Asia-Pacific Metrology Programme

APMP Key Comparison

APMP.L-K1.1.2011

Calibration of gauge blocks by interferometry

Final Report – Results

Contents

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 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 Asia Pacific Metrology Programme, Technical Committee for Length (APMP/TCL), carried out the key comparisons on gauge block measurements by interferometry APMP.L-K1[1] and APMP.L-K1.1[2] during 2001-2002 and 2005-2006, respectively. The National Metrology Institute of Japan (NMIJ/AIST) acted as the pilot laboratory in both comparisons.

This bilateral comparison between KIM-LIPI and NMIJ on calibration of gauge blocks by interferometry was planned on the request by KIM-LIPI in 2011. Its identifier is APMP.L-K1.1.2011. It was coordinated by the NMIJ as the pilot laboratory. The technical protocol and artefacts is modelled on those of APMP.L-K1 and APMP.L-K1.1.2011. Each calibration result was reported to NMC/A*STAR, which helps the comparison as a neutral bystander.

2. Organization

2.1 Participants

This bilateral comparison was planned by KIM-LIPI and NMIJ. The comparison will be done between them. The neutral bystander is NMC/A*STAR.

2.2 Participants' details

Table 1. List of participant laboratories and their contacts.

Laboratory Code	**Contact person, Laboratory**	**Phone, Fax, email**
Nurul Alfiyati	KIM-LIPI Research Centre for Calibration, Instrumentation and Metrology; Indonesian Institute of Sciences Kompleks PUSPIPTEK, Tangerang, Banten 15314 INDONESIA	Tel: +62-21-7560533 ext. 3078 Fax: +62-21-7560568 e-mail: nurul@kim.lipi.go.id
Akiko Hirai (Pilot)	NMIJ National Metrology Institute of Japan Central 3, 1-1-1 Umezono Tsukuba, Ibaraki 305-8563 JAPAN	Tel: +81-29-861-4283 Fax: +81-29-861-4080 e-mail: a-hirai@aist.go.jp
Tan Siew Leng (Neutral bystander)	NMC/A*STAR 1 Science Park Drive Singapore 118221 SINGAPORE	Tel: +65-6279-1938 Fax: +65- 6279-1993 e-mail : tan_siew_leng@nmc.a-star.edu.sg

2.3 Comparison schedule

The comparison was carried out in a circulation-type. Each laboratory had one month for calibration, including transportation.

Table 2. Schedule of the comparison.

Laboratory	**Original schedule**	**Date of measurement**	**Results received**
KIM-LIPI	October 2011	October 2011	February 2012
NMIJ	November 2011	November 2011	January 2012

3. Description of artefacts

The package contains 10 steel gauge blocks. The gauge blocks are of rectangular cross section, according to the international standard ISO 3650. The thermal expansion coefficient of the gauge block was provided by the manufacturer and not confirmed value by measurements. This value of the thermal expansion coefficient is applied to all gauge blocks.

Table 3. List of artefacts.

Identification	Nominal length (mm)	Expansion coeff. (10^{-6} K^{-1})	Manufacturer
87713	0.5	11.9 ± 1.0	KOBA
87714	1.01	11.9 ± 1.0	KOBA
87714	1.1	11.9 ± 1.0	KOBA
87713	6	11.9 ± 1.0	KOBA
87714	7	11.9 ± 1.0	KOBA
87714	8	11.9 ± 1.0	KOBA
87714	15	11.9 ± 1.0	KOBA
87713	80	11.9 ± 1.0	KOBA
87713	90	11.9 ± 1.0	KOBA
87714	100	11.9 ± 1.0	KOBA

The stability of the artefacts isn't matter because the comparison takes just two months.

No damage was occurred during the circulation.

4. Measuring instructions

Before calibration, the gauge blocks had to be inspected for damage of the measurement surfaces. Any scratches, rusty spots or other damage has to be documented with a drawing using the appropriate form in the annex (A2) of the protocol.

