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Supplementary Comparison EURAMET.L-S30

High Precision Roundness Measurement
by Error Separation Techniques

(EURAMET project #1489)

Final Report

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Contents

1 Document control

Version Draft A.1	Issued on April 2021
Version Draft A.2	Issued on April 2021
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2 Introduction

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

At its meeting in October 2012, the EURAMET Technical Committee for Length, EURAMET TC-L, decided that a comparison on high precision roundness measurement by multi-step method shall be carried out with CEM acting as the pilot laboratory. The roundness standards to be calibrated were chosen to be a glass hemisphere with a diameter of about 50 mm and a sphere with a diameter of about 30 mm. The comparison was registered in March 2013 as Project EURAMET 1269 and at KCDB as Supplementary Comparison EURAMET.L-S23.2013.

Artefacts circulation finished in October 2014. The Final Report was published in November 2016 and the Executive Report in October 2017. As conclusions, measurements on the hemisphere showed very good agreement, but in the case of the sphere, some difficulties were found in some of the participants, due to the quality of the sphere, being suggested to **select a better spherical standard and organize a new comparison**.

This is why **CEM, after locating new high quality standard spheres**, proposed this new comparison, in order to know the real capabilities to measure roundness in spherical standards by applying error separation techniques, searching for the lowest uncertainty. This kind of spheres is very important because the characterization of contact probes in Coordinate Measuring Systems (CMS) is based on using these spheres and the knowledge of its roundness with the smallest uncertainty is crucial and influencing the uncertainty associated to CMS measurements.

This comparison, presented at the TC-L meeting in October 14-15 2019 and also at the WG-MRA meeting in October 17-18, both taking place at PTB, was open to possible participants outside EURAMET interested on it.

3 Organization

3.1 Participants

Participants are listed in Table 1.

Table 1. List of participant laboratories and their contacts.

Laboratory Code	Contact person, Laboratory	Phone, Fax, email
CEM (Pilot)	Rafael Muñoz Emilio Prieto CEM C/ del Alfar, 2	Phone: +34 91 8074 801 rmunoz@cem.es eprieto@cem.es

	Tres Cantos – 28760 Madrid - Spain	
VSL	Richard Koops VSL P.O. Box 654 2600 AR Delft, The Netherlands	Phone: +31 (0) 15 - 269 15 00 rkoops@vsl.nl
DTI	Jens Bo Toftegaard DTI, Danish Technological Institute Taastrup Gregersensvej 1 DK-2630 Taastrup - Denmark	Phone: +45 72 20 20 00 jbt@teknologisk.dk
INRIM	Milena Astrua INRiM, Istituto Nazionale di Ricerca Metrologica Applied Metrology and Engineering Strada delle Cacce, 73 - 10135 - Torino - Italy	Phone: +39 011 3919 966 m.astrua@inrim.it
LNE	Hichem NOUIRA José Salgado LNE 1, rue Gaston Boissier 75724 Paris Cedex 15 - France	Phone: 01 40 43 37 00 hichem.nouira@lne.fr jose.salgado@lne.fr

3.2 Schedule

The comparison started in March 2020 with the measurement at the pilot laboratory. **Each laboratory had four weeks** for their measurements, including calibration and transportation to the following participant. The pilot laboratory repeated measurements at the end of the schedule to check the stability of the artefacts.

Because the Covid-19 causing working at home and problems in Customs, there were some delays but fortunately, the measurements could be concluded at the end of 2020 as shown in Table 2.

Table 2. Schedule of the comparison.

Laboratory	Planned date of measurement	Actual date of measurement
CEM (Pilot)	February 2020	March 2020
VSL	March 2020	April 2020
DTI	April 2020	May 2020
INRIM	May 2020	mid June-mid July 2020
LNE	June 2020	August 2020
CEM (Pilot)	July 2020	Oct-Nov 2020

4 Artefacts

4.1 Description of artefacts

The artefacts circulated were those in the next table:

Table 3. Artefacts.

Type	Manufacturer identification	Dimensions (mm)	Serial number	Material
Sphere	Saphirwerk	20	20-96-030	Alumina
		25	25-96-109	

Figure 1 – View of the two spheres on their supports.

Fixing the device:

The standards had to be clamped by each laboratory's own usual methods which had to be described shortly on the report form. The sphere standards are permanently glued to a base support (made of steel); try to remove the ball from the base was not allowed. The balls had to be measured by clamping its base support with sufficient rigidity.

5 Measuring instructions

5.1 Traceability

Measurements should be traceable to the latest realisation of the metre as set out in the current "*Mise en Pratique*". Temperature measurements should be made using the International Temperature Scale of 1990 (ITS-90).

5.2 Measurand

The measurand is the roundness defect. Peak-to-valley roundness deviation (*RON*t) had to be evaluated with reference to the least squares reference circle (LSCI) and, if possible, to the minimum zone reference circles (MZCI), in accordance with the ISO/TS 12181-1:2011.

All measurements must be performed at the speed of traverse not more than 10 revolutions per minute. Probing force must be specified and should not exceed 0.25 N. Stylus tip radius must be specified (see following paragraphs). Probing direction for measurement should be the normal to the spherical surface. In case a different orientation is used, this should be clearly reported. Results shall be reported using a Gaussian filter. Each measurement shall be preferably accompanied by its relevant plots.

Each laboratory shall use an error separation technique to remove the contribution of the spindle error. In case of using a multistep technique, as it is the common case, it is advisable to inform on the number of steps used.

The roundness of the spheres should be measured on the equator (figure 2).

