Justervesenet

EUROMET.L-K1.1
Calibration of gauge blocks by interferometry

Euromet project 643

Final Report

Kjeller, March, 01, 2005
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Justervesenet

Content

1 Introduction

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

Czech Metrology Institute donated steel gauges and Justervesenet donated tungsten carbide gauges, and both institutes proposed themselves to be pilot laboratory. It was later agreed upon that Justervesenet acts as pilot laboratory. The sets of gauge blocks differ slightly from EUROMET.L-K1, because we had to use gauge blocks, which were available at the time.

With reference to discussions in EUROMET Length meeting succeeding EUROMET.L-K1, regarding uncertainty connected to the linear thermal expansion coefficient, α, it was decided that it would be sufficient to measure the α-coefficient of the two longest gauge blocks for each type of material. It was also decided to adopt the mean value of the longer gauges for the shorter gauge blocks of similar material, and to adopt a larger uncertainty for the α-coefficient of the shorter gauge blocks.

Results in this report are presented in similar format as in the report for EUROMET L – K1. Formulas for calculation of reference values etc are similar as in this report. However, it was agreed in Euromet Length meeting in Dublin in October 2003, that no drift correction should be applied to the results.

2 Organisation

2.1 Participants

Country (code)	Laboratory	Name of contact	Address	Tel, fax, e-mail
1 - Czech Republic (CZ)	CMI	Vladimir Stezka	Czech Metrology Institute Slunečná 23 460 01 LIBEREC	Tel : 420 48 510 7544 Fax : 420 48 510 4466 e-mail : vstezka@cmi.cz
2 - Finland (FI)	MIKES	Hekki Lehto	MIKES, Metallimiehenkuja 6, 02150 ESPOO	Tel : 358 9 456 5350 Fax : 358 9 460 627 e-mail : Heikki.Lehto@mikes.fi
3 - Germany (DE)	PTB	Gerhard Bönsch	Physikalisch-Technische Bundesanstalt Lab. 5.13 Postfach 3345 38023 BRAUNSCHWEIG	Tel : 49 531 592 5130 Fax : 49 531 592 5015 e-mail : gerhard.boensch@ptb.de
4 - Norway (NO)	JV	Helge Karlsson	Justervesenet Fetveien 99 N-2007 KJELLER	Tel : 47 64 84 84 84 Fax : 47 64 84 84 85 e-mail : helge.karlsson@justervesenet.no
5 - Greece (GR)	E.I.M	Christos Bandis	Hellenic Institute of Metrology Industrial Area of Thessaloniki Block 45 Sindos, GR57022, Greece	Tel: + 30-2310-569 999 Fax: +30-2310-569 996 email: bandis@eim.org.gr
6 - Poland (PL)	GUM	Zbigniew Ramotowski	Central Office of Measures Glówny Urzad Miar (GUM) P.O. Box 10 ul. Elektoralna 2 00-950 WARSZAWA	Tel : 48 22 620 54 38 Fax : 48 22 620 83 78 e-mail : gum@gum.gov.pl
7 - Portugal (PT)	IPQ	Fernanda Saraiva	Instituto Portuguès da Qualidade Rua C à Avenida dos Três Vales 2825 MONTE DA CAPARICA	Tel : 351 1 294 81 60 Fax : 351 1 294 81 88 e-mail : fsaraiva@mail.ipq.pt
8 - Romania (RO)	INM	Gabriela Mocanu	Sos. Vitan-Bârzesti 11, 75669 Bucharest	Tel: +40-1-3345060/ext. 154 Fax: +40-1- 3345345 e-mail: mocanu@inm.ro
9 - Turkey (TR)	UME	Tanfer Yandayan	Ulusal Metroloji Entistüsü Tübitak, UME P.O.Box 21 Gebze, Kocaeli 41470	Tel: 90 262 646 63 55/235 Fax: 90 262 646 59 14 e-mail: tanfer.yandayan@ume.tubitak.gov.tr
10 – Bulgaria (BU)	NCM	V. Gavalyugov	State Agency for Standardization and Metrology 1797 Sofia, Bulgaria 52-B G.M.Dimitriv Str.	Tel: +359 2 710307 Fax: +359 2 717050 e-mail: ncm@sasm.orbitel.bg

Table 1: Participating laboratories.

2.2 Time schedule

The time schedule has been revised two times. First time after IPQ reported that one steel gauge block was impossible to wring. An extra gauge block was then sent to IPQ so that they could finish their measurements with a phase correction. JV (pilot lab) measured before and after reconditioning carried out at PTB. This delayed the circulation, and a new time schedule was defined. Some laboratories were not able to measure within this new time schedule and the circulation became even more delayed.

INM reported that severe damage had occurred to the steel gauge blocks. Because of poor wringing quality, NCM reported measurement results for only 4 steel gauge blocks, and E.I.M. reported no steel gauge blocks. All laboratories have reported measurements on all TC gauge blocks.

Before final measurements at JV, one more recondition of the steel gauges was required at PTB. JV measured once again before and after the reconditioning.

Country	Laboratory	Date
Norway	JV	February 2002
Finland	MIKES	March 2002
Poland	GUM	April 2002
Czech Republic	CMI	May 2002
Portugal	IPQ	June 2002
Norway	JV	July - August 2002
Germany	PTB	September 2002
Norway	JV	Oct – Nov 2002
Turkey	UME	December 2002
Romania	BRML-INM	January - February 2003
Bulgaria	NCM	March - April 2003
Greece	E.I.M	May - June 2003
Norway	JV	July 2003
Germany	PTB	Sept – Oct 2003
Norway	JV	Jan 2003

Table 2: Revised time schedule.

3 Standards

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

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

One of the additional steel gauge blocks, 4.5 mm, is made by a different manufacturer, TESA, and not by Mitutoyo. JV has measured the phase shift by an integrating sphere and estimated the phase shift to be equal for all steel gauge blocks within ± 5 nm.

Steel gauge blocks :

Serial number	Nominal length (mm)	Expansion coeff. (10^{-6} K^{-1})		Manufacturer
			u	
980027	0,5	10.71	0.1	Mitutoyo
980863	1.01	10.71	0.1	Mitutoyo
F33929	4.5	10.71	0.1	Tesa
982379	6	10.71	0.1	Mitutoyo
981192	7	10.71	0.1	Mitutoyo
982413	8	10.71	0.1	Mitutoyo
981491	8	10.71	0.1	Mitutoyo
990724	15	10.71	0.1	Mitutoyo
981999	80	10.77	0.065	Mitutoyo
974995	100	10.64	0.055	Mitutoyo

Table 3a : Description of steel gauge blocks.

Tungsten carbide gauge blocks :

Serial number	Nominal length (mm)	Expansion coeff. (10^{-6} K^{-1})		Manufacturer
			u	
101533	1.02	4.28	0.1	TESA
101533	6	4.28	0.1	TESA
101533	7	4.28	0.1	TESA
101533	8	4.28	0.1	TESA
101533	10	4.28	0.1	TESA
101533	12	4.28	0.1	TESA
101533	80	4.33	0.01	TESA
101533	100	4.22	0.01	TESA

Table 3b : Description of tungsten carbide gauge blocks.

4 Measurement instructions and reporting

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

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

$$\Delta l = l_{measured} - L_{nominal}$$

The mesurands were:
- the results of the measurements on both sides, Δl_1 and Δl_2, by wringing each measurement face in turn to the reference flat
- the average of Δl_1 and Δl_2.

All the results had to be reported in the table in the annex A1 of the measurement instructions.

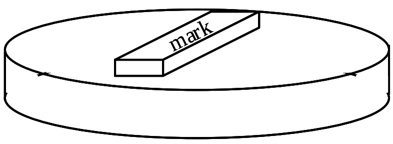


Figure 1a:
Position of the gauge block for Δl_1
The upper face is face 1.

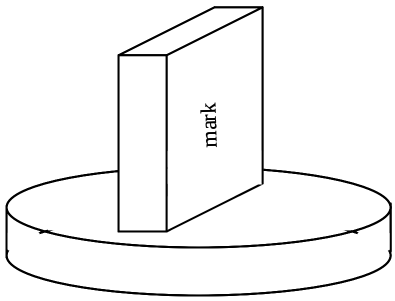


Figure 1b:
Position of the gauge block for Δl_1 (L > 6 mm)
The upper face is face 1.

The measurement results had to be appropriately corrected to the reference temperature of 20 °C using the thermal expansion coefficient given in the technical instruction. Additional corrections had to be applied according to the usual procedure of the laboratory.

The uncertainty of the measurement had to be estimated according to the *ISO Guide to the Expression of Uncertainty in Measurment*. In order to achieve optimum comparability, a mathematical model containing the principal influence parameters for gauge block calibration by interferometry has been given in the measurement instructions.

5 Measurement methods and instruments used by the participants

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

Laboratory	Manufacturer and type of interferometer
MIKES	NPL-TESA Automatic gauge block interferometer, Twyman Green design
IPQ	NPL-TESA Automatic gauge block interferometer, Twyman Green design
JV	NPL-TESA Automatic gauge block interferometer, Twyman Green design
CMI	NPL-TESA Automatic gauge block interferometer, Twyman Green design A.G.I. 300
E.I.M	NPL-TESA Automatic gauge block interferometer, Twyman Green design, A.G.I. 1/300
UME	NPL-TESA Automatic gauge block interferometer, Twyman Green design, FlaP version, phase stepping technique
GUM	Carl Zeiss Jena interferometer, Kösters type
INM	Carl Zeiss Jena interferometer, Kösters type
NCM	Carl Zeiss Jena interferometer, Kösters type
PTB	Michelson interferometer, modified TSUGAMI, phase-stepping arrangement and active temperature control, automatic evaluation

Table 4: Type and manufacturer of interferometer.

