**EUROMET Key Comparison**

**EUROMET.L-K4**

**(EUROMET Project 812)**

# Calibration of diameter standards

**GROUP 2**
**Version B**
**FINAL v. 1.2**

**MKEH**
**Hungarian Trade Licencing Office**

MKEH Budapest, May 2010
Edit Bánréti

**CONTENT**

# 1. Introduction

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

At its meeting in October 2003, the EUROMET TC Length decided upon a key comparison on diameter standards, numbered EUROMET.L-K4. This comparison follows the previous 384 (EUROMET.L-K4) comparison.

Due to the large number of the participants, it has been decided to have 2 groups in the project. The participants for the 2 groups were separated according to the claimed uncertainties. Those whose expanded uncertainties are less that or equal to 0.3 micrometer (for 50 mm gauge) belong to the group 1, the others to the group 2. The link between the two groups was served by the laboratories who took part in both the group 1 and group 2.

Mr. Gian Bartolo Picotto, INRIM (formerly IMGC) Italy acts as the pilot laboratory for the group 1, Ms. Edit Banreti, MKEH (formerly OMH) Hungary acts as the pilot for the group 2.

The measurements started in 2005, after purchasing and the preliminary measurements of the gauges.

A goal of the EUROMET key comparisons for topics in dimensional metrology is to demonstrate the equivalence of routine calibration services offered by NMIs to clients, as listed in Appendix C of the Mutual Recognition Agreement (MRA) [BIPM, 1999]. To this end, participants in this comparison agree to use the same apparatus and methods as routinely applied to client artefacts.

# 2. Organisation

## *2.1. Participants in the group 2*

Table 1

| Laboratory | Address | Contact person /tel/fax/e-mail |
|---|---|---|
| BEV | Bundesamt für Eich – und Vermessungswesen<br>Arltgasse 35<br>A-1160 Wien<br>Austria | Dr. Michael Matus<br>+43 1 21110 6540<br>+43 1 21110 6000<br>michael.matus@bev.gv.at |
| CEM | Centro Espanol de Metrologia<br>Alfar, 2<br>ES-28760 Tres Cantos (Madrid)<br>Spain | Mr. Emilio Prieto<br>+34 91 807 47 16<br>+34 91 807 48 07/809<br>eprieto@cem.mityc.es |
| CMI | Czech Metrology Institute<br>V Botanice 4<br>CZ 150 70 Praha 5<br>Czech Republic | Dr. Petr Balling<br>+420 257 288 326<br>+420 257 32 80 77<br>pballing@cmi.cz |
| DTI | Danish Technological Institute<br>Gregersensvej 1<br>DK-2630 Taastrup<br>Denmark | Mr. Jens Bo Toftegaard<br>+45 7220 3034<br>+45 7220 2999<br>jens.bo.toftegaard@teknologisk.dk |
| EIM | Hellenic Institute of Metrology<br>Industrial Area of Thessaloniki<br>Block 45<br>GR-57 022 Sindos<br>Thessaloniki<br>Greece | Dr. Christos Bandis<br>+30 2310 56 99 99<br>+30 2310 56 99 96<br>bandis@eim.gr |
| FSB | University of Zagreb<br>Faculty of Mechanical Eng. and Naval Architecture<br>Ivana Lucica 5<br>HR 10000 Zagreb<br>Croatia | Mr. Vedran Mudronja<br>+385 1 616 83 27<br>+385 1 616 85 99<br>vedran.mudronja@fsb.hr |
| GUM | Central Office of Measures<br>ul. Elektoralna 2<br>PL-00950 Warszawa<br>Poland | Mr. Zbigniew Ramotowski<br>+48 22 581 9543<br>+48 22 620 8378<br>length@gum.gov.pl |
| INRIM<br>(formerly IMGC) -link | Instituto Nazionale di Ricerca Metrologica<br>Strada delle cacce, 91<br>IT-10135 Torino<br>Italy | Mr. Gian Bartolo Picotto<br>+39 011 3977 469<br>+39 011 3977 459<br>g.picotto@inrim.it |
| INM | National Institute of Metrology<br>11, Sos. Vitan-Barzest<br>RO-042122<br>Bucharest 4<br>Romania | Mr. Alexandru Duta<br>+40 21 334 55 20<br>+40 21 334 55 33<br>alexandru.duta@inm.ro |
| LNMC | Latvian National Metrology Centre<br>157, K. Valdemara Str.<br>Riga, LV-1013<br>Latvia | Ms. Edite Turka<br>+371 7 362 086<br>+371 7 362 805<br>edite.turka@lnmc.lv |

| | | |
|---|---|---|
| METAS (link) | METAS<br>Lindenweg 50<br>CH-3003 Bern-Wabern<br>Switzerland | Dr. Rudolf Thalmann<br>+41 31 32 33 385<br>+41 31 32 33 210<br>rudolf.thalmann@metas.ch |
| METROSERT | AS Metrosert<br>Aru 10<br>EE-10317 Tallinn<br>Estonia | Mr. Lauri Lillepea<br>+372 6 019 508<br>+372 6 020 081<br>lauri.lillepea@metrosert.ee |
| MIRS | University of Maribor<br>Faculty of Mech. Eng.<br>Smetanova 17<br>SI-2000 Maribor<br>Slovenia | Dr. Bojan Acko<br>+386 2 220 7581<br>+386 2 220 7990<br>bojan.acko@uni-mb.si |
| MKEH<br>(formerly OMH) | Hungarian Trade Licencing Office<br>H-1124 Budapest<br>Németvölgyi út 37-39<br>Hungary | Ms. Edit Banreti<br>+36 1 458 59 97<br>+36 1 458 59 27<br>banretie@mkeh.hu |
| NSAI<br>(formerly NML) | NSAI National Metrology Laboratory<br>Claremont Avenue, Glasnevin<br>IE-9 Dublin<br>Ireland | Mr. Paul Turner<br>+353 1 808 2611<br>+353 1 808 2603<br>paul.turner@nsai.ie |
| NPL (link) | National Physical Laboratory<br>Queens Road<br>Teddington Middlesex<br>TW 11 OLW<br>United Kingdom | Dr. Andrew Lewis<br>+44 20 8943 6124<br>+44 20 8614 0533<br>andrew.lewis@npl.co.uk |
| NRC | Institute for National Measurement Standards (INMS)<br>National Research Council Canada (NRC)<br>1200 Montreal Road<br>Ottawa, ON, Canada<br>K1A OR6 | Mr. Kostadin Doytchinov<br>+613 991 0265<br>+613 952 1394<br>Kostadin.Doytchinov@nrc-cnrc.gc.ca |
| UME | Ulusal Metroloji Enstitüsü<br>Tübitak, UME<br>Anibal Cad. Besevler<br>TR-Gebze, Kocaeli 41470<br>Turkey | Dr. Tanfer Yandayan<br>+90 262 646 63 55/235<br>+90 262 646 59 14<br>tanfer.yandayan@ume.tubitak.gov.tr |

### 2.2. Schedule

Table 2 indicates the timetable for the group 2 with the dates for performing the measurements.
The gauges have been purchased from Switzerland. METAS had measured the gauges before the technical protocol was available in order to check if the gauges were in suitable condition for the comparison.
At the EURAMET TC-L meeting held in October 2008, METAS kindly offered to measure the gauges according to the technical protocol, to have better link between the two groups and also to the CCL comparison.

Table 2

| Laboratory | Country | Date |
|---|---|---|
| MKEH (OMH) | Hungary | May-June 2005 |
| BEV | Austria | July 2005 |
| - | - | August 2005 |
| CMI | Czech Republic | September 2005 |
| GUM | Poland | October 2005 |
| NSAI (NML) | Ireland | November 2005 |
| DTI | Denmark | December 2005 |
| NPL (link) | United Kingdom | January 2006 and March-Apr 2009 |
| MIRS | Slovenia | February 2006 |
| EIM | Greece | March 2006 |
| METROSERT | Estonia | April 2006 |
| LNMC | Latvia | May 2006 |
| MKEH (OMH) | Hungary | June 2006 |
| INRIM (link) | Italy | July 2006 |
| FSB | Croatia | August 2006 |
| INM | Romania | September 2006 |
| UME | Turkey | October 2006 |
| NRC | Canada | November 2006 |
| CEM | Spain | December 2006 |
| MKEH | Hungary | January 2007 |
| MKEH | Hungary | September 2008 |
| METAS (link) | Switzerland | February 2009 |

The comparison was organized in two loops because of the limited validity of the ATA Carnet. The first loop was organized to have the circulation within the EU countries, than an ATA Carnet was used to circulate in the second loop. There was 1 month delay in the first loop, but we had more than 6 months delay as a consequence of custom problems, delay in shipment to the next participant, etc.

The gauges were measured 4 times by the pilot laboratory, before the circulation, after the first loop, after the second loop and one year later in order to check the stability of the gauges.

# 3. Standards

The gauges that were taken part in the comparison are listed in the table 3 below.

Table 3

| Type | Manufacturer | Identification | Dimension [mm] | Material |
|---|---|---|---|---|
| Ring | Microtool | 2619 | 5 | Steel |
| Ring | Microtool | 2618 | 40 | Steel |
| Plug | Microtool | 2621 | 5 | Steel |
| Plug | Microtool | 2620 | 50 | Steel |
| Sphere | SWIP | D 4901 | 30 | Ceramic ($Al_2O_3$) |

**Inscriptions:**

Ring gauges: the two ring gauges were marked on their upper surface with their identification and two lines indicating the measurement direction.

Plug gauges: the two plug gauges were marked on their handle with their identification and their upper surface two lines indicating the measurement direction.

Sphere: the identification number and two lines indicating the measurement direction were marked on the bottom of the ball near the shaft.

# 4. Measurement instructions and reporting of results

## *4.1. Traceability*

Length measurements had to be traceable to the latest realisation of the metre as set out in the current "*Mise en Pratique*".

Temperature measurements had to be made using the International Temperature Scale of 1990 (ITS-90).

## *4.2. Measurand*

The measurand was the diameter of each gauge at 20 ºC and corrected to zero force. The diameter of the ring and plug gauges had to be measured at the marked lines in 3 different heights according to the table below. The diameter of the sphere had to be measured at the marked lines.

*„x mm↑" and „x mm↓"* refer to the required measurement locations *x* mm above and below the mid height of the cylinder. The upper side of the rings was defined by the inscription, for the plugs the handle or the holding cylinder were assumed to be below.

The measurement locations for the cylindrical gauges are shown in table 4:

Table 4

| ∅ 5 mm ring gauge | ∅ 40 mm ring gauge | ∅ 5 mm plug gauge | ∅ 50 mm plug gauge |
|---|---|---|---|
| 3 mm ↑ | 10 mm ↑ | 2 mm ↑ | 6 mm ↑ |
| middle | middle | middle | middle |
| 3 mm ↓ | 10 mm ↓ | 2 mm ↓ | 6 mm ↓ |

The roundness of the ring and plug gauges had also to be measured at the same heights as the diameter measurements and one roundness measurement for the sphere on the equator.
The straightness of the ring and plug gauges had to be measured in the marked lines (0 and 180) º.
The roundness and straightness measurements were required only if they are done normally for the customers as well.

The calibration had to be carried out as for a normal customer. It means that there was no information about the form error of the artefacts. The measurements had to be reported for zero measuring force and at the reference temperature of 20 °C, using a thermal expansion coefficient of $11{,}6 \cdot 10^{-6}$ 1/K for the cylindrical standards and $8{,}1 \cdot 10^{-6}$ 1/K for the ceramic ball, which were both assumed values because they have not been measured.

The participants were invited to report the deviation from roundness at given cut-off frequencies (in UPR) of the long-pass filter, in order to achieve a better comparability of the results. Gaussian filter had to be used, where it was available, but in any case the participants were asked to specify which type of filter they used.

For the 30 mm sphere, the participants were invited to report the deviation from roundness at 500 UPR, 150 UPR and 50 UPR.

In addition, following a decision at the 2005 EUROMET TC-L meeting, it was decided to use the results of roundness measurement on the sphere as evidence for proving CMC claims of those NMIs offering a roundness measuring service, or planning to submit a CMC for such a service, especially where such NMIs have no previous comparison evidence available. Participants were therefore invited to report the deviation from roundness of the sphere at 500, 150 and 50 UPR. These measurements had to be performed using the roundness measuring service for which the CMC claims are to be tested.

The uncertainty of measurement had to be estimated according to the ISO Guide for the Expression of Uncertainty in Measurement.

## 5. Measurement methods and instruments used by the participants

The methods and instruments used by the participants for the diameter measurements are listed in table 5, together with the traceability of those who used reference rings, plugs. The instruments for the roundness measurements are in table 6.

Table 5

| Laboratory | Equipment | Reference | Probe | Temp. [ºC] | Traceability of rings used |
|---|---|---|---|---|---|
| MKEH | SIP 550M length measuring machine. | Reference rings (12 and 40 mm) and plugs (5 and 50 mm) | Spherical $\phi$1.2 for ring 5, hooked for ring 40, flat for plugs and sphere | 19.5-20.5 | METAS |
| BEV | SIP 3002 length measuring machine with laser interferometer | Plug 50 mm, rings 20 and 40 mm | Spherical $\phi$1.2 , flat for plugs and sphere | 19.99-20.26 | METAS |
| CMI | SIP 1002M length measuring machine with laserinterferometer | Gauge blocks | Spherical for rings and plugs, flat for sphere | 19.7-20.3 | - |
| GUM | SIP 3002M length measuring machine | Gauge blocks<br>ring 5 mm | Spherical $\phi$2 for ring 5, hooked for ring 40, flat for plugs and sphere | 20.02-20.5 | Ring 5 mm: METAS |
| NML | OKM OPAL 600 Universal Measuring Machine | Gauge blocks | 1500 mN | 19.69-20.10 | - |
| DTI | ULM | | Spherical $\phi$2, $\phi$3, flat for plugs and sphere | 20.0-20.1 | DFM<br>DKD, Zeiss |
| NPL | NPL modified Zeiss metroscope (plug 50 and sphere), machine with capacitive sensors (plug 5) and NPL designed internal measuring machine (rings) | Gauge blocks and fused silica box standard | 5 mm / 2 mm diameter ball-ended 0.06 N,<br>2 mm / 0.5 mm flat,<br>0.15 N/2.5 N | 19.915-20.3 | - |
| MIRS | Zeiss ULM with laserinterferometer | External: absolute,<br>internal: gauge blocks | Spherical $\phi$2 for rings, flat for plugs and sphere | 19.71-19.95 | (gauge blocks BEV) |
| EIM | Mahr 828 with laserinterferometer | External: absolute,<br>internal: gauge blocks | Spherical $\phi$3for rings, $\phi$5 for plugs and sphere | 20.2-20.3 | - |
| METROSERT | ULM Opal with laserinterferometer | Ring<br>Plug | Spherical $\phi$0.62 for 5 mm, $\phi$10 for 40 mm, plane for plugs and sphere | 19.9-20.5 | MIKES |
| LNMC | Ring: ULM 828 CiM Plug: Optical vertical length comparator | Rings 10 and 50 mm | Spherical $\phi$3 for rings, flat for plugs | 19.8-20.1 | no information |

| | | | | | |
|---|---|---|---|---|---|
| INRIM | Moore measuring machine modified at INRIM with laserinterferometer and LVDT probe | Gauge block | Spherical, $\phi$2 and 3 mm | 19.92-20.00 | - |
| FSB | JOINT length meas. machine | Ring 50 for ring 50 mm | Spherical $\phi$1.5 for ring; plain $\phi$2 for plugs and sphere | 19.95-20.15 | INRIM |
| INM | SIP-MUL 1000 with HP5526 laserinterferometer | Gauge block 20 mm | Spherical, $\phi$3 mm | 20.00-20.60 | - |
| UME | Modified Mahr 828 CIM 1000 | Ref. ring 50 for rings, gauge blocks for plugs | Spherical, $\phi$3 and 5 mm | 19.7-20.3 | METAS |
| NRC | Mitutoyo Legex 707 CMM with MPP 300 probe | Gauge blocks | Spherical, $\phi$2 and 4 mm | 19.94-19.97 | - |
| CEM | Mitutoyo Ultra Quick Vision CMM | Gauge blocks, grade K | Spherical $\phi$2 and 4 mm | 19.89-20.10 | - |
| METAS | Cylindrical gauges: Length measuring machine designed by SIP and METAS Sphere: SIP 3002 length measurement machine (Abbe comparator) with laser interferometer and flat probes. | Gauge blocks | Spherical $\phi$1.5 for ring 5, $\phi$4 for ring 40 and plugs and flat for sphere | 19.98-20.07 | - |

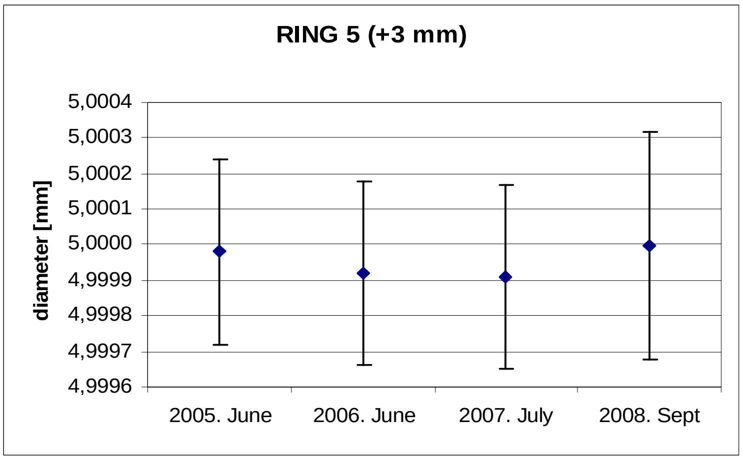
Table 6.

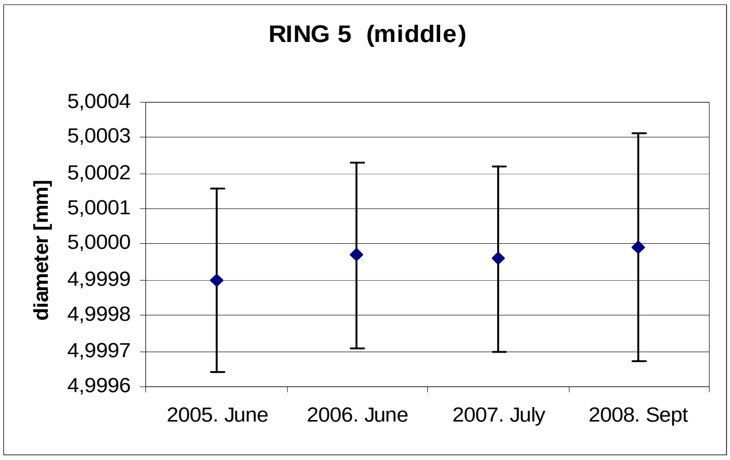
| Laboratory | Equipment |
|---|---|
| CMI | Taylor Hobson Talyrond 3-PC |
| GUM | Taylor Hobson Talyrond 210 |
| DTI | Formtester FAG 2100 |
| NPL | Taylor Hobson Talycenta (ring and plugs) and Taylor Hobson Talyrond 73 (sphere) |
| EIM | Taylor Hobson Talyrond 290 |
| METROSERT | Taylor Hobson TR 265 |
| INRIM | RTH TR30 modified at INRIM |
| FSB | Mahr MMQ 3 (ref: $\phi$50 hemisphere) |
| INM | Mahr MMQ 44 (round), TH Form Talysurf (str.) with roughness standard |
| UME | Mahr MFU 800/ MMQ 40 (results on MFU 800 was used) |
| CEM | Mitutoyo RA-H5000 0.01 µm resolution for rings and plugs, 0.001 µm with multi-step error sep. method |
| METAS | Taylor Hobson TR300 (cylindrical gauges), TR73 (sphere) |

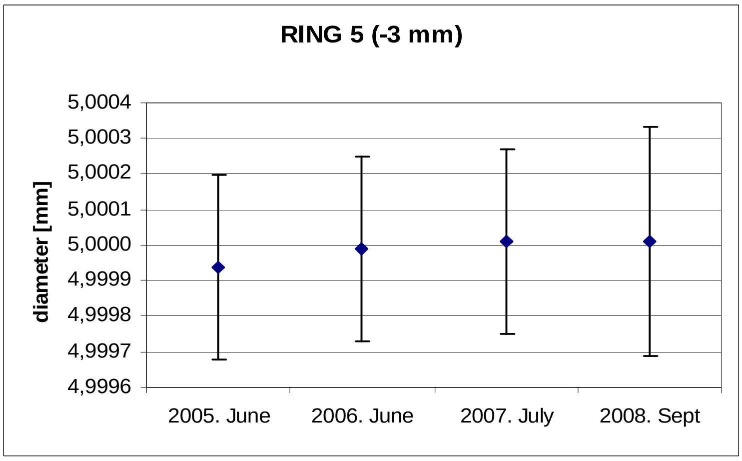
# 6. Stability of the gauges

The gauges were measured four times by the pilot laboratory, at the dates indicated in the graphs. The following diagrams show the measured diameters with the stated expanded uncertainties ($k$=2).

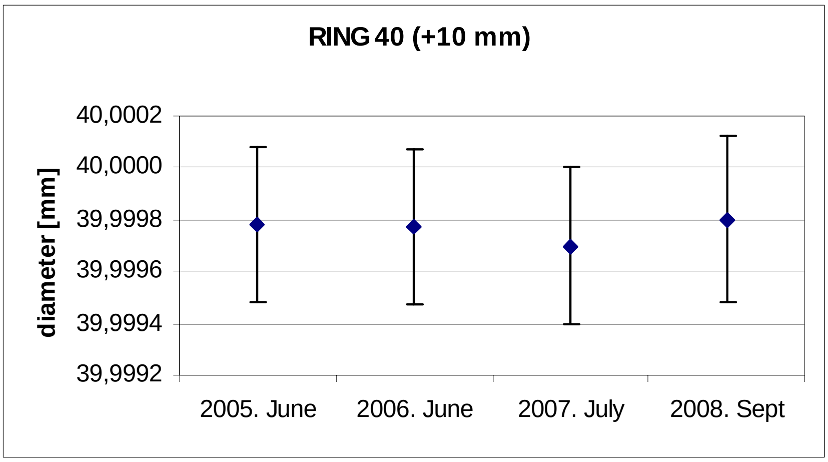
## *6.1. Stability of the ring 5 mm*

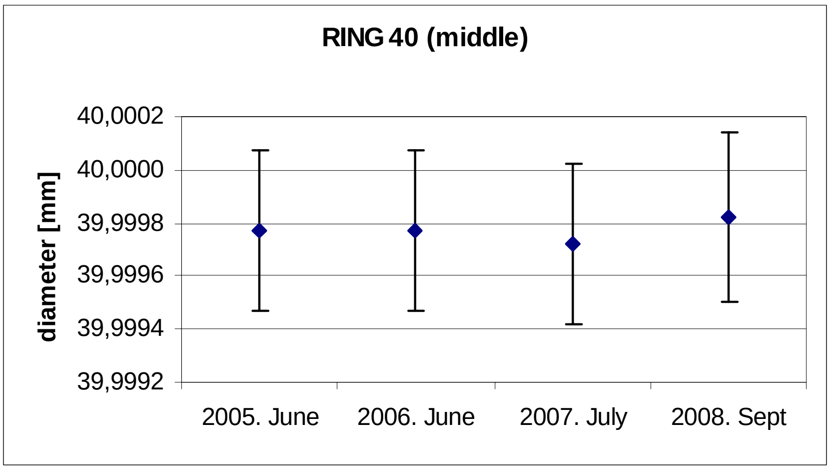


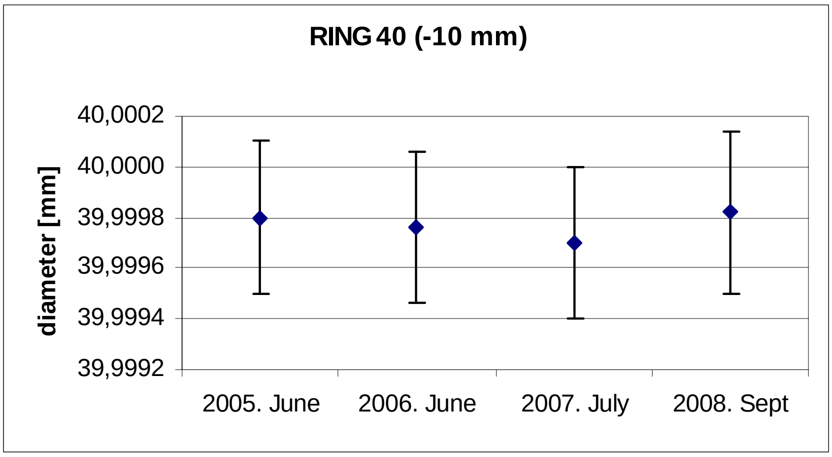



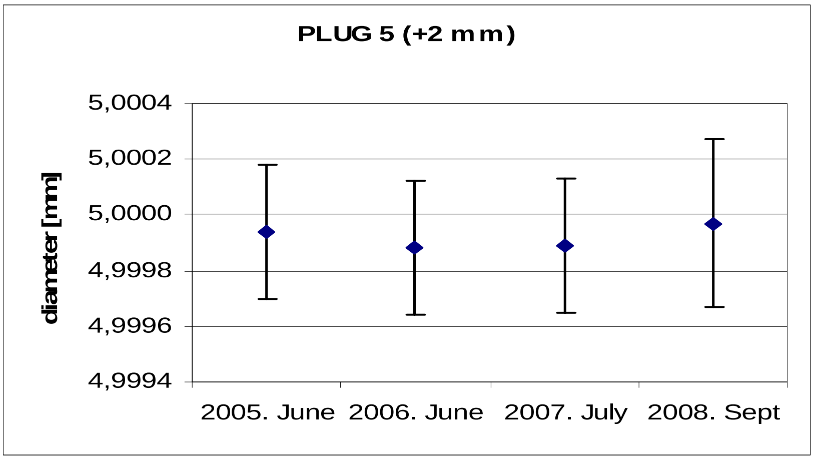
### 6.2. *Stability of the ring 40 mm*

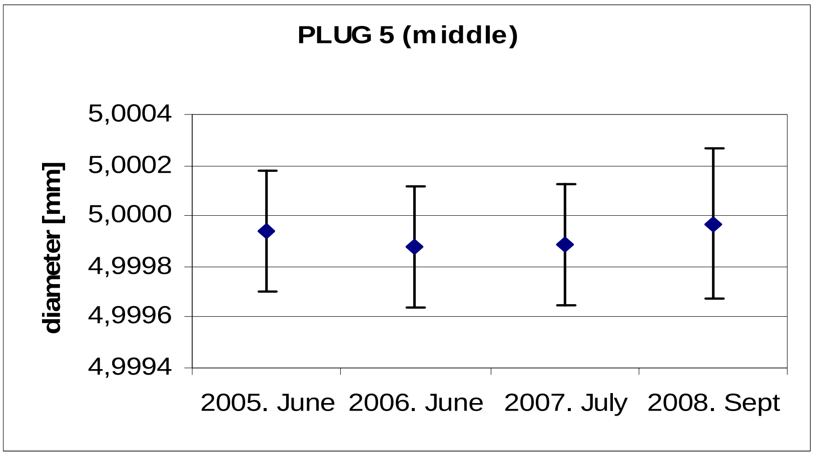


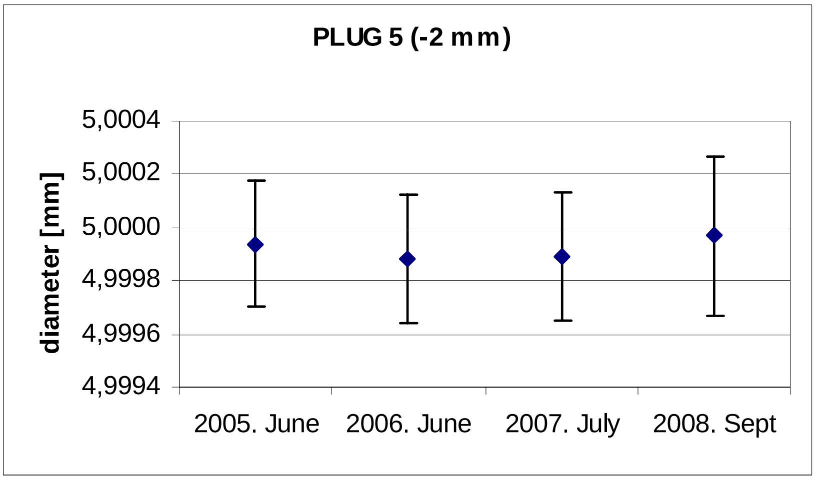



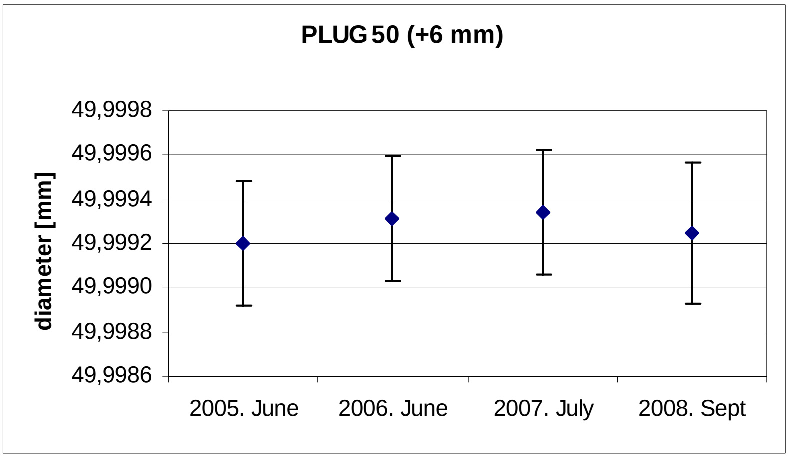
### 6.3. *Stability of the plug 5 mm*

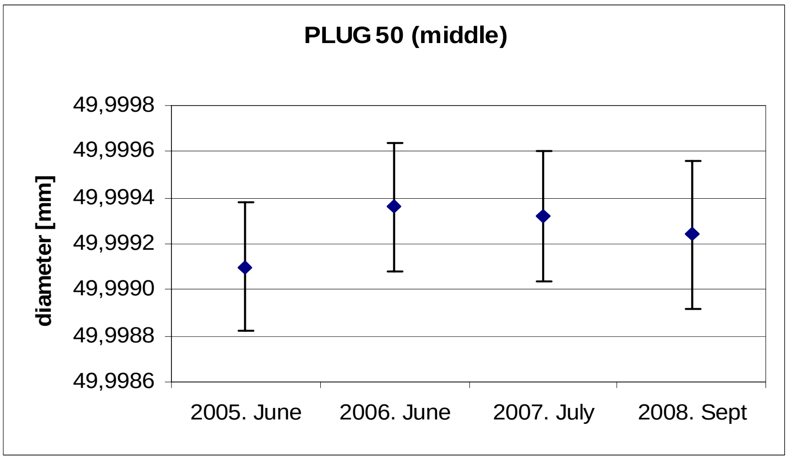


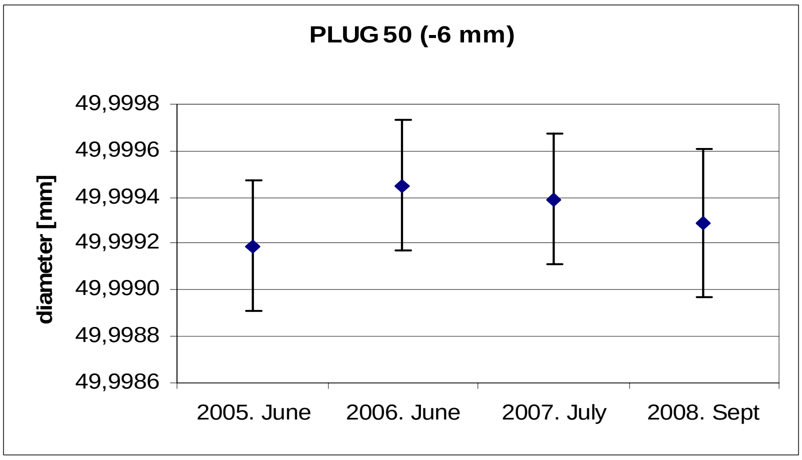



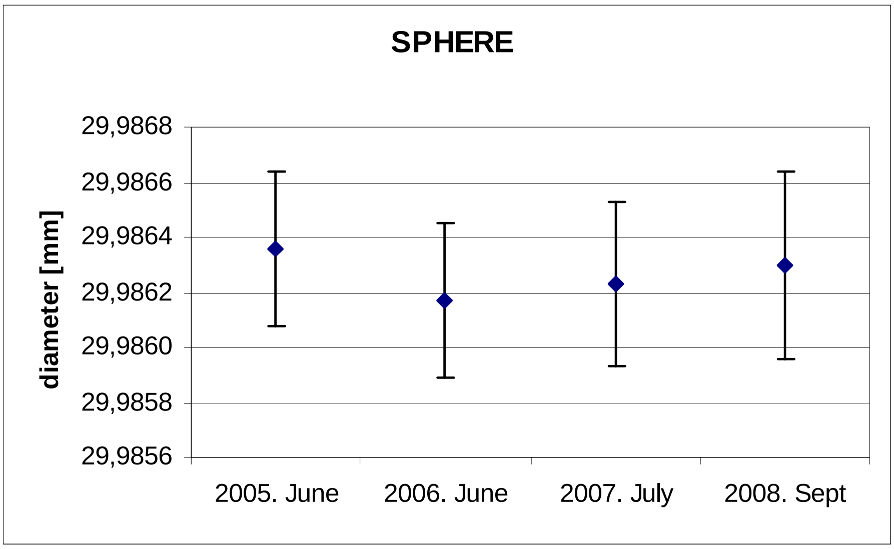
### 6.4. *Stability of the plug 50 mm*



### 6.5. Stability of the sphere 30 mm



## 7. Analysis of the results

The weighted mean is used as the reference value in the comparison.

