Follow-up of Euromet L-K4.2005

Calibration of outer diameter standards

EURAMET.L-K4. 2005.1

EURAMET project #1299

Final report

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1 Document control

Version Draft A.1	Issued on 21 December 2015
Version Draft B.1	Issued on 28 January 2016
Version Draft B.2	Issued on 12 October 2016
Version Draft B.3	Issued on 8 June 2018
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Revised Final Version	Issued on 31 October 2019

2 Introduction

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

At its meeting in October 2013, the EURAMET TC-L, decided upon a follow up comparison of the EUROMET.L-K4.2005 key comparison on diameter standards. This as a response to the executive report of the EUROMET.L-K4.2005 which contains several corrective actions to be performed for several laboratories. A few laboratories had corrective action specifically on the measurement of outer diameter standards. This follow-up comparison has the aim to validate the applied corrective actions.

The standard gauges to be calibrated were chosen to be three plug gauges with a diameter of 6 mm, 25 mm and 50 mm and a sphere with a diameter of 30 mm.

VSL (Netherlands) and SMD (Belgium) cooperatively pilot the comparison.

3 Organization

3.1 Participants

Table 1. List of participant laboratories and their contacts.

Laboratory Code	Contact person, Laboratory	Phone, Fax, email
INRIM (link)	Mr. Gian Bartolo Picotto Istituto Nazionale di Ricerca Metrologica Strada delle Cacce, 91 IT-10135 Torino Italy	+39 011 3919969 g.picotto@inrim.it
MIRS	Dr. Bojan Acko University of Maribor Faculty of Mech. Eng. Smetanova 17 SI-2000 Maribor Slovenia	+386 2 220 7581 bojan.acko@uni-mb.si
NPL	Mr. David Flack National Physical Laboratory	+44 20 8943 6347

	Hampton Road Teddington, Middlesex TW 11 OLW United Kingdom	david.flack@npl.co.uk
SMD	Mr. Hugo Piree Federal Public Service Economy Directorate-general Quality and Safety Metrology – National Standards SMD North Gate III Koning Albert II straat, 16 BE-1000 Brussels Belgium	+32 2 277 7610 hugo.piree@mineco.fgov.be
VSL	Mr. Gerard Kotte VSL Dutch Metrology Institute Thijsseweg 11 NL-2600 AR Delft The Netherlands	+31 15 269 16 01 gkotte@vsl.nl

3.2 Schedule

Table 2 Schedule of the comparison.

RMO	Laboratory	schedule	Results received
EURAMET	INRIM	14 October 2013 – 24 November 2013	6 June 2014
Pilot Lab	VSL	25 November 2013 – 05 January 2014	n/a
	NPL	06 January 2014 – 16 February 2014	11 February 2014
	MIRS	17 February 2014 – 30 March 2014	14 May 2014
	SMD	31 March 2014 – 11 May 2014	23 September 2014
Pilot Lab	VSL	12 May 2014 – 31 May 2014	n/a

4 Artefacts

4.1 Description of artefacts

The artefacts to be calibrated are described and shown in the Table 3 and in Figure 1.

The identification of the plug gauges is marked on their handle by inscription. The identification of the ball is applied on its support using a sticker.

Note: be aware with cleaning agents as it might wipe the text on the sticker.

Table 3 Description of the artefacts

Type	Manufacturer	Identification	Nominal diameter /mm	Material
Plug	Microtool	606	6	steel
Plug	Microtool	2517	25	steel
Plug	SIP / Etalon	5773	50	steel
Sphere	ZEISS	SPH30LK4	30	Steel

Figure 1 The four standards to be measured

4.2 Condition of artefacts at start/end of comparison

Two notifications about the condition of the artefacts have been received.

NPL:
On the 50 mm plug: A circumferential scratch at mid height and minor scuffing on the gauge surface, Figure 2.

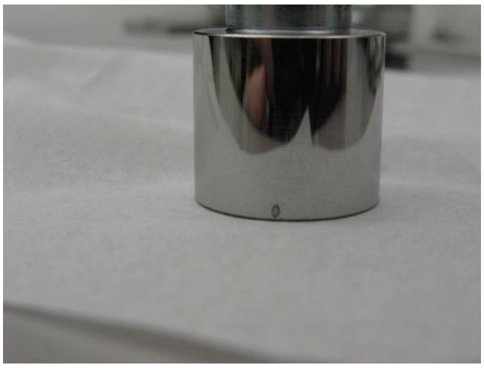

Figure 2 NPL picture with the scratch and scuffing of the 50 mm diameter plug

INRIM:
On the 25 mm plug: visible wearing on the contact area on 0° and 180° at the middle section, Figure 3.

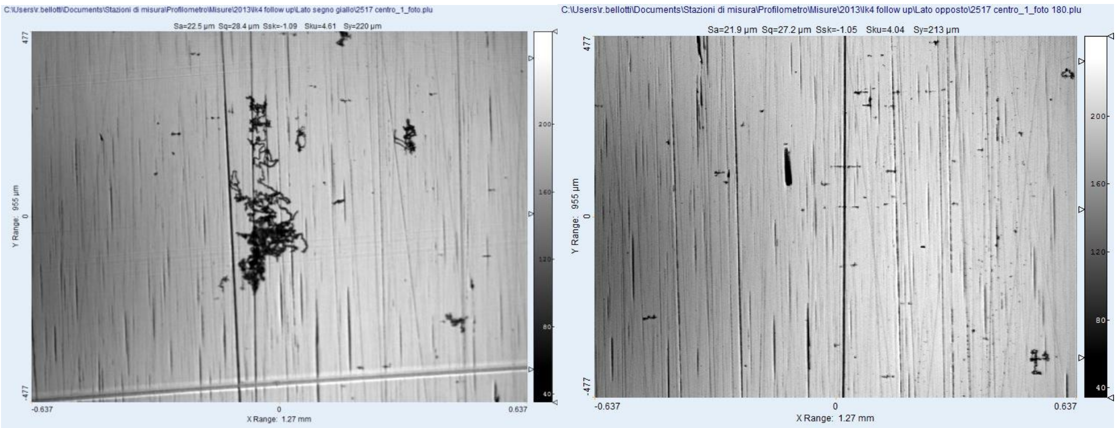

Figure 3 INRIM pictures showing damage of the 25 mm plug

INRIM reported: Please have a look at the above photos taken by an optical profilometer (image mode, confocal) on the contact 0° and 180° at the middle section. Besides of some straight engraving lines also visible at naked eyes, some wearing is clearly visible at the 0° contact point, middle section. Such a wearing and/or smearing may cause a low repeatability, namely when a low contact force is used when probing the surface, as with our measuring system (3 mN). In the case, we've taken a measurement of the diameter also along the 90° - 270° direction, where a critical wearing is not visible.

