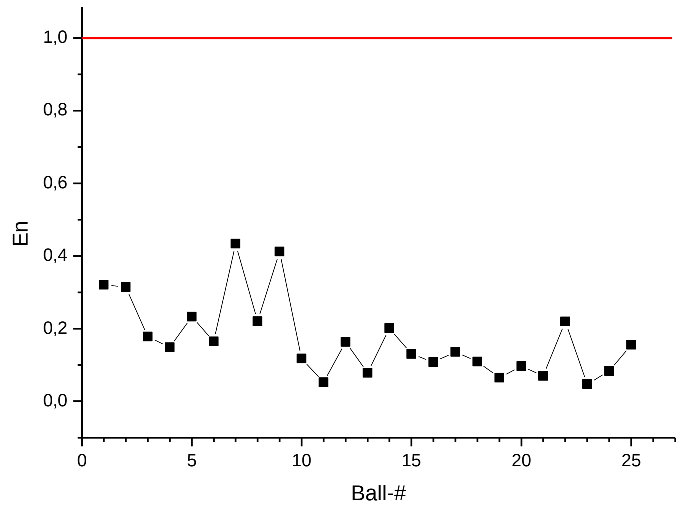

Figure 10-8 E_n numbers for VSL

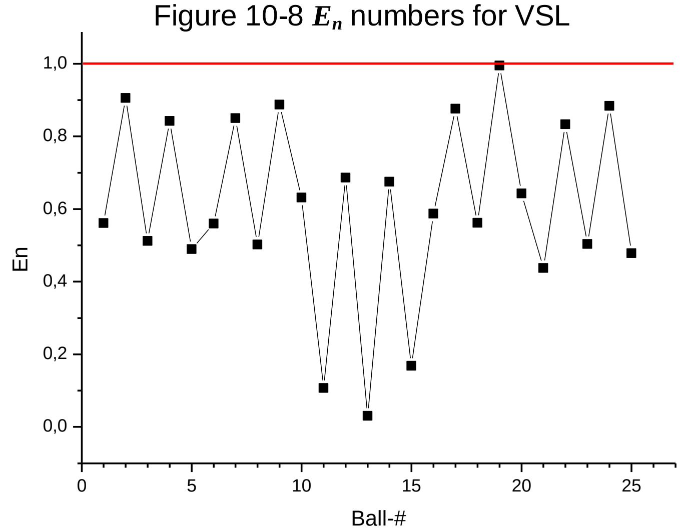

Figure 10-9 E_n numbers for OMH

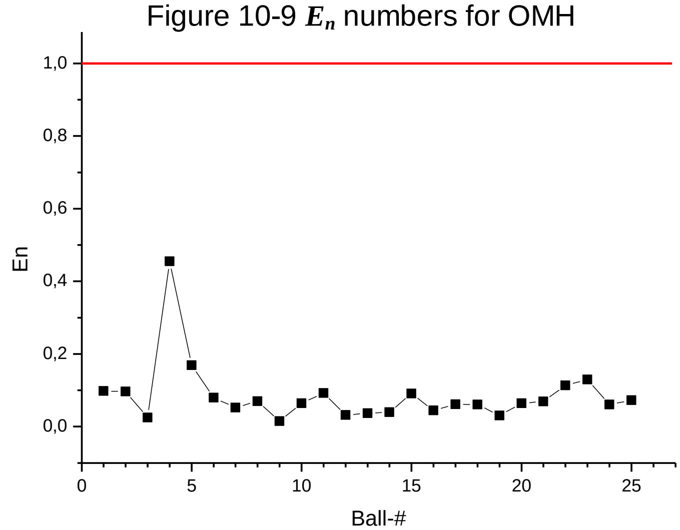

Figure 10-10 E_n numbers for CGM

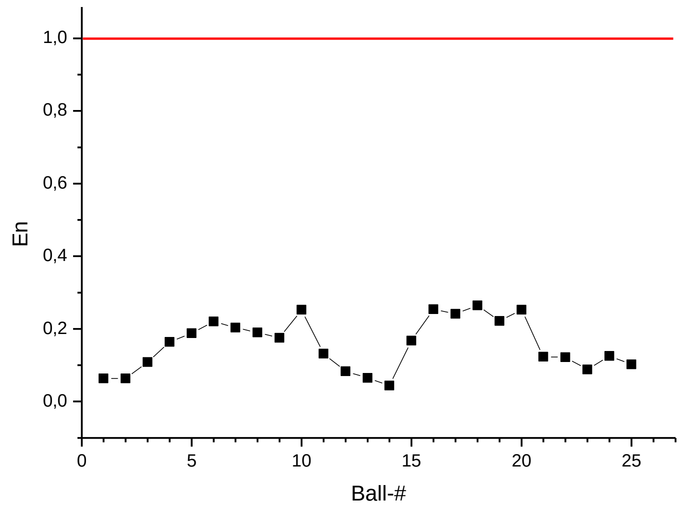

Figure 10-11 E_n numbers for IPQ

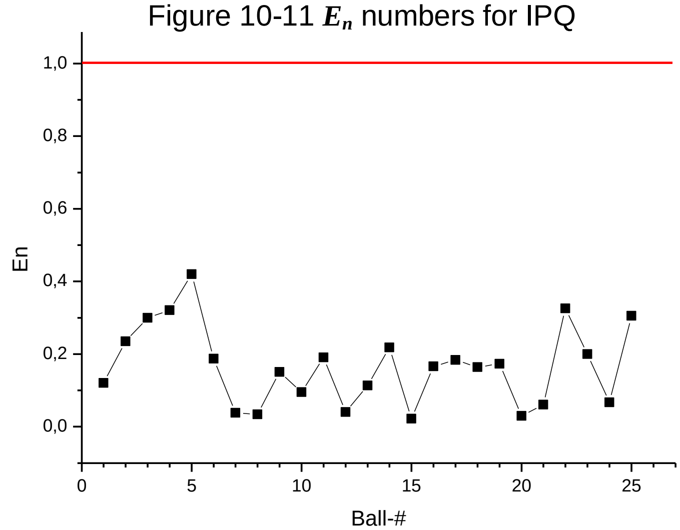

Figure 10-12 E_n numbers for NPL

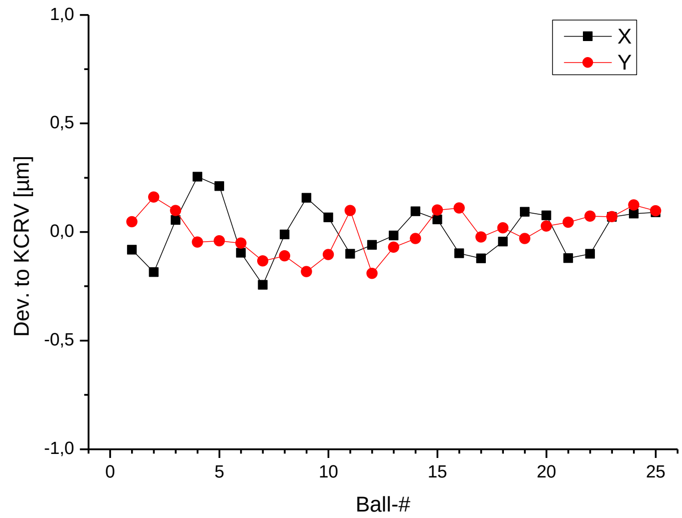

Figure 10-13 Deviation to KCRV for PTB

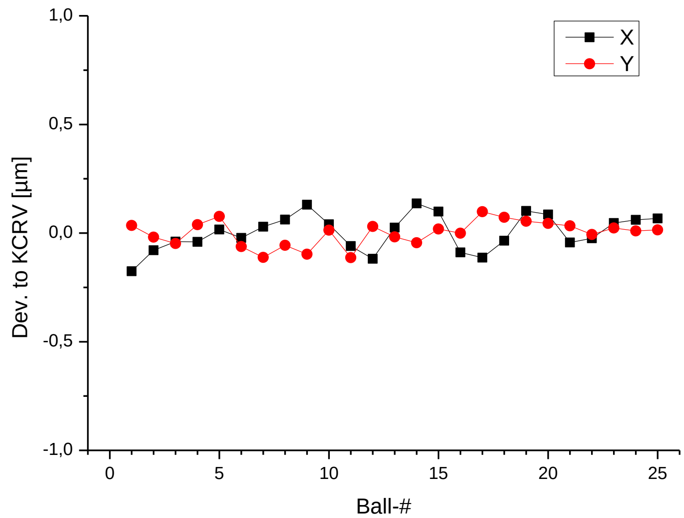

Figure 10-14 Deviation to KCRV for METAS

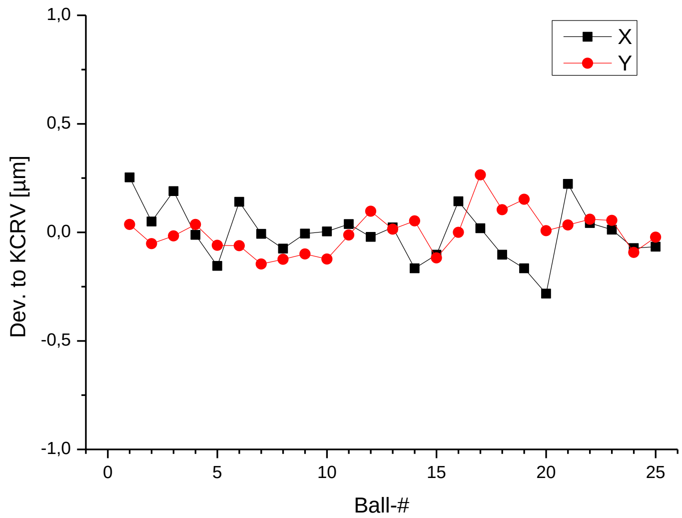