For each laboratory (*i*) the normalised weight, $w_i$ was calculated by the following formula:

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

where $u(x_i)$ is the standard uncertainty given by the laboratory *"i"* and *C* is the normalizing factor and is calculated by the following formula:

$$C = \frac{1}{\sum_{i=1}^{n} \frac{1}{u^2(x_i)}} \qquad (2)$$

where *n* is the number of the laboratories

The weighted mean (reference value) is:

$$\bar{x}_w = \sum_{i=1}^{n} w_i \cdot x_i \qquad (3)$$

The uncertainty of the deviation from the weighted mean is:

$$u(x_i - \bar{x}_w) = \sqrt{u^2(x_i) - u_{\text{int}}{}^2(\bar{x}_w)} \qquad (4)$$

The analysis of the results of each participant can be done by calculating the deviation of the given result from the weighted mean ($x_i - \bar{x}_w$) and the uncertainty of this deviation.

**The statistical consistency of the results** with the uncertainties given by the participants can be checked by the $E_n$ value for each laboratory.

$$E_n = \frac{x_i - \bar{x}_w}{2\sqrt{u^2(x_i) - u_{\text{int}}^2(\bar{x}_w)}} \qquad \text{(k=2)} \qquad (5)$$

where $x_i - \bar{x}_w$ is the deviation from the weighted mean for a result of a laboratory,

$u_{int}$ is the so called internal standard deviation that is based on the estimated standard uncertainties as reported by the participants:

$$u_{\text{int}}(\bar{x}_w) = \sqrt{C} \qquad (6)$$

*En* values are expected to be less than 1 for a coverage factor of *k*=2.

**The statistical consistency of the comparison** can be analysed by the so called Birge ratio test. The Birge ratio compares the observed spread of the results with the spread expected from the individual reported uncertainties.

The Birge ratio is:

$$R_B = \frac{u_{ext}(\bar{x}_w)}{u_{\text{int}}(\bar{x}_w)} \tag{7}$$

where $u_{ext}$ is the so called external standard deviation and can be calculated by the following formula:

$$u_{ext}(\bar{x}_w) = \sqrt{\frac{1}{I-1} \cdot \frac{\sum_{i=1}^{n} \frac{(x_i - \bar{x}_w)^2}{u^2(x_i)}}{\sum_{i=1}^{n} \frac{1}{u^2(x_i)}}} \tag{8}$$

The Birge ratio has an expectation value of $R_B$=1, when considering standard uncertainties.
For a coverage factor of $k$ = 2, the expectation value is increased and the data in a comparison are consistent provided that

$$R_B < \sqrt{1 + \sqrt{8/(I-1)}} \tag{9}$$

Where $I$ is the number of the results that are taken in the calculation.
For the cases of $I$ = 18, 17 and 16, $R_B$<1,298, 1,307 and 1,315 respectively indicates consistency.

If the calculation of a gauge shows inconsistent dataset, the largest consistent subset is determined by elimination, starting with excluding the result having the largest $E_n$ value that makes the largest contribution to the overall chi-squared value. The iteration runs until $R_B < R_{B\,crit}$.

When a result $x_i$ is excluded from the reference value, it is not correlated to it and its $E_n$ value is calculated by:

$$E_n = \frac{x_i - \bar{x}_w}{2\sqrt{u^2(x_i) + u_{\text{int}}^2(\bar{x}_w)}} \tag{10}$$

**The iteration method to determine the largest subset has been only done for the final results (chapter 9).**

**Correlations:**
Some laboratories have traceability for the reference rings used in the ring measurements from other laboratory (see table 6). This can effect the results. It was asked to check whether there is correlation between different participants. This calculation was kindly offered by Michael Matus, BEV. The outcome can be found in Appendix 2.

# 8. Results as it was submitted by the participants

The following laboratories has changed some of their results because of different reasons:

1. NPL, GB remeasured some of the gauges before the results were available (new results: 2009.07.29). The original results showed some problems for some items. NPL was requested to make re-measurements because they are one of the linking laboratories between the two groups. The new measurements were made with different operator and in the new laboratory after they had moved to the new NPL building.
2. INM, RO revised the uncertainty budgets that are in agreement with their CMC claims (2009.03.23). After checking their results, it turned out that the instrument resolution and the repeatability had not been taken into consideration in the uncertainty calculation. The laboratory will use a new device for diameter calibrations, that is to be validated with a new comparison.
3. FSB, CR introduced new value for the diameter of the ring 40 mm (2009.07.20). The reference ring of 50 mm that was used in the comparison has a new calibration certificate issued by another NMI. Both calibration certificates has been sent as a proof.
4. NML, IR sent revised uncertainties (2009. 08.31). In late 2008 NML piloted a tri-lateral intercomparison (No. 1057) with METAS and NPL in the area of pin gauge calibration. One of the main outcomes of this comparison was that the laboratory seriously underestimated the performance of their ULM OPAL single axis measuring machine and also the influence of compression on the measurement of ring gauges and plugs.

For the four laboratories the original results are kept and evaluated in the chapter 8. The evaluation with the corrected values can be found in the chapter 9.
The revised results are to be considered as final.

The graphs belonging to the measurands show the measured results with the expanded uncertainties ($k$=2).

As it was agreed at the EURAMET TC-L meeting in Lisbon, the evaluation of the roundness and straightness data of the cylindrical gauges is not shown because these parameters have been measured mainly for the diameter uncertainty estimation of the ring and plug gauges, as contributions in the uncertainty calculation. The roundness measurements of the sphere are considered to prove the CMC claims for roundness measurements.

## 8.1. Ring 5 mm - diameter

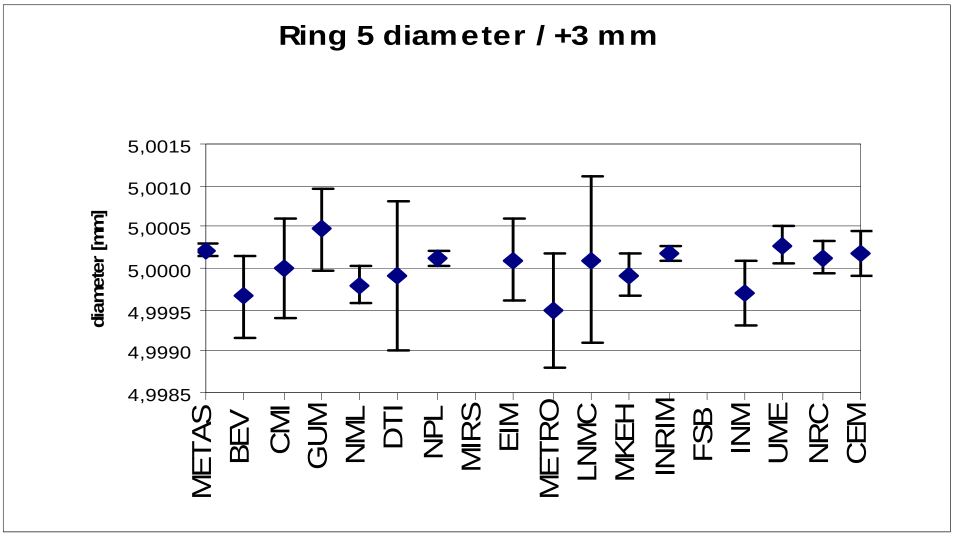
Table 7: Ring 5 mm results given by the participants:

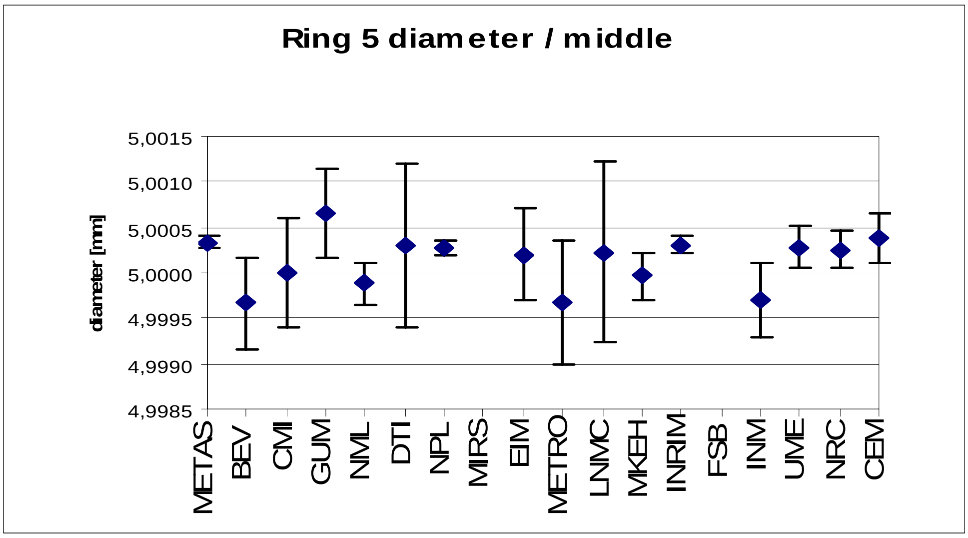
| ORIGINAL VALUES | | | | | | | CORRECTED VALUES | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | + | unc | middle | unc | - | unc | + | unc | middle | unc | - | unc |
| LABORATORY | mm | µm | mm | µm | mm | µm | mm | µm | mm | µm | mm | µm |
| METAS | 5,00022 | 0,04 | 5,00034 | 0,04 | 5,00028 | 0,04 | | | | | | |
| BEV | 4,99966 | 0,25 | 4,99966 | 0,25 | 4,99969 | 0,25 | | | | | | |
| CMI | 5,0000 | 0,3 | 5,0000 | 0,3 | 4,9996 | 0,3 | | | | | | |
| GUM | 5,00047 | 0,25 | 5,00065 | 0,25 | 5,00041 | 0,25 | | | | | | |
| NML | 4,99980 | 0,115 | 4,99988 | 0,115 | 4,99990 | 0,115 | | 0,475 | | 0,475 | | 0,475 |
| DTI | 4,9999 | 0,45 | 5,0003 | 0,45 | 5,0001 | 0,45 | | | | | | |
| NPL | 5,00013 | 0,045 | 5,00028 | 0,042 | 5,00018 | 0,039 | | | | | | |
| MIRS | NOT MEASURED | | | | | | | | | | | |
| EIM | 5,00010 | 0,25 | 5,00020 | 0,25 | 5,00022 | 0,25 | | | | | | |
| METROSERT | 4,99949 | 0,341 | 4,99968 | 0,341 | 4,99973 | 0,341 | | | | | | |
| LNMC | 5,00010 | 0,5 | 5,00023 | 0,5 | 5,00013 | 0,5 | | | | | | |
| MKEH | 4,99992 | 0,13 | 4,99997 | 0,13 | 4,99999 | 0,13 | | | | | | |
| INRIM | 5,00018 | 0,050 | 5,00031 | 0,050 | 5,00025 | 0,050 | | | | | | |
| FSB | NOT MEASURED | | | | | | | | | | | |
| INM | 4,9997 | 0,20 | 4,9997 | 0,20 | 4,9998 | 0,20 | | 0,39 | | 0,39 | | 0,39 |
| UME | 5,00028 | 0,115 | 5,00028 | 0,115 | 5,00027 | 0,115 | | | | | | |
| NRC | 5,00013 | 0,1 | 5,00025 | 0,1 | 5,00020 | 0,1 | | | | | | |
| CEM | 5,00018 | 0,14 | 5,00038 | 0,14 | 5,00036 | 0,14 | | | | | | |

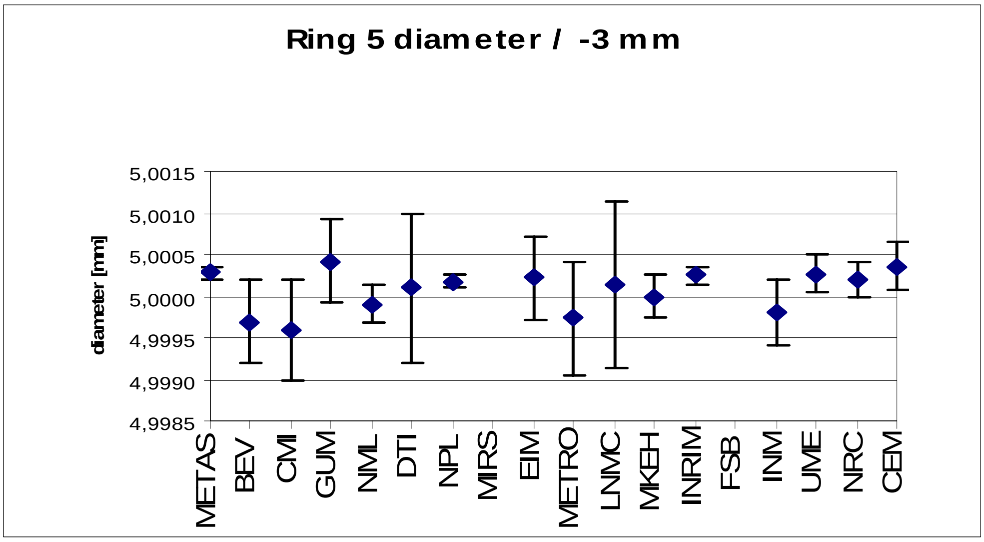
Table 8: Results evaluated with the original values ($E_n$: $k$=2)

| weighted mean: | 5,00015 | mm | 5,00027 | mm | 5,00020 | mm |
|---|---|---|---|---|---|---|
| $u_{int}$ | 0,02 | µm | 0,02 | µm | 0,02 | µm |
| u ext | 0,03 | µm | 0,04 | µm | 0,03 | µm |
| No of labs | 16 | | 16 | | 16 | |
| $R_B$ (uext/uint) | 1,466 | | 1,664 | | 1,441 | |
| $R_B$ crit | 1,315 | | 1,315 | | 1,315 | |
| | + | | middle | | - | |
| | xi-xw | En | xi-xw | En | xi-xw | En |
| METAS | 0,07 | 1,12 | 0,07 | 1,08 | 0,08 | 1,12 |
| BEV | -0,49 | -0,98 | -0,61 | -1,22 | -0,51 | -1,03 |
| CMI | -0,15 | -0,24 | -0,27 | -0,45 | -0,60 | -1,01 |
| GUM | 0,32 | 0,65 | 0,38 | 0,77 | 0,21 | 0,41 |
| NML | -0,35 | -1,53 | -0,39 | -1,72 | -0,30 | -1,35 |
| DTI | -0,25 | -0,27 | 0,03 | 0,04 | -0,10 | -0,12 |
| NPL | -0,02 | -0,20 | 0,01 | 0,17 | -0,02 | -0,37 |
| MIRS | NOT MEASURED | | | | | |
| EIM | -0,05 | -0,09 | -0,07 | -0,14 | 0,02 | 0,03 |
| METROSERT | -0,66 | -0,96 | -0,59 | -0,86 | -0,47 | -0,70 |
| LNMC | -0,05 | -0,05 | -0,04 | -0,04 | -0,07 | -0,07 |
| MKEH | -0,23 | -0,88 | -0,30 | -1,16 | -0,21 | -0,84 |
| INRIM | 0,03 | 0,38 | 0,04 | 0,47 | 0,05 | 0,51 |
| FSB | NOT MEASURED | | | | | |
| INM | -0,45 | -1,12 | -0,57 | -1,43 | -0,40 | -1,02 |
| UME | 0,13 | 0,60 | 0,01 | 0,05 | 0,07 | 0,29 |
| NRC | -0,02 | -0,08 | -0,02 | -0,09 | 0,00 | -0,02 |
| CEM | 0,03 | 0,12 | 0,11 | 0,41 | 0,16 | 0,56 |

The following graphs show the original results of the ring 5 mm with the expanded uncertainties (*k*=2).



## 8.2. Ring 40 mm - diameter

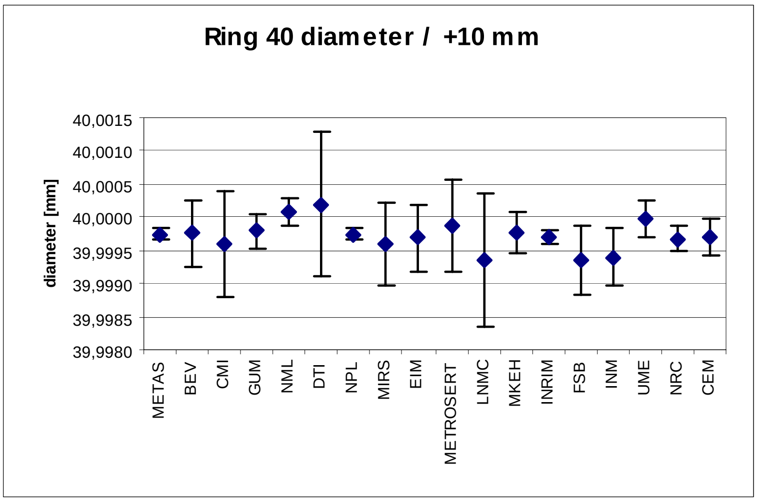
Table 9: Ring 40 mm results given by the participants:

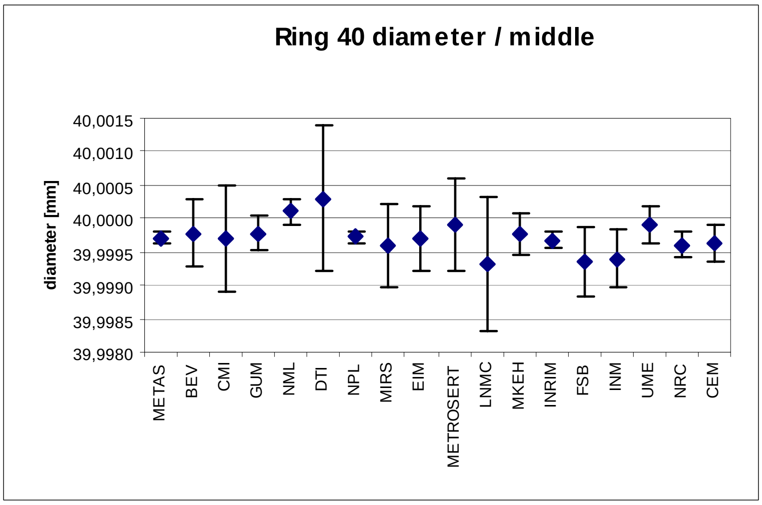
| ORIGINAL VALUES | | | | | | | CORRECTED VALUES | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | + | unc | middle | unc | - | unc | + | unc | middle | unc | - | unc |
| LABORATORY | mm | µm | mm | µm | mm | µm | mm | µm | mm | µm | mm | µm |
| METAS | 39,99974 | 0,04 | 39,99971 | 0,04 | 39,99974 | 0,04 | | | | | | |
| BEV | 39,99976 | 0,25 | 39,99977 | 0,25 | 39,99978 | 0,25 | | | | | | |
| CMI | 39,9996 | 0,4 | 39,9997 | 0,4 | 39,9996 | 0,4 | | | | | | |
| GUM | 39,99980 | 0,13 | 39,99977 | 0,13 | 39,99986 | 0,13 | | | | | | |
| NML | 40,00008 | 0,100 | 40,00010 | 0,100 | 40,00009 | 0,100 | | 0,332 | | 0,332 | | 0,332 |
| DTI | 40,0002 | 0,55 | 40,0003 | 0,55 | 39,9999 | 0,55 | | | | | | |
| NPL | 39,99975 | 0,043 | 39,99972 | 0,041 | 39,99979 | 0,041 | | | | | | |
| MIRS | 39,9996 | 0,31 | 39,9996 | 0,31 | 39,9995 | 0,31 | | | | | | |
| EIM | 39,99969 | 0,25 | 39,99970 | 0,25 | 39,99969 | 0,25 | | | | | | |
| METROSERT | 39,99986 | 0,344 | 39,99991 | 0,344 | 39,99990 | 0,344 | | | | | | |
| LNMC | 39,99936 | 0,5 | 39,99932 | 0,5 | 39,99922 | 0,5 | | | | | | |
| MKEH | 39,99977 | 0,15 | 39,99977 | 0,15 | 39,99976 | 0,15 | | | | | | |
| INRIM | 39,99970 | 0,055 | 39,99968 | 0,055 | 39,99971 | 0,055 | | | | | | |
| FSB | 39,99935 | 0,26 | 39,99935 | 0,26 | 39,99935 | 0,26 | 39,99953 | | 39,99953 | | 39,99953 | |
| INM | 39,9994 | 0,22 | 39,9994 | 0,22 | 39,9991 | 0,22 | | 0,40 | | 0,40 | | 0,40 |
| UME | 39,99998 | 0,143 | 39,9999 | 0,143 | 40,00006 | 0,143 | | | | | | |
| NRC | 39,99968 | 0,1 | 39,99961 | 0,1 | 39,99971 | 0,1 | | | | | | |
| CEM | 39,99971 | 0,14 | 39,99963 | 0,14 | 39,99962 | 0,14 | | | | | | |

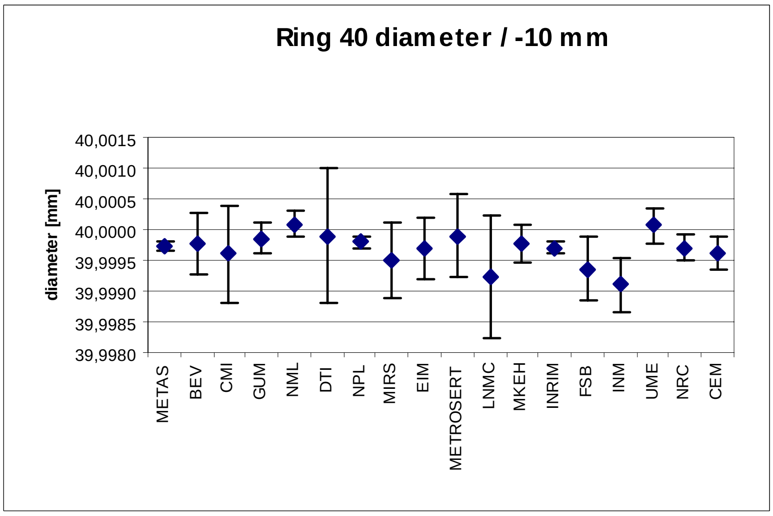
Table 10: Results evaluated with the original values (*$E_n$*: *k*=2)

| weighted mean: | 39,99975 | mm | 39,99972 | mm | 39,99976 | mm |
|---|---|---|---|---|---|---|
| $u_{int}$ | 0,022 | µm | 0,022 | µm | 0,022 | µm |
| $u_{ext}$ | 0,025 | µm | 0,027 | µm | 0,031 | µm |
| No of labs | 18 | | 18 | | 18 | |
| $R_B$ (uext/uint) | 1,133 | | 1,210 | | 1,384 | |
| $R_B$ crit | 1,298 | | 1,298 | | 1,298 | |
| | + | | middle | | - | |
| | xi-xw | En | xi-xw | En | xi-xw | En |
| METAS | -0,01 | -0,16 | -0,01 | -0,19 | -0,02 | -0,34 |
| BEV | 0,01 | 0,02 | 0,05 | 0,09 | 0,02 | 0,03 |
| CMI | -0,15 | -0,19 | -0,02 | -0,03 | -0,16 | -0,20 |
| GUM | 0,05 | 0,19 | 0,05 | 0,18 | 0,10 | 0,38 |
| NML | 0,33 | 1,69 | 0,38 | 1,93 | 0,33 | 1,68 |
| DTI | 0,45 | 0,41 | 0,58 | 0,53 | 0,14 | 0,12 |
| NPL | 0,00 | 0,00 | 0,00 | -0,04 | 0,03 | 0,40 |
| MIRS | -0,15 | -0,24 | -0,12 | -0,20 | -0,26 | -0,42 |
| EIM | -0,06 | -0,12 | -0,02 | -0,05 | -0,07 | -0,15 |
| METROSERT | 0,11 | 0,16 | 0,19 | 0,27 | 0,14 | 0,20 |
| LNMC | -0,39 | -0,39 | -0,40 | -0,40 | -0,54 | -0,54 |
| MKEH | 0,02 | 0,07 | 0,05 | 0,16 | 0,00 | -0,01 |
| INRIM | -0,05 | -0,50 | -0,04 | -0,43 | -0,05 | -0,52 |
| FSB | -0,40 | -0,77 | -0,37 | -0,72 | -0,41 | -0,80 |
| INM | -0,35 | -0,80 | -0,32 | -0,74 | -0,66 | -1,51 |
| UME | 0,23 | 0,81 | 0,18 | 0,63 | 0,30 | 1,05 |
| NRC | -0,07 | -0,36 | -0,11 | -0,58 | -0,05 | -0,27 |
| CEM | -0,04 | -0,15 | -0,09 | -0,34 | -0,14 | -0,52 |

The following graphs show the original results of the ring 40 mm with the expanded uncertainties ($k$=2).