The above observations of NPL and INRIM do not seem to have had a significant effect on the outcome of the comparison.

5 Measuring instructions

5.1 Measurands

The measurand for each gauge is the diameter at the reference temperature of 20 °C and corrected to zero force. For the correction to 20 °C the thermal expansion coefficient of 11.6 $\cdot 10^{-6}$ K^{-1} should be used.

5.2 Measurement position

The diameter of the plug gauges should be measured at 3 different heights according to Table 4.

Table 4 Measurement positions on the three plug gauges

Gauge	Diameter measurement locations
Plug Ø 6 mm	3 mm ↑ Middle 3 mm ↓
Plug Ø 25 mm	7 mm ↑ Middle 7 mm ↓
Plug Ø 50 mm	7 mm ↑ Middle 7 mm ↓

Where 'x mm ↑' refers to the measurement location x mm above the mid height of the cylinder and 'x mm ↓' refers to the measurement location x mm below the mid height of the cylinder and 'below the mid height' is defined in the direction of the handle.

The measurement position for the ball is fully determined by the measurement direction.

5.3 Measurement direction

The measurement direction is perpendicular to the core line through the gauge.

For the plug gauges the radial orientation of the measurement direction is parallel to the marks on the upper side of the gauge body. If those measurement indication marks are not present, as with the SIP plug gauge, the measurement direction is parallel to the flat part of the handle, see Figure 4.
The side opposite to the handle is considered to be the upper side.

Note: unfortunately, the lines on the plug gauges defining the measurement direction do not always precisely cross the centre of the cylinder/sphere. The measurement direction shall therefore always be parallel to this line, but not necessarily coincident.

The radial direction for the ball is indicated by a small indication pin, Figure 5.

Figure 4 Measurement direction for the SIP plug gauge

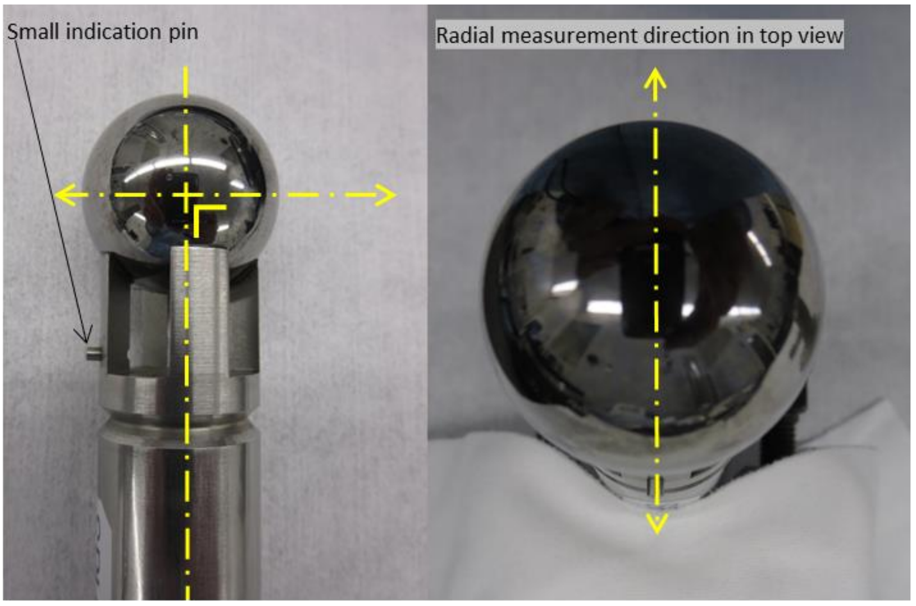

Figure 5 Measurement direction of the sphere

5.4 Measurement uncertainty

The uncertainty of measurement was estimated according to the ISO *Guide to the Expression of Uncertainty in Measurement*. The participating laboratories were encouraged to use their usual model for the uncertainty calculation.

All measurement uncertainties should be stated as standard uncertainties with, when appropriate, the corresponding effective degrees of freedom. When none was given, infinite was assumed. For efficient evaluation and subsequent assessment of CMC claims an uncertainty statement in the functional form (1) was preferred, with indication of the factor *k* used, typically 2, or the one corresponding to a level of confidence of a 95 %, in case it was different.

$$U(R) = Q[a, bR] = \sqrt{a^2 + (bR)^2} \tag{1}$$

The following tables shows the uncertainties communicated by the participants and for those having approved CMC, their values.

Table 5. Uncertainties for external cylinder of the participants in the comparison LK4.2005.1 against their approved CMC.

Lab.	U_{S23} (µm)	CMC (BIPM KCDB) (µm)	Obs.
INRIM	Individual values	Q[0.1, 0.5E-03D], D in mm INRIM/11	Individual values identical or smaller CMC
VSL-CMM	Q[0.09, 0.001D], D in mm	Q[0.2, 0.001D], D in mm VSL/25	Uncertainty smaller CMC
VSL-ULM	Q[0.5, 0.002D], D in mm	Q[0.5, 0.002D], D in mm VSL/25	Uncertainty identical CMC
NPL1 Metroscope	D, 5 mm to 100 mm (0.07 + 0.0011 D), D in mm D, 100 to 150 mm (0.05 + 0.0014 D), D in mm	(0.15 + 0.0014 D), D in mm NPL/29	Uncertainty smaller than CMC
NPL2 Meseltron	(0.08 + 0.001 D), D in mm	same	NPL/28
MIRS	Q[0.284, 2.5E-03D], D in mm	D, 0.1 mm to 10 mm Q[0.3, 3E-03D], D in mm MIRS/UM-FS/LTM-10 D, 1 mm to 300 mm Q[0.5, 3E-03D], D in mm MIRS/UM-FS/LTM-9	Uncertainty equal or smaller than CMC
SMD	D < 20 mm: Q[0.186, 1.15E-03D], D in mm D >= 20 mm: Q[0.140, 0.35E-03D], D in mm	Q[0.130, 0.00072D], D in mm SMD/2400/2	Uncertainty larger than CMC

Table 6 Uncertainties for reference sphere of the participants in the comparison LK4.2005.1 against their approved CMC.