Figure 10-15 Deviation to KCRV for CMI

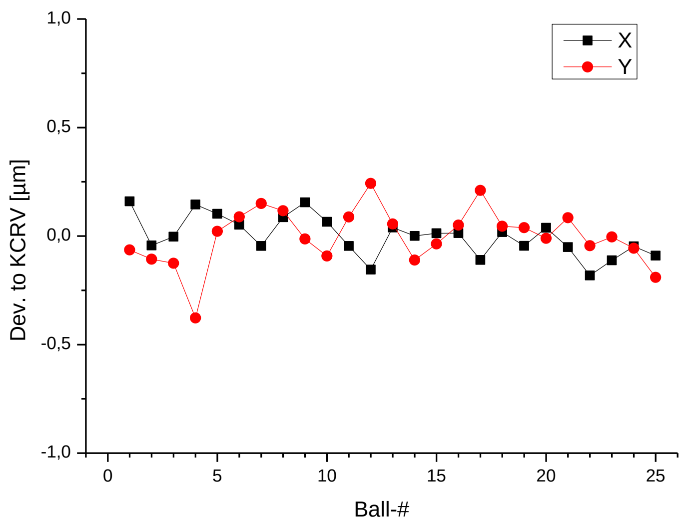

Figure 10-16 Deviation to KCRV for TUT

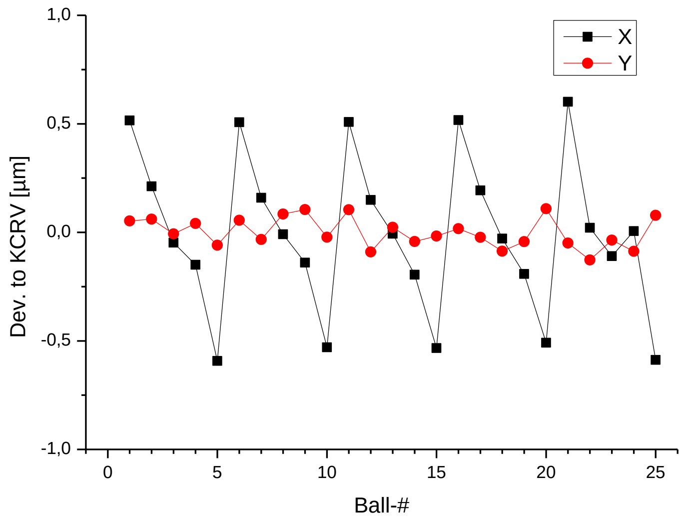

Figure 10-17 Deviation to KCRV for GUM

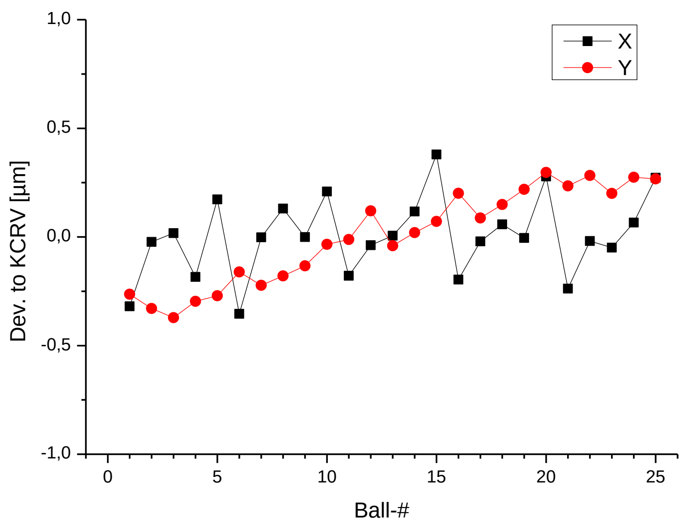

Figure 10-18 Deviation to KCRV for EI

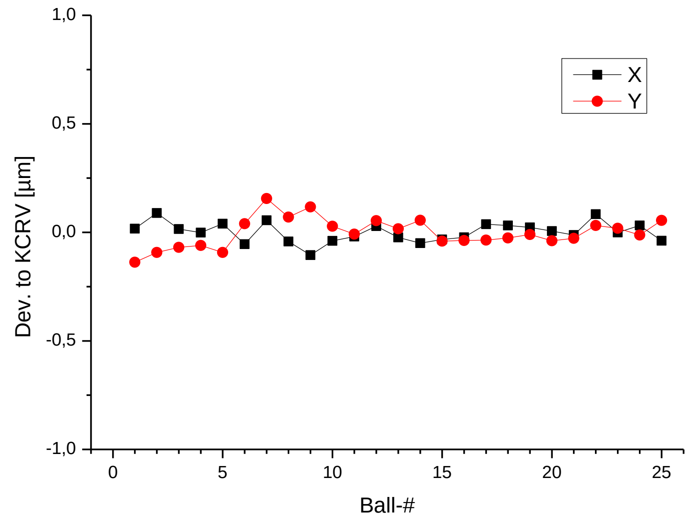

Figure 10-19 Deviation to KCRV for VSL

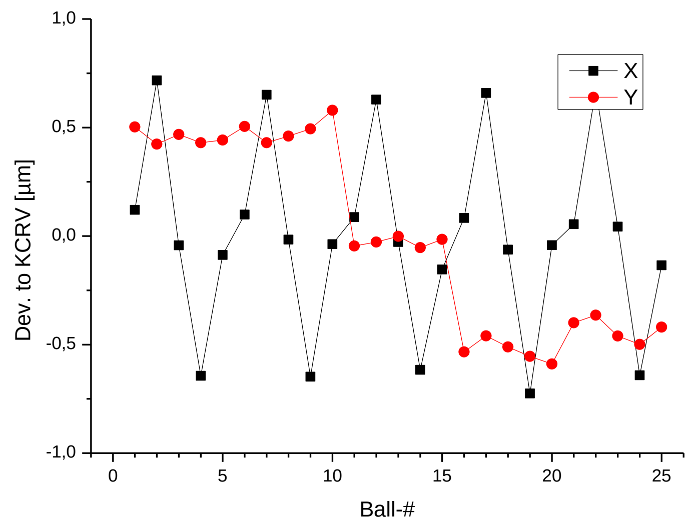

Figure 10-20 Deviation to KCRV for OMH

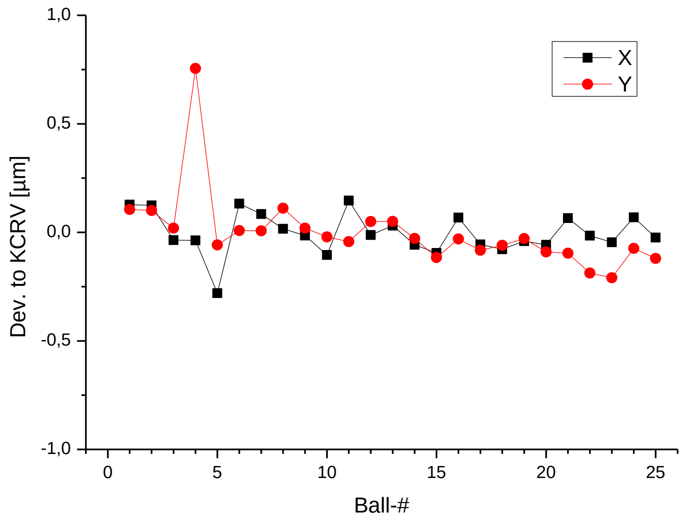

Figure 10-21 Deviation to KCRV for CGM

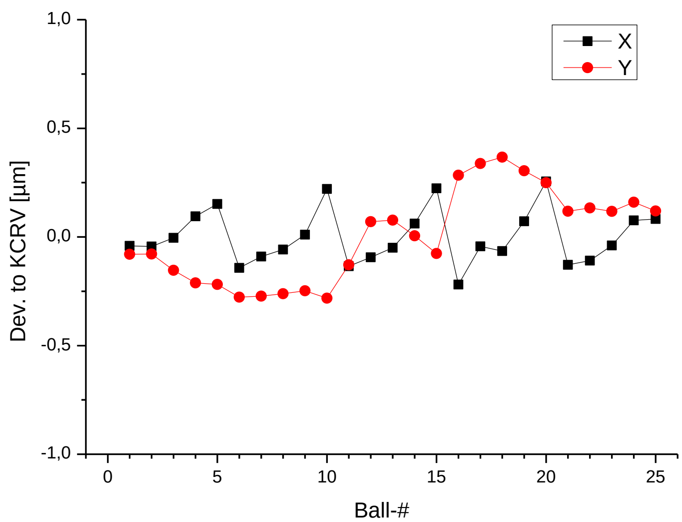