## 8.3. *Plug 5 mm - diameter*

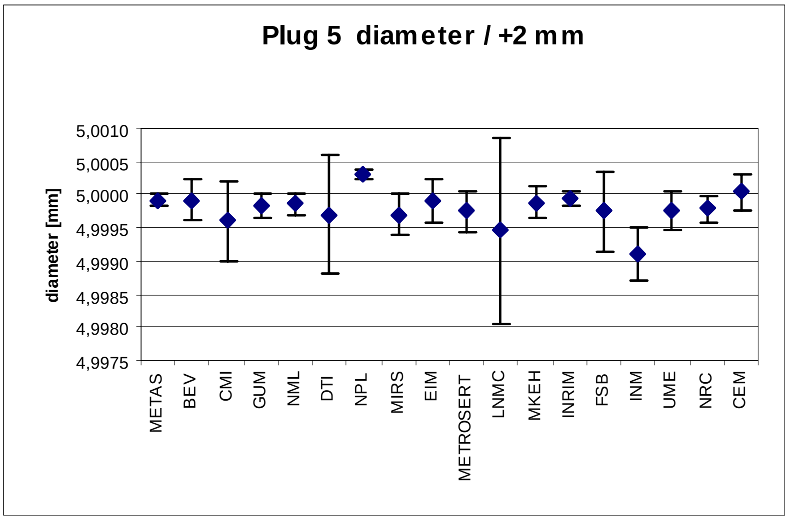
Table 11: Plug 5 mm results given by the participants:

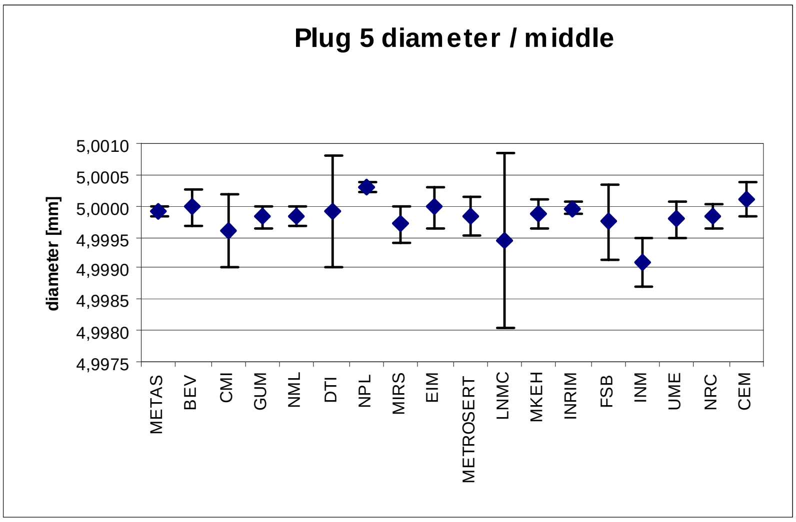
| ORIGINAL VALUES | | | | | | | CORRECTED VALUES | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | + | unc | middle | unc | - | unc | + | unc | middle | unc | - | unc |
| LABORATORY | mm | µm | mm | µm | mm | µm | mm | µm | mm | µm | mm | µm |
| METAS | 4,99992 | 0,04 | 4,99992 | 0,04 | 4,99998 | 0,04 | | | | | | |
| BEV | 4,99992 | 0,15 | 4,99997 | 0,15 | 4,99997 | 0,15 | | | | | | |
| CMI | 4,9996 | 0,3 | 4,9996 | 0,3 | 4,9996 | 0,3 | | | | | | |
| GUM | 4,999844 | 0,090 | 4,999819 | 0,090 | 4,999821 | 0,090 | | | | | | |
| NML | 4,99986 | 0,082 | 4,99983 | 0,082 | 4,99983 | 0,082 | | 0,075 | | 0,075 | | 0,075 |
| DTI | 4,9997 | 0,45 | 4,9999 | 0,45 | 4,9997 | 0,45 | | | | | | |
| NPL | 5,00030 | 0,0407 | 5,00030 | 0,0409 | 5,00032 | 0,0411 | 4,99986 | 0,046 | 4,99981 | 0,047 | 4,99987 | 0,046 |
| MIRS | 4,9997 | 0,15 | 4,9997 | 0,15 | 4,9997 | 0,15 | | | | | | |
| EIM | 4,99991 | 0,17 | 4,99997 | 0,17 | 5,00007 | 0,17 | | | | | | |
| METROSERT | 4,99975 | 0,156 | 4,99984 | 0,156 | 4,99980 | 0,156 | | | | | | |
| LNMC | 4,99946 | 0,7 | 4,99946 | 0,7 | 4,9995 | 0,7 | | | | | | |
| MKEH | 4,99988 | 0,12 | 4,99988 | 0,12 | 4,99988 | 0,12 | | | | | | |
| INRIM | 4,99993 | 0,055 | 4,99996 | 0,050 | 5,00000 | 0,050 | | | | | | |
| FSB | 4,99975 | 0,30 | 4,99975 | 0,30 | 4,99978 | 0,30 | | | | | | |
| INM | 4,9991 | 0,20 | 4,9991 | 0,20 | 4,9991 | 0,20 | | 0,39 | | 0,39 | | 0,39 |
| UME | 4,99977 | 0,150 | 4,99978 | 0,150 | 4,99974 | 0,150 | | | | | | |
| NRC | 4,99979 | 0,1 | 4,99984 | 0,1 | 4,99993 | 0,1 | | | | | | |
| CEM | 5,00004 | 0,14 | 5,00011 | 0,14 | 5,00018 | 0,14 | | | | | | |

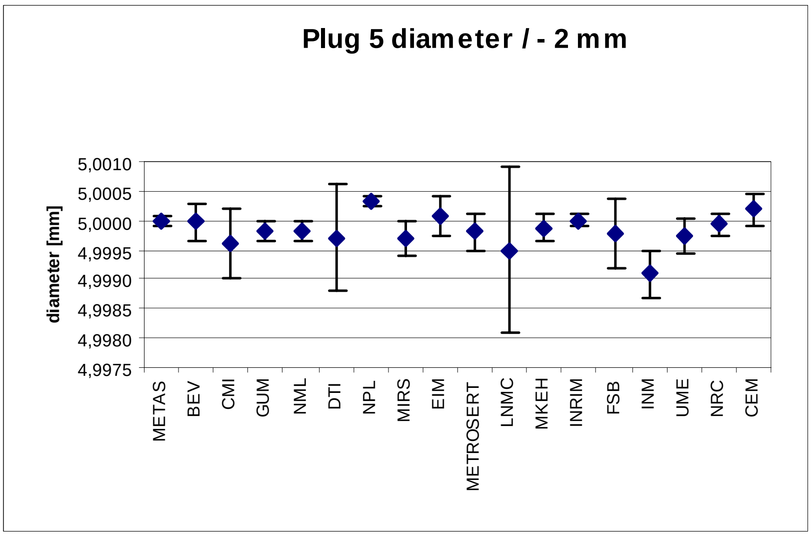
Table 12: Results evaluated with the original values ($E_n$: $k$=2)

| weighted mean: | 4,99999 | mm | 4,99999 | mm | 5,00003 | mm |
|---|---|---|---|---|---|---|
| $u_{int}$ | 0,021 | µm | 0,021 | µm | 0,021 | µm |
| $u_{ext}$ | 0,051 | µm | 0,050 | µm | 0,051 | µm |
| No of labs | 18 | | 18 | | 18 | |
| $R_B$ (uext/uint) | 2,475 | | 2,443 | | 2,463 | |
| $R_B$ crit | 1,298 | | 1,298 | | 1,298 | |
| | + | | middle | | - | |
| | xi-xw | En | xi-xw | En | xi-xw | En |
| METAS | -0,07 | -0,97 | -0,07 | -1,06 | -0,05 | -0,66 |
| BEV | -0,07 | -0,22 | -0,02 | -0,08 | -0,06 | -0,19 |
| CMI | -0,39 | -0,65 | -0,39 | -0,66 | -0,43 | -0,71 |
| GUM | -0,14 | -0,81 | -0,17 | -0,99 | -0,20 | -1,16 |
| NML | -0,13 | -0,79 | -0,16 | -1,03 | -0,20 | -1,23 |
| DTI | -0,29 | -0,32 | -0,09 | -0,10 | -0,33 | -0,36 |
| NPL | 0,31 | 4,49 | 0,31 | 4,34 | 0,29 | 4,14 |
| MIRS | -0,29 | -0,96 | -0,29 | -0,99 | -0,33 | -1,09 |
| EIM | -0,08 | -0,23 | -0,02 | -0,07 | 0,04 | 0,13 |
| METROSERT | -0,24 | -0,76 | -0,15 | -0,50 | -0,23 | -0,73 |
| LNMC | -0,53 | -0,38 | -0,53 | -0,38 | -0,53 | -0,38 |
| MKEH | -0,11 | -0,45 | -0,11 | -0,48 | -0,15 | -0,61 |
| INRIM | -0,06 | -0,55 | -0,03 | -0,36 | -0,03 | -0,27 |
| FSB | -0,24 | -0,39 | -0,24 | -0,41 | -0,25 | -0,41 |
| INM | -0,89 | -2,23 | -0,89 | -2,24 | -0,93 | -2,32 |
| UME | -0,22 | -0,73 | -0,21 | -0,72 | -0,29 | -0,96 |
| NRC | -0,20 | -1,00 | -0,15 | -0,78 | -0,10 | -0,49 |
| CEM | 0,05 | 0,19 | 0,12 | 0,42 | 0,15 | 0,56 |

The following graphs show the original results of the plug 5 mm with the expanded uncertainties (*k*=2).



## 8.4. *Plug 50 mm - diameter*

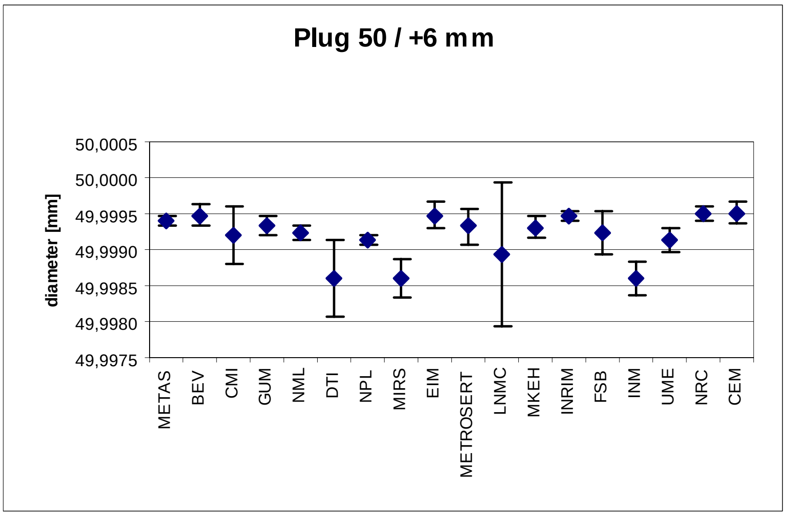
Table 13: Plug 50 mm results given by the participants:

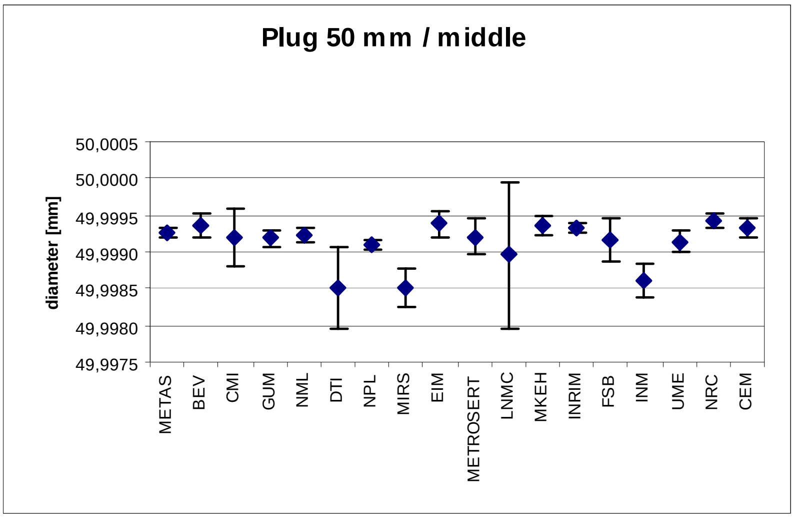
| ORIGINAL VALUES | | | | | | | CORRECTED VALUES | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | + | unc | middle | unc | - | unc | + | unc | middle | unc | - | unc |
| LABORATORY | mm | µm | mm | µm | mm | µm | mm | µm | mm | µm | mm | µm |
| METAS | 49,99940 | 0,07 | 49,99925 | 0,07 | 49,99928 | 0,07 | | | | | | |
| BEV | 49,99947 | 0,15 | 49,99936 | 0,15 | 49,99940 | 0,15 | | | | | | |
| CMI | 49,9992 | 0,4 | 49,9992 | 0,4 | 49,9992 | 0,4 | | | | | | |
| GUM | 49,99933 | 0,12 | 49,99918 | 0,12 | 49,99920 | 0,12 | | | | | | |
| NML | 49,99923 | 0,098 | 49,99922 | 0,098 | 49,99925 | 0,098 | | 0,1 | | 0,1 | | 0,1 |
| DTI | 49,9986 | 0,55 | 49,9985 | 0,55 | 49,9986 | 0,55 | | | | | | |
| NPL | 49,99912 | 0,0686 | 49,99910 | 0,0644 | 49,99911 | 0,0674 | 49,99921 | 0,058 | 49,99911 | 0,0583 | 49,99905 | 0,0638 |
| MIRS | 49,9986 | 0,26 | 49,9985 | 0,26 | 49,9986 | 0,26 | | | | | | |
| EIM | 49,99948 | 0,18 | 49,99939 | 0,18 | 49,99938 | 0,18 | | | | | | |
| METROSERT | 49,99932 | 0,239 | 49,99921 | 0,239 | 49,99921 | 0,239 | | | | | | |
| LNMC | 49,99894 | 1 | 49,99896 | 1 | 49,99910 | 1 | | | | | | |
| MKEH | 49,99931 | 0,14 | 49,99936 | 0,14 | 49,99945 | 0,14 | | | | | | |
| INRIM | 49,99946 | 0,060 | 49,99932 | 0,075 | 49,99940 | 0,060 | | | | | | |
| FSB | 49,99923 | 0,3 | 49,99917 | 0,3 | 49,99923 | 0,3 | | | | | | |
| INM | 49,9986 | 0,23 | 49,9986 | 0,23 | 49,9987 | 0,23 | | 0,41 | | 0,41 | | 0,41 |
| UME | 49,99913 | 0,156 | 49,99914 | 0,156 | 49,99924 | 0,156 | | | | | | |
| NRC | 49,99949 | 0,1 | 49,99943 | 0,1 | 49,99942 | 0,1 | | | | | | |
| CEM | 49,99951 | 0,14 | 49,99933 | 0,14 | 49,99940 | 0,14 | | | | | | |

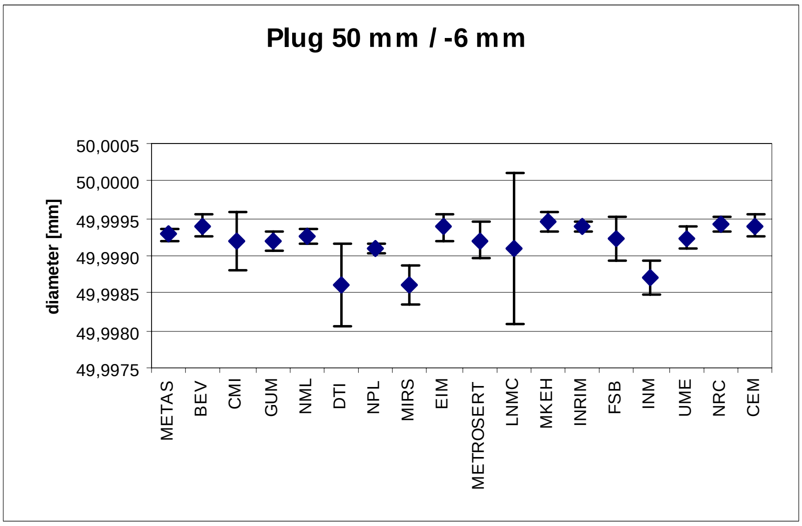
Table 14: Results evaluated with the original values ($E_n$: $k$=2)

| weighted mean: | 49,99932 | mm | 49,99923 | mm | 49,99928 | mm |
|---|---|---|---|---|---|---|
| $u_{int}$ | 0,028 | µm | 0,029 | µm | 0,028 | µm |
| $u_{ext}$ | 0,045 | µm | 0,039 | µm | 0,038 | µm |
| No of labs | 18 | | 18 | | 18 | |
| $R_B$ (uext/uint) | 1,601 | | 1,335 | | 1,350 | |
| $R_B$ crit | 1,298 | | 1,298 | | 1,298 | |
| | + | | middle | | - | |
| | xi-xw | En | xi-xw | En | xi-xw | En |
| METAS | 0,08 | 0,59 | 0,02 | 0,18 | 0,00 | 0,02 |
| BEV | 0,15 | 0,49 | 0,13 | 0,45 | 0,12 | 0,42 |
| CMI | -0,12 | -0,16 | -0,03 | -0,03 | -0,08 | -0,10 |
| GUM | 0,01 | 0,02 | -0,05 | -0,20 | -0,08 | -0,33 |
| NML | -0,09 | -0,50 | -0,01 | -0,04 | -0,03 | -0,15 |
| DTI | -0,72 | -0,66 | -0,73 | -0,66 | -0,68 | -0,62 |
| NPL | -0,20 | -1,63 | -0,13 | -1,10 | -0,17 | -1,37 |
| MIRS | -0,72 | -1,40 | -0,73 | -1,41 | -0,68 | -1,31 |
| EIM | 0,16 | 0,44 | 0,16 | 0,46 | 0,10 | 0,29 |
| METROSERT | 0,00 | -0,01 | -0,02 | -0,04 | -0,07 | -0,14 |
| LNMC | -0,38 | -0,19 | -0,27 | -0,13 | -0,18 | -0,09 |
| MKEH | -0,01 | -0,05 | 0,13 | 0,49 | 0,17 | 0,63 |
| INRIM | 0,14 | 1,28 | 0,09 | 0,67 | 0,12 | 1,15 |
| FSB | -0,09 | -0,16 | -0,06 | -0,10 | -0,05 | -0,08 |
| INM | -0,72 | -1,59 | -0,63 | -1,37 | -0,58 | -1,27 |
| UME | -0,19 | -0,63 | -0,09 | -0,28 | -0,04 | -0,12 |
| NRC | 0,17 | 0,86 | 0,20 | 1,06 | 0,14 | 0,74 |
| CEM | 0,19 | 0,68 | 0,10 | 0,38 | 0,12 | 0,45 |

The following graphs show the original results of the plug 50 mm with the expanded uncertainties (*k*=2).



### 8.5. *Sphere 30 mm - diameter*

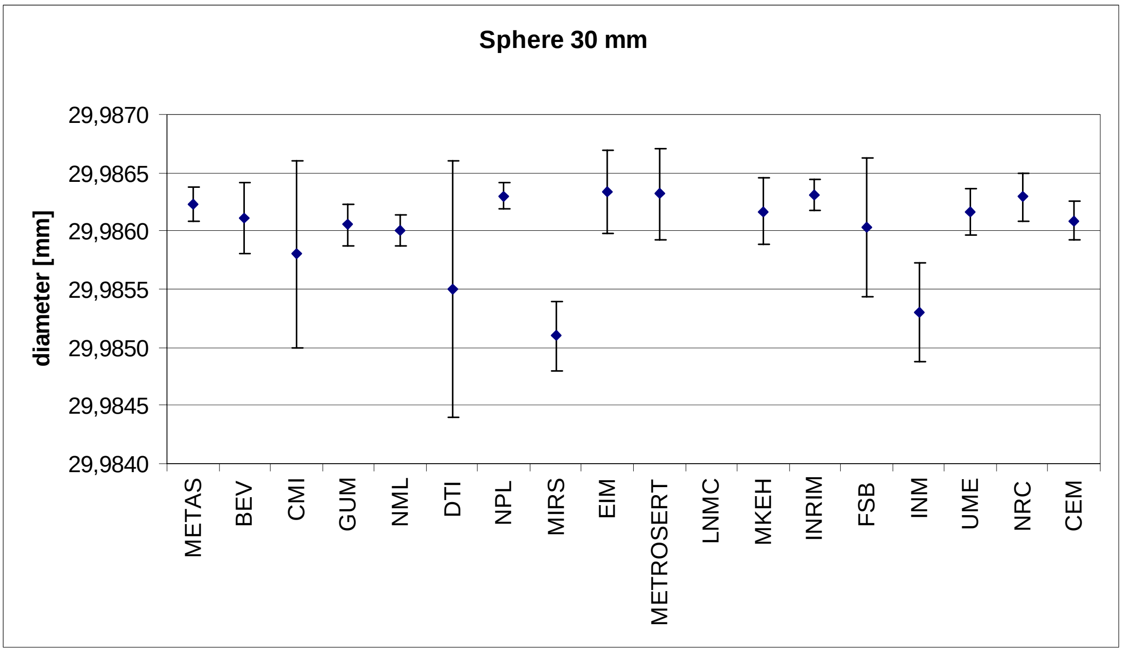
Table 15: Sphere 30 mm results given by the participants:

| | ORIGINAL VALUES | | CORRECTED VALUES | |
|---|---|---|---|---|
| | diameter | unc | diameter | unc |
| **LABORATORY** | mm | µm | mm | µm |
| METAS | 29,98623 | 0,07 | | |
| BEV | 29,98611 | 0,15 | | |
| CMI | 29,9858 | 0,4 | | |
| GUM | 29,986056 | 0,090 | | |
| NML | 29,98600 | 0,066 | | 0,09 |
| DTI | 29,9855 | 0,55 | | |
| NPL | 29,98630 | 0,0564 | 29,98636 | 0,0538 |
| MIRS | 29,9851 | 0,15 | | |
| EIM | 29,98634 | 0,18 | | |
| METROSERT | 29,98632 | 0,196 | | |
| LNMC | NOT MEASURED | | | |
| MKEH | 29,98617 | 0,14 | | |
| INRIM | 29,98631 | 0,065 | | |
| FSB | 29,98603 | 0,30 | | |
| INM | 29,98530 | 0,21 | | 0,40 |
| UME | 29,98616 | 0,100 | | |
| NRC | 29,98629 | 0,1 | | |
| CEM | 29,98609 | 0,08 | | |

Table 16: Results evaluated with the original values ($E_n$: $k$=2)

| | | |
|---|---|---|
| weighted mean: | 29,98615 | mm |
| $u_{int}$ | 0,02 | µm |
| $u_{ext}$ | 0,06 | |
| No of labs | 17 | |
| $R_B$ (uext/uint) | 2,409 | |
| $R_B$ crit | 1,307 | |
| Lab | xi-xw | En |
| METAS | 0,08 | 0,61 |
| BEV | -0,04 | -0,13 |
| CMI | -0,35 | -0,44 |
| GUM | -0,09 | -0,54 |
| NML | -0,15 | -1,22 |
| DTI | -0,65 | -0,59 |
| NPL | 0,15 | 1,48 |
| MIRS | -1,05 | -3,54 |
| EIM | 0,19 | 0,53 |
| METROSERT | 0,17 | 0,44 |
| LNMC | NOT MEASURED | |
| MKEH | 0,02 | 0,07 |
| INRIM | 0,16 | 1,33 |
| FSB | -0,12 | -0,20 |
| INM | -0,85 | -2,04 |
| UME | 0,01 | 0,05 |
| NRC | 0,14 | 0,72 |
| CEM | -0,06 | -0,39 |

The following graphs show the original results of the sphere 30 mm with the expanded uncertainties ($k$=2).



## 8.6. Sphere 30 mm - roundness

Table 17: Sphere 30 mm results given by the participants (500 UPR)

| 500 UPR | round. | u(k=1) |
|---|---|---|
| LABORATORY | µm | µm |
| METAS | 0,035 | 0,015 |
| CMI | 0,09 | 0,05 |
| GUM | 0,102 | 0,038 |
| DTI | 0,10 | 0,045 |
| NPL | not measured | |
| EIM | 0,091 | 0,07 |
| METROSERT | 0,09 | 0,05 |
| INRIM | 0,039 | 0,004 |
| FSB | 0,097 | 0,055 |
| INM | 0,10 | 0,04 |
| UME | 0,078 | 0,038 |
| CEM | 0,034 | 0,005 |

Table 18: Results evaluated with the original values ($E_n$: $k$=2)

| 500 UPR | | |
|---|---|---|
| weighted mean: | 0,039 | µm |
| $u_{int}$ | 0,003 | µm |
| $u_{ext}$ | 0,003 | µm |
| No of labs | 11 | |
| $R_B$ (uext/uint) | 1,130 | |
| $R_B$ crit | 1,376 | |
| | $x_i$-$x_w$ | **En** |
| METAS | -0,004 | -0,13 |
| CMI | 0,051 | 0,51 |
| GUM | 0,063 | 0,83 |
| DFM | 0,061 | 0,68 |
| NPL | not measured | |
| EIM | 0,052 | 0,37 |
| METROSERT | 0,051 | 0,51 |
| INRIM | 0,000 | 0,01 |
| FSB | 0,058 | 0,53 |
| INM | 0,061 | 0,77 |
| UME | 0,039 | 0,52 |
| CEM | -0,005 | -0,62 |

Table 19: Sphere 30 mm results given by the participants (150 UPR)

| **150 UPR** | round. | u(k=1) |
|---|---|---|
| **LABORATORY** | μm | μm |
| METAS | 0,032 | 0,015 |
| CMI | 0,10 | 0,05 |
| GUM | 0,078 | 0,036 |
| DTI | 0,12 | 0,045 |
| NPL | 0,038 | 0,003 |
| EIM | 0,076 | 0,07 |
| METROSERT | 0,07 | 0,04 |
| INRIM | 0,039 | 0,004 |
| FSB | 0,097 | 0,055 |
| INM | 0,08 | 0,04 |
| UME | 0,051 | 0,035 |
| CEM | 0,029 | 0,005 |

Table 20: Results evaluated with the original values (*$E_n$: k*=2)

| **150 UPR** | | |
|---|---|---|
| weighted mean: | 0,037 | μm |
| $u_{int}$ | 0,002 | μm |
| $u_{ext}$ | 0,002 | μm |
| No of labs | 12 | |
| $R_B$ (uext/uint) | 1,078 | |
| $R_B$ crit | 1,361 | |
| | **$x_i$-$x_w$** | **En** |
| METAS | -0,005 | -0,18 |
| CMI | 0,063 | 0,63 |
| GUM | 0,041 | 0,57 |
| DTI | 0,083 | 0,92 |
| NPL | 0,001 | 0,15 |
| EIM | 0,039 | 0,28 |
| METROSERT | 0,033 | 0,41 |
| INRIM | 0,002 | 0,24 |
| FSB | 0,060 | 0,54 |
| INM | 0,043 | 0,53 |
| UME | 0,014 | 0,20 |
| CEM | -0,008 | -0,92 |

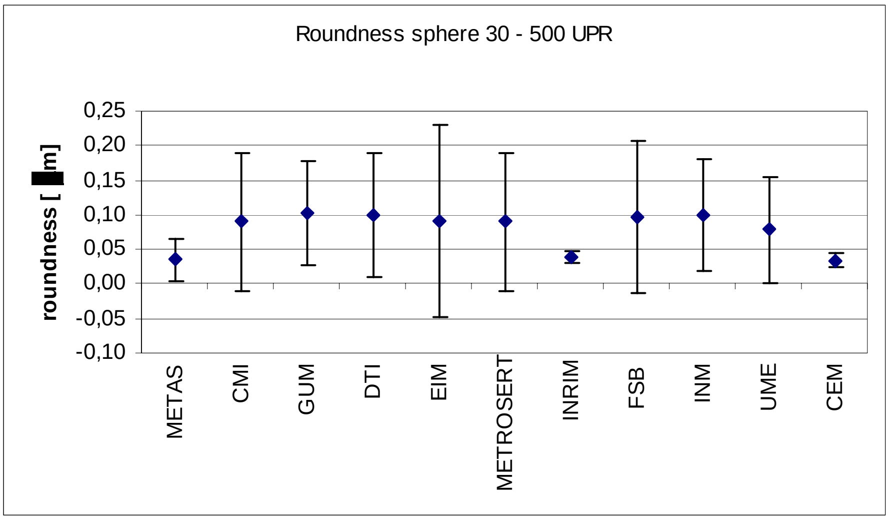
Table 21: Sphere 30 mm results given by the participants (50 UPR)

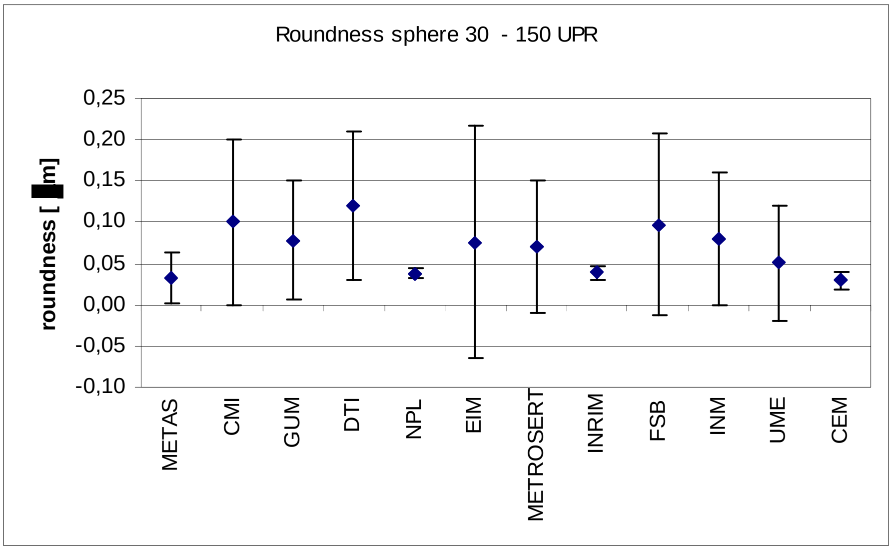
| 50 UPR | round. | u(k=1) |
|---|---|---|
| **LABORATORY** | µm | µm |
| METAS | 0,026 | 0,015 |
| CMI | 0,10 | 0,05 |
| GUM | 0,067 | 0,036 |
| DTI | 0,14 | 0,045 |
| NPL | 0,034 | 0,003 |
| EIM | 0,058 | 0,07 |
| METROSERT | 0,06 | 0,03 |
| INRIM | 0,035 | 0,004 |
| FSB | 0,097 | 0,055 |
| INM | 0,04 | 0,04 |
| UME | 0,039 | 0,032 |
| CEM | 0,024 | 0,004 |

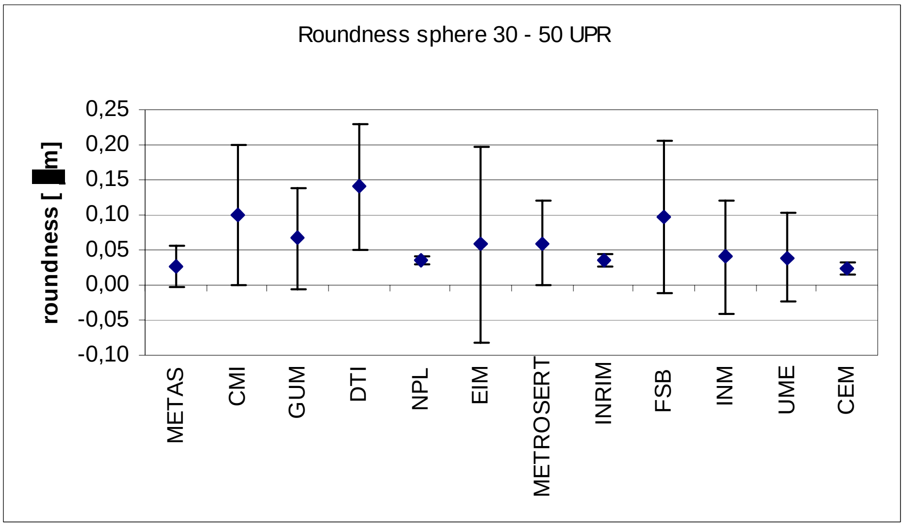
Table 22: Results evaluated with the original values ($E_n$: $k$=2)

| **50 UPR** | | |
|---|---|---|
| weighted mean: | 0,032 | µm |
| $u_{int}$ | 0,002 | µm |
| u ext | 0,002 | µm |
| No of labs | 12 | |
| $R_B$ (uext/uint) | 1,214 | |
| $R_B$ crit | 1,361 | |
| | $x_i$-$x_w$ | **En** |
| METAS | -0,006 | -0,21 |
| CMI | 0,068 | 0,68 |
| GUM | 0,035 | 0,48 |
| DTI | 0,108 | 1,20 |
| NPL | 0,002 | 0,40 |
| EIM | 0,026 | 0,18 |
| METROSERT | 0,028 | 0,46 |
| INRIM | 0,003 | 0,40 |
| FSB | 0,065 | 0,59 |
| INM | 0,008 | 0,10 |
| UME | 0,007 | 0,11 |
| CEM | -0,008 | -1,19 |

The following graphs show the original results of the roundness of the sphere 30 mm with the expanded uncertainties (*k*=2).



