Report on SIM.4.2 Regional Comparison

Stage Two: Calibration of Gauge Blocks by Mechanical Comparison

Final Report — August 14, 2002

J. E. Decker[1], J. Alschuler, J. Castillo Candanedo, E. De la cruz, E. Prieto Esteban, R. Morales, J. C. Valente de Oliveira, J. Stone, J. Stoup, J. R. Pekelsky

Dimensional Metrology Program
Institute for National Measurement Standards (INMS)
National Research Council Canada (NRC)
Ottawa, CANADA K1A 0R6

Abstract

Results of the Stage Two portion of the Inter-American System of Metrology (SIM) regional international comparison of gauge block calibration by mechanical comparison are presented. This measurement round-robin employed the same short gauge blocks that were used in Stage One, measurement by optical interferometry. The gauge blocks, 6 made of steel and 6 made of tungsten carbide, ranging in nominal length from 2 mm to 100 mm, were calibrated by 9 national metrology institutes of the SIM region. Laboratories used various techniques to establish traceability to the definition of the metre. Results of central length calibration are presented and discussed with regard to traceability, temperature control, mechanical calibration employing dissimilar materials, and the relationship with Stage One of the comparison. Measurement uncertainty evaluation is also discussed.

[1]207 M-36 Montreal Road, NRC, Ottawa, CANADA, K1A 0R6, tel. (613)991-1633, fax. (613)952-1394, e-mail: jennifer.decker@nrc.ca

1 Introduction

The Sistema Interamericano de Metrología (SIM) Regional Comparison of gauge block calibration SIM.4.2 is intended both as an exercise whereby participating national metrology institutes are able to test their measurement systems, and to provide a link to the CCL key comparison CCL-K1 "Calibration of gauge blocks by interferometry" [1] as means of support for the BIPM Mutual Recognition Arrangement (MRA). The SIM region includes the countries of the Americas.

There are two stages to the SIM.4.2 Regional Comparison of gauge block calibration. In the first stage, an ensemble of 12 gauge blocks was circulated to laboratories offering gauge block calibration by the technique of optical interferometry (June 1998 – November 1999). The second stage of the comparison involves the same gauge blocks, now circulated to laboratories offering gauge block calibration by mechanical comparison. This report provides the details and results of the second stage of this international comparison during the time period of June 1999 to June 2001, in addition to plots of results of both comparisons combined. Circulating the same gauge blocks for both Stages also allows for observation of the link between the gauge block calibration by optical interferometry and mechanical comparison.

2 Participants

Laboratories participating in this comparison represented countries of the SIM region and the EUROMET region. Participating laboratories are listed in Table 1, and the dates during which the gauge blocks were present at each lab in Table 2.

3 Gauge Block Artefacts

A total of 12 rectangular gauge blocks, ISO 3650 Grade K, were selected for this comparison. Nominal lengths of the gauge blocks represented the general range of short gauge blocks received for client calibration, and also echo the short gauge blocks used in the CCL–K1 key comparison [1]. Gauge block materials of steel (CARY, Switzerland) and tungsten carbide (Select, UK) were selected as representative of the bulk of gauge block materials seen in client calibrations. Nominal lengths of steel gauge blocks are: 2, 5, 8, 10, 50, 100 mm, and for tungsten carbide: 2, 5, 8, 20, 50, 100 mm.

Thermal expansion coefficients for the gauge blocks were not measured, rather the values provided by the manufacturer were used without additional verification. The value used for the linear thermal expansion coefficient of steel was 11.5×10^{-6}/K, and for tungsten carbide was 5.0×10^{-6}/K.

A data logger was purchased for the shipping case containing the gauge blocks. Results of temperature and humidity measurements during the travel time of the gauge blocks beginning from the November 1999 re-calibration of the gauge blocks by the pilot lab are shown in Figures 1 and 2 respectively. Temperature readings are accurate to ± 2°C; humidity readings are accurate to $\pm 5\%$ at 25°C and 60% relative humidity. Based on the data in these plots, the gauge blocks were not subjected to temperatures above 35°C, nor below 5°C. Humidity above 50% could induce corrosion, however the gauge blocks were typically coated with corrosion inhibiting coating during travel and no signs of rampant rusting were observed.

Laboratory	*Contact Information*	*Phone, E-mail*
INTI	Jeronimo Altschuler Parque Tecnolgico Miguelete: Av. General Paz entre Albarellos y Constituyentes CC 157 - (1650) San Martin Buenos Aires, Argentina	Tel. +54 11 4752-5402 Fax +54 11 4713-4140 e-mail: jeroa@inti.gov.ar
NIST	John Stoup National Institute of Standards and Technology (NIST) Room B113, Metrology Building Gaithersburg, MD 20899-0001 USA	Tel. +1 301 975 3476 Fax +1 301 869 0822 e-mail: John.Stoup@nist.gov
CEM	Emilio Prieto Esteban Centro Espanol de Metrologia (CEM) Alfar, 2 - 28760 Tres Cantos Madrid Spain	Tel. +34 91 8074 716 / 700 Fax +34 91 8074 807 e-mail: eprieto@mfom.es
MDSIC	Juan Pablo Angel Metrology Division of Superintendencia de Industria y Comerico Santa Fe de Bogota, Columbia	Phone: (571)315-3267, 315-3269 Fax: (571)315-3292 e-mail: superin8@latino.net.co
INDECOPI	Jose Dajes National Metrology Service Calle La Prosa 138 Lima 41, Peru	Tel.: +51 (1) 224-7800 Fax: +51 (1) 224-0348 e-mail: metjdaj@indecopi.gob.pe
LPMP/UTP	Mariela S. de Villalaz Laboratorio Primario de Metrologia Universidad Tecnologica de Panama Campus Octavio Mendez Pereira Apartado 6-2894 El Borado, Panama	Tel.: +507 (2) 27-4749 Fax: +507 (2)25-7724 e-mail: mvillala@utp.ac.pa
INMETRO	Jose Carlos Valente de Oliveira Av. N. S. das Gracas 50 Duque de Caxias, Rio de Janeiro, Brazil	Tel. +55 21 679-9036 Fax. +55 21 679-1505 e-mail: jcoliveira@inmetro.gov.br
LCPN-L	Roberto Morales Laboratorio Nacional de Longitud (DiCTUC) Red Nacional de Metrologia Av. Vicuna Mackenna 4860 Macul Casilla 306, Correo 22 Santiago, Chile	Tel. +56-2 686 44 03 56-2 686 40 65 Fax. +56-2 686 58 89 e-mail: lcpn-l@ing.puc.cl
NRC (pilot)	Jennifer Decker Institute for National Measurement Standards National Research Council (NRC) Canada Ottawa, K1A 0R6 Canada	Tel. +1 613 991 1633 Fax +1 613 952 1394 e-mail: Jennifer.Decker@nrc.ca

Table 1: Participants of SIM.4.2 regional comparison of gauge block calibration by mechanical comparison.

Laboratory	*Dates of Measurement*	*Results Received*
NRC (Canada – pilot)	June 1998	—
INTI (Argentina)	March, April 1999	11 June 1999
NIST (USA)	June, July 1999	13 January 2000
NRC (Canada – pilot)	October 1999	—
CEM (Spain)	December 1999 – January 2000	28 April 2000
MDSIC (Columbia)	23 February – 30 March 2000	15 May 2000
INDECOPI (Peru)	1 June 2000 – July 2000	10 July 2000
LPMP (Panama)	13 July – 14 August 2000	17 October 2000
INMETRO (Brazil)	22 November 2000	blocks immediately forwarded to pilot without measurement
NRC (Canada – pilot)	13 December 2000 – 15 January 2001	—
INMETRO (Brazil)	8 February – 14 March 2001	22 March 2001
LCPN-L (Chile)	27 March – 9 May 2001	20 April 2001
NRC (Canada – pilot)	17 May – June 2001	—

Table 2: Tour circuit of the 12 gauge blocks in Stage Two of the SIM.4.2 regional comparison of gauge block calibration by mechanical comparison.

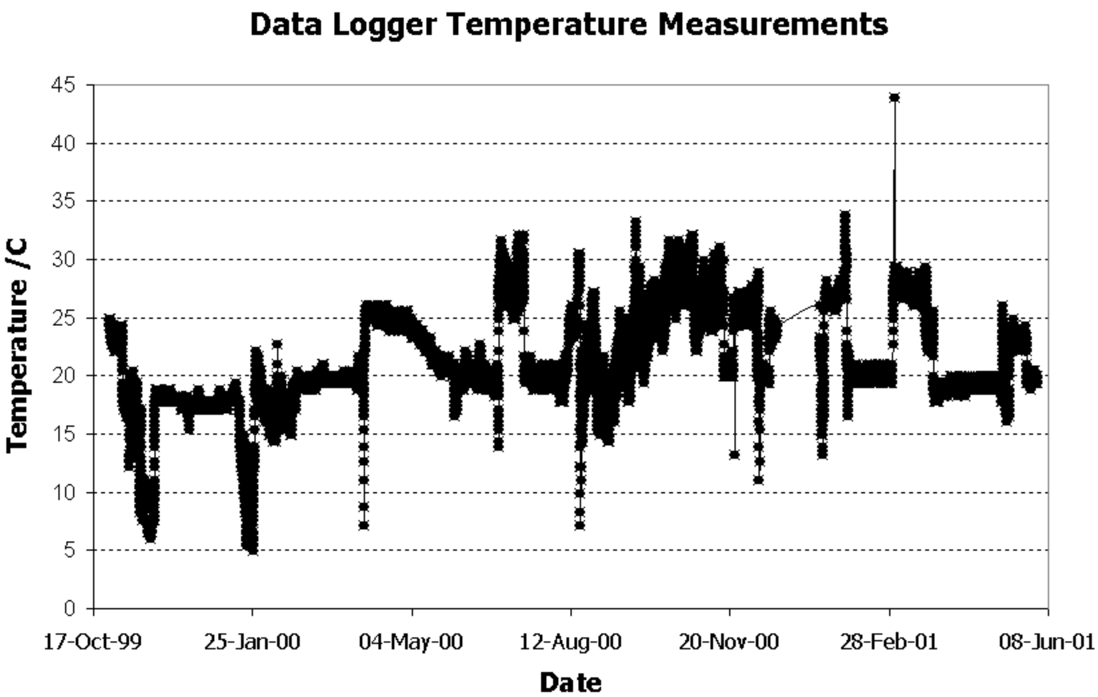

Figure 1: Results of data logger reading temperature inside the travel case during the time of the comparison. Readings are accurate to ±2°C.

