KRISS Korea Research Institute of Standards and Science

APMP Key Comparison APMP.L-K1.n01

Calibration of gauge blocks

Final Report

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1 Document control

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Version Draft A.2	Issued on 23 January 2024.
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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 in collaboration with the Consultative Committees.

Recent CIPM Key Comparison (KC) on gauge blocks by optical interferometry, CCL-K1.2011 was run during 2011 to 2012. In the annual meeting of Technical Committee for Length (TCL) of the Asia Pacific Metrology Programme (APMP) held in November 2015, it was agreed that the corresponding APMP KC will be run after the report of CCL-K1.2011 is released. At the TCL meeting in 2016, it was agreed that APMP will plan to run a regional KC on gauge block measurement by optical interferometry with KRISS as the pilot laboratory. In 2017, the artefacts were purchased, and the comparison was registered in the key comparison database (KCDB) in June 2018 as APMP.L-K1.2018. The artefact circulation has actually started in February 2020. Following the decision made in 2021 at the meeting of the Working Group on Mutual Recognition Arrangement (WG-MRA) of the Consultative Committee for Length (CCL), the comparison code has been changed from APMP.L-K1.2018 to APMP.L-K1.n01.

Usually, only measurement by optical interferometry is allowed for the key comparison on gauge block calibration. However, considering the fact that there are only few NMIs equipped with a long gauge block interferometer within the Asia Pacific region, it was discussed and decided within the Discussion Group 1 of the CCL that other measurement methods could also be used for the long gauge block calibration. However, if an NMI has several measurement methods for long gauge blocks, the method having the smallest measurement uncertainty was allowed to be used for this KC.

The basic goal of this key comparison is to demonstrate the equivalence of routine short gauge block calibration services using optical interferometry and long gauge block calibration services by the method having smallest uncertainty, offered by NMIs to clients, as listed in the KCDB. To this end, participants in this comparison agreed to use the same apparatus and methods as routinely applied to client artefacts.

The results of this comparison may also be used as the evidence of newly claimed Calibration and Measurement Capabilities (CMCs).

3 Organization

3.1 Pilot laboratory

This key comparison was coordinated and piloted by the Korea Research Institute of Standards and Science (KRISS).

3.2 Participants

The list of participant laboratories and their contact persons are shown in Table 1. Originally, 12 NMIs wished to participate in the comparison. However, NMC, A*STAR of Singapore had to withdraw its participation due to a major setback in the relocation schedule of the institute due to the pandemic. Thus, only 11 NMIs could participate in the comparison.

Table 1. List of participant laboratories and their contacts.

Lab. Code	Contact person, Laboratory address	Phone, Fax, Email address
KRISS	Chu-Shik Kang Korea Research Institute of Standards and Science (KRISS), Building 201, 267 Gajeong-ro, Yuseong-gu, Daejeon, 34113 Republic of Korea	Phone: +82 42 868 5103 Fax +82 42 868 5012 Email: cskang@kriss.re.kr
NMIJ/AIST	Akiko Hirai National Metrology Institute of Japan (NMIJ) /AIST, Central 3, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, JAPAN	Phone: +81-29-861-4283 Fax: +81-29-861-4080 E-mail: a-hirai@aist.go.jp
NMIA	Peter Cox National Measurement Institute, Australia (NMIA), 1/153 Bertie Street, Port Melbourne VIC 3207 Australia	Phone: +61 3 9644 4906 Fax: +61 3 9644 4900 email: Peter.Cox@measurement.gov.au
MSL	Chris Young Measurement Standards Laboratory of New Zealand (MSL-NZ), 69 Gracefield Road, Gracefield, Lower Hutt 5040, New Zealand	Phone: +64 4 9313530 Fax: +64 4 566 600 Email: chris.young@measurement.govt.nz
NIMT	Samana Peingbangyang National Institute of Metrology (Thailand), 3/4-5 Moo 3, Klong 5, Klong Luang, Pathumthani, 12120 THAILAND	Phone: +66-2577-5100. ext 1215 (O), 1110 (L) Fax: +66 (0) 2-577-5095 Email: samana@nimt.or.th
NMIM	Razman Mohd Halim National Metrology Institute of Malaysia (NMIM), Lot PT 4803, Bandar Baru Salak Tinggi, 43900, Sepang, Selangor Darul Ehsan, Malaysia	Phone: (603) 8778 1600 Fax: (603) 8778 1616 Email: razmanmh@sirim.my
MUSSD	A.D.D. Naminda Measurement Units, Standards and Services Department (MUSSD), Mahenawatta, Pitipana, Homagama, Colombo 1O2OO, Sri Lanka	Phone: +94-11-2182267 Fax: +94-11-2182269 Email: addimension@measurementsdept.gov.lk / addnaminda@yahoo.com
SCL	George Tang / Henry Chiu The Standards and Calibration Laboratory (SCL), 35/F Immigration Tower, 7 Gloucester Road, Wan Chai, Hong Kong	Phone.: +852 -2829 4805 / +852 -2829 4839 Fax: +852 - 2824 1302 Email: george.tang@itc.gov.hk / hklchiu@itc.gov.hk
NIM	Xudong Zhang National Institute of Metrology (NIM), No.18, Bei San Huan Dong Lu, Chaoyang Dist., Beijing, P. R. of China 100029	Phone: +86-10-64524924 Fax: +86-10-64524902 Email: zhxd@nim.ac.cn
SNSU-BSN	Ocka Hedrony / Nurul Alfiyati SNSU-BSN, Kompleks Puspiptek Ged. 420, Setu, Tangerang Selatan, Banten 15314, Indonesia	Phone: 62 818 08258759 / 62 856 1024377 Fax: 62 21 7560568 Email: ocka@bsn.go.id / nurul@bsn.go.id
CMS/ITRI	Ming-Wei Chang Center for Measurement Standards (CMS)/ITRI, Bldg. 16, No.321, Sec. 2, Guangfu Rd., East Dist., Hsinchu City 300, Taiwan	Phone: +886-3-573-2150 Fax: +886 3 572 4952 Email: MWChang@itri.org.tw
NMC, A*STAR	Siew Leng Tan / Shengkai Yu NMC, A*STAR 1 Science Park Drive, Singapore 118221	Phone: 65 62791938 / 65 62791907 Fax: 62791992 Email: tan_siew_leng@nmc.a-star.edu.sg / yu_shengkai@nmc.a-star.edu.sg

3.3 Schedule

The participating laboratories were asked to specify a preferred timetable slot for their own measurements of the gauge blocks – the timetable given in Table 2 has been drawn up taking these preferences into account. Each laboratory calibrating long gauge blocks only is given 4 weeks that include customs clearance, calibration and transportation to the following participant, and each laboratory calibrating both short and long gauge blocks is given 6 weeks. Extra 1 week is given to MUSSD and CMS/ITRI whose time slot includes the New Year's Day and the Chinese New Year's Day, respectively.

However, due to the outbreak of COVID-19 pandemic, reordering/rescheduling was inevitable because some NMIs were closed during the planned time slot. NMC, A*STAR of Singapore had to withdraw its participation due to a major setback in the relocation schedule of the institute due to the pandemic. The final version of the rearranged schedule is shown in Table 3.

An ATA (Agreement on Temporary Admission) carnet was used for exports and imports. However, during the transportation of artifacts from Hong Kong to Malaysia, an inadvertent failure to properly utilize the ATA carnet occurred. Consequently, subsequent transport had to proceed without the ATA carnet, resulting in delays, particularly during the shipment from Malaysia to Indonesia.

The second measurements of the pilot lab, which should have been conducted right after the circulation was finished, faced a significant delay, leading to a delay in data analysis and report drafting.

Table 2. Initial schedule of the comparison

Laboratory	Economy	Planned date of reception of artefacts
KRISS (Pilot lab)	Republic of Korea	6 January 2020
NIM	China	17 February 2020
NIMT	Thailand	30 March 2020
MSL	New Zealand	11 May 2020
NMIJ/AIST	Japan	22 June 2020
NMIA	Australia	3 August 2020
NMIM	Malaysia	31 August 2020
SNSU-BSN	Indonesia	12 October 2020
SCL	Hong Kong China	9 November 2020
MUSSD	Sri Lanka	7 December 2020
CMS/ITRI	Chinese Taipei	11 January 2021
NMC, A*STAR	Singapore	1 March 2021
KRISS (Pilot lab)	Republic of Korea	12 April 2021

Table 3. Actual schedule of the comparison

Laboratory	Economy	Actual date of reception of artefacts
KRISS (Pilot lab)	Republic of Korea	6 January 2020
NIMT	Thailand	21 February 2020
NIM	China	10 April 2020
NMIA	Australia	30 June 2020
NMIJ/AIST	Japan	31 July 2020
MSL	New Zealand	15 September 2020
MUSSD	Sri Lanka	13 November 2020
SCL	Hong Kong China	18 December 2020
NMIM	Malaysia	25 January 2021
SNSU-BSN	Indonesia	16 June 2021
CMS/ITRI	Chinese Taipei	20 August 2021
KRISS (Pilot lab)	Republic of Korea	20 October 2021

4 Artefacts

4.1 Description of artefacts

The package contains short gauge blocks - 9 steel and 9 tungsten carbide blocks - and 2 long gauge blocks. The gauge blocks are of rectangular cross section and comply with the calibration grade K of the standard ISO 3650. The coefficients of linear thermal expansion of the gauge blocks supplied by the manufacturers (shown in Table 4) were provided to the participants.

Table 4. List of artefacts.

Identification	Nominal length /mm	Material	Linear thermal expansion coefficient /10^{-6} K^{-1}	Manufacturer
09199X	0.5	Tungsten carbide	4.5 ± 1.0	KOBA
09609X	2	Tungsten carbide	4.5 ± 1.0	KOBA
08538X	2.5	Tungsten carbide	4.5 ± 1.0	KOBA
10019X	3	Tungsten carbide	4.5 ± 1.0	KOBA
09391X	5	Tungsten carbide	4.5 ± 1.0	KOBA
10603X	10	Tungsten carbide	4.5 ± 1.0	KOBA
08201X	20	Tungsten carbide	4.5 ± 1.0	KOBA
07583X	75	Tungsten carbide	4.5 ± 1.0	KOBA
10636X	100	Tungsten carbide	4.5 ± 1.0	KOBA
174202	0.5	Steel	10.8 ± 0.5	Mitutoyo
174732	2	Steel	10.8 ± 0.5	Mitutoyo
174429	2.5	Steel	10.8 ± 0.5	Mitutoyo
130226	3	Steel	10.8 ± 0.5	Mitutoyo
160971	5	Steel	10.8 ± 0.5	Mitutoyo
136906	10	Steel	10.8 ± 0.5	Mitutoyo
173764	20	Steel	10.8 ± 0.5	Mitutoyo
171057	75	Steel	10.8 ± 0.5	Mitutoyo
172859	100	Steel	10.8 ± 0.5	Mitutoyo
160259	400	Steel	10.8 ± 0.5	Mitutoyo
160115	500	Steel	10.8 ± 0.5	Mitutoyo

4.2 Stability check

Due to the unavailability of the option to replace blocks having drift with others or to purchase new gauge blocks, and given the well-established analysis method for gauge block key comparisons in the presence of length drift, a comprehensive checking of stability before the circulation of the artefacts was deemed unnecessary, and the two measurement results of the pilot, taken before and after the circulation, were used for the stability check.

For each gauge block, pilot's measurement results were fitted to a straight line using a weighted total least squares algorithm, from which the slope and its standard uncertainty are obtained. If the absolute value of the slope is bigger than the expanded uncertainty of the slope value, then it is considered that a significant drift is present. On the contrary, if the slope value is less than the expanded uncertainty of the slope value, it is considered that there is no significant drift. Slope and its uncertainty of each gauge block is shown in Table 5.

Table 5. Comparison of slope *a* and its expanded uncertainty *U*(*a*)

<Steel short gauge blocks>

l_n /mm	a /(nm/d)	$u(a)$ /(nm/d)	$\|a\|/U(a)$
0.5	-0.002 7	0.012 6	0.107
2	0.001 4	0.012 6	0.056
2.5	0.008 3	0.012 6	0.329
3	0.003 9	0.012 6	0.155
5	0.005 7	0.012 6	0.226
10	0.001 9	0.012 6	0.075
20	-0.006 0	0.012 7	0.236
75	-0.003 0	0.014 2	0.106
100	-0.007 9	0.015 1	0.262

<Tungsten carbide short gauge blocks>

l_n /mm	a /(nm/d)	$u(a)$ /(nm/d)	$\|a\|/U(a)$
0.5	-0.014 2	0.012 6	0.563
2	-0.009 1	0.012 6	0.361
2.5	-0.007 8	0.012 6	0.310
3	-0.006 2	0.012 6	0.246
5	-0.006 2	0.012 6	0.246
10	-0.006 2	0.012 6	0.246
20	-0.011 9	0.012 7	0.469
75	0.002 3	0.013 7	0.084
100	-0.019 1	0.014 5	0.659

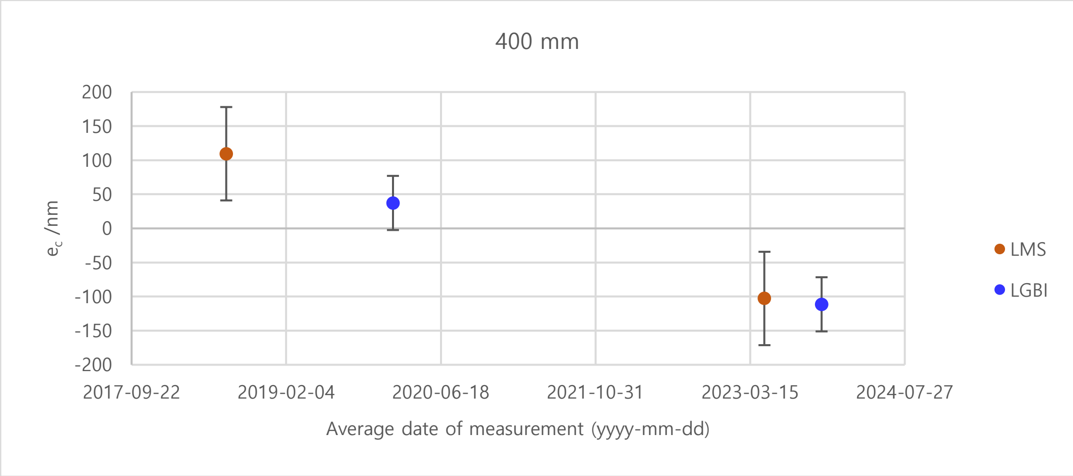
<Steel long gauge blocks>

l_n /mm	a /(nm/d)	$u(a)$ /(nm/d)	$\|a\|/U(a)$
400	-0.106 8	0.037 1	1.439
500	-0.134 9	0.045 3	1.489

As can be seen from Table 5, there were no short gauge block having significant drift, whereas two long gauge blocks showed significant drift. Drift rates of the 400 mm and 500 mm long gauge blocks correspond to 39.0 nm per year and 49.2 nm per year, respectively, which are smaller than the allowed dimensional stability of grade K and grade 0 gauge blocks (120 nm per year and 145 nm per year for 400 mm and 500 mm blocks, respectively) specified in the international standard ISO 3650:1998 [1].

In case of long gauge blocks, in order to assess the presence of any drift in the artifacts, additional supplementary measurements were performed prior to and after the circulation of the artefacts using a linear measuring system (LMS) of the pilot laboratory, which is a 1-D comparator equipped with a contacting probe and a laser interferometer. The expanded uncertainty of long gauge block calibration by using the LMS is $U=\sqrt{(66\ \mathrm{nm})^2+(0.30\times10^{-6}l_\mathrm{n})^2}$, and its ID of the CMC registered in KCDB is APMP-L-KR-00000DD6-5

Figure 1 shows the measurement results where the uncertainty bars show combined standard uncertainty (k=1) of the measured values.



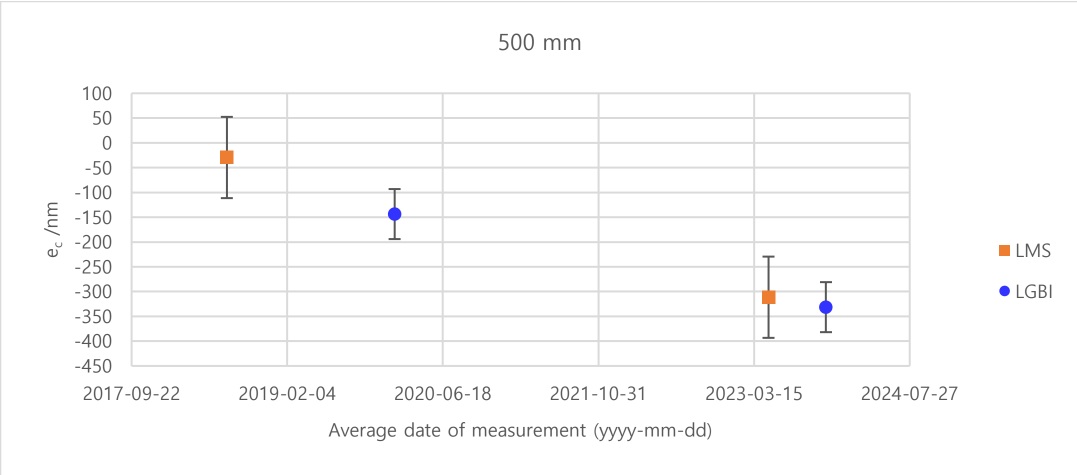


Figure 1. Measurement results of two long gauge blocks by pilot lab using a linear measuring system (LMS, brown squares) and long gauge block interferometer (LGBI, blue dots) before and after the circulation of artefacts. The uncertainty bar shows standard uncertainty (*k*=1).

4.3 Measurement method

As already mentioned in Section 2, only optical interferometry was allowed for short gauge block calibration, whereas for the long gauge block calibration, the measurement method having the smallest uncertainty in the laboratory was allowed to use. Table 6 summarizes the methods each NMI used for the short and long gauge block calibrations.

Table 6. Measuring methods of each NMI

NMI \ Artefact	Short gauge block	Long gauge block
KRISS	Gauge block interferometer	Gauge block interferometer
NIMT	Gauge block interferometer	Mechanical comparison by a universal length measuring machine
NIM	Gauge block interferometer	Gauge block interferometer
NMIA	Not measured	Linear measuring system (laser interferometer)
NMIJ/AIST	Gauge block interferometer	Gauge block interferometer
MSL	Gauge block interferometer	Not measured
MUSSD	Not measured	Mechanical comparison by a gauge block comparator
SCL	Not measured	Mechanical comparison by a gauge block comparator

NMIM	Gauge block interferometer	Mechanical comparison by a gauge block comparator
SNSU-BSN	Not measured	Mechanical comparison by a universal length measuring machine
CMS/ITRI	Not measured	(1) Linear measuring system (laser interferometer) (2) Universal length measuring machine

As shown in Table 6, CMS/ITRI reported two measurement results of long gauge blocks obtained with two different measuring systems. The results obtained by the linear measuring system is taken as the official measurement results and used for the key comparison reference value determination, because they have smaller uncertainties than those obtained by the universal length measuring machine. More information on the measurement system of each participant can be found in Appendix D.

4.4 Transportation

A plastic case containing 2 long gauge blocks and two wooden cases for the short gauge blocks, was used for the transportation of the artefacts (Figure 2).

Figure 2. Transporting case

Upon reception of the package, each laboratory was asked to check that the content is complete and that there is no apparent damage on the box or any of the standards. The confirmation of the reception was to be immediately sent to the pilot with a copy to the former participant (sender), by using the provided form (Appendix A of the Technical Protocol).

4.5 Condition of artefacts

Before the measurements, the surface condition of each gauge block was to be inspected and reported in accordance with Appendices B1, B2 and B3 of the Technical Protocol. During the circulation, several instances of damage or scratches on the measuring faces were reported.

The first laboratory, NIMT, reported that accidentally measuring faces of the 400 mm long gauge block were damaged while measuring with the long gauge block comparator. Interferograms measured with a flatness interferometer were provided by NIMT, from which an indentation was observed as a small dot near the central point of each measuring face (see Figure 3).

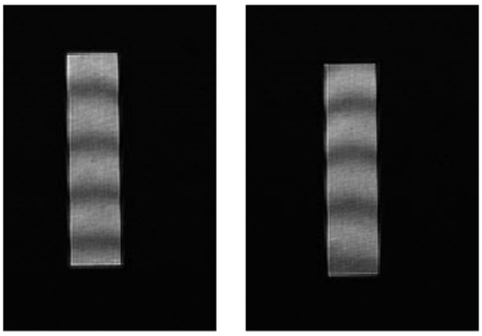


Figure 3 – Interferograms (provided by NIMT) of the two measuring faces of the 400 mm long gauge block

After consulting with CCL DG1 moderator, pilot has prepared and circulated a short document (see Appendix A) which lists possible ways to measure the 400 mm gauge block. The participants were allowed to either directly measure the central length at the central point, or make an indirect measurement by measuring at a non-central point near the central point and correct for the flatness/parallelism effect, or reject the measurement. Only the next participant, NIM, was exceptionally allowed to perform deburring of the measuring faces of the 400 mm gauge block to prevent damages on the platens of subsequent participants. A form to describe whether direct or indirect measurement was made has been included in the document, and the participants were asked to submit the filled form after the measurements. Table 7 summarizes the feedback from the participants. It turned out that most of the participants except for CMS/ITRI used the direct measurements. NMIJ/AIST has reported that they measured with both methods and found no difference between the two results, which means that the dip reported by NIMT was actually not serious.

Table 7. Summary of the feedback from participants on the 400 mm long gauge block measurement point

NMI	Measurement method	Availability of measuring at non-central point	Measured point
KRISS	Optical interferometry	Yes	Central point
NIMT	Mechanical comparison	Not asked	Central point
NIM	Optical interferometry	No	Central point
NMIA	Interferometric comparison	Yes	Central point
NMIJ/AIST	Optical interferometry	Yes	Central point
MSL	(Not Applicable)	(Not Applicable)	(Not Applicable)
MUSSD	Mechanical comparison	No	Central point
SCL	Mechanical comparison	Yes	Central point
NMIM	Mechanical comparison	No	Central point
SNSU-BSN	Mechanical comparison	Yes	Central point
CMS/ITRI	Interferometric comparison	Yes	**Non-central point**

Several laboratories including NMIJ/AIST, MSL and NMIM, reported on the defect found at the edge of the 10 mm steel gauge block. Figure 4 shows the photos provided by MSL and NMIM. NMIJ/AIST and MSL also reported that it didn’t cause problem in the wringing process.

(a) Provided by MSL (b) Provided by NMIM

Figure 4 – Photos of the 10 mm steel gauge block showing a dent on the edge of face A.

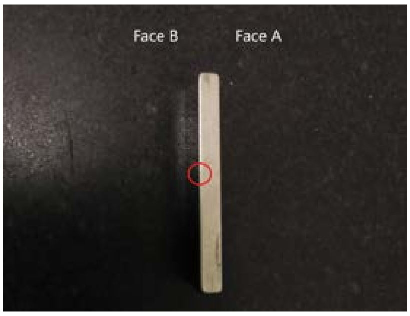
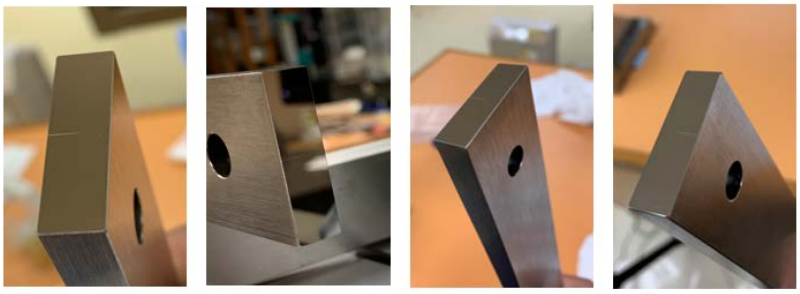


Figure 5 - Photo (provided by NMIM) of the 3 mm steel gauge block showing a dent on the edge of face B.

NMIJ/AIST and NMIM also reported on the dent located at the edge of the Face B of 3 mm steel gauge block. Figure 5 shows the photo provided by NMIM. As there was no other lab who reported on this dent, it is considered that it didn't affect the measurement.

MSL submitted the measuring face condition chart (Appendix B1 of the Technical Protocol) twice, once upon reception of the artefacts and the other before exporting the artefacts. This seems to be a good practice to follow in the future, which may make it easy to trace scratches.

Most laboratories after MUSSD reported on the straight scratches along the central points on measuring faces of long gauge blocks, which seem to be made due to improper measuring force of the gauge block comparator. Figure 6 shows the photos provided by SCL.



(a) 400 mm Face B (b) 400 mm Face A (c) 500 mm Face B (d) 500 mm Face A

Figure 6 – Photo (provided by SCL) of scratches on measuring faces of long gauge blocks

All drawings showing the surface condition of the measuring faces of the gauge blocks, as reported by the participants, are compiled in Appendix B.

5 Measuring instructions

5.1 Measurands

The measurand to be reported is the deviation e_c of the central length l_c from the nominal length l_n of a gauge block. Arithmetic mean of the two values for wringing on both faces is considered as representative for e_c, i.e.,

$$e_c = \left(e_c^A + e_c^B\right)/2 \text{ with } e_c^A = l_c^A - l_n \text{ and } e_c^B = l_c^B - l_n \quad (1)$$

where the superscripts label the face wrung to the platen, with “A” denoting the marked measuring face for gauge blocks with nominal length < 6 mm and the right-hand measuring face for gauge blocks with a nominal length ≥ 6 mm, and “B” denoting the unmarked measuring face for gauge blocks with nominal length < 6 mm and the left-hand measuring face for gauge blocks with a nominal length ≥ 6 mm, respectively (see Figure 7).

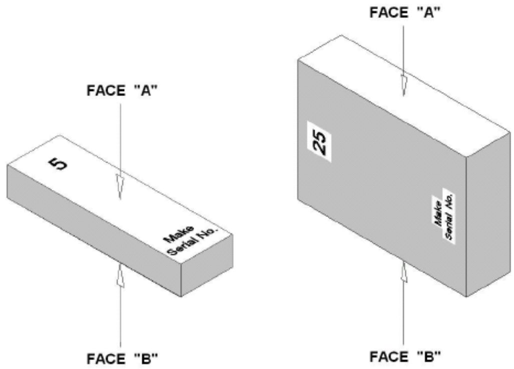


Figure 7. Nomenclature of faces

The participants were asked to make measurements based on the standard procedure that the laboratory regularly uses for this calibration service for its customers.

6 Results

6.1 Measured values and standard uncertainties as reported by participants

Measurement values and their combined standard uncertainties reported by the participants are collated in Table 8, 9 and 10. Cells corresponding to unmeasured blocks are shaded as grey.