### *8.7. Roundness and straightness of the cylindrical gauges*

The following tables show the roundness and straightness data submitted by the participants for the cylindrical gauges. The roundness of the ring and plug gauges had to be measured at the same heights as the diameter measurements. The straightness of the ring and plug gauges had to be measured at the marked lines (0 and 180) º.
The roundness and straightness measurements were required only if they are done normally for the customers.
The roundness measurements on the sphere are to be kept as evidence for proving CMC claims of those NMIs offering a roundness measuring service, or planning to submit a CMC for such a service. The roundness and straightness data for the cylindrical gauges are measured to determine the uncertainty contribution of these parameters, so they are introduced only for information without showing the complete evaluation of the results.
It is worth noting that most of the gauges suffered some scratches or damage during the comparison.

#### 8.7.1 Ring 5 mm roundness and straightness

Table 23: Ring 5 mm roundness as given by the participants

| | Original values | | | | | | Corrected values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ROUNDNESS** | + 3 mm | unc | middle | unc | -3 mm | unc | + 3 mm | unc | middle | unc | -3 mm | unc |
| **LABORATORY** | µm | µm | µm | µm | µm | µm | µm | µm | µm | µm | µm | µm |
| METAS | 0,03 | 0,03 | **0,16** | 0,03 | 0,03 | 0,03 | damaged at middle!! | | | | | |
| CMI | 0,07 | 0,05 | 0,04 | 0,05 | 0,04 | 0,05 | | | | | | |
| GUM | 0,034 | 0,032 | 0,053 | 0,032 | 0,057 | 0,033 | | | | | | |
| DTI | 0,05 | 0,04 | 0,05 | 0,04 | 0,08 | 0,04 | | | | | | |
| NPL | 0,19 | 0,0443 | 0,12 | 0,0409 | 0,09 | 0,0407 | 0,03 | 0,0365 | 0,06 | 0,0371 | 0,05 | 0,0361 |
| EIM | 0,058 | 0,07 | 0,048 | 0,07 | 0,058 | 0,07 | | | | | | |
| METROSERT | 0,05 | 0,03 | 0,07 | 0,03 | 0,05 | 0,04 | | | | | | |
| INRIM | 0,029 | 0,050 | 0,051 | 0,050 | 0,048 | 0,050 | | | | | | |
| INM | 0,06 | 0,04 | 0,10 | 0,04 | 0,04 | 0,04 | | | | | | |
| UME | 0,058 | 0,028 | 0,069 | 0,028 | 0,080 | 0,028 | | | | | | |
| CEM | 0,04 | 0,02 | 0,06 | 0,02 | 0,03 | 0,02 | | | | | | |

METAS reported damage at middle prior to measurements

Table 24: Ring 5 mm straightness as given by the participants

| **STRAIGHTNESS** | 0 | unc | 180 | unc |
|---|---|---|---|---|
| **LABORATORY** | µm | µm | µm | µm |
| METAS | 0,09 | 0,05 | **0,94** | 0,05 |
| DTI | 0,12 | 0,04 | 0,13 | 0,04 |
| EIM | 0,06 | 0,175 | 0,07 | 0,175 |
| METROSERT | 0,12 | 0,07 | 0,13 | 0,07 |
| INRIM | 0,12 | 0,05 | 0,14 | 0,05 |
| UME | 0,162 | 0,107 | 0,147 | 0,107 |
| CEM | 0,07 | 0,02 | 0,09 | 0,02 |

METAS reported damage at 180º prior to measurements

### 8.7.2 Ring 40 mm roundness and straightness

Table 25: Ring 40 mm roundness as given by the participants

| **ROUNDNESS** | + 10 mm | u (k=1) | middle | u (k=1) | -10 mm | u (k=1) |
|---|---|---|---|---|---|---|
| **LABORATORY** | µm | µm | µm | µm | µm | µm |
| METAS | 0,15 | 0,04 | 0,08 | 0,04 | 0,08 | 0,04 |
| CMI | 0,08 | 0,05 | 0,07 | 0,05 | 0,12 | 0,05 |
| GUM | 0,110 | 0,035 | 0,115 | 0,035 | 0,106 | 0,034 |
| DTI | 0,11 | 0,045 | 0,11 | 0,045 | 0,14 | 0,045 |
| NPL | 0,11 | 0,0410 | 0,10 | 0,0420 | 0,08 | 0,0430 |
| EIM | 0,158 | 0,07 | 0,108 | 0,07 | 0,170 | 0,07 |
| METROSERT | 0,11 | 0,04 | 0,1 | 0,04 | 0,10 | 0,04 |
| INRIM | 0,086 | 0,050 | 0,074 | 0,050 | 0,084 | 0,050 |
| FSB | 0,083 | 0,055 | 0,065 | 0,055 | 0,082 | 0,055 |
| INM | 0,14 | 0,04 | 0,16 | 0,04 | 0,16 | 0,04 |
| UME | 0,104 | 0,035 | 0,074 | 0,035 | 0,100 | 0,035 |
| CEM | 0,13 | 0,02 | 0,10 | 0,02 | 0,16 | 0,02 |

UME reported scratches at the middle prior to measurements

Table 26: Ring 40 mm straightness as given by the participants

| **STRAIGHTNESS** | 0 | unc | 180 | unc |
|---|---|---|---|---|
| **LABORATORY** | µm | µm | µm | µm |
| METAS | 0,05 | 0,05 | 0,09 | 0,05 |
| DTI | 0,14 | 0,09 | 0,13 | 0,09 |
| EIM | 0,21 | 0,175 | 0,15 | 0,175 |
| METROSERT | 0,20 | 0,07 | 0,25 | 0,07 |
| INRIM | 0,13 | 0,05 | 0,11 | 0,05 |
| INM | 0,15 | 0,08 | 0,21 | 0,08 |
| UME | 0,094 | 0,107 | 0,074 | 0,107 |
| CEM | 0,05 | 0,02 | 0,07 | 0,02 |

UME reported scratches at the middle prior to measurements

## 8.7.3 Plug 5 mm roundness and straightness

Table 27: Plug 5 mm roundness as given by the participants

| | Original values | | | | | | Corrected values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ROUNDNESS** | + 2 mm | unc | middle | unc | -2 mm | unc | + 2 mm | unc | middle | unc | -2 mm | unc |
| **LABORATORY** | µm | µm | µm | µm | µm | µm | µm | µm | µm | µm | µm | µm |
| METAS | 0,03 | 0,03 | 0,05 | 0,03 | 0,03 | 0,03 | | | | | | |
| CMI | 0,17 | 0,05 | 0,11 | 0,05 | 0,13 | 0,05 | | | | | | |
| GUM | 0,056 | 0,037 | 0,062 | 0,035 | 0,048 | 0,035 | | | | | | |
| DTI | 0,04 | 0,04 | 0,03 | 0,04 | 0,05 | 0,04 | | | | | | |
| NPL | 0,08 | 0,0609 | 0,08 | 0,0607 | 0,31 | 0,0604 | 0,04 | 0,0361 | 0,07 | 0,0364 | 0,31 | 0,0358 |
| EIM | 0,071 | 0,07 | 0,067 | 0,07 | 0,078 | 0,07 | | | | | | |
| METROSERT | 0,21 | 0,04 | 0,17 | 0,03 | 0,38 | 0,04 | | | | | | |
| INRIM | 0,040 | 0,050 | 0,041 | 0,050 | 0,044 | 0,050 | | | | | | |
| INM | 0,04 | 0,04 | 0,04 | 0,04 | 0,03 | 0,04 | | | | | | |
| UME | 0,254 | 0,097 | 0,051 | 0,097 | 0,064 | 0,097 | | | | | | |
| CEM | 0,06 | 0,02 | 0,08 | 0,02 | 0,04 | 0,02 | | | | | | |

UME and METROSERT reported scratches prior to measurements that may affect the measured values

Table 28: Plug 5 mm straightness as given by the participants

| **STRAIGHTNESS** | 0 | unc | 180 | unc |
|---|---|---|---|---|
| **LABORATORY** | µm | µm | µm | µm |
| METAS | 0,09 | 0,05 | 0,03 | 0,05 |
| DTI | 0,08 | 0,04 | 0,07 | 0,04 |
| EIM | 0,05 | 0,175 | 0,05 | 0,175 |
| METROSERT | 0,17 | 0,07 | 0,17 | 0,07 |
| INRIM | 0,08 | 0,05 | 0,14 | 0,05 |
| UME | 0,176 | 0,107 | 0,174 | 0,107 |
| CEM | 0,02 | 0,02 | 0,05 | 0,02 |

UME reported scratches at the straightness lines prior to measurements

### 8.7.4 Plug 50 mm roundness and straightness

Table 29: Plug 50 mm roundness as given by the participants

| ROUNDNESS | + 6 mm | unc | middle | unc | -6 mm | unc |
|---|---|---|---|---|---|---|
| **LABORATORY** | μm | μm | μm | μm | μm | μm |
| METAS | 0,16 | 0,04 | 0,20 | 0,04 | 0,14 | 0,04 |
| CMI | 0,09 | 0,05 | 0,11 | 0,05 | 0,12 | 0,05 |
| GUM | 0,197 | 0,035 | 0,171 | 0,037 | 0,167 | 0,036 |
| DTI | 0,22 | 0,045 | 0,22 | 0,045 | 0,21 | 0,045 |
| NPL | 0,13 | 0,0366 | 0,16 | 0,0371 | 0,17 | 0,0382 |
| EIM | 0,130 | 0,07 | 0,135 | 0,07 | 0,141 | 0,07 |
| METROSERT | 0,13 | 0,04 | 0,14 | 0,04 | 0,14 | 0,04 |
| INRIM | 0,114 | 0,050 | 0,132 | 0,050 | 0,137 | 0,050 |
| FSB | 0,118 | 0,055 | 0,106 | 0,055 | 0,108 | 0,055 |
| INM | 0,28 | 0,04 | 0,19 | 0,04 | 0,20 | 0,04 |
| UME | 0,137 | 0,035 | 0,177 | 0,035 | 0,110 | 0,035 |
| CEM | 0,18 | 0,03 | 0,12 | 0,03 | 0,17 | 0,03 |

More laboratories reported scratches prior to measurements but anybody reported possible affects on the measured data

Table 30: Plug 50 mm straightness as given by the participants

| STRAIGHTNESS | 0 | unc | 180 | unc |
|---|---|---|---|---|
| **LABORATORY** | mm | μm | mm | μm |
| METAS | 0,07 | 0,05 | 0,05 | 0,05 |
| DTI | 0,19 | 0,045 | 0,22 | 0,045 |
| EIM | 0,13 | 0,175 | 0,17 | 0,175 |
| METROSERT | 0,18 | 0,05 | 0,16 | 0,05 |
| INRIM | 0,17 | 0,05 | 0,13 | 0,05 |
| INM | 0,06 | 0,08 | 0,09 | 0,08 |
| UME | 0,066 | 0,053 | 0,087 | 0,053 |
| CEM | 0,10 | 0,03 | 0,08 | 0,03 |

# 9. FINAL RESULTS

The following chapter is dealing with the evaluation with the corrected submitted values as final results. Four laboratories submitted corrected results as described in the chapter 8.
The corrected values are indicated with colours.

The tables with the data submitted by the laboratories contain the standard uncertainties ($k$=1) as they were asked in the protocol.

The $E_n$ calculations are performed with the expanded uncertainties ($k$=2).
The uncertainty bars in the graphs are also with $k$=2.

### *9.1. Ring 5 mm - diameter*

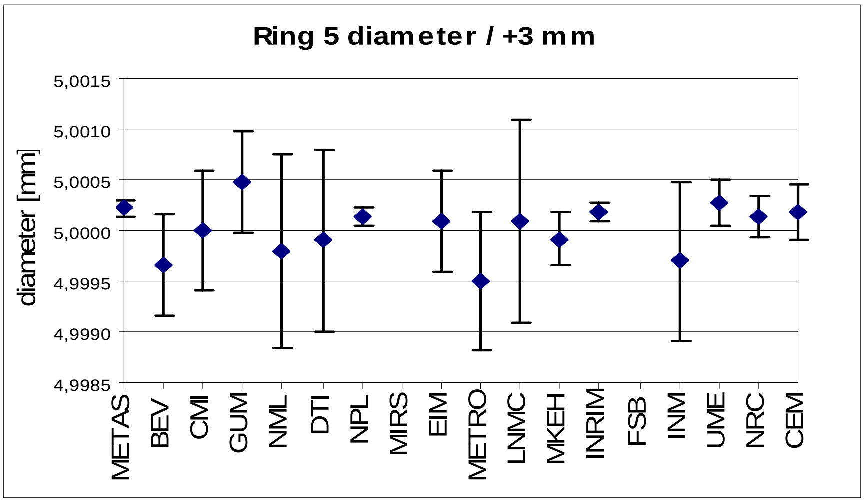
Table 31: Ring 5 mm final results as given by the participants:

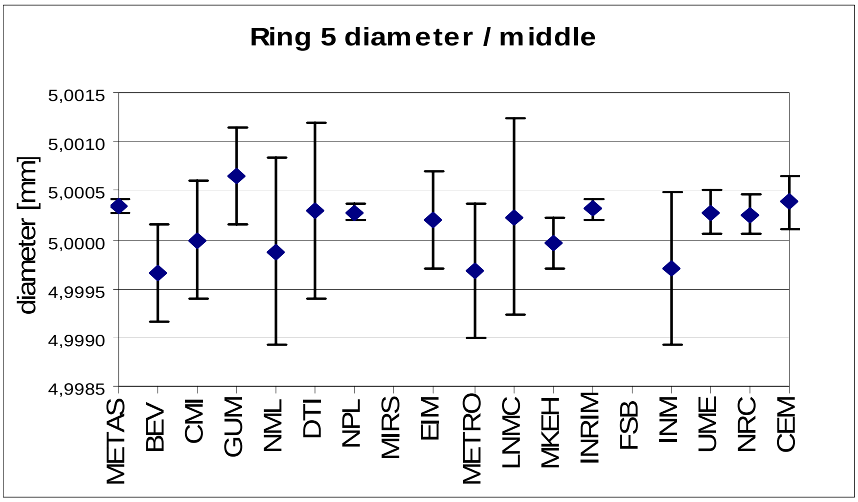
| SUBMITTED VALUES | | | | | | |
|---|---|---|---|---|---|---|
| | + | unc | middle | unc | - | unc |
| LABORATORY | mm | µm | mm | µm | mm | µm |
| METAS | 5,00022 | 0,04 | 5,00034 | 0,04 | 5,00028 | 0,04 |
| BEV | 4,99966 | 0,25 | 4,99966 | 0,25 | 4,99969 | 0,25 |
| CMI | 5,0000 | 0,3 | 5,0000 | 0,3 | 4,9996 | 0,3 |
| GUM | 5,00047 | 0,25 | 5,00065 | 0,25 | 5,00041 | 0,25 |
| NML | 4,99980 | 0,475 | 4,99988 | 0,475 | 4,99990 | 0,475 |
| DTI | 4,9999 | 0,45 | 5,0003 | 0,45 | 5,0001 | 0,45 |
| NPL | 5,00013 | 0,045 | 5,00028 | 0,042 | 5,00018 | 0,039 |
| MIRS | NOT MEASURED | | | | | |
| EIM | 5,00010 | 0,25 | 5,00020 | 0,25 | 5,00022 | 0,25 |
| METROSERT | 4,99949 | 0,341 | 4,99968 | 0,341 | 4,99973 | 0,341 |
| LNMC | 5,00010 | 0,5 | 5,00023 | 0,5 | 5,00013 | 0,5 |
| MKEH | 4,99992 | 0,13 | 4,99997 | 0,13 | 4,99999 | 0,13 |
| INRIM | 5,00018 | 0,050 | 5,00031 | 0,050 | 5,00025 | 0,050 |
| FSB | NOT MEASURED | | | | | |
| INM | 4,9997 | 0,39 | 4,9997 | 0,39 | 4,9998 | 0,39 |
| UME | 5,00028 | 0,115 | 5,00028 | 0,115 | 5,00027 | 0,115 |
| NRC | 5,00013 | 0,1 | 5,00025 | 0,1 | 5,00020 | 0,1 |
| CEM | 5,00018 | 0,14 | 5,00038 | 0,14 | 5,00036 | 0,14 |

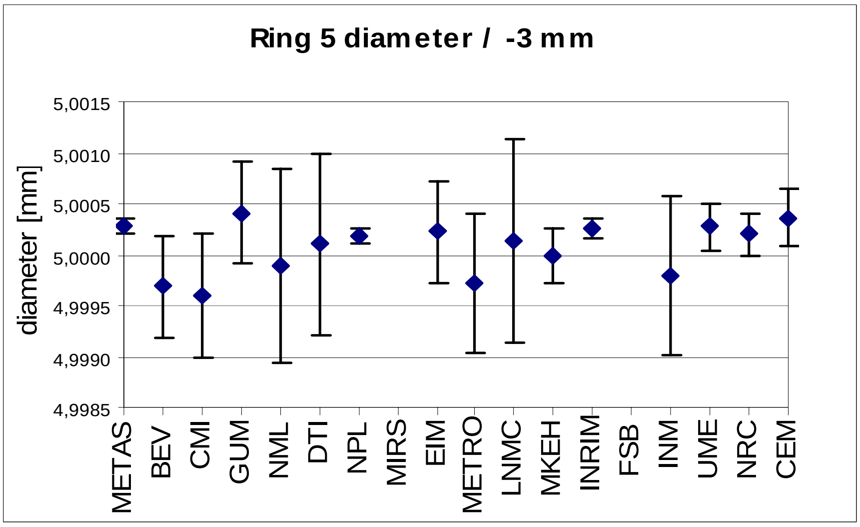
Table 32: Results evaluated with the final values

| | | | | | | |
|---|---|---|---|---|---|---|
| weighted mean: | 5,00016 | mm | 5,00029 | mm | 5,00022 | mm |
| $u_{int}$ | 0,02 | µm | 0,02 | µm | 0,02 | µm |
| $u_{ext}$ | 0,03 | µm | 0,03 | µm | 0,03 | µm |
| No of labs | 16 | | 16 | | 16 | |
| $R_B$ (uext/uint) | 1,140 | | 1,269 | | 1,187 | |
| $R_B$ crit | 1,315 | | 1,315 | | 1,315 | |
| | + | | middle | | - | |
| | xi-xw | En | xi-xw | En | xi-xw | En |
| METAS | 0,06 | 0,87 | 0,05 | 0,80 | 0,06 | 0,92 |
| BEV | -0,50 | **-1,01** | -0,63 | **-1,26** | -0,53 | **-1,06** |
| CMI | -0,16 | -0,27 | -0,29 | -0,48 | -0,62 | **-1,03** |
| GUM | 0,31 | 0,62 | 0,36 | 0,73 | 0,19 | 0,38 |
| NML | -0,36 | -0,38 | -0,41 | -0,43 | -0,32 | -0,34 |
| DTI | -0,26 | -0,29 | 0,01 | 0,01 | -0,12 | -0,13 |
| NPL | -0,03 | -0,43 | -0,01 | -0,10 | -0,04 | -0,60 |
| MIRS | NOT MEASURED | | | | | |
| EIM | -0,06 | -0,13 | -0,09 | -0,17 | 0,00 | 0,00 |
| METROSERT | -0,67 | -0,99 | -0,61 | -0,89 | -0,49 | -0,72 |
| LNMC | -0,06 | -0,06 | -0,06 | -0,06 | -0,09 | -0,09 |
| MKEH | -0,24 | -0,95 | -0,32 | **-1,24** | -0,23 | -0,89 |
| INRIM | 0,02 | 0,19 | 0,02 | 0,26 | 0,03 | 0,35 |
| FSB | NOT MEASURED | | | | | |
| INM | -0,46 | -0,59 | -0,59 | -0,75 | -0,42 | -0,54 |
| UME | 0,12 | 0,52 | -0,01 | -0,03 | 0,05 | 0,23 |
| NRC | -0,03 | -0,17 | -0,04 | -0,19 | -0,02 | -0,09 |
| CEM | 0,02 | 0,06 | 0,09 | 0,34 | 0,14 | 0,51 |

The following graphs show the final results of the ring 5 mm with the expanded uncertainties ($k$=2).



## 9.2. Ring 40 mm - diameter

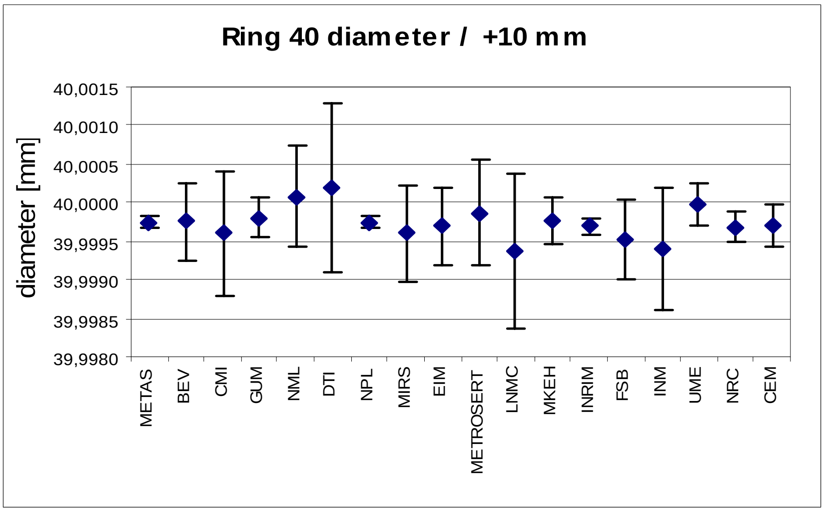
Table 33: Ring 40 mm final results as given by the participants:

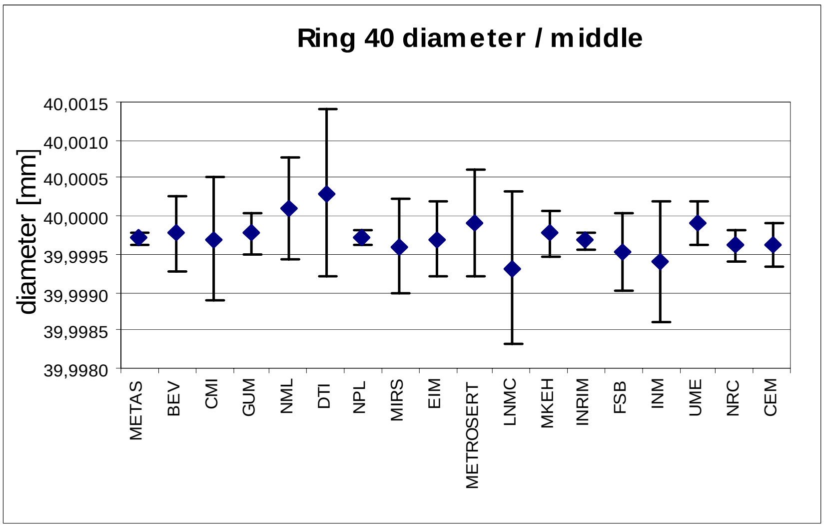
| SUBMITTED VALUES | | | | | | |
|---|---|---|---|---|---|---|
| | + | unc | middle | unc | - | unc |
| LABORATORY | mm | µm | mm | µm | mm | µm |
| METAS | 39,99974 | 0,04 | 39,99971 | 0,04 | 39,99974 | 0,04 |
| BEV | 39,99976 | 0,25 | 39,99977 | 0,25 | 39,99978 | 0,25 |
| CMI | 39,9996 | 0,4 | 39,9997 | 0,4 | 39,9996 | 0,4 |
| GUM | 39,99980 | 0,13 | 39,99977 | 0,13 | 39,99986 | 0,13 |
| NML | 40,00008 | 0,332 | 40,00010 | 0,332 | 40,00009 | 0,332 |
| DTI | 40,0002 | 0,55 | 40,0003 | 0,55 | 39,9999 | 0,55 |
| NPL | 39,99975 | 0,043 | 39,99972 | 0,041 | 39,99979 | 0,041 |
| MIRS | 39,9996 | 0,31 | 39,9996 | 0,31 | 39,9995 | 0,31 |
| EIM | 39,99969 | 0,25 | 39,99970 | 0,25 | 39,99969 | 0,25 |
| METROSERT | 39,99986 | 0,344 | 39,99991 | 0,344 | 39,99990 | 0,344 |
| LNMC | 39,99936 | 0,5 | 39,99932 | 0,5 | 39,99922 | 0,5 |
| MKEH | 39,99977 | 0,15 | 39,99977 | 0,15 | 39,99976 | 0,15 |
| INRIM | 39,99970 | 0,055 | 39,99968 | 0,055 | 39,99971 | 0,055 |
| FSB | 39,99953 | 0,26 | 39,99953 | 0,26 | 39,99953 | 0,26 |
| INM | 39,9994 | 0,4 | 39,9994 | 0,4 | 39,9991 | 0,4 |
| UME | 39,99998 | 0,143 | 39,9999 | 0,143 | 40,00006 | 0,143 |
| NRC | 39,99968 | 0,1 | 39,99961 | 0,1 | 39,99971 | 0,1 |
| CEM | 39,99971 | 0,14 | 39,99963 | 0,14 | 39,99962 | 0,14 |

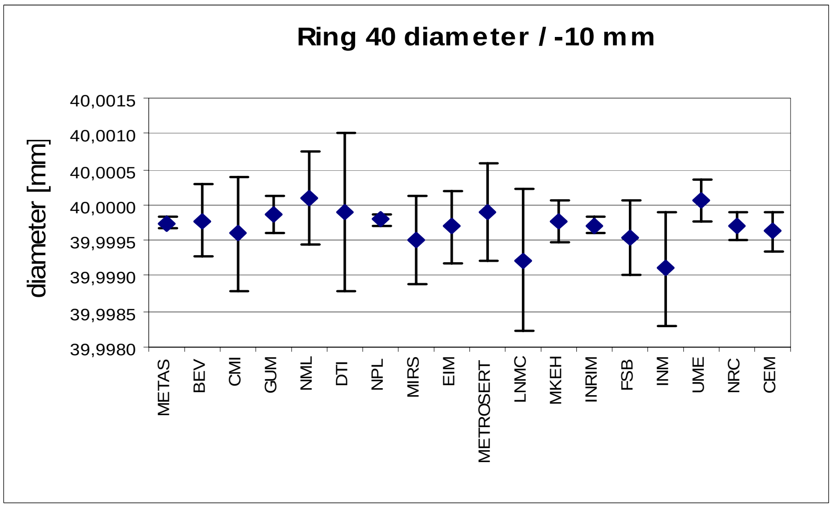
Table 34: Results evaluated with the final values

| weighted mean: | 39,99974 | mm | 39,99971 | mm | 39,99975 | mm |
|---|---|---|---|---|---|---|
| $u_{int}$ | 0,023 | µm | 0,023 | µm | 0,023 | µm |
| $u_{ext}$ | 0,016 | µm | 0,016 | µm | 0,021 | µm |
| No of labs | 18 | | 18 | | 18 | |
| $R_B$ (uext/uint) | 0,697 | | 0,710 | | 0,927 | |
| $R_B$ crit | 1,298 | | 1,298 | | 1,298 | |
| | + | | middle | | - | |
| | xi-xw | En | xi-xw | En | xi-xw | En |
| METAS | 0,00 | 0,02 | 0,00 | 0,02 | -0,01 | -0,21 |
| BEV | 0,02 | 0,04 | 0,06 | 0,12 | 0,03 | 0,05 |
| CMI | -0,14 | -0,17 | -0,01 | -0,01 | -0,15 | -0,19 |
| GUM | 0,06 | 0,24 | 0,06 | 0,24 | 0,11 | 0,42 |
| NML | 0,34 | 0,52 | 0,39 | 0,59 | 0,34 | 0,51 |
| DTI | 0,46 | 0,42 | 0,59 | 0,54 | 0,15 | 0,13 |
| NPL | 0,01 | 0,16 | 0,01 | 0,16 | 0,04 | 0,53 |
| MIRS | -0,14 | -0,22 | -0,11 | -0,18 | -0,25 | -0,41 |
| EIM | -0,05 | -0,10 | -0,01 | -0,02 | -0,06 | -0,13 |
| METROSERT | 0,12 | 0,18 | 0,20 | 0,29 | 0,15 | 0,21 |
| LNMC | -0,38 | -0,38 | -0,39 | -0,39 | -0,53 | -0,53 |
| MKEH | 0,03 | 0,11 | 0,06 | 0,21 | 0,01 | 0,02 |
| INRIM | -0,04 | -0,39 | -0,03 | -0,29 | -0,04 | -0,44 |
| FSB | -0,21 | -0,40 | -0,18 | -0,35 | -0,22 | -0,43 |
| INM | -0,34 | -0,42 | -0,31 | -0,39 | -0,65 | -0,82 |
| UME | 0,24 | 0,86 | 0,19 | 0,68 | 0,31 | **1,08** |
| NRC | -0,06 | -0,30 | -0,10 | -0,51 | -0,04 | -0,22 |
| CEM | -0,03 | -0,10 | -0,08 | -0,29 | -0,13 | -0,48 |

The following graphs show the final results of the ring 40 mm with the expanded uncertainties (*k*=2).