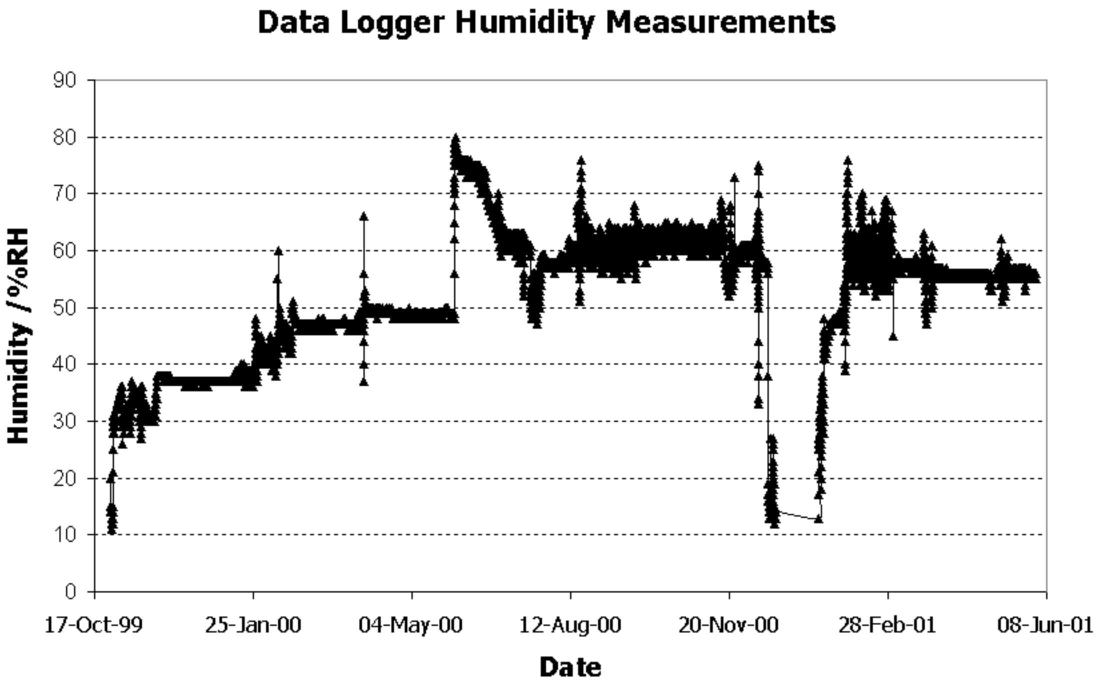

Figure 2: Results of data logger reading humidity inside the travel case during the time of the comparison. Readings are accurate to ±5% at 25°C and 60% relative humidity.

4 Calibration Technique

This report outlines the results of SIM.4.2 gauge block calibrations by mechanical comparison. Some laboratories calibrated the gauge blocks using both interferometry and mechanical comparison, however this report focuses on mechanical comparison calibrations. The pilot lab, NRC calibrated the gauge blocks by optical interferometry only, since NRC does not have capability for mechanical comparison gauge block calibration.

The protocol document provided detail as to the reporting of the calibration results and measurement uncertainty. A model for the evaluation of the measurement uncertainty was provided, along with an example.

Participants were requested to calibrate the gauge blocks in the same manner as they would for client calibrations. All laboratories participating in this comparison used mechanical comparators with opposed stylii configuration, and where the calibrated reference standard gauge block has the same nominal length as the test gauge block. The length difference between the reference standard and test gauge blocks is measured with high resolution, and the length of the test gauge block is then determined with respect to the calibrated reference standard length. The model equation for this measurement is discussed with respect to the uncertainty evaluation below.

Table 3 summarizes details of the equipment used by each laboratory. Most laboratories establish traceability to the SI definition of the metre in-house by means of optical interferometry. Some laboratories establish traceability by sending their reference standard gauge blocks to an accredited laboratory for calibration. Details are provided in Table 3.

Participants were requested to report the material of the reference standard gauge blocks along with any correction values applied to account for differences is elastic stylus deformation between the reference standard

Laboratory	*Instrument*	*Traceability of Reference Standards*
NRC	NRC Twyman-Green [2, 3] Interferometer He-Ne lasers 633, 543, 612 nm	NRC primary standard laser
INTI	Mahr Model 826-E	interferometry at INTI
NIST	Federal Products	interferometry at NIST
CEM	TESA UPC 59.30003	interferometry at CEM
MDSIC	Mahr 626 E	Steel gauge blocks (4346 PTB 97)
INDECOPI	Mahr 826E Millitron 1240	768-DKD-K-04501-98-02 (Germany)
LPMP	Mahr Millitron 1240	85-DKD-K-09001-96-11 (Germany)
INMETRO	TESA UPC	interferometry at INMETRO
LCPN-L	TESA UPC	PTB (Germany)

Table 3: Summary of instrumentation and traceability for gauge block calibration by mechanical comparison of the SIM 4.2 Regional Comparison.

	Steel Gauge Blocks		Tungsten Carbide Gauge Blocks	
	Reference Standard Material	Deformation Correction /nm	Reference Standard Material	Deformation Correction /nm
INTI	steel (Cary)	0	tungsten carbide (Select)	0
NIST	steel	0	chromium carbide	−12
CEM	steel	0	tungsten carbide	0
MDSIC	steel	0	steel	−100 to −120
INDECOPI	steel	0	steel	−50
LPMP	steel	0	–	–
INMETRO	steel	0	tungsten carbide	0
LCPN-L	steel	0	steel	−61

Table 4: Summary of reference standard materials and sylus deformation corrections for mechanical comparison calibrations. NIST stylus radius = 3.175 mm for unused sylii.

and the test gauge blocks. These data are listed in Table 4.

5 Comparison Data

Following convention, gauge block central length l is reported as a deviation d from nominal length L,

$$d = l - L \tag{1}$$

where a plus sign indicates that the gauge block is longer than the nominal length, and a minus sign that it is shorter.

Tables 5 and 7 tabulate the deviation from nominal length reported by each participant, and Tables 6 and 8 the standard uncertainties reported. In regard to the December 2000 pilot lab measurement of the gauge blocks, NRC would not typically report a length value for the 5 mm steel gauge block due to compromised

Nominal Length /mm	Deviation from Nominal Length for Steel Gauge Blocks /nm									
	INTI	NIST	NRC	CEM	MDSIC	INDECOPI	LPMP	NRC	INMETRO	LCPN-L
2	24	60	2	40	31	30	43	31	33	20
5	-54	-36	-78	-30	-92	-70	-48	—	-64	-60
8	46	82	16	60	21	50	51	60	59	30
10	19	25	-7	30	-30	10	36	15	11	-10
50	17	33	30	30	-2	110	110	45	-22	10
100	-93	-128	-119	-120	-90	-60	42	-93	-80	-120

Table 5: Central length expressed as deviation from nominal length reported by each participant for mechanical comparison calibration (NRC by interferometry) of steel gauge blocks (nm units).

Nominal Length /mm	Standard Uncertainties for Steel Gauge Blocks /nm									
	INTI	NIST	NRC	CEM	MDSIC	INDECOPI	LPMP	NRC	INMETRO	LCPN-L
2	23	13	14	28	19	30	74	14	18	28
5	23	14	14	28	20	30	75	—	18	28
8	23	13	14	28	21	31	76	14	18	28
10	24	14	14	28	22	32	77	14	19	28
50	37	17	18	34	34	44	104	15	25	35
100	63	28	26	47	50	62	150	20	35	50

Table 6: Combined standard uncertainty attributed to steel gauge block central length measurement by mechanical comparison as reported by each participant (nm units).

wringing as a result of deleterious wear. The average deviation from nominal length measured by NRC in December 2000 for right hand wringing is -55 nm, and for left hand wringing is $+80$ nm. Similarly, NRC was not able to complete the closure measurement on the 8 mm tungsten carbide gauge block because of the effect of wear on the wringing. LPMP (Panama) withdrew their results for tungsten carbide gauge blocks altogether, due to technical difficulties they experienced during the time that the SIM.4.2 Comparison gauge blocks were in their lab. The closure measurements by the NRC Pilot were completed on 29 June 2001.

Central length values measured by mechanical comparison are plotted in Figures 3 to 14. The Pilot measurements (NRC) by optical interferometry are included in the plots for information.

6 Measurement Uncertainty

Laboratories were requested to adhere as much as possible to the measurement uncertainty evaluation found in the ISO *Guide to the Expression of Uncertainty in Measurement* [5], §H.1 Annex H: Examples, and also detailed in [6]. A brief version of this example was provided in the protocol document.

A conventional model equation for the gauge block measurement by mechanical comparison is

$$l = d + l_s(1 + \alpha_s\theta_s - \alpha\,\delta\theta - \alpha\theta_s) \tag{2}$$

Nominal Length /mm	Deviation from Nominal Length for Tungsten Carbide Gauge Blocks /nm								
	INTI	NIST	NRC	CEM	MDSIC	INDECOPI	NRC	INMETRO	LCPN-L
2	-23	-3	-27	0	-9	20	-9	-17	-41
5	5	14	4	10	-24	40	21	4	-11
8	34	44	31	20	7	60	44	29	19
20	4	1	9	0	-65	80	22	25	-1
50	-32	-20	-22	-50	-84	100	-15	-38	5
100	-52	-16	-35	-90	50	400	-29	-18	59

Table 7: Central length expressed as deviation from nominal length reported by each participant for mechanical comparison calibration (NRC by interferometry) of tungsten carbide gauge blocks (nm units).

Nominal Length /mm	Standard Uncertainties for Tungsten Carbide Gauge Blocks /nm								
	INTI	NIST	NRC	CEM	MDSIC	INDECOPI	NRC	INMETRO	LCPN-L
2	23	13	14	28	66	30	13	18	28
5	23	13	14	28	67	30	13	18	28
8	23	16	14	28	67	31	13	18	28
20	25	16	15	28	67	35	13	20	29
50	34	20	18	30	68	46	14	25	33
100	56	31	26	37	71	67	17	33	44

Table 8: Combined standard uncertainty attributed to tungsten carbide gauge block central length measurement by mechanical comparison as reported by each participant (nm units).

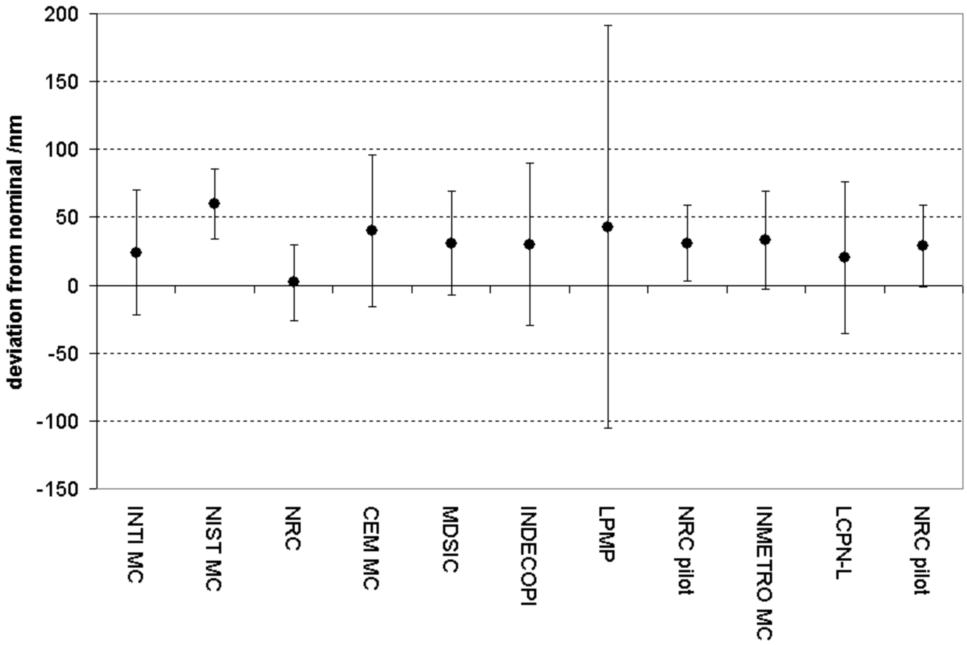

Figure 3: Plot of central length reported by each participant for the 2 mm steel gauge block. Error bars represent the k=2 expanded uncertainties submitted by the participants.