Further details of the measurement procedure and conditions are summarized in tables A1a and A1b in the appendix 1.

6 Measurement results

Results given in this chapter are taken from data sheets given by the laboratories, and do not include any correction such as drift.

6.1 Steel gauge blocks: deviation from nominal length

	Steel gauge blocks : Nominal length in mm									
Laboratory	**0,5**	**1,01**	**4,5*)**	**6*)**	**7**	**8**	**8**)**	**15**	**80**	**100**
JV	-57	-122	-27	85	-52	-16	-5	34	32	-194
MIKES	-56	-100			-46	-1	9	55	61	-168
GUM	-45	-106			-44	7	-6	63	83	-147
CMI	-60	-100			-60	0	0	50	70	-170
IPQ	-38	-82	7		-46	2	11	60	104	-150
PTB	-82	-125	-20	82	-73	-18	-10	42	36	-191
UME	-72	-101	-5	94	-62	-10	1	57	53	-185
INM	***)	-102	-16	96	-72	-4	2	42	32	-152
NCM		-98	-12		-50					-185
E.I.M										

Table 5a: Steel gauge blocks, deviation from nominal value (in nm) as reported by laboratories.
**) 4,5 mm and 6 mm were included in the second loop only as additional gauges to the set in order to be able to measure the phase correction by stack method. This was necessary because other steel gauges were gradually degrading in wringing quality.*
***) Two 8 mm steel gauge blocks, tabulated with decreasing serial number, id 982413 and id 981491.*
****) Measurement result (-45) was reported without measurement uncertainty. Results with no statement of measurement uncertainty have been excluded from the calculations.*

[light grey box] *Gauge block not available for measurement*

[dark grey box] *Gauge block not measured because of damaged measurement surface*

Comments given by the participants:

JV: JV measured up to 6 times during the entire circulation. Only first measurement result is stated in this table.

6.2 Steel gauge blocks: combined standard uncertainty

	Steel gauge blocks : Nominal length in mm									
Laboratory	**0,5**	**1,01**	**4,5*)**	**6*)**	**7**	**8**	**8**)**	**15**	**80**	**100**
JV	13	13	13	13	13	13	13	13	21	24
MIKES	10	10			10	10	10	10	15	17
GUM	18	18			18	18	18	18	22	24
CMI	10	10			10	10	10	11	18	21
IPQ	12	12	13		13	13	13	15	25	28
PTB	10	10	9	9	9	9	9	9	11	12
UME	15	13	13	13	13	13	13	13	16	17
INM		18	16	13	13	14	14	14	27	32
NCM		13	13		14					35
E.I.M										

Table 5b: Steel gauge blocks, combined standard uncertainty (in nm) as reported by laboratories.
**) 4,5 mm and 6 mm were included in the second loop only as additional gauges to the set.*
***) Two 8 mm steel gauge blocks, tabulated with decreasing serial number, id 982413 and id 981491.*

(light grey) *Gauge block not available for measurement*

(dark grey) *Gauge block not measured because of damaged measurement surface*

Comments given by the participants:

6.3 Steel gauge blocks: graphics

The following figures represent the results for each laboratory with error bars corresponding to one standard uncertainty.

Fig 2a: 0.5 mm steel gauge block

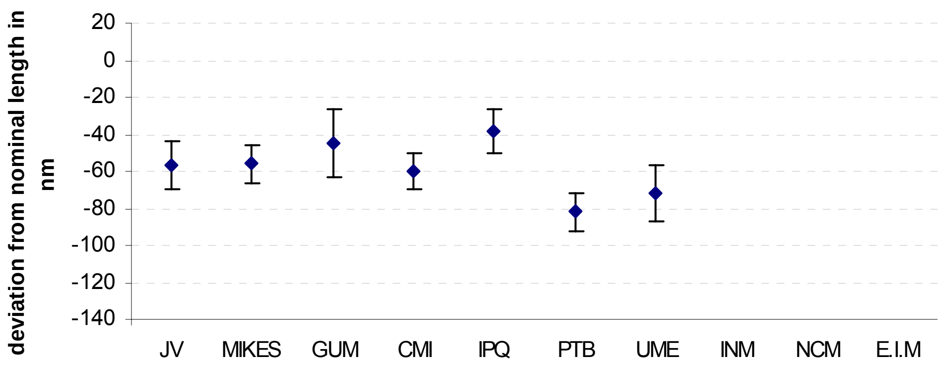


Fig 2b: 1.01 mm steel gauge block

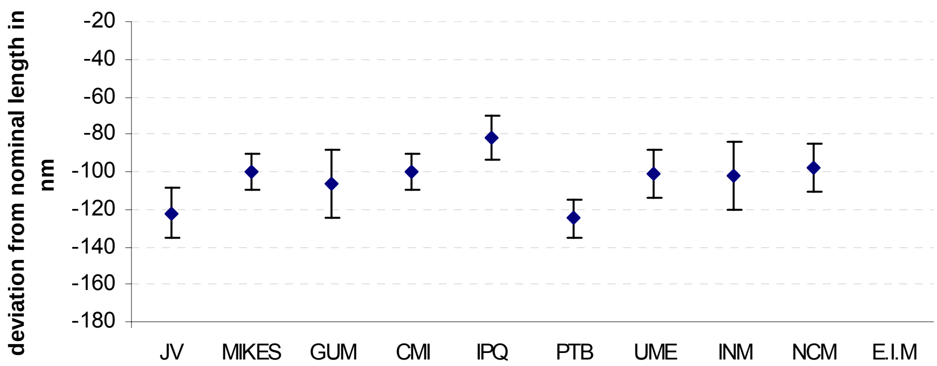


Fig 2c: 4.5 mm steel gauge block

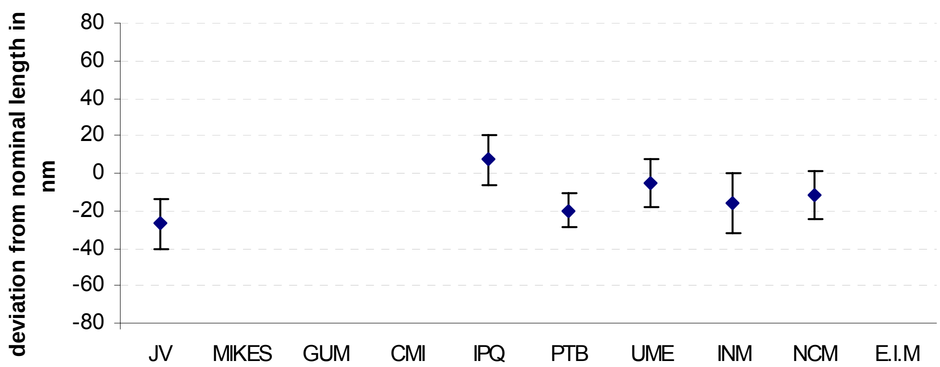


Fig 2d: 6 mm steel gauge block

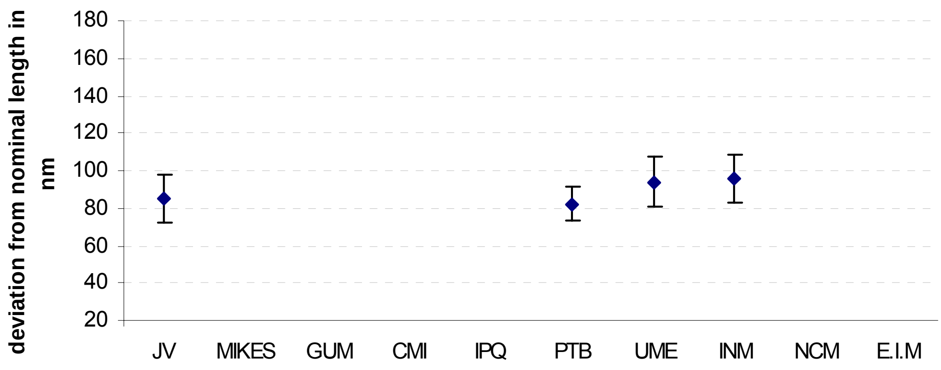


Fig 2e: 7 mm steel gauge block

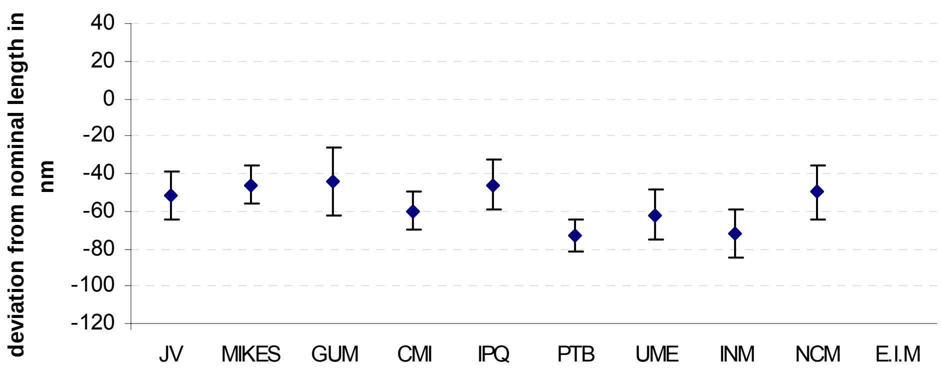
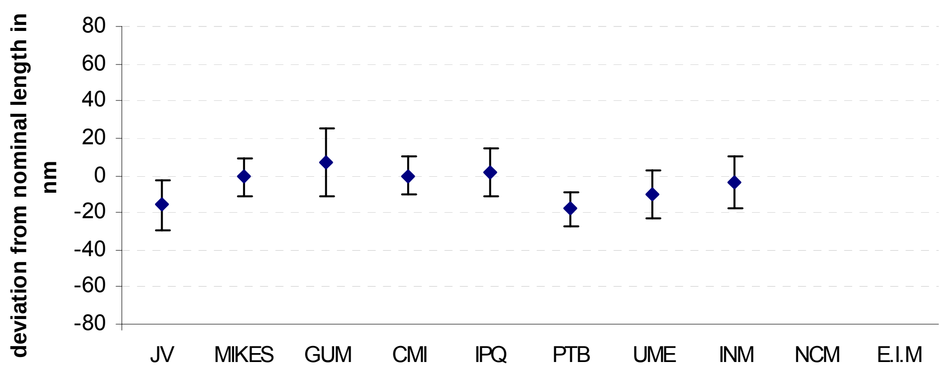