Lab.	U_{S23}	CMC (BIPM KCDB) (µm)	Obs.
INRIM	46,3 nm	Q[0.1, 0.5E-03D] D in mm INRIM/13	Uncertainty smaller than CMC
VSL-CMM		Q[0.1, 0.0008D], D in mm VSL/25	
VSL-ULM	Not applicable		
NPL1 Metroscope	0.116 µm	0.11(NPL/48)	No significant difference

NPL2 Meseltron	Not applicable		
MIRS	Q[0.284, 2.5E-03D] µm, D in mm	Only CMC for 0.1 to 10 mm not 50 mm MIRS/UM-FS/LTM-12	
SMD	Q[0.156, 0.35E-03D] µm, D in mm	No CMC	

6 Analysis of results

6.1 Stability of artefacts

The pilot laboratory VSL performed measurements at the beginning and at the end of the comparison. Differences in the measured diameters were observed for the 6 mm and 25 mm plug. The difference was most pronounced for the 6 mm plug. Based on the CMC uncertainty of VSL the results of the 6 mm plug were still in good agreement, but with the intended improved uncertainty budget of VSL they were not in agreement. One of the causes could be a small drift but the results of the other participants did not indicate an apparent drift.

Further investigation showed that the way of mounting the plugs at the beginning of the comparison was different from the mounting at the end of the comparison.
A detailed comparison of the results showed that the differences between the measurement results using the two ways of mounting the plugs depended on the distance from the mounting base. The effect of the mounting was then further studied, also by using capacitive sensors. Small movements of the plugs were observed where the magnitude depended on the way of mounting and the position on the plug (middle, high or low). To minimize the effect of the movement, the mounting method was further improved and a lower measuring force of 0.1 N was used instead of the original 0.2N. Measurements performed after these adjustments showed negligible movement of the plugs with respect to the uncertainty. The results of these measurements are indicated in Figure 6~~Figure 6~~, where the VSL results are indicated by circles.

Therefore, it was concluded that the indication for drift of the artefacts shown in the results of VSL (the pilot) was actually due to the different mounting of the artefacts at the beginning and at the end of the comparison and amplified by the measuring force. Also, the results of the other participants do not indicate a significant drift during the comparison. It was therefore concluded that there was no significant drift. Therefore, no uncertainty due to drift was taken into account when analysing the measurement data of all participants.

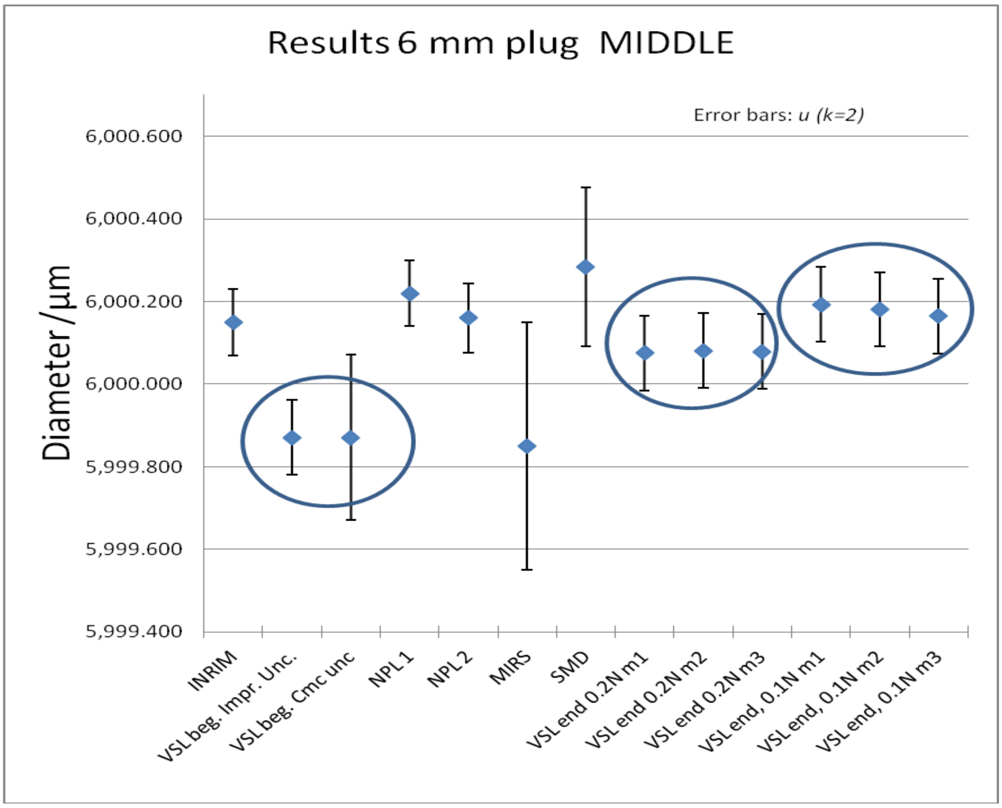

Figure 6. Stability of the 6 mm plug during comparison. Results of pilot are indicated by blue circles. The uncertainty bars represent the expanded uncertainty (*k*=2).

6.2 Calculation of the KCRV

The Key Comparison Reference Value (KCRV) is calculated as the weighted mean of the participants' results. The check for consistency of the comparison results with their associated uncertainties was based on using the Birge ratio. The degrees of equivalence for each laboratory and standard with respect to the KCRV were evaluated by using E_n values.

To avoid biasing the weighted mean, only the first results from the pilot laboratory (VSL) were included, where the value with the smallest uncertainty was used to calculate the KCRV. The VSL results obtained after the results were received from the other participants are only included for information to illustrate the effects of proper mounting and measurement force but were excluded from the calculation of the KCRV.

NPL submitted two results for the 6 mm plug. NPL 1 is the modified Metroscope and NPL 2 is the Meseltron Movotelit. Since NPL 1 has the lowest uncertainty this result was taken to contribute to the weighted mean.

To each result (x_i) a normalized weight, w_i, was attributed, given by:

$$w_i = C \cdot \frac{1}{[u(x_i)]^2} \qquad (2)$$

where the normalizing factor, *C*, is given by:

$$C = \frac{1}{\sum_{i=1}^{N}\left(\frac{1}{u(x_i)}\right)^2} \tag{3}$$

The weighted mean $\overline{x}_w$ is given by:

$$\overline{x}_w = \sum_{i=1}^{N} w_i \cdot x_i \tag{4}$$

and the uncertainty of the weighted mean is calculated by:

$$u(\overline{x}_w) = \sqrt{\frac{1}{\sum_{i=1}^{N}\left(\frac{1}{u(x_i)}\right)^2}} = \sqrt{C} \tag{5}$$

For the determination of the KCRV, statistical consistency of the results contributing to the KCRV is required. A check for statistical consistency of the results with their associated uncertainties can be made by the Birge ratio, R_B, which compares the observed spread of the results with the expected spread from the individual reported uncertainties.