The measurand was the deviation from nominal length at the centre, $\Delta l = l - L$, as defined in the International Standard ISO 3650. The gauge blocks had to be measured by interferometry, in their vertical position wrung to a flat auxiliary plate. The central length of a gauge block is the perpendicular distance between the centre point of the free measuring surface and the plane surface of the auxiliary plate of the same material and surface texture upon which the other measuring surface of the gauge block has been wrung. The results of the measurements on both sides (Δl_{left} and $\Delta l_{\mathrm{right}}$) by wringing each measurement face in turn upon the reference flat and the average of the two wringings had to be reported on the table in the annex A1of the protocol ("left" refers to the measurement surface left to the marking on the side face of gauge blocks longer than 6 mm or to the non-marked measurement surface).

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

5. Results

5.1 Results and standard uncertainties as reported by participants

Table 4. Deviation from nominal length (in nm) of the steel gauge blocks, as reported by the laboratories.

	Gauge block nominal length / mm									
Lab	**0.5**	**1.01**	**1.1**	**6**	**7**	**8**	**15**	**80**	**90**	**100**
KIM-LIPI	207	88	27	110	48	-27	11	-378	23	101
NMIJ	194	87	12	110	44	-34	5	-395	-19	64

Table 5. Standard uncertainties (in nm), as reported by the laboratories.

	Gauge block nominal length / mm									
Lab	**0.5**	**1.01**	**1.1**	**6**	**7**	**8**	**15**	**80**	**90**	**100**
KIM-LIPI	12	12	12	12	12	12	13	17	19	20
NMIJ	14	14	14	14	14	14	15	17	18	19

5.2 Measurement uncertainties

It was required for the participants to estimate the uncertainty of measurement according to the *ISO Guide for 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 was given in the following [4]. The participating laboratories are encouraged to follow this model as closely as possible, however adapted to their instruments and procedures.
The length of a gauge block measured by interferometry and fringe fraction determination is described by

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

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);

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

F_i fractional part of fringe order;

λ_i vacuum wavelengths of the different light sources used;

n index of refraction of the air;

Δt_g = (20 - t_g) is the difference of the gauge block temperature t_g 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, with zero expectation value $\langle \delta l_\Omega \rangle = 0$;

Δl_s aperture correction accounting for the shift in phase resulting from the finite aperture diameter s of the light source:

$$\Delta l_s = \frac{s^2}{16 f^2} L \tag{2}$$

f is the focal length of the collimating lens;

δl_A correction for wave front errors as a result of imperfect interferometer optics, with zero expectation value $\langle \delta l_A \rangle = 0$;

δl_G correction accounting for flatness deviation and variation in length of the gauge block, with zero expectation value $\langle \delta l_G \rangle = 0$;

δl_w length attributed to the wringing film, with zero expectation value $\langle \delta l_w \rangle = 0$, since the length of the gauge block is defined to include the wringing film;

Δl_Φ phase change accounting for the difference in the apparent optical length to the mechanical length.

The length l of the gauge block being expressed as a function of input quantities x_i

$$l = f(x_i)\,, \tag{3}$$

the combined standard uncertainty $u_c(l)$ is the quadratic sum of the standard uncertainties of the input quantities $u(x_i)$ each weighted by a sensitivity coefficient c_i

$$u_c^2(l) = \sum_i c_i^2 u^2(x_i), \text{with} c_i = \frac{\partial l}{\partial x_i}\,. \tag{4}$$

In some cases, higher order terms of Eq.(4) might have to be taken into account as well.

Table 5. Standard uncertainty components (in nm) for 100 mm gauge block according to the specified uncertainty budget of the protocol.