Fig 2f: 8 mm steel gauge block, id 982413



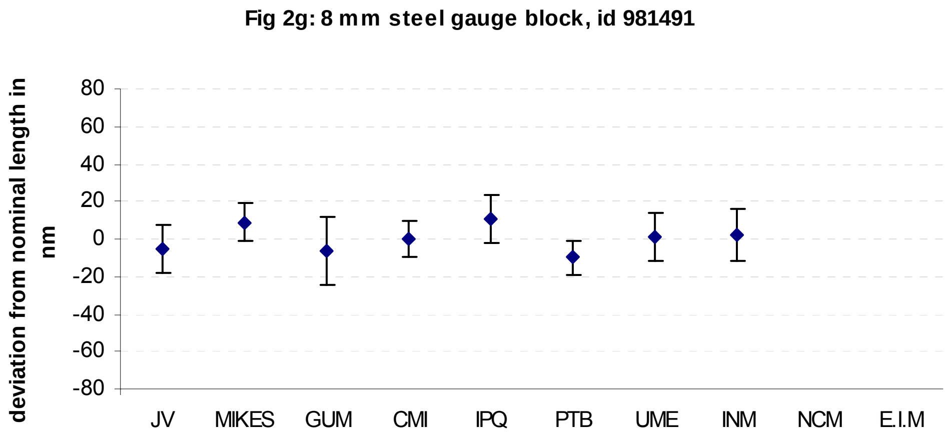


Fig 2g: 8 mm steel gauge block, id 981491
deviation from nominal length in nm
80
60
40
20
0
-20
-40
-60
-80
JV
MIKES
GUM
CMI
IPQ
PTB
UME
INM
NCM
E.I.M

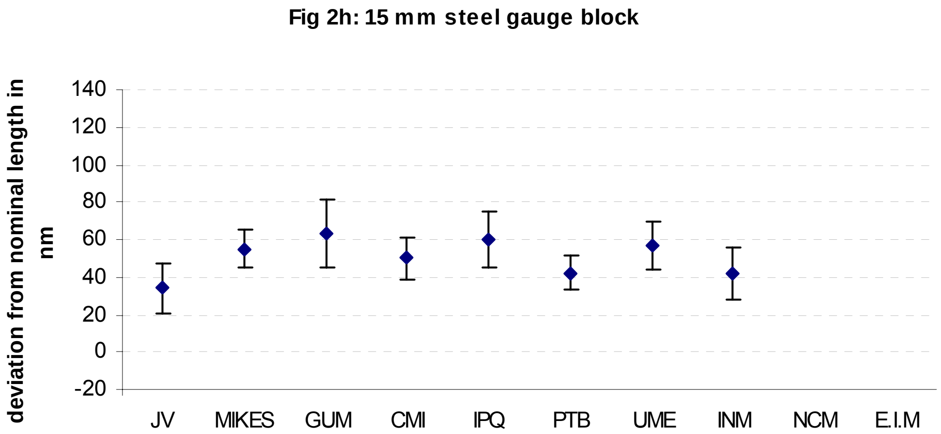


Fig 2h: 15 mm steel gauge block
deviation from nominal length in nm
140
120
100
80
60
40
20
0
-20
JV
MIKES
GUM
CMI
IPQ
PTB
UME
INM
NCM
E.I.M

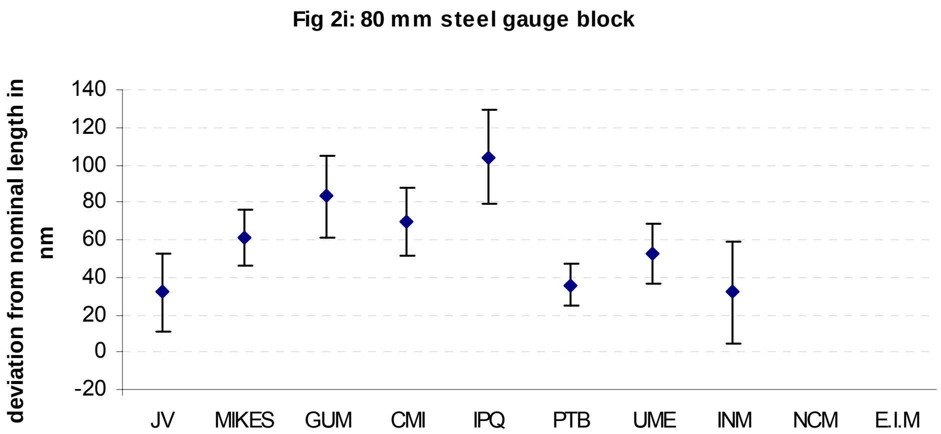


Fig 2i: 80 mm steel gauge block
deviation from nominal length in nm
140
120
100
80
60
40
20
0
-20
JV
MIKES
GUM
CMI
IPQ
PTB
UME
INM
NCM
E.I.M

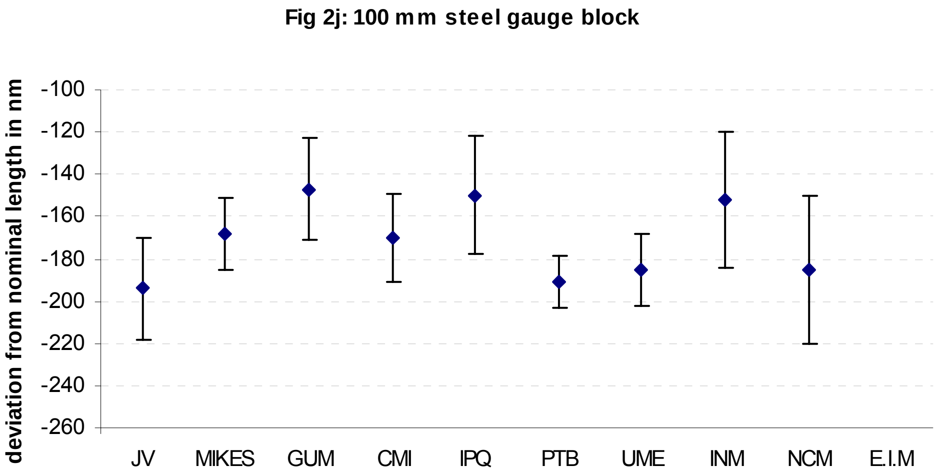


Figure 2a, b, c, d, e, f, g, h, i, j: Results for steel gauge blocks reported from each laboratory with error bars corresponding to one standard uncertainty.

6.4 Tungsten carbide gauge blocks: deviation from nominal length

	Tungsten carbide gauge blocks : Nominal length in mm							
Laboratory	**1,02**	**6**	**7**	**8**	**10**	**12**	**80**	**100**
JV	-1	-20	-17	29	-50	106	46	168
MIKES	10	-11	-14	38	-41	117	65	176
GUM	-4	-22	-13	32	-50	105	51	172
CMI	0	-10	0	30	-50	110	70	180
IPQ	-11	-29	-6	26	-36	97	70	187
PTB	-15	-27	-28	16	-60	100	45	159
UME	8	-11	1	43	-37	125	72	189
INM	8	-24	-21	36	-54	102	86	235
NCM	36	-4	-3	42	-50	106	95	208
E.I.M	5	-9	3	38	-45	114	55	175

Table 6a: Steel gauge blocks, deviation from nominal value (in nm) as reported by the laboratories.

Comments given by the participants:

JV: JV measured up to 6 times during the entire circulation. Only first measurement result is stated in this table.

6.5 Tungsten carbide gauge blocks: combined standard deviation

	Tungsten carbide gauge blocks : Nominal length in mm							
Laboratory	**1,02**	**6**	**7**	**8**	**10**	**12**	**80**	**100**
JV	14	14	14	14	14	14	17	18
MIKES	10	10	10	10	10	10	14	15
GUM	18	18	18	18	18	18	19	19
CMI	10	10	10	10	10	10	18	21
IPQ	12	13	13	13	14	14	25	28
PTB	9	8	8	8	11	8	10	11
UME	13	13	13	13	13	13	14	15
INM	14	14	14	14	14	16	22	25
NCM	12	12	12	13	13	18	27	33
E.I.M	12	12	12	12	12	12	13	13

Table 6b: Tungsten carbide gauge blocks, combined standard uncertainty (in nm) as reported by laboratories.

Comments given by the participants:

6.6 Tungsten carbide gauge blocks: graphics

The following figures represent the results for each laboratory with error bars corresponding to one standard uncertainty.

