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Report on EURAMET
Bilateral Line-scale Comparison

<Euramet #1320>
EURAMET L-K7.2014

Final Report

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Paris, June 2015

Contents

1 Document control

Version Draft A.1 Issued on 1 December 2014.
Version Draft A.2 Issued on 4 December 2014
Version Draft B.1 Issued on 17 February2015
Final report Issued on 17 June 2015

2 Introduction

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

The comparison is organised within the EU-Indonesia Trade Support Programme II, Sub-project Number APE12-06b, “Improvement of traceability of Metrology and Calibration measurements of Puslit KIM”.

Two National Metrology Institutes take part in this comparison: LNE (France) and KIM-LIPI (Indonesia).

LNE is acting as the pilot laboratory and in this function is responsible for providing the travelling standard, the evaluation of the measurement results and the final report.

The comparison will be accomplished in accordance with the EURAMET Guidelines on Conducting Comparisons and BIPM Guidelines for Planning, Organising, Conducting and Reporting Key, Supplementary and Pilot Comparisons.

The comparison was registered in BIPM KCDB; artefact circulation started in August 2014 and was completed in October 2014.

3 Organization

3.1 Participants

Table 1. List of participant laboratories and their contacts.

Laboratory Code	**Contact person, Laboratory**	**Phone, Fax, email**
LNE	Mr. José SALGADO LNE Laboratoire National de Métrologie et d’Essais 1, rue Gaston Boissier F-75015 Paris France	Tel. +33 1 40 43 39 57 Fax +33 1 40 43 37 37 e-mail: jose.salgado@lne.fr
KIM-LIPI	Ms. Nurul Alfiyati **KIM-LIPI**: Pusat Penelitian Kalibrasi, Instrumentasi, dan Metrologi Lembaga Ilmu Pengetahuan Indonesia (Puslit KIM-LIPI) Kompleks PUSPIPTEK Gedung 420 Tangerang Selatan, **Banten Indonesia**	Tel. +62-21-7560533 ext 3078 Fax. +62-21-7560568 e-mail: nurul@kim.lipi.go.id

3.2 Schedule

Table 2. Schedule of the comparison.

RMO	Laboratory	Original schedule	Date of measurement	Results received
EURAMET	LNE	August 2014	August 2014	November 2014
APMP	KIM-LIPI	September 2014	Sept- Oct 2014	November 2014
EURAMET	LNE	October 2014	Oct – Nov 2014	November 2014

4 Artefacts

4.1 Description of artefacts

The measurement artefact is a high precision glass scale from HEINDENHAIN belonging to LNE (ref manufacturer 297 634-02, sn 9 026 940) of 300 mm long with a line each millimeter.

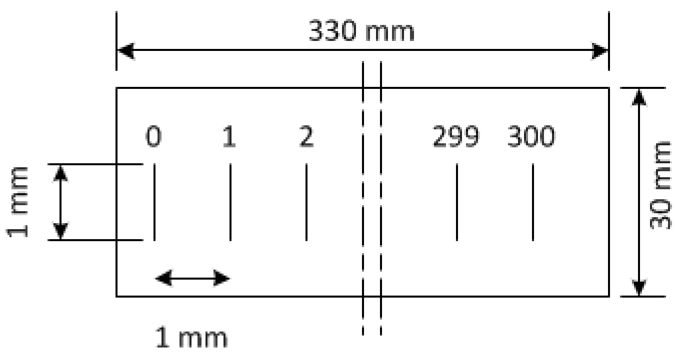


Figure 1 : *Heindenhain line-scale dimensions.*

The scale is made of glass (B 270) with a given value of CTE **α** = $9.4 \cdot 10^{-6}$ K^{-1} given by the manufacturer. A standard uncertainty of $1 \cdot 10^{-6}$ K^{-1} should be taken for the uncertainty budget.

The graduation line thickness is 4 µm. The overall dimensions on the scale are 330 mm for total length, 30 mm for the width and 20 mm for thickness. The line scale is contained in a wooden box.