The Birge ratio is defined as

$$R_B = \frac{u_{ext}(\overline{x}_w)}{u(\overline{x}_w)} \tag{6}$$

where $u_{ext}(\overline{x}_w)$ is the external standard deviation

$$u_{ext}(\overline{x}_w) = \sqrt{\frac{1}{(N-1)} \cdot \frac{\sum_{i=1}^{N} w_i (x_i - \overline{x}_w)^2}{\sum_{i=1}^{N} w_i}} \tag{7}$$

The data in a comparison are consistent provided that

$$R_B < \sqrt{1 + \sqrt{\frac{8}{N-1}}} \tag{8}$$

where *N* is the number of laboratories.

For each laboratory's result, the E_n value is calculated as the ratio of the deviation from the weighted mean, divided by the expanded uncertainty of this deviation.

$$E_n = \frac{x_i - \overline{x}_w}{\sqrt{U^2(x_i) - U^2(\overline{x}_w)}} \tag{9}$$

Laboratories with $E_n > 1$ were excluded from the calculation of the KCRV unless the Birge criterion (8) was still valid.

6.3 6 mm plug results

The following three tables show the measurement results sent by the participants for the upper, middle and lower measurement position, the KCRV, deviations from the KCRV, the E_n values and the Birge ratios (R_B and critical). On/off indicates if a result contributes to the KCRV.

Standard:	**6 mm plug**	**ID 606**				
Position:	***Up: 3 mm ↑ middle***					
Lab name	Reported result					
	Diameter /µm	*u* /µm	U(95) /µm	on/off	En	Deviation /µm
INRIM	6000.195	0.050	0.100	1	0.31	-0.025
VSL beg. Impr. Unc.	5999.891	0.045	0.090	0	3.04	-0.329
VSL beg. Cmc. Unc.	5999.891	0.100	0.200	0	1.58	-0.329
NPL 1	6000.212	0.041	0.082	1	0.15	-0.008
NPL 2	6000.170	0.042	0.084	0	0.49	-0.050
MIRS	5999.800	0.150	0.300	0	1.37	-0.420
SMD	6000.349	0.093	0.186	1	0.73	0.129
VSL end, 0,1N m2	6000.207	0.045	0.090	0	0.12	-0.013
VSL end, ULM	6000.182	0.045	0.090	0	0.35	-0.038

	Diameter /µm	*u* /µm	U(95) /µm
KCRV	**6000.22**	**0.03**	**0.06**

2	N-1	0.018	u_{ext}
2.21	chiobs^2	0.017	u_{int}
5.99	chi^2(0.05)	1.052	R_B
avg En<1	**0.397**	1.76	limit2s
Chi ok		**Birge 2s ok**	

Standard:	**6 mm plug**	**ID 606**				
Position:	***Middle***					
Lab name	Reported result					
	Diameter /µm	*u* /µm	U(95) /µm	on/off	En	Deviation /µm
INRIM	6000.150	0.040	0.080	1	0.33	-0.020
VSL beg. Impr. Unc.	5999.871	0.045	0.090	0	2.85	-0.299
VSL beg. Cmc unc	5999.871	0.100	0.200	0	1.44	-0.299
NPL 1	6000.192	0.040	0.080	1	0.38	0.022
NPL 2	6000.160	0.042	0.084	0	0.10	-0.010
MIRS	5999.850	0.150	0.300	1	1.08	-0.320
SMD	6000.284	0.096	0.192	1	0.62	0.114
VSL end 0.2N m2	6000.081	0.045	0.090	0	0.84	-0.089
VSL end, 0.1N m2	6000.181	0.045	0.090	0	0.11	0.011
VSL end, ULM	6000.150	0.045	0.090	0	0.19	-0.020

	Diameter /µm	*u* /µm	U(95) /µm
KCRV	**6000.17**	**0.03**	**0.05**

3	N-1	0.023	u_{ext}
6.51	chiobs^2	0.016	u_{int}
7.81	chi^2(0.05)	1.473	R_B
avg En<1	**0.602**	1.64	limit2s
Chi ok		**Birge 2s ok**	

Note: although the MIRS result has E_n > 1 the Birge ratio is still OK so this result is included in the calculation of the KCRV.

Standard:	**6 mm plug**	**ID 606**				
Position:	***Low: 3 mm ↓ middle***					
Lab name	Reported result					
	Diameter /µm	*u* /µm	U(95) /µm	on/off	En	Deviation /µm
INRIM	6000.120	0.035	0.070	1	0.35	-0.017
VSL beg. Impr. Unc	5999.854	0.045	0.090	0	2.74	-0.283
VSL beg. Cmc unc	5999.854	0.100	0.200	0	1.37	-0.283
NPL 1	6000.162	0.041	0.082	1	0.39	0.025
NPL 2	6000.120	0.042	0.084	0	0.17	-0.017
MIRS	5999.870	0.150	0.300	1	0.90	-0.267
SMD	6000.242	0.098	0.196	1	0.55	0.105
VSL end, 0.1N m2	6000.099	0.045	0.090	0	0.37	-0.038
VSL end, ULM	6000.102	0.045	0.090	0	0.34	-0.035

	Diameter /µm	*u* /µm	U(95) /µm
KCRV	**6000.14**	**0.03**	**0.05**

3	N-1	0.021	u_{ext}
4.92	chiobs^2	0.016	u_{int}
7.81	chi^2(0.05)	1.281	R_B
avg En<1	**0.549**	1.64	limit2s
Chi ok		**Birge 2s ok**	

The following graphs show the measurement results for the 6 mm plug of all participants and the calculated KCRV.