Fig 3a: 1.02 mm tungsten carbide gauge block

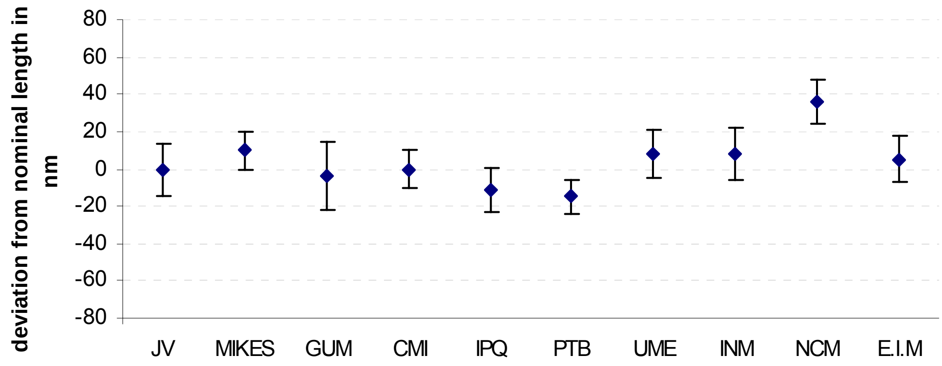


Fig 3b: 6 mm tungsten carbide gauge block

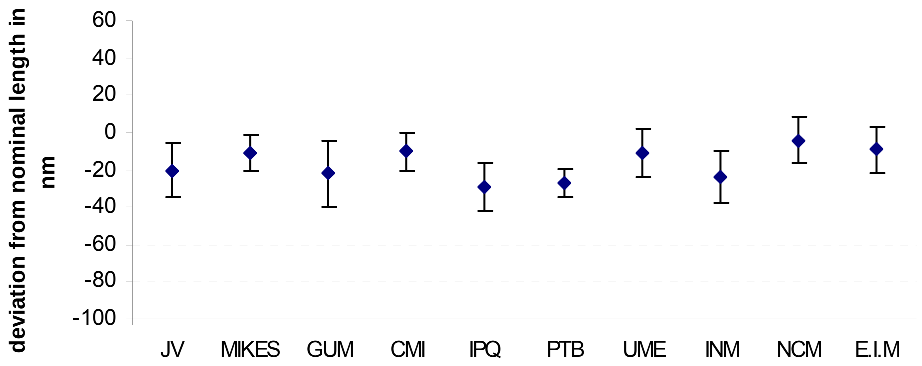


Fig 3c: 7 mm tungsten carbide gauge block

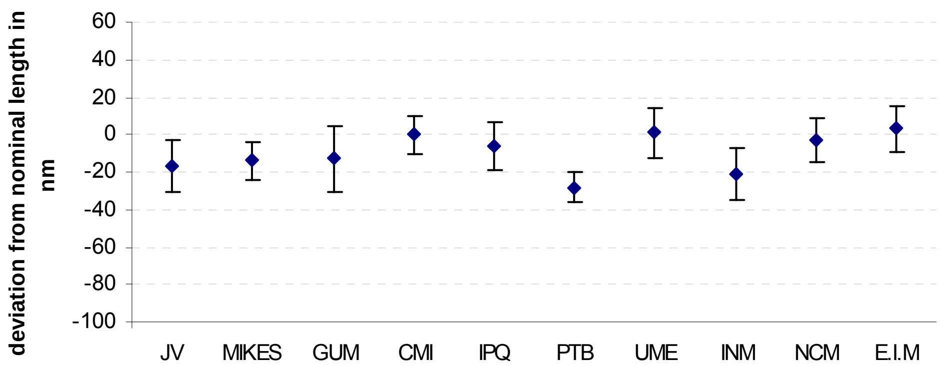


Fig 3d: 8 mm tungsten carbide gauge block

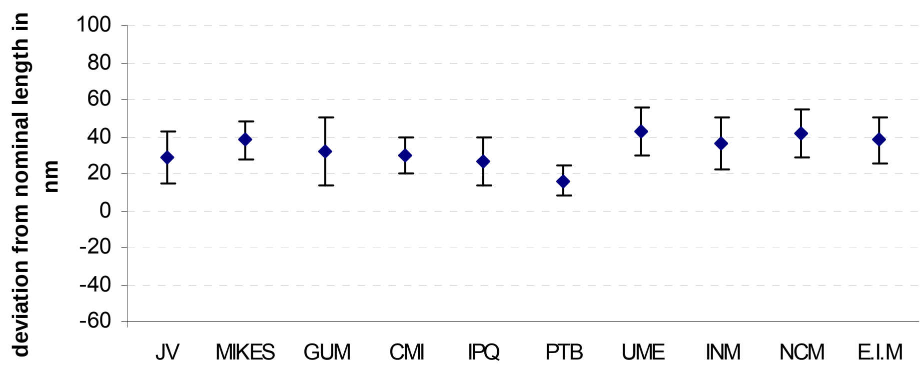


Fig 3e: 10 mm tungsten carbide gauge block

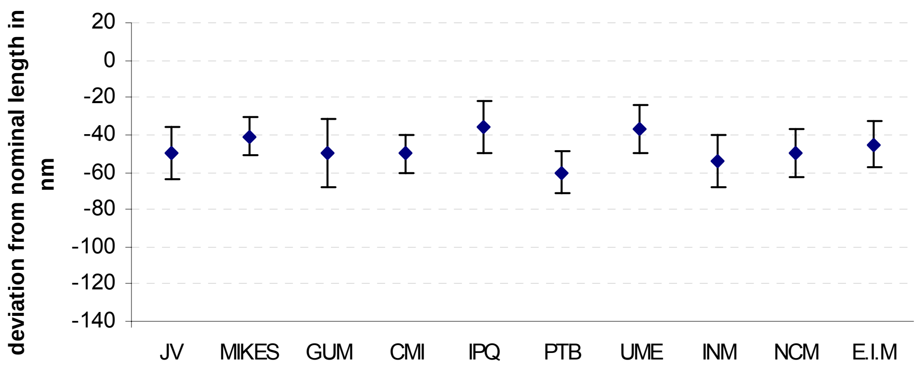
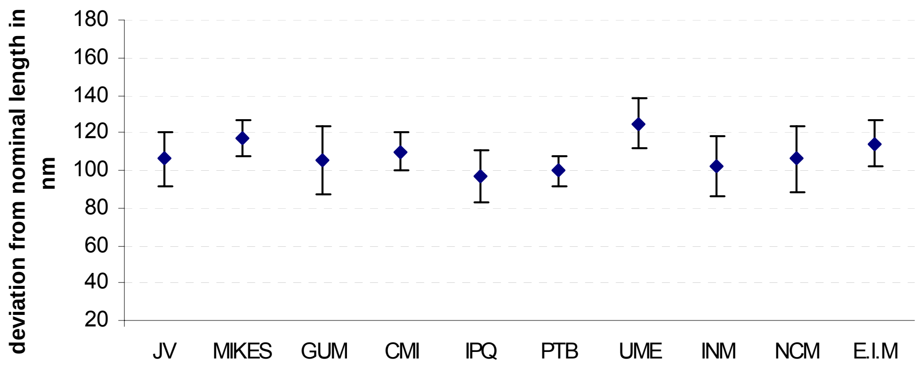
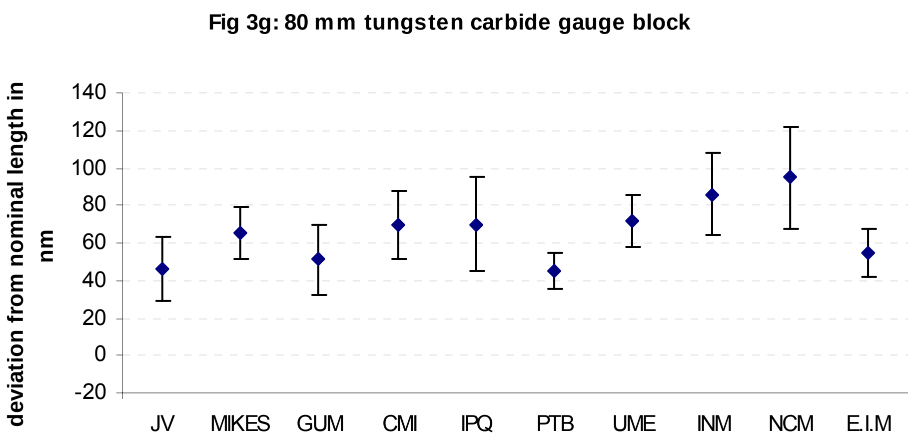


Fig 3f: 12 mm tungsten carbide gauge block





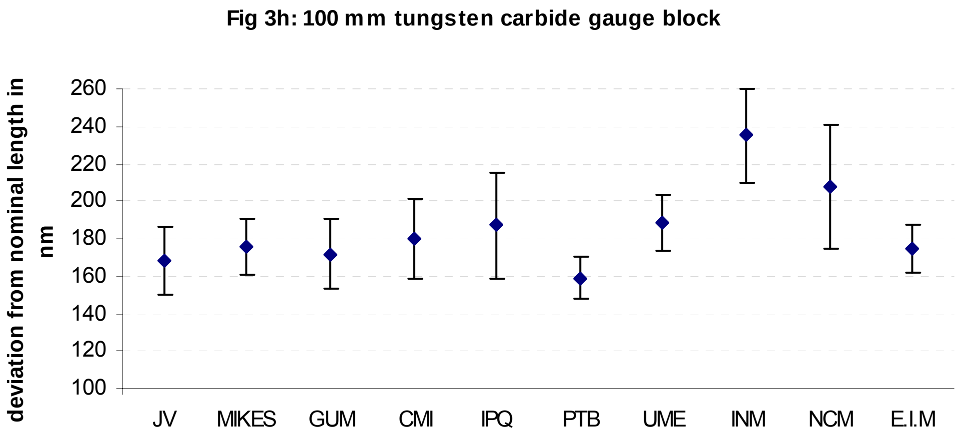


Figure 3a, b, c, d, e, f, g, h: Results for TC gauge blocks reported from each laboratory with error bars corresponding to one standard uncertainty.