According with ISO/TS 12181-2:2011 and assuming that most of the participants use a roundness measuring system with 350 sample points or more and spherical tips not smaller than 1 mm diameter, measurements shall be made with the following filter transmissions: 1-15 UPR and 1-50 UPR.

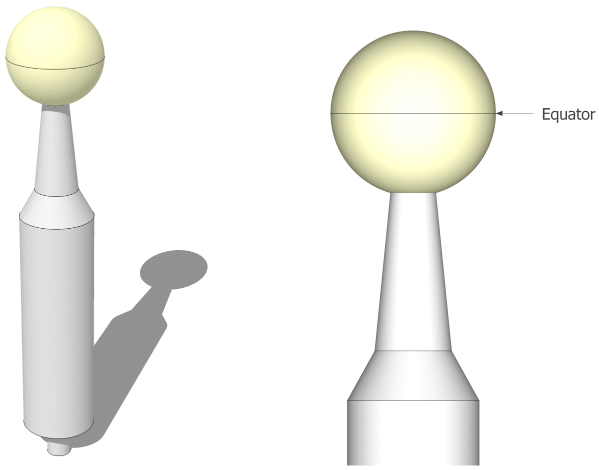

Figure 2 – Measurement plane on the sphere.

5.3 Equipment and measuring methods

A shallow overview of the equipment and the measuring methods used is given in Table 4. All instruments were of rotating workpiece type and equipped with an inductive transducer with a lever-type stylus. The calibration of the probe was made by using different traceable transfer standards: piezo-actuators, flick-standards, gauge blocks … In those laboratories applying the multi-step method for compensation of spindle errors, the number of steps varied from 8 to 24.

Table 4. Equipment and measurement details.

Set-up	Participant				
	CEM	**VSL**	**DTI**	**INRIM**	**LNE**
Rotating workpiece or probe (CW or CCW)	CW	CW	CW	CW	CW
Rotation speed (rev/min)	6	6	6	6	4
Number of measured values per revolution	7200	7200	4000	1000	3600
Filtering conditions	Gauss 50% Low-pass	Gauss 50%	Gauss	Gauss	Gauss
Error separation technique: Number of steps	12	Full Reversal method (extended Donaldson Reversal)	NO	8	24
Stylus static force (mN)	40	38	59	27	--
Ball tip diameter (mm)	1.6	2	5	3	1.6

5.4 Measurement uncertainty

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

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

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

The following table shows the uncertainties communicated by the participants.

Table 5. Uncertainties of the participants in the comparison S30 (U_{S30}) against their approved CMC.

Lab.	U_{S30}	CMC (BIPM KCDB)	Obs.
CEM	Q[7 nm, 14E-03 *R*]	Q[7 nm, 14E-03 *R*]	U_{S30} = CMC
VSL	Q[6.2 nm, 15E-03 *R*] nm	Q[10 nm, 30E-03 *R*	U_{S30} < CMC
DTI	Q[0.09 µm, 0.06 *R*]	Q[0.09 µm, 0.06 *R*]	U_{S30} = CMC
INRIM	Q[7 nm, 10E-03 *R*]	Q[7 nm, 10E-03 *R*]	U_{S30} = CMC
LNE	24 nm	50 nm	U_{S30} = CMC/2

6 Results

6.1 Reporting of results

Following receipt of all measurement reports from the participating laboratories, the pilot laboratory analysed the results and invited some participants to "check their results for numerical errors but without being informed of the magnitude or sign of the apparent anomaly", according to the last paragraph of Section 8.1 in Document CIPM MRA-G-11 on Comparisons.

After receiving confirmation of the communicated values, or the corrected values and the corresponding explanation in case of having detected wrong ones, the pilot laboratory prepared a first draft A.1 report, which was circulated to the participants for possible comments, additions or corrections.

6.2 Results and standard uncertainties as reported by participants

The confirmed results are collected in the tables below.

Table 6. Results and uncertainties for the 20 mm sphere.

20 mm sphere s/n 20-96-030	**15 UPR**				**50 UPR**			
	LSCI		**MZCI**		**LSCI**		**MZCI**	
Participant	***RONt* (µm)**	***U*(*k*=2) (µm)**	***RONt* (µm)**	***U*(*k*=2) (µm)**	***RONt* (µm)**	***U*(*k*=2) (µm)**	***RONt* (µm)**	***U*(*k*=2) (µm)**
CEM#1	0.014	0.007	0.014	0.007	0.020	0.007	0.020	0.007
VSL	0.014	0.006	0.013	0.006	0.016	0.006	0.015	0.006
DTI	0.060	0.080	0.050	0.080	0.080	0.080	0.080	0.080
INRIM	0.014	0.007			0.020	0.007		
LNE	0.013	0.024	0.012	0.024	0.017	0.024	0.016	0.024
CEM#2	0.015	0.007	0.015	0.007	0.022	0.007	0.022	0.007

Table 7. Results and uncertainties for the 25 mm sphere.