Table 8. Measurement results of the participants for steel short gauge blocks

l_n / mm		0.5	2	2.5	3	5	10	20	75	100
Serial number		174202	174732	174429	130226	160971	136906	173764	171057	172859
KRISS1	e_c^A/ nm	-24	-24	40	13	-9	-22	-21	24	19
	e_c^B / nm	-17	-24	32	6	-6	-31	-11	14	22
	e_c / nm	**-21**	**-24**	**36**	**9**	**-7**	**-27**	**-16**	**19**	**20**
	$u(e_c)$/nm (k=1)	**13**	**13**	**13**	**13**	**13**	**13**	**13**	**14**	**15**
NIMT	e_c^A/ nm	-38	-22	39	27	-5	-23	-8	20	42
	e_c^B / nm	-20	-17	38	9	-2	-26	-35	51	65
	e_c / nm	**-29**	**-20**	**39**	**18**	**-4**	**-25**	**-22**	**36**	**54**
	$u(e_c)$/nm (k=1)	**13**	**13**	**13**	**13**	**13**	**13**	**13**	**17**	**20**
NIM	e_c^A/ nm	-10	-18	40	21	8	-21	-11	19	5
	e_c^B / nm	-7	-16	42	25	2	-21	-10	21	1
	e_c / nm	**-9**	**-17**	**41**	**23**	**5**	**-21**	**-11**	**20**	**3**
	$u(e_c)$/nm (k=1)	**7**	**7**	**7**	**7**	**7**	**8**	**8**	**12**	**14**
NMIA	e_c^A/ nm									
	e_c^B / nm									
	e_c / nm									
	$u(e_c)$/nm (k=1)									
NMIJ /AIST	e_c^A/ nm	-13	-33	30	0	-9	-44	-19	18	22
	e_c^B / nm	-17	-29	34	-5	4	-34	-13	6	14
	e_c / nm	**-15**	**-31**	**32**	**-2**	**-3**	**-39**	**-16**	**12**	**18**
	$u(e_c)$/nm (k=1)	**12**	**12**	**12**	**12**	**17**	**12**	**12**	**17**	**16**
MSL	e_c^A/ nm	-5	-21	42	17	-7	-39	-24	26	19
	e_c^B / nm	-9	-20	35	8	-11	-32	-26	8	21
	e_c / nm	**-7**	**-21**	**38**	**12**	**-9**	**-36**	**-25**	**17**	**20**
	$u(e_c)$/nm (k=1)	**11**	**11**	**11**	**11**	**11**	**11**	**11**	**12**	**13**
MUSSD	e_c^A/ nm									
	e_c^B / nm									
	e_c / nm									
	$u(e_c)$/nm (k=1)									
SCL	e_c^A/ nm									
	e_c^B / nm									
	e_c / nm									
	$u(e_c)$/nm (k=1)									
NMIM	e_c^A/ nm	-12	-16	38	12	-5	-32	-16	22	40
	e_c^B / nm	-19	-15	38	12	-10	-27	-17	21	37
	e_c / nm	**-16**	**-16**	**38**	**12**	**-8**	**-30**	**-17**	**22**	**39**
	$u(e_c)$/nm (k=1)	**14**	**14**	**14**	**14**	**14**	**14**	**15**	**26**	**32**
SNSU-BSN	e_c^A/ nm									
	e_c^B / nm									
	e_c / nm									
	$u(e_c)$/nm (k=1)									
CMS /ITRI	e_c^A/ nm									
	e_c^B / nm									
	e_c / nm									
	$u(e_c)$/nm (k=1)									
KRISS2	e_c^A/ nm	-20	-22	50	12	-5	-20	-21	20	5
	e_c^B / nm	-29	-22	45	18	6	-28	-28	10	13
	e_c / nm	**-24**	**-22**	**48**	**15**	**1**	**-24**	**-24**	**15**	**9**
	$u(e_c)$/nm (k=1)	**13**	**13**	**13**	**13**	**13**	**13**	**13**	**14**	**15**

Table 9. Measurement results of the participants for tungsten carbide short gauge blocks

l_n / mm		0.5	2	2.5	3	5	10	20	75	100
Serial number		09199X	09609X	08538X	10019X	09391X	10603X	08201X	07583X	10636X
KRISS1	e_c^A / nm	-36	-68	63	24	77	-35	173	87	1
	e_c^B / nm	-43	-72	68	43	82	-28	175	78	-7
	e_c / nm	**-39**	**-70**	**65**	**33**	**80**	**-31**	**174**	**83**	**-3**
	$u(e_c)$/nm (k=1)	**13**	**13**	**13**	**13**	**13**	**13**	**13**	**14**	**15**
NIMT	e_c^A / nm	-46	-55	64	45	92	-16	171	75	7
	e_c^B / nm	-43	-65	68	19	86	-28	176	84	5
	e_c / nm	**-45**	**-60**	**66**	**32**	**89**	**-22**	**174**	**80**	**6**
	$u(e_c)$/nm (k=1)	**13**	**13**	**13**	**13**	**13**	**13**	**13**	**14**	**15**
NIM	e_c^A / nm	-34	-62	68	50	89	-21	171	59	-22
	e_c^B / nm	-35	-64	72	45	93	-21	177	65	-24
	e_c / nm	**-35**	**-63**	**70**	**48**	**91**	**-21**	**174**	**62**	**-23**
	$u(e_c)$/nm (k=1)	**7**	**7**	**7**	**7**	**7**	**8**	**8**	**12**	**15**
NMIA	e_c^A / nm									
	e_c^B / nm									
	e_c / nm									
	$u(e_c)$/nm (k=1)									
NMIJ /AIST	e_c^A / nm	-40	-65	69	29	87	-29	165	78	-12
	e_c^B / nm	-36	-79	64	44	86	-24	157	66	-19
	e_c / nm	**-38**	**-72**	**67**	**36**	**87**	**-26**	**161**	**72**	**-16**
	$u(e_c)$/nm (k=1)	**12**	**15**	**12**	**19**	**12**	**12**	**12**	**15**	**13**
MSL	e_c^A / nm	-55	-72	70	30	88	-23	158	86	-7
	e_c^B / nm	-54	-76	70	38	92	-31	161	78	-11
	e_c / nm	**-54**	**-74**	**70**	**34**	**90**	**-27**	**159**	**82**	**-9**
	$u(e_c)$/nm (k=1)	**11**	**11**	**11**	**11**	**11**	**11**	**11**	**12**	**13**
MUSSD	e_c^A / nm									
	e_c^B / nm									
	e_c / nm									
	$u(e_c)$/nm (k=1)									
SCL	e_c^A / nm									
	e_c^B / nm									
	e_c / nm									
	$u(e_c)$/nm (k=1)									
NMIM	e_c^A / nm	-54	-73	66	39	89	-24	159	74	-5
	e_c^B / nm	-53	-69	64	27	85	-33	161	86	-1
	e_c / nm	**-54**	**-71**	**65**	**33**	**87**	**-29**	**160**	**80**	**-3**
	$u(e_c)$/nm (k=1)	**14**	**14**	**14**	**14**	**14**	**14**	**14**	**18**	**20**
SNSU-BSN	e_c^A / nm									
	e_c^B / nm									
	e_c / nm									
	$u(e_c)$/nm (k=1)									
CMS /ITRI	e_c^A / nm									
	e_c^B / nm									
	e_c / nm									
	$u(e_c)$/nm (k=1)									
KRISS2	e_c^A / nm	-58	-84	55	17	72	-43	157	93	-26
	e_c^B / nm	-60	-82	54	32	70	-37	158	78	-33
	e_c / nm	**-59**	**-83**	**54**	**25**	**71**	**-40**	**157**	**86**	**-29**
	$u(e_c)$/nm (k=1)	**13**	**13**	**13**	**13**	**13**	**13**	**13**	**14**	**15**

Table 10. Measurement results of the participants for steel long gauge blocks

l_n / mm		400	500
Serial number		160259	160115
KRISS1	e_c^A/ nm	41	-154
	e_c^B/ nm	34	-133
	e_c / nm	**37**	**-144**
	$u(e_c)$/nm (k=1)	**41**	**50**
NIMT	e_c^A/ nm		
	e_c^B/ nm		
	e_c / nm	**-270**	**-540**
	$u(e_c)$/nm (k=1)	**160**	**198**
NIM	e_c^A/ nm	-99	-305
	e_c^B/ nm	-87	-301
	e_c / nm	**-93**	**-303**
	$u(e_c)$/nm (k=1)	**35**	**43**
NMIA	e_c^A/ nm		
	e_c^B/ nm		
	e_c / nm	**546**	**440**
	$u(e_c)$/nm (k=1)	**162**	**195**
NMIJ/AIST	e_c^A/ nm	66	-129
	e_c^B/ nm	61	-122
	e_c / nm	**63**	**-126**
	$u(e_c)$/nm (k=1)	**36**	**44**
MSL	e_c^A/ nm		
	e_c^B/ nm		
	e_c / nm		
	$u(e_c)$/nm (k=1)		
MUSSD	e_c^A/ nm	450	-618
	e_c^B/ nm	454	-554
	e_c / nm	**452**	**-586**
	$u(e_c)$/nm (k=1)	**153**	**172**
SCL	e_c^A/ nm	-100	100
	e_c^B/ nm	200	100
	e_c / nm	**100**	**100**
	$u(e_c)$/nm (k=1)	**279**	**353**
NMIM	e_c^A/ nm		
	e_c^B/ nm		
	e_c / nm	**59**	**-69**
	$u(e_c)$/nm (k=1)	**261**	**301**
SNSU-BSN	e_c^A/ nm		
	e_c^B/ nm		
	e_c / nm	**70**	**-29**
	$u(e_c)$/nm (k=1)	**186**	**216**
CMS/ITRI	e_c^A/ nm		
	e_c^B/ nm		
	e_c / nm	**10**	**-110**
	$u(e_c)$/nm (k=1)	**82**	**99**
KRISS2	e_c^A/ nm	-106	-335
	e_c^B/ nm	-117	-327
	e_c / nm	**-111**	**-331**
	$u(e_c)$/nm (k=1)	**41**	**50**

6.2 Measurement uncertainties

Standard uncertainty components as reported by the participants can be found in Appendix C.

7 Analysis

7.1 Calculation of the Key Comparison Reference Values and Degrees of Equivalence

In case of short gauge block measurement results, the key comparison reference value (KCRV) of each gauge block was calculated as the weighted mean of the participants' results. However, in case of long gauge block measurement results, drift was taken in to account, and the KCRV became a function of time, resulting in different KCRV for different NMI.

7.1.1 Short gauge blocks

If we denote the total number of participants submitting a result as *I*, and denote the i-th laboratory's measured value and its associated standard uncertainty as x_i and $u(x_i)$, respectively, the KCRV is the weight mean $\overline{x}_w$ of the participants' results provided that they are statistically consistent. The weighted mean is calculated by equation (1),

$$\overline{x}_w = \sum_{i=1}^{I} w_i \cdot x_i \qquad (1)$$

where w_i is the weight calculated by equation (2),

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

with the normalizing factor C being

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

The standard uncertainty of the weighted mean, which is also called internal standard deviation, is calculated by:

$$u(\overline{x}_w) = u_{\text{int}}(\overline{x}_w) = \sqrt{\frac{1}{\sum_{i=1}^{I} \left(\frac{1}{u(x_i)} \right)^2}} = \sqrt{C} \qquad (3)$$

The external standard deviation, $u_{ext}(\overline{x}_w)$, is calculated by:

$$u_{ext}(\overline{x}_w) = \sqrt{\frac{1}{(I-1)} \cdot \frac{\sum_{i=1}^{I} w_i (x_i - \overline{x}_w)^2}{\sum_{i=1}^{I} w_i}} \qquad (4)$$

Using equations (3) and (4), the Birge ratio, R_B, is calculated as

$$R_B = \frac{u_{ext}(\overline{x}_w)}{u(\overline{x}_w)} . \qquad (5)$$

The data in a key comparison are considered consistent provided that R_B is less than or equal to $R_{B,\max}$:

$$R_{B,\max} = \sqrt{1+\sqrt{8/(I-1)}} \qquad (6)$$

where I is the number of laboratories reporting measurement results. Table 11 lists $R_{B,\max}$ for several values of I.

Table 11. $R_{B,\max}$ values for several I values.

I	6	7	8	9	10
$R_{B,\max}$	1.505	1.468	1.438	1.414	1.394

For each laboratory and each gauge block, normalized error or E_n value is calculated as the ratio of the degrees of equivalence (DoE) and its expanded uncertainty, as shown in equation (7).

$$E_n = \frac{x_i - \bar{x}_w}{2\sqrt{[u(x_i)]^2 - [u_{\text{int}}(\bar{x}_w)]^2}} \qquad (7)$$

If the absolute value of E_n is bigger than 1, the result becomes an outlier.

In case $R_B > R_{B,\max}$, the result corresponding to maximum $|E_n|$ value is excluded and the weighted mean is recalculated. This is repeated until the condition $R_B \le R_{B,\max}$ is fulfilled.

For all short gauge blocks, the Birge ratios are less than 1.505, which means that all measurement results are statistically consistent. Furthermore, all $|E_n|$ values are less than 1. Therefore, for each short gauge block, the weighted mean calculated with measurement results of all participants becomes the KCRV without any iteration process.

Table 12 shows the KCRV and Birge ratio of all short gauge blocks.

Table 12. Weighted mean, its internal/external standard deviation and Birge ratio of short gauge block measurement results

Material	l_n /mm	$\bar{x}_w$/nm	u_{int} /nm	u_{ext} /nm	R_B
Steel	0.5	-13.7	4.4	3.1	0.712
Steel	2	-20.5	4.4	2.1	0.488
Steel	2.5	38.2	4.4	1.3	0.303
Steel	3	14.8	4.4	3.7	0.858
Steel	5	-1.9	4.5	2.7	0.599
Steel	10	-28.4	4.6	3.0	0.666
Steel	20	-16.8	4.6	2.3	0.500
Steel	75	20.2	6.1	2.9	0.485
Steel	100	20.4	6.6	6.5	0.972
Tungsten carbide	0.5	-41.8	4.4	3.4	0.792
Tungsten carbide	2	-67.0	4.5	2.3	0.506
Tungsten carbide	2.5	68.1	4.4	0.9	0.217
Tungsten carbide	3	39.6	4.5	3.2	0.711
Tungsten carbide	5	88.4	4.4	1.6	0.364
Tungsten carbide	10	-25.0	4.6	1.7	0.365
Tungsten carbide	20	168.2	4.6	3.1	0.683
Tungsten carbide	75	75.8	5.6	3.6	0.638
Tungsten carbide	100	-8.8	6.0	4.2	0.696

Figure 8 shows the measurement results of the participants together with the KCRV and its uncertainty. All uncertainties shown as bars or dotted lines correspond to standard uncertainty (k=1).

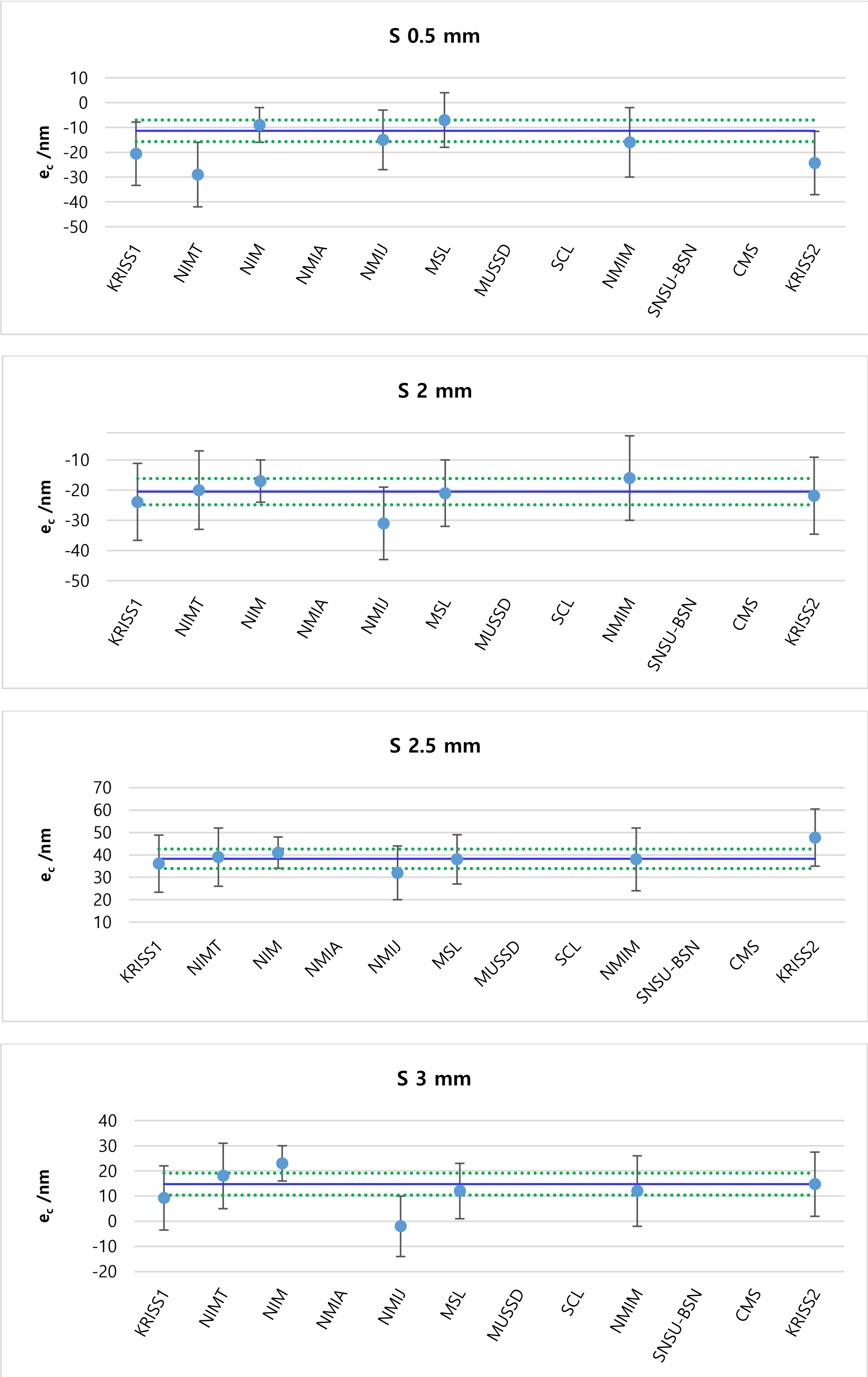


Figure 8. Measurement results and KCRV for short gauge blocks.

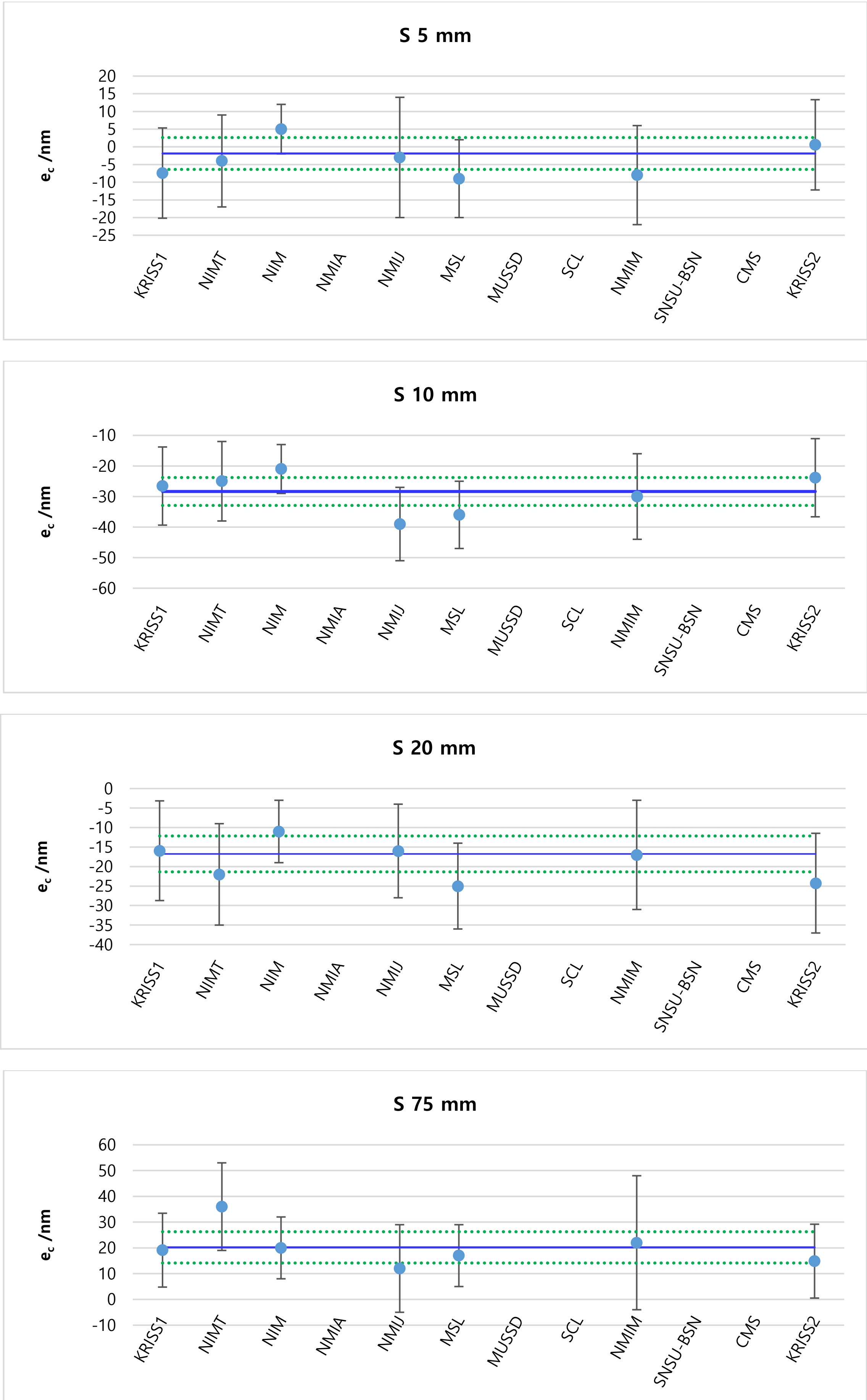


Figure 8. Measurement results and KCRV for short gauge blocks (continued).

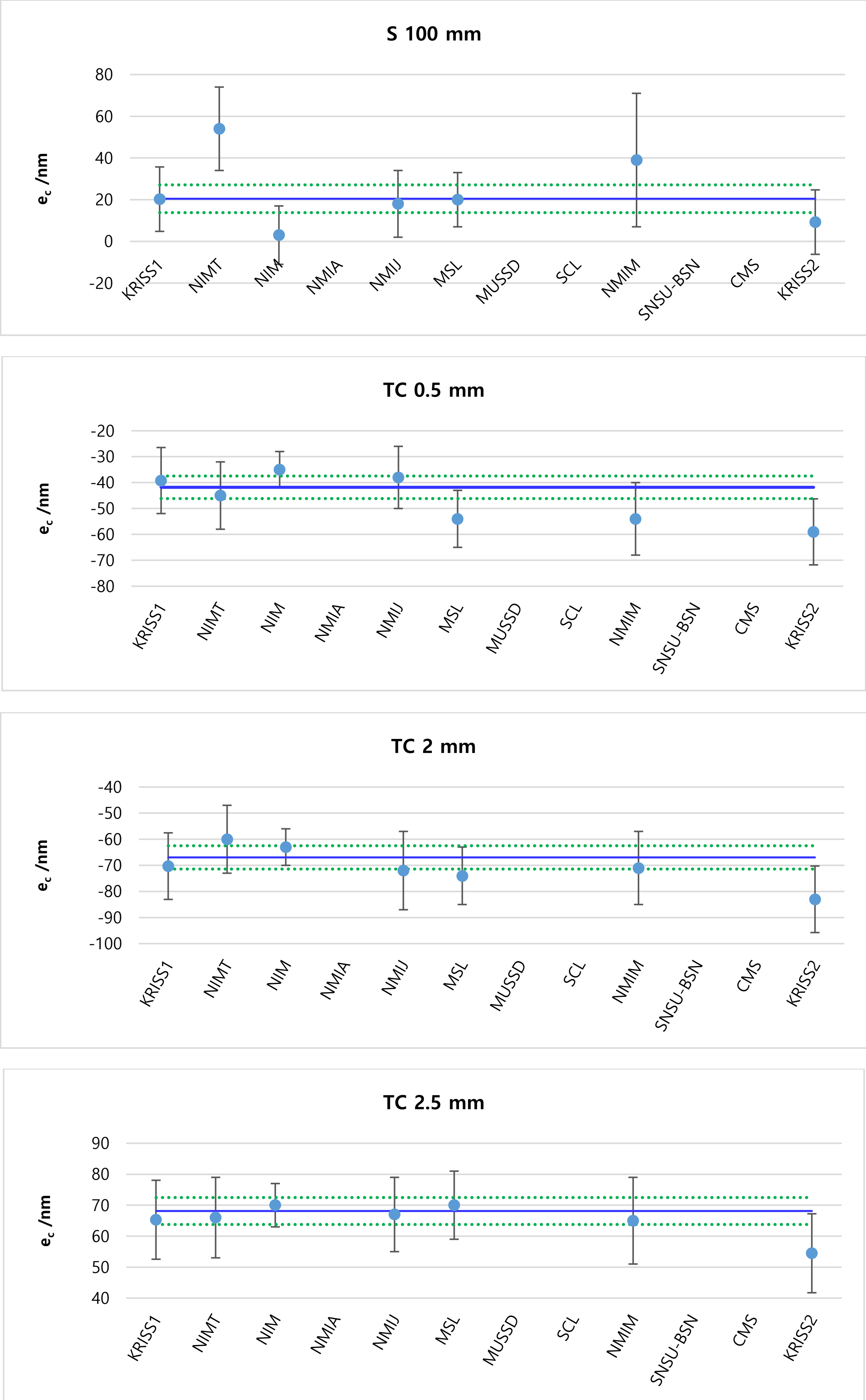


Figure 8. Measurement results and KCRV for short gauge blocks (continued).

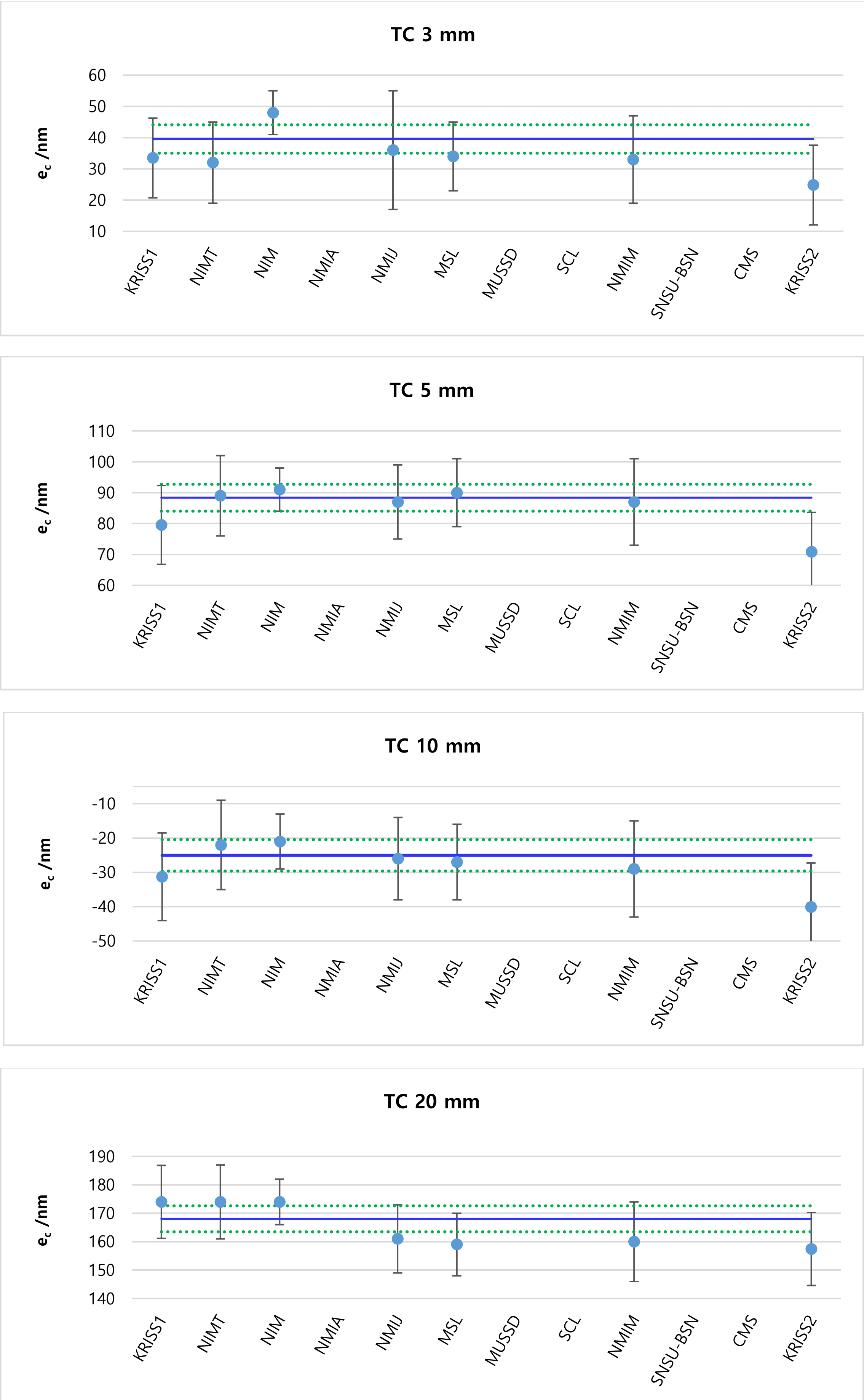
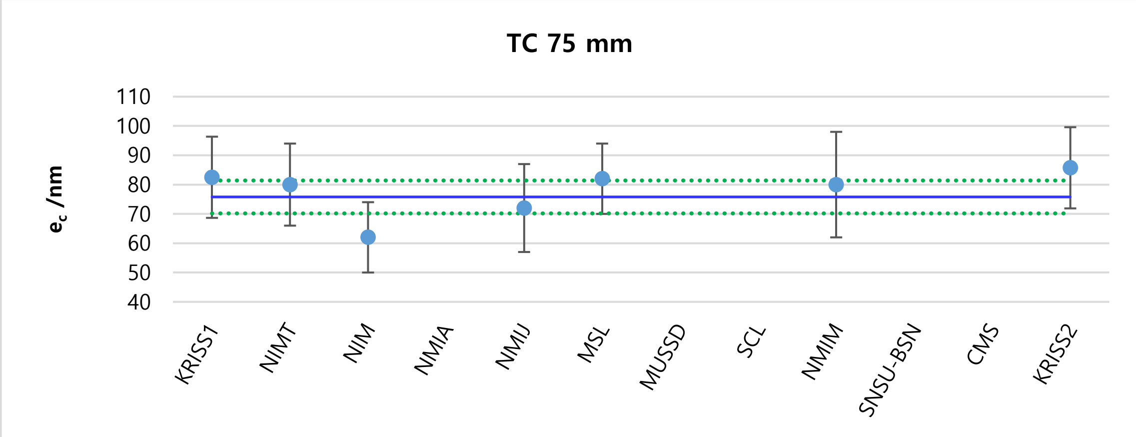


Figure 8. Measurement results and KCRV for short gauge blocks (continued).



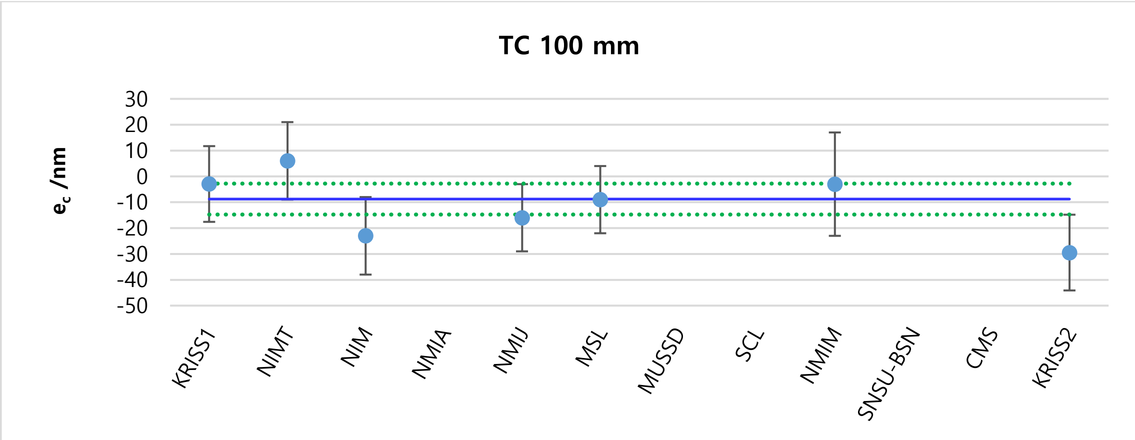


Figure 8. Measurement results and KCRV for short gauge blocks (continued).

Tables 13 and 14 show the E_n values of steel and tungsten carbide short gauge blocks, respectively.