6.7 Difference between the two measurements ΔL_1 and ΔL_2

Tables 7a and 7b summarizes deviations between two measurement surfaces of each gauge block with a mean value and standard deviation for each participant.

Steel	0.5	1.01	4.5	6	7	8	8	15	80	100	Mean	Std.Dev.
JV	-18	-4	-9	-3	-7	-13	-3	-9	4	2	-6.0	6.6
MIKES	10	12			-14	-2	-15	0	1	5	-0.4	10.0
GUM	13	-11			3	4	14	8	10	10	6.4	8.0
CMI	0	0			0	0	-10	0	0	0	-1.3	3.5
IPQ	19	-12	-2		-13	-6	-19	8	7	65	5.2	25.4
PTB	4	-6			0	-10	1	3	11	12	1.9	7.5
UME	2	-4	5	14	-17	0	1	10	22	5	3.8	10.5
INM		0	-4	-9	-9	10	17	3	-9	-2	-0.3	9.1
NCM		14	5		3					47	17.3	20.4
E.I.M												

Table 7a: Difference between Δl_1 and Δl_2 for steel gauge blocks. Mean value and standard deviation is calculated for each participant.

No measurements were made because gauge block was not available at the time or because of poor wringing quality.

TC	1.02	6	7	8	10	12	80	100	Mean	Std.Dev
JV	-11	-6	-9	4	-21	-1	0	-6	-6.3	7.7
MIKES	0	4	-9	-1	-7	6	5	4	0.3	5.7
GUM	-5	0	3	10	-10	6	12	3	2.4	7.3
CMI	-10	0	10	10	-10	10	0	0	1.3	8.3
IPQ	4	-11	13	4	9	5	32	-10	5.8	13.6
PTB	1	-1	11	10	-17	-3	14	6	2.6	10.0
UME	-4	2	13	13	-11	1	14	1	3.6	9.0
INM	3	3	-12	-19	1	3	7	-24	-4.8	11.8
NCM	-12	11	11	14	-12	12	16	29	8.6	14.0
E.I.M	3	3	-46	-4	-17	0	1	9	-6.4	17.7

Table 7b: Difference between Δl_1 and Δl_2 for TC gauge blocks. Mean value and standard deviation is calculated for each participant.

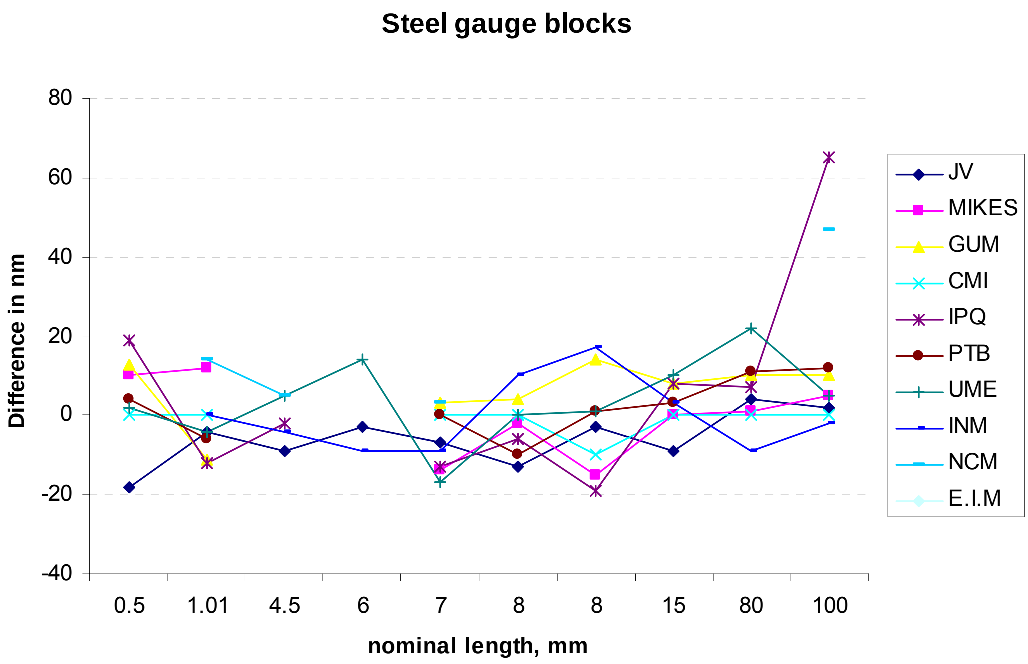


Figure 4a: Differences between Δl_1 and Δl_2 for all steel gauge blocks and all laboratories. Note that two additional gauge blocks have been introduced in the second loop, laboratories in the first loop have not measured these. In the second loop, the wear of the gauges became substantial and not all gauges were possible to measure.

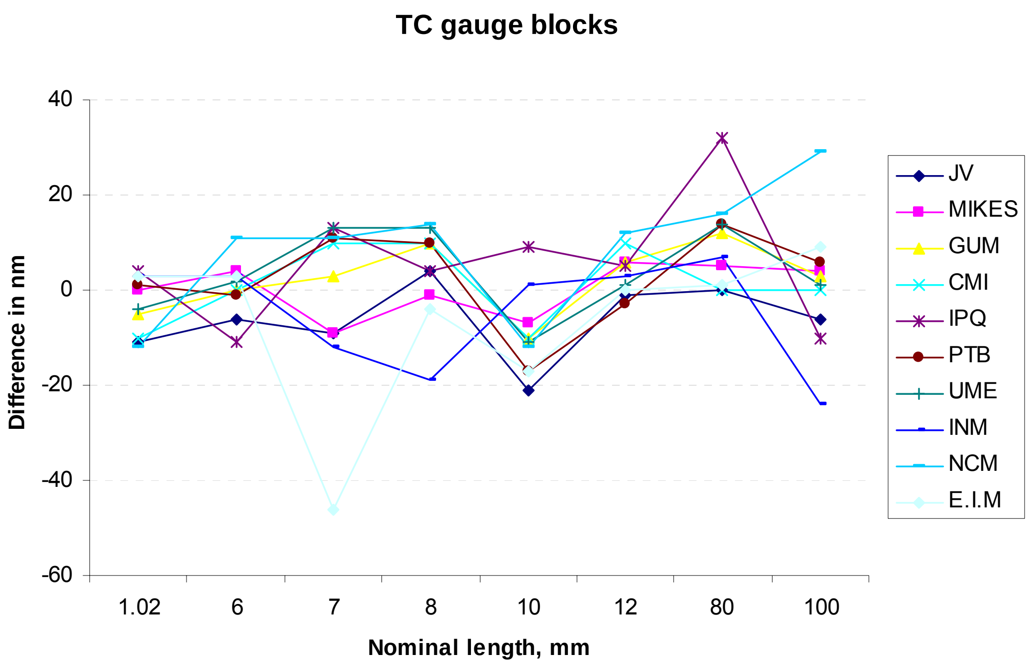


Figure 4b: Differences between Δl_1 and Δl_2 for all TC gauge blocks and all laboratories.

7 Measurement uncertainties

7.1 Description of the components as given by the laboratories

An example of a mathematical model was given in the protocol with a list (non exhaustive) of uncertainty sources.

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

where:

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

L nominal length of the gauge block

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

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

F_i fractional part of fringe order

λ_i vacuum wavelength of the different light sources used

n index of refraction of the air

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

α linear coefficient of thermal expansion of the gauge block

δl_Ω obliquity correction for the shift in phase resulting from the angular alignment errors of the collimating assembly, with zero expectation value $<\delta l_\Omega> = 0$

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

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

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

δl_W length correction attributed to the wringing film, with zero expectation value $<\delta l_W> = 0$, since the length of the gauge block is defined to include wringing film

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

In table 8, the uncertainty contributions are summarized for all the laboratories. The numerical values are standard uncertainties given for the case of a steel gauge block.

Table 9 give for the 100 mm steel gauge block the numerical value of the contribution. Only major contributions are reported and the uncertainty given for the 100 mm gauge blocks of this comparison.

For some laboratories the uncertainty on the linear expansion coefficient is different from the values given in the technical protocol. In these cases the uncertainty has been overestimated.