## 9.3. Plug 5 mm - diameter

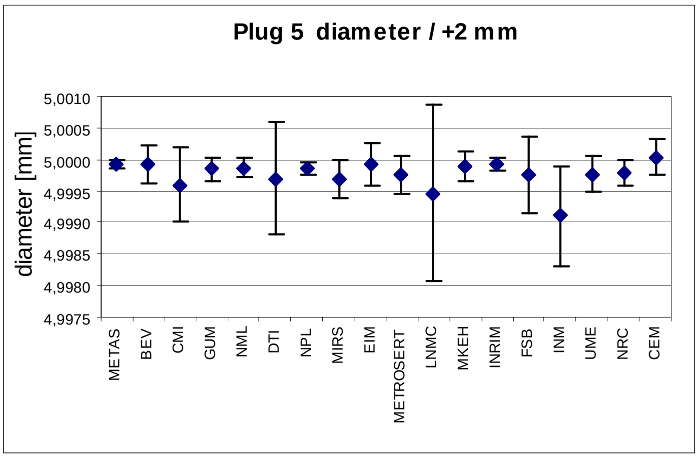
Table 35: Plug 5 mm final results as given by the participants:

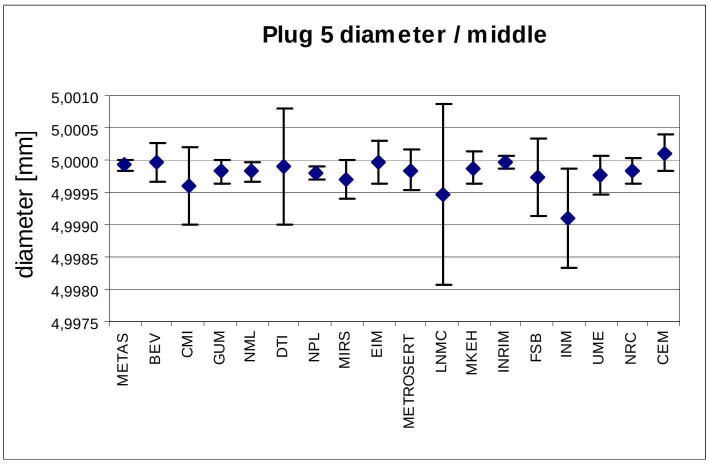
| SUBMITTED VALUES | | | | | | |
|---|---|---|---|---|---|---|
| | + | unc | middle | unc | - | unc |
| LABORATORY | mm | µm | mm | µm | mm | µm |
| METAS | 4,99992 | 0,04 | 4,99992 | 0,04 | 4,99998 | 0,04 |
| BEV | 4,99992 | 0,15 | 4,99997 | 0,15 | 4,99997 | 0,15 |
| CMI | 4,9996 | 0,3 | 4,9996 | 0,3 | 4,9996 | 0,3 |
| GUM | 4,999844 | 0,090 | 4,999819 | 0,090 | 4,999821 | 0,090 |
| NML | 4,99986 | 0,075 | 4,99983 | 0,075 | 4,99983 | 0,075 |
| DTI | 4,9997 | 0,45 | 4,9999 | 0,45 | 4,9997 | 0,45 |
| NPL | 4,99986 | 0,046 | 4,99981 | 0,047 | 4,99987 | 0,046 |
| MIRS | 4,9997 | 0,15 | 4,9997 | 0,15 | 4,9997 | 0,15 |
| EIM | 4,99991 | 0,17 | 4,99997 | 0,17 | 5,00007 | 0,17 |
| METROSERT | 4,99975 | 0,156 | 4,99984 | 0,156 | 4,99980 | 0,156 |
| LNMC | 4,99946 | 0,7 | 4,99946 | 0,7 | 4,9995 | 0,7 |
| MKEH | 4,99988 | 0,12 | 4,99988 | 0,12 | 4,99988 | 0,12 |
| INRIM | 4,99993 | 0,055 | 4,99996 | 0,050 | 5,00000 | 0,050 |
| FSB | 4,99975 | 0,30 | 4,99975 | 0,30 | 4,99978 | 0,30 |
| INM | 4,9991 | 0,39 | 4,9991 | 0,39 | 4,9991 | 0,39 |
| UME | 4,99977 | 0,150 | 4,99978 | 0,150 | 4,99974 | 0,150 |
| NRC | 4,99979 | 0,1 | 4,99984 | 0,1 | 4,99993 | 0,1 |
| CEM | 5,00004 | 0,14 | 5,00011 | 0,14 | 5,00018 | 0,14 |

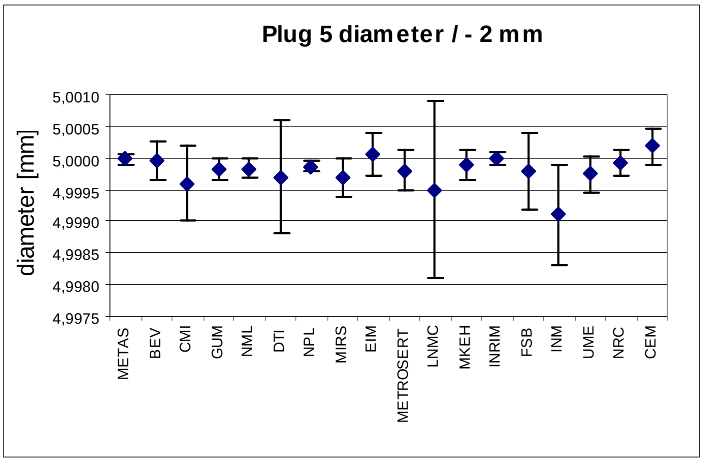
Table 36: Results with the final values

| | | | | | | |
|---|---|---|---|---|---|---|
| weighted mean: | 4,99988 | mm | 4,99988 | mm | 4,99992 | mm |
| $u_{int}$ | 0,021 | µm | 0,021 | µm | 0,021 | µm |
| $u_{ext}$ | 0,018 | µm | 0,021 | µm | 0,025 | µm |
| No of labs | 18 | | 18 | | 18 | |
| $R_B$ (uext/uint) | 0,865 | | 1,016 | | 1,180 | |
| $R_B$ crit | 1,298 | | 1,298 | | 1,298 | |
| | + | | middle | | - | |
| | xi-xw | En | xi-xw | En | xi-xw | En |
| METAS | 0,04 | 0,62 | 0,04 | 0,59 | 0,06 | 0,87 |
| BEV | 0,04 | 0,14 | 0,09 | 0,30 | 0,05 | 0,17 |
| CMI | -0,28 | -0,47 | -0,28 | -0,47 | -0,32 | -0,54 |
| GUM | -0,03 | -0,20 | -0,06 | -0,35 | -0,10 | -0,57 |
| NML | -0,02 | -0,13 | -0,05 | -0,34 | -0,09 | -0,63 |
| DTI | -0,18 | -0,20 | 0,02 | 0,02 | -0,22 | -0,25 |
| NPL | -0,02 | -0,23 | -0,07 | -0,83 | -0,05 | -0,62 |
| MIRS | -0,18 | -0,60 | -0,18 | -0,60 | -0,22 | -0,74 |
| EIM | 0,03 | 0,09 | 0,09 | 0,27 | 0,15 | 0,44 |
| METROSERT | -0,13 | -0,42 | -0,04 | -0,13 | -0,12 | -0,39 |
| LNMC | -0,42 | -0,30 | -0,42 | -0,30 | -0,42 | -0,30 |
| MKEH | 0,00 | 0,01 | 0,00 | 0,00 | -0,04 | -0,17 |
| INRIM | 0,05 | 0,51 | 0,08 | 0,89 | 0,08 | 0,87 |
| FSB | -0,13 | -0,21 | -0,13 | -0,22 | -0,14 | -0,23 |
| INM | -0,78 | -1,00 | -0,78 | -1,00 | -0,82 | **-1,05** |
| UME | -0,11 | -0,36 | -0,10 | -0,34 | -0,18 | -0,61 |
| NRC | -0,09 | -0,45 | -0,04 | -0,20 | 0,01 | 0,05 |
| CEM | 0,16 | 0,58 | 0,23 | 0,83 | 0,26 | 0,94 |

The following graphs show the final results of the plug 5 mm with the expanded uncertainties (*k*=2).



## 9.4. *Plug 50 mm - diameter*

Table 37: Plug 50 mm final results as given by the participants:

| SUBMITTED VALUES | | | | | | |
|---|---|---|---|---|---|---|
| | + | unc | middle | unc | - | unc |
| LABORATORY | mm | µm | mm | µm | mm | µm |
| METAS | 49,99940 | 0,07 | 49,99925 | 0,07 | 49,99928 | 0,07 |
| BEV | 49,99947 | 0,15 | 49,99936 | 0,15 | 49,99940 | 0,15 |
| CMI | 49,9992 | 0,4 | 49,9992 | 0,4 | 49,9992 | 0,4 |
| GUM | 49,99933 | 0,12 | 49,99918 | 0,12 | 49,99920 | 0,12 |
| NML | 49,99923 | 0,1 | 49,99922 | 0,1 | 49,99925 | 0,1 |
| DTI | 49,9986 | 0,55 | 49,9985 | 0,55 | 49,9986 | 0,55 |
| NPL | 49,99921 | 0,058 | 49,99911 | 0,0583 | 49,99905 | 0,0638 |
| MIRS | 49,9986 | 0,26 | 49,9985 | 0,26 | 49,9986 | 0,26 |
| EIM | 49,99948 | 0,18 | 49,99939 | 0,18 | 49,99938 | 0,18 |
| METROSERT | 49,99932 | 0,239 | 49,99921 | 0,239 | 49,99921 | 0,239 |
| LNMC | 49,99894 | 1 | 49,99896 | 1 | 49,99910 | 1 |
| MKEH | 49,99931 | 0,14 | 49,99936 | 0,14 | 49,99945 | 0,14 |
| INRIM | 49,99946 | 0,060 | 49,99932 | 0,075 | 49,99940 | 0,060 |
| FSB | 49,99923 | 0,3 | 49,99917 | 0,3 | 49,99923 | 0,3 |
| INM | 49,9986 | 0,41 | 49,9986 | 0,41 | 49,9987 | 0,41 |
| UME | 49,99913 | 0,156 | 49,99914 | 0,156 | 49,99924 | 0,156 |
| NRC | 49,99949 | 0,1 | 49,99943 | 0,1 | 49,99942 | 0,1 |
| CEM | 49,99951 | 0,14 | 49,99933 | 0,14 | 49,99940 | 0,14 |

Table 38: Plug 50 mm results evaluated with the final values

| weighted mean: | 49,99934 | mm | 49,99923 | mm | 49,99927 | mm |
|---|---|---|---|---|---|---|
| $u_{int}$ | 0,03 | µm | 0,03 | µm | 0,03 | µm |
| $u_{ext}$ | 0,04 | µm | 0,03 | µm | 0,04 | µm |
| No of labs | 18 | | 18 | | 18 | |
| $R_B$ (uext/uint) | 1,361 | | 1,220 | | 1,396 | |
| $R_B$ crit | 1,298 | | 1,298 | | 1,298 | |
| | + | | middle | | - | |
| | xi-xw | En | xi-xw | En | xi-xw | En |
| METAS | 0,06 | 0,48 | 0,02 | 0,15 | 0,01 | 0,09 |
| BEV | 0,13 | 0,45 | 0,13 | 0,44 | 0,13 | 0,45 |
| CMI | -0,14 | -0,17 | -0,03 | -0,04 | -0,07 | -0,09 |
| GUM | -0,01 | -0,04 | -0,05 | -0,22 | -0,07 | -0,29 |
| NML | -0,11 | -0,56 | -0,01 | -0,05 | -0,02 | -0,10 |
| DTI | -0,74 | -0,67 | -0,73 | -0,66 | -0,67 | -0,61 |
| NPL | -0,13 | **-1,26** | -0,12 | **-1,19** | -0,22 | **-1,91** |
| MIRS | -0,74 | **-1,43** | -0,73 | **-1,41** | -0,67 | **-1,29** |
| EIM | 0,14 | 0,40 | 0,16 | 0,45 | 0,11 | 0,31 |
| METROSERT | -0,02 | -0,04 | -0,02 | -0,04 | -0,06 | -0,12 |
| LNMC | -0,40 | -0,20 | -0,27 | -0,14 | -0,17 | -0,08 |
| MKEH | -0,03 | -0,10 | 0,13 | 0,47 | 0,18 | 0,66 |
| INRIM | 0,12 | **1,14** | 0,09 | 0,65 | 0,13 | **1,24** |
| FSB | -0,11 | -0,18 | -0,06 | -0,10 | -0,04 | -0,06 |
| INM | -0,74 | -0,90 | -0,63 | -0,77 | -0,57 | -0,70 |
| UME | -0,21 | -0,68 | -0,09 | -0,30 | -0,03 | -0,09 |
| NRC | 0,15 | 0,79 | 0,20 | **1,04** | 0,15 | 0,79 |
| CEM | 0,17 | 0,62 | 0,10 | 0,36 | 0,13 | 0,48 |

The results show interesting situation. The dataset is consistent at the mid-height, but inconsistent at the upper and lower heights.

Three method is introduced below to see the different approaches to exclude results from the reference value.

The first approach is to concentrate on the value at the mid-height as the most important parameter of the diameter gauges. In this case, the dataset is considered to be consistent at the mid-height and the results can be found in the table 38.

The second approach is to consider the largest $E_n$ value to be excluded from the calculation of the reference value and the reference values for all three heights are calculated from the remaining laboratories. The recomputed results are shown in the table 39.

Table 39: Plug 50 mm evaluation with excluding NPL results at all 3 heights to get consistent dataset

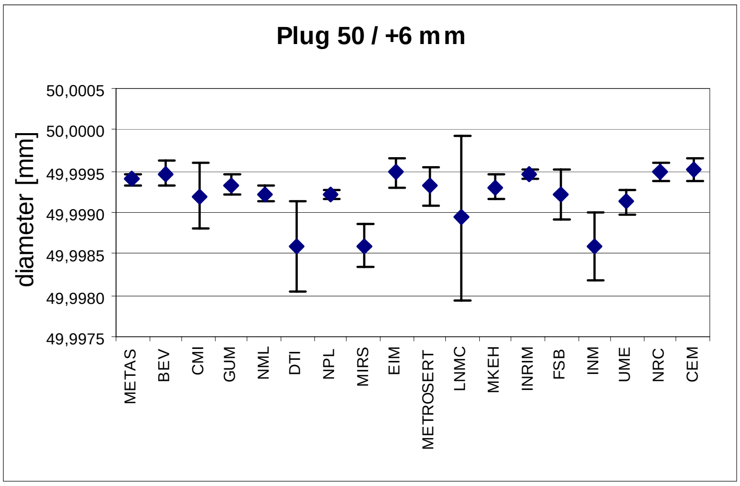
| | | | | | | |
|---|---|---|---|---|---|---|
| weighted mean: | 49,99938 | mm | 49,99927 | mm | 49,99932 | mm |
| $u_{int}$ | 0,03 | µm | 0,03 | µm | 0,03 | µm |
| $u_{ext}$ | 0,04 | µm | 0,04 | µm | 0,03 | µm |
| No of labs | 17 | | 17 | | 17 | |
| $R_B$ (uext/uint) | 1,254 | | 1,109 | | 1,077 | |
| $R_B$ crit | 1,307 | | 1,307 | | 1,307 | |
| | + | | middle | | - | |
| | xi-xw | En | xi-xw | En | xi-xw | En |
| METAS | 0,02 | 0,19 | -0,02 | -0,15 | -0,04 | -0,33 |
| BEV | 0,09 | 0,32 | 0,09 | 0,31 | 0,08 | 0,27 |
| CMI | -0,18 | -0,22 | -0,07 | -0,09 | -0,12 | -0,15 |
| GUM | -0,05 | -0,20 | -0,09 | -0,38 | -0,12 | -0,52 |
| NML | -0,15 | -0,77 | -0,05 | -0,26 | -0,07 | -0,37 |
| DTI | -0,78 | -0,71 | -0,77 | -0,70 | -0,72 | -0,66 |
| NPL | -0,17 | **-1,26** | -0,17 | **-1,26** | -0,27 | **-1,91** |
| MIRS | -0,78 | **-1,50** | -0,77 | **-1,49** | -0,72 | **-1,40** |
| EIM | 0,10 | 0,29 | 0,12 | 0,34 | 0,06 | 0,17 |
| METROSERT | -0,06 | -0,12 | -0,06 | -0,12 | -0,11 | -0,23 |
| LNMC | -0,44 | -0,22 | -0,31 | -0,15 | -0,22 | -0,11 |
| MKEH | -0,07 | -0,24 | 0,09 | 0,34 | 0,13 | 0,47 |
| INRIM | 0,08 | 0,82 | 0,05 | 0,38 | 0,08 | 0,77 |
| FSB | -0,15 | -0,24 | -0,10 | -0,17 | -0,09 | -0,15 |
| INM | -0,78 | -0,95 | -0,67 | -0,82 | -0,62 | -0,76 |
| UME | -0,25 | -0,80 | -0,13 | -0,42 | -0,08 | -0,26 |
| NRC | 0,11 | 0,60 | 0,16 | 0,85 | 0,10 | 0,52 |
| CEM | 0,13 | 0,49 | 0,06 | 0,23 | 0,08 | 0,29 |

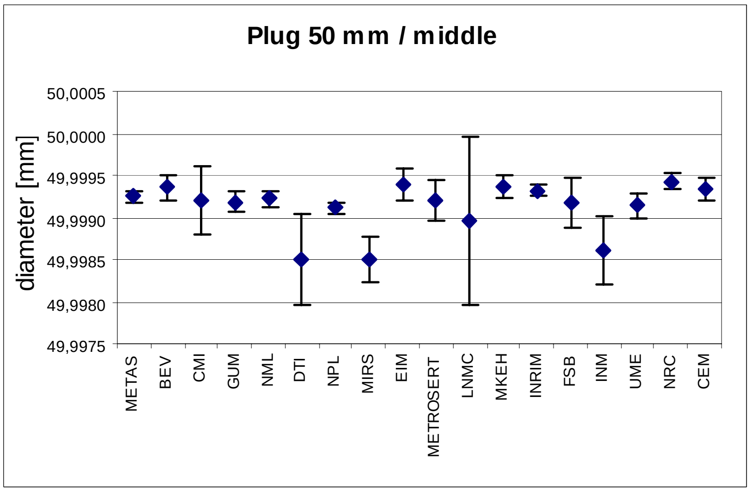
The third approach is to consider the three dataset independent at all three heights and the calculation is done separately. In this case, MIRS result is excluded at +6 mm, NPL result is excluded at -6 mm and left unchanged at middle. This calculation is shown in the table 40.

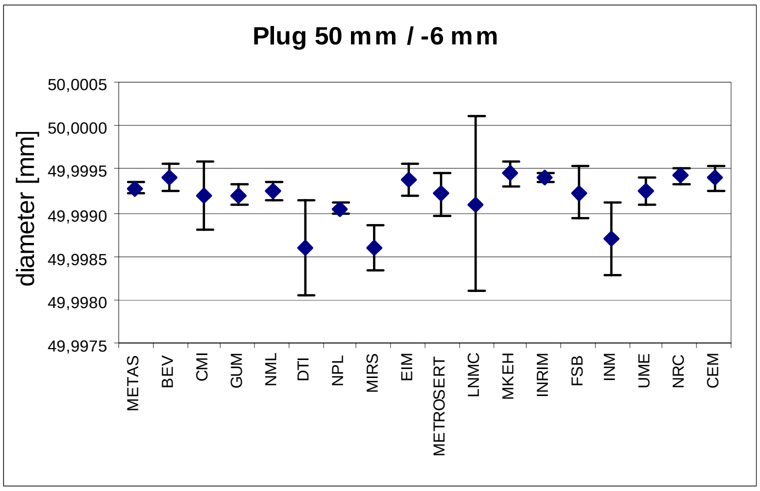
Table 40: Plug 50 mm evaluation with excluding MIRS at +6 mm and NPL at -6 mm

| | | | | | | |
|---|---|---|---|---|---|---|
| weighted mean: | 49,99935 | mm | 49,99923 | mm | 49,99932 | mm |
| $u_{int}$ | 0,03 | µm | 0,03 | µm | 0,03 | µm |
| $u_{ext}$ | 0,03 | µm | 0,04 | µm | 0,03 | µm |
| No of labs | 17 | | 18 | | 17 | |
| $R_B$ (uext/uint) | 1,208 | | 1,238 | | 1,077 | |
| $R_B$ crit | 1,307 | | 1,298 | | 1,307 | |
| | + | | middle | | - | |
| | xi-xw | En | xi-xw | En | xi-xw | En |
| METAS | 0,05 | 0,41 | 0,02 | 0,17 | -0,04 | -0,33 |
| BEV | 0,12 | 0,42 | 0,13 | 0,45 | 0,08 | 0,27 |
| CMI | -0,15 | -0,18 | -0,03 | -0,04 | -0,12 | -0,15 |
| GUM | -0,02 | -0,07 | -0,05 | -0,21 | -0,12 | -0,52 |
| NML | -0,12 | -0,61 | -0,01 | -0,04 | -0,07 | -0,37 |
| DTI | -0,75 | -0,68 | -0,73 | -0,66 | -0,72 | -0,66 |
| NPL | -0,14 | **-1,34** | -0,13 | **-1,26** | -0,27 | **-1,91** |
| MIRS | -0,75 | **-1,43** | -0,73 | **-1,41** | -0,72 | **-1,40** |
| EIM | 0,13 | 0,37 | 0,16 | 0,46 | 0,06 | 0,17 |
| METROSERT | -0,03 | -0,06 | -0,02 | -0,04 | -0,11 | -0,23 |
| LNMC | -0,41 | -0,20 | -0,27 | -0,13 | -0,22 | -0,11 |
| MKEH | -0,04 | -0,13 | 0,13 | 0,48 | 0,13 | 0,47 |
| INRIM | 0,11 | **1,06** | 0,09 | 0,66 | 0,08 | 0,77 |
| FSB | -0,12 | -0,20 | -0,06 | -0,10 | -0,09 | -0,15 |
| INM | -0,75 | -0,91 | -0,63 | -0,77 | -0,62 | -0,76 |
| UME | -0,22 | -0,71 | -0,09 | -0,29 | -0,08 | -0,26 |
| NRC | 0,14 | 0,74 | 0,20 | **1,05** | 0,10 | 0,52 |
| CEM | 0,16 | 0,59 | 0,10 | 0,37 | 0,08 | 0,29 |

The following graphs show the final results of the plug 50 mm with the expanded uncertainties (*k*=2).



### *9.5. Sphere 30 mm - diameter*

Table 41: Sphere 30 mm final results given by the participants:

| SUBMITTED VALUES | | |
|---|---|---|
| | diameter | unc |
| **LABORATORY** | mm | µm |
| METAS | 29,98623 | 0,07 |
| BEV | 29,98611 | 0,15 |
| CMI | 29,9858 | 0,4 |
| GUM | 29,986056 | 0,090 |
| NML | 29,98600 | 0,09 |
| DTI | 29,9855 | 0,55 |
| NPL | 29,98636 | 0,0538 |
| MIRS | 29,9851 | 0,15 |
| EIM | 29,98634 | 0,18 |
| METROSERT | 29,98632 | 0,196 |
| LNMC | NOT MEASURED | |
| MKEH | 29,98617 | 0,14 |
| INRIM | 29,98631 | 0,065 |
| FSB | 29,98603 | 0,30 |
| INM | 29,98530 | 0,40 |
| UME | 29,98616 | 0,100 |
| NRC | 29,98629 | 0,1 |
| CEM | 29,98609 | 0,08 |

Table 42: Results evaluated with the final values

| | | |
|---|---|---|
| weighted mean: | 29,98618 | mm |
| $u_{int}$ | 0,02 | µm |
| $u_{ext}$ | 0,06 | µm |
| No of labs | 17 | |
| $R_B$ (uext/uint) | 2,305 | |
| $R_B$ crit | 1,307 | |
| Lab | xi-xw | En |
| METAS | 0,05 | 0,35 |
| BEV | -0,07 | -0,25 |
| CMI | -0,38 | -0,48 |
| GUM | -0,13 | -0,74 |
| NML | -0,18 | **-1,06** |
| DTI | -0,68 | -0,62 |
| NPL | 0,18 | **1,85** |
| MIRS | -1,08 | **-3,66** |
| EIM | 0,16 | 0,44 |
| METROSERT | 0,14 | 0,35 |
| LNMC | NOT MEASURED | |
| MKEH | -0,01 | -0,05 |
| INRIM | 0,13 | **1,05** |
| FSB | -0,15 | -0,26 |
| INM | -0,88 | **-1,11** |
| UME | -0,02 | -0,12 |
| NRC | 0,11 | 0,55 |
| CEM | -0,09 | -0,62 |

The dataset is not consistent. MIRS results are excluded first from the reference value determination. The results are shown in the table 43.

Table 43: Results evaluated with the final values – MIRS excluded

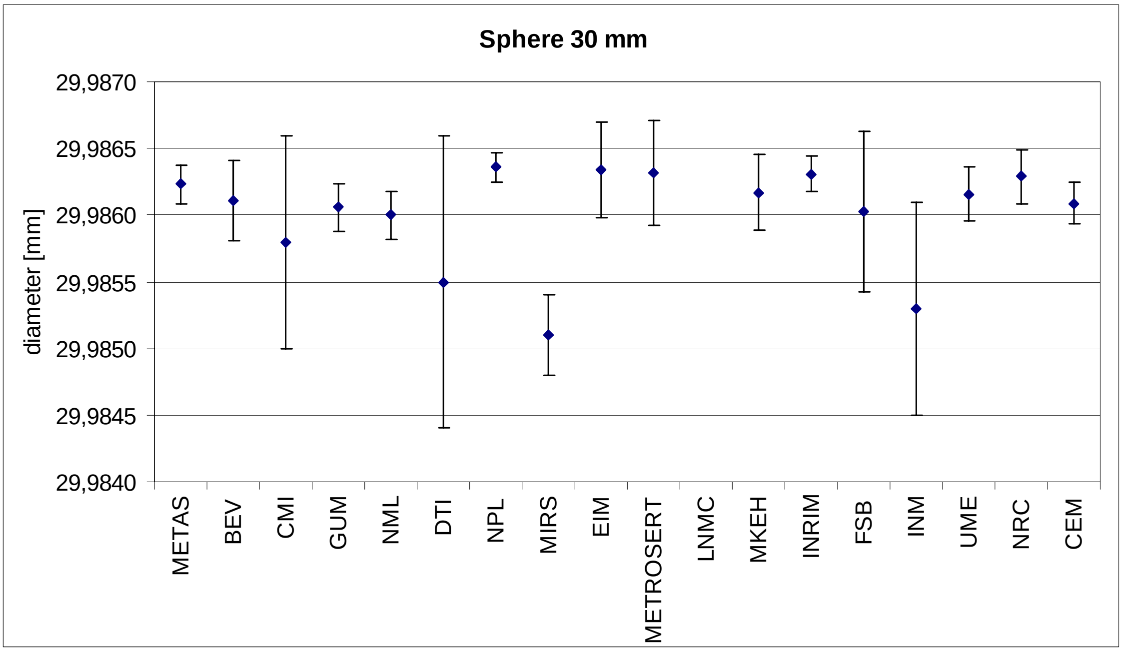
| | | |
|---|---|---|
| weighted mean: | 29,98621 | mm |
| $u_{int}$ | 0,03 | µm |
| $u_{ext}$ | 0,04 | µm |
| No of labs | 16 | |
| $R_B$ (uext/uint) | 1,445 | |
| $R_B$ crit | 1,315 | |
| Lab | xi-xw | En |
| METAS | 0,02 | 0,12 |
| BEV | -0,10 | -0,35 |
| CMI | -0,41 | -0,52 |
| GUM | -0,16 | -0,92 |
| NML | -0,21 | **-1,24** |
| DTI | -0,71 | -0,65 |
| NPL | 0,15 | **1,53** |
| MIRS | -1,11 | **-3,66** |
| EIM | 0,13 | 0,35 |
| METROSERT | 0,11 | 0,27 |
| LNMC | NOT MEASURED | |
| MKEH | -0,04 | -0,16 |
| INRIM | 0,10 | 0,80 |
| FSB | -0,18 | -0,31 |
| INM | -0,91 | **-1,15** |
| UME | -0,05 | -0,28 |
| NRC | 0,08 | 0,39 |
| CEM | -0,12 | -0,82 |

The dataset is still not consistent, the results with excluding NPL is shown in the table 44.

