RESULTS AND DISCUSSIONS ON LENGTH INM KEY COMPARISONS

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La mitingul din 14 octombrie din Paris, directorii Institutelor Naționale de Metrologie (NMIs) din statele membre ale convenției metrului şi reprezentanții a două organizații internaționale au semnat ***Aranjamentul de Recunoaştere Mutuală (CIPM MRA)*** *a etaloanelor naționale şi a certificatelor de măsurare şi etalonare emise de NMIS. Suportul tehnic pentru acest aranjament este setul de rezultate obținute pe parcursul timpului în comparații cheie organizate de* ***Comitetele Consultative*** *ale CIPM, BIPM şi organizații regionale de metrologie (RMOs) şi publicate de bipm în baza de date pentru comparații cheie. acest articol prezintă rezultate şi discuții asupra participări Institutului Național de Metrologie (INM) în comparații cheie pentru cale plan paralele.*

At a meeting held in Paris on 14 October 1999, the directors of the national metrology institutes (NMIs) of thirty-eight Member States of the ***Metre Convention*** *and representatives of two international organizations signed a* ***Mutual Recognition Arrangement (CIPM MRA)*** *for national measurement standards and for calibration and measurement certificates issued by NMIs. The technical basis of this arrangement is the set of results obtained in the course of time through key comparisons carried out by the* ***Consultative Committees*** *of the International Committee for Weights and Measures CIPM, the Bureau International des Poids et Mesures BIPM and the regional metrology organizations (**RMOs**), and published by the BIPM in the* ***key comparison database****. This paper presents Results and discussion on INM Length key comparisons for gauge block.*

Keywords: length, key comparisons, gauge blocks

1. Introduction

The Mutual Recognition Arrangement (CIPM MRA) is an arrangement between national metrology institutes which specifies terms for the mutual recognition of national measurement standards and for recognition of the validity of calibration and measurement certificates issued by national metrology institutes. It is drawn up by the CIPM with the authority given it under Article 10 (1921) of the Rules Annexed to the Metre Convention [1]: EUROMET.L-K1.1: Calibration of Gauge Blocks by Interferometer and EUROMET.L-K2 Calibration of long gauge blocks.

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Each signatory to this arrangement is the national metrology institute designated by the appropriate national governmental or other official authority of the Member State of the Metre Convention as being responsible for national measurement standards. For any state that has more than one such designated institute, the arrangement is signed by one institute on behalf of all, the names of the other institutes being attached to the document.

The technical basis of this arrangement is the set of results obtained in the course of time through key comparisons carried out by the **Consultative Committees** of the CIPM, the BIPM and the regional metrology organizations (**RMOs**), and published by the BIPM and maintained in the **key comparison database**. Detailed technical provisions are given in the Technical Supplement to this arrangement.

Key comparisons carried out by Consultative Committees or the BIPM are referred to as **CIPM key comparisons**; key comparisons carried out by regional metrology organizations are referred to as **RMO key comparisons**; RMO key comparisons must be linked to the corresponding CIPM key comparisons by means of joint participants. The degree of equivalence derived from an RMO key comparison has the same status as that derived from a CIPM key comparison (figure 1).