4.2 Stability of artefacts

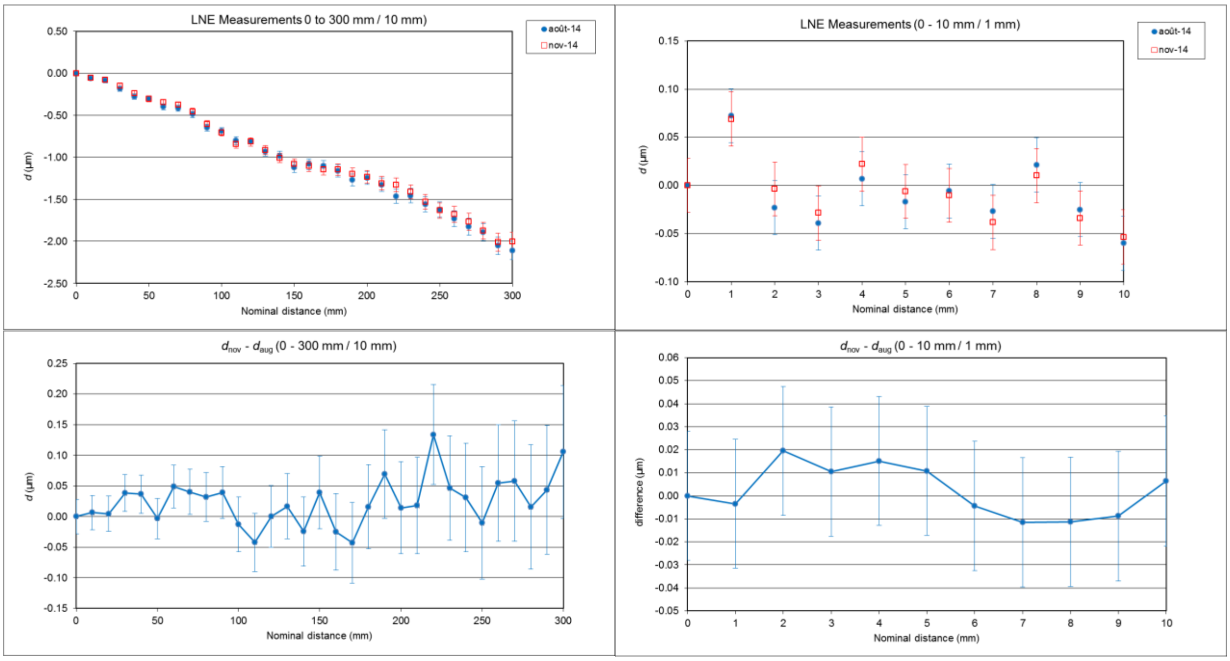


Figure 2. Stability of the line scale: upper graphs, deviation from nominal distance *d* measured by LNE, on left side from 0 to 300 mm every 10 mm, on the right side from 0 to 10 mm every mm. Lower graphs, the difference between August and November measurements. Error bars show standard uncertainty (k=1).

Acting as pilot, LNE has measured the line-scale twice. First measurement was performed on August 1st; the second measurement was performed on November 7th. The deviation from nominal distance *d*, is plotted on the upper graphs Figure 2. The differences between second measurement and first measurement is plotted on the lower graphs Figure 2, where the errors bars represents the standard uncertainties (k=1). No significant drift is seen within the reported uncertainties at 95% confidence level (k=2).

4.3 Condition of artefacts at start/end of comparison

No significant damage to the scale has been seen during the comparison.

5 Measuring instructions

5.1 Measurands

Before calibration, the line scale must be inspected for damage. No cleaning of the scale should be tried besides blowing away dust particles using dry, clean air or other clean gases.

It is recommended to support the measurement object at the Airy points, held only by their gravity forces. If additional clamping of the scale is required during measurement, e.g. because of a fast moving carriage, it is recommended to lightly pinch the scale on the sides at one of the Airy support points. The participants are asked to describe the line scale support.

The measurement result to be reported is the distance from the zero line to the measured line at 20°C according Table 3.

Table 3: *Distances to measure*

Distance range	Pitch
0 mm to 10 mm	1 mm
10 mm to 300 mm	10 mm

The air and material temperatures during measurement should be reported also.