	JV	**MIKES**	**GUM**	**CMI**	**IPQ**	**PTB**	**UME**	**INM**	**NCM**	**E.I.M**
λ_i	$5.3\ 10^{-9}$ $1.8\ 10^{-8}$	$5\ 10^{-9}$ $1\ 10^{-8}$	$6.8\ 10^{-9}$	$2\ 10^{-8}$	$2\ 10^{-8}$	$2\ 10^{-9}$	$1.1\ 10^{-8}$	$3\ 10^{-8}$	$4\ 10^{-8}$	$1\ 10^{-8}$ $2\ 10^{-8}$
F_i	0.025 fringes	0.025 fringes	0.05 fringes	0.025 fringes	0.025 fringes	0.003 fringes	0.003 fringes	0.05 fringes	0.04 fringes	0.014 fringe
n	$8.6\ 10^{-8}$	$6\ 10^{-8}$	$2.7\ 10^{-8}$	$6\ 10^{-8}$	$1.7\ 10^{-7}$	$3\ 10^{-8}$	$5\ 10^{-8}$	$5.8\ 10^{-8}$	$2.9\ 10^{-7}$	$1.7\ 10^{-8}$
Δt_g	9 mK	10 mK	14 mK	10 mK	5 mK	5 mK	8 mK	20 mK	10 mK	10 mK
α	$0.12\ 10^{-6}\ K^{-1}$	$0.5\ 10^{-6}\ K^{-1}$	$5.5\ 10^{-8}\ K^{-1}$	$1\ 10^{-7}\ K^{-1}$	$1\ 10^{-7}\ K^{-1}$	$0.1\ 10^{-6}\ K^{-1}$	$1\ 10^{-7}\ K^{-1}$	$0.032\ 10^{-6}\ K^{-1}$	$0.055\ 10^{-6}\ K^{-1}$	$0.058\ 10^{-6}\ K^{-1}$
Δl_Ω	$1\ 10^{-8}$	$5\ 10^{-8}$	$1.1\ 10^{-8}$	$1\ 10^{-8}$	-	$4.1\ 10^{-8}$	$5.8\ 10^{-7}$	$0.18\ 10^{-6}$	-	$1.1\ 10^{-8}$
Δl_S	$1\ 10^{-8}$	-	$6.5\ 10^{-9}$	$1\ 10^{-8}$	$7\ 10^{-9}$	$4\ 10^{-9}$	$8.7\ 10^{-9}$	$3.6\ 10^{-8}$	$3\ 10^{-9}$	$1.1\ 10^{-8}$
δl_A	0.02 fringe	2.5 nm	8 nm	5.9 nm	5 nm	3 nm	5.2 nm	3.4 nm	3 nm	3.4 nm
δl_G	2.1 nm	3 nm	4 nm	2.5 nm	3.6 nm	4 nm	2.5 nm	3 nm	3.8 nm	2 nm
δl_W	6 nm	5 nm	7 nm	4 nm	5 nm	5 nm	5.3 nm	5 nm	6 nm	8 nm
Δl_Φ	6 nm	6 nm	11 nm	4 nm	6 nm	3 nm	6.1 nm	9.4 nm	6 nm	7.9 nm
Δl_R roughness correction gauge / platten					6.4 nm	4 nm				
Other contri-butions	10 nm temp diff. gauge and platten			9 nm temp diff. gauge and platten		4 nm	7.5 nm 1 nm			

Table 8. Standard uncertainties quoted by the different laboratories for the uncertainty contributions given in the model of the technical protocols.

Comments from laboratories:

	JV	MIKES	GUM	CMI	IPQ	PTB	UME	INM	NCM	E.I.M
λ_i	0.53 nm 1.8 nm	1.1 nm	1.4 nm	2.8 nm	3.1 nm	0.8 nm	1.1 nm	1.5 nm	12.4 nm	1 nm 2 nm
F_i	6.0 nm	5.3 nm	6.6 nm	5.3 nm	2.7 nm	1 nm	1 nm	6.6 nm	5.6 nm	2.3 nm 2.0 nm
n	8.6 nm	6 nm	2.7 nm	6 nm	17 nm	5 nm	5 nm	5.8 nm	29 nm	1.7 nm
Δt_g	11.4 nm	12.1 nm	15 nm	10 nm	7.6 nm	5.8 nm	9 nm	21.3 nm	11 nm	4.3 nm
α	11.6 nm	5 nm	1.5 nm	10 nm	3 nm	0.5	3 nm	0.8 nm	0.3 nm	1.7 nm
Δl_Ω	1 nm	5 nm	1.1 nm	1 nm	0.01 nm	4.1 nm	0.6 nm	18 nm		1.1 nm
Δl_S	1 nm	-	0.7 nm	1 nm	0.007 nm	0.4 nm	0.9 nm	3.6 nm	0.3 nm	6 nm
δl_A	6.3 nm	2.5 nm	8 nm	5.9 nm	5 nm	3 nm	5.2 nm	3.4 nm	3 nm	3.4 nm
δl_G	2.1 nm	3 nm	4 nm	2.5 nm	3.6 nm	4 nm	2.5 nm	3 nm	3.8 nm	2 nm
δl_W	6 nm	5 nm	7 nm	4 nm	5 nm	5 nm	5.3 nm	5 nm	6 nm	8 nm
Δl_Φ	6 nm	6 nm	11 nm	4 nm	6 nm	3 nm	6.1 nm	9.4 nm	6 nm	7.9 nm
Other contributions not reported										
Combined standard uncertainty	24 nm	17 nm	24 nm	21 nm	28 nm	12 nm	17 nm	31.7 nm	35 nm	13 nm

Table 9. Standard uncertainties quoted by the different laboratories for the major uncertainty contributions for a 100 mm steel gauge block.

8 Analysis of the results

8.1 Outliers

Some reported measurement results seem to be inconsistent with other results, and may change the estimate and specially the reference values.

A numerical outliers test was performed according to the standard ISO 5725-2:1994[1]. Details of this test are given in appendix 2 of the report EUROMET.L-K1.

Results are declared outliers if the test gives a Grubbs value greater than its 1 % critical value, and results are declared stragglers if the test gives a Grubbs value greater than its 5 % critical value.

Results of this test are that no results are outliers or stragglers for steel gauge blocks or for TC gauge blocks. No results are excluded from the following computations.

8.2 Stability of the gauge blocks

Figure 5a) (steel) and 5b) (TC) display all measurement results for the gauge blocks for each laboratory in the same diagram. We see that there is very small systematic drift of the gauge blocks. After the Euromet Length meeting in Dublin Oct. 2003 it was decided that no drift correction should be applied for any of the gauge blocks.

We will not apply any drift correction for the gauge blocks, but we will rather add to the measurement uncertainty of the reference value an uncertainty component for the instability of the gauge blocks, which is calculated from the natural spread given by the standard deviation of results at the pilot laboratory, JV.

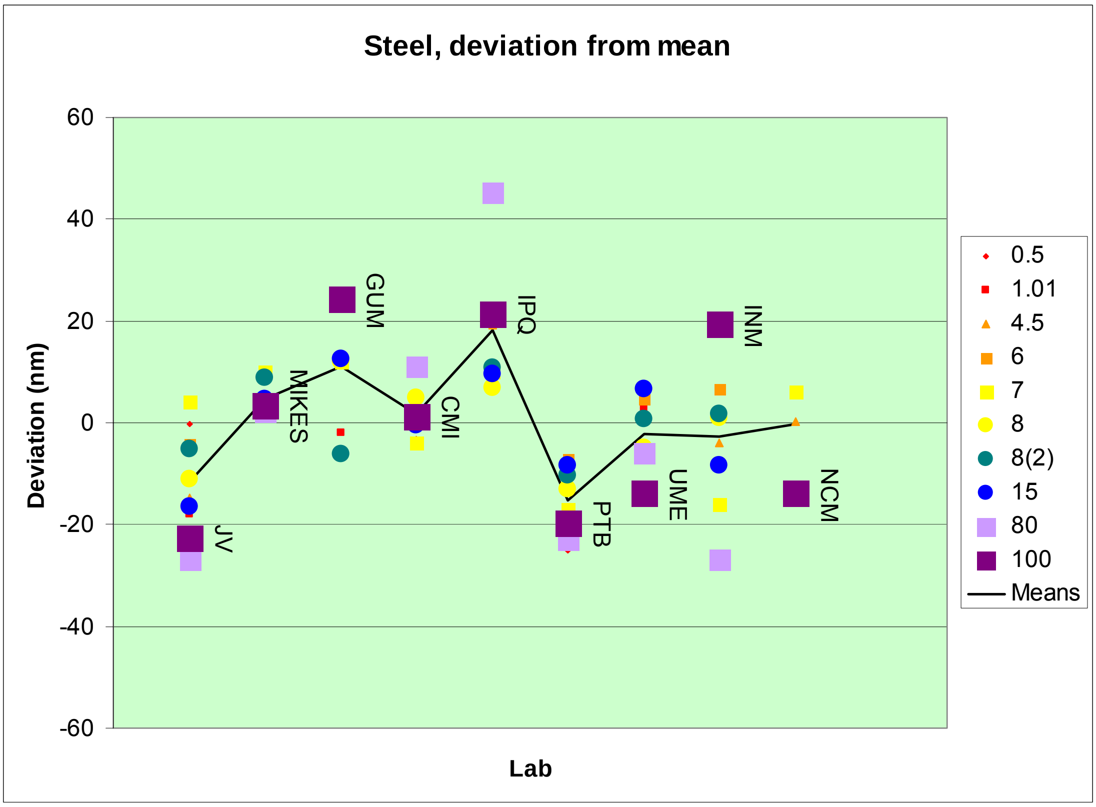


Figure 5a: Measurement results for all steel gauge blocks for each laboratory.