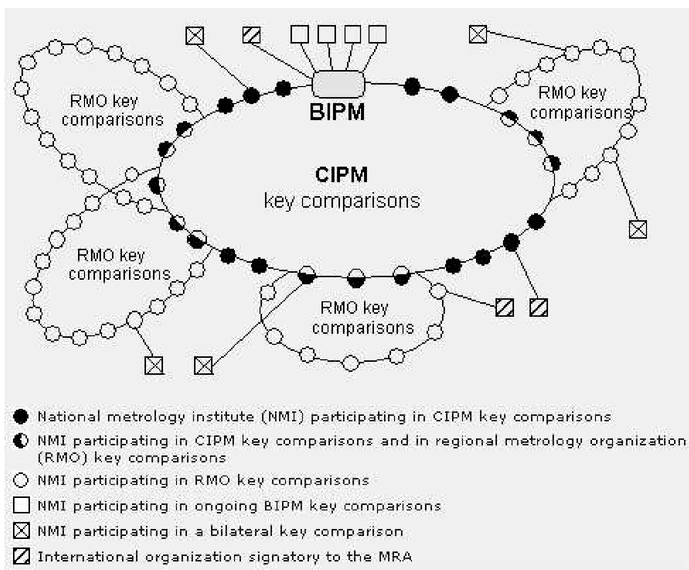

Fig. 1. The degree of equivalence

The procedures used by Consultative Committees for selecting, conducting and evaluating key comparisons, including the detailed technical protocols and periodicity of the comparisons, are designed to ensure that [2]:

- the comparisons test all the principal techniques in the field;
- the results are clear and unequivocal;

- the results are robust;
- the results are easy to compare with those of corresponding comparisons carried out by regional metrology organizations;
- overall, the comparisons are sufficient in range and frequency to demonstrate and maintain equivalence between the participating laboratories.

The participating institutes must report the results of a comparison to the pilot institute as soon as possible and at the latest six weeks after the measurements are completed. The measurement results together with the uncertainties and any additional information required should be reported in the format given in the instructions as part of the protocol, usually by completing the standard forms annexed to the instruction

The organization of a key comparison is the responsibility of the pilot institute helped by the two or three nominated participants. The first task of this small group is to draw up the detailed technical protocol for the comparison and its dispatch, inviting participation as defined by the Consultative Committee. In those Committees having permanent Working Groups or Sections responsible for specific areas of activity the draft protocol must be sent to the chairman of the relevant Working Group or Section. The invitation to participate is sent directly to the delegates of member institutes present at the last meeting of the Consultative Committee, plus absent members. Copies of the invitation and the draft protocol are also sent to the BIPM executive secretary of the Consultative Committee. For rules on eligibility for participation in Consultative Committee key comparisons.

The main points decided by the small group headed by the pilot institute are the following:

- the list of participants with full details of mailing and electronic addresses;
- the travelling standard or standards to be used in the comparison;
- whether or not a pilot comparison or any other preliminary work needs to be carried out among a restricted number of participants to verify the performance of the travelling standard;
- the pattern of the full scale comparison; this ranges from the simple circulation of a single;

  travelling standard around all the participants to the sending of an individual travelling;

  standard directly to each participant from the pilot institute, or from each participant to the pilot institute or some combination of these;
- the starting date, detailed timetable, means of transport and itinerary to be followed by each travelling standard; this starting date is subsequently referred to as the starting date for the comparison;
- the procedure in the case of failure of a travelling standard;
- the procedure in the case of an unexpected delay at a participant institute.

2. EUROMET.L-K1.1: Calibration of Gauge Blocks by Interferometer

This project was defined to follow up EUROMET.L-K1, key comparison on gauge blocks measured by interferometry. The motivation for a new project was that a few laboratories did not receive satisfactory results in EUROMET.L-K1, and there were also new participants who wanted to take part. A sufficient number of laboratories with good results in EUROMET.L-K1, volunteered to take part in this new project as well.

The set contains originally 8 gauge blocks of steel and 8 gauge blocks of tungsten carbide. After the first circulation (Feb. – Oct. 2002), 2 additional steel gauge blocks, 4.5 mm and 6 mm, have been added to the steel set. The gauge blocks are of rectangular cross section, according to the international standard ISO 3650.

The thermal expansion coefficient of the gauge blocks has been measured by PTB (measurement uncertainties are stated as standard uncertainty). The mean value of the thermal expansion coefficient for the two longest gauge blocks has been adopted for smaller gauges. A corresponding larger uncertainty has also been adopted.

The measurand was the central length of the gauge block, as defined in the International Standard ISO 3650. The gauge block had to me measured by interferometry, in their vertical position wrung to a flat plate, which was provided by each laboratory. The central length of a gauge block is defined as the perpendicular distance between the centre point of the free measuring surface and the plane surface of an auxiliary plate of the same material and surface texture upon which the other measuring surface has been wrung.