The measurand was the deviation from nominal length at the centre of each line, $d = l_c - l_n$

6 Results

6.1 Results and standard uncertainties as reported by participants

The results reported by the participants are plotted in Figure 3. Values of the deviation from nominal length and measurement uncertainties are given Table 4 and Table 5.

Only first measurement made by LNE is shown, and will be taken into account for assessing the KCRV.

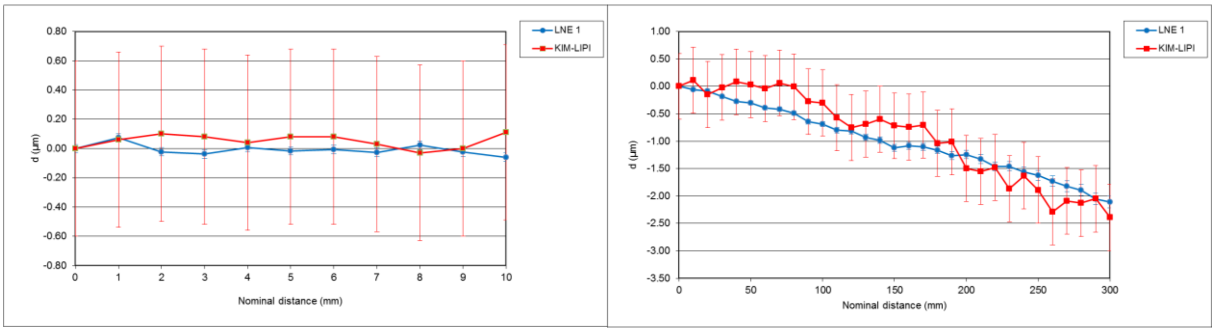


Figure 3: Comparison between LNE and KIM-LIPI results. On the left results for nominal distance 0 mm-10 mm with a pitch of 1 mm. On the right results for 0 mm-300 mm with a pitch of 10 mm. Errors bars corresponds to the standard uncertainty (*k*=1).

Table 4: Results and uncertainties reported by participants: distance 0 mm- 300mm every 10 mm.

Nominal distance (mm)	*d* (µm) LNE 1	*u* (µm) LNE 1	*d* (µm) KIM-LIPi	*u* (µm) KIM-LIPI
0	0.000	0.028	0.000	0.600
10	-0.060	0.028	0.110	0.600
20	-0.084	0.029	-0.150	0.600
30	-0.188	0.030	-0.020	0.600
40	-0.278	0.031	0.080	0.600
50	-0.304	0.033	0.030	0.600
60	-0.397	0.035	-0.040	0.600
70	-0.416	0.037	0.060	0.600
80	-0.490	0.040	-0.010	0.600
90	-0.648	0.042	-0.280	0.601
100	-0.691	0.045	-0.300	0.601
110	-0.801	0.048	-0.570	0.601
120	-0.815	0.050	-0.750	0.601
130	-0.930	0.053	-0.690	0.601
140	-0.983	0.056	-0.600	0.601
150	-1.120	0.060	-0.720	0.602
160	-1.082	0.063	-0.740	0.602
170	-1.104	0.066	-0.710	0.602
180	-1.163	0.069	-1.040	0.602
190	-1.268	0.072	-1.010	0.603
200	-1.246	0.075	-1.500	0.603
210	-1.327	0.079	-1.550	0.603
220	-1.463	0.082	-1.480	0.603
230	-1.458	0.085	-1.870	0.604
240	-1.560	0.089	-1.630	0.604
250	-1.623	0.092	-1.890	0.604
260	-1.731	0.095	-2.290	0.605
270	-1.825	0.099	-2.090	0.605
280	-1.890	0.102	-2.130	0.605
290	-2.054	0.105	-2.050	0.606
300	-2.108	0.109	-2.390	0.606

Table 5. Results and uncertainties reported by participants: 0 mm- 10 mm every mm.