Table 13. E_n values of steel short gauge blocks

NMI \ l_n /mm	0.5	2	2.5	3	5	10	20	75	100
KRISS	-0.284	-0.140	-0.090	-0.229	-0.231	0.074	0.034	-0.042	-0.007
NIMT	-0.623	0.021	0.030	0.132	-0.087	0.138	-0.216	0.497	0.889
NIM	0.432	0.320	0.250	0.751	0.642	0.560	0.440	-0.010	-0.708
NMIA	-	-	-	-	-	-	-	-	-
NMIJ.AIST	-0.056	-0.469	-0.280	-0.750	-0.034	-0.480	0.034	-0.258	-0.084
MSL	0.334	-0.024	-0.013	-0.137	-0.355	-0.382	-0.412	-0.155	-0.020
MUSSD	-	-	-	-	-	-	-	-	-
SCL	-	-	-	-	-	-	-	-	-
NMIM	-0.085	0.169	-0.010	-0.104	-0.231	-0.062	-0.008	0.036	0.296
SNSU-BSN	-	-	-	-	-	-	-	-	-
CMS/ITRI	-	-	-	-	-	-	-	-	-

Table 14. E_n values of tungsten carbide short gauge blocks

NMI \ l_n /mm	0.5	2	2.5	3	5	10	20	75	100
KRISS	0.109	-0.140	-0.117	-0.255	-0.366	-0.261	0.249	0.266	0.219
NIMT	-0.130	0.285	-0.087	-0.311	0.025	0.125	0.245	0.164	0.537
NIM	0.622	0.366	0.171	0.789	0.239	0.308	0.453	-0.650	-0.517
NMIA	-	-	-	-	-	-	-	-	-
NMIJ.AIST	0.171	-0.176	-0.050	-0.097	-0.062	-0.043	-0.317	-0.136	-0.313
MSL	-0.603	-0.351	0.093	-0.279	0.080	-0.098	-0.452	0.292	-0.010
MUSSD	-	-	-	-	-	-	-	-	-
SCL	-	-	-	-	-	-	-	-	-
NMIM	-0.458	-0.153	-0.118	-0.249	-0.052	-0.150	-0.304	0.123	0.151
SNSU-BSN	-	-	-	-	-	-	-	-	-
CMS/ITRI	-	-	-	-	-	-	-	-	-

7.1.2 Long gauge blocks

In case of long gauge blocks, as the effect of drift had to be taken in to account, an analysis proposed in reference [2] has been followed. In this analysis, the KCRV becomes a linear function of time whose slope β is determined by the results of pilot, but intercept is determined by the results of all participants.

The KCRV at any time t becomes

$$\begin{aligned} KCRV(t) &= \sum_{i=1}^{I} w_i(\alpha_i + \beta t) \\ &= \sum_{i=1}^{I} w_i X_i - \beta \sum_{i=1}^{I} w_i (t_i - t) \end{aligned} \tag{8}$$

where w_i is the weight defined in equation (2), β is the slope determined by least squares fitting of the pilot's results (see equation 9), and α_i is defined in equation 10.

$$\beta = \frac{\sum_{k=1}^{3} (\mathrm{t}_{1k} - \mathrm{t}_1)(X_{1k} - X_1)}{\sum_{k=1}^{3} (\mathrm{t}_{1k} - \mathrm{t}_1)^2} \tag{9}$$

$$\alpha_i = X_i - \beta t_i \tag{10}$$

In equations 9 and 10, X_{1k} denotes the pilot's measured value taken at time t_{1k} (k = 1, …, K), and X_1 and t_1 denote their arithmetic mean, while X_i and t_i (i = 2, …, I) denote the measured value and time of laboratories other than the pilot. As each participant took measurements for several weeks, the estimated day in the middle of the period was determined by the pilot, and used for t_{1k} and t_i values.

Square of standard uncertainty of KCRV becomes

$$u^2(KCRV(t)) = \sum_{i=1}^{I} w_i^2 u^2(X_i) + \frac{\sigma_{1,A}^2 \left[\sum_{i=1}^{I} w_i (t_i - \mathrm{t}) \right]^2}{\sum_{k=1}^{K} (t_{1k} - \mathrm{t}_1)^2} \tag{11}$$

where $u(X_i)$ denotes the standard uncertainty of X_i, and $\sigma_{1,\mathrm{A}}$ is defined as equation (12).

$$\sigma_{1,\mathrm{A}}^2 = \frac{\sum_{k=1}^{K} (X_{1k} - \alpha_1 - \beta\, \mathrm{t}_{1k})^2}{K-2} \tag{12}$$

As can be seen in equation (12), to follow this analysis, at least three measurement results of pilot obtained using a gauge block interferometer (GBI) are required ($K \geq 3$). The pilot had total of 4 results but with only 2 obtained by GBI, and the other two were obtained by the linear measuring system (LMS) equipped with a laser interferometer. Since figure 1 shows that all four results show consistent drift, as an approximate approach for the slope determination, the pilot used the two measurement results obtained by GBI and one LMS result which was measured between the two GBI results[1].

Degree of equivalence (DoE) D_i of the *i*-th laboratory with respect to KCRV, and its standard uncertainty $u(D_i)$ are calculated as

$$D_i = X_i - KCRV(t_i) \tag{13}$$

$$\begin{aligned} u^2(D_i) &= (1-2w_i)u^2(X_i) + u^2(KCRV(\mathrm{t}_i)) \\ &= u^2(X_i) - u^2(KCRV(t_i)) \quad \text{(when } X_i \text{ contributees to KCRV)} \\ &= u^2(X_i) + u^2(KCRV(t_i)) \quad \text{(when } X_i \text{ doesn't contribute to KCRV)} \end{aligned} \tag{14}$$

The normalized error E_n is calculated as

$$E_\mathrm{n} = \frac{D_i}{2u(D_i)} \ . \tag{15}$$

7.1.2.1 KCRV for 400 mm long gauge block calculated from results of all participants (1st trial)

When results of all participants were used, the KCRV for 400 mm gauge block at any time *t* became:

$$\begin{aligned} KCRV(t) &= 4877.94 \text{ nm} - 0.11061 \text{ nm } \times t \\ &= 11.84 \text{ nm} - 0.11061 \text{ nm } \times (t - t^*) \\ &= 11.84 \text{ nm} - 0.11061 \text{ nm } \times (t - 43992.13) \end{aligned} \tag{16}$$

where t^* is the weighted mean of t_i, i.e., $t^* = \sum_{i=1}^{I} w_i t_i$, while t, t_i and t^* are numbers with unit 1, and correspond to number of days since January 1, 1900.

[1] After circulating the Draft A.2 report, in which the slope of the KCRV for each long gauge block was determined using these three data, the pilot asked the participants whether, even at this stage, a third measurement using the LGBI should be conducted by the pilot and all three data sets obtained with the LGBI should be used in determining each KCRV slope, in order to fully follow the reference analysis method. The majority of participants responded that either approach would be acceptable, but some preferred to retain the current analysis. Since any modification made after circulating a Draft A report containing KCRVs requires the consent of all participants, it was decided to maintain the existing analysis results.

Figure 9 shows the measurement results of 400 mm block together with KCRV and its standard uncertainty. In the figure, all uncertainties shown as bars or dotted lines correspond to standard uncertainty (k=1), and $\sigma^2_{1,A}$ is 70.8 nm^2. Orange dots labelled as KRISS0 and KRISS1.5 are results of the pilot obtained with LMS, which are shown for reference only.

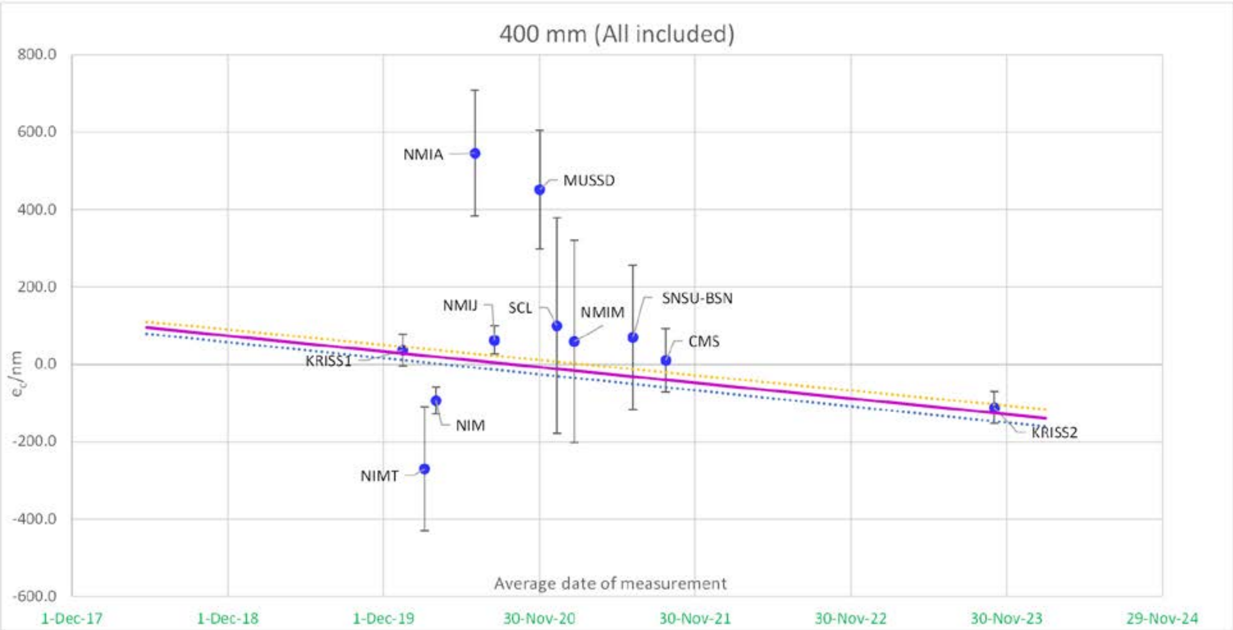


Figure 9. Measurement results and KCRV for 400 mm long gauge block (- all participants included). Dotted lines represent the standard uncertainty of KCRV. Orange dots labeled as KRISS0 and KRISS1.5 are results of pilot obtained with LMS, but are not used for KCRV calculation.

En values of the measurement results are shown in Table 15.

Table 15. En values for 400 mm long gauge block measurements when all results are used for KCRV calculation

NMI	D_i/nm	$u(D_i)$/nm	E_n
KRISS	8.4	35.7	0.117
NIMT	-292.5	158.8	-0.921
NIM	-112.5	28.8	-1.956
NMIA	536.6	160.8	1.669
NMIJ/AIST	58.7	30.0	0.979
MSL	-	-	-
MUSSD	459.4	151.7	1.514
SCL	111.8	278.3	0.201
NMIM	75.4	260.2	0.145
SNSU-BSN	101.5	185.0	0.274
CMS/ITRI	50.0	79.6	0.314

In case of long gauge block measurements, I = 10, and thus $R_{B,\max} = 1.39$ (see Table 11). The internal and external standard deviation of the weighted mean calculated by equations (3) and (4) were 20.0 nm and

40.6 nm, respectively, resulting in R_B = 2.04. As $R_B > R_{B,\max}$, the outlier with maximum En value has to be removed and KCRV recalculated.

7.1.2.2 KCRV for 400 mm long gauge block with result of NIM excluded (2nd trial)

Since the result of NIM gives the maximum |En| value, it is excluded, and only 9 laboratory's results are used for the KCRV recalculation. When NIM's results were excluded, the KCRV became

$$\begin{aligned} KCRV(t) &= 4932.12\ \text{nm} - 0.11061\ \text{nm} \times t \\ &= 62.35\ \text{nm} - 0.11061\ \text{nm} \times (t - 44025.43) \end{aligned} \tag{17}$$

Figure 10 shows the measurement results of 400 mm block together with KCRV and its standard uncertainty, when NIM's result is excluded. In the figure, all uncertainties shown as bars or dotted lines correspond to standard uncertainty (k=1). Orange dots labelled as KRISS0 and KRISS1.5 are results of the pilot obtained with LMS, which are shown for reference only.

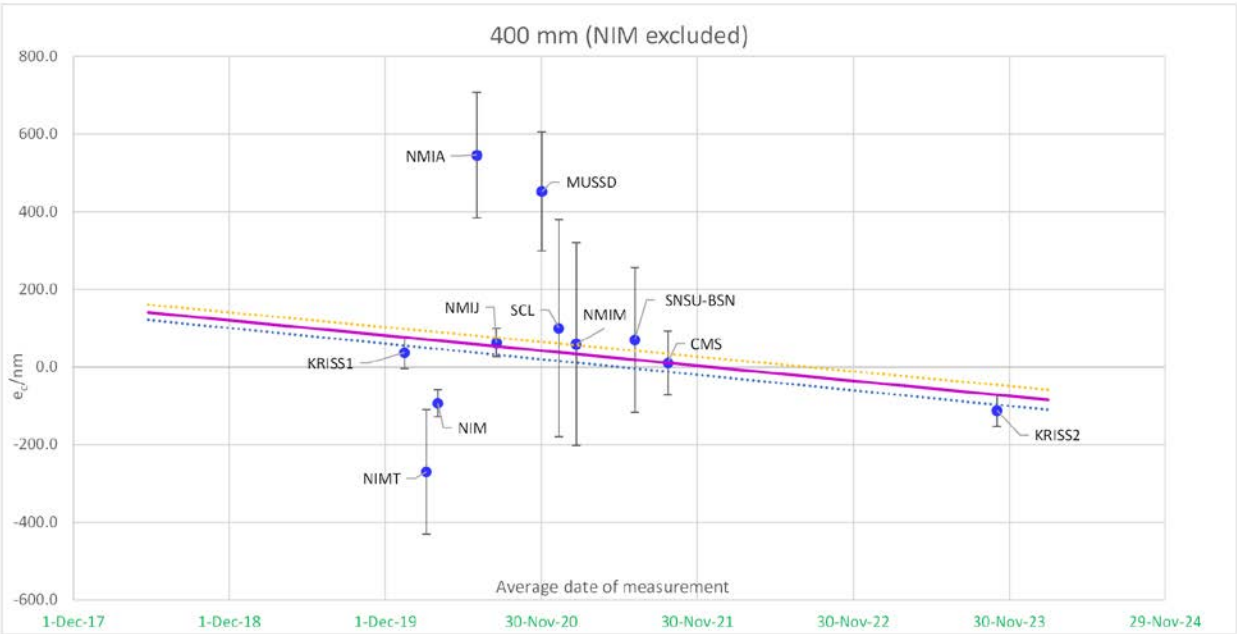


Figure 10. Measurement results and KCRV for 400 mm long gauge block (- NIM's result excluded). Dotted lines represent the standard uncertainty of KCRV. Orange dots labeled as KRISS0 and KRISS1.5 are results of pilot obtained with LMS, but are not used for KCRV calculation.

E_n values of the measurement results are shown in Table 16. When calculating NIM's E_n value by equation (15), equation (18) was used for $u(D_i)$.

$$u^2(D_i) = u^2(X_i) + u^2(KCRV(\mathrm{t}_i)) \tag{18}$$

Table 16. E_n values for 400 mm long gauge block measurements when NIM's result is excluded for KCRV calculation

NMI	D_i/nm	$u(D_i)$/nm	E_n
KRISS	-45.8	32.9	-0.696
NIMT	-346.7	158.1	-1.096
NIM	-166.7	42.6	-1.956
NMIA	482.4	160.2	1.506

NMIJ/AIST	4.5	26.6	0.084
MSL	-	-	-
MUSSD	405.2	151.1	1.341
SCL	57.6	277.9	0.104
NMIM	21.2	259.9	0.041
SNSU-BSN	47.3	184.4	0.128
CMS/ITRI	-4.2	78.4	-0.027

The internal and external standard deviation of the weighted mean calculated by equations (3) and (4) were 24.3 nm and 40.2 nm, respectively, resulting in R_B = 1.66. As $R_{B,\max} = 1.41$ for I=9 (see Table 11), $R_B > R_{B,\max}$, and thus the next outlier with biggest E_n value has to be additionally removed and KCRV recalculated.

7.1.2.3 KCRV for 400 mm long gauge block with results of NIM and NMIA excluded (3rd trial)

Since NMIA's $|E_n|$ value is the second largest, the result of NIM and NMIA are excluded and KCRV was recalculated using 8 laboratory's results. The KCRV became

$$\begin{aligned} KCRV(t) &= 4921.03\ \text{nm} - 0.11061\ \text{nm} \times t \\ &= 51.22\ \text{nm} - 0.11061\ \text{nm} \times (t - 44025.69) \end{aligned} \quad (19)$$

Figure 11 shows the measurement results of 400 mm block together with KCRV and its standard uncertainty, when the results of NIM and NMIA are excluded. In the figure, all uncertainties shown as bars or dotted lines correspond to standard uncertainty (k=1). Orange dots labelled as KRISS0 and KRISS1.5 are results of the pilot obtained with LMS, which are shown for reference only.

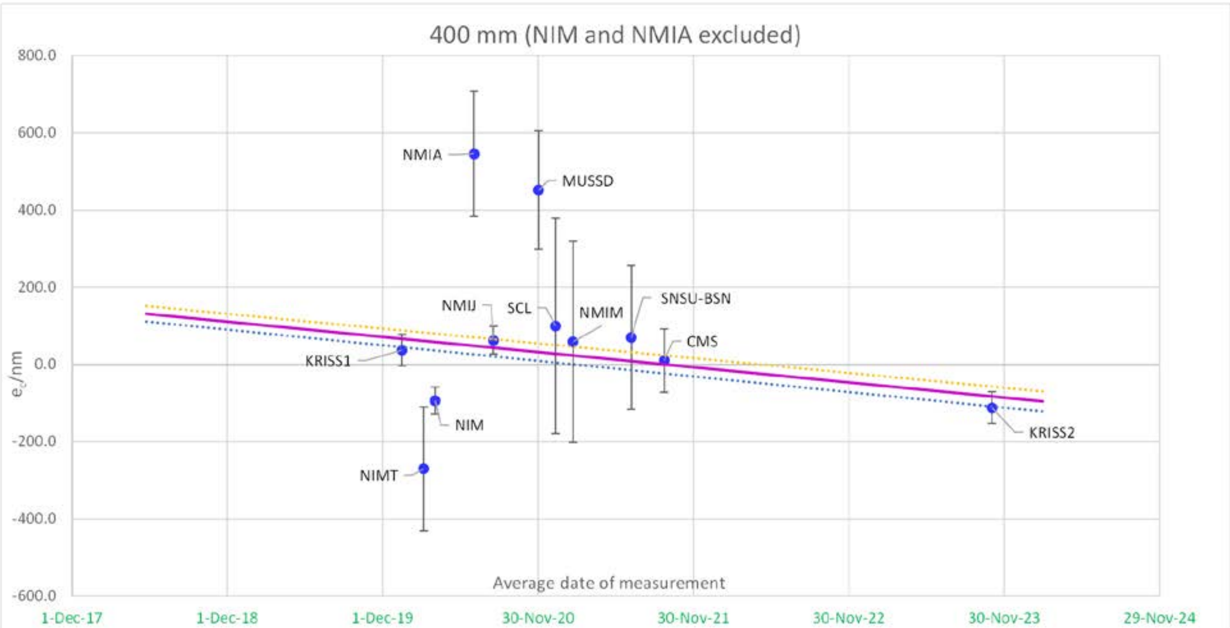


Figure 11. Measurement results and KCRV for 400 mm long gauge block (-results of NIM and NMIA excluded). Dotted lines represent the standard uncertainty of KCRV. Orange dots labeled as KRISS0 and KRISS1.5 are results of pilot obtained with LMS, but are not used for the KCRV calculation.

En values of the measurement results are shown in Table 17. When calculating E_n values of NIM and NMIA by equation (15), equation (18) was used for $u(D_i)$.

Table 17. E_n values for 400 mm long gauge block measurements when results of NIM and NMIA are excluded for KCRV calculation

NMI	D_i/nm	$u(D_i)$/nm	E_n
KRISS	-34.7	32.7	-0.590
NIMT	-335.6	158.1	-1.066
NIM	-155.6	42.8	-1.930
NMIA	493.5	163.9	1.512
NMIJ/AIST	15.6	26.3	0.353
MSL	-	-	-
MUSSD	416.3	151.0	1.385
SCL	68.7	277.9	0.124
NMIM	32.3	259.8	0.062
SNSU-BSN	58.4	184.4	0.159
CMS/ITRI	6.9	78.3	0.045

The internal and external standard deviation of the weighted mean calculated by equations (3) and (4) were 24.6 nm and 33.3 nm, respectively, resulting in R_B = 1.36. As $R_{B,\max} = 1.44$ for $I = 8$ (see Table 11), $R_B < R_{B,\max}$, which means that this set of data is statistically consistent. The final KCRV is thus the equation (19) for the 400 mm long gauge block.

7.1.2.4 KCRV for 500 mm long gauge block calculated from results of all participants (1st trial)

When results of all participants were used, the KCRV for 500 mm gauge block at any time *t* became:

$$\begin{aligned} KCRV(t) &= 5835.63 \text{ nm} - 0.13696 \text{ nm} \times t \\ &= -189.88 \text{nm} - 0.13696 \text{ nm} \times (t - 43993.61) \end{aligned} \quad (20)$$

t is a number with unit 1, and corresponds to the number of days since January 1, 1900.

Figure 12 shows the measurement results of 500 mm block together with KCRV and its standard uncertainty. In the figure, all uncertainties shown as bars or dotted lines correspond to standard uncertainty (k=1), and $\sigma_{1,A}^2$ is 14.2 nm^2. Orange dots labelled as KRISS0 and KRISS1.5 are results of the pilot obtained with LMS, which are shown for reference only.

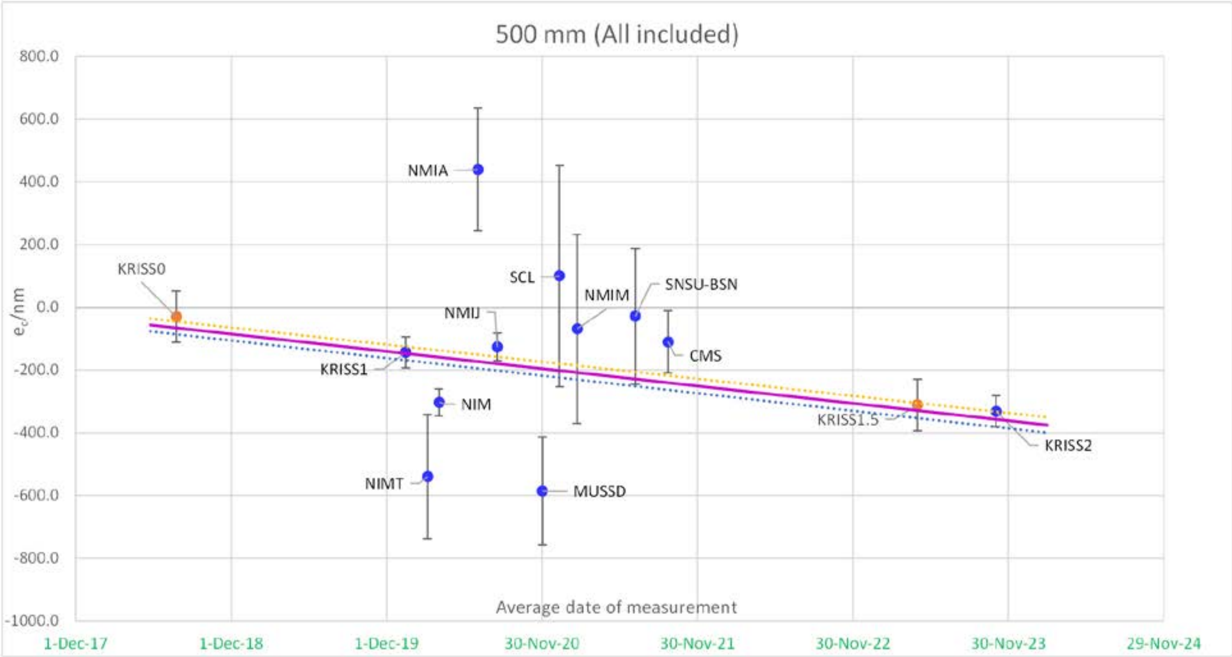


Figure 12. Measurement results and KCRV for 500 mm long gauge block (- all participants included). Dotted lines represent the standard uncertainty of KCRV. Orange dots labeled as KRISS0 and KRISS1.5 are results of pilot obtained with LMS, but are not used for KCRV calculation.

E_n values of the measurement results are shown in Table 18.

Table 18. E_n values when all results are used for KCRV calculation

NMI	D_i/nm	$u(D_i)$/nm	E_n
KRISS	25.5	43.2	0.295
NIMT	-363.5	196.5	-0.925
NIM	-122.8	35.5	-1.731
NMIA	632.7	193.5	1.635
NMIJ/AIST	73.0	36.7	0.995
MSL	-	-	-
MUSSD	-372.5	170.3	-1.094
SCL	319.0	352.2	0.453
NMIM	155.6	300.0	0.259
SNSU-BSN	214.3	214.6	0.499
CMS/ITRI	143.9	96.0	0.750

In case of long gauge block measurements, I = 10, and thus $R_{B,\max} = 1.39$ (see Table 11). The internal and external standard deviation of the weighted mean calculated by equations (3) and (4) were 24.3 nm and 47.2 nm, respectively, resulting in R_B = 1.94. As $R_B > R_{B,\max}$, the outlier with maximum En value has to be removed and KCRV recalculated.

7.1.2.5 KCRV for 500 mm long gauge block with result of NIM excluded (2nd trial)

Since the result of NIM gives the maximum |En| value, it is excluded, and only 9 laboratory's results are used for the KCRV recalculation. When NIM's results were excluded, the KCRV became

$$KCRV(t) = 5893.28\ \text{nm} - 0.13696\ \text{nm} \times t$$
$$= -136.77\ \text{nm} - 0.13696\ \text{nm} \times (t - 44026.76) \qquad (21)$$

Figure 13 shows the measurement results of 500 mm block together with KCRV and its standard uncertainty, when NIM's result is excluded. In the figure, all uncertainties shown as bars or dotted lines correspond to standard uncertainty (k=1). Orange dots labelled as KRISS0 and KRISS1.5 are results of the pilot obtained with LMS, which are shown for reference only.

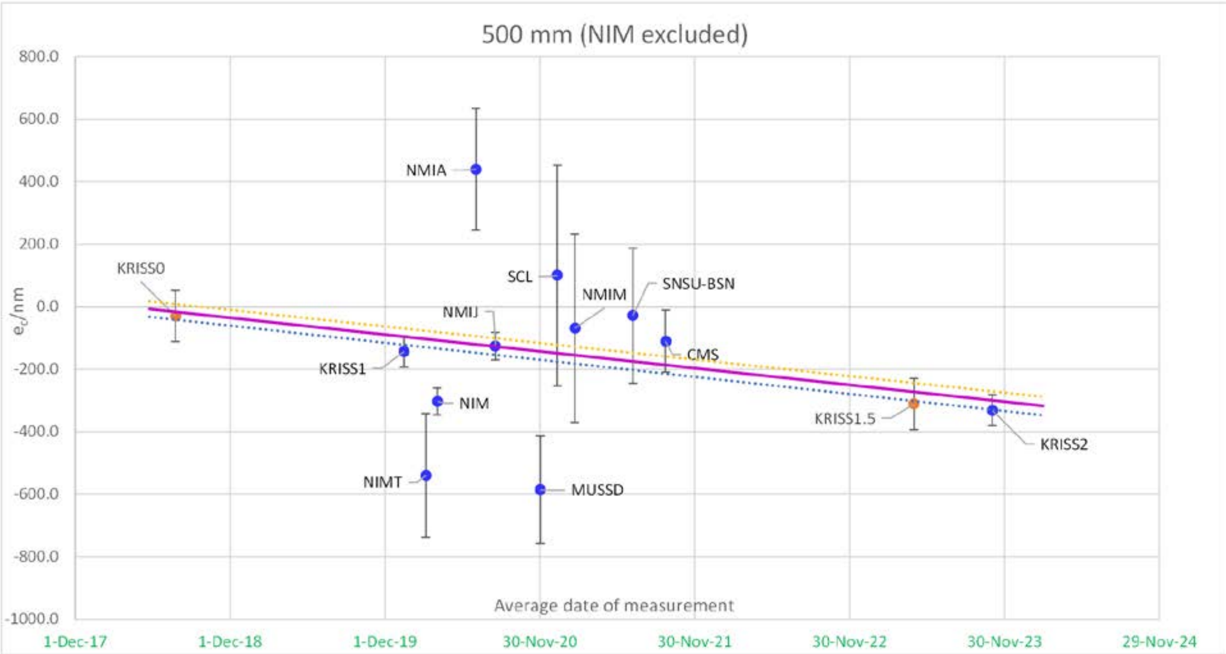


Figure 13. Measurement results and KCRV for 500 mm long gauge block (- NIM's result excluded). Dotted lines represent the standard uncertainty of KCRV. Orange dots labeled as KRISS0 and KRISS1.5 are results of pilot obtained with LMS, but are not used for KCRV calculation.

En values of the measurement results are shown in Table 19. When calculating NIM's E_n value by equation (15), equation (18) was used for $u(D_i)$.

Table 19. E_n values when NIM's result is excluded for KCRV calculation

NMI	D_i/nm	$u(D_i)$/nm	E_n
KRISS	-32.1	39.8	-0.403
NIMT	-421.1	195.8	-1.075
NIM	-180.4	52.1	-1.731
NMIA	575.0	192.8	1.492
NMIJ/AIST	15.3	32.7	0.234
MSL			
MUSSD	-430.2	169.5	-1.269
SCL	261.3	351.8	0.371
NMIM	97.9	299.6	0.163
SNSU-BSN	156.7	214.0	0.366
CMS/ITRI	86.2	94.5	0.456

The internal and external standard deviation of the weighted mean calculated by equations (3) and (4) were 29.5 nm and 48.8 nm, respectively, resulting in R_B = 1.66. As $R_{B,\max} = 1.41$ for *l*=9 (see Table 11), $R_B > R_{B,\max}$, and thus the next outlier with biggest E_n value has to be additionally removed and KCRV recalculated.