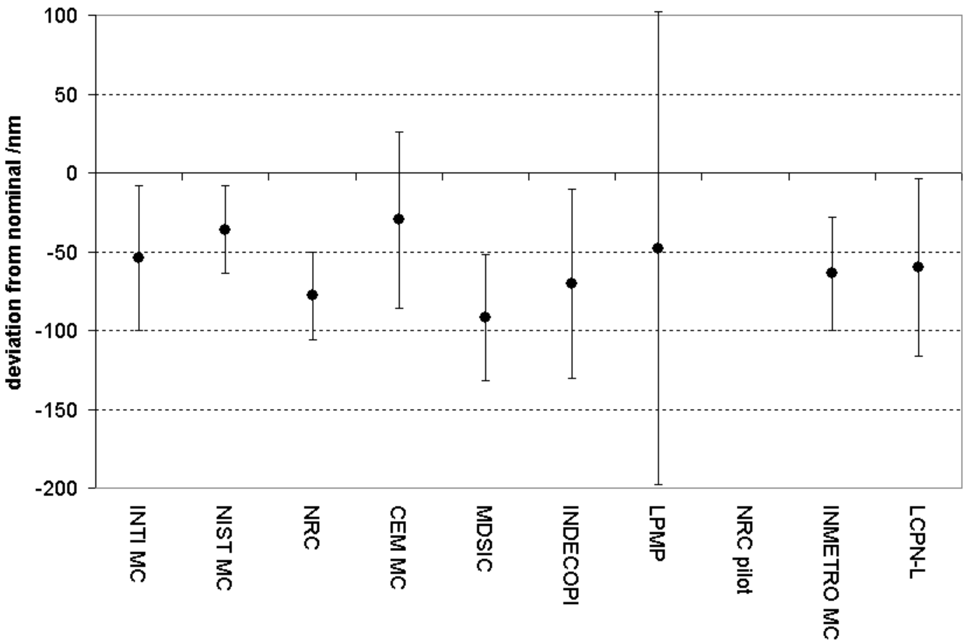

Figure 4: Plot of central length reported by each participant for the 5 mm steel gauge block. Error bars represent the k=2 expanded uncertainties submitted by the participants. Some NRC calibrations by interferometry are missing because the wringing of gauge block was damaged during the comparison.

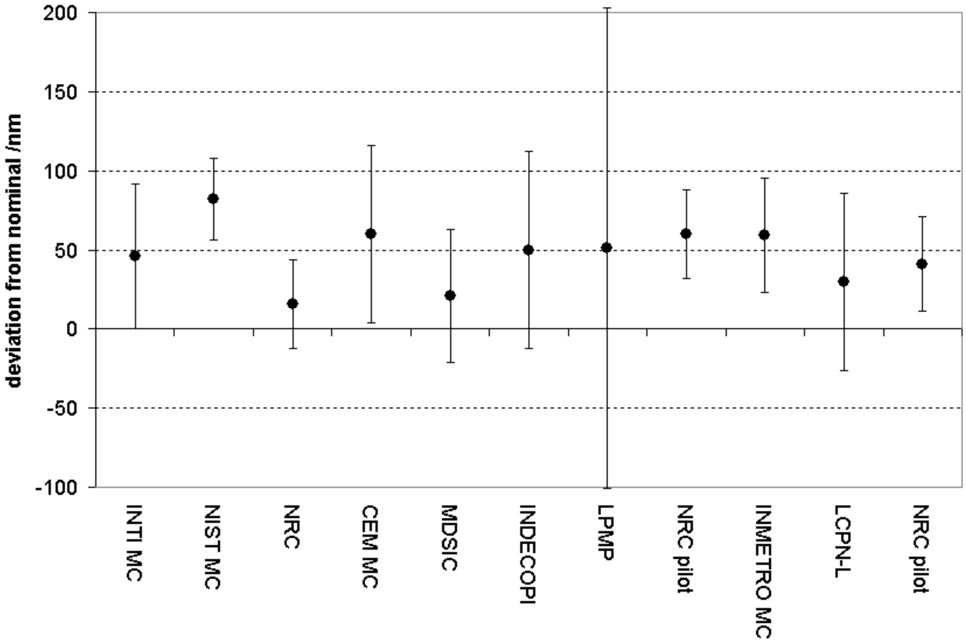

Figure 5: Plot of central length reported by each participant for the 8 mm steel gauge block. Error bars represent the k=2 expanded uncertainties submitted by the participants.

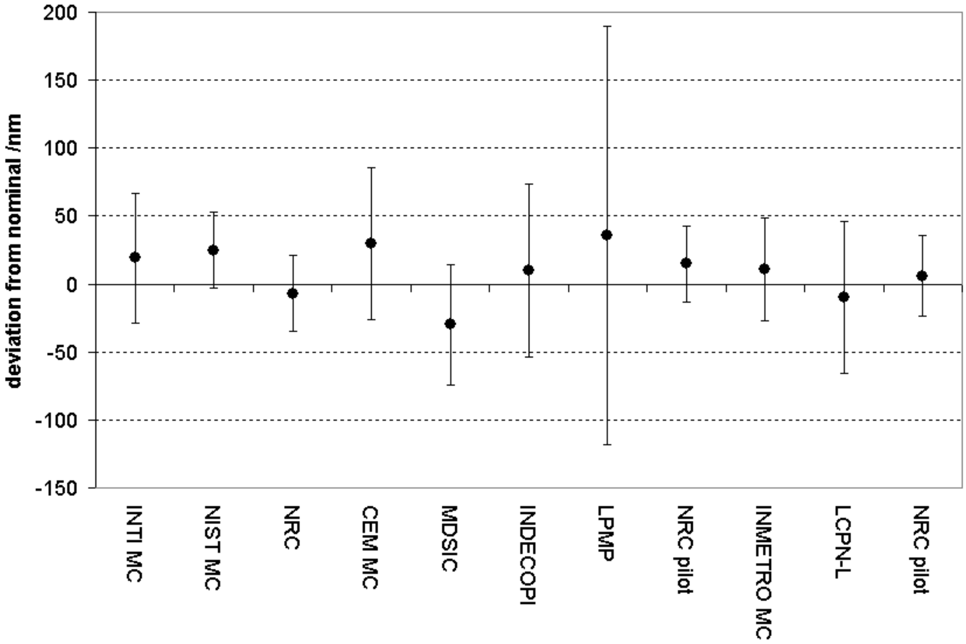

Figure 6: Plot of central length reported by each participant for the 10 mm steel gauge block. Error bars represent the k=2 expanded uncertainties submitted by the participants.

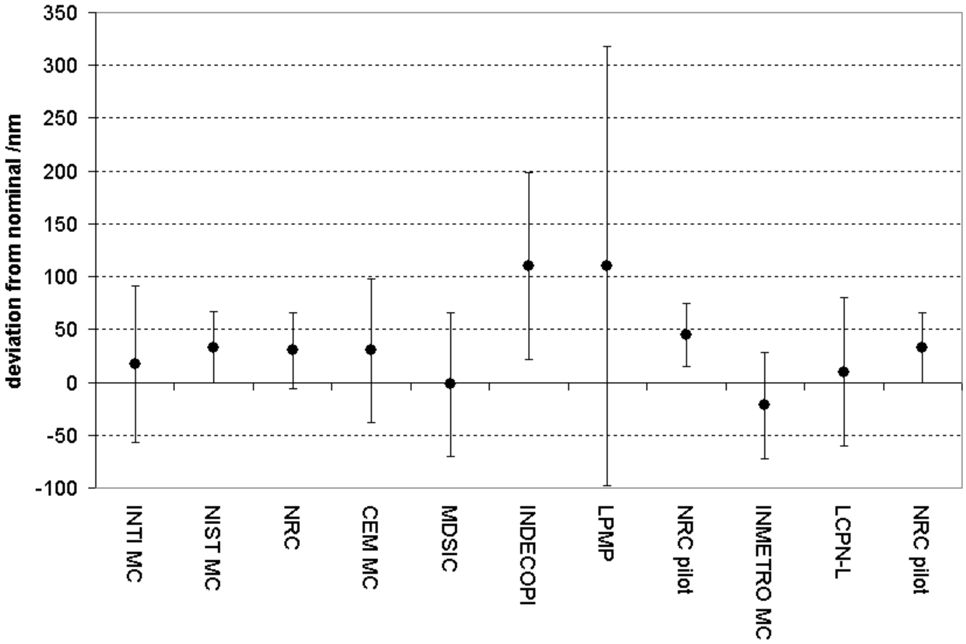

Figure 7: Plot of central length reported by each participant for the 50 mm steel gauge block. Error bars represent the k=2 expanded uncertainties submitted by the participants.

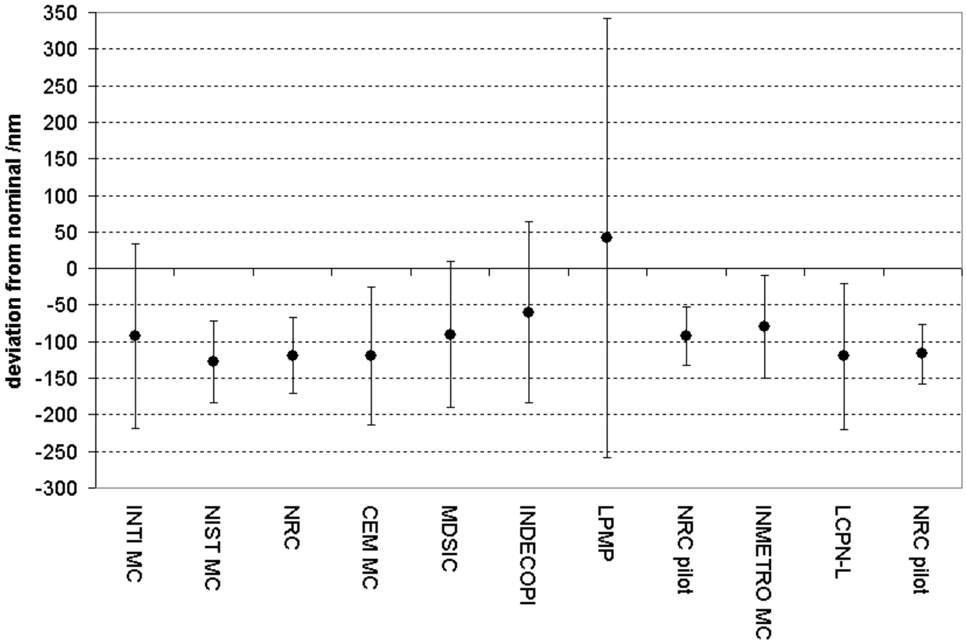

Figure 8: Plot of central length reported by each participant for the 100 mm steel gauge block. Error bars represent the k=2 expanded uncertainties submitted by the participants.

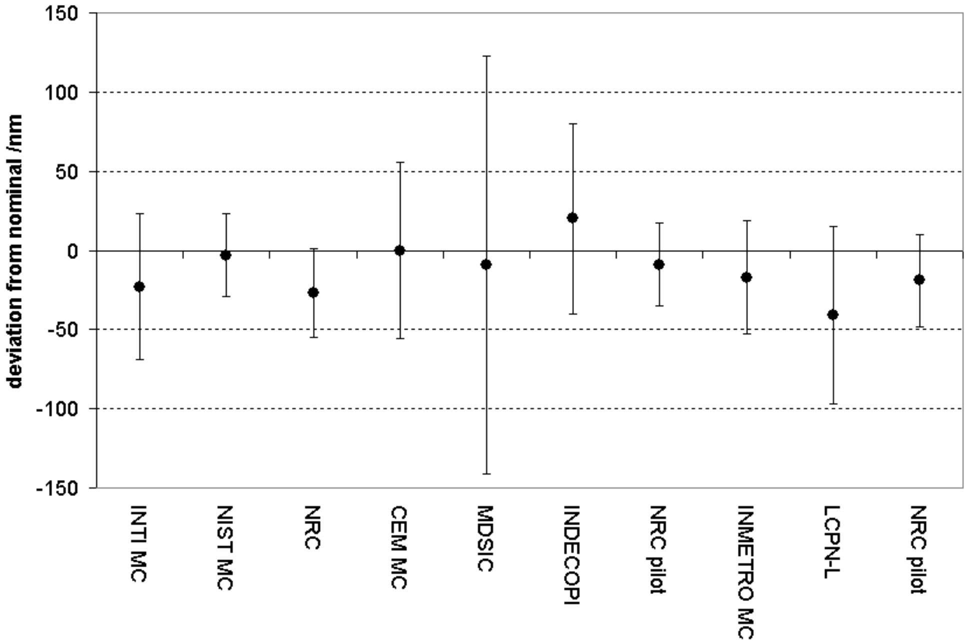

Figure 9: Plot of central length reported by each participant for the 2 mm tungsten carbide gauge block. Error bars represent the k=2 expanded uncertainties submitted by the participants.