Nominal distance (mm)	*d* (µm) LNE 1	*u* (µm) LNE 1	*d* (µm) KIM-LIPi	*u* (µm) KIM-LIPI
0	0.000	0.028	0.000	0.600
1	0.073	0.028	0.060	0.600
2	-0.023	0.028	0.100	0.600
3	-0.039	0.028	0.080	0.600
4	0.007	0.028	0.040	0.600
5	-0.017	0.028	0.080	0.600
6	-0.006	0.028	0.080	0.600
7	-0.027	0.028	0.030	0.600
8	0.022	0.028	-0.030	0.600
9	-0.025	0.028	0.000	0.600
10	-0.060	0.028	0.110	0.600

6.2 Measurement uncertainties

Participants had to report their uncertainty budget.

6.2.1 LNE

Table 6: LNE's uncertainty budget.

Source	Distrib.	$u(x_i)$ unit	n_i	$c_i = \partial dl/\partial x_i$	$u_i(dl)$ /nm
Repeatability of centre line detection SE	/	25 nm	200	1	25 nm
Air wavelength (including t_{air},P_{air},RH_{air}, C_{CO2}, l_0, formulas)	N	$0.06\ 10^{-6}\ L$	12	1	$0.06\ 10^{-6}\ L$
Dl res Interferometer resolution	R	4 nm	200	1	4 nm
Errors of interferometer alignment dl_{li}	R	$0.02\ 10^{-6}\ L$	50	1	$0.02\ 10^{-6}\ L$
Errors of scale alignment dl_{Si}	R	$0.003\ 10^{-6}\ L$	50	1	$0.003\ 10^{-6}\ L$
Dt_s scale temperature	N	$0.28\ 10^{-6}\ L$	12.	1	$0.28\ 10^{-6}\ L$
$az_{,cr}$ (assumed ± $1\ 10^{-6}\ K^{-1}$)	N	$0.17\ 10^{-6}\ L$	50	1	$0.17\ 10^{-6}\ L$
dl_{Ai} Abbe offset	N	11 nm	12	1	11 nm
				Qu	28 nm $0.35\ 10^{-6}\ L$
				QU	56 nm $0.70\ 10^{-6}\ L$

The expanded uncertainty with a coverage factor (k=2) 95% is: Q[56, 0.7 L] in nm with L in mm.

Remark: This uncertainty is slightly different from LNE's CMC (Q[50, 0.8 L]), which was assessed for a CTE of $11.5\ 10^{-6}\ K^{-1}$ instead of $9.2\ 10^{-6}$ here.

6.2.2 KIM-LIPI

Table 7. Standard uncertainty budget reported by KIM-LIPI.

Constant uncertainty components

Uncertainty source	Unit	Distr.	Semi-range or Exp.uncert. or Std. dev.	Div.	Deg. Of freedom/ v_i	Std. Unc./ c_i	Sens. Coeff/ c_i	$c_i.u_i$
Repeatability (l_{s3})	µm	N.	0.1	3.162	9	0.0316	2	0.063
Display resolution (l_{s2})	µm	Rect	0.05	1.732	10000	0.0289	2	0.058
Calibration of laser interferometer (l_{s1})	µm	N.	0.08	2	10000	0.0410	1	0.041
Line detection (l_W)	µm	Rect	0.5	1.732	200	0.2887	2	0.577
Abbe error (l_a)	µm	Rect	0.2	1.732	50	0.115	1	0.115
Combined uncertaity (u_c) for constant uncertainty components (µm)							0.5964	
Effective degree of freedom							226	

Length-dependent uncertainty components

Uncertainty source	Unit	Distr.	Semi-range or Exp.uncert. or Std. dev.	Div.	Deg. Of freedom/ v_i	Std. Unc. /c_i	Sens. Coeff/ c_i	$c_i.u_i$
Interferometer								
Calibration of laser interferometer (l_{s1})	µm	N	0.024 *L*	2	10000	0.012 *L*	1	0.012 *L*
Air temperature (t_{air})	°C	N	0.07	2	10000	0.04	9.6E-07 L	3.36E-08 *L*
Air pressure (p_{air})	Pa	N	50	2	10000	25	2.7E-09 L	6.75E-08 *L*
Material Temperature								
Temperature difference (δθ)	°C	Rect	0.50	1.732	12.5	0.29	9.4E-06 *L*	2.71E-06 *L*
Thermal exp. Cofficient (δα)	/ °C	Rect	2.0E-06	1.732	50	1.15E-06	0.5 *L*	5.77E-07 *L*
Cosine error (I_G)	µm	Rect	0.5 *L*	1.732	200	0.29 *L*	1	0.29 L
Combined uncertaity (u_c) for length-dependent uncertainty components (µm)							0.289 *L*	
Effective degree of freedom							201	