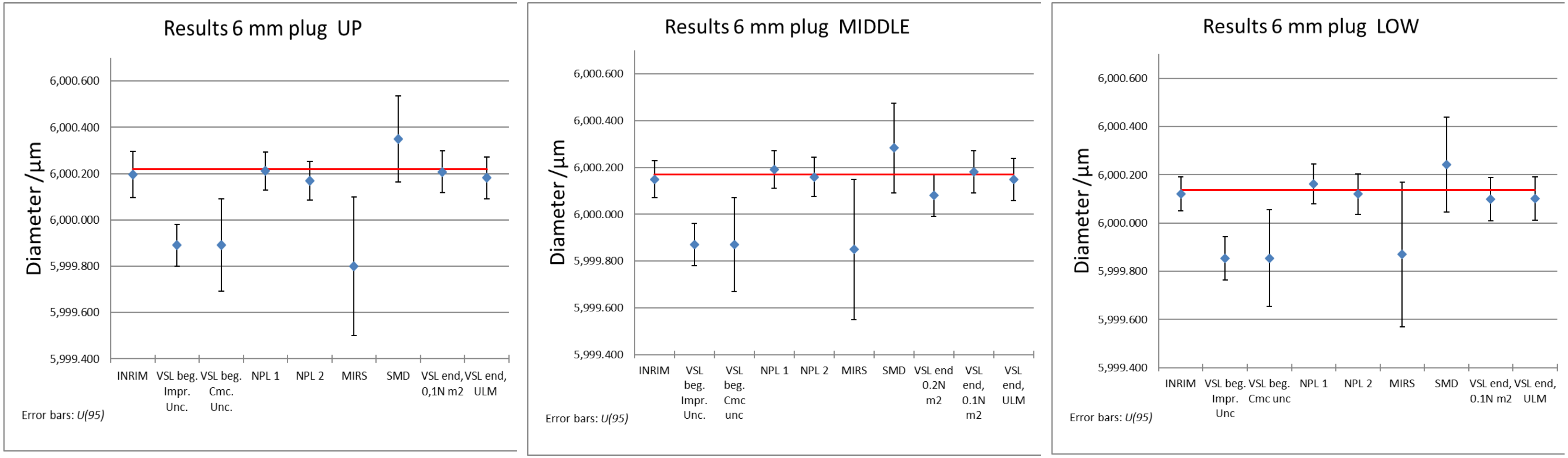

Figure 7 Graphical representation of the results for the 6 mm plug for the three measurement positions. The red line indicates the KCRV. The error bars correspond to the expanded uncertainty.

6.4 25 mm plug results

The following three tables show the measurement results sent by the participants for the upper, middle and lower measurement position, the KCRV, deviations from the KCRV, the E_n values and the Birge ratios (R_B and critical). On/off indicates if a result contributes to the KCRV.

Standard:	**25 mm plug ID 2517**					
Position:	***Up: 7 mm ↑ middle***					
Lab name	Reported result					
	Diameter /µm	*u* /µm	U(95) /µm	on/off	En	Deviation /µm
INRIM	25000.010	0.035	0.070	1	0.12	0.006
VSL beg. Impr. Unc.	24999.921	0.047	0.094	1	1.01	-0.083
VSL beg. Cmc. Unc.	24999.921	0.101	0.202	0	0.40	-0.083
NPL 1	25000.045	0.045	0.090	1	0.53	0.041
MIRS	24999.780	0.150	0.300	1	0.75	-0.224
SMD	25000.115	0.071	0.142	1	0.83	0.111
VSL end, 0,1N m2	25000.067	0.047	0.094	0	0.61	0.063
VSL end, ULM	25000.042	0.047	0.094	0	0.37	0.039

	Diameter /µm	*u* /µm	U(95) /µm
KCRV	**25000.00**	**0.02**	**0.04**

4	N-1	0.027	u_{ext}
8.70	chiobs^2	0.018	u_{int}
9.49	chi^2(0.05)	1.475	R_B
avg En<1	**0.647**	1.56	limit2s
Chi ok		**Birge 2s ok**	

Note: although the VSL result has E_n > 1 the Birge ratio is still OK so this result is included in the calculation of the KCRV.

Standard:	25 mm plug	ID 2517				
Position:	***Middle***					
Lab name	Reported result					
	Diameter /µm	*u* /µm	U(95) /µm	on/off	En	Deviation /µm
INRIM	25000.020	0.055	0.110	1	0.03	0.003
VSL beg. Impr. Unc.	24999.945	0.045	0.090	1	0.97	-0.072
VSL beg. Cmc. Unc.	24999.945	0.101	0.202	0	0.35	-0.072
NPL 1	25000.065	0.045	0.090	1	0.65	0.048
MIRS	24999.790	0.150	0.300	1	0.77	-0.227
SMD	25000.120	0.071	0.142	1	0.78	0.103
VSL end 0.2N m1	24999.995	0.045	0.090	0	0.21	-0.022
VSL end, 0,1N m2	25000.075	0.045	0.090	0	0.56	0.058
VSL end, ULM	25000.044	0.045	0.090	0	0.26	0.027

	Diameter /µm	*u* /µm	U(95) /µm
KCRV	**25000.02**	**0.03**	**0.05**

4	N-1	0.025	u_{ext}
8.12	chiobs^2	0.018	u_{int}
9.49	chi^2(0.05)	1.425	R_B
avg En<1	**0.639**	1.56	limit2s
Chi ok		**Birge 2s ok**	

Standard:	**25 mm plug ID 2517**					
Position:	***Low: 7 mm ↓ middle***					
Lab name	Reported result					
	Diameter /µm	*u* /µm	U(95) /µm	on/off	En	Deviation /µm
INRIM	25000.040	0.045	0.090	1	0.04	0.003
VSL beg. Impr. Unc.	24999.993	0.045	0.090	1	0.59	-0.044
VSL beg. Cmc. Unc.	24999.993	0.101	0.202	0	0.21	-0.044
NPL 1	25000.075	0.050	0.100	1	0.44	0.038
MIRS	24999.780	0.150	0.300	1	0.87	-0.257
SMD	25000.118	0.071	0.142	1	0.61	0.081
VSL end, 0,1N m2	24999.999	0.045	0.090	0	0.37	-0.038
VSL end, ULM	24999.959	0.045	0.090	0	0.76	-0.078

	Diameter /µm	*u* /µm	U(95) /µm
KCRV	**25000.04**	**0.02**	**0.05**

4	N-1	0.023	u_{ext}
5.79	chiobs^2	0.019	u_{int}
9.49	chi^2(0.05)	1.203	R_B
avg En<1	**0.510**	1.56	limit2s
Chi ok		**Birge 2s ok**	

The following graphs show the measurement results for the 25 mm plug of all participants.