The measurement result to be reported is the deviation of central length from nominal length

$$\Delta l = l_{measured} - L_{nominal} \qquad (1)$$

The measurement results had to be appropriately corrected to the reference temperature of 20 °C using the thermal expansion coefficient given in the technical instruction. Additional corrections had to be applied according to the usual procedure of the laboratory. The uncertainty of the measurement had to be estimated according to the *ISO Guide to the Expression of Uncertainty in Measurement*. In order to achieve optimum comparability, a mathematical model containing the principal influence parameters for gauge block calibration by interferometry has been given in the measurement instructions.

2.1 Description of the measurement instrument and the method used by INM

Make and type of interferometer: Carl Zeiss Jena interferometer - Köster.

Light sources / Wave lengths used: Cd 114 spectral lamp with wave lengths defined in air at temperature 20^0C, pressure 101,3 kPa and humidity 1,33 kPa, according to Resolution 2 of CIPM 1983: 0,64385026 μm; 0,50858474 μm; 0,47999360 μm and 0,46781737 μm

***Method of fringe fraction determination*:** Visual observation of fringe pattern, dedicated interference fringe processing software developed by INM.

Method used for determination of refractive index of the air: Edlen's equation.

Range of gauge block temperature during measurements:

- steel: 19, 55 ^{0}C to 20,35 ^{0}C
- tungsten carbide: 19,70 ^{0}C to 20,50 ^{0}C.

Type of temperature sensors are used and what is the uncertainty of the calibration of the temperature sensors*:* Glass thermometers (Hg), uncertainty of calibration 0,01 ^{0}C.

Method of phase correction measurement*:* Pack experimental method.

2.2. Measurement uncertainties

If all quantities on which the result of a measurement depends are varied, its uncertainty can be evaluated by statistical means. However, because this is rarely possible in practice, the uncertainty of a measurement result is usually evaluated using a mathematical model of the measurement and the law of propagation of measurement uncertainty.

All laboratories have measured the gauge blocks by optical interferometry, applying the method of fringe fractions.

An estimate of the measurand, denoted by *l*, is obtained using input estimates for the values of the N quantities. Thus the output estimate *l*, which is the result of the measurement, is given by:

$$l = \frac{1}{q}\sum_{i=1}^{q}\left(k_i + F_i\right)\frac{\lambda_i}{2n} + \Delta t_g \cdot \alpha \cdot L + \delta l_\Omega + \Delta l_s + \delta l_A + \delta l_g + \delta l_w + \Delta l_\Phi \quad (2)$$

where:

l length of the gauge block at the reference temperature of 20 °C

L nominal length of the gauge block

q number of wavelengths used for the determination of the length based on the method of exact fractions (i = 1, …, q)

k_i integer part of number of half wavelengths within gauge block length (fringe order)

F_i fractional part of fringe order

λ_i vacuum wavelength of the different light sources used

n index of refraction of the air

$\Delta t_g = (20 - t_g)$ is the difference of the gauge block temperature tg in °C during the measurement from the reference temperature of 20 °C

α linear coefficient of thermal expansion of the gauge block

δl_{Ω} obliquity correction for the shift in phase resulting from the angular alignment errors of the collimating assembly

Δl_S aperture correction accounting for the shift in phase resulting from the finite aperture diameter s, and focal length f of the collimating lens

δl_A corrections for wave front errors as a result of imperfect interferometer optics

δl_G correction accounting for flatness deviation and variation in length of the gauge block

δl_W length correction attributed to the wringing film

Δl_{Φ} phase change accounting for the difference in the apparent optical length to the mechanical length.

Type A evaluation of standard uncertainty

In most cases, the best available estimate of the expectation or expected value μ_q of quantity q that varies randomly, and for which n independent observations q_k have been obtained under the same conditions of measurement, is the arithmetic mean or average of the n observations. Thus, for an input quantity $X_{i,j}$, the arithmetic mean is used as the input estimate x_i in equation (2) to determine the measurement result l [4, 5].

The individual observations differ in value because of random variations in the influence quantities or random effect. The experimental variance or the observations, which estimates the variance of the probability distribution of q, is given by s^2.