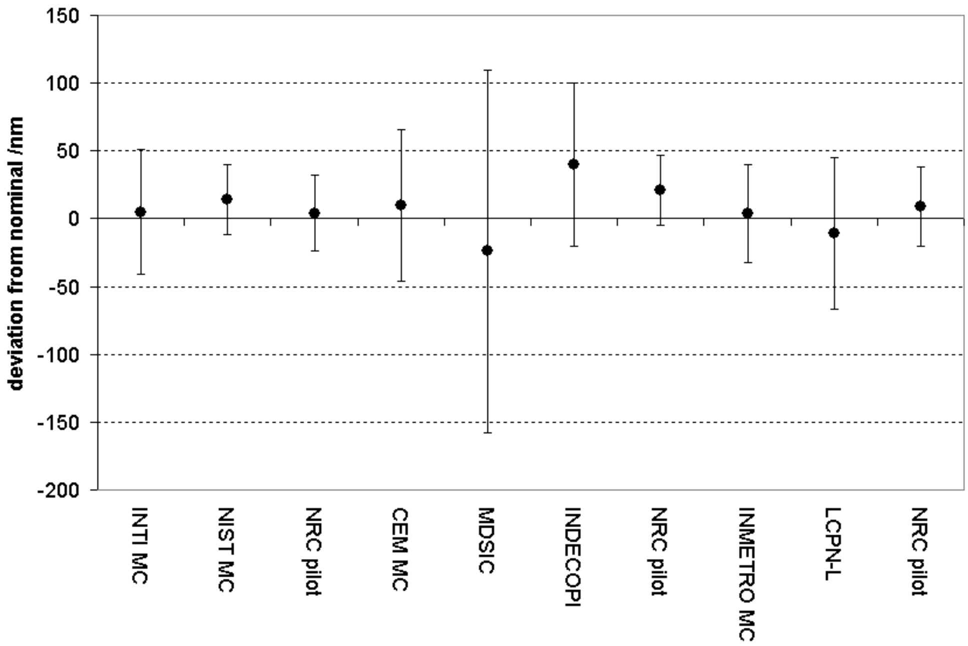

Figure 10: Plot of central length reported by each participant for the 5 mm tungsten carbide gauge block. Error bars represent the k=2 expanded uncertainties submitted by the participants.

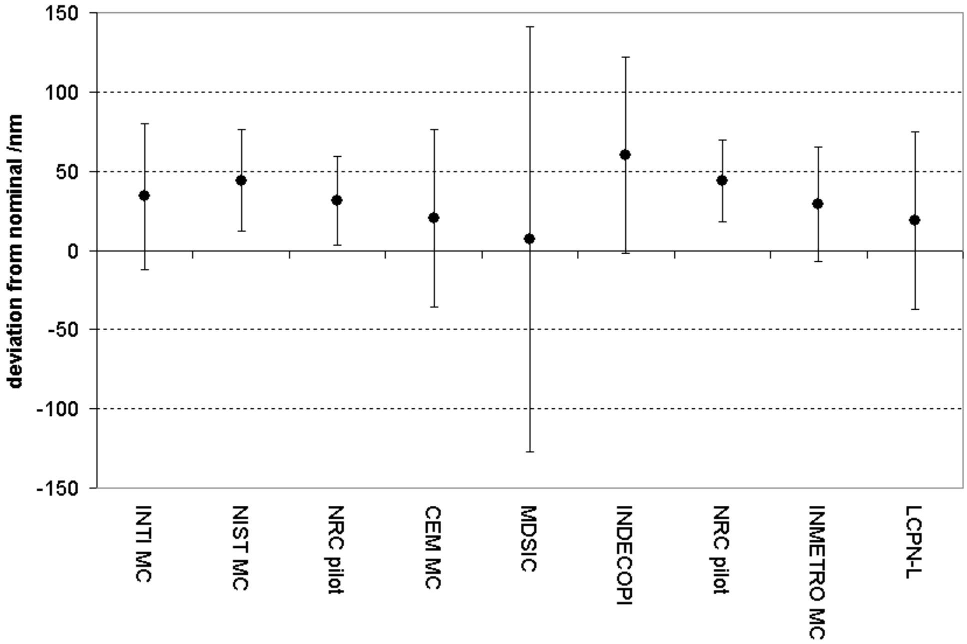

Figure 11: Plot of central length reported by each participant for the 8 mm tungsten carbide gauge block. Error bars represent the k=2 expanded uncertainties submitted by the participants. The closure pilot calibration by interferometry is missing because the wringing of gauge block was damaged during the comparison.

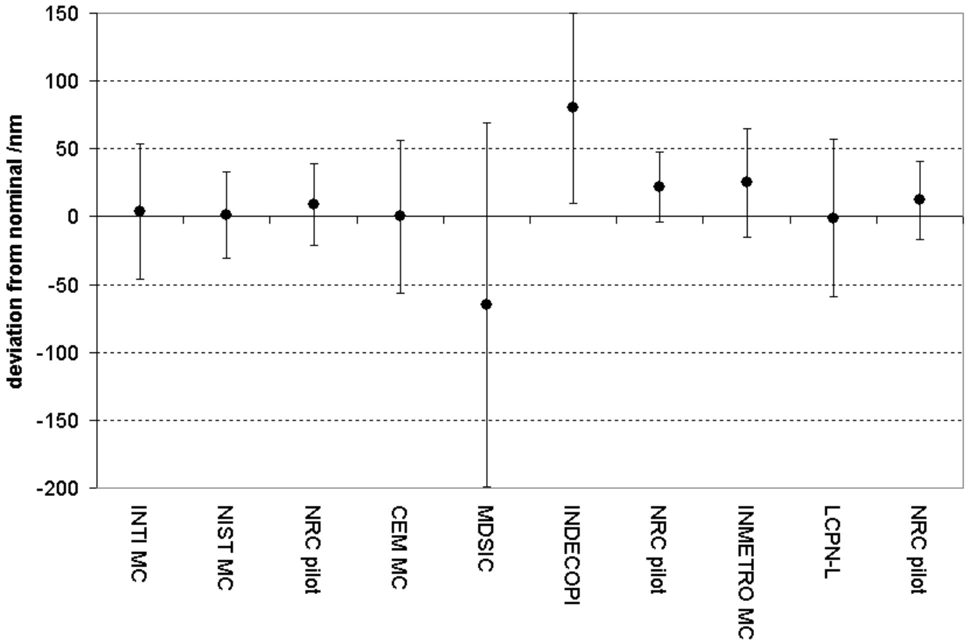

Figure 12: Plot of central length reported by each participant for the 20 mm tungsten carbide gauge block. Error bars represent the k=2 expanded uncertainties submitted by the participants.

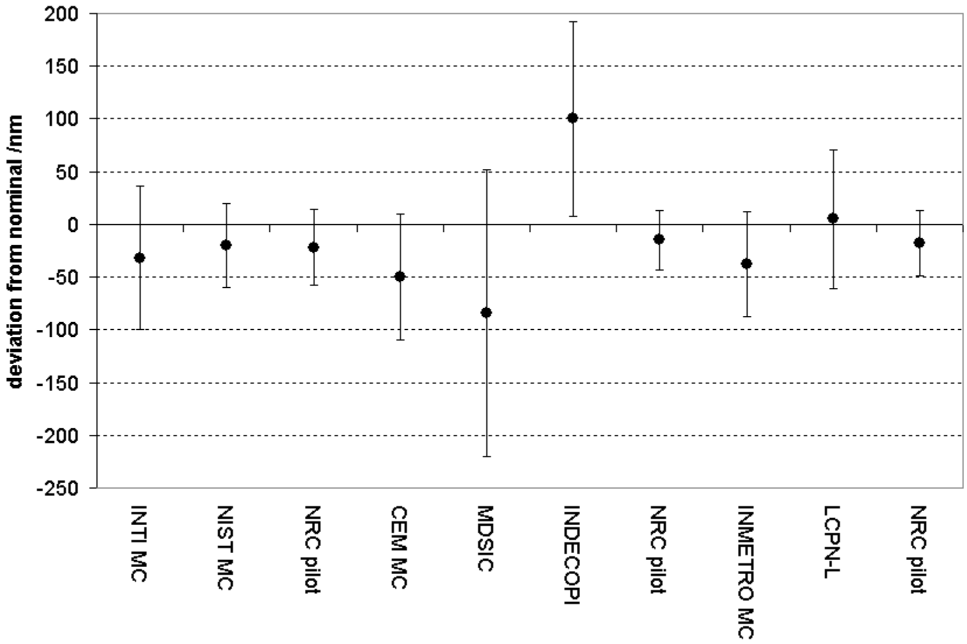

Figure 13: Plot of central length reported by each participant for the 50 mm tungsten carbide gauge block. Error bars represent the k=2 expanded uncertainties submitted by the participants.

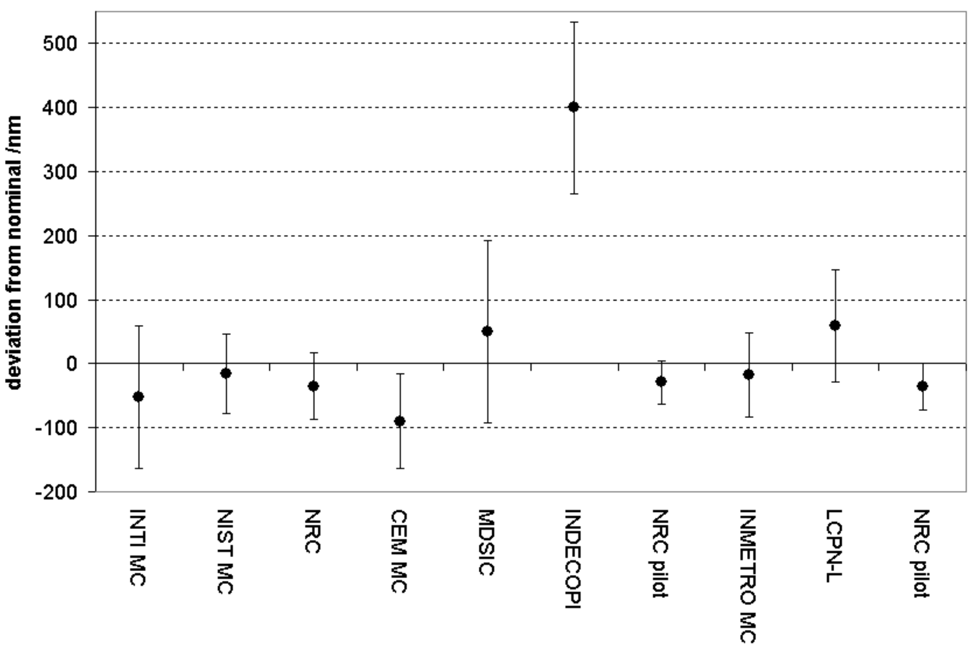

Figure 14: Plot of central length reported by each participant for the 100 mm tungsten carbide gauge block. Error bars represent the k=2 expanded uncertainties submitted by the participants.

where

- l is the length of the test gauge block,
- d is the length difference between the reference standard and test gauge blocks measured on the comparator instrument,
- l_s is the length of the reference standard gauge block,
- t is the temperature of the gauge block,
- $\theta = t - 20°\mathrm{C}$
- $\delta\theta = \theta - \theta_s$ is the difference in temperature between the reference standard and test gauge blocks,
- α represents the linear thermal expansion coefficient of the test gauge block,
- α_s represents the linear thermal expansion coefficient of the reference standard.