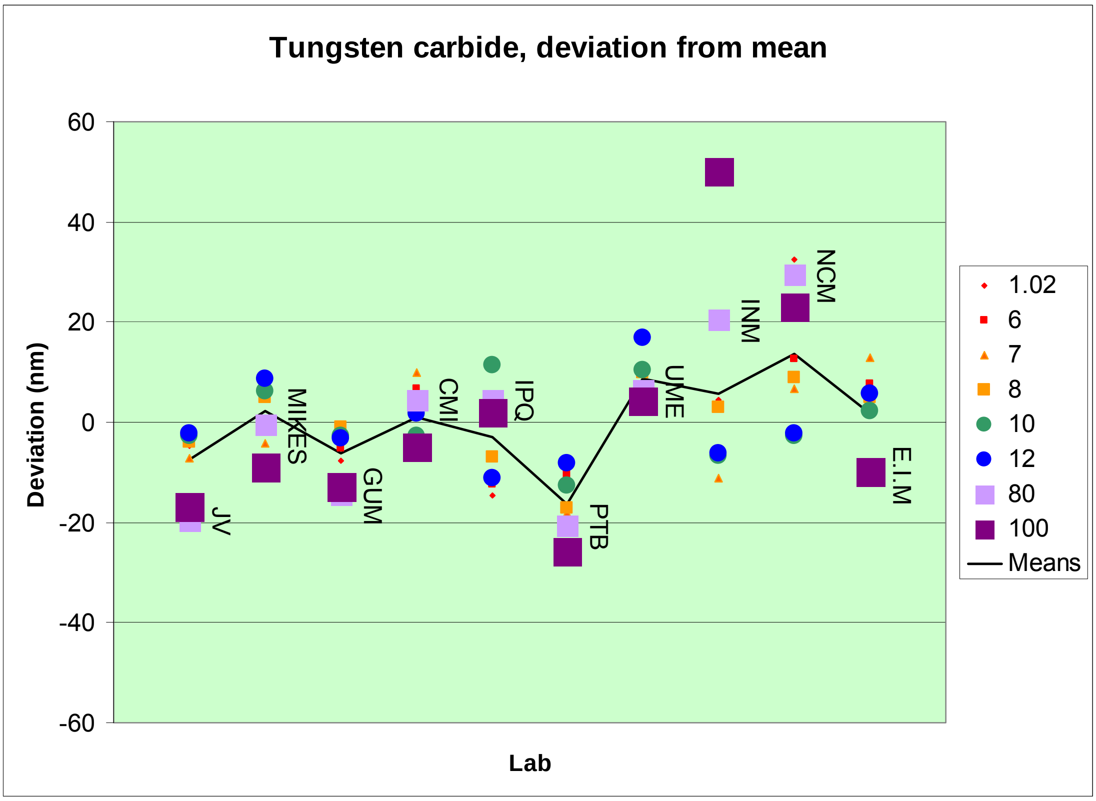


Figure 5b: Measurement results for all TC gauge blocks for each laboratory.

8.2.1 Monitoring by the pilot laboratory

No drift correction is applied, and the monitoring of the pilot lab is used to give an uncertainty component due to instability of each gauge block, called an artefact uncertainty.

The plan was to measure three times at the pilot laboratory, in February 2002, August 2002 and at the end of the circulation. Two steel gauge blocks were added during the circulation, 4.5 mm and 6 mm, so no measurement has been carried out for these gauge blocks in Feb 2002. Many gauge blocks have been reconditioned at PTB, so additional measurements had to be carried out at the pilot laboratory to monitor also any change of value because of the reconditioning work.

The following figures show the drift for all steel gauge blocks. Results of each laboratory are plotted versus months from first measurement. All results of the pilot laboratory are identified by a larger square. PTB (results marked with a blue diamond white inside) has measured twice on many gauge blocks. An artefact uncertainty is calculated for each gauge block as one standard deviation from all measurements by the pilot laboratory, summarized in table A2e in appendix 2.