This estimate of variance and its positive square root s, termed the *experimental standard deviation*, characterize the variability of the observed value, or more specifically, their dispersion about their mean.

Type B evaluation of standard uncertainty

For an estimate x_i of an input quantity X_i that has not been obtained from repeated observations [4,5], the associated estimated variance $u^2(x_i)$ or the standard uncertainty $u(x_i)$ is evaluated by scientific judgement based on all or the available information on the possible variability of X_i. The pool of information may include:

- previous measurement data
- experience with or general knowledge of the behaviour and properties of relevant materials and instruments
- manufacturer's specifications
- data provided in calibration and other certificates
- uncertainties assigned to reference data taken from handbooks

The evaluation of the combined standard uncertainty

The estimated standard deviation associated with the output estimate of measurement result, termed *combined standard uncertainty* (u_c), is determined from the estimated standard deviation associated with each input estimate, termed *standard uncertainty* [4,5], by equation:

$$u_c = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial K}{\partial C_i} \right)^2 u^2 (C_i)} \qquad (3)$$

The evaluation of the expanded uncertainty

Although u_c can be universally used to express the uncertainty of a measurement result it is necessary to give a measure of uncertainty that defines an interval about the measurement result that may be expanded to encompass a large fraction of the distribution of values that could reasonably be attributed to the measured.

The additional measure of uncertainty is termed expanded uncertainty U.

$$U = k\, u_c = 0.32\text{''} \text{ for } k = 2 \qquad (4)$$

Table 1 give for 100 mm tungsten carbide gauge block the numerical value of the contributions..

Table 1

The evaluation of calibration uncertainty for the 100 mm tungsten carbide gauge block

x_i	$u(x_I)$	n_i	$c_i = \partial l / \partial x_i$	$u_I(l)$
λ_i	3×10^{-8}	100	$L/4\lambda_i$	$0,015 \times 10^{-6} L$
F_I	0,05 fr.	100	$\lambda_I / 2q^*$	6,6 nm
n	$5,8 \times 10^{-8}$	65	L	$0,058 \times 10^{-6} L$
t_g	0,02 K	50	αL	$0,084 \times 10^{-6} L$
α	$0,006 \times 10^{-6}$ K^{-1}	100	$\Delta t_g . L = 0,18.L$	$0,001 \times 10^{-6} L$
δl_Ω	$0,18 \times 10^{-6}$	100	L	$0,18 \times 10^{-6} L$
Δl_s	$3,6 \times 10^{-8}$	14	L	$0,036 \times 10^{-6} L$
δl_A	3,4 nm	14	1	3,4 nm
δl_G	3 nm	14	1	3 nm
δl_W	5 nm	14	1	5 nm
Δl_Φ	9,4 nm	99	1	9,4 nm

2.3. Comparison of results to the reference values

The gauge blocks are the basic standards in the field of length metrology used in all metrology institutes which are dealing with these kind of measurements. In order to compare the metrological performances of these standards, some inter-laboratory comparisons are usually organised.

The reference value x_{ref} and its associated uncertainty u_{ref} considered as consensus value for all participating laboratories are calculated by pilot laboratory using the following relationships [4]:

$$x_{ref} = \frac{1}{n} \sum_{i=1}^{n} x_i \qquad (5)$$

$$u(x_{ref}) = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (x_i - x_{ref})^2} \qquad (6)$$

Table 2 and 3 give differences of measured lengths (Δx) of steel and tungsten carbide gauge block with respect to the reference values and expanded uncertainties of these differences according to equations (5) and (6). All results are in nm [4].