Some examples of the evaluation of standard uncertainties attributed to these influences are described in detail in [5, 6, 7]. Each laboratory submitted an uncertainty budget along with their calibrations. Table 9 itemizes the uncertainty components for each laboratory for the above-listed major influence parameters evaluated for the case of steel reference standard and steel test gauge blocks. Entries in italic are length dependent uncertainty components evaluated for 100 mm nominal length. The bottom line of Table 9 is the quadrature sum of the components in the Table column. The components of standard uncertainty associated with thermal expansion of the reference standard $u(\alpha_s)$ were listed in the budget submitted by LPMP; however this standard uncertainty component was not included in their quadrature sum for the combined standard uncertainty.

Table 10 summarizes the temperature range of the measurements, the range of reported expanded uncertainties and the range of degrees of freedom for steel gauge blocks of nominal lengths 2 and 100 mm. A wide range of measurement uncertainties is observed for labs of this comparison; up to a factor of about 5. Measurement uncertainties for the 100 mm steel gauge block in Table 9 may differ from those of Table 10 if the laboratory added other uncertainty components to the value submitted to the comparison that were not outlined in their uncertainty budget. NIST employs a particular gauge block calibration design for drift-elimination paired with statistical control that is specific to NIST. These methods have been described elsewhere [8].

7 Discussion

7.1 General Observations

The same gauge blocks were used in both stages of the SIM.4.2 gauge block comparison, therefore all data can be plotted on the same scale to demonstrate the progression from calibration by optical interferometry and calibration by mechanical comparison. Details regarding results for the comparison by optical interferometry are outlined in the report “Stage One: Calibration of Gauge Blocks by Optical Interferometry” [4]. Figures 15 to 26 plot the compiled data from both Stages of the comparison. Some of the longer error bars in these figures are left cut-off for clarity in observing the calibration values, since the data in the figures for the mechanical comparison portion details the results with complete error bars.

	Components of Standard Uncertainty /nm							
	INTI	NIST	CEM	MDSIC	INDECOPI	LPMP	LCPN-L	INMETRO
l_s	10.5	8.9	8.4	6.7	-	-	14	30
l_s	*18*	*9*	*15*	6.7	*50*	*100*	4	-
d	20	1.2	17.3	6.4	15.3	53.76	18	5
θ	(0.17°C)	(0.2°C)	(0.029°C)	(0.5°C)	-	(0.59°C)	-	-
α_s	*29*	*12*	*12*	-	-	*59*	-	-
α	*32*	-	-	*28.9*	*2.8*	-	-	-
$\delta\theta$	*33*	*20*	*35.2*	*33.2*	*33.4*	*93.8*	-	*14*
$u(\alpha_s)u(\theta_s)$	*10*	*0.6*	-	-	-	-	*20*	-
$u(\alpha)u(\theta_s)$	*10*	-	-	-	-	-	*10*	-
$u(\alpha)u(\delta\theta)$	*2*	-	-	-	-	-	-	*6*
reproducibility	-	*13*	6.7	-	-	-	6	-
comparator-block interaction geometry	-	2	-	9	-	-	7	-
wringing geometry	-	8	-	3.85	-	-	-	-
other	-	-	18.5	12	-	-	3	6
other	-	-	3.85	2.1	-	-	*20*	-
u_c	**61**	**31**	**49**	**48**	**62**	**161**	**39**	**35**

Table 9: Summary of components of standard uncertainty for steel gauge block calibration by mechanical comparison reported by participants of the SIM.4.2 Regional Comparison. Length dependent terms are in italics and are based on a 100 mm nominal gauge block length. The combined standard uncertainty listed in bold face is the quadrature sum of the components.

Laboratory	*Maximum Temperature Variation During Measurements* /°C	*Range of Expanded Uncertainty (Steel)* /nm	*Range of Degrees of Freedom (Steel)*
INTI MC	20 ± 1	$46 - 126$	$92 - 3678$
NIST MC	$20 - 20.2$	$26 - 56$	$132 - 223$
CEM MC	20 ± 0.2	$56 - 94$	$268 - 273$
MDSIC	$19.5 - 20.5$	$38 - 100$	$669 - 31026$
INDECOPI	$19.88 - 20.12$ (steel)	$60 - 124$	$27 - 29$
LPMP	$19.2 - 21.5$ (max 1.4°C during measure)	$148 - 300 (k = 2.31)$	$5 - 6$
INMETRO	20 ± 0.2	$18 - 35$	$1260 - 20500$
LCPN-L	20 ± 0.5	$28 - 50$	$163 - 964$

Table 10: Summary of details submitted for temperature range during measurements, expanded ($k = 2$, except for LPMP where k is listed in the table) uncertainties and degrees of freedom for range 'boundary' values of 2 mm and 100 mm nominal (steel) gauge block lengths.

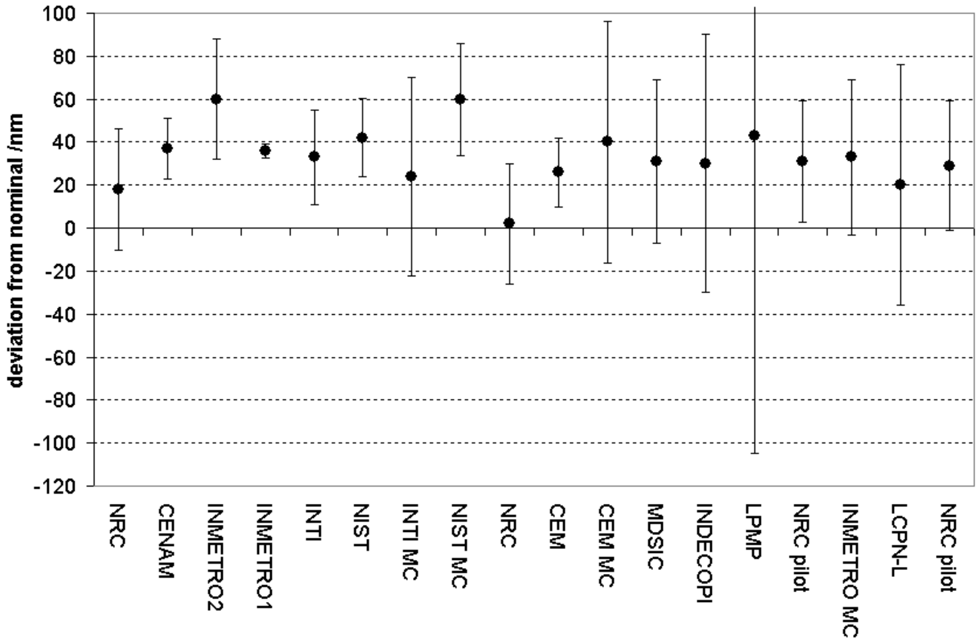

Figure 15: Plot of central length reported by participants in Stage One and Stage Two for the 2 mm steel gauge block. 'MC' denotes mechanical comparison measurement. Error bars represent the k=2 expanded uncertainties submitted by the participants.

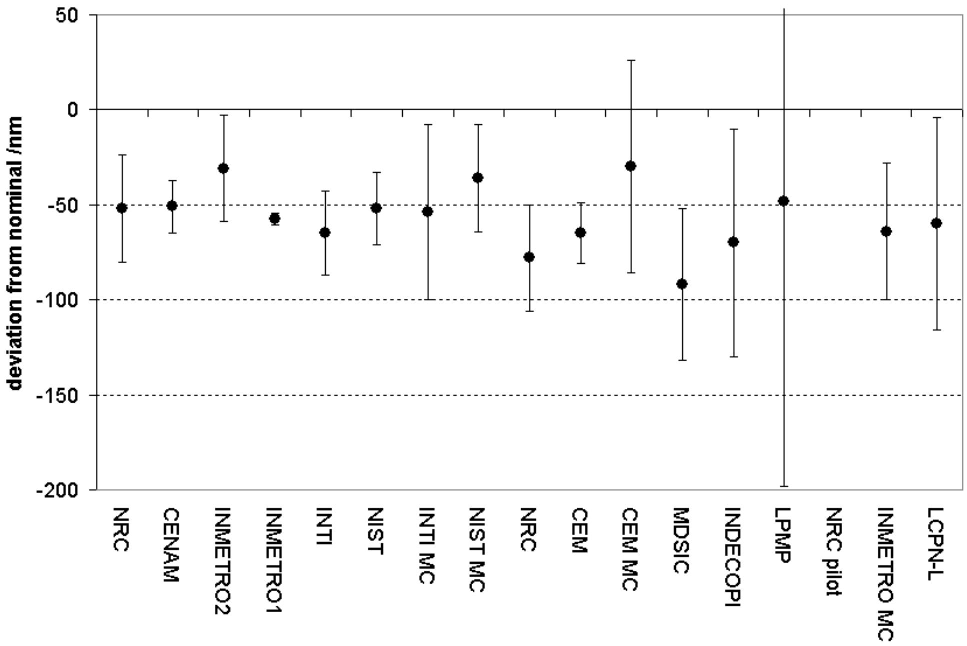

Figure 16: Plot of central length reported by participants in Stage One and Stage Two for the 5 mm steel gauge block. 'MC' denotes mechanical comparison measurement. Error bars represent the k=2 expanded uncertainties submitted by the participants.

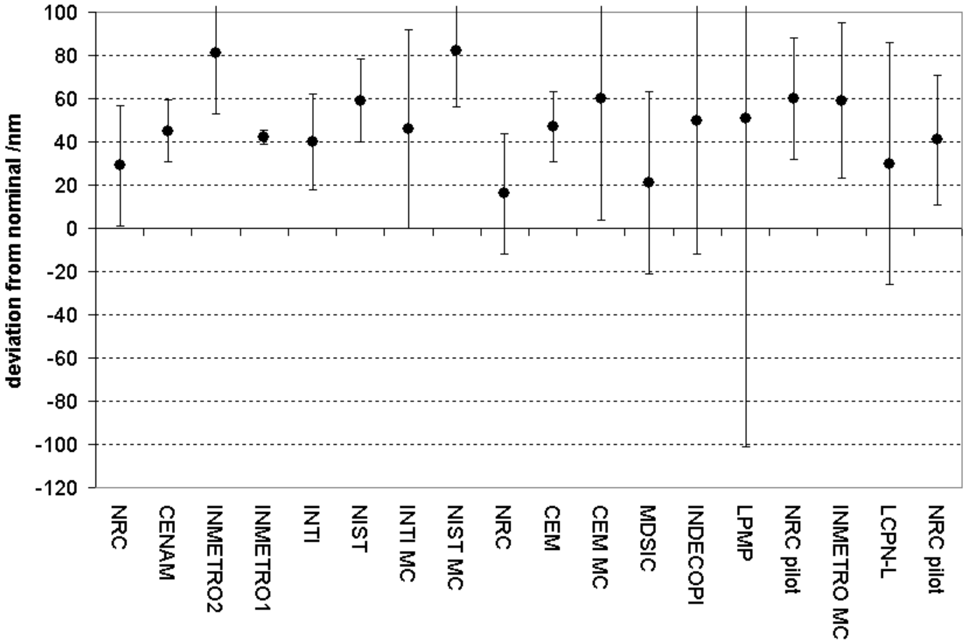

Figure 17: Plot of central length reported by participants in Stage One and Stage Two for the 8 mm steel gauge block. 'MC' denotes mechanical comparison measurement. Error bars represent the k=2 expanded uncertainties submitted by the participants.