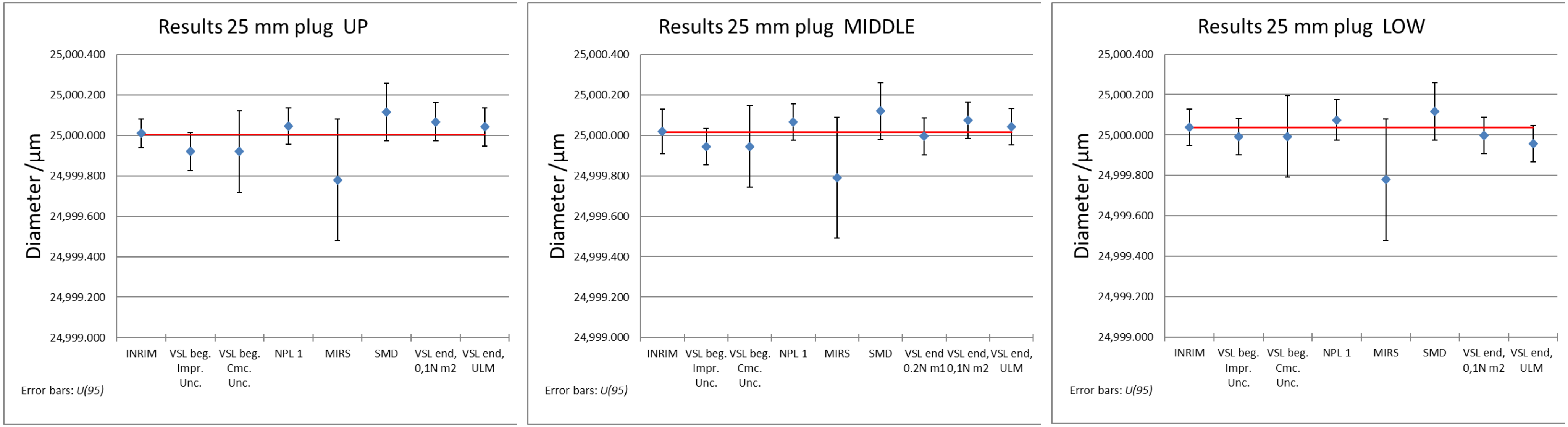

Figure 8 Graphical representation of the results for the 25 mm plug for the three measurement positions. The red line indicates the KCRV. The error bars correspond to the expanded uncertainty.

6.5 50 mm plug results

The following three tables show the measurement results sent by the participants for the upper, middle and lower measurement position, the KCRV, deviations from the KCRV, the E_n values and the Birge ratios (R_B and critical). On/off indicates if a result contributes to the KCRV.

Standard:	**50 mm plug**	**ID 5773**				
Position:	***Up: 7 mm ↑ middle***					
Lab name	Reported result					
	Diameter /µm	*u* /µm	U(95) /µm	**on/off**	En	Deviation /µm
INRIM	50001.890	0.040	0.080	1	0.66	0.040
VSL beg. Impr. Unc.	50001.715	0.052	0.104	1	1.49	-0.135
VSL beg. Cmc. Unc.	50001.715	0.103	0.207	0	0.63	-0.135
NPL 1	50001.906	0.057	0.114	1	0.55	0.056
MIRS	50001.780	0.160	0.320	1	0.22	-0.070
SMD	50001.916	0.082	0.164	1	0.42	0.066
VSL end, 0,1N m2	50001.925	0.052	0.104	0	0.64	0.075
VSL end, ULM	50001.932	0.052	0.104	0	0.70	0.082

	Diameter /µm	*u* /µm	U(95) /µm
KCRV	**50001.85**	**0.03**	**0.05**

4	N-1	0.032	u_{ext}
9.49	chiobs^2	0.021	u_{int}
9.49	chi^2(0.05)	1.540	R_B
avg En<1	**0.669**	1.56	limit2s
Chi ok		**Birge 2s ok**	

Note: although the VSL result has E_n > 1 the Birge ratio is still OK so this result is included in the calculation of the KCRV.

Standard:	**50 mm plug**	**ID 5773**				
Position:	***Middle***					
Lab name	Reported result					
	Diameter /µm	*u* /µm	U(95) /µm	on/off	En	Deviation /µm
INRIM	50001.790	0.035	0.070	1	0.31	0.016
VSL beg. Impr. Unc.	50001.750	0.045	0.090	1	0.31	-0.024
VSL beg. Cmc. Unc.	50001.750	0.103	0.207	0	0.11	-0.024
NPL 1	50001.786	0.059	0.118	1	0.11	0.012
MIRS	50001.680	0.160	0.320	1	0.30	-0.094
SMD	50001.766	0.079	0.158	1	0.05	-0.008
VSL end 0.2N m1	50001.803	0.045	0.090	0	0.29	0.029
VSL end, 0,1N m2	50001.770	0.045	0.090	0	0.04	-0.004
VSL end, ULM	50001.764	0.045	0.090	0	0.10	-0.010

	Diameter /µm	*u* /µm	U(95) /µm
KCRV	**50001.77**	**0.02**	**0.05**

4	N-1	0.008	u_{ext}
0.89	chiobs^2	0.017	u_{int}
9.49	chi^2(0.05)	0.471	R_B
avg En<1	**0.217**	1.56	limit2s
Chi ok		**Birge 2s ok**	

Standard:	50 mm plug ID 5773					
Position:	*Low: 7 mm ↓ middle*					
Lab name	Reported result					
	Diameter /µm	*u* /µm	U(95) /µm	on/off	En	Deviation /µm
INRIM	50001.570	0.035	0.070	1	0.01	0.000
VSL beg. Impr. Unc.	50001.597	0.045	0.090	1	0.34	0.027
VSL beg. Cmc. Unc.	50001.597	0.103	0.207	0	0.13	0.027
NPL 1	50001.546	0.057	0.114	1	0.23	-0.024
MIRS	50001.460	0.160	0.320	1	0.35	-0.110
SMD	50001.565	0.075	0.150	1	0.04	-0.005
VSL end 0.2N m2	50001.500	0.045	0.090	0	0.69	-0.070
VSL end, 0,1N m2	50001.509	0.045	0.090	0	0.60	-0.061
VSL end, ULM	50001.562	0.045	0.090	0	0.08	-0.008

	Diameter /µm	*u* /µm	U(95) /µm
KCRV	**50001.57**	**0.02**	**0.05**

4	N-1	0.009	u_{ext}
1.01	chiobs^2	0.017	u_{int}
9.49	chi^2(0.05)	0.503	R_B
avg En<1	**0.195**	1.56	limit2s
Chi ok		**Birge 2s ok**	

The following graphs show the measurement results for the 50 mm plug of all participants.