Table 44: Results evaluated with the final values – MIRS and NPL excluded to get consistent dataset

| | | |
|---|---|---|
| weighted mean: | 29,98617 | mm |
| $u_{int}$ | 0,03 | µm |
| $u_{ext}$ | 0,04 | µm |
| No of labs | 15 | |
| $R_B$ (uext/uint) | 1,251 | |
| $R_B$ crit | 1,325 | |
| Lab | xi-xw | En |
| METAS | 0,06 | 0,45 |
| BEV | -0,06 | -0,21 |
| CMI | -0,37 | -0,47 |
| GUM | -0,12 | -0,69 |
| NML | -0,17 | **-1,01** |
| DTI | -0,67 | -0,61 |
| NPL | 0,19 | **1,53** |
| MIRS | -1,07 | **-3,51** |
| EIM | 0,17 | 0,47 |
| METROSERT | 0,15 | 0,38 |
| LNMC | NOT MEASURED | |
| MKEH | 0,00 | -0,01 |
| INRIM | 0,14 | **1,17** |
| FSB | -0,14 | -0,24 |
| INM | -0,87 | **-1,09** |
| UME | -0,01 | -0,07 |
| NRC | 0,12 | 0,61 |
| CEM | -0,08 | -0,56 |

The following graphs show the final results of the sphere 30 mm with the expanded uncertainties (*k*=2).



## *9.6. Sphere 30 mm - roundness*

Table 45: Sphere 30 mm final results given by the participants (500 UPR)

| **500 UPR** | round. | u(k=1) |
|---|---|---|
| **LABORATORY** | µm | µm |
| METAS | 0,035 | 0,015 |
| CMI | 0,09 | 0,05 |
| GUM | 0,102 | 0,038 |
| DTI | 0,10 | 0,045 |
| NPL | not measured | |
| EIM | 0,091 | 0,07 |
| METROSERT | 0,09 | 0,05 |
| INRIM | 0,039 | 0,004 |
| FSB | 0,097 | 0,055 |
| INM | 0,10 | 0,04 |
| UME | 0,078 | 0,038 |
| CEM | 0,034 | 0,005 |

Table 46: Results evaluated with the final values

| **500 UPR** | | |
|---|---|---|
| weighted mean: | 0,039 | µm |
| $u_{int}$ | 0,003 | µm |
| $u_{ext}$ | 0,003 | µm |
| No of labs | 11 | |
| $R_B$ (uext/uint) | 1,130 | |
| $R_B$ crit | 1,376 | |
| | $\mathbf{x_i-x_w}$ | **En** |
| METAS | -0,004 | -0,13 |
| CMI | 0,051 | 0,51 |
| GUM | 0,063 | 0,83 |
| DFM | 0,061 | 0,68 |
| NPL | not measured | |
| EIM | 0,052 | 0,37 |
| METROSERT | 0,051 | 0,51 |
| INRIM | 0,000 | 0,01 |
| FSB | 0,058 | 0,53 |
| INM | 0,061 | 0,77 |
| UME | 0,039 | 0,52 |
| CEM | -0,005 | -0,62 |

Table 47: Sphere 30 mm final results given by the participants (150 UPR)

| **150 UPR** | round. | u(k=1) |
|---|---|---|
| **LABORATORY** | μm | μm |
| METAS | 0,032 | 0,015 |
| CMI | 0,10 | 0,05 |
| GUM | 0,078 | 0,036 |
| DTI | 0,12 | 0,045 |
| NPL | 0,038 | 0,003 |
| EIM | 0,076 | 0,07 |
| METROSERT | 0,07 | 0,04 |
| INRIM | 0,039 | 0,004 |
| FSB | 0,097 | 0,055 |
| INM | 0,08 | 0,04 |
| UME | 0,051 | 0,035 |
| CEM | 0,029 | 0,005 |

Table 48: Results evaluated with the final values

| **150 UPR** | | |
|---|---|---|
| weighted mean: | 0,037 | μm |
| $u_{int}$ | 0,002 | μm |
| $u_{ext}$ | 0,002 | μm |
| No of labs | 12 | |
| $R_B$ (uext/uint) | 1,078 | |
| $R_B$ crit | 1,361 | |
| | **$x_i$-$x_w$** | **En** |
| METAS | -0,005 | -0,18 |
| CMI | 0,063 | 0,63 |
| GUM | 0,041 | 0,57 |
| DTI | 0,083 | 0,92 |
| NPL | 0,001 | 0,15 |
| EIM | 0,039 | 0,28 |
| METROSERT | 0,033 | 0,41 |
| INRIM | 0,002 | 0,24 |
| FSB | 0,060 | 0,54 |
| INM | 0,043 | 0,53 |
| UME | 0,014 | 0,20 |
| CEM | -0,008 | -0,92 |

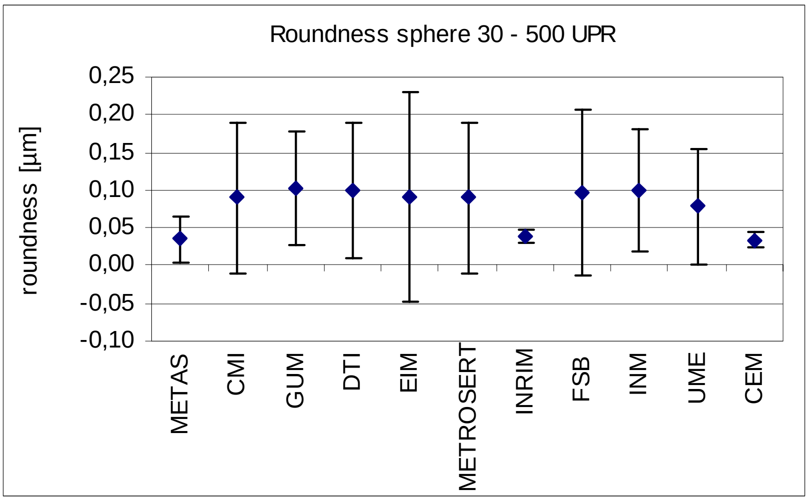
Table 49: Sphere 30 mm final results given by the participants (50 UPR)

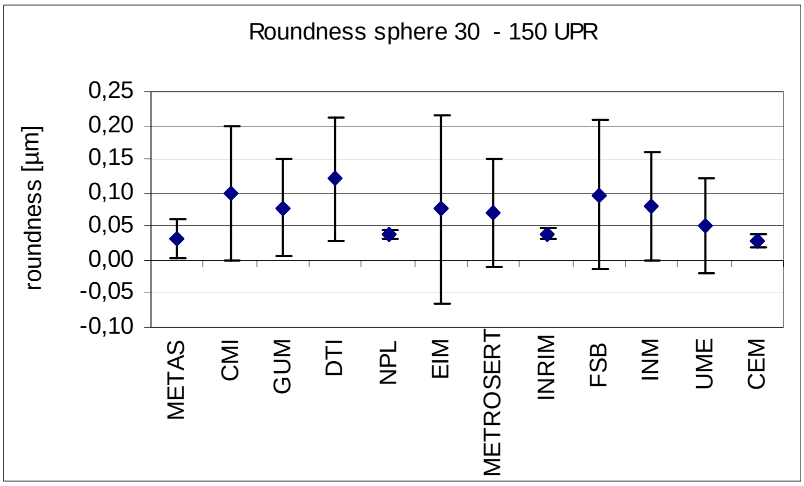
| **50 UPR** | round. | u(k=1) |
|---|---|---|
| **LABORATORY** | µm | µm |
| METAS | 0,026 | 0,015 |
| CMI | 0,10 | 0,05 |
| GUM | 0,067 | 0,036 |
| DTI | 0,14 | 0,045 |
| NPL | 0,034 | 0,003 |
| EIM | 0,058 | 0,07 |
| METROSERT | 0,06 | 0,03 |
| INRIM | 0,035 | 0,004 |
| FSB | 0,097 | 0,055 |
| INM | 0,04 | 0,04 |
| UME | 0,039 | 0,032 |
| CEM | 0,024 | 0,004 |

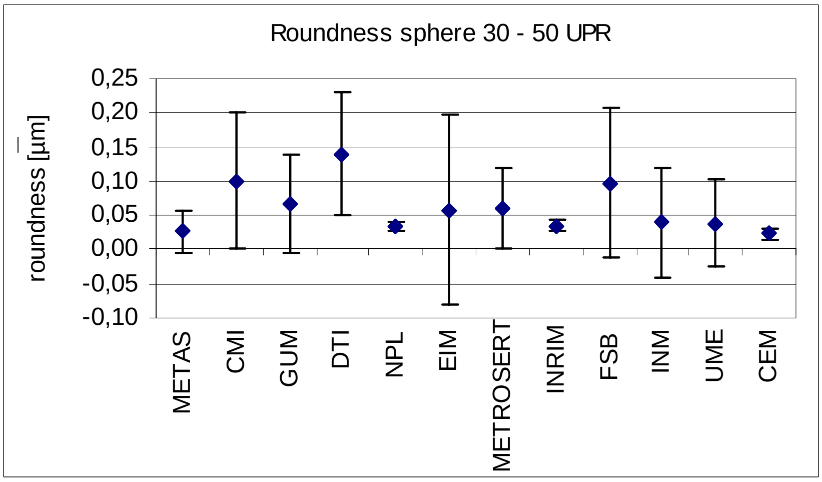
Table 50: Results evaluated with the final values

| **50 UPR** | | |
|---|---|---|
| weighted mean: | 0,032 | µm |
| $u_{int}$ | 0,002 | µm |
| $u_{ext}$ | 0,002 | µm |
| No of labs | 12 | |
| $R_B$ (uext/uint) | 1,214 | |
| $R_B$ crit | 1,361 | |
| | **$x_i$-$x_w$** | **En** |
| METAS | -0,006 | -0,21 |
| CMI | 0,068 | 0,68 |
| GUM | 0,035 | 0,48 |
| DTI | 0,108 | **1,20** |
| NPL | 0,002 | 0,40 |
| EIM | 0,026 | 0,18 |
| METROSERT | 0,028 | 0,46 |
| INRIM | 0,003 | 0,40 |
| FSB | 0,065 | 0,59 |
| INM | 0,008 | 0,10 |
| UME | 0,007 | 0,11 |
| CEM | -0,008 | **-1,19** |

The following graphs show the final results of the roundness of the sphere 30 mm with the expanded uncertainties ($k$=2).



# 10. DISCUSSION OF RESULTS

The results of diameter measurements are consistent for the rings of 5 mm and 40 mm and also for the plug of 5 mm. An interesting situation can be seen for the plug 50 mm, where the dataset is consistent at mid-height but inconsistent at +6 mm and -6 mm caused by different laboratories. Three approaches has been introduced to handle the situation to be able to compare the different methods.
The dataset for the diameter of the sphere is not consistent, after two steps of iteration reached consistency.

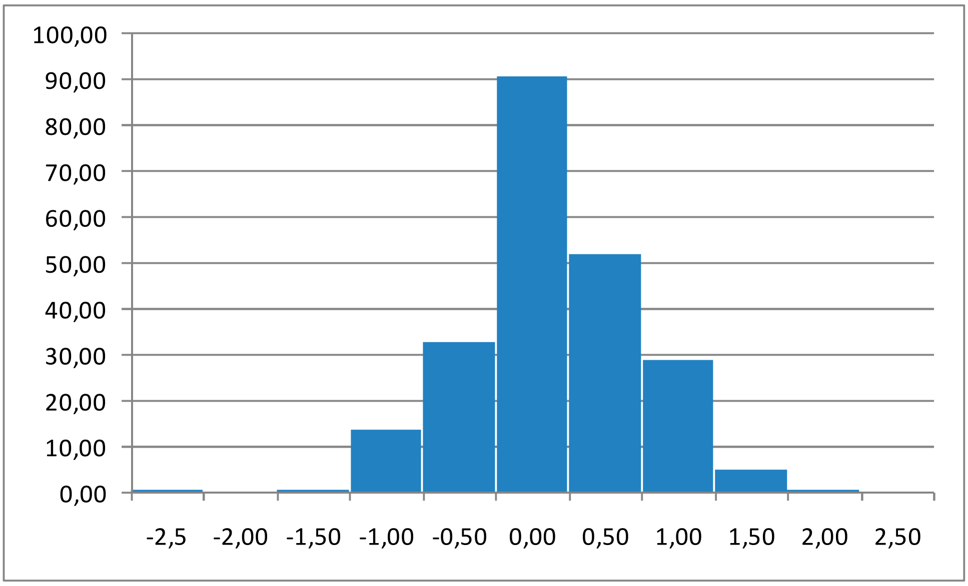
The roundness data of the sphere shows good consistency at different filters (500, 150 and 50 UPR).

It is worth noting that although the evaluation of the roundness and straightness data of the cylindrical gauges is not included in the protocol, they show good consistency.

The main problem of the comparison can be that one of the linking laboratory's results for the diameter of the plug 50 mm and the sphere seems to be outliers and also the second linking laboratory's $E_n$ value for the sphere is larger than 1, so the linking procedure between the two groups might be more difficult.

## 10. 1. Histograms of $E_n$ values

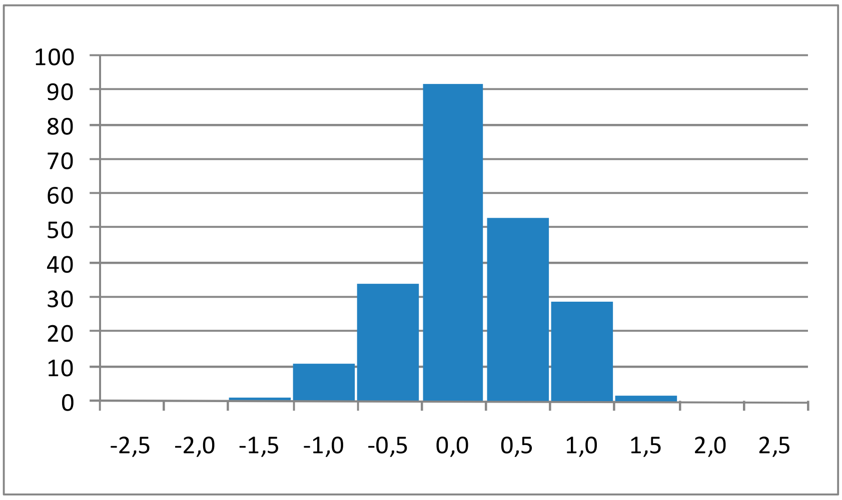
10.1.1. The following diagram contains the histogram of all $E_n$ values calculated from the total dataset of the diameter measurements, altogether from 227 results.




Histogram of $E_n$ values ($k$=2) from the total 227 elements of the original dataset

A number of 21 $E_n$ values exceed the range of ± 1 ($k$=2), which gives 7,6 %, larger than the expected 5% consistency check.

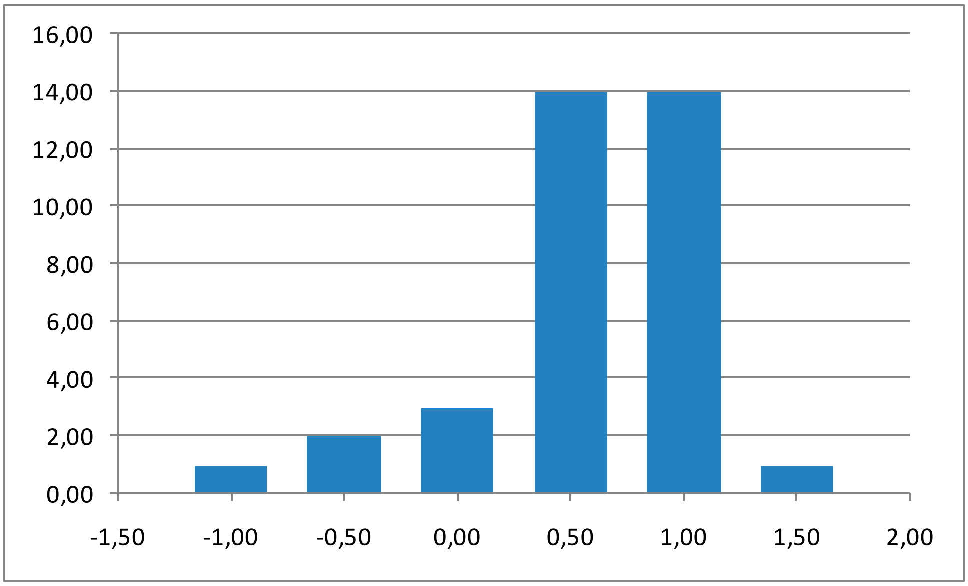
10.1.2. The following diagram contains the histogram of the $E_n$ values after excluding 5 results from calculation of KCRD (3 for plug 50 mm, 2 for sphere).




Histogram of $E_n$ values ($k$=2) from 227 elements, after excluding 5 data from the calculation of KCRD

In this case a number of 10 $E_n$ values exceed the range of ±1 ($k$=2), which gives 4,4 %, less than the expected 5% consistency check.

10.1.3 The histogram of $E_n$ values from the submitted results of the sphere roundness measurements are shown in the following diagram.




Histogram of $E_n$ values calculated for the roundness measurements of the sphere at different filters

A number of 2 from the total 34 data exceeds the expected range of ±1 that gives 5,9 %, that exceeds the expected 5% consistency check.

# 11. CONCLUSIONS

The diameter comparison was carried out in two groups. This protocol deals with the results of group 2.

The comparison was organized to have two loops, one within EU and another for non EU countries. The measurements were taken according to the scheduled dates in the first loop but than more delay came from the custom problems, *etc*.

Altogether 18 laboratories took part in the comparison, 17 from EURAMET and NRC, Canada.

Newly purchased gauges were used in the comparison. The pilot laboratory measured the gauges four times to monitor the stability of the gauges. The results show good stability for every gauge so no additional artefact uncertainty was applied in calculation of the KCRV. The cylindrical gauges suffered visible scratches that might cause some problems in the roundness measurements. No scrathes on the sphere.

Overall, the comparison has been successful. The comparison showed that these kind of measurements that could be kept “simple” measurements can cause trouble for the laboratories and makes the participants to think over the estimated uncertainty and the procedure.

## 12. ACKNOWLEDGEMENT

The pilot laboratory would like to acknowledge the kind assistance of all the participating laboratories. Particular thanks Mr. Gian Bartolo Picotto for the co-operation in piloting the two groups, Dr.Rudolf Thalmann for the assistance in choosing and purchasing the gauges and checking them to see if they would be good for the comparison, Dr. Michael Matus and Dr. Andrew Lewis for the mathematical assistance in the evaluation process.

## 13. REFERENCES

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[5] A. Lewis, EUROMET.L-K2, Calibration of long gauge blocks, Final Report

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# 14. Appendix 1

## DEVIATIONS FROM THE REFERENCE VALUES WITH THEIR UNCERTAINTIES

The reference values of the measured parameters were determined as weighted means.

$$\bar{x}_w = \sum_{i=1}^{n} w_i \cdot x_i$$

The deviation of the individual results from the weighted mean was calculated ($x_i - x_w$) and the uncertainty of this deviation:

$$U(x_i - \bar{x}_w) = 2\sqrt{u^2(x_i) - u_{\text{int}}{}^2(\bar{x}_w)} \quad (k=2)$$

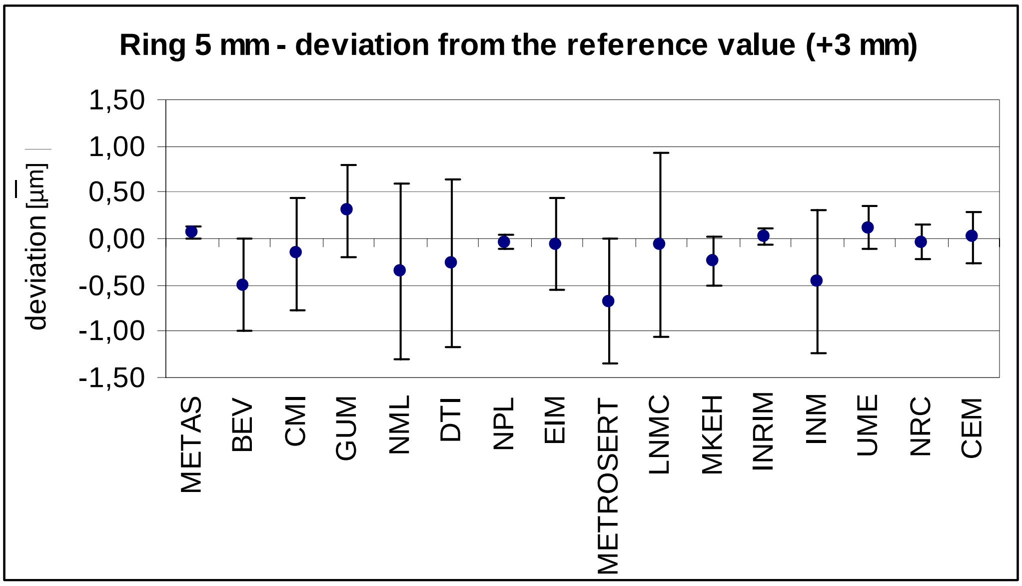
The repeated measurements of the gauges shows good stability, there is no need to introduce an additional artefact uncertainty.

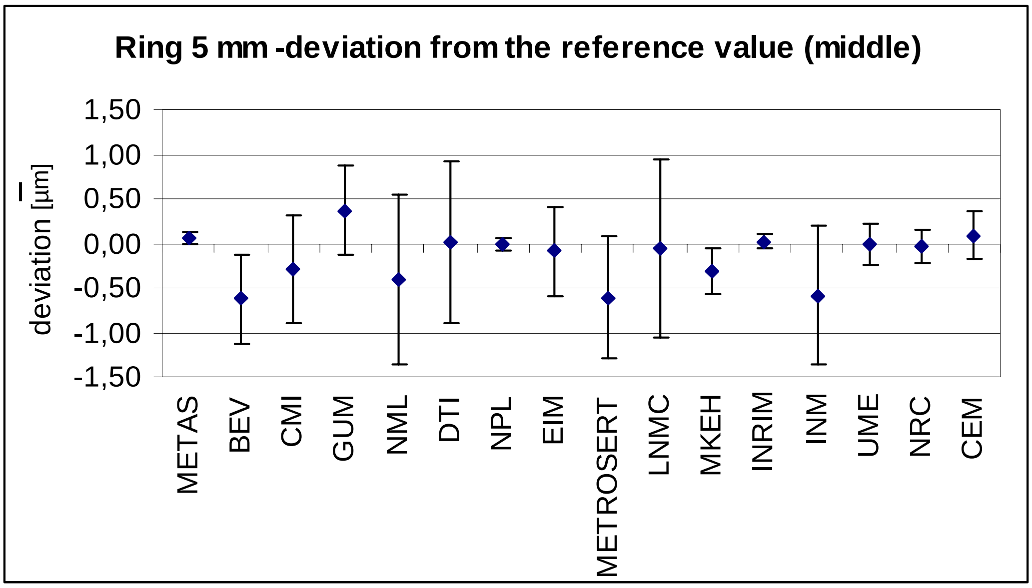
The deviations from the reference values together with their uncertainties can be found in the following tables and graphs.

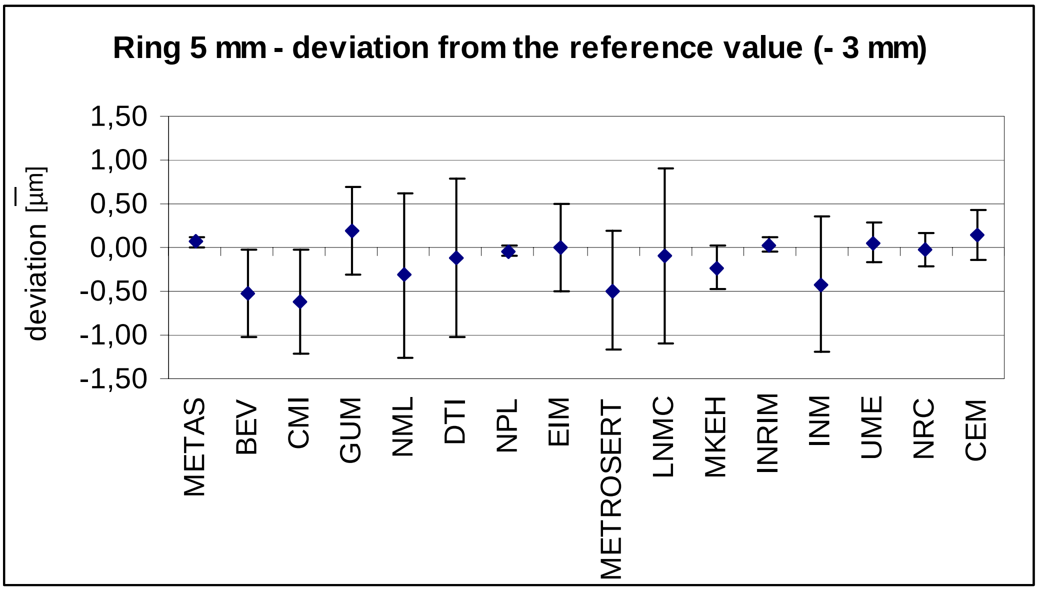
### *14.1 Ring 5 mm – diameter*

Table 51. Deviation from the reference value with its uncertainty

| | +3 mm | | middle | | -3 mm | |
|---|---|---|---|---|---|---|
| | $x_i$-$x_w$ | U (xi-xw) | $x_i$-$x_w$ | U (xi-xw) | $x_i$-$x_w$ | U (xi-xw) |
| METAS | 0,06 | 0,07 | 0,05 | 0,07 | 0,06 | 0,07 |
| BEV | -0,50 | 0,50 | -0,63 | 0,50 | -0,53 | 0,50 |
| CMI | -0,16 | 0,60 | -0,29 | 0,60 | -0,62 | 0,60 |
| GUM | 0,31 | 0,50 | 0,36 | 0,50 | 0,19 | 0,50 |
| NML | -0,36 | 0,95 | -0,41 | 0,95 | -0,32 | 0,95 |
| DTI | -0,26 | 0,90 | 0,01 | 0,90 | -0,12 | 0,90 |
| NPL | -0,03 | 0,08 | -0,01 | 0,07 | -0,04 | 0,06 |
| EIM | -0,06 | 0,50 | -0,09 | 0,50 | 0,00 | 0,50 |
| METROSERT | -0,67 | 0,68 | -0,61 | 0,68 | -0,49 | 0,68 |
| LNMC | -0,06 | 1,00 | -0,06 | 1,00 | -0,09 | 1,00 |
| MKEH | -0,24 | 0,26 | -0,32 | 0,26 | -0,23 | 0,26 |
| INRIM | 0,02 | 0,09 | 0,02 | 0,09 | 0,03 | 0,09 |
| INM | -0,46 | 0,78 | -0,59 | 0,78 | -0,42 | 0,78 |
| UME | 0,12 | 0,23 | -0,01 | 0,23 | 0,05 | 0,23 |
| NRC | -0,03 | 0,19 | -0,04 | 0,19 | -0,02 | 0,20 |
| CEM | 0,02 | 0,28 | 0,09 | 0,28 | 0,14 | 0,28 |