7.1.2.6 KCRV for 500 mm long gauge block with results of NIM and NMIA excluded (3rd trial)

Since NMIA's $|E_n|$ value is the second largest, the result of NIM and NMIA are excluded and KCRV was recalculated using 8 laboratory's results. The KCRV became

$$\begin{aligned} KCRV(t) &= 5879.85\,\text{nm} - 0.13696\ \text{nm} \times t \\ &= -150.24\ \text{nm} - 0.13696\ \text{nm} \times (t - 44027.06) \end{aligned} \quad (22)$$

Figure 14 shows the measurement results of 500 mm block together with KCRV and its standard uncertainty, when the results of NIM and NMIA are excluded. In the figure, all uncertainties shown as bars or dotted lines correspond to standard uncertainty (*k*=1). Orange dots labelled as KRISS0 and KRISS1.5 are results of the pilot obtained with LMS, which are shown for reference only.

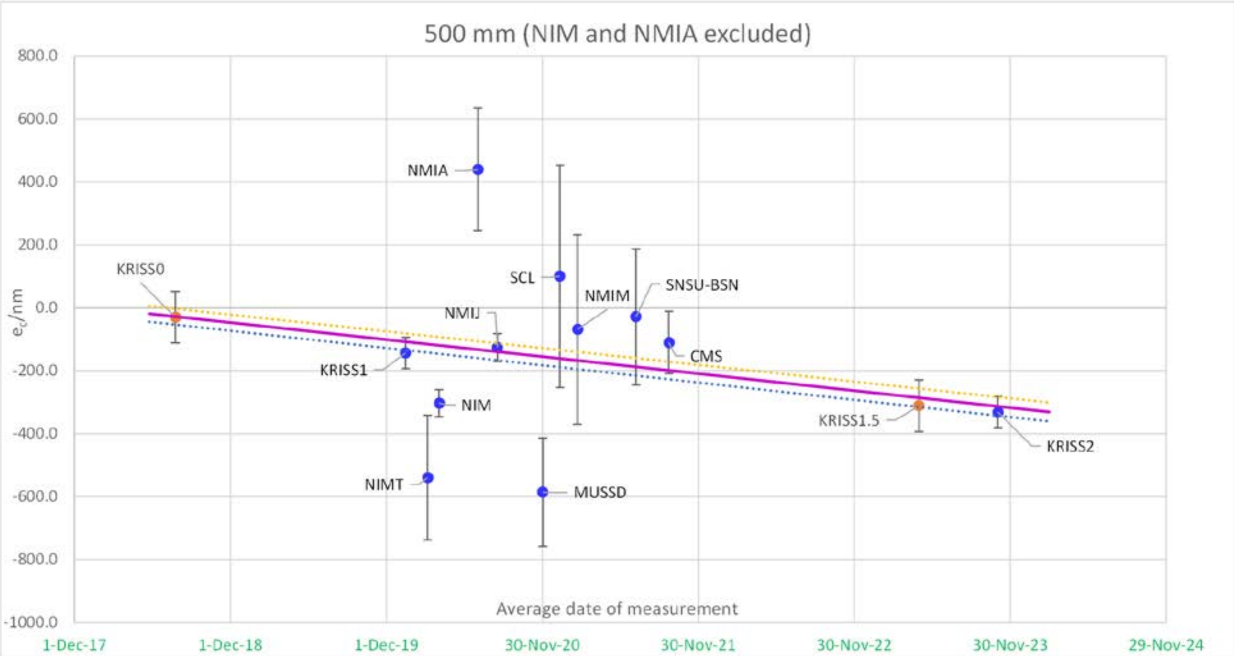


Figure 14. Measurement results and KCRV for 500 mm long gauge block (-results of NIM and NMIA excluded). Dotted lines represent the standard uncertainty of KCRV. Orange dots labeled as KRISS0 and KRISS1.5 are results of pilot obtained with LMS, but are not used for the KCRV calculation.

E_n values of the measurement results are shown in Table 20. When calculating E_n values of NIM and NMIA by equation (15), equation (18) was used for $u(D_i)$.

Table 20. E_n values for 500 mm long gauge block measurements when results of NIM and NMIA are excluded for KCRV calculation

NMI	D_i/nm	$u(D_i)$/nm	E_n
KRISS	-18.7	39.6	-0.236
NIMT	-407.7	195.7	-1.041
NIM	-167.0	52.3	-1.596
NMIA	588.5	197.3	1.492

NMIJ/AIST	28.8	32.4	0.444
MSL	-	-	-
MUSSD	-416.7	169.4	-1.230
SCL	274.7	351.7	0.391
NMIM	111.4	299.5	0.186
SNSU-BSN	170.1	213.9	0.398
CMS/ITRI	99.7	94.4	0.528

The internal and external standard deviation of the weighted mean calculated by equations (3) and (4) were 29.8 nm and 40.7 nm, respectively, resulting in $R_B = 1.37$. As $R_{B,\max} = 1.44$ for $I = 8$ (see Table 11), $R_B < R_{B,\max}$, which means that this set of data is statistically consistent. The final KCRV is thus the equation (22) for the 500 mm long gauge block.

7.2 Correlation between laboratories

The potential for correlations between the participants' measurement results was investigated.

In this KC, the measurement method for short gauge blocks was limited to optical interferometry. A correlation could exist if the light sources of the laser interferometers used by two NMIs had been calibrated by the same NMI. However, given that the contribution of the vacuum wavelength of each light source to the overall uncertainty is very small, the effect of such correlation can be regarded as negligible.

In contrast, for the long gauge blocks, the measurement method was not limited to optical interferometry, and each NMI was allowed to use the measurement method with the smallest uncertainty available to the NMI. Therefore, the possibilities for correlations are more diverse than in the case of the short gauge blocks. For example, if the reference long gauge block of an NMI that performed measurements using mechanical comparison method was calibrated by another NMI participating in this KC, the measurement results of the two NMIs would have a non-negligible correlation. Likewise, if the reference long gauge blocks of two or more NMIs were calibrated by another NMI that did not participate in this KC, the results of those NMIs would also be correlated.

Therefore, the calibration sources (NMIs) for the reference long gauge blocks used by participants who did not employ the LGBI were investigated, and the results are shown in Table 21.

Table 21. Traceability of reference long gauge blocks of each NMI

NMI	Source of traceability
NIMT	VTT MIKES
NMIA	NPL
MUSSD	PTB
SCL	NPL
NMIM	NMIJ/AIST
SNSU-BSN	NPL
CMS/ITRI	PTB

The possibility of correlation was examined in two cases.

First, since the reference LGBs of NMIM had been calibrated by NMIJ/AIST, the correlation between the results of NMIM and NMIJ/AIST was investigated. If such correlation existed, it would most likely be due to the influence of the thermometers, barometers, and hygrometers used for air refractive index measurement. Therefore, NMIJ/AIST was asked to confirm the calibration dates of these environmental instruments at the time of calibrating NMIM's reference LGBs and at the time of measuring LGBs of the key comparison. The confirmation revealed that the environmental instruments had been recalibrated once between the calibration date of NMIM's reference LGBs and the date of NMIJ's participation in the key comparison. It was therefore concluded that the results of the two NMIs were not correlated.

Second, attention was given to the fact that three NMIs (SCL, SNSU-BSN, and NMIA) had their reference LGBs calibrated by NPL (of the United Kingdom). Although NPL did not participate in this comparison, it was considered that the results of these three NMIs might be correlated. In this key comparison, SCL and SNSU-BSN both calibrated the LGBs using mechanical comparison method, so if the calibration date of their reference LGBs by NPL were close, their results could be correlated. In the case of NMIA, the situation was different, as NMIA used the interferometric comparison method, and used only one 100 mm gauge block for the reference. The pilot requested NPL to confirm the calibration dates of the reference LGBs for the three institutions, and it was confirmed that the reference LGBs of all three NMIs had been calibrated using different measuring systems (See Table 22). The PLBI, GBI and LBM are different instruments using different sensors. The only traceability relationship between them is that the LBM uses a length bar calibrated in the GBI for its traceability. However, NPL confirmed that between the NMIA calibration in the GBI and the recalibration of the length bar used in the LBM, the GBI was re-calibrated. This breaks the traceability link between the GBI and the LBM between the NMIA and SNSU-BSN calibrations. Thus, the two instruments were independent of each other at the times they performed the calibrations for NMIA and SNSI-BSN. Thus, although these 3 labs had their items calibrated at NPL, they were calibrated in 3 independent instruments which therefore had no correlated uncertainties.

Table 22. NPL's measurement system and calibration dates for the reference GBs of the 3 NMIs.

NMI	Identification of the measurement system	Calibration dates	Nominal length of calibrated artefacts
SCL	PLBI	15/08/2017 to 27/08/2017	125 mm - 500 mm
SNSU-BSN	LBM	27/07/2020 to 20/08/2020	125 mm - 500 mm
NMIA	GBI	15/05/2018 to 31/05/2018	0.5 mm - 100 mm

It may be noted from Table 21 that the reference LGBs of both MUSSD and CMS/ITRI were calibrated by PTB. For MUSSD, the mechanical comparison method was used, with PTB-calibrated long gauge blocks of the same nominal length as those under calibration serving as references. In contrast, CMS/ITRI employed the interferometric comparison method, using a single 100 mm gauge block calibrated by PTB to establish a reference point. Communication with PTB confirmed that the short gauge block of CMS/ITRI had been calibrated using a short gauge block interferometer, while the two long gauge blocks of MUSSD were calibrated using a mechanical comparator. As completely different measurement systems were involved, the two calibration results can be regarded as having negligible correlation.

In conclusion, there is no significant correlation among the measurement results of any of the NMIs participating in this key comparison.

7.3 Linking of results to other comparison

To link results of this key comparison to other comparison, two candidate KCs might be considered: CCL-K1.2011 or CCL-K1.n01.

In CCL-K1.2011, 3 NMIs (NIM, NMIJ/AIST and NMC, A*STAR) from APMP had participated. However, NMC, A*STAR did not participate in APMP.L-K1.n01, and thus only NIM and NMIJ/AIST can be the linking labs. Considering that NIM's results are outliers in case of long gauge blocks of this comparison, only NMIJ/AIST could link results of the two comparisons in the case of long gauge blocks.

On the other hand, CCL-K1.n01 is not yet finished, and only has two NMIs (NIM and NMC, A*STAR) from APMP. Among these two, NMC,A*STAR did not participate in APMP.L-K1.n01, and due to NIM's issue on long gauge block results mentioned above, it would not be possible to link results of APMP.L-K1.n01 to CCL-K1.n01.

In conclusion, this comparison can only be linked to CCL-K1.2011 via NMIJ/AIST and NIM, although the long gauge block results can be linked by NMIJ/AIST only.

8 Conclusion

A total of twenty gauge blocks were circulated in this key comparison: 9 short steel gauge blocks, 9 short tungsten carbide gauge blocks, and 2 long steel gauge blocks.

In contrast to short gauge blocks, for which only optical interferometry was permitted, long gauge blocks could be measured by whichever method offered the smallest measurement uncertainty in the respective laboratory. In practice, three types of methods were employed: optical interferometry (- excess fraction method -), interferometric comparison, and mechanical comparison (using a long gauge block comparator or a universal measuring machine).

The temporal drift of each long gauge block length was taken into account in determining the KCRV, with each KCRV expressed as a function of time. Nevertheless, the observed drift rates were within the permissible limits for grade K or grade 0 gauge blocks specified in the international standard ISO 3650:1988.

For all 18 short gauge blocks, the participants' results showed |En| < 1, indicating that the measurement results were mutually comparable and consistent.

For the long gauge blocks, however, the results from two laboratories had to be excluded in calculating the KCRVs. The |En| values of four laboratories were found to be greater than 1, although for one of them the values were only slightly above the threshold (1.07 and 1.05, for the 400 mm and 500 mm blocks, respectively).

The results of this comparison can be used to support existing CMCs or future CMC submissions. Laboratories whose long gauge block measurement results were unsatisfactory should identify the root cause of the discrepancies and take corrective action, or otherwise revise their CMCs upward.

9 References

[1] ISO 3650:1998, "Geometrical Product Specifications (GPS) — Length standards — Gauge blocks".

[2] Nien Fan Zhang et al., "Statistical analysis of key comparisons with linear trends," Metrologia **41** 231 -237 (2004).

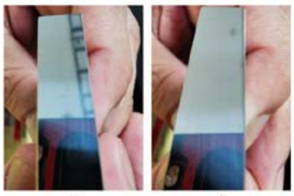
Appendix A – Document additionally circulated after receiving report from NIMT

1

Important Notice on the APMP.L-K1.2018

(Chu-Shik Kang, April 15, 2020)

Please note that the long gauge block of nominal length 400 mm has an indentation at the central point of each measuring face, due to some unexpected accident during the comparison. The photos of the measuring faces are shown in Fig. 1. and the interference fringes obtained from a flatness interferometer are shown in Fig. 2.



(a) (b)

Fig. 1 Photos of measuring faces of the 400 mm long gauge block. (a) left measuring face (b) right measuring face. (Photos provided by NIMT)

(a) (b)

Fig. 2 Interference fringes of measuring faces of the 400 mm long gauge block obtained by a flatness interferometer: (a) left measuring face (b) right measuring face. (Photos by NIMT)

2

When an indentation is made, it is likely that there would be a burr around the hole (see Fig. 3(a)) which might damage the surface of a platen (or base plate) during the wringing process.

So, the pilot asked NIM to remove the burrs by exceptionally allowing the deburring. Please note that all other NMIs are not allowed to perform a deburring as specified in the technical protocol.

(a) Burr on measuring face (b) Deburred measuring face

Fig. 3 Schematic of the surface before and after the deburring process

As the measuring face after the deburring is expected have a dip as shown in Fig. 3(b), measuring the central length of this long gauge block by using routine calibration method might result in negative measurement error, referencing to the measured value obtained before the accident.

Although it may be ideal to replace the damaged gauge block with a different one, as it is practically impossible to do so during the intercomparison, the pilot of the APMP.L-K1.2018 decided through discussion with Dr. Andrew Lewis, the moderator of CCL Discussion Group 1 (gauge block), that the participant should decide one of the following three options for the measurement of the 400 mm long gauge block:

1. If the participant's instrument allows to measure length at 'non-central point' which is near the central point, the central length is to be measured 'indirectly' using extrapolation. That is, the length at the 'non-central point' is measured first, and then the extrapolated central length is found by applying a correction for the flatness/parallelism (see Fig. 4).
2. If the participant's instrument doesn't allow to measure at 'non-central point', then just measure using the normal way keeping in mind that the uncertainty might increase for this measurement.
3. If it is usual to reject the measurement when indentations are found at the central points of the measuring faces in the routine calibration of long gauge blocks, then the participant may decide not to measure this gauge block.

3

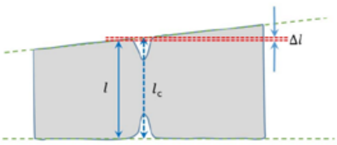


Fig. 4 Indirect measurement of extrapolated central length ($l_c = l + \Delta l$) where l, l_c and Δl denote non-central length, extrapolated central length, and correction for flatness/parallelism, respectively.

In either case, please fill in and submit the Table entitled "Detailed information on the measurement of 400 mm long gauge block" given in the Appendix when you submit the Measurement Report.

[End of document]

4

Appendix

Table: Detailed information for the measurement of 400 mm long gauge block

Measurement method used for the 400 mm gauge block	**(Mark 'O')**
optical interferometry	
mechanical comparison	
interferometric comparison	
other method (please describe):	
this long gauge block was rejected and not measured	
Availability of non-central length measurement	**(Mark 'O')**
instrument used allowed measuring non-central lengths	
instrument used only allows measuring central lengths	
Measured position	**(Mark 'O')**
central point (direct measurement)	
non-central point (indirect measurement)	
In case of indirect measurement	**(Enter value)**
distance of measuring point from central point:	
length at non-central point:	
correction value for flatness/parallelism:	
(indirectly measured) central length:	

Date: ______________________________

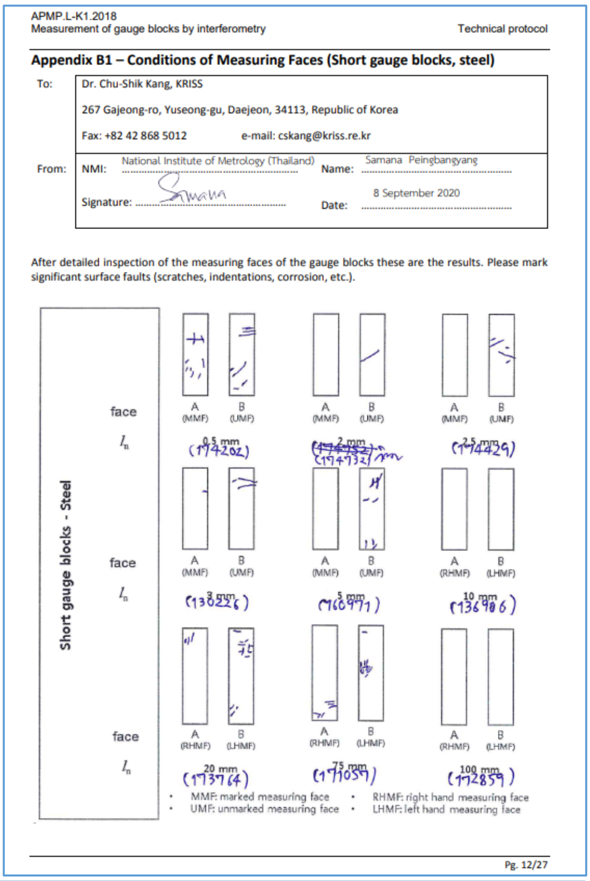
NMI: ______________________________

Name: ______________________________

Signature: ______________________________

Appendix B – Surface inspection results of participants

1. NIMT

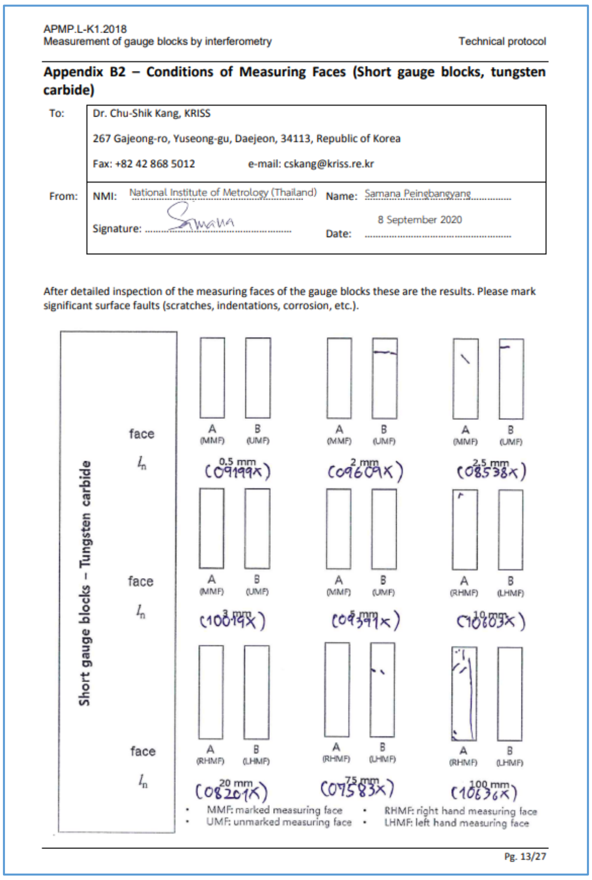

APMP.L-K1.2018
Measurement of gauge blocks by interferometry — Technical protocol

Appendix B1 – Conditions of Measuring Faces (Short gauge blocks, steel)

To:	Dr. Chu-Shik Kang, KRISS 267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr
From:	NMI: National Institute of Metrology (Thailand) Name: Samana Peingbangyang Signature: Samana Date: 8 September 2020

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

Pg. 12/27

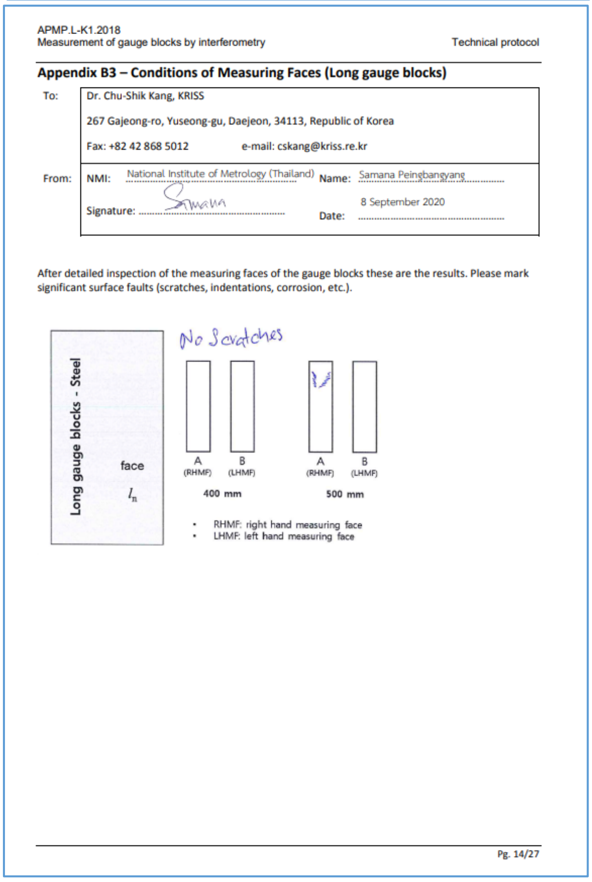

APMP.L-K1.2018
Measurement of gauge blocks by interferometry — Technical protocol

Appendix B2 – Conditions of Measuring Faces (Short gauge blocks, tungsten carbide)

To:	Dr. Chu-Shik Kang, KRISS 267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr
From:	NMI: National Institute of Metrology (Thailand) Name: Samana Peingbangyang Signature: Samana Date: 8 September 2020

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

Pg. 13/27

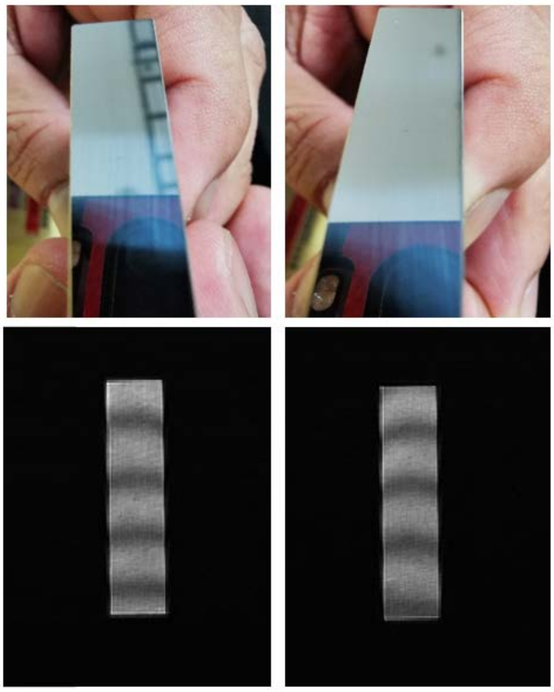

APMP.L-K1.2018
Measurement of gauge blocks by interferometry — Technical protocol

Appendix B3 – Conditions of Measuring Faces (Long gauge blocks)

To:	Dr. Chu-Shik Kang, KRISS 267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr
From:	NMI: National Institute of Metrology (Thailand) Name: Samana Peingbangyang Signature: Samana Date: 8 September 2020

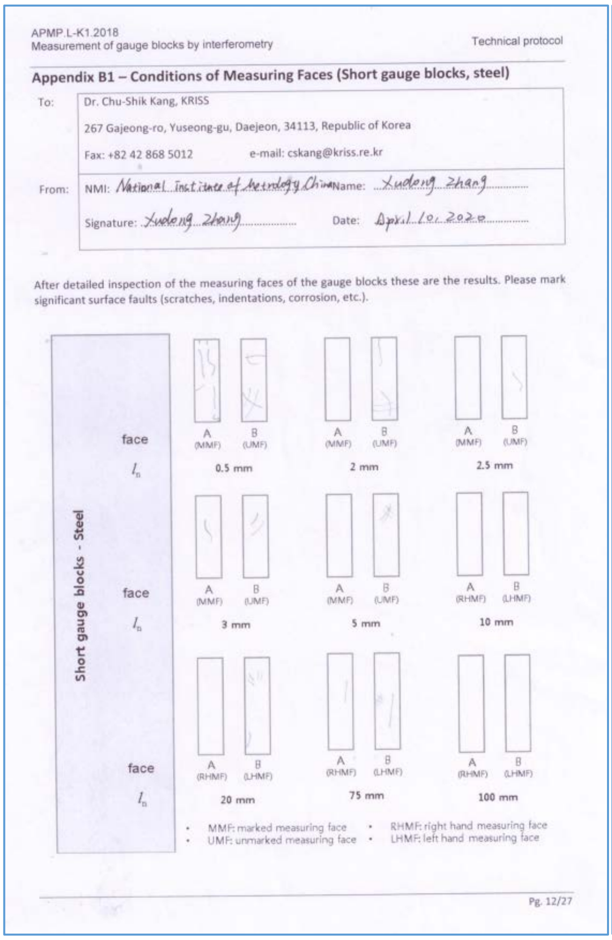
After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

Pg. 14/27



400 mm left 400 mm right

2. NIM

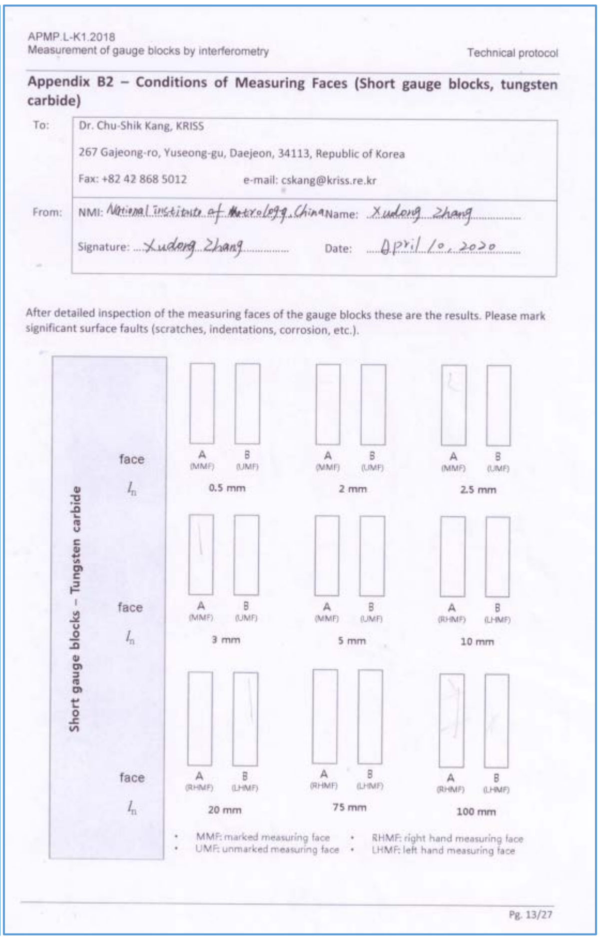

APMP.L-K1.2018
Measurement of gauge blocks by interferometry
Technical protocol

Appendix B1 – Conditions of Measuring Faces (Short gauge blocks, steel)

To: Dr. Chu-Shik Kang, KRISS
267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea
Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr

From: NMI: National Institute of Metrology China Name: Xudong Zhang
Signature: Xudong Zhang Date: April 10, 2020

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

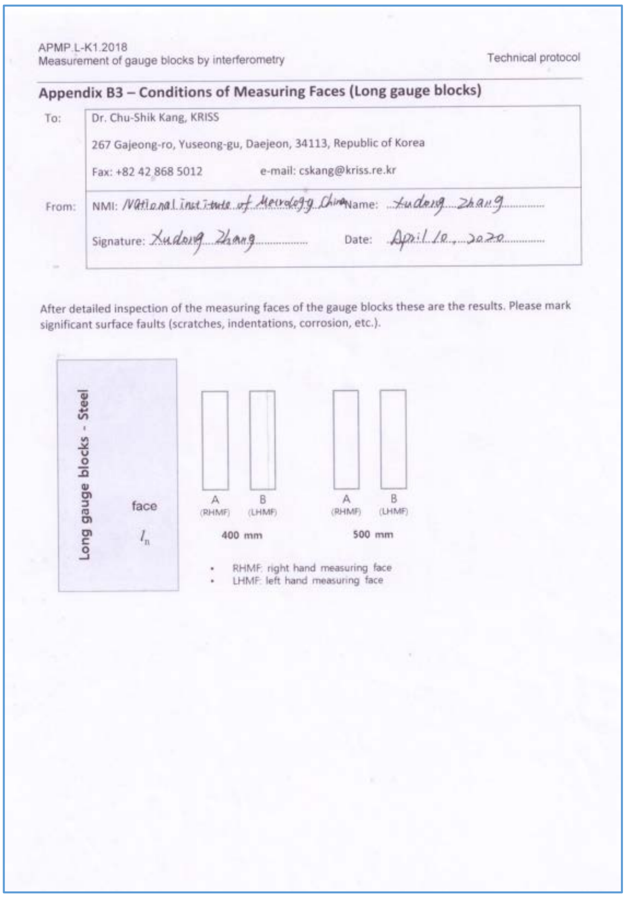

APMP.L-K1.2018
Measurement of gauge blocks by interferometry
Technical protocol

Appendix B2 – Conditions of Measuring Faces (Short gauge blocks, tungsten carbide)

To: Dr. Chu-Shik Kang, KRISS
267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea
Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr

From: NMI: National Institute of Metrology, China Name: Xudong Zhang
Signature: Xudong Zhang Date: April 10, 2020

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).