Table 2

Comparison of results of steel gauge block

Steel gauge blocks	0.5 mm	1.01 mm	4.5 mm	6 mm	7 mm	8 mm	8 mm	15 mm	80 mm	100 mm
JV	2 ± 30	-18 ± 27	-15 ± 26	-4 ± 28	4 ± 32	-11 ± 28	-5 ± 26	-16 ± 25	-27 ± 46	-23 ± 48
MIKES	3 ± 27	4 ± 23			10 ± 28	4 ± 24	9 ± 22	5 ± 20	2 ± 39	3 ± 38
GUM	14 ± 37	-2 ± 35			12 ± 39	12 ± 35	-6 ± 34	13 ± 33	24 ± 48	24 ± 48
CMI	-1 ± 27	4 ± 23			-4 ± 28	5 ± 24	0 ± 22	0 ± 22	11 ± 42	1 ± 44
IPQ	21 ± 29	22 ± 25	19 ± 26		10 ± 32	7 ± 28	11 ± 26	10 ± 28	45 ± 52	21 ± 55
PTB	-23 ± 27	-21 ± 23	-8 ± 21	-7 ± 25	-17 ± 27	-13 ± 22	-10 ± 21	-8 ± 19	-23 ± 34	-20 ± 32
UME	-13 ± 33	3 ± 27	7 ± 26	5 ± 28	-6 ± 32	-5 ± 28	1 ± 26	7 ± 25	-6 ± 40	-14 ± 38
INM		2 ± 35	-4 ± 30	7 ± 28	-16 ± 32	1 ± 29	2 ± 28	-8 ± 27	-27 ± 55	19 ± 61
NCM		6 ± 27	0 ± 26		6 ± 33					-14 ± 66
E.I.M										

Table 3

Comparison of results of carbide gauge block

TC gauge blocks	1.02 mm	6 mm	7 mm	8 mm	10 mm	12 mm	80 mm	100 mm
JV	-5 ± 28	-3 ± 27	-7 ± 28	-4 ± 27	-3 ± 27	-2 ± 27	-20 ± 34	-17 ± 37
MIKES	6 ± 22	6 ± 20	-4 ± 22	5 ± 21	6 ± 21	9 ± 21	-1 ± 29	-9 ± 33
GUM	-8 ± 35	-5 ± 34	-3 ± 34	-1 ± 34	-3 ± 34	-3 ± 34	-15 ± 37	-13 ± 39
CMI	-4 ± 22	7 ± 20	10 ± 22	-3 ± 21	-3 ± 21	2 ± 21	5 ± 36	-5 ± 42
IPQ	-15 ± 25	-12 ± 25	4 ± 26	-7 ± 26	11 ± 27	-11 ± 27	5 ± 47	2 ± 54
PTB	-19 ± 21	-10 ± 17	-18 ± 19	-17 ± 18	-13 ± 22	-8 ± 18	-21 ± 24	-26 ± 27
UME	4 ± 27	6 ± 25	11 ± 26	10 ± 26	10 ± 25	17 ± 26	7 ± 29	4 ± 33
INM	4 ± 28	-7 ± 27	-11 ± 28	3 ± 27	-7 ± 27	-6 ± 31	21 ± 42	50 ± 49
NCM	32 ± 25	13 ± 24	7 ± 25	9 ± 26	-3 ± 25	-2 ± 34	30 ± 51	23 ± 62
E.I.M	1 ± 26	8 ± 24	13 ± 25	5 ± 25	2 ± 24	6 ± 25	-11 ± 28	-10 ± 30

The "normalized error" so-called "E_n – criterion" is evaluated in order to check the internal consistence between the result of a particular measurement and the reference value:

$$E_n = \frac{1}{k} \cdot \frac{x_i - x_{ref}}{\sqrt{u_i^2 - u_{ref}^2}} \tag{7}$$

The acceptance criteria is $|E_n| \le 1$.

Variance of values inside of a INM laboratory is small. For all INM results, normalized error was $|E_n| \le 1$.

3. EUROMET.L-K2: Calibration of long gauge blocks

At its meeting in November 1997, the EUROMET Technical Committee for Length, TC-L, decided upon a key comparison on long gauge block measurements, numbered EUROMET.L-K2, with the National Physical Laboratory (NPL) as the pilot laboratory. This comparison would be the RMO equivalent of the comparison CCL-K2, which was also piloted by NPL [5].