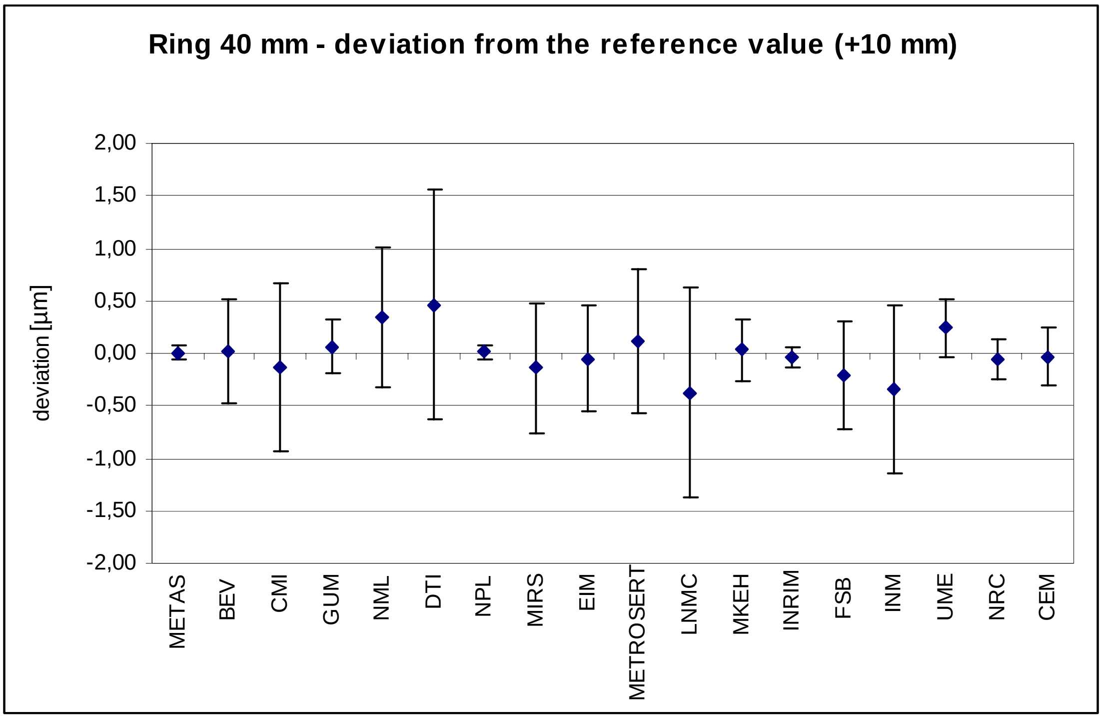

Ring 5 mm -deviation from the reference value (middle)
deviation [µm]
1,50
1,00
0,50
0,00
-0,50
-1,00
-1,50
METAS
BEV
CMI
GUM
NML
DTI
NPL
EIM
METROSERT
LNMC
MKEH
INRIM
INM
UME
NRC
CEM

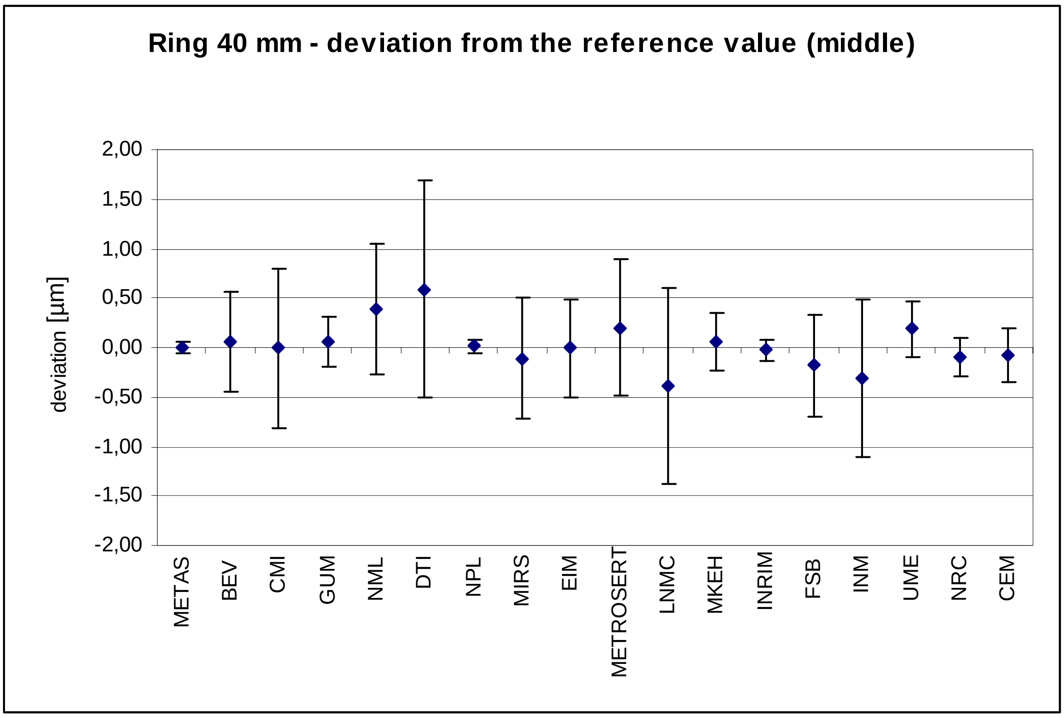

Ring 5 mm - deviation from the reference value (- 3 mm)
deviation [µm]
1,50
1,00
0,50
0,00
-0,50
-1,00
-1,50
METAS
BEV
CMI
GUM
NML
DTI
NPL
EIM
METROSERT
LNMC
MKEH
INRIM
INM
UME
NRC
CEM

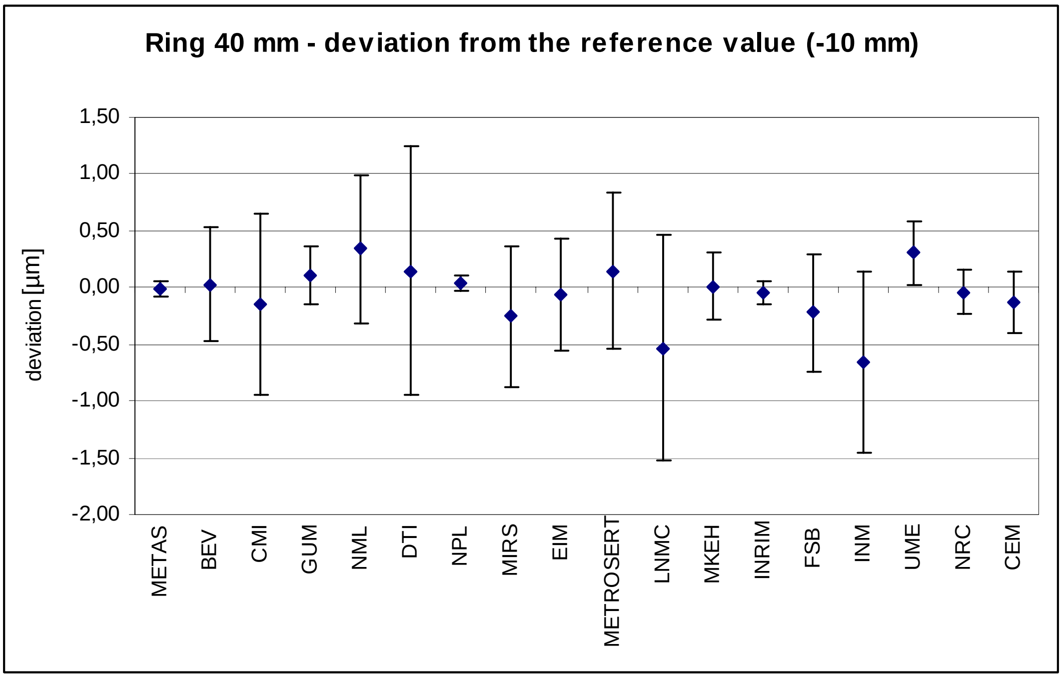
### *14.2 Ring 40 mm – diameter*

Table 52. Deviation from the reference value with its uncertainty

| | +10 mm | | middle | | -10 mm | |
|---|---|---|---|---|---|---|
| | $x_i$-$x_w$ | U (xi-xw) | $x_i$-$x_w$ | U (xi-xw) | $x_i$-$x_w$ | U (xi-xw) |
| METAS | 0,00 | 0,07 | 0,00 | 0,07 | -0,01 | 0,07 |
| BEV | 0,02 | 0,50 | 0,06 | 0,50 | 0,03 | 0,50 |
| CMI | -0,14 | 0,80 | -0,01 | 0,80 | -0,15 | 0,80 |
| GUM | 0,06 | 0,26 | 0,06 | 0,26 | 0,11 | 0,26 |
| NML | 0,34 | 0,66 | 0,39 | 0,66 | 0,34 | 0,66 |
| DTI | 0,46 | 1,10 | 0,59 | 1,10 | 0,15 | 1,10 |
| NPL | 0,01 | 0,07 | 0,01 | 0,07 | 0,04 | 0,07 |
| MIRS | -0,14 | 0,62 | -0,11 | 0,62 | -0,25 | 0,62 |
| EIM | -0,05 | 0,50 | -0,01 | 0,50 | -0,06 | 0,50 |
| METROSERT | 0,12 | 0,69 | 0,20 | 0,69 | 0,15 | 0,69 |
| LNMC | -0,38 | 1,00 | -0,39 | 1,00 | -0,53 | 1,00 |
| MKEH | 0,03 | 0,30 | 0,06 | 0,30 | 0,01 | 0,30 |
| INRIM | -0,04 | 0,10 | -0,03 | 0,10 | -0,04 | 0,10 |
| FSB | -0,21 | 0,52 | -0,18 | 0,52 | -0,22 | 0,52 |
| INM | -0,34 | 0,80 | -0,31 | 0,80 | -0,65 | 0,80 |
| UME | 0,24 | 0,28 | 0,19 | 0,28 | 0,31 | 0,28 |
| NRC | -0,06 | 0,19 | -0,10 | 0,19 | -0,04 | 0,19 |
| CEM | -0,03 | 0,28 | -0,08 | 0,28 | -0,13 | 0,28 |



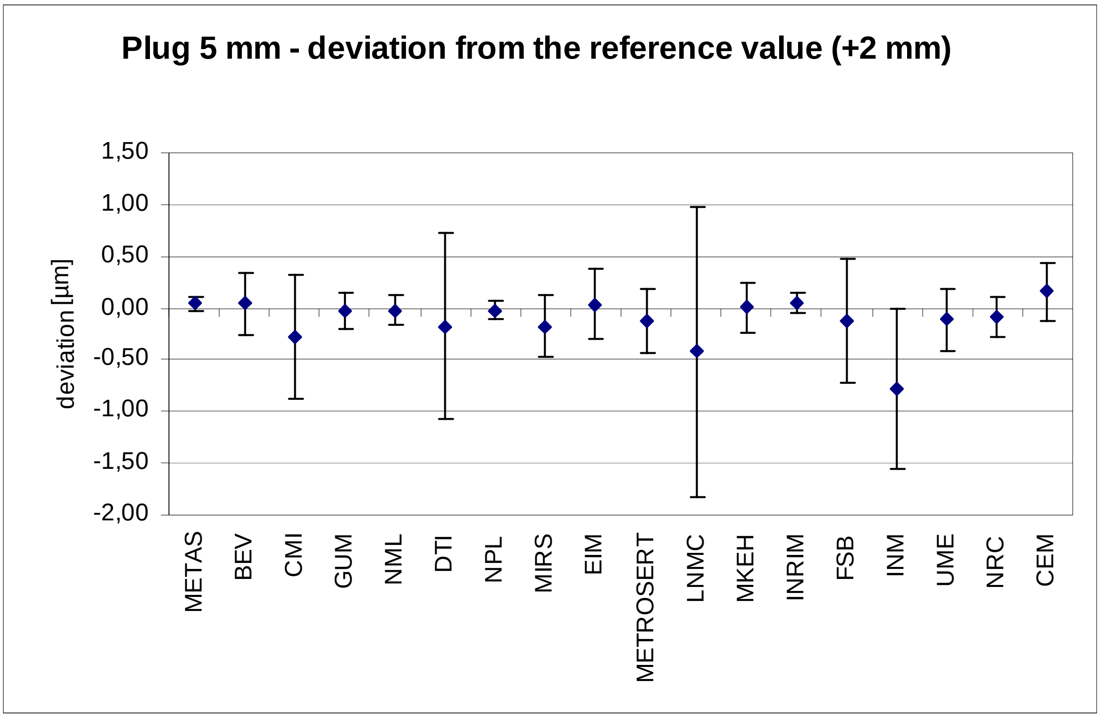

Ring 40 mm - deviation from the reference value (middle)
deviation [µm]
2,00
1,50
1,00
0,50
0,00
-0,50
-1,00
-1,50
-2,00
METAS
BEV
CMI
GUM
NML
DTI
NPL
MIRS
EIM
METROSERT
LNMC
MKEH
INRIM
FSB
INM
UME
NRC
CEM

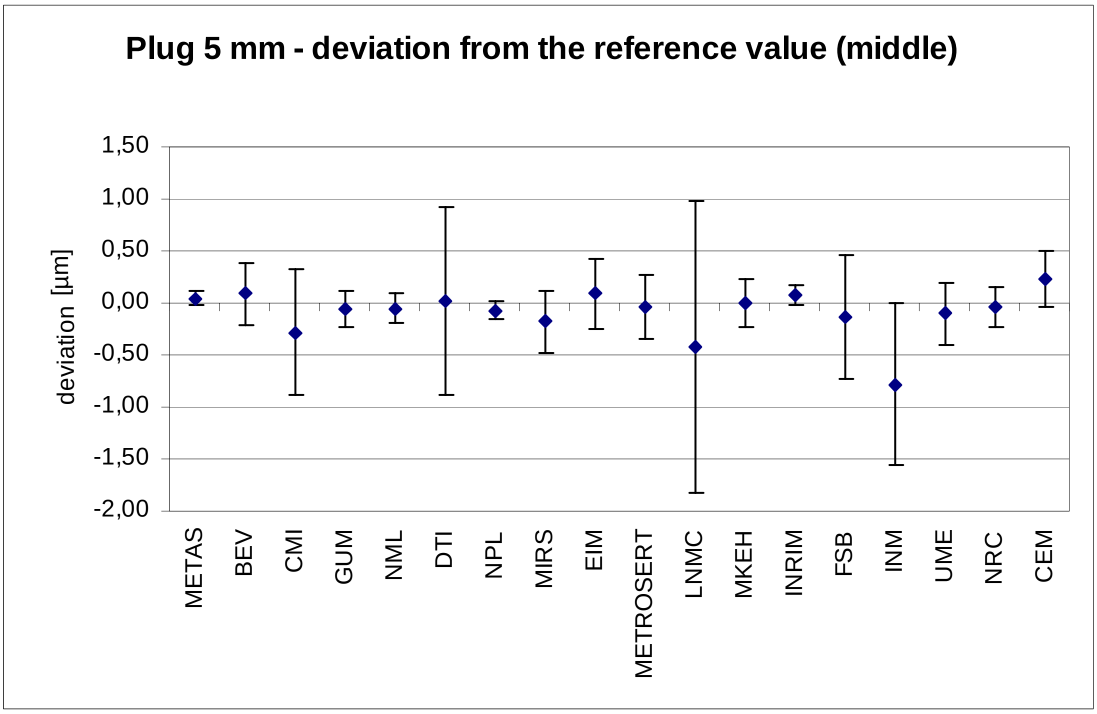

Ring 40 mm - deviation from the reference value (-10 mm)
deviation [µm]
1,50
1,00
0,50
0,00
-0,50
-1,00
-1,50
-2,00
METAS
BEV
CMI
GUM
NML
DTI
NPL
MIRS
EIM
METROSERT
LNMC
MKEH
INRIM
FSB
INM
UME
NRC
CEM

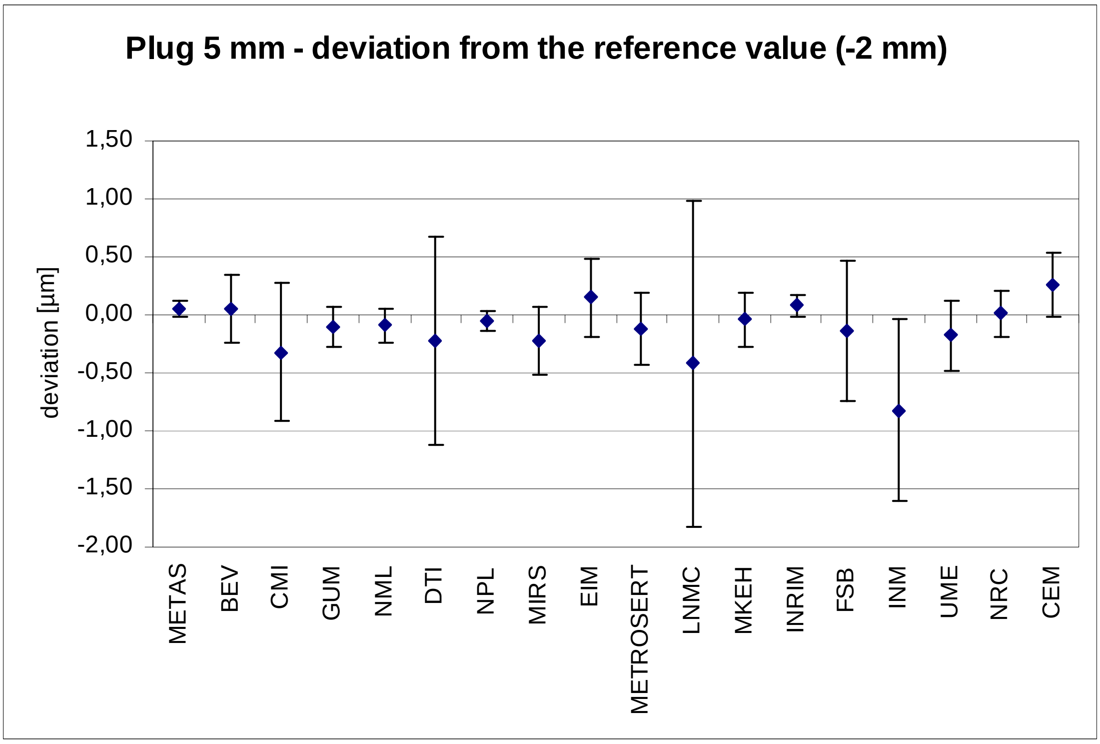
### *14.3 Plug 5 mm – diameter*

Table 53. Deviation from the reference value with its uncertainty

| | +2 mm | | middle | | -2 mm | |
|---|---|---|---|---|---|---|
| | $x_i$-$x_w$ | U (xi-xw) | $x_i$-$x_w$ | U (xi-xw) | $x_i$-$x_w$ | U (xi-xw) |
| METAS | 0,04 | 0,07 | 0,04 | 0,07 | 0,06 | 0,07 |
| BEV | 0,04 | 0,30 | 0,09 | 0,30 | 0,05 | 0,30 |
| CMI | -0,28 | 0,60 | -0,28 | 0,60 | -0,32 | 0,60 |
| GUM | -0,03 | 0,17 | -0,06 | 0,17 | -0,10 | 0,18 |
| NML | -0,02 | 0,14 | -0,05 | 0,14 | -0,09 | 0,14 |
| DTI | -0,18 | 0,90 | 0,02 | 0,90 | -0,22 | 0,90 |
| NPL | -0,02 | 0,08 | -0,07 | 0,08 | -0,05 | 0,08 |
| MIRS | -0,18 | 0,30 | -0,18 | 0,30 | -0,22 | 0,30 |
| EIM | 0,03 | 0,34 | 0,09 | 0,34 | 0,15 | 0,34 |
| METROSERT | -0,13 | 0,31 | -0,04 | 0,31 | -0,12 | 0,31 |
| LNMC | -0,42 | 1,40 | -0,42 | 1,40 | -0,42 | 1,40 |
| MKEH | 0,00 | 0,24 | 0,00 | 0,24 | -0,04 | 0,24 |
| INRIM | 0,05 | 0,10 | 0,08 | 0,09 | 0,08 | 0,09 |
| FSB | -0,13 | 0,60 | -0,13 | 0,60 | -0,14 | 0,60 |
| INM | -0,78 | 0,78 | -0,78 | 0,78 | -0,82 | 0,78 |
| UME | -0,11 | 0,30 | -0,10 | 0,30 | -0,18 | 0,30 |
| NRC | -0,09 | 0,20 | -0,04 | 0,20 | 0,01 | 0,20 |
| CEM | 0,16 | 0,28 | 0,23 | 0,28 | 0,26 | 0,28 |




Plug 5 mm - deviation from the reference value (middle)
1,50
1,00
0,50
0,00
-0,50
-1,00
-1,50
-2,00
deviation [µm]
METAS
BEV
CMI
GUM
NML
DTI
NPL
MIRS
EIM
METROSERT
LNMC
MKEH
INRIM
FSB
INM
UME
NRC
CEM


Plug 5 mm - deviation from the reference value (-2 mm)
1,50
1,00
0,50
0,00
-0,50
-1,00
-1,50
-2,00
deviation [µm]
METAS
BEV
CMI
GUM
NML
DTI
NPL
MIRS
EIM
METROSERT
LNMC
MKEH
INRIM
FSB
INM
UME
NRC
CEM

### *14.4 Plug 50 mm – diameter*

Table 54. Deviation from the reference value with its uncertainty from the complete dataset (approach 1)

| | +6 mm | | middle | | -6 mm | |
|---|---|---|---|---|---|---|
| | $x_i$-$x_w$ | U (xi-xw) | $x_i$-$x_w$ | U (xi-xw) | $x_i$-$x_w$ | U (xi-xw) |
| METAS | 0,06 | 0,13 | 0,02 | 0,13 | 0,01 | 0,13 |
| BEV | 0,13 | 0,29 | 0,13 | 0,29 | 0,13 | 0,29 |
| CMI | -0,14 | 0,80 | -0,03 | 0,80 | -0,07 | 0,80 |
| GUM | -0,01 | 0,23 | -0,05 | 0,23 | -0,07 | 0,23 |
| NML | -0,11 | 0,19 | -0,01 | 0,19 | -0,02 | 0,19 |
| DTI | -0,74 | 1,10 | -0,73 | 1,10 | -0,67 | 1,10 |
| NPL | -0,13 | 0,10 | -0,12 | 0,10 | -0,22 | 0,11 |
| MIRS | -0,74 | 0,52 | -0,73 | 0,52 | -0,67 | 0,52 |
| EIM | 0,14 | 0,36 | 0,16 | 0,36 | 0,11 | 0,36 |
| METROSERT | -0,02 | 0,47 | -0,02 | 0,47 | -0,06 | 0,47 |
| LNMC | -0,40 | 2,00 | -0,27 | 2,00 | -0,17 | 2,00 |
| MKEH | -0,03 | 0,27 | 0,13 | 0,27 | 0,18 | 0,27 |
| INRIM | 0,12 | 0,11 | 0,09 | 0,14 | 0,13 | 0,11 |
| FSB | -0,11 | 0,60 | -0,06 | 0,60 | -0,04 | 0,60 |
| INM | -0,74 | 0,82 | -0,63 | 0,82 | -0,57 | 0,82 |
| UME | -0,21 | 0,31 | -0,09 | 0,31 | -0,03 | 0,31 |
| NRC | 0,15 | 0,19 | 0,20 | 0,19 | 0,15 | 0,19 |
| CEM | 0,17 | 0,27 | 0,10 | 0,27 | 0,13 | 0,27 |

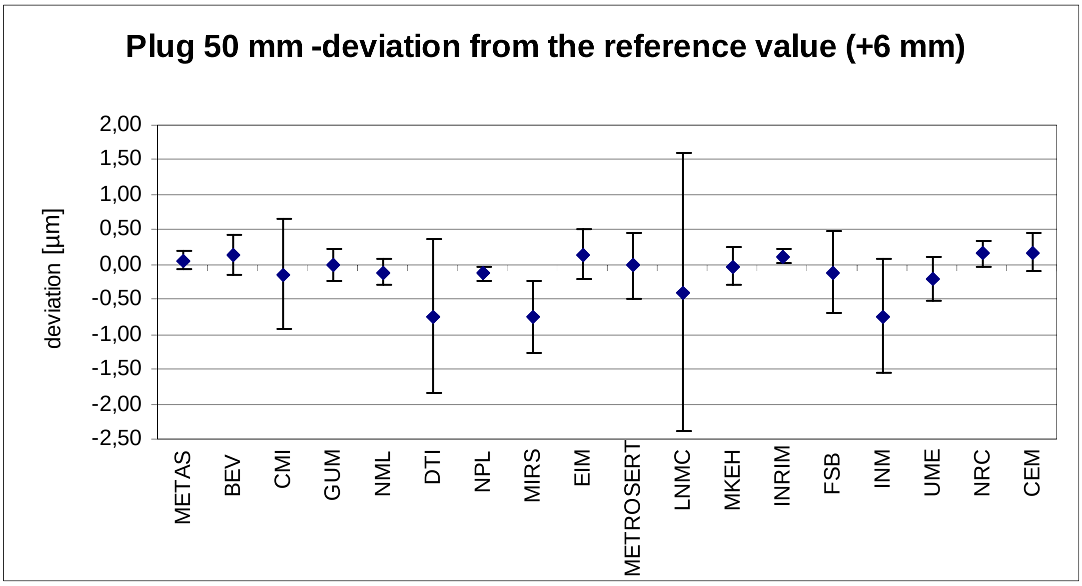
Table 55. Deviation from the reference value with its uncertainty excluding NPL (approach 2)

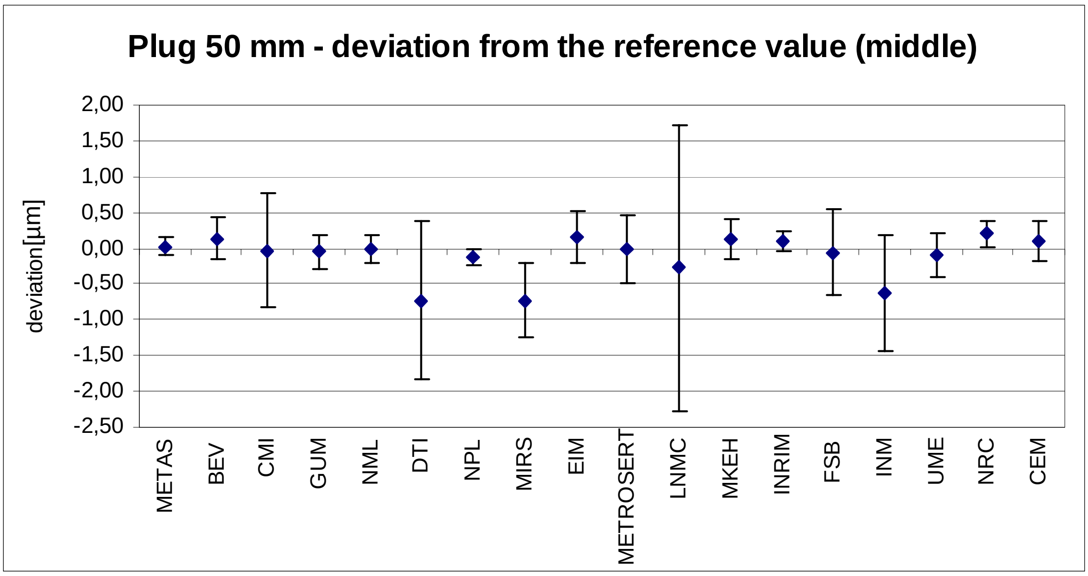
| | +6 mm | | middle | | -6 mm | |
|---|---|---|---|---|---|---|
| | $x_i$-$x_w$ | U (xi-xw) | $x_i$-$x_w$ | U (xi-xw) | $x_i$-$x_w$ | U (xi-xw) |
| METAS | 0,02 | 0,13 | -0,02 | 0,12 | -0,04 | 0,13 |
| BEV | 0,09 | 0,29 | 0,09 | 0,29 | 0,08 | 0,29 |
| CMI | -0,18 | 0,80 | -0,07 | 0,80 | -0,12 | 0,80 |
| GUM | -0,05 | 0,23 | -0,09 | 0,23 | -0,12 | 0,23 |
| NML | -0,15 | 0,19 | -0,05 | 0,19 | -0,07 | 0,19 |
| DTI | -0,78 | 1,10 | -0,77 | 1,10 | -0,72 | 1,10 |
| NPL | -0,17 | 0,10 | -0,17 | 0,10 | -0,27 | 0,11 |
| MIRS | -0,78 | 0,52 | -0,77 | 0,52 | -0,72 | 0,52 |
| EIM | 0,10 | 0,35 | 0,12 | 0,35 | 0,06 | 0,35 |
| METROSERT | -0,06 | 0,47 | -0,06 | 0,47 | -0,11 | 0,47 |
| LNMC | -0,44 | 2,00 | -0,31 | 2,00 | -0,22 | 2,00 |
| MKEH | -0,07 | 0,27 | 0,09 | 0,27 | 0,13 | 0,27 |
| INRIM | 0,08 | 0,10 | 0,05 | 0,13 | 0,08 | 0,10 |
| FSB | -0,15 | 0,60 | -0,10 | 0,60 | -0,09 | 0,60 |
| INM | -0,78 | 0,82 | -0,67 | 0,82 | -0,62 | 0,82 |
| UME | -0,25 | 0,31 | -0,13 | 0,31 | -0,08 | 0,31 |
| NRC | 0,11 | 0,19 | 0,16 | 0,19 | 0,10 | 0,19 |
| CEM | 0,13 | 0,27 | 0,06 | 0,27 | 0,08 | 0,27 |