APMP.L-K1.2018
Measurement of gauge blocks by interferometry
Technical protocol

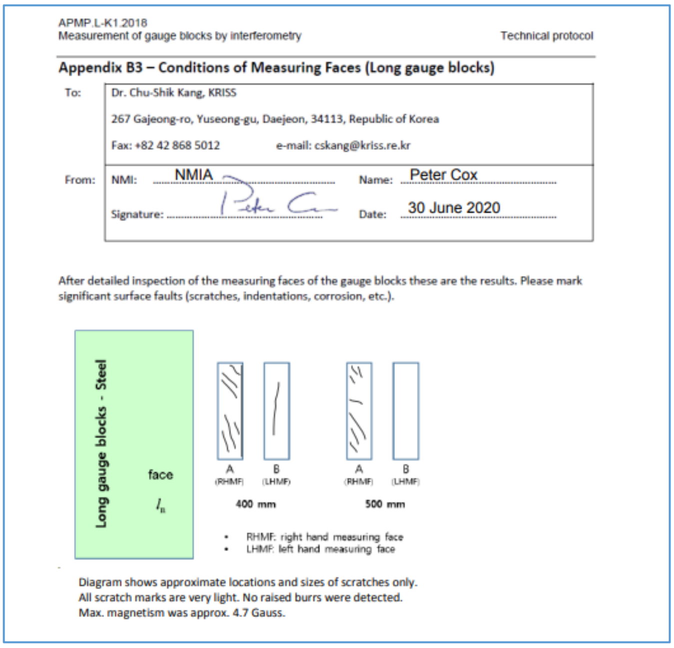
Appendix B3 – Conditions of Measuring Faces (Long gauge blocks)

To: Dr. Chu-Shik Kang, KRISS
267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea
Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr

From: NMI: National Institute of Metrology China Name: Xudong Zhang
Signature: Xudong Zhang Date: April 10, 2020

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

3. NMIA



APMP.L-K1.2018
Measurement of gauge blocks by interferometry Technical protocol

Appendix B3 – Conditions of Measuring Faces (Long gauge blocks)

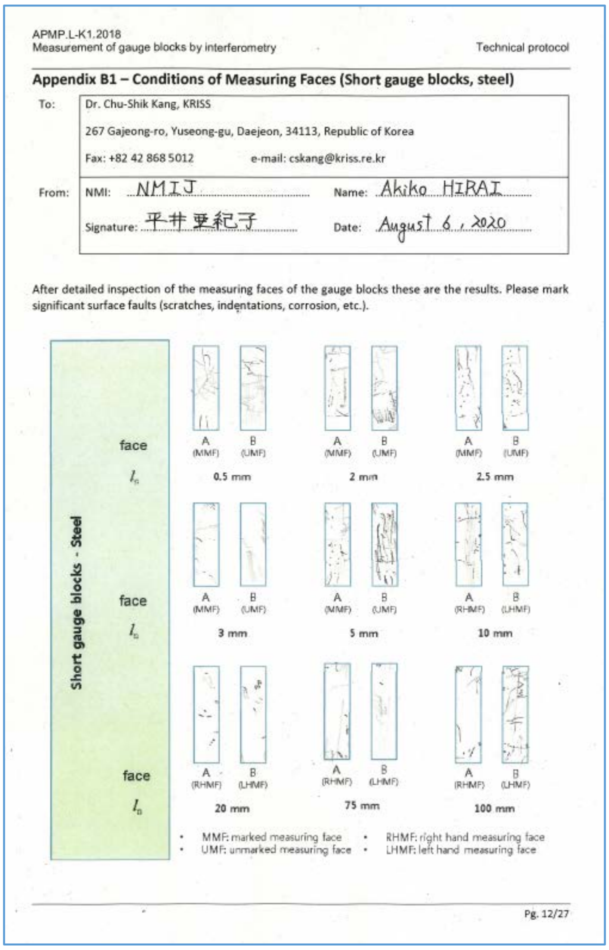
To: Dr. Chu-Shik Kang, KRISS
267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea
Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr

From: NMI: NMIA Name: Peter Cox
Signature: Peter Cox Date: 30 June 2020

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

Diagram shows approximate locations and sizes of scratches only.
All scratch marks are very light. No raised burrs were detected.
Max. magnetism was approx. 4.7 Gauss.

4. NMIJ/AIST



APMP.L-K1.2018
Measurement of gauge blocks by interferometry Technical protocol

Appendix B1 – Conditions of Measuring Faces (Short gauge blocks, steel)

To: Dr. Chu-Shik Kang, KRISS
267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea
Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr

From: NMI: NMIJ Name: Akiko HIRAI
Signature: 平井 亜紀子 Date: August 6, 2020

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

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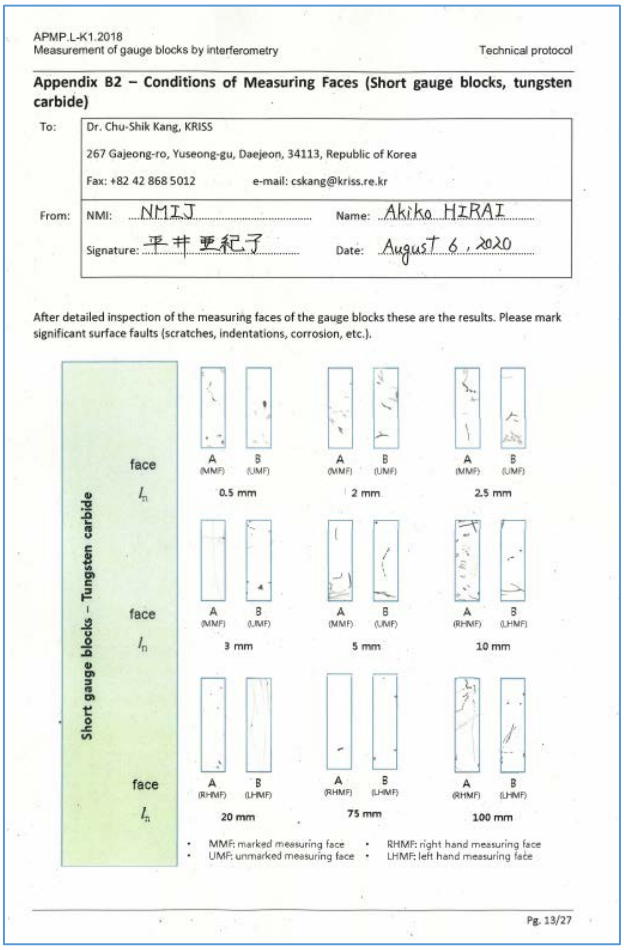

APMP.L-K1.2018
Measurement of gauge blocks by interferometry Technical protocol

Appendix B2 – Conditions of Measuring Faces (Short gauge blocks, tungsten carbide)

To: Dr. Chu-Shik Kang, KRISS
267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea
Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr

From: NMI: NMIJ Name: Akiko HIRAI
Signature: 平井 亜紀子 Date: August 6, 2020

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

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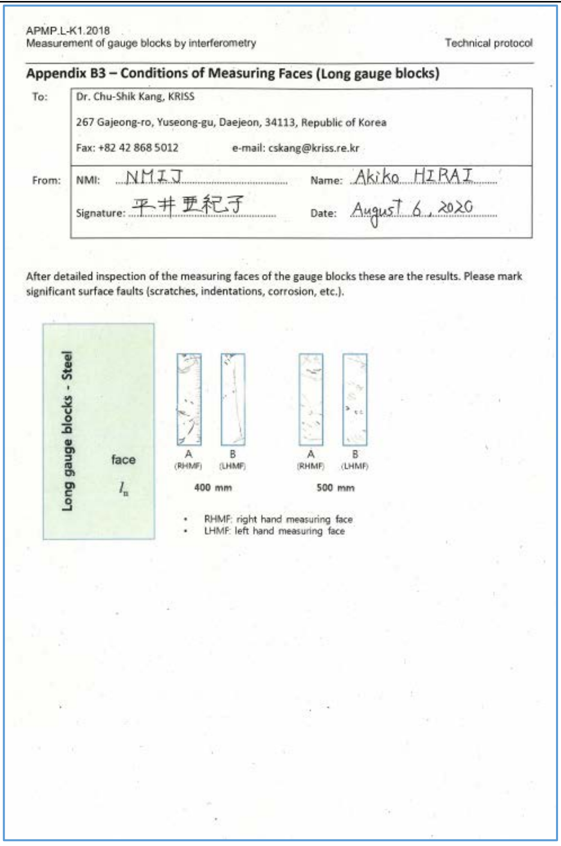
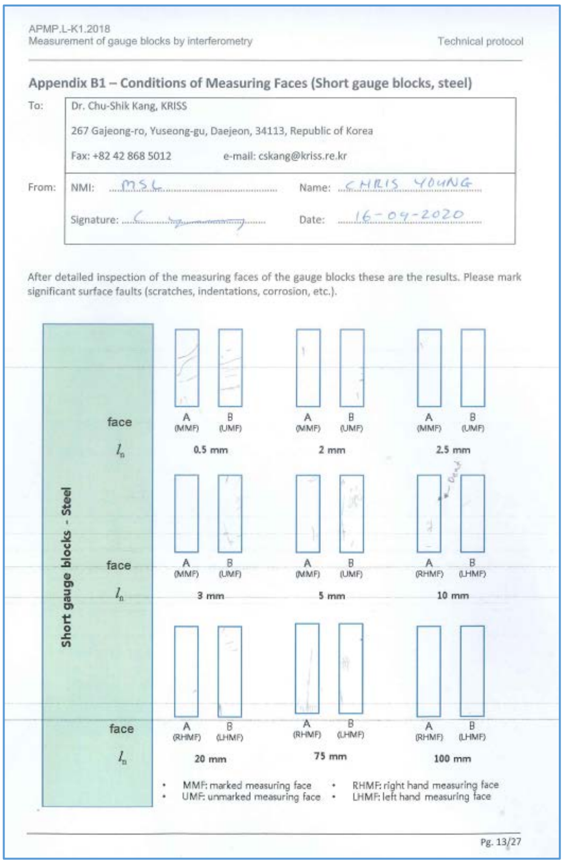

APMP.L-K1.2018
Measurement of gauge blocks by interferometry — Technical protocol

Appendix B3 – Conditions of Measuring Faces (Long gauge blocks)

To:	Dr. Chu-Shik Kang, KRISS 267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr	
From:	NMI: NMIJ Signature: 平井亜紀子	Name: Akiko HIRAI Date: August 6, 2020

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

5. MSL


APMP.L-K1.2018
Measurement of gauge blocks by interferometry — Technical protocol

Appendix B1 – Conditions of Measuring Faces (Short gauge blocks, steel)

To:	Dr. Chu-Shik Kang, KRISS 267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr	
From:	NMI: MSL Signature:	Name: CHRIS YOUNG Date: 16-09-2020

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

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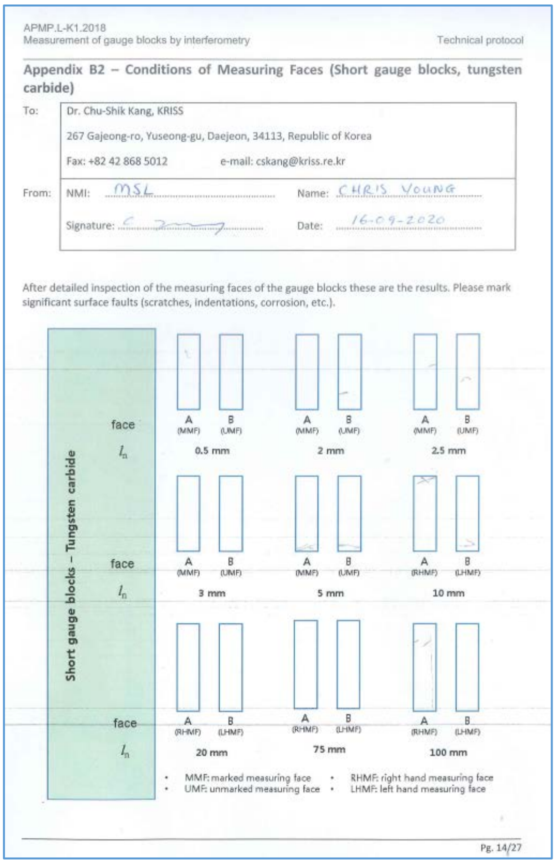

APMP.L-K1.2018
Measurement of gauge blocks by interferometry — Technical protocol

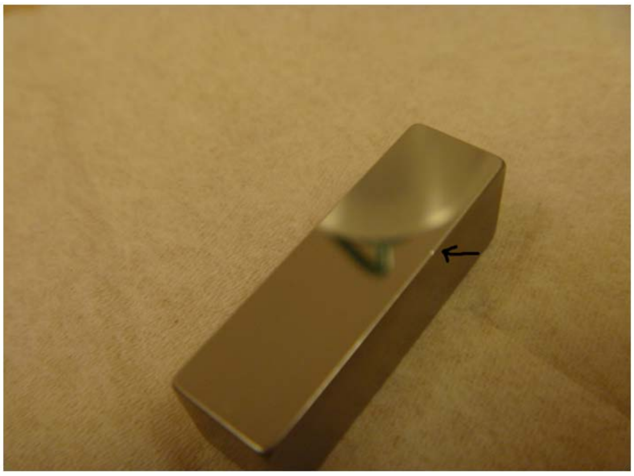
Appendix B2 – Conditions of Measuring Faces (Short gauge blocks, tungsten carbide)

To:	Dr. Chu-Shik Kang, KRISS 267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr	
From:	NMI: MSL Signature:	Name: CHRIS YOUNG Date: 16-09-2020

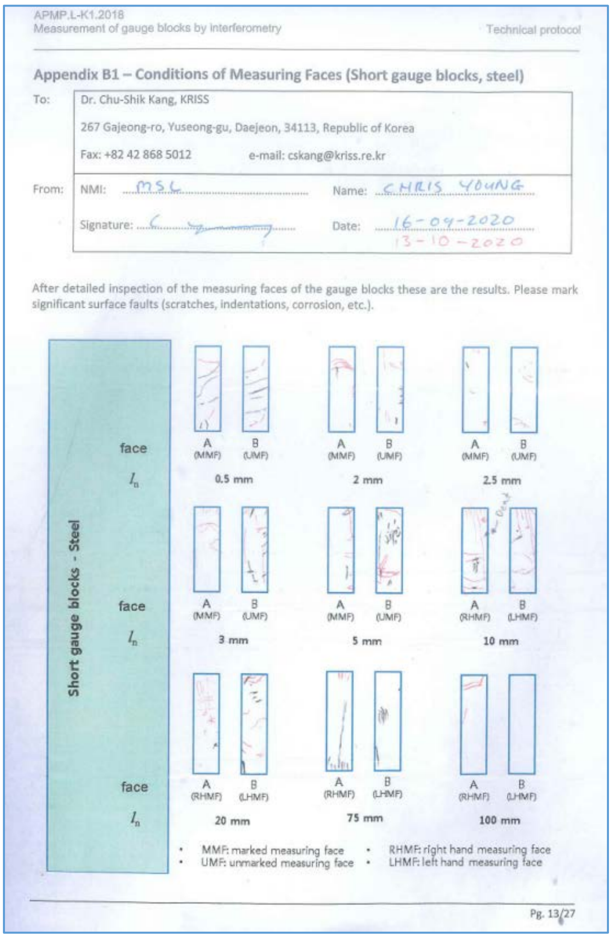
After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

Pg. 14/27

(Before measurement)



10 mm steel gauge block side A



APMP.L-K1.2018
Measurement of gauge blocks by interferometry

Technical protocol

Appendix B1 – Conditions of Measuring Faces (Short gauge blocks, steel)

To: Dr. Chu-Shik Kang, KRISS
267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea
Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr

From: NMI: MSL Name: CHRIS YOUNG
Signature: Date: 16-09-2020 / 13-10-2020

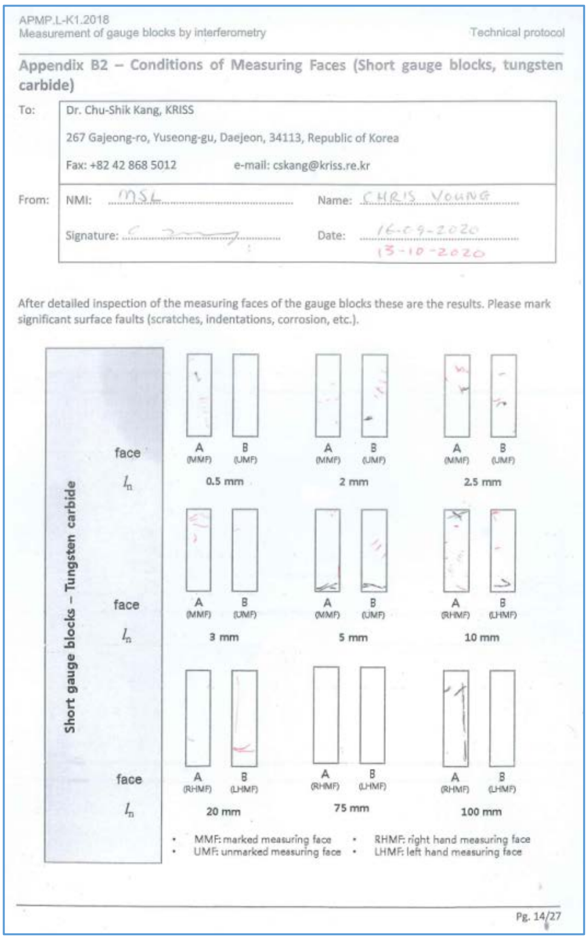
After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

Short gauge blocks – Steel

face l_n	A (MMF) B (UMF) 0.5 mm	A (MMF) B (UMF) 2 mm	A (MMF) B (UMF) 2.5 mm
face l_n	A (MMF) B (UMF) 3 mm	A (MMF) B (UMF) 5 mm	A (RHMF) B (LHMF) 10 mm
face l_n	A (RHMF) B (LHMF) 20 mm	A (RHMF) B (LHMF) 75 mm	A (RHMF) B (LHMF) 100 mm

- MMF: marked measuring face
- UMF: unmarked measuring face
- RHMF: right hand measuring face
- LHMF: left hand measuring face

Pg. 13/27



APMP.L-K1.2018
Measurement of gauge blocks by interferometry

Technical protocol

Appendix B2 – Conditions of Measuring Faces (Short gauge blocks, tungsten carbide)

To: Dr. Chu-Shik Kang, KRISS
267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea
Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr

From: NMI: MSL Name: CHRIS YOUNG
Signature: Date: 16-09-2020 / 13-10-2020

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

Short gauge blocks – Tungsten carbide

face l_n	A (MMF) B (UMF) 0.5 mm	A (MMF) B (UMF) 2 mm	A (MMF) B (UMF) 2.5 mm
face l_n	A (MMF) B (UMF) 3 mm	A (MMF) B (UMF) 5 mm	A (RHMF) B (LHMF) 10 mm
face l_n	A (RHMF) B (LHMF) 20 mm	A (RHMF) B (LHMF) 75 mm	A (RHMF) B (LHMF) 100 mm

- MMF: marked measuring face
- UMF: unmarked measuring face
- RHMF: right hand measuring face
- LHMF: left hand measuring face

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(After measurement)

6. MUSSD

APMP.L-K1.2018
Measurement of gauge blocks by interferometry

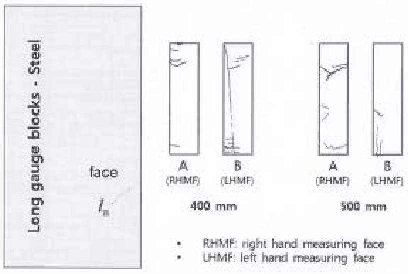
Technical protocol

Appendix B3 – Conditions of Measuring Faces (Long gauge blocks)

To: Dr. Chu-Shik Kang, KRISS
267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea
Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr

From: NMI: MUSSD - Sri Lanka Name: A. D. D. Naminda
Signature: [signature] Date: 2020 November 13

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).



7.. SCL

APMP.L-K1.2018
Measurement of gauge blocks by interferometry

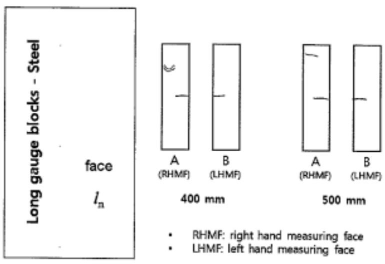
Technical protocol

Appendix B3 – Conditions of Measuring Faces (Long gauge blocks)

To: Dr. Chu-Shik Kang, KRISS
267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea
Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr

From: NMI: Standards & Calibration Laboratory Name: George Tang
Signature: [signature] Date: 21st December 2020

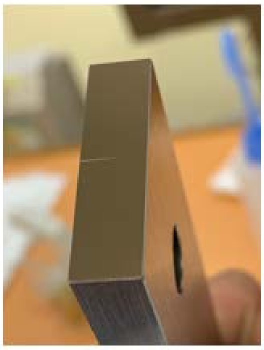
After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).



*Note from SCL:

The horizontal scratches were found from the the center of all 4 measuring faces all the way to the back face (opposite to the front face where make and S/N were found). Refer to photo attachments for details.

Other scratches were relatively minor compared to those horizontal scratches.


400 mm left


400 mm right


500 mm left


500 mm right

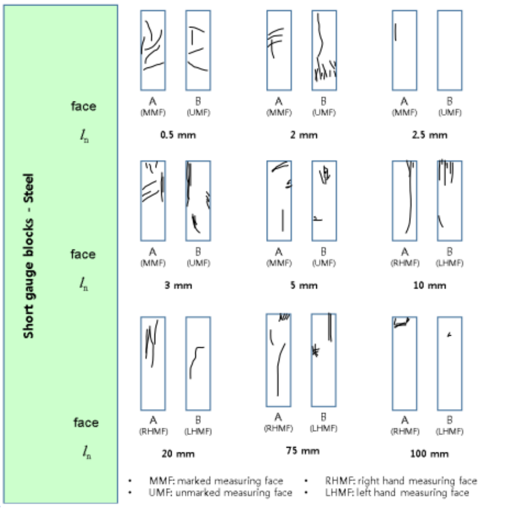
8. NMIM

APMP.L-K1.2018
Measurement of gauge blocks by interferometry — Technical protocol

Appendix B1 – Conditions of Measuring Faces (Short gauge blocks, steel)

To:	Dr. Chu-Shik Kang, KRISS 267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr	
From:	NMI: National Metrology Institute of Malaysia	Name: Razman Mohd Halim
	Signature: razman	Date: 25 January 2021

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).



- MMF: marked measuring face
- UMF: unmarked measuring face
- RHMF: right hand measuring face
- LHMF: left hand measuring face

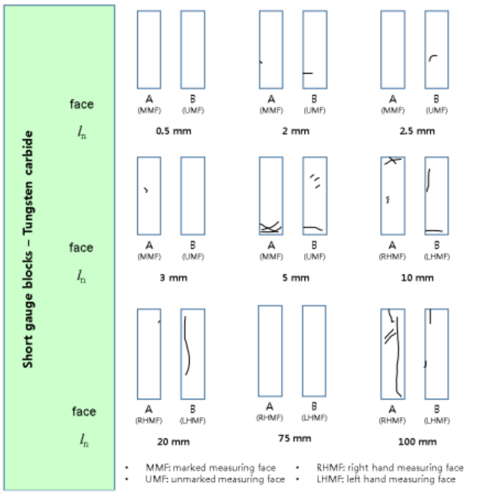
Pg. 12/27

APMP.L-K1.2018
Measurement of gauge blocks by interferometry — Technical protocol

Appendix B2 – Conditions of Measuring Faces (Short gauge blocks, tungsten carbide)

To:	Dr. Chu-Shik Kang, KRISS 267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr	
From:	NMI: National Metrology Institute of Malaysia	Name: Razman Mohd Halim
	Signature: razman	Date: 25 January 2021

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).



- MMF: marked measuring face
- UMF: unmarked measuring face
- RHMF: right hand measuring face
- LHMF: left hand measuring face

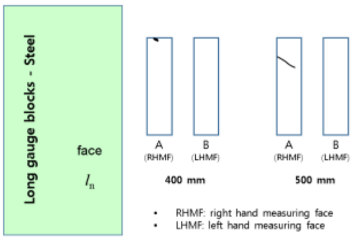
Pg. 13/27

APMP.L-K1.2018
Measurement of gauge blocks by interferometry — Technical protocol

Appendix B3 – Conditions of Measuring Faces (Long gauge blocks)

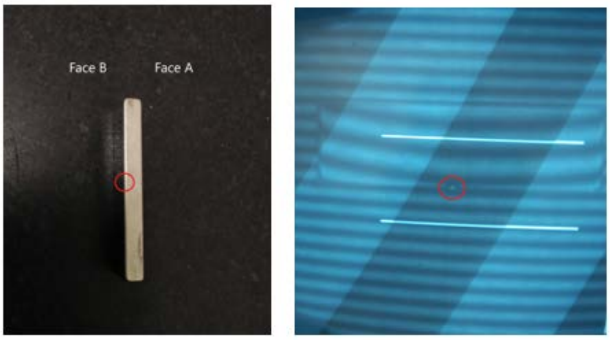
To:	Dr. Chu-Shik Kang, KRISS 267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr	
From:	NMI: National Metrology Institute of Malaysia	Name: Razman Mohd Halim
	Signature: razman	Date: 25 January 2021

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

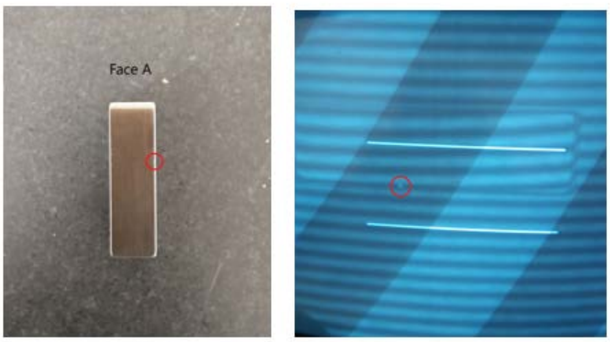


- RHMF: right hand measuring face
- LHMF: left hand measuring face

Pg. 14/27

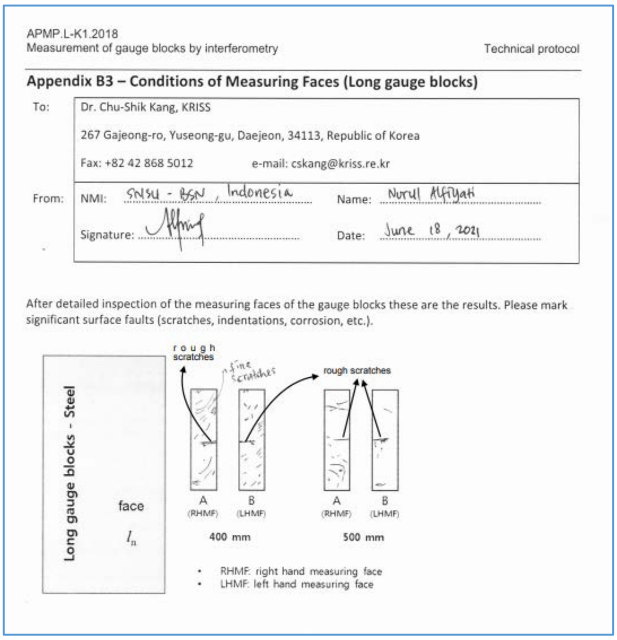


3 mm steel gauge block



10 mm steel gauge block

9.. SNSU-BSN


APMP.L-K1.2018
Measurement of gauge blocks by interferometry

Technical protocol

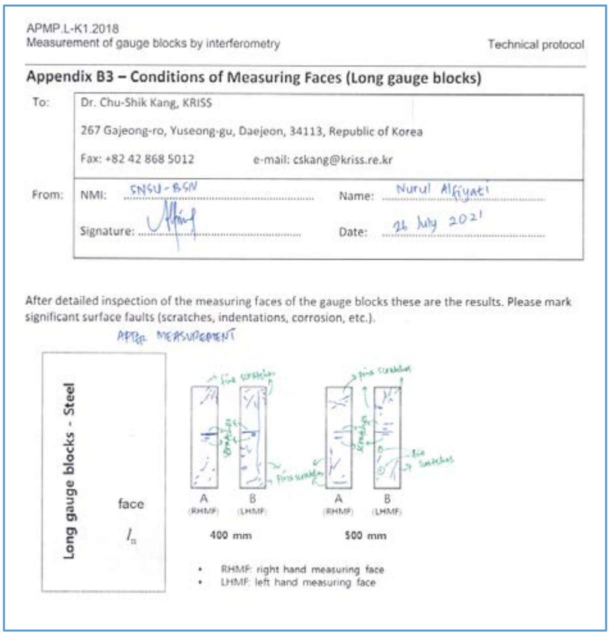
Appendix B3 – Conditions of Measuring Faces (Long gauge blocks)

To:	Dr. Chu-Shik Kang, KRISS 267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr
From:	NMI: SNSU - BSN, Indonesia Name: Nurul Alfiyati Signature: [signature] Date: June 18, 2021

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

- RHMF: right hand measuring face
- LHMF: left hand measuring face

(Before measurement)


APMP.L-K1.2018
Measurement of gauge blocks by interferometry

Technical protocol

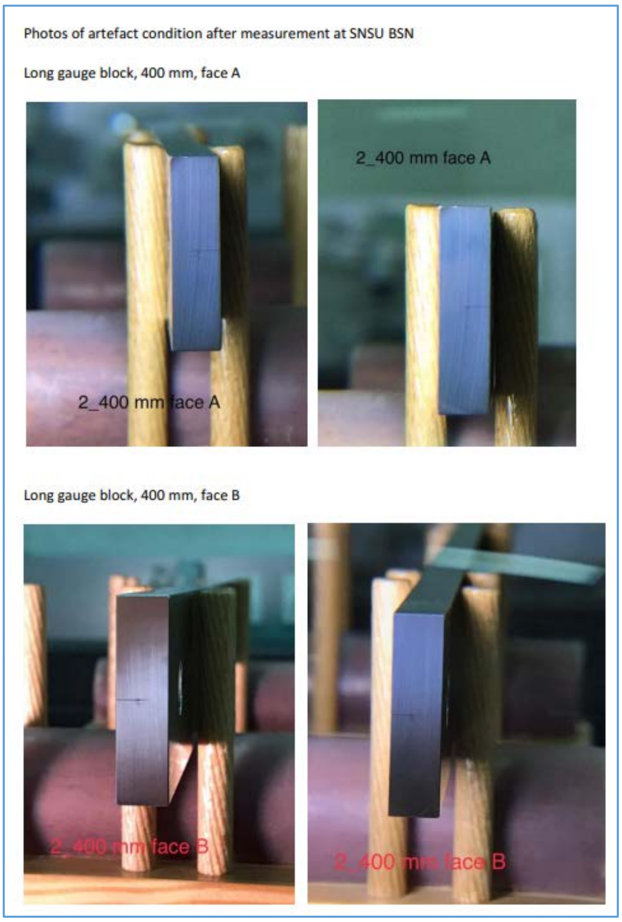
Appendix B3 – Conditions of Measuring Faces (Long gauge blocks)

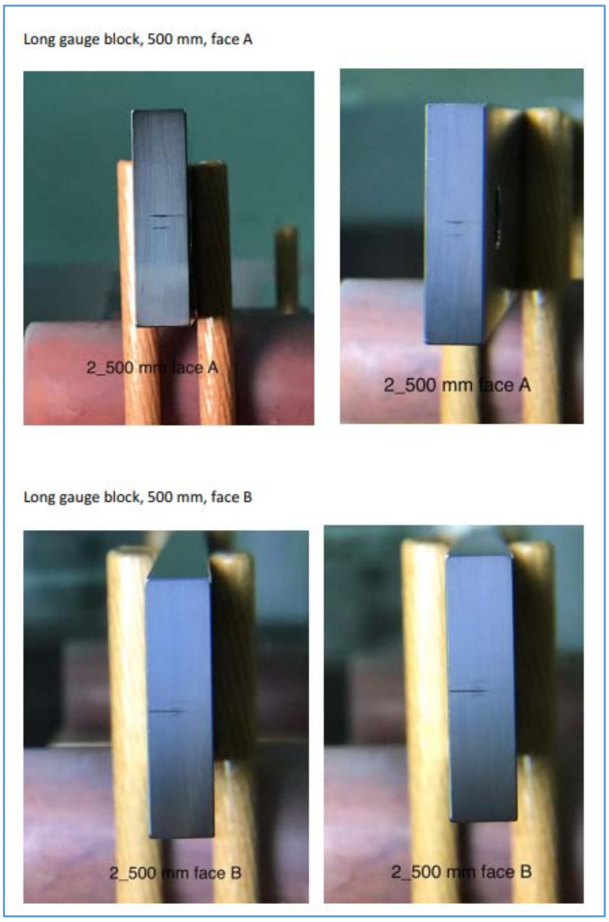
To:	Dr. Chu-Shik Kang, KRISS 267 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea Fax: +82 42 868 5012 e-mail: cskang@kriss.re.kr
From:	NMI: SNSU - BSN Name: Nurul Alfiyati Signature: [signature] Date: 26 July 2021

After detailed inspection of the measuring faces of the gauge blocks these are the results. Please mark significant surface faults (scratches, indentations, corrosion, etc.).