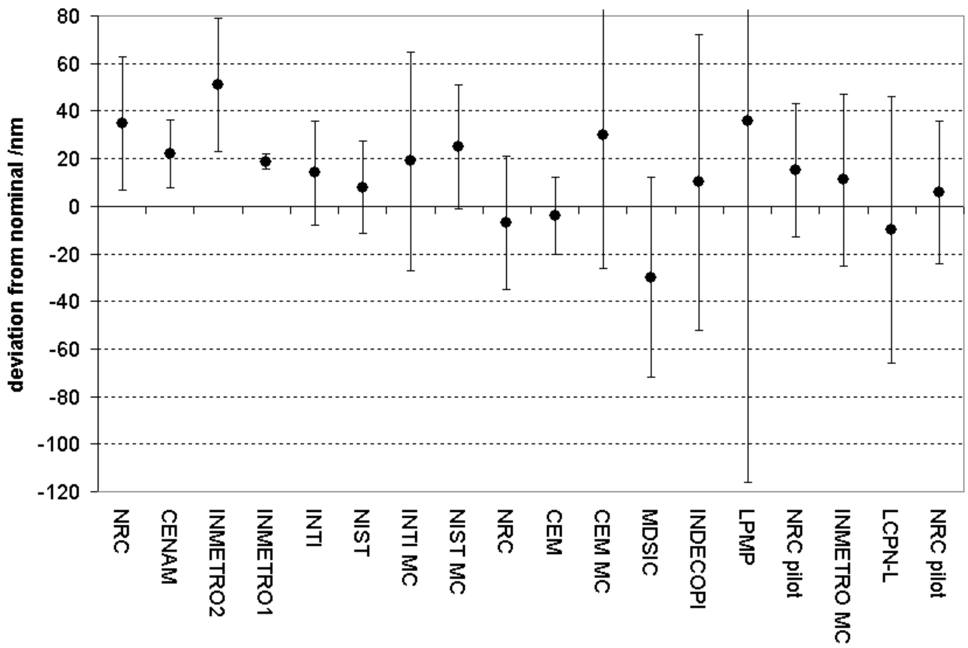

Figure 18: Plot of central length reported by participants in Stage One and Stage Two for the 10 mm steel gauge block. 'MC' denotes mechanical comparison measurement. Error bars represent the k=2 expanded uncertainties submitted by the participants.

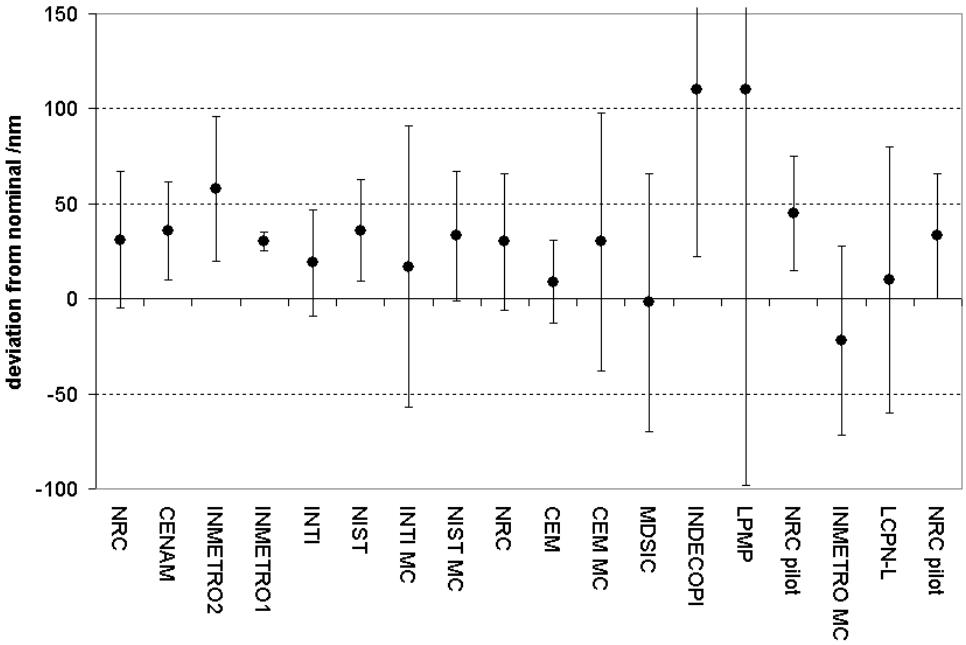

Figure 19: Plot of central length reported by participants in Stage One and Stage Two for the 50 mm steel gauge block. 'MC' denotes mechanical comparison measurement. Error bars represent the k=2 expanded uncertainties submitted by the participants.

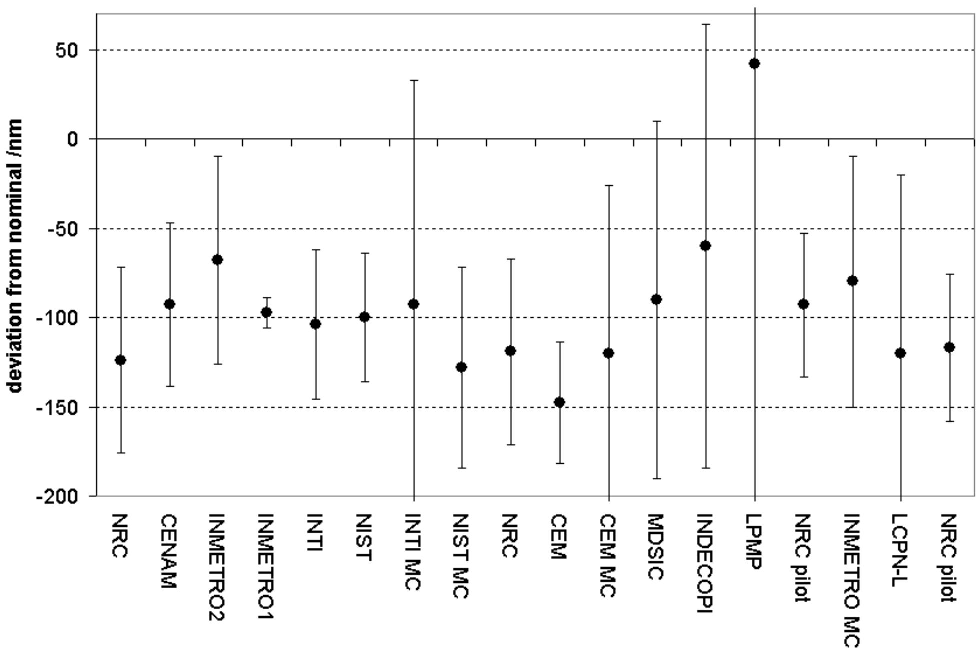

Figure 20: Plot of central length reported by participants in Stage One and Stage Two for the 100 mm steel gauge block. 'MC' denotes mechanical comparison measurement. Error bars represent the k=2 expanded uncertainties submitted by the participants.

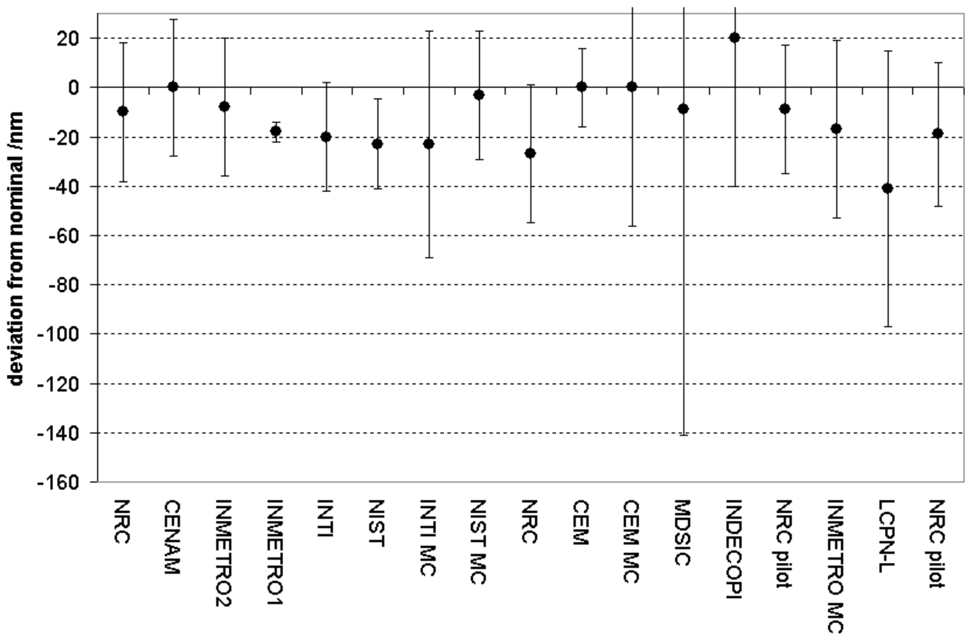

Figure 21: Plot of central length reported by participants in Stage One and Stage Two for the 2 mm tungsten carbide gauge block. 'MC' denotes mechanical comparison measurement. Error bars represent the k=2 expanded uncertainties submitted by the participants.

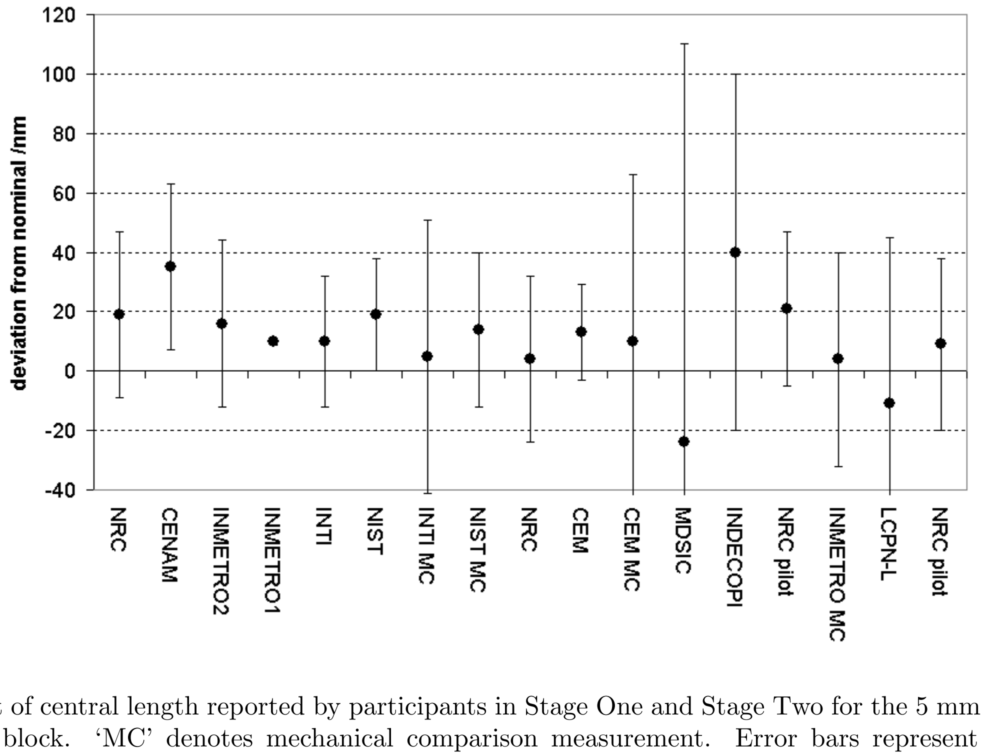

Figure 22: Plot of central length reported by participants in Stage One and Stage Two for the 5 mm tungsten carbide gauge block. 'MC' denotes mechanical comparison measurement. Error bars represent the k=2 expanded uncertainties submitted by the participants.