This EUROMET key comparison is linked with the CCL and other RMO comparisons through mutual competence of participating laboratories. Laboratories participating in both the CIPM and the RMO comparisons establish the link between these comparisons and assure their equivalence. All members of EUROMET TC-L were invited to participate. 23 laboratories expressed an interest.

The comparison was organized in two loops, the first being limited to laboratories able to make direct measurement by interferometry, with the second loop consisting of all other laboratories. Approximately one quarter of the 23 participants used direct interferometry on the gauge and platen surfaces. One quarter used some form of dynamic fringe counting interferometry, e.g. using a white light interference as a fiducial. The remaining half of the participants used mechanical comparison techniques, either with reference gauges of a similar size, or with a smaller artefact e.g. a short gauge block used to provide the traceability reference.

Four gauge blocks made of steel were circulated in each loop. The thermal expansion coefficient of the gauge blocks had been measured by the pilot laboratory and another laboratory (PTB) before the comparison. The weighted mean of the pilot laboratory and PTB results of expansion measurement (and their calculated uncertainties) were given to the participating laboratories in the technical protocol.

The measurement quantity was the central length of the gauge blocks, as defined in International Standard ISO 3650. Any laboratory departing from the conditions specified in ISO 3650 had to make the relevant corrections to their measurand. ISO 3650 specifies that the gauge blocks had to be measured by interferometry, in the horizontal position wrung to a flat plate.

The measurement results had to be appropriately corrected to the reference temperature of 20 °C using the thermal expansion coefficients given above. Additional corrections (aperture, phase correction) had to be applied according to the usual procedure of the laboratory.

The uncertainty of measurement had to be estimated according to the ISO Guide for the Expression of Uncertainty in Measurement. In order to achieve optimum comparability, a mathematical model [5] containing the principal influence parameters for gauge block calibration by interferometry had been given in the technical protocols.

3.1 Description of the measurement instrument and the method used by INM

Make and type of instrument: One coordinate machine SIP 1000 with TESA comparator.
Light sources / wavelengths used or traceability path: Standard gauge blocks of nominal lengths:150 mm, 500 mm and 900 mm, trade mark CEJ, with certificate issued by PTB, no. 4191 PTB 04
Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections etc):

- comparative method
- the difference in central length is determined in horizontal position.

Range of gauge block temperature during measurements description of temperature measurement method: 19.40 ^{0}C to 19.60 ^{0}C & digital thermometer, resolution 0.01K, U = 0.05 K.

3.2. Measurement uncertainties

The calibration of the gauge block of L mm nominal length is carried out by comparison method. The coordinate machine SIP 1000, equipped by TESA comparator was used for these measurements. A calibrated gauge block of the same nominal length and the same material as reference standard was used. The difference in central length was determined in horizontal position.

Model Equation

$$l_x = l_s + \delta l_D + \delta l + \delta l_c - L*(\alpha_{av}*\delta t + \delta_\alpha*\Delta t_{av} + u_{at}) - \delta l_v \quad (8)$$

where:

l_x length of the gauge block to be calibrated

l_s length of the reference gauge block at the reference temperature of t_0=20 °C according to its calibration certificate

δl_D change of the length of the reference gauge block since its last calibration due to drift

δl observed difference in length between the unknown and the reference gauge block

δl_c correction for non-linearity and offset of the comparator

L nominal length of the gauge blocks under consideration

α_{av} average of the thermal expansion coefficients of the unknown and the reference gauge block

δt difference of temperature between the unknown and the reference gauge block

δ_α difference in the thermal expansion coefficients between the unknown and the reference gauge block

Δt_{av} deviation of the average temperature of the unknown and the standard gauge block from the reference temperature

u_{at} correction for second order terms of ($\delta_{\alpha}*\Delta\tau_{\alpha\varpi}$)

δl_{v} correction for non-central contacting of the measuring faces of the unknown gauge block

3.3. Comparison of results to the reference values

A summary of all of the measurement data is represented in Figure 1, as deviation from weighted means (it is difficult to include uncertainty bars in this plot) [5].