25 mm sphere s/n 25-96-109	**15 UPR**				**50 UPR**			
	LSCI		**MZCI**		**LSCI**		**MZCI**	
Participant	***RONt* (µm)**	***U*(*k*=2) (µm)**	***RONt* (µm)**	***U*(*k*=2) (µm)**	***RONt* (µm)**	***U*(*k*=2) (µm)**	***RONt* (µm)**	***U*(*k*=2) (µm)**
CEM#1	0.022	0.007	0.022	0.007	0.032	0.007	0.031	0.007
VSL	0.024	0.006	0.022	0.006	0.031	0.006	0.028	0.006
DTI	0.050	0.080	0.050	0.080	0.080	0.080	0.080	0.080
INRIM	0.016	0.007			0.023	0.007		
LNE	0.031	0.024	0.030	0.024	0.039	0.024	0.037	0.024
CEM#2	0.019	0.007	0.019	0.007	0.030	0.007	0.028	0.007

7 Analysis of results

7.1 Artefacts Stability

The stability of the standards was determined by CEM by measuring at the beginning and at the end of the measurement loop. No instability was observed in both spheres, as shown in the following graphs; the maximum deviation being always much less than the uncertainty:

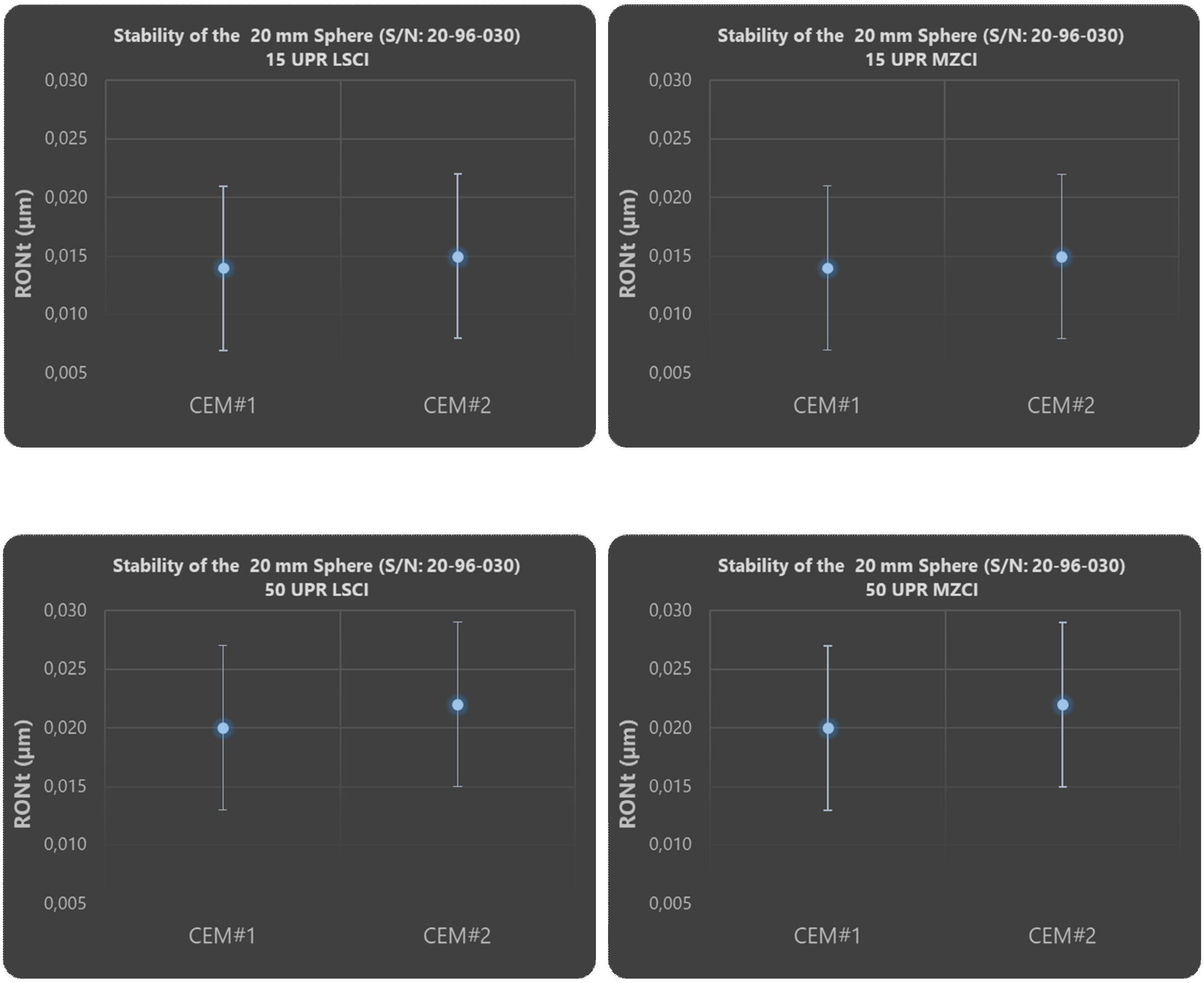

Figure 3 – Stability of the 20 mm sphere for different UPR values (15 and 50) and evaluation criteria (LSCI and MZCI)