- RHMF: right hand measuring face
- LHMF: left hand measuring face

(After measurement)





10. CMS/TRI

Only photos were submitted without the filled form.

Appendix C – Uncertainty budgets reported by the participants

C1. Uncertainty budgets for short gauge block calibration

1. KRISS

Measurement Function (mathematical model of measurement):

$$e = L - L_0$$
$$= \left\{ \frac{\lambda}{2}(m+F) - L_0(n-1) - L_0\alpha(t_{GB} - 20) + l_\phi + l_w + l_E + l_A + l_{ob} + l_G \right\} - L_0$$

Definition of variables in the measurement function:

e: deviation of central length from nominal length
L: central length of gauge block
L_0: nominal length of gauge block
λ: vacuum wavelength of red laser
m: integral part of the interference order
F: fractional part of the interference order
n: refractive index of air
α: thermal expansion coefficient of gauge block
t_{GB}: temperature of gauge block
l_ϕ: phase correction
l_w: correction for wringing layer
l_E: correction for aberration of optics
l_A: correction for aperture effect
l_{ob}: correction for obliquity effect
l_G: correction for geometrical effect (non-central positioning)

Uncertainty budget for Steel gauge blocks

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i	degrees of freedom ν_i
λ	5.82E-09 $\times\lambda$	L_0/λ	Normal	5.82E-09 L_0	∞
m	0	-	-	0.0 nm	-
F	0.009	316.5 nm	t	3.0 nm	11
n	2.27E-08	L_0	Normal	2.27E-08 L_0	∞
α	5.77E-07 /℃	0.09 ℃ $\times L_0$	Rectangular	5.20E-08 L_0	50
t_{GB}	4.9E-03 ℃	-10.8E-06/℃ L_0	Normal	5.30E-08 L_0	∞
l_ϕ	4.6 nm	1	Rectangular	4.6 nm	50
l_W	4.9 nm	1	Rectangular	4.9 nm	50
l_E	9.9 nm	1	Rectangular	9.9 nm	∞
l_A	1.13E-10$\times L_0$	1	Trapezoidal	1.13E-02 nm	50
D	2886.8 nm	3.95E-14/nm$\times L_0$	Rectangular	-	50
f	288675.1 nm	4.90E-18/nm$\times L_0$	Rectangular	-	50
l_{ob}	3.73E-08	L_0	Rectangular	3.73E-08 L_0	50
l_G	3.2 nm	1	Rectangular	3.2 nm	50
2^{nd} order term (α)	2.83E-09	L_0	-	2.83E-09 L_0	-
combined standard uncertainty (k = 1) u_c = Q[12.8, 0.086 L_0] nm (L_0 in mm) or u_c =Q[12.8 nm, 0.086$\times10^{-6}$ L_0]					ν_{eff} > 890

Uncertainty budget for Tungsten carbide gauge blocks

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i	degrees of freedom ν_i
λ	5.82E-09 $\times\lambda$	L_0/λ	Normal	5.82E-09 L_0	∞
m	0	-	-	0.0 nm	-
F	0.009	316.5 nm	t	3.0 nm	11
n	2.27E-08	L_0	Normal	2.27E-08 L_0	∞
α	5.77E-07 /℃	0.09 ℃ × L_0	Rectangular	5.20E-08 L_0	50
t_{GB}	4.9E-03 ℃	-4.5E-06/℃ L_0	Normal	2.21E-08 L_0	∞
l_ϕ	4.6 nm	1	Rectangular	4.6 nm	50
l_W	4.9 nm	1	Rectangular	4.9 nm	50
l_E	9.9 nm	1	Rectangular	9.9 nm	∞
l_A	1.13E-10× L_0	1	Trapezoidal	1.13E-02 nm	50
D	2886.8 nm	3.95E-14/nm×L_0	Rectangular	-	50
f	288675.1 nm	4.90E-18/nm×L_0	Rectangular	-	50
l_{ob}	3.73E-08	L_0	Rectangular	3.73E-08 L_0	50
l_G	3.2 nm	1	Rectangular	3.2 nm	50
2nd order term (α)	2.83E-09	L_0	-	2.83E-09 L_0	-
combined standard uncertainty (k = 1) u_c = Q[12.8, 0.072 L_0] nm (L_0 in mm) or u_c =Q[12.8 nm, 0.072×10^{-6} L_0]					ν_{eff} > 890

2. NIMT

Measurement Function (mathematical model of measurement):

$$d = l - L$$
$$d = l_{fit} - L + l_t + l_w + l_A + l_\Omega + l_n + l_G + l_\Phi + l_F + l_R$$

Definition of variables in the measurement function:

d : deviation from nominal length of the gauge block

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

$l_{fit} = \frac{\lambda}{2}(N+\varepsilon)$: the best-fit solution for gauge block length, base on the method of exact fraction for wavelengths of light

L : nominal length of the gauge block

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

ε : fractional part of fringe order

λ : vacuum wavelengths of the different light sources used

$l_t = \theta\alpha L$: the gauge temperature correction. This correction arises from the gauge block temperature offset $\theta = 20 - t_g$, where t_g is the gauge block temperature in degrees Ceclius and 20 ^{0}C is the ISO 1 standard reference temperature for dimensional measurements

α : linear coefficient of thermal expansion of the gauge block

l_w : the length attributed to the wringing influence

l_A : the correction for wavefront errors as a result of imperfect interferometer optics

l_Ω : the obliquity correction is a length correction accounting for the shift in phase resulting from the optical design and alignment properties inherent in the interferometer

l_n : the refractive index correction is $l_n=(n-1)L$ where n is the refractive index of air evaluated using a modified version of the Edlen equation

l_G : the gauge block geometry correction accounts for non-flatness and non-parallelism of the gauge block

$l_\phi = \frac{1}{n-1}\left(l_p - \sum_{i=1}^{n} l_i\right)$: the phase change correction is an end effect correction accounting for the difference in the apparent optical length to the mechanical length

l_F : the pate bending correction is the auxiliary plate was bended by the result of molecular when the measuring faces of the gauge block was wrung to the auxiliary plate during the measurement.

l_R : the variation of surface texture on the reflection of the light wave.

Uncertainty budget for Steel gauge blocks

Source of Uncertainty	Probability Distribution	Standard Uncer., $u(x_i)$	c_i		Contribution Uncer., $u_i(y)$		v_{eff}
Vacuum wavelength; $u(\lambda)$	Nomal	7.00E-09	1.00E+00	L	7.00E-09	L	100
Fringe fraction; $u(\varepsilon)$	Normal	0.0076	316.5000000		2.41		9
Refractive index of air; u(n)							
Edlen equation; u(E)	Normal	1.00E-08		L	1.00E-08	L	100
IPRT calibration; $u(t_{cal})$	Normal	7.50E-03	9.50E-07	L/C	7.13E-09	L	100
IPRT resolution; $u(t_{read})$	Rectangular	2.89E-05	9.50E-07	L/C	2.74E-11	L	100
IPRT drift; $u(t_{drift})$	Rectangular	5.77E-03	9.50E-07	L/C	5.48E-09	L	100
IPRT bridge resistance; $u(t_{ohm})$	Normal	1.25E-04	9.50E-07	L/C	1.19E-10	L	100
IPRT Seft heating	Rectangular	2.89E-03	9.50E-07	L/C	2.74E-09	L	100
Pressure calibration; $u(p_{cal})$	Normal	1.50E+00	2.70E-09	L/Pa	4.05E-09	L	100
Pressure resolution; $u(p_{read})$	Rectangular	2.89E-01	2.70E-09	L/Pa	7.79E-10	L	100
Pressure drift; $u(p_{drift})$	Rectangular	2.31E+00	2.70E-09	L/Pa	6.24E-09	L	100
RH calibration; $u(RH_{cal})$	Normal	8.50E-01	8.50E-09	L/%	7.23E-09	L	100
RH resolution; $u(Rh_{read})$	Rectangular	2.89E-02	8.50E-09	L/%	2.45E-10	L	100
RH drift; $u(Rh_{drift})$	Rectangular	5.77E-01	8.50E-09	L/%	4.91E-09	L	100
Gauge block temperature; $u(l_{tg})$							
IPRT calibration; $u(t_{cal})$	Normal	7.50E-03	1.15E-05	L	8.63E-08	L	100
IPRT resolution; $u(t_{read})$	Rectangular	2.89E-05	1.15E-05	L	3.32E-10	L	100
IPRT drift; $u(t_{drift})$	Rectangular	5.77E-03	1.15E-05	L	6.64E-08	L	100
IPRT bridge resistance; $u(t_{ohm})$	Normal	1.25E-04	1.15E-05	L	1.44E-09	L	100
IPRT Seft heating	Rectangular	2.89E-03	1.15E-05	L	3.32E-08	L	100
Temperature gradient; $u(\theta)$	Rectangular	5.77E-03	1.15E-05	L	6.64E-08	L	100
CTE; $u(\alpha)$	Rectangular	2.89E-07	2.00E-01	L	5.77E-08	L	100
Wringing influence; $u(l_w)$	Rectangular	9.00	1		9.00		100
Obliquity; $u(l_\Omega)$							
Pinhole radius; $u(l_s)$	Rectangular	7.30E+02	4.17E-14	L	3.04E-11	L	100
Collimator aperture; $u(l_c)$	Rectangular	1.50E+04	3.33E-13	L	5.00E-09	L	100
Phase change correction; $u(l_\phi)$	Rectangular	6.00	1		6.00		100
Flatness and Parallel; $u(l_G)$	Rectangular	2.57	1		2.57		100
Wavefront error; $u(l_A)$	Rectangular	3.46	1		3.46		100
Bending of plate; $u(l_F)$	Rectangular	5.00	1		5.00		100
Variation of roughness; $u(l_R)$	Rectangular	0.00	1		0.00		100
Combined standard uncertainty (k =1), u_c					12.90	1.45E-07	L

Uncertainty budget for tungsten carbide gauge blocks

Source of Uncertainty	Probability Distribution	Standard Uncer., $u(x_i)$	c_i		Contribution Uncer., $u_i(y)$		v_{eff}
Vacuum wavelength; $u(\lambda)$	Nomal	7.00E-09	1.00E+00	L	7.00E-09	L	100
Fringe fraction; $u(\varepsilon)$	Normal	0.0076	316.4955175		2.41		9
Refractive index of air; u(n)							
Edlen equation; u(E)	Normal	1.00E-08		L	1.00E-08	L	100
IPRT calibration; $u(t_{cal})$	Normal	7.50E-03	9.50E-07	L/C	7.13E-09	L	100
IPRT resolution; $u(t_{read})$	Rectangular	2.89E-05	9.50E-07	L/C	2.74E-11	L	100
IPRT drift; $u(t_{drift})$	Rectangular	5.77E-03	9.50E-07	L/C	5.48E-09	L	100
IPRT bridge resistance; $u(t_{ohm})$	Normal	1.25E-04	9.50E-07	L/C	1.19E-10	L	100
IPRT Seft heating	Rectangular	2.89E-03	9.50E-07	L/C	2.74E-09	L	100
Pressure calibration; $u(p_{cal})$	Normal	1.50E+00	2.70E-09	L/Pa	4.05E-09	L	100
Pressure resolution; $u(p_{read})$	Rectangular	2.89E-01	2.70E-09	L/Pa	7.79E-10	L	100
Pressure drift; $u(p_{drift})$	Rectangular	2.31E+00	2.70E-09	L/Pa	6.24E-09	L	100
RH calibration; $u(RH_{cal})$	Normal	8.50E-01	8.50E-09	L/%	7.23E-09	L	100
RH resolution; $u(Rh_{read})$	Rectangular	2.89E-02	8.50E-09	L/%	2.45E-10	L	100
RH drift; $u(Rh_{drift})$	Rectangular	5.77E-01	8.50E-09	L/%	4.91E-09	L	100
Gauge block temperature; $u(l_{tg})$							
IPRT calibration; $u(t_{cal})$	Normal	7.50E-03	4.50E-06	L	3.38E-08	L	100
IPRT resolution; $u(t_{read})$	Rectangular	2.89E-05	4.50E-06	L	1.30E-10	L	100
IPRT drift; $u(t_{drift})$	Rectangular	5.77E-03	4.50E-06	L	2.60E-08	L	100
IPRT bridge resistance; $u(t_{ohm})$	Normal	1.25E-04	4.50E-06	L	5.63E-10	L	100
IPRT Seft heating	Rectangular	2.89E-03	4.50E-06	L	1.30E-08	L	100
Temperature gradient; $u(\theta)$	Rectangular	5.77E-03	4.50E-06	L	2.60E-08	L	100
CTE; $u(\alpha)$	Rectangular	2.89E-07	2.00E-01	L	5.77E-08	L	100
Wringing influence; $u(l_w)$	Rectangular	9.00	1		9.00		100
Obliquity; $u(l_\Omega)$							
Pinhole radius; $u(l_s)$	Rectangular	7.30E+02	4.17E-14	L	3.04E-11	L	100
Collimator aperture; $u(l_x)$	Rectangular	1.50E+04	3.33E-13	L	5.00E-09	L	100
Phase change correction; $u(l_\phi)$	Rectangular	6.00	1		6.00		100
Flatness and Parallel; $u(l_G)$	Rectangular	2.57	1		2.57		100
Wavefront error; $u(l_A)$	Rectangular	3.46	1		3.46		100
Bending of plate; $u(l_F)$	Rectangular	5.00	1		5.00		100
Variation of roughness; $u(l_R)$	Rectangular	0.00	1		0.00		100
Combined standard uncertainty (k =1), uc					12.90	7.99E-08	L

3. NIM

Measurement Function (mathematical model of measurement):

The phase shifting interferometer for short gauge block is used for measuring the center length of the gauge block with wringing onto a platen. The measured length *l* of the gauge block can be expressed as

$$l = \frac{1}{q}\sum_{i=1}^{q}\frac{(k_i + F_i)\lambda_i}{2n} - L\alpha(t_g - 20)$$

The model equation includes all corrections to the measured value of gauge block length due to influences parameters impacting on measuring results and can be expressed as

$$l = \frac{1}{q}\sum_{i=1}^{q}\frac{(k_i+F_i)\lambda_i}{2n} - L\alpha\left(t_g - 20\right) + \delta l_s + \delta l_\Omega + \delta l_A + \delta l_W + \delta l_\Phi + \delta l_G$$

Definition of variables in the measurement function:

L ——Nominal length of gauge block

l —— The length of measured gauge block at a reference temperature of 20℃

k_i ——Integer part of fringe order

F_i ——Fractional part of fringe order

λ_i —— Vacuum wavelength

q ——Number of wavelengths used to determine length, based on the method of exact fractions

n ——Refractive index of air

p ——Pressure of air

t ——Temperature of air

f ——Humidity of air

x —— Carbon dioxide content

t_g —— Temperature of gauge block

α ——Thermal expansion coefficient of gauge block

δl_s ——Obliquity correction – size of the source aperture

δl_Ω —— Obliquity correction – alignment error of the entrance aperture of the collimating assembly (expectation value equals zero)

δl_A —— Correction for wave front errors as a result of imperfect interferometer optics (expectation value equals zero)

δl_G ——Correction accounting for flatness deviation and variation in length of the gauge block (expectation value equals zero)

δl_W —— Correction accounting for the wringing film (expectation value equals zero)

δl_Φ ——Phase change correction

Uncertainty budget for steel gauge blocks

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i	degrees of freedom ν_i
633nm vacuum wave length	$0.03\times10^{-8}\lambda_r$	L/λ_r	normal	$0.03\times10^{-8}L$	50
543nm vacuum wave length	$2.5\times10^{-8}\lambda_g$	L/λ_g	normal	$2.5\times10^{-8}L$	50
Refractive index of air	2.64×10^{-8}	L	normal	$2.64\times10^{-8}L$	44
Fringe fraction of 633nm laser	0.01	$\lambda_r/2$	normal	3.2 nm	9
Fringe fraction of 543nm laser	0.01	$\lambda_g/2$	normal	2.7 nm	9
Gauge block temperature	9.0×10^{-3}℃	$L\alpha$	rectangular	$9.72\times10^{-8}L$	50
Thermal expansion coefficient	2.89×10^{-7}℃$^{-1}$	$L(t_g-20)$	rectangular	$5.77\times10^{-8}L$	12
Source size	28.87 μm	$dL/8f^2$	rectangular	$0.67\times10^{-8}L$	12
Alignment error	$0.26\times10^{-8}L$	1	rectangular	$0.26\times10^{-8}L$	2
Wave front errors	3.0 nm	1	rectangular	3.0 nm	12
Wringing film	3.0 nm	1	rectangular	3.0 nm	12
Phase correction	3.5 nm	1	rectangular	3.5 nm	12
Gauge block flatness and parallelism	0.289 mm	40.4 nm/7.4mm	rectangular	1.6 nm	12
combined standard uncertainty (k = 1) u_c				Q[7 nm + $0.12\times10^{-6}L$]	

Uncertainty budget for tungsten carbide gauge blocks

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i	degrees of freedom ν_i
633nm vacuum wave length	$0.03\times10^{-8}\lambda_r$	L/λ_r	normal	$0.03\times10^{-8}L$	50
543nm vacuum wave length	$2.5\times10^{-8}\lambda_g$	L/λ_g	normal	$2.5\times10^{-8}L$	50
Refractive index of air	2.64×10^{-8}	L	normal	$2.64\times10^{-8}L$	44
Fringe fraction of 633nm laser	0.01	$\lambda_r/2$	normal	3.2 nm	9
Fringe fraction of 543nm laser	0.01	$\lambda_g/2$	normal	2.7 nm	9
Gauge block temperature	9×10^{-3}℃	$L\alpha$	rectangular	$4.05\times10^{-8}L$	50
Thermal expansion coefficient	5.77×10^{-7}℃$^{-1}$	$L(t_g-20)$	rectangular	$11.55\times10^{-8}L$	20
Source size	28.87 µm	$dL/8f^2$	rectangular	$0.67\times10^{-8}L$	12
Alignment error	$0.26\times10^{-8}L$	1	rectangular	$0.26\times10^{-8}L$	2
Wave front errors	3.0 nm	1	rectangular	3.0 nm	12
Wringing film	3.0 nm	1	rectangular	3.0 nm	12
Phase correction	3.5 nm	1	rectangular	3.5 nm	12
Gauge block flatness and parallelism	0.289 mm	40.4 nm/7.4mm	rectangular	1.6 nm	12
combined standard uncertainty (k = 1) u_c				Q[7 nm + $0.13\times10^{-6}L$]	

4. NMIJ/AIST

Measurement Function (mathematical model of measurement):

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

Definition of variables in the measurement function:

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:

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

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.

Uncertainty budget for steel gauge blocks

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i	degrees of freedom ν_i
$\Delta\lambda_i/\lambda_i$	1.46×10^{-8}	L	Uniform	$1.46\times10^{-8}\ L$	∞
n	2.80×10^{-8}	L	Normal	$2.80\times10^{-8}\ L$	∞
δl_A	5 nm	1	Uniform	5 nm	∞
s	1.73 μm	$6.25\times10^{-10}\ L$	Uniform	$1.08\times10^{-9}\ L$	∞
δl_Ω	1.44×10^{-5} rad	$1.69\times10^{-4}\ L$	Uniform	$2.45\times10^{-9}\ L$	∞
Δt_g	9.76×10^{-3} K	$10.8\times10^{-6}\ L$	Uniform	$1.05\times10^{-7}\ L$	∞
α	$2.89\times10^{-7}\ K^{-1}$	$0.02\ L$	Uniform	$5.78\times10^{-9}\ L$	∞
δl_w	5 nm	1	Normal	5 nm	∞
F_i	5 nm	1	Normal	5 nm	∞
Δl_ϕ	8.66 nm	1	Normal	8.66 nm	∞
combined standard uncertainty (k = 1) u_c				$\sqrt{12.2^2+(0.11\times L)^2}$ nm (L: mm)	

Uncertainty budget for tungsten carbide gauge blocks

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i	degrees of freedom ν_i
$\Delta\lambda_i/\lambda_i$	1.46×10^{-8}	L	Uniform	$1.46\times10^{-8}\ L$	∞
n	2.80×10^{-8}	L	Normal	$2.80\times10^{-8}\ L$	∞
δl_A	5 nm	1	Uniform	5 nm	∞
s	1.73 μm	$6.25\times10^{-10}\ L$	Uniform	$1.08\times10^{-9}\ L$	∞
δl_Ω	1.44×10^{-5} rad	$1.69\times10^{-4}\ L$	Uniform	$2.45\times10^{-9}\ L$	∞
Δt_g	9.76×10^{-3} K	$4.5\times10^{-6}\ L$	Uniform	$4.39\times10^{-8}\ L$	∞
α	$5.77\times10^{-7}\ K^{-1}$	$0.02\ L$	Uniform	$1.15\times10^{-8}\ L$	∞
δl_w	5 nm	1	Normal	5 nm	∞
F_i	5 nm	1	Normal	5 nm	∞
Δl_ϕ	7.88 nm	1	Normal	7.88 nm	∞
combined standard uncertainty (k = 1) u_c				$\sqrt{11.7^2+(0.055\times L)^2}$ nm (L: mm)	

5. MSL

Measurement Function (Mathematical Model of Measurement)

The length l of the gauge at the reference temperature of 20 °C is given by:

$$l = \frac{\lambda_0}{2n}(F_1 + \kappa_1) + \theta_g \alpha L + \delta l_{\Omega s} L + \delta l_A + \delta l_G + \delta l_w + \Delta l_\Phi + \Delta l_\gamma$$

Definition of Variables in the Measurement Function

Term	Description of Term
L	The nominal length of the gauge
λ_0	Vacuum wavelength of the red laser source
n	Index of refraction of the air
F_1	Fractional part of the fringe order for the red laser source
κ_1	An integer number representing the fringe order
θ_g	Amount the gauge departs from reference temperature $\theta_g = t - 20$ °C
α	Linear coefficient of thermal expansion of the gauge block
$\delta l_{\Omega s}$	Obliquity and aperture corrections
δl_A	Correction for wave front errors as a result of imperfect optics
δl_G	Correction due to the flatness deviation and variation in length
δl_W	Length attributed to the wringing film
Δl_Φ	Phase change
Δl_γ	Change in length due to compression of the gauge block under its own weight when measured in the vertical orientation

Uncertainty Budget

Source of uncertainty	Standard uncertainty	Sensitivity coefficient	Probability distribution	Uncertainty contribution	Degrees of freedom
u(n)	0.028 x 10^{-6}	L	normal	0.028 x 10^{-6} L	37
u(λ_0)	2.645 x 10^{-6} nm	L/λ_0	rectangular	0.004 x 10^{-6} L	50
u(θ_g)	0.004 K	αL	normal	0.018 x 10^{-6} L	50
u(α)	0.577 x 10^{-6} K^{-1}	u(θ_g)L	rectangular	0.042 x 10^{-6} L	50
u($\delta l_{\Omega s}$)	0.040 x 10^{-6}	L	normal	0.040 x 10^{-6} L	50
u(F_1)	4 nm	1	normal	4 nm	14
u(δl_A)	5 nm	1	normal	5 nm	50
u(δl_G)	2 nm	1	normal	2 nm	50
u(δl_W)	5 nm	1	normal	5 nm	8
u(Δl_Φ)	7 nm	1	normal	7 nm	7
u(Δl_γ)	< 1 nm	1	normal	0.5 nm	50

6. NMIM

Measurement Function (mathematical model of measurement):

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

Definition of variables in the measurement function:

- l — length of the gauge block at the reference temperature of 20°C
- 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 departure (in °C) of the gauge block temperature t_g from the reference temperature of 20°C during the measurement
- α — linear coefficient of thermal expansion of the gauge block
- L — nominal length 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

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

f is the focal length of the collimating lens

- δl_A — correction for wave front errors because 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

Uncertainty budget for steel gauge blocks

SOURCE OF UNCERTAINTY, x_i	STANDARD UNCERTAINTY, $u(x_i)$		SENSITIVITY COEFFICIENTS, $c_i \equiv \delta f/\delta_{xi}$			PROBABILITY DISTRIBUTION	UNCERTAINTY CONTRIBUTION $u_i \equiv u(x_i)\,\lvert c_{xi} \rvert$ [nm] for L [mm]				DEGREES OF FREEDOM, v_i
	Value	Unit	Formula	Calculation			Absolute		Relative		
Fitted Length, $u_c(l_{fit})$											
Frequency Stabilised He-Ne laser 633 nm (red) calibration, $u(\lambda_r)$	8.00E-09		$L/q\lambda_r$	1265.98	L	Normal			**0.006**	nm L(mm)	1000
Frequency Stabilised He-Ne laser 543 nm (green) calibration, $u(\lambda_g)$	5.00E-09		$L/q\lambda_g$	1087.03	L	Normal			**0.005**	nm L(mm)	1000
Red Fringe Fraction, $u(F_r)$	0.01	fringe	$\lambda_r/2q$	158.25		Rectangular	**1.6**	nm			10
Green Fringe Fraction, $u(F_g)$	0.01	fringe	$\lambda_g/2q$	135.88		Rectangular	**1.4**	nm			10
Red Fringe Integer, $u(\kappa_r)$	0		$\lambda_r/2q$	158.25			0.0				
Green Fringe Integer, $u(\kappa_g)$	0		$\lambda_g/2q$	135.88			0.0				
Difference in temp. of gauge block from 20°C, $u_c(\Delta t_g)$									**0.281**	nm L(mm)	1000
Gauge Temperature Calibration (PT100)											
T1 Platen, $u(\theta_1)$	0.015	°C	αL	1.08E-05	/°C L	Normal			0.162	nm L(mm)	1000
T2 Air, $u(\theta_2)$	0.015	°C	αL	1.08E-05	/°C L	Normal			0.162	nm L(mm)	1000
T3 Gauge, $u(\theta_3)$	0.015	°C	αL	1.08E-05	/°C L	Normal			0.162	nm L(mm)	1000
Resolution, $u(\theta_4)$	0.0003	°C	αL	1.08E-05	/°C L	Rectangular			0.003	nm L(mm)	1000
Thermal Expansion Coefficient, u(α)	5.77E-07	/°C	$\Delta t_g.L$	0.1	°C L	Rectangular			**0.06**	nm L(mm)	1000
Nominal Length of gauge block, u(L)	0		$\Delta t_g.\alpha$	1.08E-06			**0**				
<u>Higher order terms</u>	0.026	L	1			Rectangular			**0.03**	nm L(mm)	1000
Obliquity Correction, $u(\delta l_\Omega)$	0.01	L nm		1		Rectangular			**0.01**	nm L(mm)	1000
Aperture Correction from Source Size, $u(\Delta l_s)$	0.007	L nm		1		Rectangular			**0.007**	nm L(mm)	1000
Wavefront Errors Correction, $u(\delta l_A)$	5	nm		1		Rectangular	**5**	nm			1000
									0.048		1000
Refractive Index of Air, $u(\delta l_n)$	4.68E-08		L			Rectangular			0.047	nm L(mm)	1000
Edlen equation, $u(E)$	1.00E-08		L			Rectangular			0.01	nm L(mm)	1000
Parallelism / Flatness, $u(\delta l_G)$	2.5	nm		1		Rectangular	**2.5**	nm			1000
Wringing, $u(\delta l_w)$	10	nm		1		Rectangular	**10**	nm			10
Phase Change Correction, $u(\Delta l_\Phi)$	8.539	nm		1		Rectangular	**8.5**	nm			1000
Combined Standard Uncertainty (k=1), u_c							**14**	**nm**	**0.29**	**nm L(mm)**	43