Total combined uncertainty, u_c (*L* in m)	**Q[0.60, 0.29 *L*] µm**
Expanded Uncertainty at k = 2 (*L* in m)	***U* = Q[1.2, 0.58 *L*] µm**

KIM-LIPI's CMC is Q[50, 0.8 *L*] in µm , L in m. KIM-LIPI have revised their uncertainties to Q[1.3, 1.4 *L*], which are still in review by APMP.

7 Analysis

7.1 Calculation of the KCRV

Following the recommendations of CCL MRA, we use the weighted mean to compute the reference value. For the following calculations only one of LNE's (LNE1) results have been taken into account.

The analysis for each measurand proceeds as follows:

Each laboratory reports a measured value, x_i , and its associated standard uncertainty $u(x_i)$.

We compute the normalised weight, w_i , for the result x_i is given by:

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

where the normalising factor, C, is given by:

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

Then calculate the weighted mean, $\bar{x}_w$, which is given by:

$$\bar{x}_w = \sum_{i=1}^{I} w_i \cdot x_i \tag{3}$$

The uncertainty of the weighted mean is calculated by:

$$u(\bar{x}_w) = \sqrt{\frac{1}{\sum_{i=1}^{I} \left(\frac{1}{u(x_i)} \right)^2}} = \sqrt{C} \tag{4}$$

After deriving the weighted mean and its associated standard uncertainty, the deviation of each laboratory's result from the weighted mean is determined simply as $x_i - \bar{x}_w$. The uncertainty of this deviation is calculated as a combination of the uncertainties of the result, $u(x_i)$, and the uncertainty of the weighted mean $u(\bar{x}_w)$. The uncertainty of the deviation from the weighted mean is given by equation (5), which includes a minus sign to take into account the correlation between the two uncertainties (it would be a plus sign if dealing with uncorrelated uncertainties, such as when comparing data from two separate laboratories).

$$u(x_i - \bar{x}_w) = \sqrt{[u(x_i)]^2 - [u_{\text{int}}(\bar{x}_w)]^2} \tag{5}$$

For the determination of the key comparison reference value KCRV, statistical consistency of the results contributing to the KCRV is required. A check for statistical consistency of the results with their associated uncertainties can be made by calculating the E_n value for each laboratory's result, where E_n is defined as the ratio of the deviation from the weighted mean, divided by the expanded uncertainty of this deviation – the expanded uncertainty is obtained from the standard uncertainty by multiplying by a suitable value of *k* to obtain a 95 % confidence level.

$$E_n = \frac{x_i - \bar{x}_w}{\sqrt{[U(x_i)]^2 - [U_{\text{int}}(\bar{x}_w)]^2}} \tag{6}$$

This process is iterated until there are no inconsistent results contributing to the weighted mean.

Sometimes, a situation is reached where there are two results that need to be excluded, but exclusion of one of the results causes the other result to become consistent, and vice versa. The pilot has to choose which one to exclude. The choice may require further iterations since it is the largest consistent subset that is required and this may require exploration of both options of which to exclude first.

After reaching consistency, the calculated weighted mean is the KCRV.

A statistically better way to check for consistency than the criterion $|E_n| < 1$ is to investigate the so-called Birge ratio R_B which compares the observed spread of the results with the spread expected from the individual reported uncertainties.

The application of least squares algorithms and the χ^2-test leads to the Birge ratio

$$R_B = \frac{u_{ext}(\bar{x}_w)}{u(\bar{x}_w)}, \quad (7)$$

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

$$u_{ext}(\bar{x}_w) = \sqrt{\frac{1}{(I-1)} \cdot \frac{\sum_{i=1}^{I} w_i (x_i - \bar{x}_w)^2}{\sum_{i=1}^{I} w_i}}\,. \quad (8)$$

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

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

where I is the number of laboratories. As an example, for the case $I = 2$, a value of $R_B < 1.96$ indicates consistency (for $k = 2$). The reference values are given in **Table 8**.