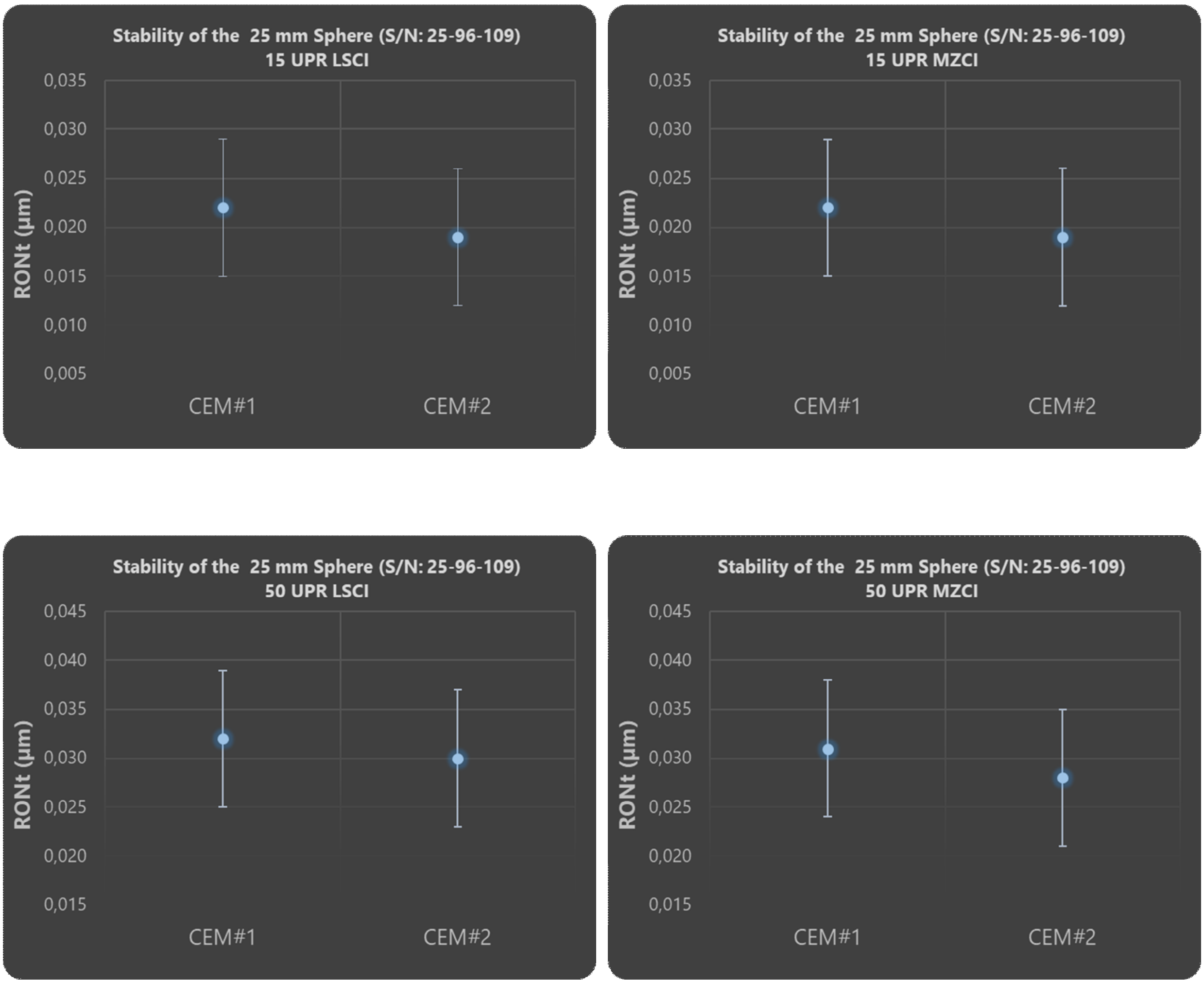

Figure 4 – Stability of the 25 mm sphere for different UPR values (15 and 50) and evaluation criteria (LSCI and MZCI)

7.2 Calculation of the Reference Values

The Reference Values are calculated for any of the spheres and any of the parameters, as the weighted mean of the participants' results. The check for consistency of the comparison results with their associated uncertainties was based on using the Birge ratio. The degrees of equivalence for each laboratory and standard with respect to the KCRV were evaluated by using E_n values.

To avoid biasing the weighted mean, only the first set of measurements from the pilot laboratory (CEM1) was included in the determination of the reference value.

1 participant, DTI, is not using error separation techniques and in consequence has larger uncertainties than the rest of participants. Due to this, their values have no influence at all on the calculation of the RV, as was checked in Excel files by taking in and out their values. This fact permits to represent together the results of all participants, no matter they used multistep technique or not, in order to show all of them graphically.

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

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

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

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

The weighted mean $\overline{x}_{\mathrm{w}}$ is given by:

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

and the uncertainty of the weighted mean is calculated by:

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

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

The Birge ratio is defined as

$$R_{\mathrm{B}} = \frac{u_{\mathrm{ext}}\left(\overline{x}_{\mathrm{w}}\right)}{u\left(\overline{x}_{\mathrm{w}}\right)} \tag{6}$$

where $u_{\mathrm{ext}}\left(\overline{x}_{\mathrm{w}}\right)$ is the external standard deviation

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

The data in a comparison are consistent provided that

$$R_{\mathrm{B}} < \sqrt{1 + \sqrt{\frac{8}{N-1}}} \tag{8}$$

where *N* is the number of laboratories.

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

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

Sign "+" in the denominator, for those laboratories getting $E_n > 1$ and hence excluded from the calculation of the reference value.

7.3 Results for the 20 mm sphere

The following tables show the measurement results sent by the participants, together with the E_n values (k=2), weighted mean, Birge ratios (R_B and critical) and new E_n* value for those Labs not fulfilling the E_n < 1 condition:

- Roundness (RONt) according to LSCI Criterion.

	LSCI				
	15 UPR		E_n	Excluded Labs.	E_n for excluded Labs.
Participant	***RONt* (µm)**	***U* (*k*=2) (µm)**			
CEM1	0.014	0.007	-0.01		
VSL	0.014	0.006	-0.02		
DTI	0.060	0.080	0.57		
INRIM	0.014	0.007	-0.01		
LNE	0.013	0.024	-0.05		
Weighted mean	0.014				
R_B	**0.58**				
R_B (critical)	1.55				

Table 8.