The reference value x_{ref} and its associated uncertainty u_{ref} considered as consensus value for all participating laboratories are calculated by pilot laboratory using the following relationships [5]:

$$x_{ref} = \frac{\sum_{j=1}^{m} u_j^{-2} \cdot x_j}{\sum_{j=1}^{m} u_j^{-2}}, \quad u_{ref} = \left(\sum_{j=1}^{m} u_j^{-2} \right)^{-1/2} \tag{9}$$

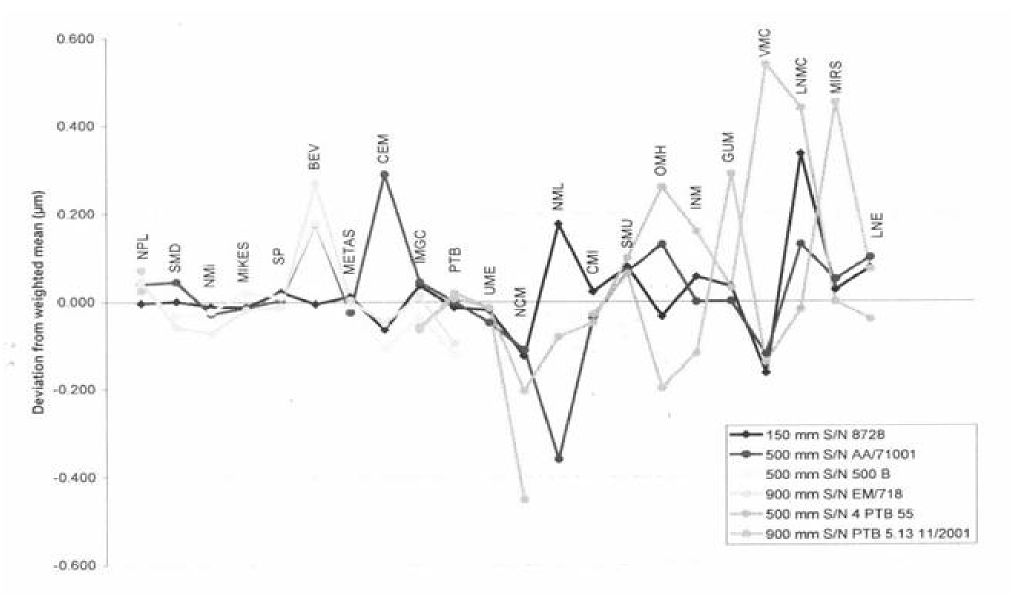

Fig. 1- Laboratory deviations from weighted means

4. Conclusions

The principal aim of these key comparisons has been to determine the degree on which results of measurement of gauge blocks made by a selection of NMIs can be deemed to be equivalent.

This has resulted in a set of data which can be used by the metrology community to gain insight into degrees of equivalence of NMI measurements of gauge blocks. However one should also try to maximise the scientific value of this comparison. It would be useful for each participant to examine their results and measurement processes in light of these key comparisons, and seek explanations for any significant offsets of their results from those of other laboratories.

Calibration measurement methods presented in this paper were used and put in practice at the INM specialised laboratory.

Experimental results and the associated measurement uncertainty of INM laboratory are in good agreement with the reported results by other experienced national laboratories. As a consequence, the measurement capabilites in this field were recognised in the framework of mutual recognition arrangement at international level [6], and these kinds of calibration are included in the BIPM-database, as it follows:

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End standard. Gauge blocks: central length *L*, 0.5 mm to 100 mm Absolute expanded uncertainty ($k = 2$, level of confidence 95%) in nm: Q[30, 0.2*L*], *L* in mm Interferometry, exact fractions Approved on 22 March 2005 Internal NMI service identifier: INM/2
End standards. Long gauge block: central length *L*, 100 mm to Absolute expanded uncertainty ($k = 2$, level of confidence 95%) in nm: Q[100, 0.9*L*], *L* in mm 1000 mm Mechanical comparison Orientation: horizontal Approved on 04 May 2006 Internal NMI service identifier: INM/10

R E F E R E N C E S

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