Table 8: Key comparison reference value $\bar{x}_w$ and associated standard uncertainty $u(\bar{x}_w)$ and Birge ratio.

Nominal distance (mm)	$\bar{x}_w$	$u(\bar{x}_w)$	$\|E_n\|$ LNE	$\|E_n\|$ KIM-LIPI	R_B
0	0.000	0.028	0.00	0.00	0.00
1	0.072	0.028	0.01	0.01	0.02
2	-0.023	0.028	0.10	0.10	0.20
3	-0.039	0.028	0.10	0.10	0.20
4	0.007	0.028	0.03	0.03	0.05
5	-0.017	0.028	0.08	0.08	0.16
6	-0.006	0.028	0.07	0.07	0.14
7	-0.027	0.028	0.05	0.05	0.09
8	0.021	0.028	0.04	0.04	0.09
9	-0.025	0.028	0.02	0.02	0.04
10	-0.060	0.028	0.14	0.14	0.28
20	-0.084	0.029	0.05	0.05	0.11
30	-0.187	0.030	0.14	0.14	0.28
40	-0.277	0.031	0.30	0.30	0.60
50	-0.303	0.033	0.28	0.28	0.56
60	-0.396	0.035	0.30	0.30	0.59
70	-0.414	0.037	0.40	0.40	0.79
80	-0.488	0.040	0.40	0.40	0.80
90	-0.646	0.042	0.31	0.31	0.61
100	-0.689	0.045	0.32	0.32	0.65
110	-0.800	0.047	0.19	0.19	0.38
120	-0.814	0.050	0.05	0.05	0.11
130	-0.928	0.053	0.20	0.20	0.40
140	-0.980	0.056	0.32	0.32	0.63
150	-1.116	0.059	0.33	0.33	0.66
160	-1.078	0.062	0.28	0.28	0.56
170	-1.099	0.065	0.32	0.32	0.65
180	-1.162	0.068	0.10	0.10	0.20
190	-1.264	0.072	0.21	0.21	0.43
200	-1.249	0.075	0.21	0.21	0.42
210	-1.330	0.078	0.18	0.18	0.37
220	-1.464	0.081	0.01	0.01	0.03
230	-1.466	0.084	0.34	0.34	0.68
240	-1.561	0.088	0.06	0.06	0.12
250	-1.629	0.091	0.22	0.22	0.44
260	-1.781	0.094	0.43	0.43	0.85
270	-1.832	0.097	0.22	0.22	0.43
280	-1.897	0.101	0.20	0.20	0.39
290	-2.054	0.104	0.00	0.00	0.01
300	-2.117	0.107	0.23	0.23	0.46

7.2 Calculation of Degrees of Equivalence

The Degree of Equivalence, DoE, for a laboratory result x_i is calculated simply as $x_i - \bar{x}_w$. The standard uncertainty of the DoE is calculated using

$u(x_i - \bar{x}_w) = \sqrt{[u(x_i)]^2 - [u_{int}(\bar{x}_w)]^2}$ for results which contributed to the weighted mean

Table 9: Degrees of equivalence $x_i - \bar{x}_w$ and associated expanded uncertainty $U(x_i - \bar{x}_w)$.