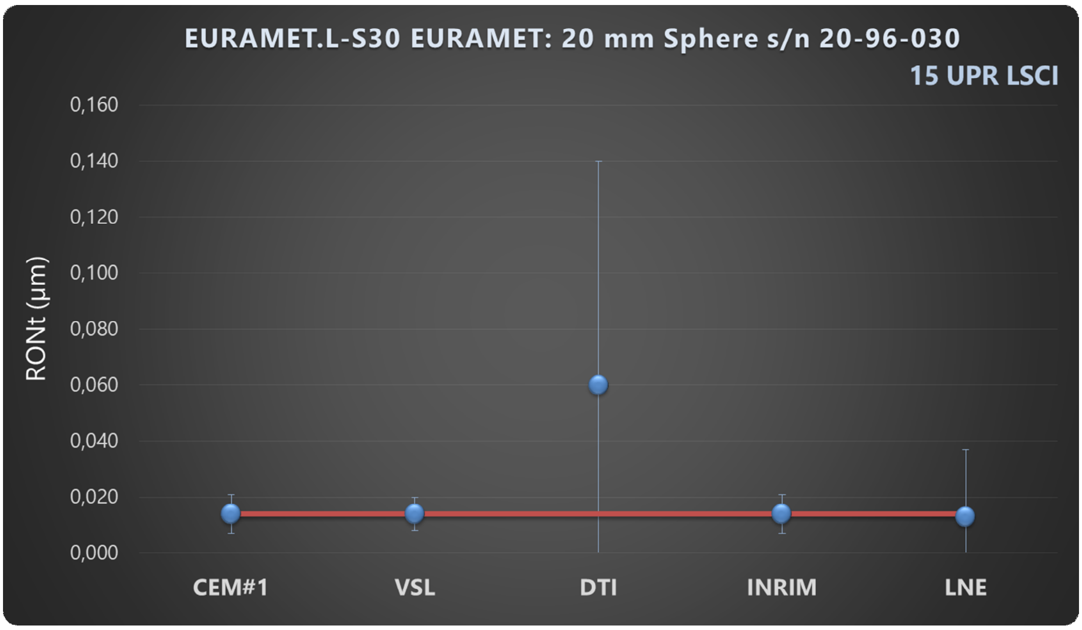

Figure 5

	LSCI				
	50 UPR		E_n	Excluded Labs.	E_n for excluded Labs.
Participant	*RONt* (µm)	*U* (*k*=2) (µm)			
CEM#1	0.020	0.007	0.26		
VSL	0.016	0.006	-0.53		
DTI	0.080	0.080	0.77		
INRIM	0.020	0.007	0.26		
LNE	0.017	0.024	-0.06		
Weighted mean	0.018				
R_B	**0.93**				
R_B (critical)	1.55				

Table 9.

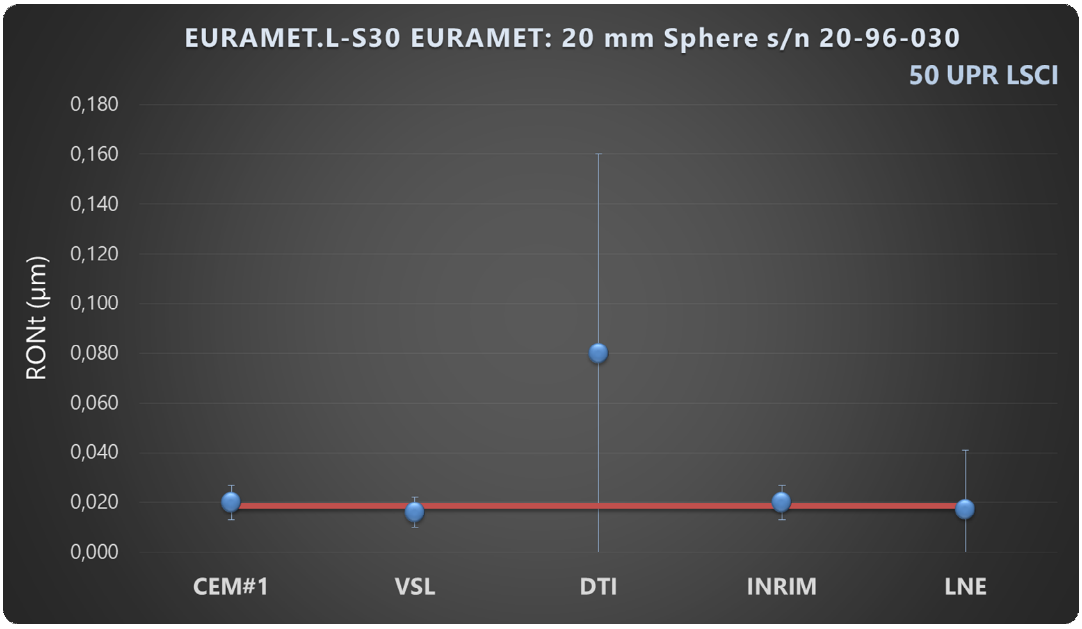

Figure 6

- Roundness RONt according to MZCI Criterion

	MZCI 15 UPR		E_n	Excluded Labs.	E_n for excluded Labs.
Participant	***RONt* (µm)**	***U* (*k*=2) (µm)**			
CEM#1	0.014	0.007	0.09		
VSL	0.013	0.006	-0.12		
DTI	0.050	0.080	0.46		
LNE	0.012	0.024	-0.06		
Weighted mean	0.013				
R_B	**0.55**				
R_B (critical)	1.62				

Table 10.