Factor	**KIM-LIPI**	**NMIJ**
λ_i	1.1	1.5
F_i	1.0	5
n	4.3	2.8
Δt_g	15.0	11.6
α	1.6	1.2
δl_Ω	0.6	0.25
Δl_s	0.9	0.1
δl_A	3.7	5
δl_G	4.0	N/A*1
δl_w	5.7	5
Δl_Φ	6.8	11.6
δl_Φ *2	6.1	N/A*3
R*4	0.3	N/A*1
$\boldsymbol{u_c}$	**19.8**	**19**

*1 Included in the uncertainty of F_i. *2 Variation of the phase change correction.
*3 Included in the uncertainty of Δl_Φ. *4 Repeatability.

6. Analysis of the results

6.1 Calculation of degrees of equivalence

The aim of this analysis is to find the degree of equivalence between the measurement performed by KIM-LIPI and NMIJ. The procedure suggested by Cox [3] was followed.
Based on that procedure, the degrees of equivalence between pairs of institutes *i* and *j* are evaluated by calculating the quantities $d_{i,j}$ and $U(d_{i,j})$ where

$$d_{i,j} = x_i - x_j, \tag{1}$$

$$U(d_{i,j}) = 2u(d_{i,j}), \tag{2}$$

$$u^2(d_{i,j}) = u^2(x_i) + u^2(x_j). \tag{3}$$

Here x_i and $u(x_i)$ are the result and standard uncertainty, respectively, from institute *i*. Please note that the difference $d_{i,j}$ of the deviations of institute measurements x_i and x_j from the KCRV x_{ref} does not depend on x_{ref}.

Table 6. Degrees of equivalence between KIM-LIPI and NMIJ.

	Gauge block nominal length / mm									
	0.5	**1.01**	**1.1**	**6**	**7**	**8**	**15**	**80**	**90**	**100**
$d_{i,j}$	13	1	15	0	4	7	6	17	42	37
$U(d_{i,j})$	37.0	37.0	37.0	37.0	37.1	37.1	39.1	48.7	51.8	54.9
$d_{i,j}/U(d_{i,j})$	0.35	0.03	0.41	0.00	0.11	0.19	0.15	0.35	0.81	0.67

6.2 Discussion of results

The E_n number, which is the ratio of $d_{i,j}$ to $U(d_{i,j})$, is shown in Figure 1.

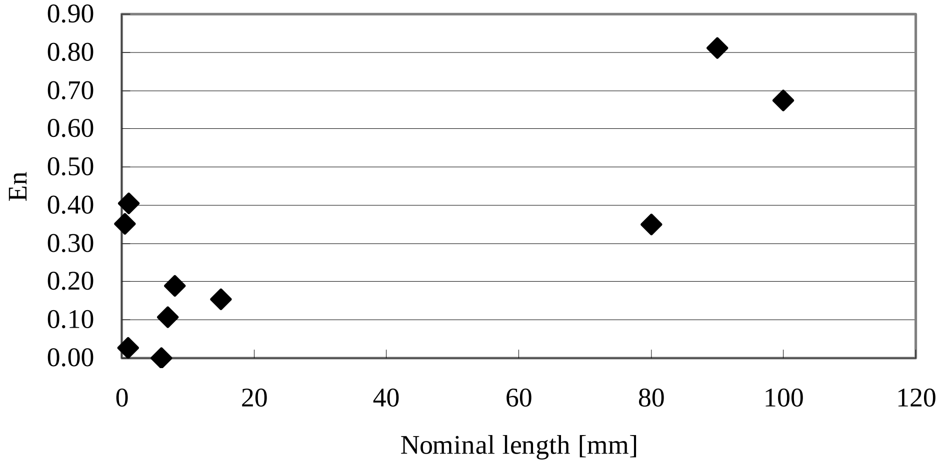

Figure 1 E_n number of each gauge block.

Good agreement between the results of KIM-LIPI and NMIJ for all gauge blocks was found. However, there are signs of possibilities of latent errors as follows:

(i) All the *E*n numbers are positive. It means the results of KIM-LIPI are always larger than those of NMIJ. Some offset might be included in the results of either and/or both laboratory.