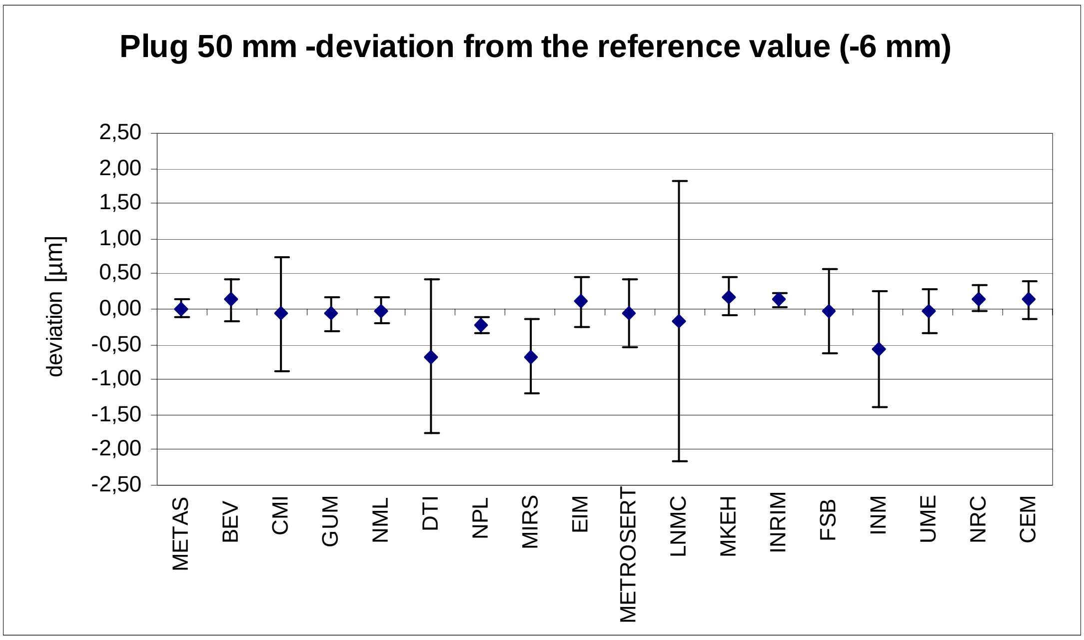
Table 56. Deviation from the reference value with its uncertainty excluding NPL at -6 mm, MIRS at +6 mm (approach 3)

| | +6 mm | | middle | | -6 mm | |
|---|---|---|---|---|---|---|
| | $x_i$-$x_w$ | U (xi-xw) | $x_i$-$x_w$ | U (xi-xw) | $x_i$-$x_w$ | U (xi-xw) |
| METAS | 0,05 | 0,13 | 0,02 | 0,13 | -0,04 | 0,13 |
| BEV | 0,12 | 0,29 | 0,13 | 0,29 | 0,08 | 0,29 |
| CMI | -0,15 | 0,80 | -0,03 | 0,80 | -0,12 | 0,80 |
| GUM | -0,02 | 0,23 | -0,05 | 0,23 | -0,12 | 0,23 |
| NML | -0,12 | 0,19 | -0,01 | 0,19 | -0,07 | 0,19 |
| DTI | -0,75 | 1,10 | -0,73 | 1,10 | -0,72 | 1,10 |
| NPL | -0,14 | 0,10 | -0,13 | 0,10 | -0,27 | 0,00 |
| MIRS | -0,75 | 0,00 | -0,73 | 0,52 | -0,72 | 0,52 |
| EIM | 0,13 | 0,36 | 0,16 | 0,36 | 0,06 | 0,35 |
| METROSI | -0,03 | 0,47 | -0,02 | 0,47 | -0,11 | 0,47 |
| LNMC | -0,41 | 2,00 | -0,27 | 2,00 | -0,22 | 2,00 |
| MKEH | -0,04 | 0,27 | 0,13 | 0,27 | 0,13 | 0,27 |
| INRIM | 0,11 | 0,11 | 0,09 | 0,14 | 0,08 | 0,10 |
| FSB | -0,12 | 0,60 | -0,06 | 0,60 | -0,09 | 0,60 |
| INM | -0,75 | 0,82 | -0,63 | 0,82 | -0,62 | 0,82 |
| UME | -0,22 | 0,31 | -0,09 | 0,31 | -0,08 | 0,31 |
| NRC | 0,14 | 0,19 | 0,20 | 0,19 | 0,10 | 0,19 |
| CEM | 0,16 | 0,27 | 0,10 | 0,27 | 0,08 | 0,27 |

The following graphs show the deviations from the reference values with the total dataset (approach 1)




Plug 50 mm - deviation from the reference value (middle)
deviation[µm]
2,00
1,50
1,00
0,50
0,00
-0,50
-1,00
-1,50
-2,00
-2,50
METAS
BEV
CMI
GUM
NML
DTI
NPL
MIRS
EIM
METROSERT
LNMC
MKEH
INRIM
FSB
INM
UME
NRC
CEM


Plug 50 mm -deviation from the reference value (-6 mm)
deviation [µm]
2,50
2,00
1,50
1,00
0,50
0,00
-0,50
-1,00
-1,50
-2,00
-2,50
METAS
BEV
CMI
GUM
NML
DTI
NPL
MIRS
EIM
METROSERT
LNMC
MKEH
INRIM
FSB
INM
UME
NRC
CEM

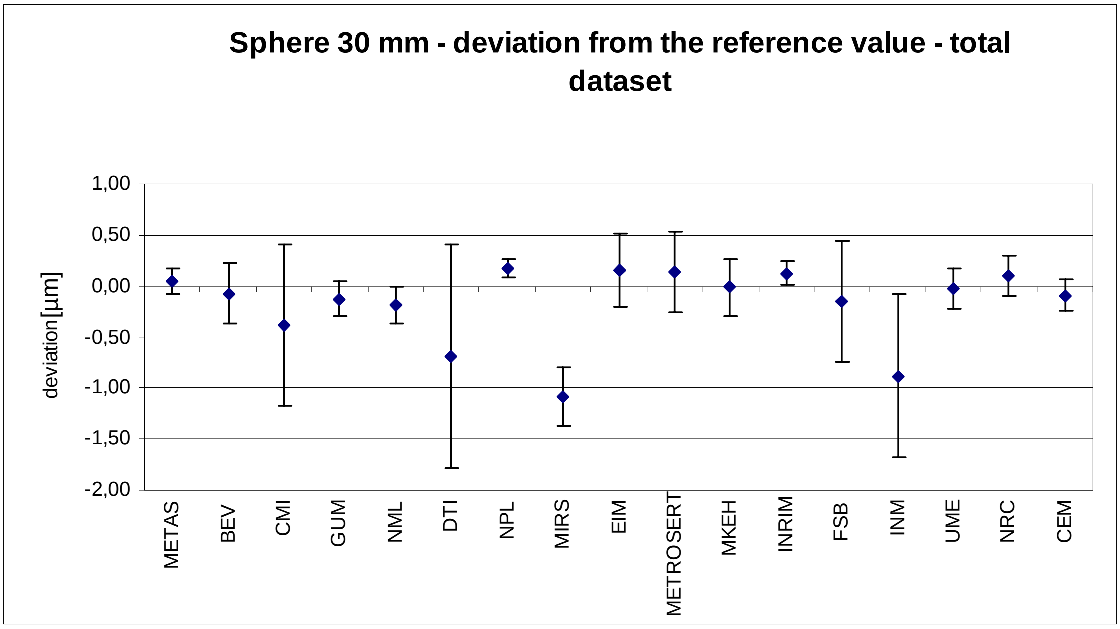
### *14.5 Sphere 30 mm – diameter*

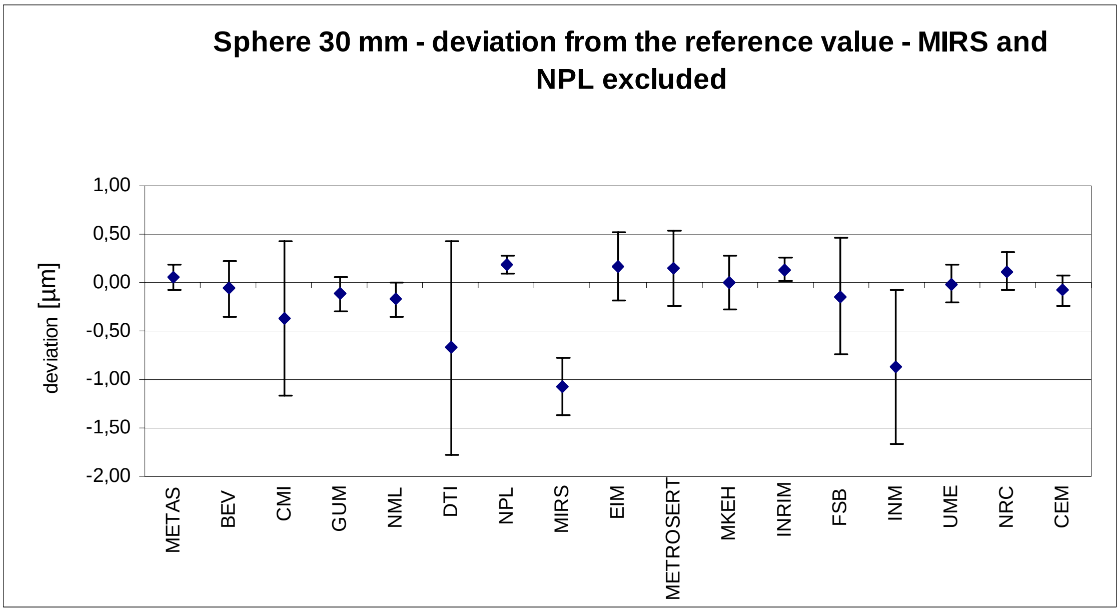
Table 57. Deviation from the reference value with its uncertainty with total dataset

| | $x_i$-$x_w$ | U (xi-xw) |
|---|---|---|
| METAS | 0,046 | 0,131 |
| BEV | -0,074 | 0,296 |
| CMI | -0,384 | 0,798 |
| GUM | -0,128 | 0,173 |
| NML | -0,184 | 0,173 |
| DTI | -0,684 | 1,099 |
| NPL | 0,176 | 0,095 |
| MIRS | -1,084 | 0,296 |
| EIM | 0,156 | 0,357 |
| METROSERT | 0,136 | 0,389 |
| MKEH | -0,014 | 0,276 |
| INRIM | 0,126 | 0,120 |
| FSB | -0,154 | 0,598 |
| INM | -0,884 | 0,798 |
| UME | -0,024 | 0,194 |
| NRC | 0,106 | 0,194 |
| CEM | -0,094 | 0,152 |

Table 58. Deviation from the reference value with its uncertainty MIRS and NPL excluded

| | $x_i$-$x_w$ | U (xi-xw) |
|---|---|---|
| METAS | 0,057 | 0,128 |
| BEV | -0,063 | 0,294 |
| CMI | -0,373 | 0,798 |
| GUM | -0,117 | 0,171 |
| NML | -0,173 | 0,171 |
| DTI | -0,673 | 1,099 |
| NPL | 0,187 | 0,091 |
| MIRS | -1,073 | 0,294 |
| EIM | 0,167 | 0,355 |
| METROSERT | 0,147 | 0,388 |
| MKEH | -0,003 | 0,274 |
| INRIM | 0,137 | 0,117 |
| FSB | -0,143 | 0,597 |
| INM | -0,873 | 0,798 |
| UME | -0,013 | 0,192 |
| NRC | 0,117 | 0,192 |
| CEM | -0,083 | 0,149 |


Sphere 30 mm - deviation from the reference value - total dataset
deviation[µm]
1,00
0,50
0,00
-0,50
-1,00
-1,50
-2,00
METAS
BEV
CMI
GUM
NML
DTI
NPL
MIRS
EIM
METROSERT
MKEH
INRIM
FSB
INM
UME
NRC
CEM


Sphere 30 mm - deviation from the reference value - MIRS and NPL excluded
deviation [µm]
1,00
0,50
0,00
-0,50
-1,00
-1,50
-2,00
METAS
BEV
CMI
GUM
NML
DTI
NPL
MIRS
EIM
METROSERT
MKEH
INRIM
FSB
INM
UME
NRC
CEM

## *14.6 Sphere 30 mm – roundness*

Table 59. Deviation from the reference value with its uncertainty at 500 UPR

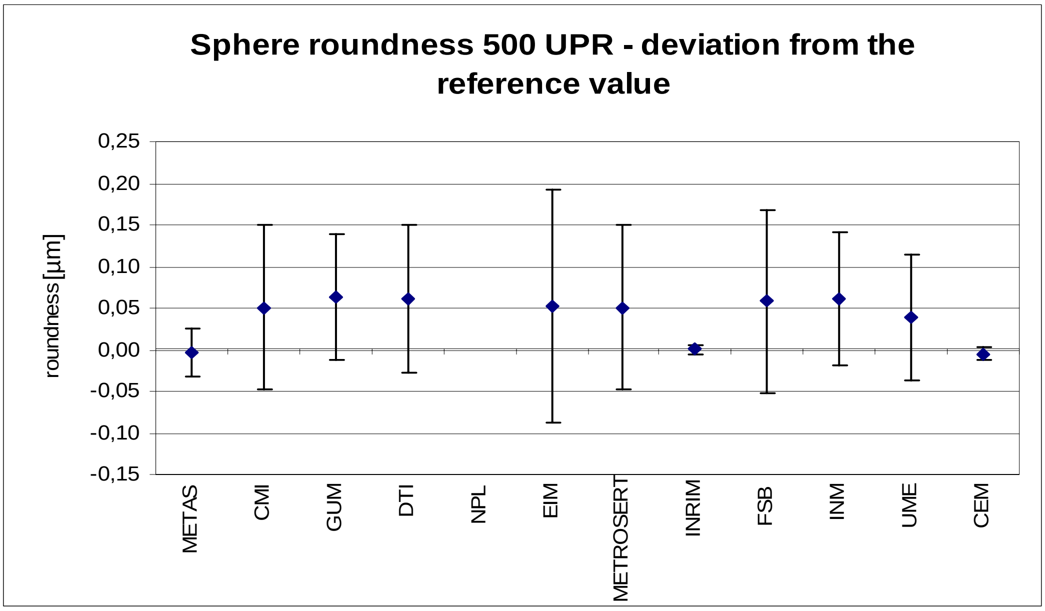
| **500 UPR** | xi-xw | U (xi-xw) |
|---|---|---|
| METAS | -0,004 | 0,029 |
| CMI | 0,051 | 0,100 |
| GUM | 0,063 | 0,076 |
| DFM | 0,061 | 0,090 |
| NPL | not measured | |
| EIM | 0,052 | 0,140 |
| METROSERT | 0,051 | 0,100 |
| INRIM | 0,000 | 0,005 |
| FSB | 0,058 | 0,110 |
| INM | 0,061 | 0,080 |
| UME | 0,039 | 0,076 |
| CEM | -0,005 | 0,008 |

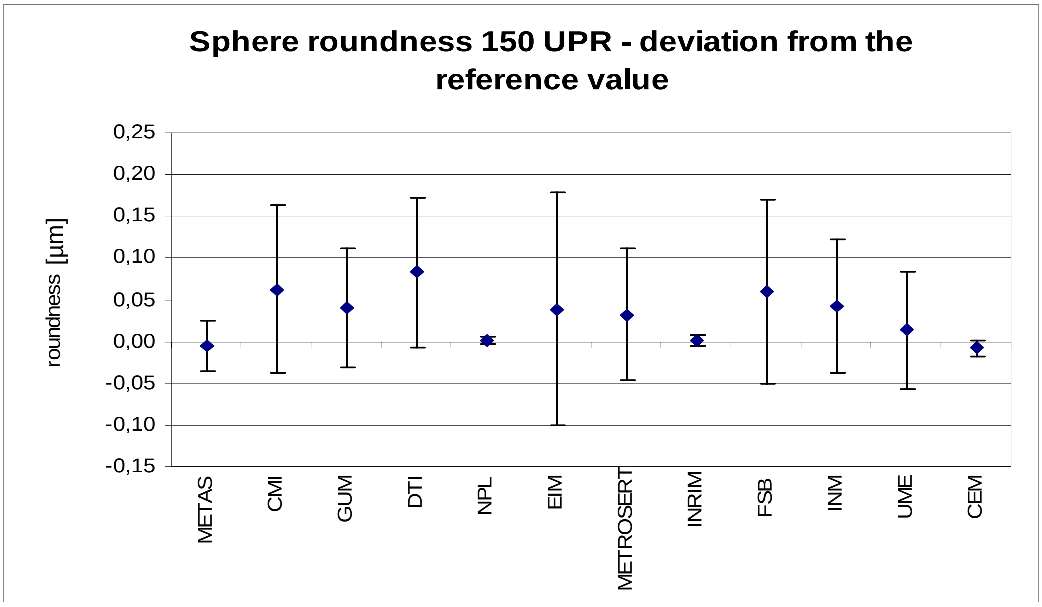
Table 60. Deviation from the reference value with its uncertainty at 150 UPR

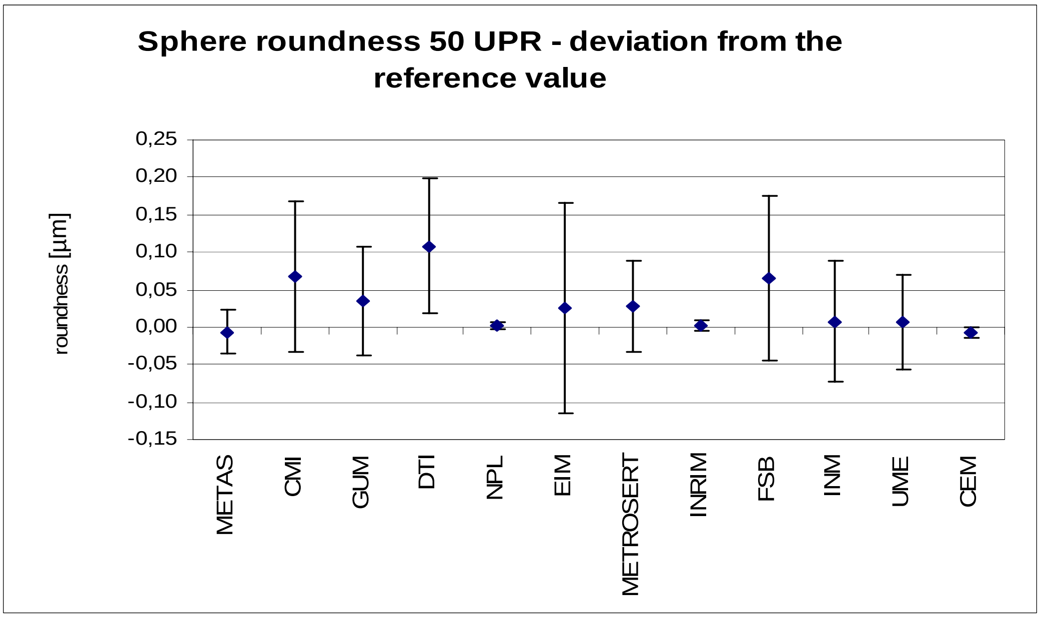
| **150 UPR** | $x_i$-$x_w$ | U (xi-xw) |
|---|---|---|
| METAS | -0,005 | 0,030 |
| CMI | 0,063 | 0,100 |
| GUM | 0,041 | 0,072 |
| DTI | 0,083 | 0,090 |
| NPL | 0,001 | 0,004 |
| EIM | 0,039 | 0,140 |
| METROSERT | 0,033 | 0,080 |
| INRIM | 0,002 | 0,007 |
| FSB | 0,060 | 0,110 |
| INM | 0,043 | 0,080 |
| UME | 0,014 | 0,070 |
| CEM | -0,008 | 0,009 |

Table 61. Deviation from the reference value with its uncertainty at 50 UPR

| **50 UPR** | $x_i$-$x_w$ | U (xi-xw) |
|---|---|---|
| METAS | -0,006 | 0,030 |
| CMI | 0,068 | 0,100 |
| GUM | 0,035 | 0,072 |
| DFM | 0,108 | 0,090 |
| NPL | 0,002 | 0,004 |
| EIM | 0,026 | 0,140 |
| METROSERT | 0,028 | 0,060 |
| INRIM | 0,003 | 0,007 |
| FSB | 0,065 | 0,110 |
| INM | 0,008 | 0,080 |
| UME | 0,007 | 0,064 |
| CEM | -0,008 | 0,007 |


Sphere roundness 500 UPR - deviation from the reference value
roundness [µm]
0,25
0,20
0,15
0,10
0,05
0,00
-0,05
-0,10
-0,15
METAS
CMI
GUM
DTI
NPL
EIM
METROSERT
INRIM
FSB
INM
UME
CEM


Sphere roundness 150 UPR - deviation from the reference value
roundness [µm]
0,25
0,20
0,15
0,10
0,05
0,00
-0,05
-0,10
-0,15
METAS
CMI
GUM
DTI
NPL
EIM
METROSERT
INRIM
FSB
INM
UME
CEM


Sphere roundness 50 UPR - deviation from the reference value
roundness [µm]
0,25
0,20
0,15
0,10
0,05
0,00
-0,05
-0,10
-0,15
METAS
CMI
GUM
DTI
NPL
EIM
METROSERT
INRIM
FSB
INM
UME
CEM

# 15. Appendix 2

## CORRELATIONS (by Michael Matus)

The evaluation of comparison data in the presence of correlation between different participants can be handled using a straightforward generalization of the standard technique [1]. The theoretical background and formulas are outlined in [2, 3]. For the application the knowledge of the complete covariance matrix is necessary, that is not only the individual uncertainties must be known, but also the covariances between the results of different laboratories. These numerical values are not provided by the participants therefore the pilot must somehow deduce them using existing information.

The physical cause for correlation in this comparison originates from the traceability chain. Some participants use standard gauges calibrated by another participant. Therefore pair wise correlation is expected between {METAS, BEV, MKEH, UME} and {INRIM, FSB}, respectively.

### 15.1 Generalized Birge test

References [2,3] present a generalization of the classical Birge test, where correlations can be covered in a natural way. The necessary information are the complete covariance matrix **D** and the vector **x** of the results. Then the following holds:

- The KCRV:

  $m = \mathbf{B}^{\mathrm{T}}\mathbf{x}$ with $\mathbf{B}^{\mathrm{T}} = \left(\mathbf{1}^{\mathrm{T}}\mathbf{D}^{-1}\mathbf{1}\right)^{-1}\mathbf{1}^{\mathrm{T}}\mathbf{D}^{-1}$

- The internal uncertainty

  $u_{\mathrm{int}} = \sqrt{\left(\mathbf{1}^{\mathrm{T}}\mathbf{D}^{-1}\mathbf{1}\right)^{-1}}$

- The generalized Birge ratio

  $R_{\mathrm{B}} = \sqrt{\frac{1}{n-1}\left(\mathbf{x}-\mathbf{1}m\right)^{\mathrm{T}}\mathbf{D}^{-1}\left(\mathbf{x}-\mathbf{1}m\right)}$

The external uncertainty $u_{\mathrm{ext}}$ can be get by multiplying $R_{\mathrm{B}}$ with $u_{\mathrm{int}}$. However its value is not really needed. It is not completely clear for me if a simple formula for the $E_{\mathrm{n}}$ values exists also, taking into account the different correlations (both between the $x_i$ and the $x_i$ and $m$ respectively). For the time being the classical evaluation was used.

## 15.2 Estimation of covariance values

Only the diagonal elements (variances) of **D** are given by the participants, the non-diagonal values (covariances) must be deduced by other ways. The following general example explains how numerical values for them were found here. Assume:

- Lab 0 performs a measurement $x_0$ with uncertainty $u(x_0)$
- Lab A performs a measurement $x_A$ with uncertainty $u(x_A)$
- Lab B performs a measurement $x_B$ with uncertainty $u(x_B)$
- Lab A gets traceability by Lab 0 via an artefact
- Lab B gets traceability by Lab 0 via an (different) artefact

Then it is clear that:

- Results of Lab A correlate with results of Lab 0, covariance $u\left(x_\mathrm{A}, x_0\right) \neq 0$
- Results of Lab B correlate with results of Lab 0, covariance $u\left(x_\mathrm{B}, x_0\right) \neq 0$
- Results of Lab A correlate with results of Lab B, covariance $u\left(x_\mathrm{A}, x_\mathrm{B}\right) \neq 0$, even if Lab 0 does not take part in this comparison

The correlation originates by the standards (calibrated by the same Lab 0 and used by Lab A and Lab B, respectively) by an unknown parameter $\delta_0$ with uncertainty $u\left(\delta_0\right)$. This parameter can be seen as a bias produced by Lab 0 during its calibration. It is (assumed) constant but unknown (otherwise Lab 0 would have corrected for it) so the best estimate is 0. The uncertainty $u\left(\delta_0\right)$ can only be estimated by Lab 0 who knows which part of his uncertainty budget includes components common in the respective measurements. Without this special knowledge all that can be concluded is $u\left(\delta_0\right) \leq u\left(x_0\right)$. Now the results of the two labs can be modeled by this common bias $x_\mathrm{A} = x'_\mathrm{A} + \delta_0$ and $x_\mathrm{B} = x'_\mathrm{B} + \delta_0$. With this model it is possible to calculate the covariance $u\left(x_\mathrm{A}, x_0\right)$ according to GUM, clause F.1.2.3. Using its terminology one finds:

$$x_\mathrm{A} = F\left(x'_\mathrm{A}, x'_\mathrm{B}, \delta_0\right) \equiv x'_\mathrm{A} + \delta_0$$

$$x_\mathrm{B} = G\left(x'_\mathrm{A}, x'_\mathrm{B}, \delta_0\right) \equiv x'_\mathrm{B} + \delta_0$$

$$u\left(x_\mathrm{A}, x_\mathrm{B}\right) = \frac{\partial F}{\partial x'_\mathrm{A}}\frac{\partial G}{\partial x'_\mathrm{A}}u^2\left(x'_\mathrm{A}\right) + \frac{\partial F}{\partial x'_\mathrm{B}}\frac{\partial G}{\partial x'_\mathrm{B}}u^2\left(x'_\mathrm{B}\right) + \frac{\partial F}{\partial \delta_0}\frac{\partial G}{\partial \delta_0}u^2\left(\delta_0\right) = u^2\left(\delta_0\right)$$

The correlation coefficient which is more readily interpreted than the covariance is:

$$r(x_A, x_B) = \frac{u^2(\delta_0)}{u(x_A)u(x_B)}$$

It is perfectly valid for Lab 0 to take over the role of one of the labs, in this case the correlation coefficient simplifies to:

$$r(x_A, x_0) = \frac{u(\delta_0)}{u(x_A)}$$

This way the full correlation matrices have been calculated. They are shown in the Appendix.

### 15.3 Results

The results for the calculation without and with (maximum) correlation are summarized in the following tables. Presented values are rounded to the next nm, $R_B$ and $E_n$ values are calculated with non-rounded values. Since the uncertainties are quite small, even a 0.1 nm change can have a significant impact on these values. For the 5 mm ring it proved necessary to remove results from BEV (with the highest $E_n$ value) to fulfil the $R_B$ criterion. (This is no problem since the deviation is too large, I know the reason for it, and have taken corrective actions already)

| Ring 5 mm middle section | no correlation | full correlation all labs | full correlation BEV removed |
|---|---|---|---|
| $x_{ref}$ | 287 nm | 303 nm | 303 nm |
| $u_{int}$ | 23 nm | 24 nm | 24 nm |
| $u_{ext}$ | 29 nm | 32 nm | 29 nm |
| $R_B$ | 1.269 | 1.372 | 1.215 |
| $R_{B\ crit}$ | 1.315 | 1.315 | 1.325 |
| $n$ | 16 | 16 | 15 |

| Ring 40 mm middle section | no correlation | full correlation |
|---|---|---|
| $x_{ref}$ | –291 nm | –297 nm |
| $u_{int}$ | 23 nm | 23 nm |
| $u_{ext}$ | 16 nm | 17 nm |
| $R_B$ | 0.710 | 0.708 |
| $R_{B\ crit}$ | 1.298 | 1.298 |
| $n$ | 18 | 18 |

## 15.4 Conclusion

It is clear that the outcome of this comparison does not depend on whether or not correlation between participants is considered. Even with the extreme correlation coefficients, still compatible with physical principles, the numerical values are effected only marginally. In reality the correlations will be smaller and consequently the results will change even less. The “=” in $u(\delta_0) \leq u(x_0)$ is very unrealistic, even when there is only little time between the respective measurements. For example the standard gauges of BEV were calibrated by METAS in September 2004 but METAS took part in the comparison in February 2009. It is very likely that METAS recalibrated in between temperature and environmental sensors, gauge blocks for probe constants, etc. or even changed the calibration procedure.

*“For the calculations presented in the following, correlations between different participants have been neglected. To check if this assumption is justifiable, data for the 5 mm and 40 mm rings was evaluated both ways, classical as well as taking into account an extreme (but physical reasonable) correlation derived from the stated traceability chains.  The techniques outlined in reference [2,3] were used for this evaluation. The results changed only marginally and did not affect conclusions drawn from the data. Since in reality the correlations are even smaller it is justifiable to evaluate the comparison data without taking correlation into account.”*

## 15.5 Correlation matrix for the results of the 5 mm ring (middle section)

| | METAS | BEV | CMI | GUM | NML | DTI | NPL | EIM | METROSERT | LNMC | MKEH | INRIM | INM | UME | NRC | CEM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| METAS | 1 | 0.160 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.308 | 0 | 0 | 0.348 | 0 | 0 |
| BEV | 0.160 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.049 | 0 | 0 | 0.056 | 0 | 0 |
| CMI | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| GUM | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NML | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| DTI | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NPL | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EIM | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| METROSERT | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| LNMC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| MKEH | 0.308 | 0.049 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0.107 | 0 | 0 |
| INRIM | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| INM | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| UME | 0.348 | 0.056 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.107 | 0 | 0 | 1 | 0 | 0 |
| NRC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| CEM | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

## 15.6 Correlation matrix for the results of the 40 mm ring (middle section)

| | METAS | BEV | CMI | GUM | NML | DTI | NPL | MIRS | EIM | METROSERT | LNMC | MKEH | INRIM | FSB | INM | UME | NRC | CEM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| METAS | 1 | 0.160 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.267 | 0 | 0 | 0 | 0.280 | 0 | 0 |
| BEV | 0.160 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.043 | 0 | 0 | 0 | 0.045 | 0 | 0 |
| CMI | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| GUM | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NML | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| DTI | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NPL | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| MIRS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EIM | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| METROSERT | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| LNMC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| MKEH | 0.267 | 0.043 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0.075 | 0 | 0 |
| INRIM | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0.212 | 0 | 0 | 0 | 0 |
| FSB | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.212 | 1 | 0 | 0 | 0 | 0 |
| INM | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| UME | 0.280 | 0.045 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.075 | 0 | 0 | 0 | 1 | 0 | 0 |
| NRC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| CEM | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

## 15.7 References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