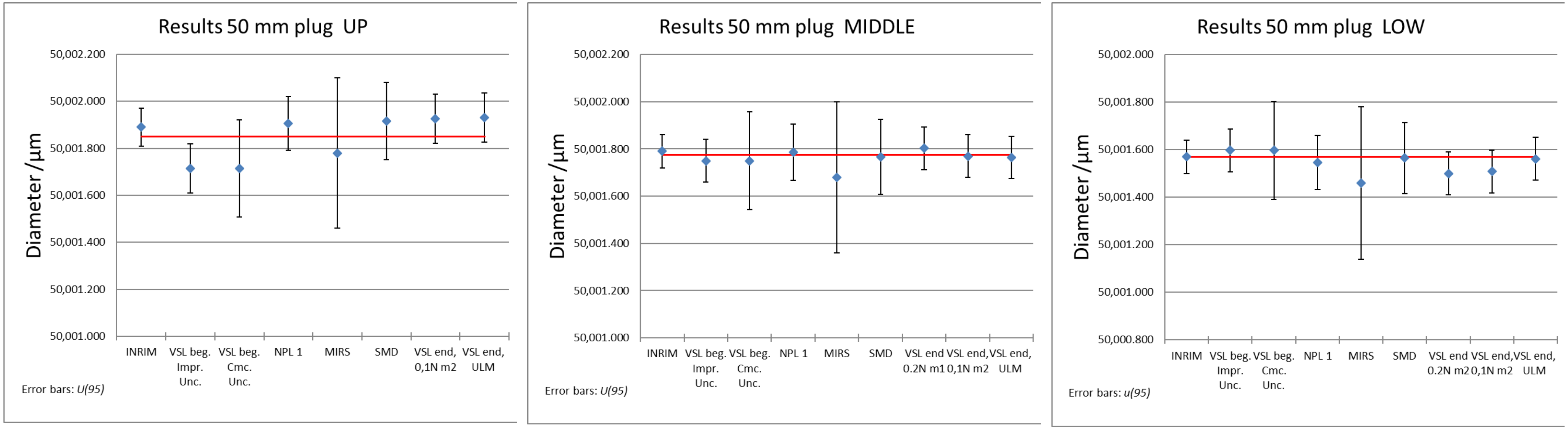

Figure 9 Graphical representation of the results for the 50 mm plug for the three measurement positions. The red line indicates the KCRV. The error bars correspond to the expanded uncertainty.

6.6 30 mm sphere results

The table below shows the measurement results sent by the participant for the 30 mm diameter sphere, the KCRV, deviations from the KCRV, the E_n values and the Birge ratios (R_B and critical). On/off indicates if a result contributes to the KCRV.

Standard:	**30 mm sphere**	**ID SPH30LK4**				
Position:	***Measurement direction conform protocol***					
Lab name	Reported result					
	Diameter /µm	*u* /µm	U(95) /µm	on/off	En	Deviation /µm
INRIM	3000.300	0.050	0.100	1	0.16	0.012
VSL beg. Impr. Unc.	3000.501	0.051	0.103	0	1.74	0.213
VSL beg. Cmc unc	3000.501	0.110	0.220	0	0.93	0.213
NPL 1	3000.290	0.058	0.116	1	0.02	0.002
MIRS	3000.090	0.150	0.300	1	0.68	-0.198
SMD	3000.310	0.078	0.156	1	0.15	0.022
VSL end 0.2N m1	3000.471	0.051	0.103	0	1.49	0.183
VSL end 0.2N m1	3000.471	0.110	0.220	0	0.80	0.183
VSL end, 0.1N m1	3000.568	0.110	0.220	0	1.22	0.280

	Diameter /µm	*u* /µm	U(95) /µm
KCRV	**3000.29**	**0.03**	**0.07**

3	N-1	0.018	u_{ext}
1.88	chiobs^2	0.023	u_{int}
7.81	chi^2(0.05)	0.792	R_B
avg En<1	**0.252**	1.64	limit2s
Chi ok		**Birge 2s ok**	

The following graph shows the measurement results for the 30 mm diameter sphere of all participants.

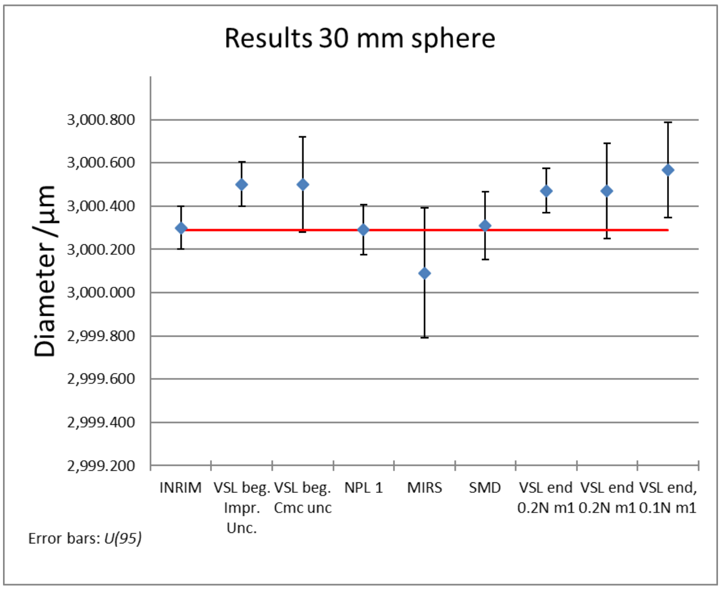

Figure 10 Graphical representation of the results for the 30 mm diameter sphere. The red line indicates the KCRV. The error bars correspond to the expanded uncertainty.

7 Discussion of results

1) The stability of artefacts was maintained along the comparison.

2) After circulating of the draft B1 report NPL discovered during a measurement service audit, that they have been assuming an incorrect material for the anvils on the comparator (NPL1). This means that the compression corrections they had been applying on this (and other measurements) were incorrect. They have re-calculated the values and made some minor changes to their results. The analysis of the comparison has been revaluated using these results and a new KCRV has been calculated. The E_n values for all participants only change slightly using the corrected results of NPL and do not affect the conclusions and CMC support evaluation. Therefore, it was decided to use the corrected results of NPL as the final results for the evaluation.