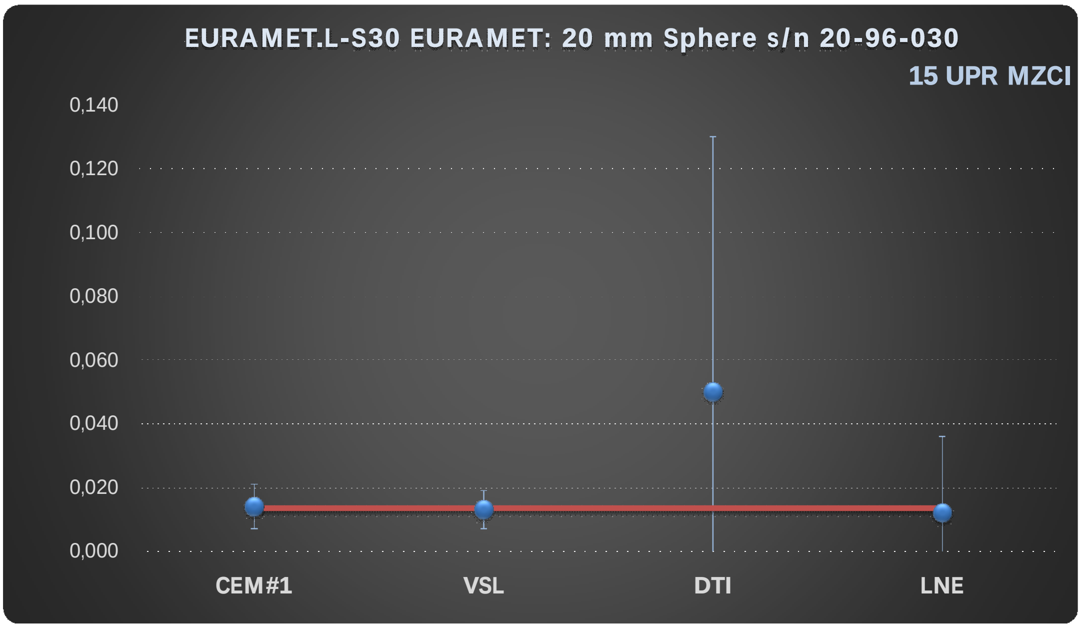

Figure 7

	MZCI				
	50 UPR				
Participant	*RONt* (µm)	*U* (*k*=2) (µm)	E_n	Excluded Labs.	E_n for excluded Labs.
CEM#1	0.020	0.007	0.51		
VSL	0.015	0.006	-0.57		
DTI	0.080	0.080	0.79		
LNE	0.016	0.024	-0.05		
Weighted mean	0.017				
R_B	1.10				
R_B (critical)	1.62				

Table 11.

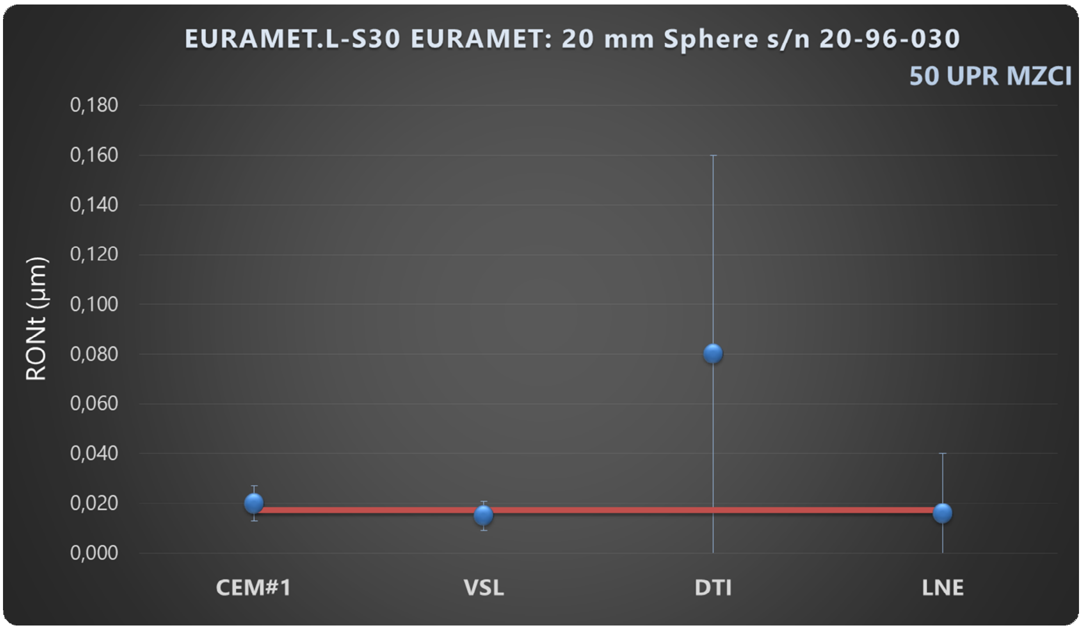

Figure 8

7.4 Results for the 25 mm sphere

The following tables show the measurement results sent by the participants, together with the E_n values (k=2), weighted mean, Birge ratios (R_B and critical) and new E_n* value for those Labs not fulfilling the E_n < 1 condition:

- Roundness (RONt) according to LSCI Criterion.

	LSCI		E_n	Excluded Labs.	E_n for excluded Labs.
	15 UPR				
Participant	***RONt* (µm)**	***U* (*k*=2) (µm)**			
CEM#1	0.022	0.007	0.11		
VSL	0.024	0.006	0.57		
DTI	0.050	0.080	0.36		
INRIM	0.016	0.007	**-0.90**		
LNE	0.031	0.024	0.41		
Weighted mean	0.021				
R_B	1.04				
R_B (critical)	1.55				

Table 12.