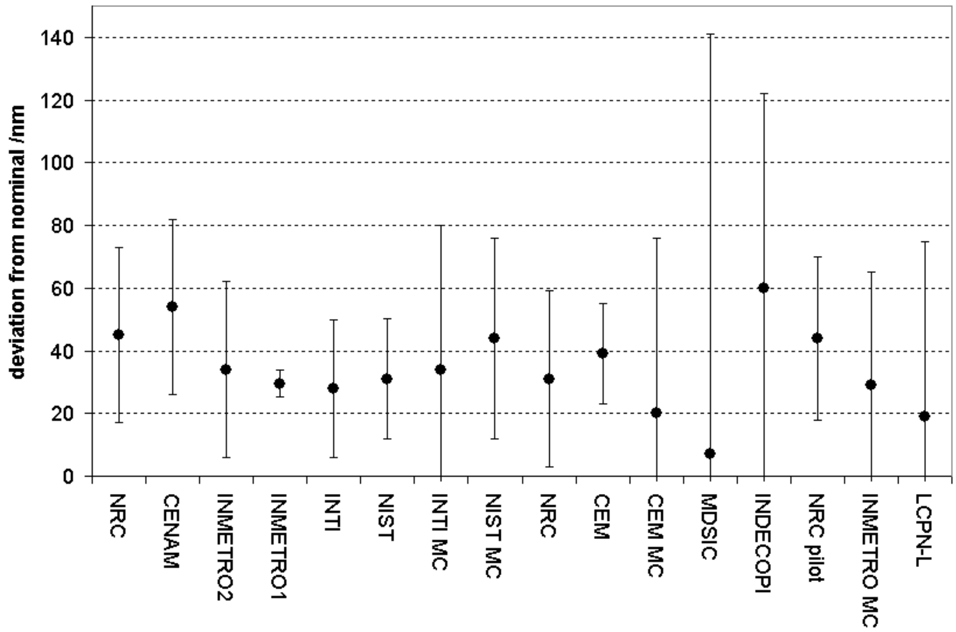

Figure 23: Plot of central length reported by participants in Stage One and Stage Two for the 8 mm tungsten carbide gauge block. 'MC' denotes mechanical comparison measurement. Error bars represent the k=2 expanded uncertainties submitted by the participants.

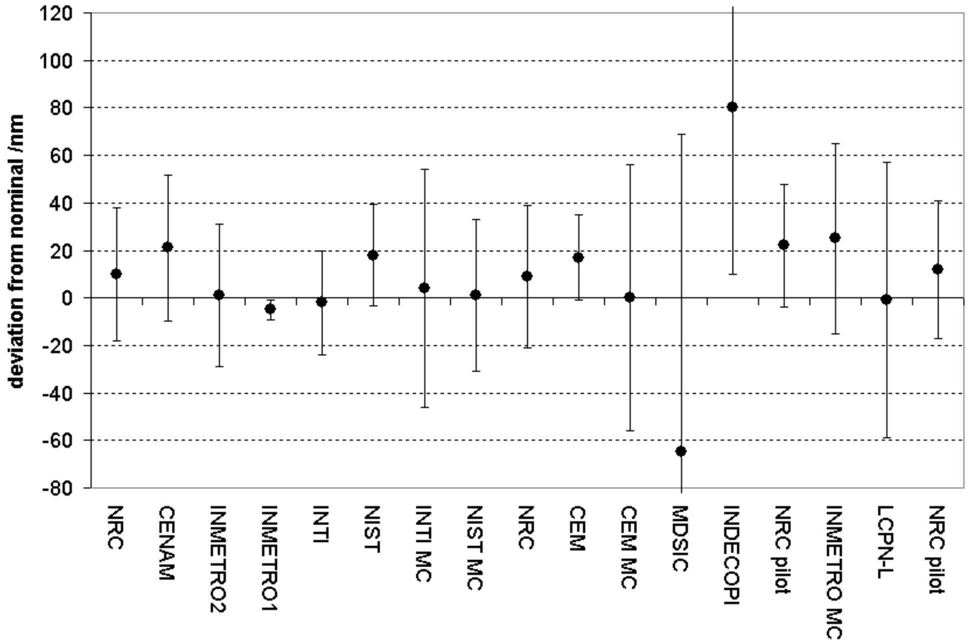

Figure 24: Plot of central length reported by participants in Stage One and Stage Two for the 20 mm tungsten carbide gauge block. 'MC' denotes mechanical comparison measurement. Error bars represent the k=2 expanded uncertainties submitted by the participants.

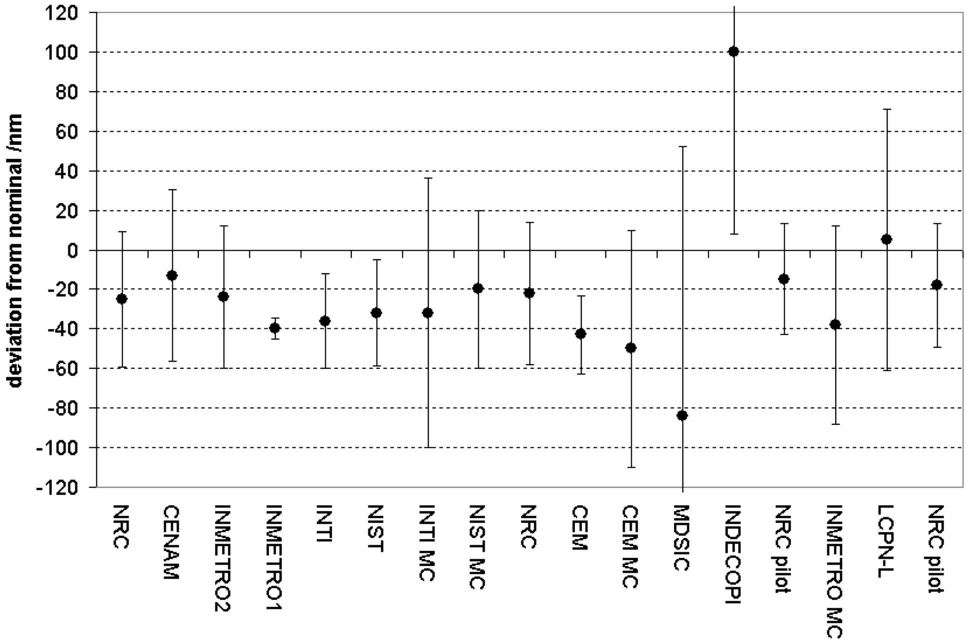

Figure 25: Plot of central length reported by participants in Stage One and Stage Two for the 50 mm tungsten carbide gauge block. 'MC' denotes mechanical comparison measurement. Error bars represent the k=2 expanded uncertainties submitted by the participants.

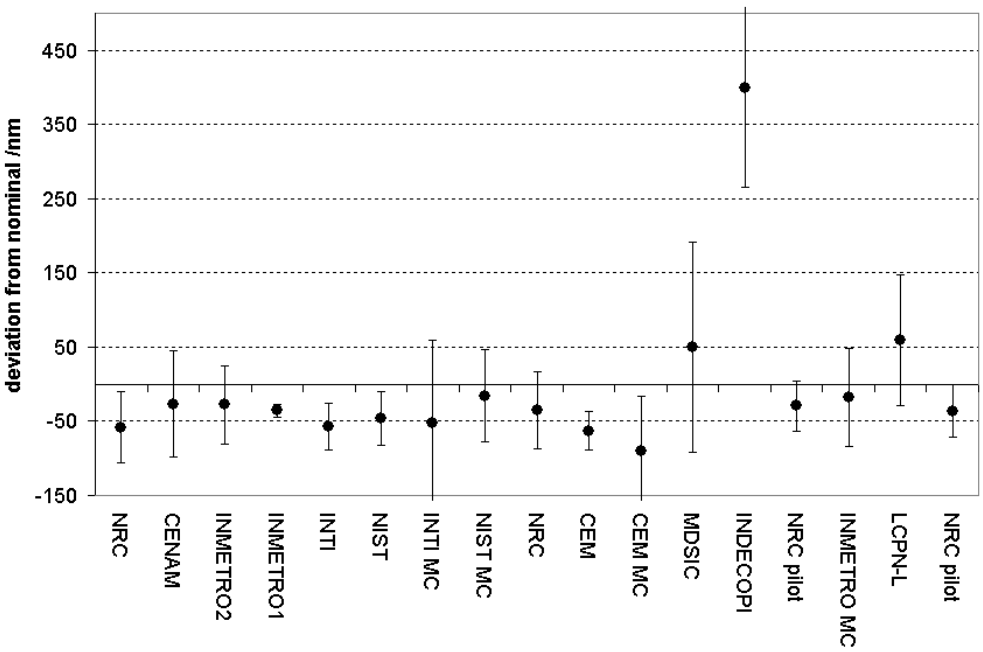

Figure 26: Plot of central length reported by participants in Stage One and Stage Two for the 100 mm tungsten carbide gauge block. 'MC' denotes mechanical comparison measurement. Error bars represent the k=2 expanded uncertainties submitted by the participants.

Figures 15 to 26 offer the opportunity to examine calibration data on the same gauge block samples by numerous labs calibrating the gauge blocks by interferometry with lowest measurement uncertainty. In that regard, the length value of each gauge block is determined to a tight band by Stage One of the comparison (average scatter of about ±25 nm). Furthermore, Stage Two of the comparison applies a calibration technique that is at least one more step removed from direct traceability to the definition of the metre compared to optical interferometry. It is therefore reasonable to assume that the lengths of the gauge blocks have been determined by Stage One of the comparison, and measurement excursions from the Stage One reference value could be considered to contain errors.

Observation of the data plots demonstrates that some laboratories are experiencing difficulties in specific measurement cases. In particular, for the tungsten carbide gauge blocks, some laboratories report much longer values compared to the majority of the other labs and the interferometric calibrations of Stage One of this comparison. There could be several reasons for these discrepancies; however the first one that comes to mind is the difficulty in accommodating for the different materials of the reference standard and test gauge blocks in the comparison technique. In this situation, temperature drifting effects can influence the length equivalent corrections for temperature, but can also dominate the elastic stylus deformation corrections, particularly when these deformation corrections are determined in-house in the same thermal environment. This reaffirms the importance of knowledge of an accurate value for the linear thermal expansion coefficient of gauge block materials, and also the accurate estimation of gauge block temperature during calibrations. Drift eliminating calibration design can also expedite correction for thermal effects.

Data plotted for both Stage One and Stage Two together demonstrate that with only a few exceptions already mentioned, the mechanical comparison calibrations agree very well with the calibrations by interferometry even with the various methods and degrees of traceability to the definition of the metre (see Table 3).

7.2 Data Analysis

A histogram is created using the simple arithmetic mean of the reported length values x_i from the n participating labs

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i. \tag{3}$$

The histogram in Figure 27 is a plot of the number of occurrences of the difference between each participants submitted measurement value and the simple arithmetic mean of equation (3). This histogram demonstrates that there are data that could be considered outliers.