Nominal distance (mm)	LNE		KIM-LIPI	
	$x_i - \bar{x}_w$	$U(x_i - \bar{x}_w)$	$x_i - \bar{x}_w$	$U(x_i - \bar{x}_w)$
0	0.000	0.003	0.000	1.199
1	0.000	0.003	-0.012	1.199
2	0.000	0.003	0.123	1.199
3	0.000	0.003	0.119	1.199
4	0.000	0.003	0.033	1.199
5	0.000	0.003	0.097	1.199
6	0.000	0.003	0.086	1.199
7	0.000	0.003	0.057	1.199
8	0.000	0.003	-0.051	1.199
9	0.000	0.003	0.025	1.199
10	0.000	0.003	0.170	1.199
20	0.000	0.003	-0.066	1.199
30	0.000	0.003	0.167	1.199
40	-0.001	0.003	0.357	1.199
50	-0.001	0.004	0.333	1.199
60	-0.001	0.004	0.356	1.198
70	-0.002	0.005	0.474	1.198
80	-0.002	0.005	0.478	1.198
90	-0.002	0.006	0.366	1.198
100	-0.002	0.007	0.389	1.198
110	-0.001	0.008	0.230	1.198
120	0.000	0.008	0.064	1.198
130	-0.002	0.009	0.238	1.198
140	-0.003	0.011	0.380	1.197
150	-0.004	0.012	0.396	1.197
160	-0.004	0.013	0.338	1.197
170	-0.005	0.014	0.389	1.197
180	-0.002	0.016	0.122	1.197
190	-0.004	0.017	0.254	1.197
200	0.004	0.019	-0.251	1.196
210	0.004	0.020	-0.220	1.196
220	0.000	0.022	-0.016	1.196
230	0.008	0.024	-0.404	1.196
240	0.001	0.026	-0.069	1.195
250	0.006	0.028	-0.261	1.195
260	0.013	0.030	-0.509	1.195
270	0.007	0.032	-0.258	1.194
280	0.007	0.034	-0.233	1.194
290	0.000	0.036	0.004	1.194
300	0.009	0.038	-0.273	1.194

7.3 Discussion of results

From **Table 8** we can see that all the reported results are consistent: E_n values < 1 and R_B < 1.96. Since the uncertainties from LNE and KIM-LIPI are very different, the weighted mean gives reference values, which are very close to LNE's values. No outliers are seen for the 39 deviation to nominal distance, the comparison is successful.

7.4 Linking of result to other comparisons

The results of this comparison will be able to be linked, through LNE, to the coming APMP L-K7 comparison where LNE is participating. Until the results from APMP L-K7 are published no link can be provided, neither if LNE is failing during this comparison.

7.5 Conclusions regarding CMCs

1- LNE's existing CMCs are supported

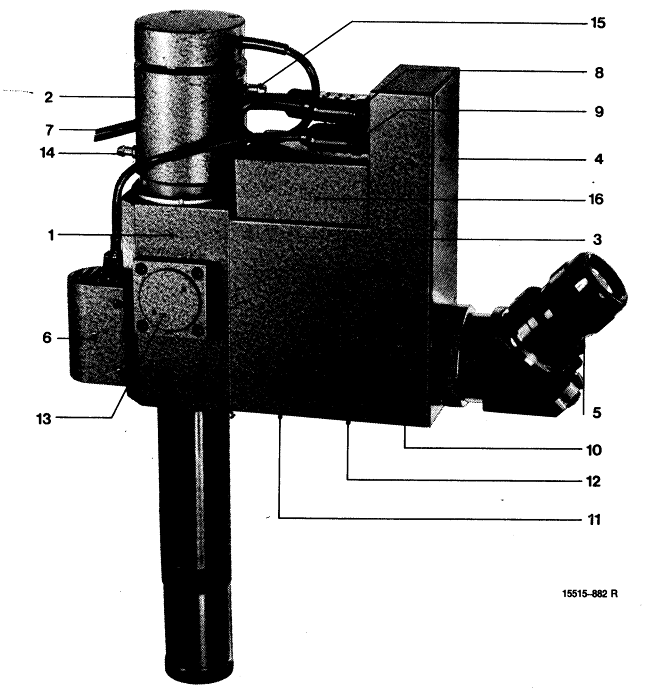
2- The revised CMC claims at KIM-LIPI are supported.