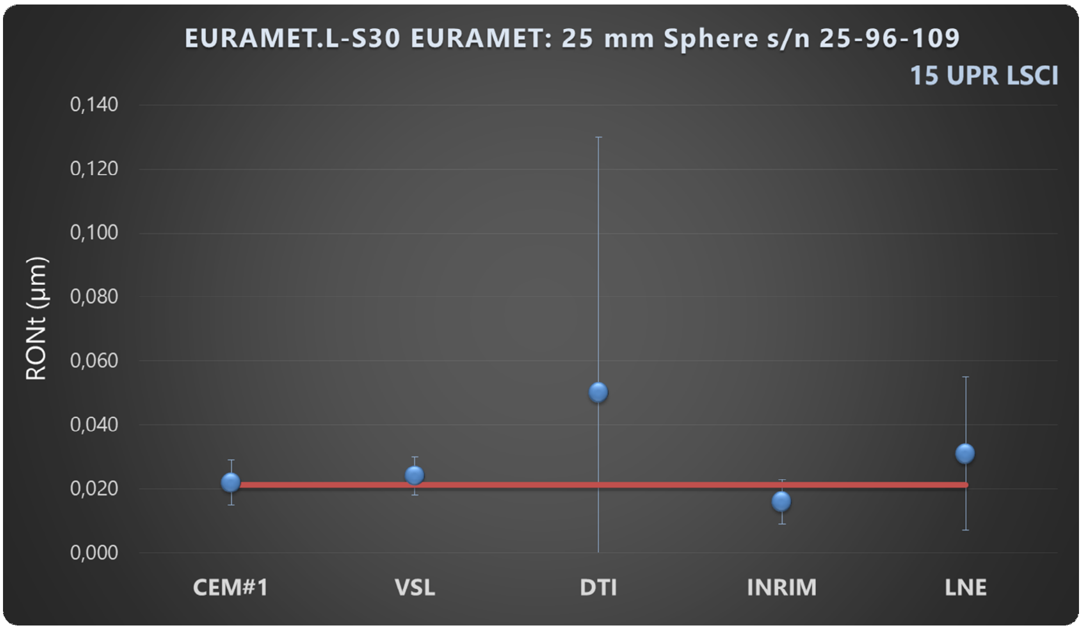

Figure 9

	LSCI				
	50 UPR		E_n	Excluded Labs.	E_n for excluded Labs.
Participant	***RONt* (µm)**	***U* (*k*=2) (µm)**			
CEM#1	0.032	0.007	0.46		
VSL	0.031	0.006	0.37		
DTI	0.080	0.080	0.63		
INRIM	0.023	0.007	-1.06		
LNE	0.039	0.024	0.41		
Weighted mean	0.029				
R_B	**1.27**				
R_B (critical)	1.55				

Table 13.

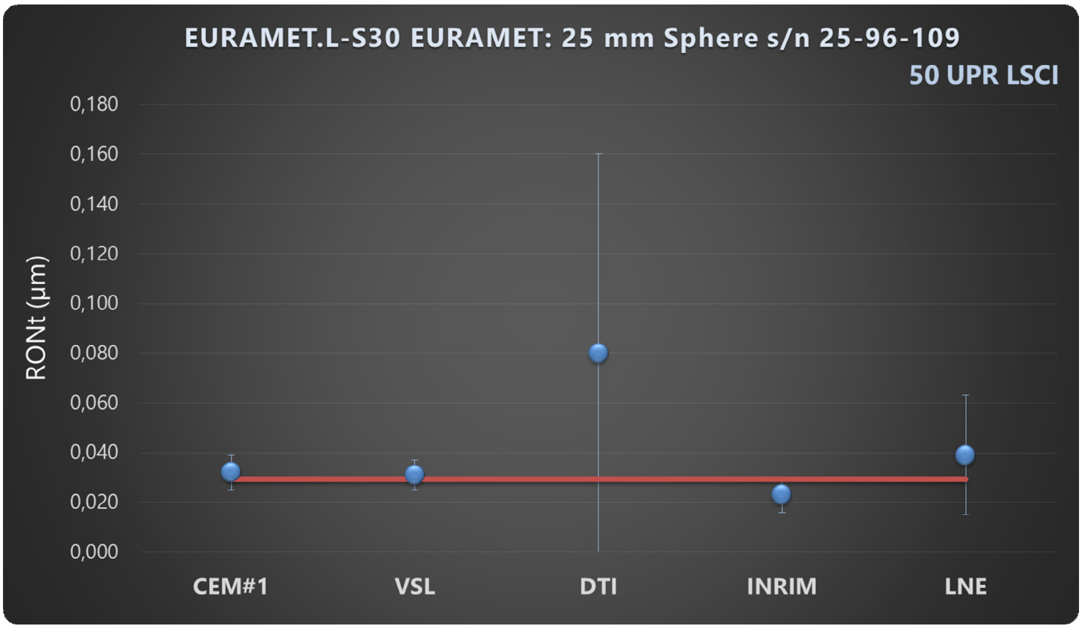

Figure 10

In this case, although the INRIM value of En results to be slightly higher than unity, it fulfills the criterion of the Birge test ($R_B < R_{B\ critical}$). Therefore, this result can be considered as compatible.

- Roundness RONt according to MZCI Criterion

	MZCI				
	15 UPR		E_n	Excluded Labs.	E_n for excluded Labs.
Participant	***RONt* (µm)**	***U* (*k*=2) (µm)**			
CEM#1	0.022	0.007	-0.07		
VSL	0.022	0.006	-0.091		
DTI	0.050	0.080	0.35		
LNE	0.030	0.024	0.32		
Weighted mean	0.022				
R_B	**0.55**				
R_B (critical)	1.62				

Table 14.