Uncertainty budget for tungsten carbide gauge blocks

SOURCE OF UNCERTAINTY, x_i	STANDARD UNCERTAINTY, $u(x_i)$		SENSITIVITY COEFFICIENTS, $c_i \equiv \delta f/\delta_{xi}$			PROBABILITY DISTRIBUTION	UNCERTAINTY CONTRIBUTION $u_i \equiv u(x_i)\ \lvert c_{xi} \rvert$ [nm] for L [mm]				DEGREES OF FREEDOM, v_i
	Value	Unit	Formula	Calculation			Absolute		Relative		
Fitted Length, $u_c(l_{fit})$											
Frequency Stabilised He-Ne laser 633 nm (red) calibration, $u(\lambda_r)$	8.00E-09		$L/q\lambda_r$	1265.98	L	Normal			**0.006**	nm L(mm)	1000
Frequency Stabilised He-Ne laser 543 nm (green) calibration, $u(\lambda_g)$	5.00E-09		$L/q\lambda_g$	1087.03	L	Normal			**0.005**	nm L(mm)	1000
Red Fringe Fraction, $u(F_r)$	0.01	fringe	$\lambda_r/2q$	158.25		Rectangular	**1.6**	nm			10
Green Fringe Fraction, $u(F_g)$	0.01	fringe	$\lambda_g/2q$	135.88		Rectangular	**1.4**	nm			10
Red Fringe Integer, $u(\kappa_r)$	0		$\lambda_r/2q$	158.25			0.0				
Green Fringe Integer, $u(\kappa_g)$	0		$\lambda_g/2q$	135.88			0.0				
Difference in temp. of gauge block from 20°C, $u_c(\Delta t_g)$									**0.117**	nm L(mm)	1000
Gauge Temperature Calibration (PT100)											
T1 Platen, $u(\theta_1)$	0.015	°C	αL	4.50E-06	/°C L	Normal			0.0675	nm L(mm)	1000
T2 Air, $u(\theta_2)$	0.015	°C	αL	4.50E-06	/°C L	Normal			0.0675	nm L(mm)	1000
T3 Gauge, $u(\theta_3)$	0.015	°C	αL	4.50E-06	/°C L	Normal			0.0675	nm L(mm)	1000
Resolution, $u(\theta_4)$	0.0003	°C	αL	4.50E-06	/°C L	Rectangular			0.001	nm L(mm)	1000
Thermal Expansion Coefficient, u(α)	5.77E-07	/°C	$\Delta t_g.L$	0.1	°C L	Rectangular			**0.06**	nm L(mm)	1000
Nominal Length of gauge block, u(L)	0		$\Delta t_g.\alpha$	4.50E-07			**0**				
Higher order terms	0.026	L	1			Rectangular			**0.03**	nm L(mm)	1000
Obliquity Correction, $u(\delta l_\Omega)$	0.01	L nm		1		Rectangular			**0.01**	nm L(mm)	1000
Aperture Correction from Source Size, $u(\Delta l_s)$	0.007	L nm		1		Rectangular			**0.007**	nm L(mm)	1000
Wavefront Errors Correction, $u(\delta l_A)$	5	nm		1		Rectangular	**5**	nm			1000
									0.048		1000
Refractive Index of Air, $u(\delta l_n)$	4.68E-08		L			Rectangular			0.047	nm L(mm)	1000
Edlen equation, $u(E)$	1.00E-08		L			Rectangular			0.01	nm L(mm)	1000
Parallelism / Flatness, $u(\delta l_G)$	2.5	nm		1		Rectangular	**2.5**	nm			1000
Wringing, $u(\delta l_w)$	10	nm		1		Rectangular	**10**	nm			10
Phase Change Correction, $u(\Delta l_\Phi)$	8.539	nm		1		Rectangular	**8.5**	nm			1000
Combined Standard Uncertainty (k =1), u_c							**14**	**nm**	**0.14**	**nm L(mm)**	43

C2. Uncertainty budgets for long gauge block calibration

1. KRISS

Measurement Function (mathematical model of measurement):

$$e = L - L_0$$
$$= \left\{ \frac{\lambda}{2}(m+F) - L_0(n-1) - L_0\alpha(t_{GB} - 20) + l_\phi + l_w + l_E + l_A + l_{ob} + l_G \right\} - L_0$$

Definition of variables in the measurement function:

e: deviation of central length from nominal length
L: central length of gauge block
L_0: nominal length of gauge block
λ: vacuum wavelength of red laser
m: integral part of the interference order
F: fractional part of the interference order
n: refractive index of air
α: thermal expansion coefficient of gauge block
t_{GB}: temperature of gauge block
l_ϕ: phase correction
l_W: correction for wringing layer
l_E: correction for aberration of optics
l_A: correction for aperture effect
l_{ob}: correction for obliquity effect
l_G: correction for geometrical effect (non-central positioning)

Uncertainty budget

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i	degrees of freedom ν_i
λ	5.82E-09 $\times\lambda$	L_0/λ	Normal	5.82E-09 L_0	∞
m	0	-	-	0.0 nm	-
F	0.031	316.5 nm	t	9.8 nm	29
n	5.68E-08	L_0	Normal	5.68E-08 L_0	∞
α	5.77E-07 /°C	0.055 °C × L_0	Rectangular	3.18E-08 L_0	50
t_{GB}	6.2E-03 °C	-10.8E-06/°C L_0	Normal	6.70E-08 L_0	∞
l_ϕ	5.8 nm	1	Rectangular	5.8 nm	50
l_W	6.9 nm	1	Rectangular	6.9 nm	50
l_E	8.1 nm	1	Rectangular	8.1 nm	∞
l_A	3.21E-11× L_0	1	Trapezoidal	3.21E-11 L_0	50
D	2 886.8 nm	1.11E-14/nm×L_0	Rectangular	-	50
f	288 675.1 nm	7.41E-19/nm×L_0	Rectangular	-	50
l_{ob}	4.15E-10	L_0	Rectangular	4.15E-10 L_0	50
l_G	2.4 nm	1	Rectangular	2.4 nm	50
2nd order term (α)	3.58E-09	L_0	-	3.58E-09 L_0	-
combined standard uncertainty (k = 1) u_c = Q[15.8, 0.094 L_0] nm (L_0 in mm) or u_c = Q[15.8 nm, 0.094×10^{-6} L_0]					ν_{eff} > 204

2. NIMT

Measurement Function (mathematical model of measurement):

$$l_x = l_s + \delta l_D + \delta l_{vs} + \delta l_{cs} + \delta l_{IND} + \delta l_c - L\left[\left(\bar{\alpha} \times \delta t\right) + \left(\delta\alpha \times \Delta\bar{t}\right)\right] - \delta l_{cx} - \delta l_{vx}$$

Definition of variables in the measurement function:

l_x	:	Length of the unknown gauge block at reference temperature (t_0 = 20 °C)
l_s	:	Length of the reference gauge block at reference temperature (t_0 = 20 °C)
δl_D	:	Change of the length of the reference gauge block since its last calibration due to drift
δl_{IND}	:	Observed difference in length between the unknown and the reference gauge block
δl_c	:	Variation in observed length difference by influence of the comparator
L	:	Nominal length of the gauge block
$\bar{\alpha}$	=	$\frac{\alpha_x + \alpha_s}{2}$: Average of the thermal expansion coefficient of the unknown and reference gauge block
δt	=	$t_x - t_s$: Temperature difference between unknown and reference gauge block
$\delta\alpha$	=	$\alpha_x - \alpha_s$: Difference in the thermal expansion coefficient between the unknown and reference gauge blocks
$\Delta\bar{t}$	=	$\left(\frac{t_x + t_s}{2}\right) - t_0$: Deviation of the average temperature of unknown and reference gauge block from reference temperature
δl_{vx}	:	Variation in length of the unknown gauge block
δl_{vs}	:	Variation in length of the reference gauge block
δl_{cx}	:	Influence in length due to non-centric touching of the measuring faces of the unknown gauge block
δl_{cs}	:	Influence in length due to non-centric touching of the measuring faces of the reference gauge block

Uncertainty budget for the 400 mm long gauge block

Uncertainty budget of Steel Long Gauge Block 400 mm

Quantity X_i	Estimate x_i	Standard Uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$	degree of freedom ν_i
Ref GB (l_s)	400 mm	2.65E-02 µm	Normal	1	2.65E-02 µm	100
Drift of Ref GB (δl_D)	0.00 mm	6.90E-02 µm	Rectangular	1	6.90E-02 µm	100
Variation of Ref GB (δl_{vs})	0.00 mm	7.70E-03 µm	Normal	1	7.70E-03 µm	100
Noncentric touch Ref GB (δl_{cs})	0.00 mm	1.20E-02 µm	Rectangular	1	1.20E-02 µm	100
Repeat of meas (δl_{RND})	0.00 mm	0.00E+00 µm	Normal	1	0.00E+00 µm	3
Acc of comparator (δl_c)	0.00 mm	2.90E-02 µm	Rectangular	1	2.90E-02 µm	100
Temp different ($\bar{\alpha} \cdot \delta t$)	0.00	3.13E-07	Special	-400 mm	-1.25E-01 µm	100
Themal expansion different ($\delta\alpha \cdot \Delta\bar{t}$)	0.00	1.41E-07	Special	-400 mm	-5.64E-02 µm	100
Noncentric touch UUC (δl_{cx})	0.00 mm	1.73E-02 µm	Rectangular	-1	-1.73E-02 µm	100
Variation of UUC (δl_{vx})	0.00 mm	8.00E-03 µm	Rectangular	-1	-8.00E-03 µm	100
Res of comparator (δl_{ic})	0.00 mm	2.90E-03 µm	Rectangular	1	2.90E-03 µm	100
Elastic deform (δl_{elas})	0.00 mm	2.30E-03 µm	Rectangular	1	2.30E-03 µm	100
combined standard uncertainty u_c ($k=1$)					0.160 µm	236

Uncertainty budget for the 500 mm long gauge block

Uncertainty budget of Steel Long Gauge Block 500 mm

Quantity X_i	Estimate x_i	Standard Uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$	degree of freedom ν_i
Ref GB (l_s)	500 mm	3.15E-02 µm	Normal	1	3.15E-02 µm	100
Drift of Ref GB (δl_D)	0.00 mm	8.40E-02 µm	Rectangular	1	8.40E-02 µm	100
Variation of Ref GB (δl_{vs})	0.00 mm	9.00E-03 µm	Normal	1	9.00E-03 µm	100
Noncentric touch Ref GB (δl_{cs})	0.00 mm	1.20E-02 µm	Rectangular	1	1.20E-02 µm	100
Repeat of meas (δl_{RND})	0.00 mm	0.00E+00 µm	Normal	1	0.00E+00 µm	3
Acc of comparator (δl_c)	0.00 mm	2.90E-02 µm	Rectangular	1	2.90E-02 µm	100
Temp different ($\bar{\alpha} \cdot \delta t$)	0.00	3.13E-07	Special	-500 mm	-1.57E-01 µm	100
Themal expansion different ($\delta\alpha \cdot \Delta\bar{t}$)	0.00	1.41E-07	Special	-500 mm	-7.05E-02 µm	100
Noncentric touch UUC (δl_{cx})	0.00 mm	1.73E-02 µm	Rectangular	-1	-1.73E-02 µm	100
Variation of UUC (δl_{vx})	0.00 mm	9.00E-03 µm	Rectangular	-1	-9.00E-03 µm	100
Res of comparator (δl_{ic})	0.00 mm	2.90E-03 µm	Rectangular	1	2.90E-03 µm	100
Elastic deform (δl_{elas})	0.00 mm	2.30E-03 µm	Rectangular	1	2.30E-03 µm	100
combined standard uncertainty u_c ($k=1$)					0.198 µm	225

3. NIM

Measurement Function (mathematical model of measurement):

The phase shifting interferometer for long gauge block is used for measuring the center length of the gauge block with wringing onto a platen. The measured length l of the gauge block can be expressed as

$$l = \frac{1}{q}\sum_{i=1}^{q}\frac{(k_i + F_i)\lambda_i}{2n} - L\alpha(t_g - 20)$$

The model equation includes all corrections to the measured value of gauge block length due to influences parameters impacting on measuring results and can be expressed as

$$l = \frac{1}{q}\sum_{i=1}^{q}\frac{(k_i+F_i)\lambda_i}{2n} - L\alpha\left(t_g - 20\right) + \delta l_s + \delta l_\Omega + \delta l_A + \delta l_W + \delta l_\Phi + \delta l_G$$

Definition of variables in the measurement function:

L —— Nominal length of gauge block

l —— The length of measured gauge block at a reference temperature of 20℃

k_i —— Integer part of fringe order

F_i —— Fractional part of fringe order

λ_i —— Vacuum wavelength

q —— Number of wavelengths used to determine length, based on the method of exact fractions

n —— Refractive index of air

p —— Pressure of air

t —— Temperature of air

f —— Humidity of air

x —— Carbon dioxide content

t_g—— Temperature of gauge block

α —— Thermal expansion coefficient of gauge block

δl_s —— Obliquity correction – size of the source aperture

δl_Ω —— Obliquity correction – alignment error of the entrance aperture of the collimating assembly (expectation value equals zero)

δl_A —— Correction for wave front errors as a result of imperfect interferometer optics (expectation value equals zero)

δl_G —— Correction accounting for flatness deviation and variation in length of the gauge block (expectation value equals zero)

δl_W —— Correction accounting for the wringing film (expectation value equals zero)

δl_Φ —— Phase change correction

Uncertainty budget

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i	degrees of freedom ν_i
633nm vacuum wave length	$0.03\times10^{-8}\lambda_r$	L/λ_r	normal	$0.03\times10^{-8}L$	50
543nm vacuum wave length	$2.5\times10^{-8}\lambda_g$	L/λ_g	normal	$2.5\times10^{-8}L$	50
Refractive index of air	2.64×10^{-8}	L	normal	$2.64\times10^{-8}L$	44
Fringe fraction of 633nm laser	0.015	$\lambda_r/2$	normal	4.8 nm	9
Fringe fraction of 543nm laser	0.015	$\lambda_g/2$	normal	4.1 nm	9
Gauge block temperature	5.2×10^{-3}℃	$L\alpha$	rectangular	$5.62\times10^{-8}L$	50
Thermal expansion coefficient	2.89×10^{-7}℃$^{-1}$	$L(t_g-20)$	rectangular	$4.62\times10^{-8}L$	20
Source size	28.87 µm	$dL/8f^2$	rectangular	$0.11\times10^{-8}L$	12
Alignment error	$0.17\times10^{-8}L$	1	rectangular	$0.17\times10^{-8}L$	2
Wave front errors	3.5 nm	1	rectangular	3.5 nm	12
Wringing film	3.5 nm	1	rectangular	3.5 nm	12
Phase correction	5.0 nm	1	rectangular	5.0 nm	12
Gauge block flatness and parallelism	0.289 mm	$\frac{\sqrt{80^2+(24\times10^{-8}L)^2}}{7.4}$	rectangular	Q[3.12nm,$0.94\times10^{-8}L$]	12
combined standard uncertainty (k = 1) u_c				Q[10 nm + $8.2\times10^{-8}L$]	

4. NMIA

Measurement Function (mathematical model of measurement):

Length of test bar at 20 °C = $R + \delta L_{un} + R_{nom}\alpha_r(\theta\text{-}20) - (T_{nom}\alpha_t(\theta\text{-}20))$

Definition of variables in the measurement function:

Where:
R is the reported reference gauge block length at 20 °C.
δL_{un} is the difference between the laser readings on the reference gauge block and the length bar.
θ is the temperature of the reference gauge block / length bar at the time of measurement.
α_r is the coefficient of thermal expansion (CTE) of the reference gauge block.
α_t is the coefficient of thermal expansion (CTE) of the length bar.
R_{nom} is the nominal length of the reference gauge block (ref).
T_{nom} is the nominal length of the length bar (test).

Uncertainty budget

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i	degrees of freedom ν_i
Air Temp.	0.058 C	1.0 nm/mm/C	normal	0.043 L	10
Air Press.	0.077 hPa	0.3 nm/mm/hPa	normal	0.023 L	30
Rel. Hum.	1.2 %	0.033 nm/mm/%RH	normal	0.040 L	30
Alignment	2.5e-4 rad	250 nm/mm	normal	0.062 L	10
CTE of test.	5.8e-7 /C	2.5e-5 nm.C	normal	0.144 L	10
Temp. diff. test	0.029 C	10.8 nm/mm/C	normal	0.312 L	30
Laser calib.	35.7 nm	1.0	normal	35.7	30
Ref. gauge block	15.0 nm	1.0	normal	15.0	30
Secular change	5.9 nm	1.0	normal	5.9	30
CTE ref. g.b.	5.8e-7 /C	2.5e-5 nm.C	normal	0.1	10
Temp. diff. ref	0.035 C	10.8 nm/mm/C	normal	0.4	30
Repeatability	56.6 nm	1.0	normal	56.6	43
combined standard uncertainty (k = 1) u_c				Q[74,0.36 L]	75

5. NMIJ/AIST

Measurement Function (mathematical model of measurement):

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

Definition of variables in the measurement function:

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:

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

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.

Uncertainty budget

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i	degrees of freedom ν_i
$\Delta\lambda_i/\lambda_i$	2.5×10^{-11}	L	Uniform	$2.5\times10^{-11}\,L$	∞
n	1.85×10^{-8}	L	Normal	$1.85\times10^{-8}\,L$	∞
δl_A	5.8 nm	1	Uniform	5.8 nm	∞
s	5 µm	$3.9\times10^{-11}\,L$	Uniform	$1.95\times10^{-10}\,L$	∞
δl_Ω	2.56×10^{-5} rad	$1.72\times10^{-4}\,L$	Uniform	$4.4\times10^{-9}\,L$	∞
Δt_g	6.72×10^{-3} K	$11.5\times10^{-6}\,L^*$	Uniform	$7.26\times10^{-8}\,L$	∞
α	5.77×10^{-7} K^{-1*}	$0.05\,L$	Uniform	$1.44\times10^{-8}\,L$	∞
δl_w	4.1 nm	1	Normal	4.1 nm	∞
F_i	3.2 nm	1	Normal	3.2 nm	∞
Δl_ϕ	8.7 nm	1	Normal	8.7 nm	∞
combined standard uncertainty ($k = 1$) u_c				$\sqrt{11.7^2+(0.085\times L)^2}$ nm (L: mm)	

* Although the coefficient of thermal expansion (10.8 ± 0.5) x 10^{-6} K^{-1} was used to obtain the measurement results, (11.5 ± 1.0) x 10^{-6} K^{-1} was used in the uncertainty evaluation following our technical manual for long gauge block.

6. MUSSD

Measurement Function (mathematical model of measurement):

$$\delta L = L_s + D + d_1 - L_s[\delta\alpha\theta_0 + \alpha_s.\delta\theta] - L_n$$

Definition of variables in the measurement function:

δL: deviation of the length of the test gauge block from its nominal length

L_s: length of the reference gauge block at 20 °C

D: central length deviation between the test and reference gauge blocks

d_1: quantity describing the systematic effect of the comparator used

α_s: thermal expansion coefficient of the reference gauge block

α: thermal expansion coefficient of the test gauge block

$\delta\alpha = \alpha - \alpha_s$: difference in thermal expansion coefficients

θ_0: average temperature deviation of the test gauge block from 20 °C

$\delta\theta$: temperature difference between the test and reference gauge blocks

L_n: nominal length of the test gauge block

Uncertainty budget

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i	degrees of freedom ν_i
Calibration of reference standard	28 nm (k=2)	1	Normal	28 nm	∞
Random effect of readings	10.2 nm	1	t-distribution	10.2 nm	4
*Thermal expansion coefficient	0.115×10^{-6} °C^{-1}	$0.13 l_n$	Rectangular	$0.015 \times 10^{-6}\ l_n$	50
Systematic effect of the comparator	40 nm (k=2)	1	Normal	40 nm	∞
Temperature difference between the test block and reference block	0.029 °C	$11.5 \times 10^{-6}\ l_n$	Rectangular	$0.33 \times 10^{-6}\ l_n$	∞
*Difference between thermal expansions of the gauge blocks	0.4×10^{-6} °C^{-1}	$0.07\ l_n$	Rectangular	$0.03 \times 10^{-6}\ l_n$	50
combined standard uncertainty (k = 1) u_c			(400 mm)	153 nm	Infinite
			(500 mm)	172 nm	Infinite

*degrees of freedom are 50 based on a 10 % relative uncertainty

7. SCL

Measurement Function (mathematical model of measurement):

$L = S(1-\delta\alpha\theta_s-\alpha_s\delta\theta-\delta\alpha\delta\theta)+R$

Definition of variables in the measurement function:

L: Measurand, central length of the gauge block under test at 20 °C
S: Central length of standard gauge block at 20 °C
α_S: Coefficient of thermal expansion of standard gauge block
θ_S: Temperature deviation from 20 °C of the standard gauge block (T_{std} – 20 °C)
$\delta\alpha$: Difference in coefficient of thermal expansion between the standard and test gauge block (α-α_S)
$\delta\theta$: Difference in temperature between the standard and test gauge blocks (θ-θ_s)
R: Reading of comparator

Uncertainty budget 400 mm

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i	degrees of freedom ν_i
Standard gauge block	30.61 nm	1	Normal	30.61 nm	∞
Drift of standard gauge block	2.55 nm	1	Rectangular	2.55 nm	200
Uncertainty of drift	21.36 nm	1	Normal	21.36 nm	∞
Instrument error of comparator	11.55 nm	1	Rectangular	11.55 nm	200
Calibration uncertainty of the comparator	60.91 nm	1	Normal	60.91 nm	250
Repeat-ability of measurement readings	57.74 nm	1	Rectangular	57.74 nm	∞
Readability of comparator reading	28.87 nm	1	Rectangular	28.87 nm	∞
Difference in contact deformation	57.74 nm	1	Rectangular	57.74 nm	200
Coefficient of thermal expansion of standard gauge block	2.89x10^-7/°C	1.2x10^7	Rectangular	3.46 nm	200
Temperature deviation from 20 °C of standard gauge block	0.0577 °C	40	Rectangular	2.31 nm	200
Difference in coefficient of thermal expansion between standard and test gauge blocks	4.08x10^-7/°C	1.2x10^8	Rectangular	49.81 nm	200
Difference in temperature between standard and test gauge blocks	0.0577 °C	4320	Rectangular	249.42 nm	200
combined standard uncertainty (k = 1) u_c = 278.3 nm				U = 547.6 nm	k = 1.968

Uncertainty budget 500 mm

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i	degrees of freedom ν_i
Standard gauge block	33.16 nm	1	Normal	33.16 nm	∞
Drift of standard gauge block	21.68 nm	1	Rectangular	21.68 nm	200
Uncertainty of drift	29.50 nm	1	Normal	29.50 nm	∞
Instrument error of comparator	11.55 nm	1	Rectangular	11.55 nm	200
Calibration uncertainty of the comparator	60.91 nm	1	Normal	60.91 nm	250
Repeat-ability of measurement readings	57.74 nm	1	Rectangular	57.74 nm	∞
Readability of comparator reading	28.87 nm	1	Rectangular	28.87 nm	∞
Difference in contact deformation	57.74 nm	1	Rectangular	57.74 nm	200
Coefficient of thermal expansion of standard gauge block	2.89x10^-7/°C	2x10^7	Rectangular	5.77 nm	200
Temperature deviation from 20 °C of standard gauge block	0.0577 °C	50	Rectangular	2.89 nm	200
Difference in coefficient of thermal expansion between standard and test gauge blocks	4.08x10^-7/°C	2.8x10^8	Rectangular	114.31 nm	200
Difference in temperature between standard and test gauge blocks	0.0577 °C	5400	Rectangular	311.77 nm	200
combined standard uncertainty (k = 1) u_c = 352.3 nm				U = 693.1 nm	k = 1.967

8. NMIM

Measurement Function (mathematical model of measurement):

$$\delta L = L(1+\alpha\theta) - L_S(1+\alpha_S\theta_S)$$

$$L = L_S + \delta L - L_S[\delta\alpha\cdot\theta + \alpha_S\cdot\delta\theta]$$

$$L_{20} = L_{S20} + \delta L - L_{S20}(\delta\alpha\cdot\theta + \alpha_S\cdot\delta\theta) + \delta l_{cos} + \delta L_{drift}$$

Definition of variables in the measurement function:

L_{20} : the length test gauge block at 20˚C

δL : measured deviation

L_{S20} : length of standard gauge block at 20˚C

α_S : coefficient expansion of the standard gauge block

α : coefficient expansion of the test gauge block

$\delta\alpha$: different of coefficient expansion between standard and test gauge block

θ_S : temperature deviation of standards gauge block from 20˚C

θ : temperature deviation of test gauge block from 20˚C

$\delta\theta$: different of temperature between standard and test gauge block

δL_{cos} : error due to alignment (cosine error)

δL_{drift} : error due to drift of the standard gauge block

Uncertainty budget

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i		degrees of freedom ν_i
				Absolute	Relative	
$u(L_{S20})$	0.098 µm	1	Normal	0.049 µm		∞
$u(\delta L)$	0.038 µm	1		0.038 µm		5
Repeatability, $u(\delta L_1)$	0.08 µm	1	Normal			4
Resolution, $u(\delta L_2)$	0.01 µm	1	Rectangular			∞
$u(\alpha_S)$	0.000001 /°C	-0.03 L°C	Rectangular		0.00000017L	∞
$u(\delta\alpha)$	0.000001 /°C	-0.47 L°C	Rectangular		-0.0000004L	∞
$u(\theta)$	0.35 °C	0.0000002L/°C			0.0000001L	∞
Temp variation, $u(\theta_1)$	0.50 °C	1	Rectangular			∞
Calibration of temp sensor $u(\theta_2)$	0.03 °C	1	Normal			∞
Resolution, $u(\theta_3)$	0.01 °C	1	Rectangular			∞
$u(\delta\theta)$	0.05 °C	-0.00001L/°C	Rectangular		-0.0000002L	∞
$u(\delta L_{cos})$	0.20 µm	1	Rectangular	0.115 µm		∞
$u(\delta L_{drift})$	0.20 µm	1	Rectangular	0.115 µm		∞
combined standard uncertainty (k = 1) u_c				0.168 µm	0.501L	1937

9. SNSU-BSN

Measurement Function (mathematical model of measurement):

$$l_X = l_S + \delta l_D + \delta l + \delta l_C - L(\bar{\alpha} \cdot \delta\theta + \delta\alpha \cdot \bar{\theta}) + \delta l_V + \delta l_F$$

Definition of variables in the measurement function:

l_S = *length of the reference gauge block at the reference temperature 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 considered;*

$\bar{\alpha}$ =*average of the thermal expansion coefficients of the unknown and reference gauge blocks;*

$\delta\theta$ =*temperature difference between the unknown and reference gauge blocks;*

$\delta\alpha$ = *difference in the thermal expansion coefficients between the unknown and the reference gauge blocks;*

$\bar{\theta}$ =*deviation of the average temperature of the unknown and the reference gauge blocks from the reference temperature;*

δl_V =*correction for non-central contacting of the measuring faces of the unknown gauge*

block.

δl_F =*correction for contact deformation*

source of uncertainty x_i	standard uncertainty $u(x_i)$	sensitive coefficient c_i	probability distribution	uncertainty contribution u_i	degrees of freedom v_i
Readability of instrument $u(l_S)$	0.0029 µm	1	Rectangular	0.0029 µm	∞
Repeatability of measurement $u(\delta l)$	0.0018 µm	1	Type A	0.0018 µm	4
Comparator uncertainty $u(\delta l_C)$	0.0900 µm	1	Normal	0.0900 µm	50
Reference block value L	0.0729 µm	1	Normal	0.0729 µm	∞
	2.04E-7L	1	Normal	2.04E-7L	∞
Drift $u(\delta l_D)$	0.0098 µm	1	Triangular	0.0098 µm	12.5
	1.8E-7L	1	Triangular	1.8E-7L	12.5
Non central contacting $u(\delta l_V)$	0.0064 µm	1	Rectangular	0.0064 µm	12.5
Contact deformation $u(\delta l_F)$	0.0058 µm	1	Rectangular	0.0058 µm	12.5

10. CMS/ITRI

Measurement Function (mathematical model of measurement):

Case 1: The long gauge block measurement system with laser interferometer

The actual size value of long gauge block to be calibrated X = Size value of set zero long gauge block + Reading value of laser interferometer + Temperature correction value.

According to the abovementioned measurement principle, the measurement equation can be derived. As for the calibration result, the source of uncertainty is come from the reading of *L* during measurement, so ...

$$L(1+\alpha\cdot\theta) = L_L\,(1+\alpha_L\cdot\theta_L) + L_s(1+\alpha_s\cdot\theta_s) \quad (1)$$

where

L: the size of long gauge block to be calibrated at 20 ℃

α: the thermal expansion coefficient of long gauge block to be calibrated

θ: the temperature difference with respect to 20 ℃ for long gauge block to be calibrated

L_s: the size of standard long gauge block at 20 ℃

α_s: the thermal expansion coefficient of standard long gauge block

θ_s: the temperature difference with respect to 20 ℃ for standard long gauge block

L_L : the size of laser rule at 20 ℃

α_L: the thermal expansion coefficient of laser rule

θ_L: the temperature difference with respect to 20 ℃ for laser rule

Uncertainty budget

source of uncertainty X_i	standard uncertainty $u(x_i)$	sensitive coefficient C_i	probability distribution	uncertainty contribution u_i	degrees of freedom $\nu(x_i)$
Set long gauge block L_s	22.29 nm	1	Normal	22.29 nm	43
Value reading system of laser interferometer L_L	$[(21.08\ nm)^2 + (3.24\times10^{-8}L)^2]^{0.5}$	1	1	$[(21.08\ nm)^2 + (3.24\times10^{-8}L)^2]^{0.5}$	97
Measurement Repeated L_{L1}	t	20 nm			11
Resolution of positioning sensor tip L_{L3}	Rectangle	5 nm			50
Laser interferometer value reading L_{L4}	Normal	$[(3.17\ nm)^2 + (3.24\times10^{-8}L)^2]^{0.5}$			130.5
Temperature difference of laser beam and long gauge block $\delta\alpha_L$	Rectangle	5.8×10^{-7} °C^{-1}	−0.04L °C	$2.32\times10^{-8}L$	50
Temperature error at test area		0.0168 °C	$[(50\ nm)^2 + (1.05\times10^{-7}L)^2]^{0.5}$	$[(0.84\ nm/°C)^2 + (1.77\times10^{-5}L/°C)^2]^{0.5}$	56.0
Thermal expansion coefficient of laser interferometer α_L	Rectangle	5.77×10^{-8} °C^{-1}	−0.04L °C	$0.231\times10^{-8}L$	50
Temperature difference of laser beam and long gauge block to be calibrated $\delta\theta_L$	Rectangle	0.023 °C	$-1\times10^{-6}L$ °C^{-1}	$2.3\times10^{-8}L$	50
Thermal expansion coefficient difference of set long gauge block and long gauge block to be calibrated $\delta\alpha_s$	Rectangle	0.82×10^{-6} °C^{-1}	-0.04×10^{8} nm/°C	3.28 nm	50
Thermal expansion coefficient of set long gauge block α_s	Rectangle	5.8×10^{-7} °C^{-1}	-1×10^{6} nm °C	0.58 nm	50
Temperature difference of set standard and long gauge block to be calibrated $\delta\theta_s$	Rectangle	0.0115 °C	−1100 nm/°C	12.70 nm	50

Appendix D – Information of the measurement system reported by the participants

1. KRISS

Ever

Short gauge block:

Make and type of instrument(s) ....