Consider the values of the arithmetic mean $\overline{x}$ and the weighted mean

$$\overline{x}_w = \frac{\sum_{i=1}^{n} u^{-2}(x_i)\cdot x_i}{\sum_{i=1}^{n} u^{-2}(x_i)} \tag{4}$$

where $u(x_i)$ is the standard uncertainty reported by each participant, compared to the reference value determined in Stage One (simple arithmetic mean). These values are listed in Table 11, included are the standard uncertainties in the means. Considerable differences in the means are observed for some gauge blocks and likewise, excellent agreement is observed for others. Short gauge blocks of high quality result in mean values that are similar whereas the mean values of the longer and poorer quality gauge blocks differ with the technique of measurement. Gauge block quality primarily affects wringing and geometrical (form) errors, and therefore how similar the length measurement is by interferometry and by mechanical comparison. Imperfect temperature compensation also impacts longer gauge blocks to a greater extent (see for example Table 10). Nevertheless, there is more scatter in the measurement data of Stage Two than in Stage One. In most cases

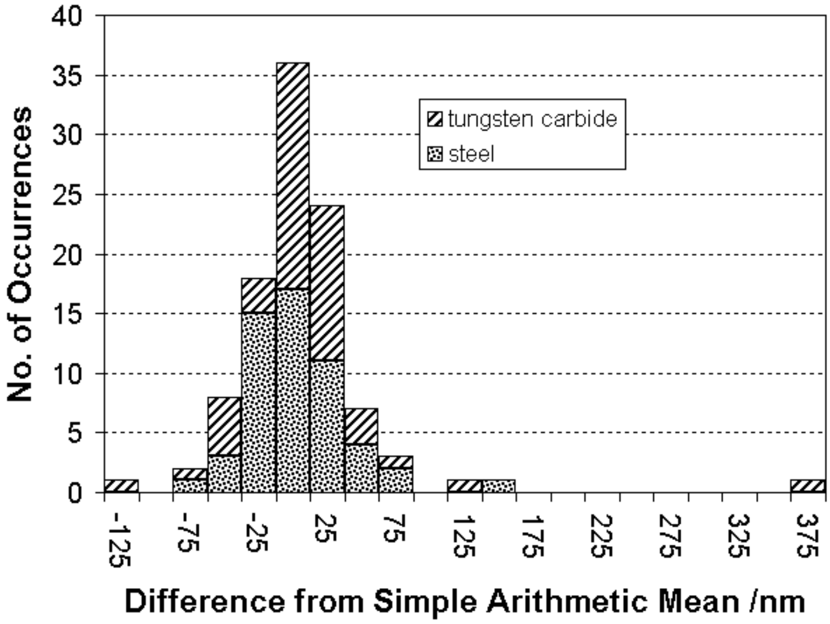

Figure 27: Histogram of the number of occurrences of the difference from the simple arithmetic mean value evaluated from all measurement values submitted to the comparison.

the the value of the weighted mean of Stage Two is closer to the reference value of Stage One than the simple arithmetic mean.

The reference values determined in Stage One are used as the reference values for this comparison. Length values determined in Stage One were unchanged throughout the comparison duration as demonstrated by periodic measurement by the pilot lab. The measurement technique of Stage One is inherently lower uncertainty because interferometry is a technique that utilizes a reference closer to the definition of the metre than mechanical comparison. Moreover, using the Stage One values means that identifying and removing outlier data can be avoided. Participants of this comparison deemed this consideration to be important. The gauge block lengths from Stage One provide knowledge whereby Stage Two labs can investigate their current procedures to make improvements. Labs with outlying measurement values are aware of their discrepancies and are taking action to correct their situation.

8 Conclusions

Results from the SIM.4.2 Regional comparison of gauge block calibration by mechanical comparison are presented and discussed. The comparison took 26 months to complete (April 1999 – June 2001) and included 8 national metrology institutes from the SIM region and one NMI from EUROMET.

Measurement agreement is satisfactory within a band of about ±50 nm for most participating laboratories, however improvements in length compensation for thermal behaviours between dissimilar gauge block materials would improve the results of some laboratories.

Results are presented that link the gauge block calibration techniques of optical interferometry and mechanical

Steel Gauge Blocks				Tungsten Carbide Gauge Blocks			
Nominal Length	Arithmetic Mean	Weighted Mean	Stage One S A Mean	Nominal Length	Arithmetic Mean	Weighted Mean	Stage One S A Mean
/mm	/nm			/mm	/nm		
2	31 ± 11	32 ± 7	36 ± 4	2	-13 ± 11	-14 ± 7	-11 ± 4
5	-59 ± 11	-61 ± 7	-53 ± 4	5	5 ± 11	8 ± 7	17 ± 4
8	46 ± 11	48 ± 7	49 ± 4	8	31 ± 11	34 ± 7	37 ± 4
10	57 ± 11	7 ± 7	21 ± 4	20	7 ± 12	10 ± 8	9 ± 4
50	35 ± 15	24 ± 9	31 ± 5	50	-18 ± 13	-21 ± 10	-30 ± 6
100	-85 ± 22	-108 ± 14	-105 ± 8	100	37 ± 17	-7 ± 14	-45 ± 8

Table 11: Comparison of the simple arithmetic mean of Stage Two, the weighted mean of Stage Two and the simple arithmetic mean of Stage One, all with standard uncertainties. Only the opening measurement by the pilot lab (by interferometry) is included in the Stage Two results.

comparison. Little difference is observed is progressing from interferometry to mechanical comparison for short steel gauge blocks. Laboratories obtaining traceability from their own calibrations by optical interferometry show excellent agreement with Stage One gauge block calibrations by interferometry. Some exceptions can be identified primarily for tungsten carbide gauge blocks, and especially for longer nominal lengths. These excursions are attributed to difficulties in correctly evaluating thermal corrections and/or elastic deformation corrections. This comparison demonstrates the importance of thermal compensation for accurate gauge block length calibrations.

Chromium carbide gauge blocks are widely used in North America. It would be useful to include a sample of this material in future SIM regional international comparisons.

9 Acknowledgements

The SIM-4.2 Regional Gauge Block Comparison participants gratefully acknowledge the financial support of the SIM regional committee. NRC also thanks Mike Dagenais and Donna Woods for gauge block calibrations and Lorne Munro for expert maintenance of the Dimensional Metrology lab and the interferometer instrument. The author thanks NRC colleagues Alan Steele and Barry Wood, and Ruedi Thalmann (METAS) for fruitful discussions.

References

[1] Thalmann, R., 2001, “CCL Key Comparison CCL-K1, Calibration of gauge blocks by interferometry,” to be published.

[2] Decker, J.E. and Pekelsky, J.R., “Gauge Block Calibration by Optical Interferometry at the National Research Council Canada,” presented at the Measurement Science Conference, Pasadena, CA, January 1997. National Research Council of Canada (NRC) Document No. 40002, 17 pages.

[3] Decker, J.E., Bustraan, K., de Bonth, S., Pekelsky, J.R., 2000, “Updates to the NRC Gauge Block Interferometer,” NRC Document No. 42753, 9 pages.

[4] Decker, J.E., Pekelsky J.R., 2001, "Report of SIM.4.2 Regional Comparison, Stage One: Calibration of Gauge Blocks by Optical Interferometry," to be published.

[5] ISO *Guide to the Expression of Uncertainty in Measurement*, ©1993, (International Organization for Standardization (ISO) Central Secretariat, Switzerland, Internet iso@iso.ch).

[6] Decker, J.E., Pekelsky J.R., 1996, "Uncertainty of Gauge Block Calibration by Mechanical Comparison: A Worked Example, Case 1: Gauges of Like Material," NCSL Canadian Region Spring Meeting, Ottawa, CANADA, 37 pages, NRC Document No. 39998. (http://www.nrc.ca/inms/mechmet/menu.html)

[7] Decker, J.E., Ulrich, A., Pekelsky, J.R., 1998, "Uncertainty of Gauge Block Calibration by Mechanical Comparison: A Worked Example for Gauge Blocks of Dissimilar Materials," SPIE Conference on Recent Develpments in Optical Gauge Block Metrology, Proc. of SPIE, **3477**, 225–246.

[8] Doiron, T., Beers, J.S., 1995, "The Gage Block Handbook," NIST Monograph 180, U.S. Department of Commerce, National Insitute of Standards and Technology, (U.S. Government Printing Office, Washington), 154 pages.

A Comparison Reference Value and Equivalence Tables

The MRA stipulates listing the results of international comparisons on the database web sites. The values to be listed are the difference from the comparison reference value, and the uncertainty in this difference, for each participant of the comparison.

Since Stage One of the SIM.4.2 Gauge Block comparison focused on the technique of optical interferometry, the average gauge block length value has been determined during Stage One by the technique of optical interferometry. This technique provides more direct traceability to the definition of the metre, and with lower measurement uncertainty. Therefore, unless the length of the gauge block has changed significantly during the time period of the combined comparisons, the average length value of each of the gauge blocks used in Stage Two can be considered to be known. Using the arithmetic average from Stage One also offers the advantage that all data from Stage Two can be accepted and compared without identification of outliers nor leaving out participant values. Furthermore, the measurement values of Stage One and Stage Two can be considered largely uncorrelated. Uncertainty values in the Tables are expanded uncertainties (k=2) evaluated as the simple quadrature sum of the standard uncertainty of the participant and the standard uncertainty in the Stage One arithmetic mean value.

Participant	Nominal Length of Steel Gauge Blocks /mm					
	2	5	8	10	50	100
INTI MC	-12 ± 47	-1 ± 47	-3 ± 47	-2 ± 49	-14 ± 75	12 ± 127
NIST MC	24 ± 27	17 ± 29	33 ± 27	4 ± 29	2 ± 35	-23 ± 58
CEM MC	4 ± 57	23 ± 57	11 ± 57	9 ± 57	-1 ± 69	-15 ± 95
MDSIC	-5 ± 39	-39 ± 41	-28 ± 43	-51 ± 45	-33 ± 69	15 ± 101
INDECOPI	-6 ± 61	-17 ± 61	1 ± 63	-11 ± 64	79 ± 89	45 ± 125
LPMP	7 ± 148	5 ± 150	2 ± 152	15 ± 154	79 ± 208	147 ± 300
INMETRO MC	-3 ± 37	-11 ± 37	10 ± 37	-10 ± 39	-53 ± 51	25 ± 72
LCPN-L	-16 ± 57	-7 ± 57	-19 ± 57	-31 ± 57	-21 ± 71	-15 ± 101

Table 12: The difference between the calibration value submitted by each participant and the simple arithmetic mean of Stage One of the comparison for steel gauge blocks. Uncertainty values are expanded uncertainties (k=2) evaluated as the simple quadrature sum of the standard uncertainty of the participant and the standard uncertainty in the Stage One arithmetic mean value.

Participant	Nominal Length of Tungsten Carbide Gauge Blocks /mm					
	2	5	8	20	50	100
INTI MC	-12 ± 47	-12 ± 47	-3 ± 47	-5 ± 51	-2 ± 69	-7 ± 113
NIST MC	8 ± 27	-3 ± 27	7 ± 33	-8 ± 33	10 ± 42	29 ± 64
CEM MC	11 ± 57	-7 ± 57	-17 ± 57	-9 ± 57	-20 ± 61	-45 ± 76
MDSIC	2 ± 132	-41 ± 134	-30 ± 134	-74 ± 134	-54 ± 137	95 ± 143
INDECOPI	31 ± 61	23 ± 61	23 ± 63	71 ± 70	130 ± 93	445 ± 135
INMETRO MC	-6 ± 37	-13 ± 37	-8 ± 37	16 ± 41	-8 ± 51	27 ± 68
LCPN-L	-30 ± 57	-28 ± 57	-18 ± 57	-10 ± 59	35 ± 67	104 ± 89

Table 13: The difference between the calibration value submitted by each participant and the simple arithmetic mean of Stage One of the comparison for tungsten carbide gauge blocks. Uncertainty values are expanded uncertainties (k=2) evaluated as the simple quadrature sum of the standard uncertainty of the participant and the standard uncertainty in the Stage One arithmetic mean value.