(ii) The *E*n number increases in proportion to the nominal length of the gauge blocks. It suggests that there might be length-dependent error in the results of either and/or both laboratory.

(iii) The *E*n number for 90 mm gauge block is rather large. KIM-LIPI explains that they had two values of results from repeated measurements: One was 23 nm and another was -19 nm, which is very close to the result of NMIJ. They got data around 23 nm two times and around -19 nm four times from six measurements. The result of 23 nm was adapted because it was obtained under the best fringe and good temperature (close to 20 degree). We examined the data and measurement conditions, however found no reason of such strange results. There was no dependency on the measurement surface, temperature, and fringe quality. The results of 90 mm measured by KIM-LIPI after the circulation showed good convergence, however, the result is much different from either of two values previously obtained.

6.3 Difference between left and right wringing

The laboratories had to measure the gauge blocks wrung to both the left and the right measurement surface and to report both these results and the mean. Table 7 shows the standard deviation and the absolute maximum value of the differences between the two wrings. Figure 2 shows the difference between left and right wringing. This figure might partly reflect the ability of the laboratories to repeatedly wring gauge blocks. The abilities are in the same order.

Table 7 Standard deviation and absolute maximum value of the differences between left and right wringing.

Lab.	KIM-LIPI	NMIJ
Stdev / nm	10.0	7.2
Max / nm	17.0	12.0

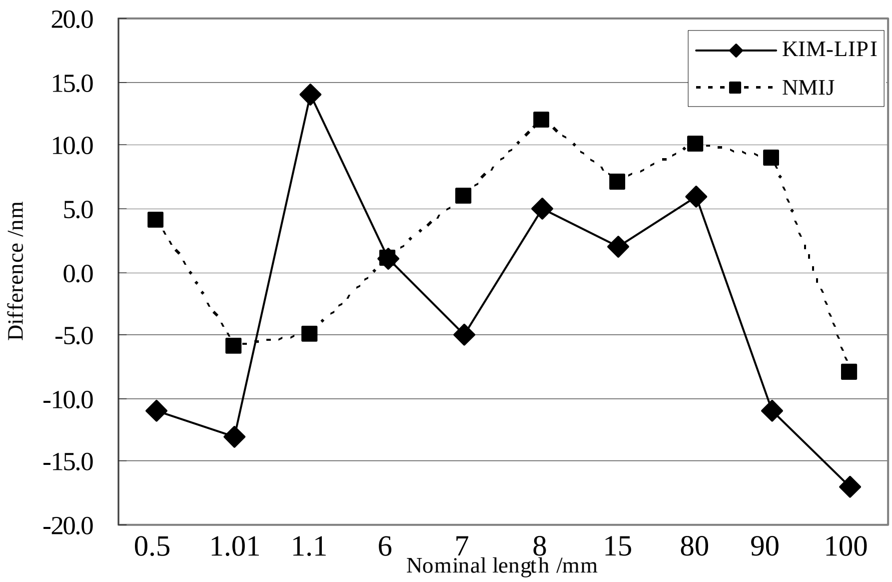

Figure 2 Differences between left and right wringing for all gauge blocks.

6.4 Linking of result to APMP.L-K1.1

The set of nominal length of gauge blocks is the same as that of the preceding comparison, APMP.L-K1.1. The material of the gauge blocks is the same, steel, although the manufacturers and thermal expansion coefficient are different. Therefore, it has less meaning to link the results of this comparison to that of APMP.L-K1.1.

7. Conclusions

The results of the bilateral comparison of calibration of gauge blocks by interferometry between KIM-LIPI and NMIJ are presented. The agreement between the laboratories is well within the expanded uncertainties. There are possibilities of latent errors in the results of either laboratory or both laboratories, further investigation and comparison with other laboratories are advisable.