3) For the 6 mm plug the following was observed:

   VSL: The VSL results at the beginning of the comparison show E_n values > 1 (also for the CMC uncertainty). The VSL measurements at end of the comparison show E_n values < 1 (also with the improved uncertainty). The results at the end are due to an improved mounting method and lower measuring force. See section on stability of the artefact for further explanation. The results of the secondary technique of VSL (ULM with laser interferometer) have an E_n value < 1. The VSL results at the beginning have been excluded from contributing to the KCRV due to E_n > 1. Secondary VSL results have not been used at all for the calculation of the KCRV to avoid bias.

   MIRS: The Up and Middle measurement results have E_n values of 1.37 and 1.08 respectively. For the KCRV of the up diameter, the result of MIRS was excluded. For the middle diameter, the Birge ratio was satisfied and the result of MIRS was included.

   NPL: For NPL only the result of NPL1 contributes to the reference value, as only one result per NMI is allowed to contribute. Both NPL1 and NPL2 have E_n values < 1.

4) For the 25 mm plug the following was observed:

   VSL: The VSL results at the beginning of the comparison show E_n values < 1 based on CMC uncertainty and for the improved uncertainty only the Up measurement result has E_n = 1.01. The VSL measurements at the end of the comparison show E_n values < 1 (also with the improved uncertainty). The results at the end used an improved mounting method and lower measuring force. See section on stability of artefact for further explanation. The results of the secondary technique of VSL (ULM with laser interferometer) have an E_n value < 1.

5) For the 50 mm plug the following was observed:

   VSL: The VSL results at the beginning of the comparison show E_n values < 1 based on CMC uncertainty. The E_n value based on the improved uncertainty is 1.49 for the Up measurement. The VSL measurements at the end of the comparison show E_n values < 1 (also with the improved uncertainty). The results at the end used an improved mounting method and lower measuring force. See section on stability of artefact for further explanation. The results of the secondary technique of VSL (ULM with laser interferometer) have an E_n value <1. Only the first results of VSL have been included in the calculation of the KCRV.

6) For the 30 mm Sphere the following was observed:

VSL: The VSL results at beginning and at the end of the comparison show E_n values < 1 based on the former CMC uncertainty (before sept 2015) and the E_n values >1 based on the improved CMC uncertainty (after sept 2015). No VSL results were included in the calculation of the KCRV.

8 Conclusion and CMC support.

INRIM

The results of INRIM support their respective CMC's.

NPL

The results of NPL both the initial as well as the corrected results agree within their stated uncertainties and support reducing their CMCs to the uncertainties stated for this comparison.

In fact for the 2016 CMC submission process, the performance in this comparison (draft B1) was used as evidence to have NPL CMC claim uncertainties revert back to the values which they claimed prior to the poor performance in the earlier K4 comparison. They were approved on 12 Sept 2016. As stated above, the small change in the NPL values after draft B1 does not change the conclusions of this comparison.

SMD

SMD submitted higher uncertainties than their CMC claim. The following explanation and action was given by SMD. The 6 mm plug was calibrated with a 5 mm reference plug that has a higher uncertainty than the reference plugs used for the calibration of the 25 mm and 50 mm plugs (150 nm uncertainty for the 5 mm plug, at k = 2, and 100 nm uncertainty for the other plugs). This led to a higher uncertainty for the 6 mm plug. An uncertainty of around 0.15 µm (k = 2) instead of the reported 0.19 µm would be possible if the 6 mm plug was calibrated with our 30 mm reference plug. This would still be higher than the 0.13 µm uncertainty of our CMC claim.
After studying the results, two problems have been identified. A) The CMC claim was calculated based on previous calibrations of our reference plugs, with lower uncertainty, and it was not recalculated after more recent calibrations. B) The contribution to the uncertainty of the measuring machine itself depends on the difference between the nominal diameters of the reference plug and the measured plug. For the CMC claim, the contribution based on the difference in diameter was assumed to be negligible, which is true for diameter differences smaller than 15 mm. However, due to the higher uncertainty of our 5 mm plug, this contribution should be taken into account for smaller plugs, because these smaller plugs should ideally be compared to the 30 mm reference plug with its lower uncertainty.
Based on the results in this comparison, SMD will submit newly calculated CMC's for diameter measurement (plug and ring diameters, as the calculations for rings are almost identical).

VSL

The results at the beginning of the comparison for VSL are not in agreement with the CMC for the "CMM with laser interferometer calibration set-up" for the 6 mm plug. VSL measurements at end of comparison show E_n values < 1 (also with improved uncertainty). The results at the end are due to an improved mounting method and lower measuring force. The results at the beginning for the 25 mm and 50 mm plug support the current CMC. The results with the "ULM with laser interferometer" support the CMC claim of this calibration set-up. The improved CMM set-up, see section on stability, supports the current-CMC and provides evidence for an improved CMC claim. VSL has decided to participate in the next K4 comparison (EURAMET.L-K4. 2016) to provide further evidence for a possible improved CMC claim.

The VSL results of the 30 mm sphere do not support their recently improved CMC (September 2015) which was supported by the previous K4 comparison. The VSL results agree for the previous CMC value (Before September 2015). This is probably due to the difference in the way the sphere is mounted by the manufacturer/supplier. In the previous K4 comparison the sphere was mounted on a plate while in this comparison it was mounted on a shaft. This results in a different way of mounting the artefact. VSL has decided not to issue certificates with the improved uncertainty but with the previous CMC uncertainty (before September 2015). Furthermore, for current diameter measurements of spheres with the CMM, the sphere will be removed from the shaft when possible. In case a shaft remains, the measurement will be performed for varying forces and extrapolated to a force free diameter, or alternatively the displacement of the shaft will be monitored and corrected for. A development project has started in the beginning of 2017 to resolve the issue. The improved set-up will then be tested in the upcoming EURAMET.L-K4.2016.

MIRS

The results of MIRS of the 6 mm plug do not support their submitted uncertainty and the results of the 25 mm plug might indicate a significant systematic uncertainty. MIRS provided the following explanation. In original comparison, the results of MIRS/UM-FS/LTM has supported the CMC for small diameters (5 mm plug), but not for bigger diameters (50 mm) - 2-point method (1D comparator + laser interferometer) was used for all measurements. As a consequence, new calibration procedure was written (and accredited) in which diameters up to 10 mm shall be measured by using the 2-point method (1D comparator + laser interferometer); while diameters above 10 mm are measured on a CMM by using a substitution method. In this follow-up comparison, substitution method on a CMM was used also for 6 mm in order to check capability of this method for small diameters (this measurement is faster than the 2-point measurement). However, this method is not used for clients requesting the uncertainty at the CMC level.