The KRISS short gauge block interferometer was originally manufactured by Tsugami and later modified by KRISS for automated operation. It is a conventional gauge block interferometer based on a Twyman–Green configuration.

Light sources / wavelengths used or traceability path (if applicable): ....

Frequency-stabilized lasers with wavelengths of 633 nm, 795 nm, and 895 nm are used to determine the integral part of the interference order, while only the fractional order of the 633 nm interferogram is used to determine the central length of a gauge block. The vacuum wavelength of the 633 nm laser is calibrated against an iodine-stabilized He-Ne laser, and the wavelengths of the other lasers are taken from the literature after verification with a wavemeter.

Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections, thermal expansion correction etc.): ....

The KRISS short gauge block interferometer employs three frequency-stabilized lasers with nominal wavelengths of 633 nm, 795 nm, and 895 nm. The gauge blocks are measured in a vertical orientation, and the refractive index of air is determined using the equation proposed by Boensch and Potulski[1], based on measured values of air temperature, relative humidity, barometric pressure, and carbon dioxide concentration in air. The measurement principle follows the well-known exact-fraction (or excess-fraction) method, in which the excess fraction of each interferogram is evaluated using the Fast Fourier Transform technique. The platens used in the measurements are made of the same materials as the gauge blocks (hardened steel manufactured by Mitutoyo and tungsten carbide manufactured by KOBA), and it was considered that there was no significant difference in surface roughness; therefore, no phase correction was applied. The temperature of each gauge block was measured using an SPRT attached to its side face, and the thermal expansion effect was corrected using the thermal expansion coefficients provided in the technical protocol.

Range of gauge block temperature during measurements & description of temperature measurement method: ....

Temperature was measured using SPRTs. During the short gauge block measurements, the air temperature ranged from 19.065 °C to 20.090 °C, while the gauge block temperature ranged from 19.766 °C to 20.001 °C.

Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC ....

$U = \sqrt{23^2 + (0.19l)^2}$ nm (l in mm) or $U = \sqrt{(23\ \mathrm{nm})^2 + (0.19 \times 10^{-6} l)^2}$

[1] Boensch, G. & Potulski, E., "Measurement of the refractive index of air and comparison with modified Edlén's formulae," *Metrologia*, 35(2), 133-139 (1998).

If the reported uncertainty is significantly bigger than that of the related CMC, explanation for the increased uncertainty ....

Not applicable.

Long gauge block:

Make and type of instrument(s) ....

The KRISS long gauge block interferometer is an in-house-developed measurement system based on a Twyman–Green configuration.

Light sources / wavelengths used or traceability path (if applicable): ....

Frequency-stabilized lasers with wavelengths of 633 nm, 795 nm, and 895 nm are used to determine the integral part of the interference order, while only the fractional order of the 633 nm interferogram is used to determine the central length of a gauge block. The vacuum wavelength of the 633 nm laser is calibrated against an iodine-stabilized He-Ne laser, and the wavelengths of the other lasers are taken from the literature after verification with a wavemeter.

Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections, thermal expansion correction etc.): ....

The KRISS long gauge block interferometer employs three frequency-stabilized lasers with nominal wavelengths of 633 nm, 795 nm, and 895 nm. The long gauge blocks are measured in a horizontal orientation, and the refractive index of air is determined using the equation proposed by Boensch and Potulski[2], based on the measured values of temperature, relative humidity, barometric pressure, and carbon dioxide concentration in air. The measurement principle follows the well-known exact-fraction (or excess-fraction) method, in which the excess fraction of each interferogram is evaluated using the Fast Fourier Transform technique. The platens used in the measurements are made of the same material as the long gauge blocks (hardened steel manufactured by Mitutoyo), and it was considered that there was no significant difference in surface roughness; therefore, no phase correction was applied. The temperature of each long gauge block was measured using a thermistor attached to its side face, and the thermal expansion correction was applied using the thermal expansion coefficient provided in the technical protocol.

Range of gauge block temperature during measurements & description of temperature measurement method: ....

Temperature was measured using thermistors. During the long gauge block measurements, the air temperature ranged from 19.822 °C to 20.104 °C, while the long gauge block temperature ranged from 19.820 °C to 20.100 °C.

Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC ....

KRISS does not yet have a CMC for long gauge block calibration by optical interferometry. The results of this key comparison will serve as supporting evidence for a future CMC submission.

[2] Boensch, G. & Potulski, E., "Measurement of the refractive index of air and comparison with modified Edlén's formulae," *Metrologia*, 35(2), 133-139 (1998).

If the reported uncertainty is significantly higher than that of the related CMC, explanation for the increased uncertainty ....

Not applicable.

2. NIMT

Short gauge block:

Make and type of instrument(s)

The original gauge block interferometer (Twyman-Green) is manufactured by Mitutoyo, Japan but modified optical parts, temperature measuring system and analysis software by National Institute of Metrology (Thailand)

Light sources / wavelengths used or traceability path:

Frequency stabilized HeNe laser, central wavelength 633nm

Frequency stabilized HeNe laser, central wavelength 543nm

Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections etc):

The central length of gauge block was measured by frequency stabilized HeNe laser 633 nm. Both measuring faces of gauge block was wrung with the Quartz platen in a vertical orientation. The phase correction was determined by five-stacking method and applied to the optically measured length of each gauge block. The coefficient of the thermal expansion for gauge block was applied to length of each gauge block. The fringe fraction was determined using 4 point method by means of relation between intensity of fraction fringe measured by optical power meter and the displacement of optical wedge.

Range of gauge block temperature during measurements & description of temperature measurement method:

Gauge block temperature during the measurement is 19.800 - 20.200 degree Celsius using platinum resistance thermometer with precision thermometry bridge and the standard resistor 100 Ohm in oil bath.

Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC

Steel = Q[26, 0.30*10-6L] and Tungsten carbide = Q[26, 0.18*10-6L]

If the reported uncertainty is significantly bigger than that of the related CMC, explanation for the increased uncertainty

N/A

Long gauge block:

Make and type of instrument(s) ....

Universal Length Measuring Machine (ULM) made by Mahr, Germany. Model : 828 CiM.

Light sources / wavelengths used or traceability path (if applicable): ....

Standard gauge block made of steel was calibrated by MIKES, Finland using optical interferometry method.

Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections, thermal expansion correction etc.): ....

The length of gauge block under calibration was determined by comparison with the reference gauge block having the same length and same material using universal length measuring machine (ULM). Both gauge block were placed in a horizontal orientation. The thermal expansion coefficient of gauge block was applied to the length of each gauge block.

Range of gauge block temperature during measurements & description of temperature measurement method:............................

Gauge block temperature during measurement is 20+- 0.3 degree Celsius.

Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC............................

Q[50,0.8*10-6L] for steel gauge block

If the reported uncertainty is significantly higher than that of the related CMC, explanation for the increased uncertainty ....

N/A

3. NIM

Short gauge block:

Make and type of instrument(s) ....

NIM's short gauge block interferometer is homemade. Five step phase stepping method is used for the calculation of the fractions of the interference fringes, and the length of gauge block is measured by the method of exact fractions. In the chamber, the refractive index is obtained by using of the temperature, pressure and humidity measurements of the air.

Light sources / wavelengths used or traceability path: ....

The gauge block interferometer uses two stable lasers as the measuring lights: 633nm and 543nm. The lasers are directly traceable to the wavelength primary standards of NIM.

Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections etc):..

The short steel gauge blocks wringing onto the steel platen. The phase change correction is determined by the stack method.

The tungsten carbide gauge blocks wringing onto the optical flat. The phase change correction is determined by the stack method.

Range of gauge block temperature during measurements & description of temperature measurement method:..

The thermocouples and the platinum resistance thermometers are used to measure the temperatures of the air and the gauge blocks.

The gauge block temperatures during measurement are range from 19.83℃ to 20.20℃.

Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC...

The uncertainty of the claimed CMC of end standards is U = Q[22 nm, 0.2L], k=2, L in mm, values range from 22 nm to 30 nm, the measurement range: (0.5~100)mm, method: interferometry by exact fractions, NMI Internal Service identifier: 4

If the reported uncertainty is significantly bigger than that of the related CMC, explanation for the increased uncertainty ....

NO...

Long gauge block:

Make and type of instrument(s) ....

NIM's short gauge block interferometer is homemade. Five step phase stepping method is used for the calculation of the fractions of the interference fringes, and the length of gauge block is measured by the method of exact fractions. In the chamber, the refractive index is obtained by using of the temperature, pressure and humidity measurements of the air.

Light sources / wavelengths used or traceability path (if applicable): ....

The gauge block interferometer uses two stable lasers as the measuring lights: 633nm and 543nm. The lasers are directly traceable to the wavelength primary standards of NIM.

Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections, thermal expansion correction etc.): ....

The long steel gauge blocks wringing onto a steel platen. The phase change correction is determined by the stack method.

Range of gauge block temperature during measurements & description of temperature measurement method: ....

The thermocouples and the platinum resistance thermometers are used to measure the temperatures of the air and the gauge blocks.

The gauge block temperatures during measurement are range from 19.85℃ to 20.16℃.

Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC ....

The uncertainty of the claimed CMC of end standards is U = Q[70 nm, 0.28L], k=2, L in mm, values range from 78 nm to 289 nm, the measurement range: (125~1000) mm, method: Interferometry by exact fractions. NMI Internal Service identifier: 5

If the reported uncertainty is significantly higher than that of the related CMC, explanation for the increased uncertainty ....

NO.

4. NMIA

Long gauge block:

Make and type of instrument(s)

Pratt & Whitney horizontal measuring machine fitted with custom made length bar mounting & alignment fixtures, Tesa inductive probes and Renishaw ML10 laser interferometer.

Light sources / wavelengths used or traceability path (if applicable):

Renishaw ML10 HeNe laser interferometer calibrated by comparison over a common beam path against Keysight 5519A HeNe laser interferometer, calibrated against NMIA Memlo frequency comb.
Reference 1 mm and 100 mm gauge blocks calibrated by NPL (UK).

Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections, thermal expansion correction etc.):

Comparison against reference gauge blocks and laser interferometer using a pair of Tesa inductive probes as a null indicator. Measurements are made horizontally with the length bar supported at its Airy points and aligned with the axis of measurement. Refractive index corrections for air temperature, pressure and relative humidity are made for the wavelength of the laser interferometer. Temperature corrections for the length bar and reference gauge blocks are made to refer the measured length to 20 deg. C.

Range of gauge block temperature during measurements & description of temperature measurement method:

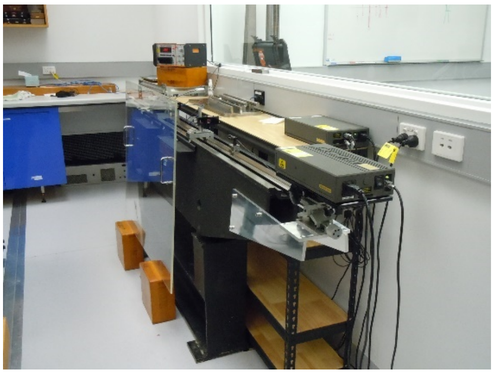
Range: 19.94 deg. C to 20.30 deg. C, using magnetic surface mount sensors from a Renishaw EC10 environmental monitoring unit.

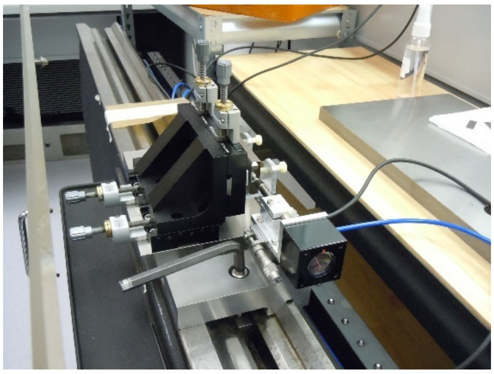
Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC.

1.08.05 Length bars, U95% = Q[94, 1.02 L], L length in millimetres

If the reported uncertainty is significantly higher than that of the related CMC, explanation for the increased uncertainty

For gauge blocks of 400 mm and 500 mm nominal length, the reported uncertainty is less than the currently listed CMC.





5. NMIJ/AIST

Short gauge block:

Make and type of instrument(s) ....

NRLM-TSUGAMI, Twyman-Green interferometer

Light sources / wavelengths used or traceability path: ....

Zeeman stabilized He-Ne laser (633 nm), I_2 stabilized SHG of Nd:YAG laser (532 nm), and Rb stabilized laser diode (780 nm).

Zeeman stabilized He-Ne laser is calibrated by I_2 stabilized offset-locked laser and traceable to the optical frequency comb, which is the Japanese national standard of length. The frequencies of other lasers were confirmed by the optical frequency comb.

Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections etc): ....

A 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. The platens made of steel and BK7 were basically used for steel and tungsten carbide gauge blocks, respectively. The face A of the gauge block of steel 10 mm was difficult to wring on steel platen, therefore it was wrung on a BK7 platen. The difference of phase change on reflection at gauge block and platen were corrected by stack method in the cases the materials of gauge block and platen were different. The gauge blocks were measured in vertical orientation, however no compression correction was made.

....

Range of gauge block temperature during measurements & description of temperature measurement method: ....

From 19.97 °C to 20.04 °C. Two Pt temperature sensors were attached to gauge blocks of 100 mm. One sensor was attached to gauge blocks of 75 mm. The temperature of gauge blocks shorter than 75 mm were assumed to be the same as air temperature. The ratio of resistance of the Pt sensors to a standard resistance were measured by AC bridge and converted to temperature.

....

Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC ....

Q[23.4, 0.104*L*] nm, L in mm. Values range from 23 nm to 26 nm for L = 0.5 mm to 100 mm. It has no identifier.

If the reported uncertainty is significantly bigger than that of the related CMC, explanation for the increased uncertainty ....

The CMC is for the case of tungsten carbide gauge block whose uncertainty of thermal expansion coefficient is smaller than that used in this comparison. Therefore, the reported uncertainty is bigger than the CMC. Extra uncertainty of difference by wringing faces was added for the gauge block whose abs(e_c^A-e_c^B) exceeds 10 nm. In this measurement, steel 5 mm, 75 mm, tungsten carbide 2 mm, 3 mm, and 75 mm showed large difference. The gauge block of steel 75 mm had a bump on the edge of the face A and it may have cause the difference. (The gauge blocks of steel 10 mm and 3 mm also had a bump on the edge, however its effect on the measured length were seemed to be small.) The reason of the large difference by wringing faces of other gauge blocks might be the flatness of faces.

....

Long gauge block:

Make and type of instrument(s) ....

NRLM design, Twyman-Green interferometer ....

....

....

Light sources / wavelengths used or traceability path (if applicable):...

I_2 stabilized offset-locked He-Ne laser (633 nm), I_2 stabilized SHG of Nd:YAG laser (532 nm), and Rb stabilized laser diode (780 nm). The frequencies of the lasers were confirmed by the optical frequency comb.

....

Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections, thermal expansion correction etc.):..

A 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. The platens made of steel were used. No phase change correction was made. The gauge blocks were measured in horizontal orientation.

....

....

....

....

Range of gauge block temperature during measurements & description of temperature measurement method: ....

From 19.98 °C to 20.03 °C. Three Pt temperature sensors were attached to each gauge block. The ratio of resistance of the Pt sensors to a standard resistance were measured by AC bridge and converted to temperature.

....

....

Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC ....

Q[20.2, 0.170*L*] nm, L in mm. Values are 71 nm and 87 nm for L = 400 mm and 500 mm, respectively. It has no identifier.

If the reported uncertainty is significantly higher than that of the related CMC, explanation for the increased uncertainty ....

....

....

6. MSL

Short gauge block:

Make and type of instrument (s):

Modified Hilger Gauge Measuring Interferometer type TN190.

Customised zirconia ceramic interferometer platen manufactured by Opus Metrology.

Light sources / wavelengths used for traceability path:

Hewlett Packard HP5519A Laser Head.

Description of measuring Technique (including any corrections such as phase correction and platen material, vertical to horizontal correction etc):

The deviation from nominal length was measured using an NPL-Hilger Type TN190 gauge block interferometer according to technical procedure MSLT.L.005.005. The gauge block interferometer is modified to allow semi-automatic data collection for the fringe patterns and analysis of the fringe images.

The primary light source used in the measurements was a frequency-stabilised and calibrated Helium-Neon laser source at 633 nm. A secondary light source was used to confirm measurements made with the Helium-Neon laser. The secondary light source was the 546 nm emission line of a high-pressure mercury-198 discharge lamp.

A surface correction of -12 nm to allow for the different surface properties of the gauges and the wringing platen was determined by the stack method and applied to the measured lengths.

An orientation correction to allow for the deformation of each gauge under its own weight in the vertical orientation has also been applied.

Deviation is defined as the measured length minus the nominal length.

Range of gauge block temperatures during measurements and description of temperature measurement method:

The air temperature between the interferometer platen and the optical flat was in the range 19.95 °C to 20.11 °C. The temperature of the interferometer platen was in the range 19.91 °C to 20.09 °C.

Relevant 95% CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of CMC:

Q[30, 0.4L], L in mm, values range from 30 nm to 50 nm, identifier MSL/4.

7. MUSSD

Long gauge block:

Make and type of instrument(s)

Mahr 130B-16 comparator: 600 mm range

KOBA grade K steel gauge block: 500 mm, serial number: 87356

KOBA grade K steel gauge block: 400 mm, serial number: 87374

(Gauge blocks are PTB calibrated in 2020)

AHLBORN - ALMEMO 2590 multichannel precision thermometer

TESA monochromatic light unit (wavelength = 575 nm)

MITUTOYO 45 mm optical flat

Light sources / wavelengths used or traceability path (if applicable):

Not Applicable

Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections, thermal expansion correction etc.):

All gauge blocks (400 mm and 500 mm test and reference) were cleaned first.

Both blocks were checked for the surface conditions by interferometry using the monochromatic light unit and an optical flat of 45 mm diameter. Straight line fringe patterns can be observed on both gauge block faces.

Both test gauge block and the reference gauge block were placed for thermal stabilization about 9 hours before the calibration.

Test gauge block was compared with the reference gauge block. Five repeated measurements were taken.

The measurement cycle is "reference-test-reference-test" and so on.

The thermal expansion coefficient of the test gauge blocks was assumed as 10.8×10^{-6} °C^{-1}

The difference in thermal expansion coefficients between the two gauge blocks is taken as

11.5×10^{-6} °C^{-1} $- 10.8 \times 10^{-6}$ °C^{-1} $= 0.7 \times 10^{-6}$ °C^{-1}

The variation of the thermal expansion coefficient of the reference gauge blocks is taken to be

$\pm 0.2 \times 10^{-6}$ °C^{-1}

Range of gauge block temperature during measurements & description of temperature measurement method:

The maximum temperature variation is within the range 20.0 ± 0.5 °C approximately.

Temperature of both gauge blocks was measured separately with contact temperature sensors. Additionally, the ambient temperature was measured using a third sensor.

Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC

Impossible to claim CMC for long gauge blocks because of the scratching of gauge block faces during the calibration which leads to unpredictable measurement errors.

If the reported uncertainty is significantly higher than that of the related CMC, explanation for the increased uncertainty

We assume that the uncertainty is significantly higher than the CMC expected because of the technical problem given above.

8. SCL

Long gauge block:

Make and type of instrument(s) ....

1. Standard gauge block set: Make: OPUS, Model: - .... :

2. Comparator: Make: Carl Zeiss Jena, Model: ULM 01-600 C...

Light sources / wavelengths used or traceability path (if applicable): N/A ....

Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections, thermal expansion correction etc.): ....

Measurement by comparison against standard gauge block using a comparator. Standard gauge block and test gauge block were supported horizontally at Airy points.

....

....

....

Range of gauge block temperature during measurements & description of temperature measurement method:...

Range of gauge block temperature during measurement: 19.41 °C to 19.85 °C. The gauge block temperature was obtained by temperature sensors attached to gauge block. ....

....

....

Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC..

Existing CMC: Q[395, 4L] nm, L in mm Identifier: SCL/2.2.2-01...

....

If the reported uncertainty is significantly higher than that of the related CMC, explanation for the increased uncertainty..

N/A ....

....

9. NMIM

Short gauge block:

Make and type of instrument(s)

NPL-TESA gauge block interferometer based on Twyman-Green Interferometer.

Model No.: AGI300.

Serial No.: 303.

Light sources / wavelengths used or traceability path:

Two frequency-stabilized He-Ne lasers with wavelengths 633 nm and 543 nm were used. The 633 nm frequency-stabilized He-Ne laser is calibrated using NMIM primary iodine-stabilized He-Ne laser while 543 nm frequency-stabilized He-Ne laser is traceable to NPL.

Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections etc):

The gauge blocks were calibrated by interferometric measurement using the exact-fraction method. Gauge blocks were wrung onto platen of same material. For Face A measurement, Face B was wrung and left in the chamber for at least 3 hours for acclimatization. To take the measurement, gauge block was positioned horizontally, parallel to the marker on screen and observed using a CCD camera linked to a PC. The gauge blocks were measured at least 5 times using the computer software and automatically compensated corrections due to temperature, humidity and pressure. The steps were repeated for Face B measurement by wringing Face A to the platen. Phase correction was measured by stacking 4 gauge blocks.

Range of gauge block temperature during measurements & description of temperature measurement method:

Range of gauge block temperature during measurements: From 19.3 to 20.3 °C

Temperature measured using 3 PT100 probes for platen, air and gauge block.

Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC

Q [30, 0.30L] nm, L in mm. Identifier: NMIM/5.

If the reported uncertainty is significantly bigger than that of the related CMC, explanation for the increased uncertainty………

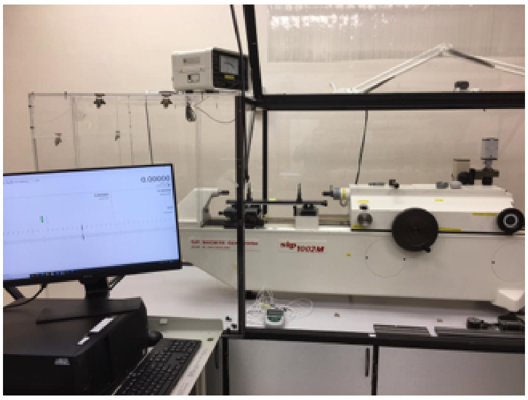
Reported uncertainty for steel gauge block at k=1 is [14,0.29L] nm. Uncertainty for CMC at k=1 is [15,0.15L] nm. Relative part on reported uncertainty is slightly bigger than CMC due to larger recent uncertainty of calibrated PT100 probes.

Long gauge block:

Make and type of instrument(s):

The maker of the reference gauge block used is OPUS, grade K which is made from steel. The serial no is 13914L (400 mm) and 13915L (500 mm).

The comparator used is SIP with SIP smart interface. The serial no is 1006 and model no is 1002M. The type of the comparator is only able to measure central length of the gauge blocks.



Light sources / wavelengths used or traceability path (if applicable):

The measurement method used is mechanical comparison which the reference standard used is traceable to NMIJ

Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections, thermal expansion correction etc.):

If the reference gauge block is referred to as R and the test gauge block as T, the sequence of the measurement for central length is done by the pattern as follow: R-T-R-T-R-T-R. Both gauge block is aligned at the airy point horizontally side by side.

Range of gauge block temperature during measurements & description of temperature measurement method:

Range of gauge block temperature during measurements is from 19.5 °C to 20.3 °C . Temperature measured using 2 PT100 probes for test and reference gauge block

Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC:

Q [364, 0.978L] nm, L in mm. Identifier: NMIM/6

If the reported uncertainty is significantly higher than that of the related CMC, explanation for the increased uncertainty ....

....

....

10. SNSU-BSN

Long gauge block:

Make and type of instrument(s) :

Type and model of instrument: Comparator using two contacting probe, model ULM 1000, serial number 5355028.

Manufacturer : Mahr.

Contact tips: spherical end, material tungsten carbide, radius 25 mm.

Measuring force of probe : 2.5 N

Light sources / wavelengths used or traceability path (if applicable): -

Traceable through standard gauge blocks grade K calibrated by NPL UK

Description of measuring technique (including any corrections such as phase correction & platen material, vertical to horizontal corrections, thermal expansion correction etc.):

Long gauge block measurement was performed by comparative method with standard gauge blocks grade K by using ULM 1000 machine. Both artefact and standard gauge block had same nominal length and same material. Material of standard gauge block is steel, manufactured by Koba with CTE is 11.5 x 10^{-6}/K

Range of gauge block temperature during measurements & description of temperature measurement method:

Range of gauge block temperature during measurements were 19.96 °C to 20.04 °C for 400 mm length of gauge block and 19.99 °C to 20.03 °C for 500 mm length of gauge block. They were measured by using surface temperature sensors located on long gauge blocks both UUT and reference block.

Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC :

Existing CMC of SNSU-BSN is Q[0.24, 0.001L] µm, L in mm. NMI service identifier of existing CMC is 202

If the reported uncertainty is significantly higher than that of the related CMC, explanation for the increased uncertainty : -

11. CMS/ITRI

Long gauge block:

Make and type of instrument(s) ....

Case 1 : homemade by itri , The long gauge block measurement system with laser interferometer.

Light sources / wavelengths used or traceability path (if applicable): ....

The wavelengths is 633nm.

Description of measuring technique (including any corrections such as phase correction & platen material,vertical to horizontal corrections, thermal expansion correction etc.): ....

No.

Range of gauge block temperature during measurements & description of temperature measurement method: ....

Case 1: The range of gauge block temperature is (20±0.04) ℃..

Case 2: The range of gauge block temperature is (20±0.3) ℃..

Relevant 95 % CMC uncertainty claim for the service(s) related to this comparison topic (if existing) and identifier of the CMC..............................

Case 1: The CMC uncertainty claim $((67^2+(365*L)^2)^{0.5}$, L in m.

Case 2: The CMC uncertainty claim $((84^2+(735*L)^2)^{0.5}$, L in m.

If the reported uncertainty is significantly higher than that of the related CMC, explanation for the increased uncertainty ....

The reported uncertainty is same as CMC .

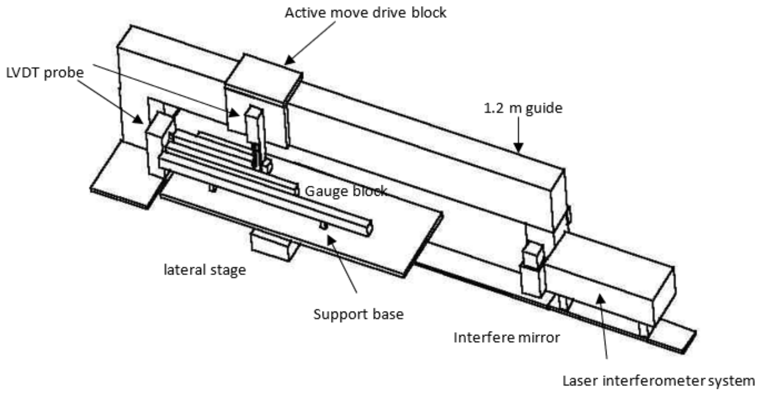


Fig. 1 Illustration of long gauge block calibration system

Appendix E – Results of CMS/ITRI using a universal measuring machine

CMS/ITRI submitted additional measurement results of long gauge blocks calibrated by a mechanical comparison method using a universal measuring machine. As the participants of this key comparison was asked to use the measurement method having the smallest uncertainty in the lab, the results shown in this appendix were not used in determining the KCRV. However, the results are shown here so that CMS/ITRI may use this appendix as the supporting evidence for their future CMC (of long gauge block calibration by mechanical comparison method) submission.

The measurement results obtained using a universal measuring machine of NIM are shown in Table E-1.

Table E-1. Submitted results

Case2: The long gauge block calibration system bases on Universal bases on Universal Measuring System.

Long gauge blocks, steel				
l_n / mm	Serial number	Deviation of central length from nominal length Material / µm	$u(e_c)$ /µm	
400	160259	**-0.09**	**0.16**	**1.98**
500	160115	**-0.32**	**0.19**	**1.98**

Functional form of standard uncertainty

Gauge block set	a / nm	b / 1	Comment
Long, steel	**84**	**740**	l_n unit: m

Since the KCRVs of the 400 mm and 500 mm long gauge blocks for CMS are 3 nm ± 25 nm (k = 1) and −210 nm ± 30 nm (k = 1), respectively, the corresponding DoE and E_n values are presented in Table E-2. In the calculation of E_n value, the following equation was used.

$$E_n = \frac{x_{CMS} - x_{KCRV}(t_{CMS})}{2\sqrt{\left[u(x_{CMS})\right]^2 + \left[u(x_{KCRV}(t_{CMS}))\right]^2}}$$

Table E-2. E_n value of CMS' 2nd result

l_n	x_{CMS}	$u(x_{CMS})$	x_{KCRV}	$u(x_{KCRV})$	E_n
400	-90	160	3	25	-0.287
500	-320	190	-210	30	-0.286

Since $|E_n|$ values are all smaller than 1, CMS' 2nd measurement results using a universal measuring machine can be used to underpin the future CMC submission of CMS.

End of document