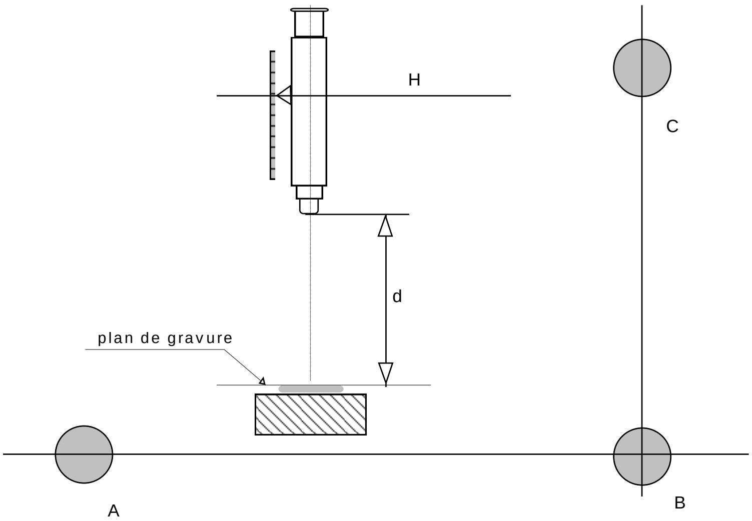
8 Appendix A Equipment and measuring processes of the participants

8.1 LNE

In A) a free description can be given including drawings and references, whereas in B) a tabular form has to be filled out. Please add requested line profile image on "0" line under A).

A) Description of the measurement methods and instruments





The X value of the intersection of the optical axis of the microscope with the plane of the lines is known through 3 interferometric axis.
Abbe principle could be respected indirectly as the position of the 3 reflectors according to the intersection point is known.

B) Tabular description of the measurement methods and instruments

Line detection

Parameters	Parameters used for the measurement
Microscope type:	**Leitz Photoelectric microscope**
Light source	*White light*
Wavelength(s)	/
Slit length	*0,1 mm*
Slit width	*2 µm*
Polarization	/
Coherence	/
Aperture/magnification	*10 x*

Detection mode	*Position of a line obseved through a vibrating slit*
Detection principle	*The position of the line is detected as the signal given by the photomultiplicator passes by a minimum value.*
Detection velocity	5 µm/s
Sampling frequency (image/interferometer)	*The microscope deliver a signal as the centre line is detected by the microscope*
Edge detection criterion	*/*
Edge detection short term repeatability (1s)	*About 40 to 60 nm (depending of line and scale)*

Displacement measurement

Parameters	Parameters normally used for the measurement equipment	Achievable **standard uncertainty** for measurands
Interferometer light source / wavelength	633 nm	4 fm
Resolution of displac. Interferometer	0.01 µm	
Interferometer medium		
Refractive index:		
=> refractometer:		//
=> Edlen´s formula:	Revised Edlen Formulas	$1\ 10^{-8}$
Air temperature	20 °C	0.03 °C
Air pressure	1013 mbar	9 Pa
Air humidity	50 %	5 %
CO_2-content	300 ppm	60 ppm
Guide error	//	//
Abbe offset	corrected	18 nm
Alignment error:		
Interferometer	0	negligible
Scale	0	$0.28\ 10^{-6}\ L$

9 Other measurement conditions

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Scale temperature	*20 °C*	*0.03 °C*
Number of repeat measurements in one scale position	*10*	
Number of scale orientations	*1*	
kind of support	*Gauge blocks at Airy points*	
clean room class	*no*	

9.1 KIM-LIPI

The measurement was performed by using SIP 414 length measuring machine with a standard Agilent 5519 B laser interferometer. A standard linear interferometer, an Agilent 10751C air sensor, and 3 material temperature sensors were used.
The artefact was placed on the transparent table illuminated from below by light source. An appropriate eyepiece of 81x objective magnification microscope with a central cross wire, were used to determine the line width and line quality of line-scale. The carriage of SIP machine was moved by hand wheel manually. The distance moved was shown from the display of interferometer system.

The length between two graduation lines is determined as the difference between the means of indicated position when the cross wire of the microscope is pointing at the left and right edge of the graduation lines.
The measurement was carried out 3 times at each graduation line after 1 series of measurement was completed, except at a few exemplary lines which were measured at least ten times to determine the repeatability of the measurement.
The line-scale was supported at the airy points by using gauge blocks with nominal length 5 mm during the measurement. The air temperature during the measurement was (20 ± 0.2) °C, air pressure was (100.51 ± 0.40) kPa, and relative humidity was 50 %.