Figure 10-22 Deviation to KCRV for IPQ

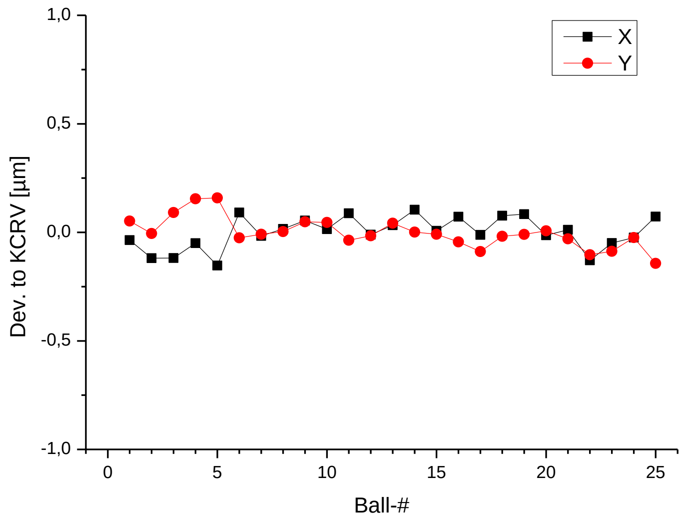

Figure 10-23 Deviation to KCRV for NPL

11 Conclusion and summary

This comparison involved 12 laboratories from EURAMET.

IMGC (now INRIM) withdrew from the comparison. All other 11 laboratories measured the ball plate.

The comparison lasted from April 2004 to March 2006.

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

The stability was checked by PTB before, during and after the measurement campaign. No significant changes were found.

The overall results look reasonable. We can conclude this comparison is valid and it can be a supporting evidence for participants' CMC claims. However, the results of some participants show noticeable systematic, namely length periodic, effects both at the E_n – number plots and in the KCRV deviation graphs. They might be a hint for further optimization of the CMC.

GUM reported that their CMM measuring probe was damaged right before the intercomparison. It was repaired and the CMM performance was checked by internal comparison measurements with externally calibrated standards before the measurements. Yet, the stability suffered loss by the repair and influenced the measurement results negatively, Therefore, GUM decided to improve the maintenance and repair of the CMM and to introduce corrections into their analysis software. Such the current status of the machine can be assumed to be superior to the status during the measurement campaign of the intercomparison.

It should be noted again that the harmonization of the uncertainties overestimates VSL's true uncertainties. However, the effect to the rating of the results is quite limited.

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