References

[1] Report on Key comparison APMP.L-K1. http://kcdb.bipm.org/appendixB/appbresults/apmp.l-k1/apmp.l-k1.1_final_report.pdf
[2] Report on Key comparison APMP.L-K1.1. http://kcdb.bipm.org/appendixB/appbresults/apmp.l-k1/apmp.l-k1.1_final_report.pdf
[3] Cox M G 2002 The evaluation of key comparison data Metrologia **39** 589-95
[4] Decker J E and Pekelsky J R 1997, Uncertainty Evaluation for the Measurement of Gauge Blocks by Optical Interferometry Metrologia **34** 479-93

Appendix A Measurement conditions

Table A1. Measurement instruments and conditions reported by the participating laboratories.

Lab.	KIM-LIPI	NMIJ
Make and type of interferometer	NPL TESA, Twyman-Green	NRLM-TSUGAMI, Twyman-Green
Light sources, Wavelengths	Two frequencies stabilized He-Ne Laser, 633 nm Two frequencies stabilized He-Ne Laser, 543 nm	Zeeman stabilized Laser, 633 nm I_2 stabilized SHG of Nd:YAG laser, 532 nm Rb stabilized laser diode, 780 nm
Fringe fractioning method	Fringe fraction determined by phase stepping method. Evaluation of interferograms taken by a CCD in the computer. The combination of image processing and computing techniques is used to analyze the interferograms	The fringe fraction was calculated by image processing of an interference image. The interference fringes were generated by tilting a gauge block and a platen. The fringes on the gauge block and the platen were fitted to sinusoidal functions and their phase difference was calculated
Refractive index determination	Edlén	Ciddor
Temperature range / ^{o}C	19.494 - 20.178 (That extreme temperature happened only for the thin gauges. For gauge blocks 80 mm – 100 mm, the temperature when measured was 19.949 ^{o}C – 20.043 ^{o}C.)	19.97 - 20.05
Material of reference flats	Steel	Steel
Phase correction applied	-34 nm	+5 nm

Appendix B Reporting Forms

B1

Measurement results:

Steel gauge blocks:

Id. no.	nom. length	central length (**deviation** from nominal length)			uncert. (1s)	eff. deg. of freedom
	L (mm)	Δl_{left} (µm)	Δl_{right} (µm)	Δl (µm)	u_c (nm)	ν_{eff}
87713	0.5					
87714	1.01					
87714	1.1					
87713	6					
87714	7					
87714	8					
87714	15					
87713	80					
87713	90					
87714	100					

B2

Inspection of the measurement surfaces, steel gauge blocks

0.5 mm

left right

1.01 mm

left right

1.1 mm

left right

6 mm

left right

7 mm

left right

8 mm

left right

15 mm

left right

80 mm

left right

90 mm

left right

100 mm

left right

B3

Description of the measurement instrument

Make and Type of interferometer..
....
....
....
....
....

Light sources / Wave lengths used:..
....
....
....
....

Method of fringe fraction determination: ....
....
....
....
....

Method used for determination of refractive index of the air:...
....
....
....
....

Range of gauge block temperature during measurements:..
....
....
....

Phase correction:

gauge block material	material of reference flats	phase correction applied (give range, if applicable)
steel		

B4

Uncertainty of measurement

x_i	$u(x_i)$	ν_i	$c_i = \partial l/\partial x_i$	$u_i(l)$ / nm

Combined standard uncertainty: $u_c(l) =$

B5

Telefax Telefax Telefax Telefax Telefax

To: **Ms. Tan Siew Leng**
NMC/A*STAR

1 Science Park Drive
Singapore 118221
Singapore
Fax: +65-6279-1994*
e-mail: tan_siew_leng@nmc.a-star.edu.sg

From: (participating laboratory)

We confirm having received the standards of the *bilateral comparison APMP. L-K1.1.2011 on gauge block measurement* on ....(date).

After visual inspection

no damage has been noticed.

the following damage(s) must be reported:
....
....
....
....

Date: Signature:

....

* As of the date when the technical protocol was finalized.