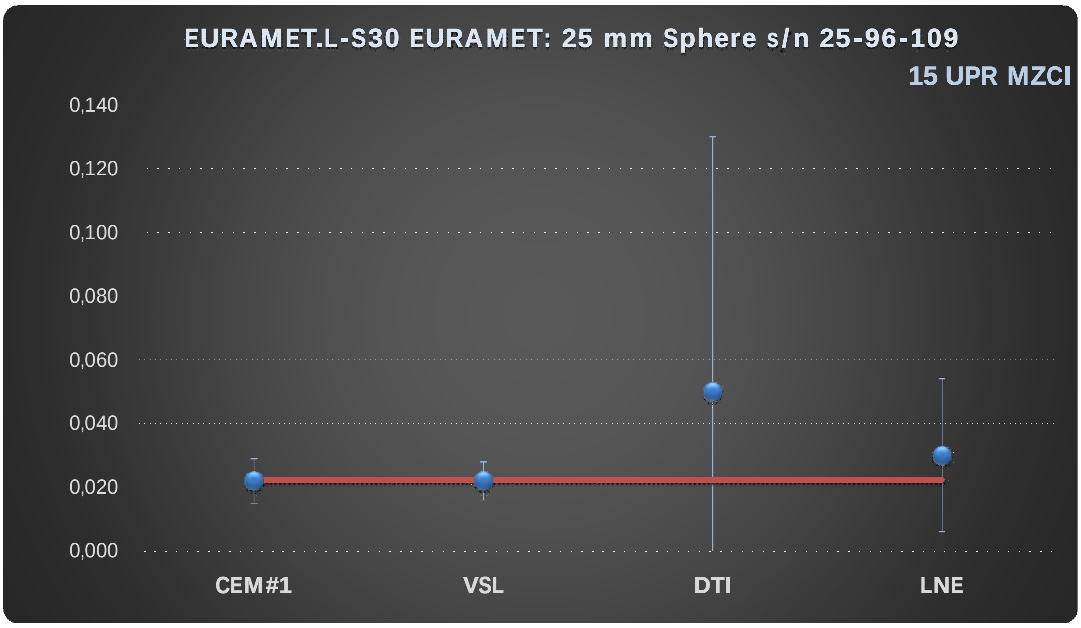

Figure 11

	MZCI				
	50 UPR		E_n	Excluded Labs.	E_n for excluded Labs.
Participant	***RONt* (µm)**	***U* (*k*=2) (µm)**			
CEM#1	0.031	0.007	0.24		
VSL	0.028	0.006	-0.42		
DTI	0.080	0.080	0.63		
LNE	0.037	0.024	0.31		
Weighted mean	0.030				
R_B	**0.90**				
R_B (critical)	1.62				

Table 15.

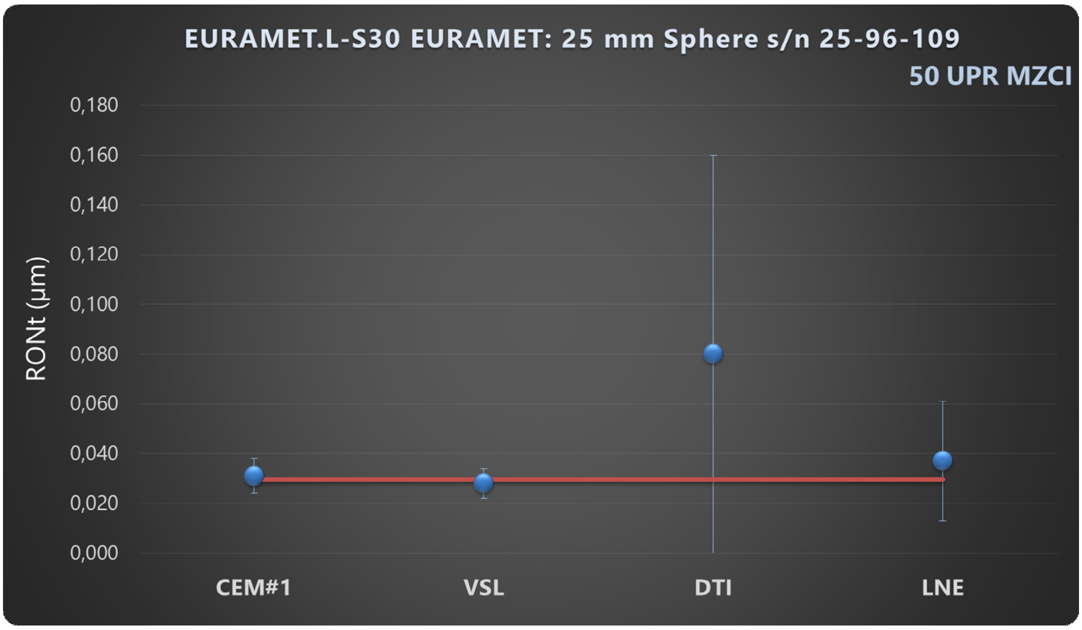

Figure 12

8 Conclusions

1) Stability of artifacts was maintained along the comparison.

2) All participants used as uncertainties their approved CMCs. The only exceptions were VSL and LNE who communicated uncertainty values lower than their CMCs.

3) There was a very good agreement between the results sent by all laboratories; the one not using error separation technique, DTI, showed, as expected, a higher uncertainty.

4) With respect to the last comparison EURAMET.L-S23, where measuring the spheres was an issue because the lack of quality of the spheres and the difficulty for fixing them with sufficient rigidity, this time the comparison has been very successful, obtaining the full compatibility of all participants' results.

9 References

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