Fig 6a: Steel 0.5 mm

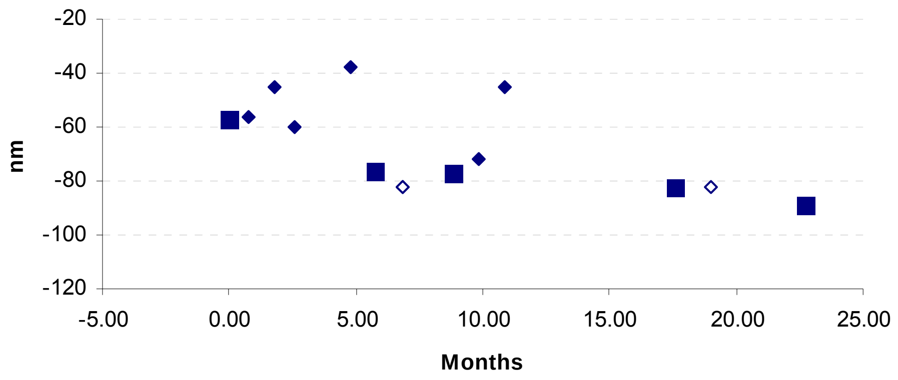


Fig 6b: Steel, 1.01 mm

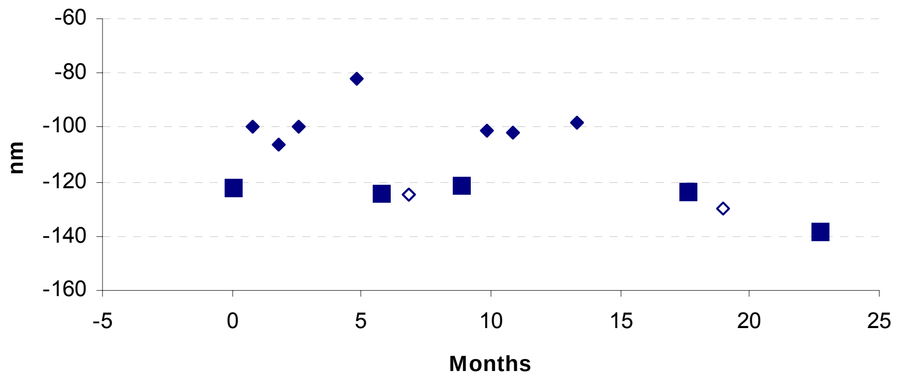


Fig 6c: Steel 4.5 mm

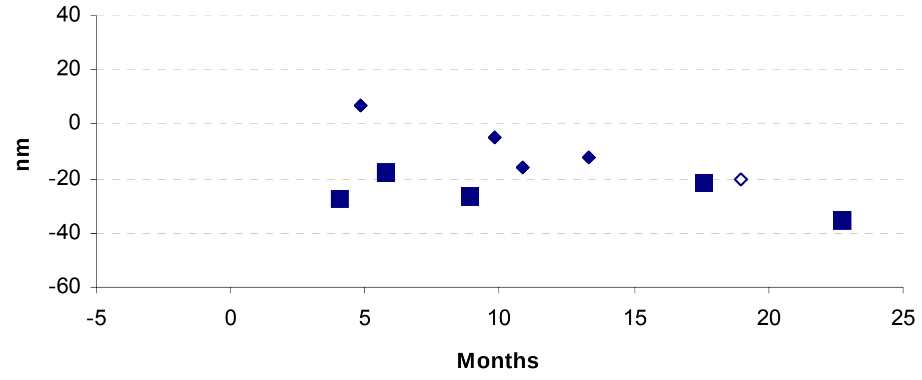


Fig 6d: Steel, 6 mm

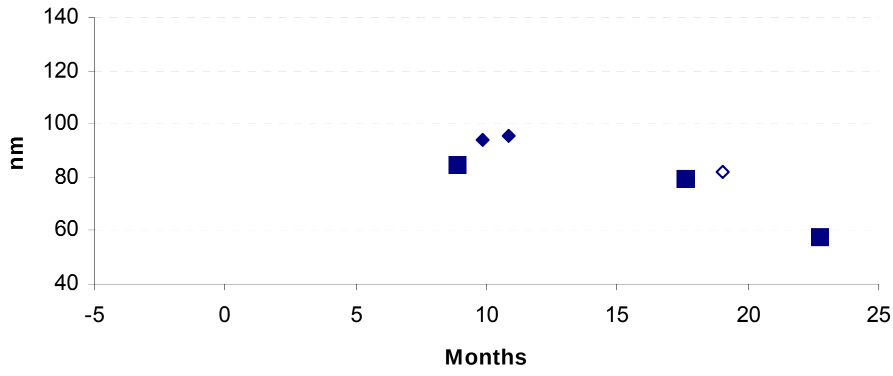


Fig 6e: Steel, 7 mm

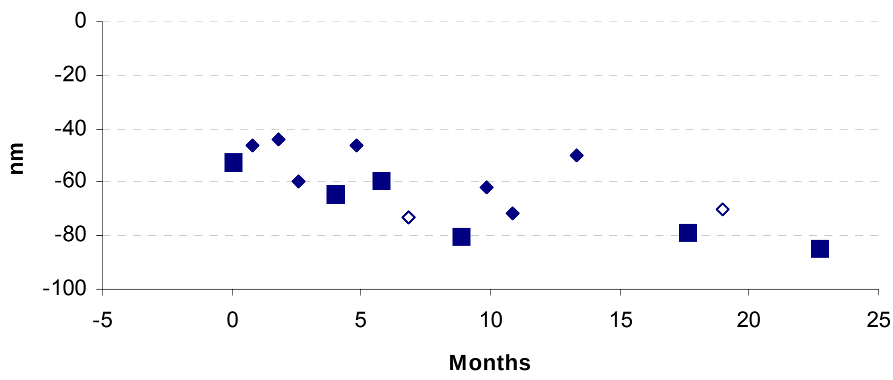


Fig 6f: Steel, 8 nm id 982413

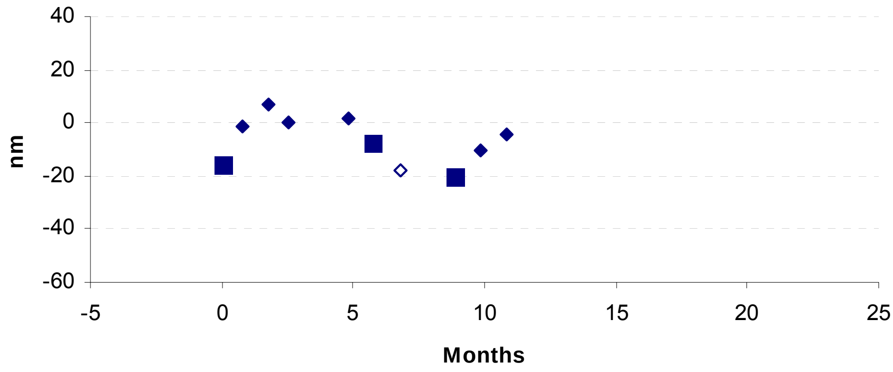


Fig 6g: Steel, 8 mm id 981491

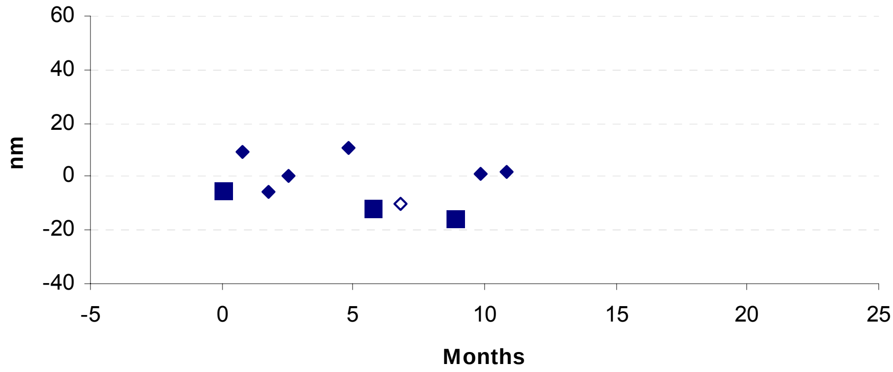
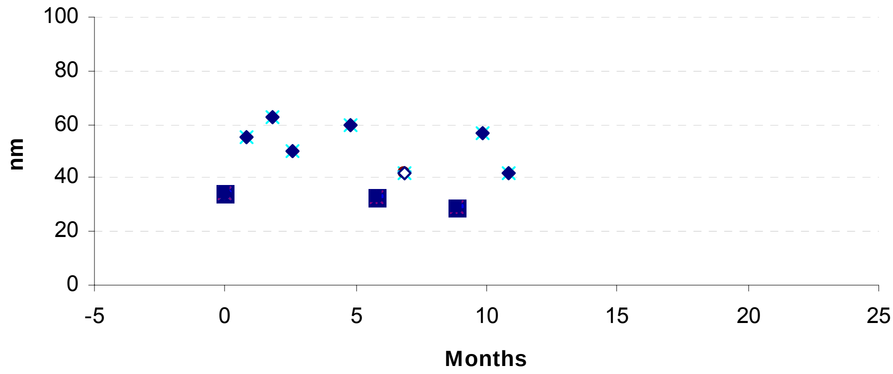
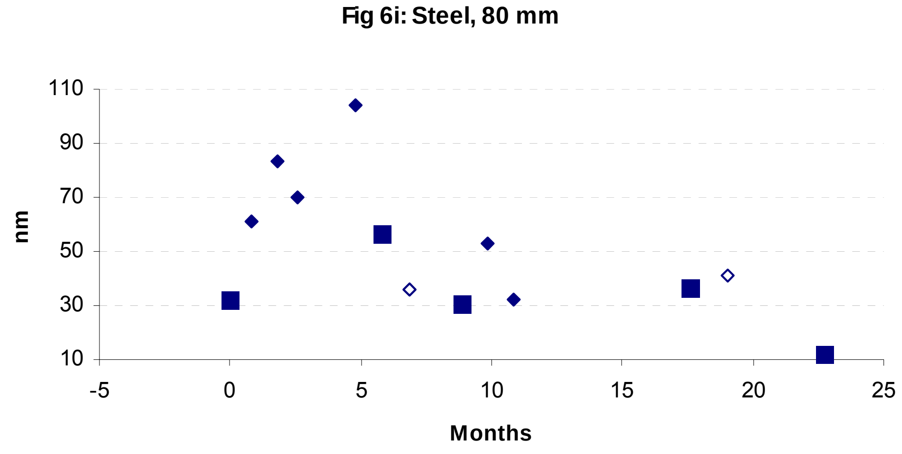


Fig 6h: Steel, 15 mm





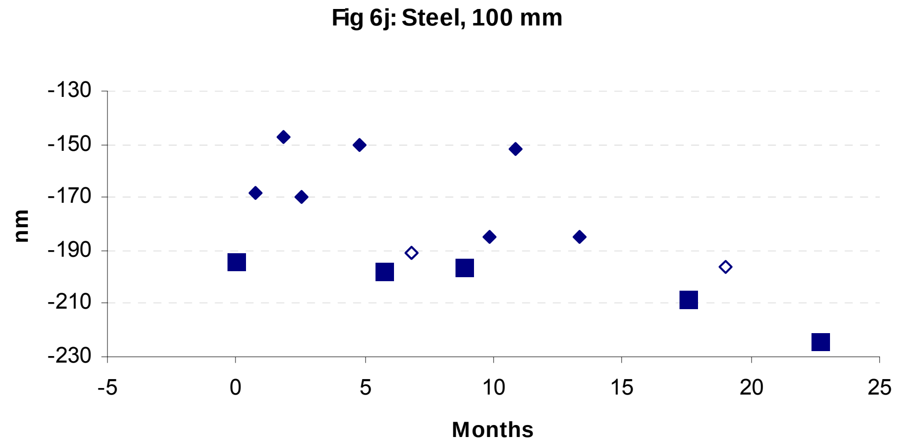


Figure 6a, b, c, d, e, f, g, h, i, j. Results in nm versus time (month) for steel gauge blocks. JV (pilot) is marked with a large blue square. PTB is marked with a blue diamond with white inside.

In figure 7 similar plots are given for all tungsten carbide gauge blocks.

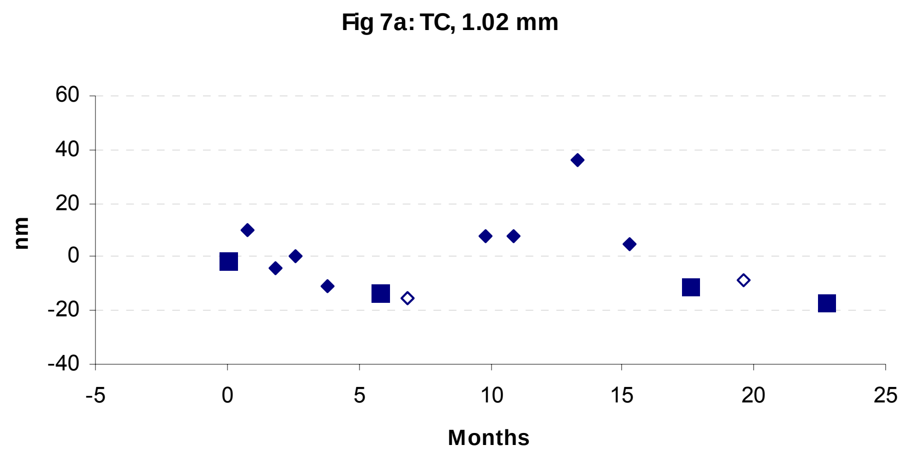


Fig 7a: TC, 1.02 mm
60
40
20
0
-20
-40
nm
-5
0
5
10
15
20
25
Months

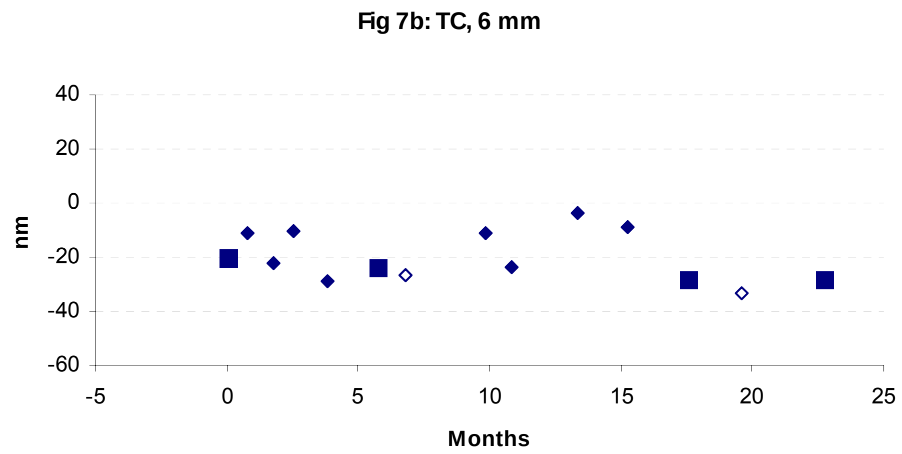


Fig 7b: TC, 6 mm
40
20
0
-20
-40
-60
nm
-5
0
5
10
15
20
25
Months

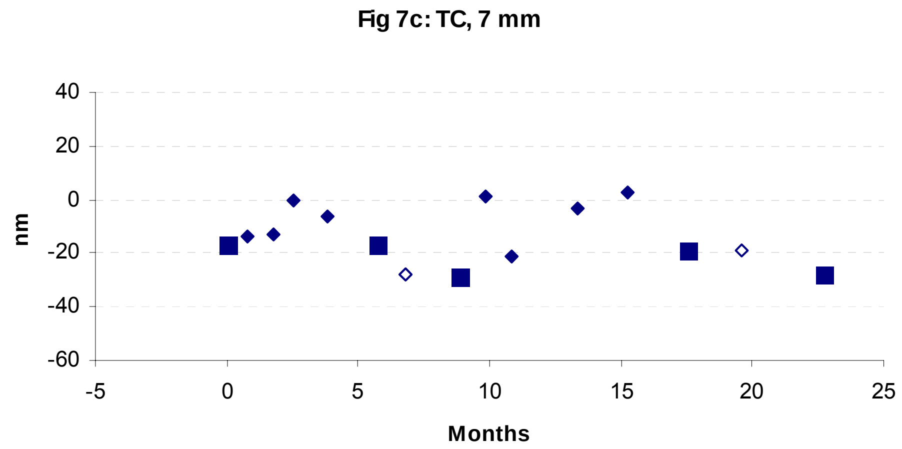


Fig 7c: TC, 7 mm
40
20
0
-20
-40
-60
nm
-5
0
5
10
15
20
25
Months

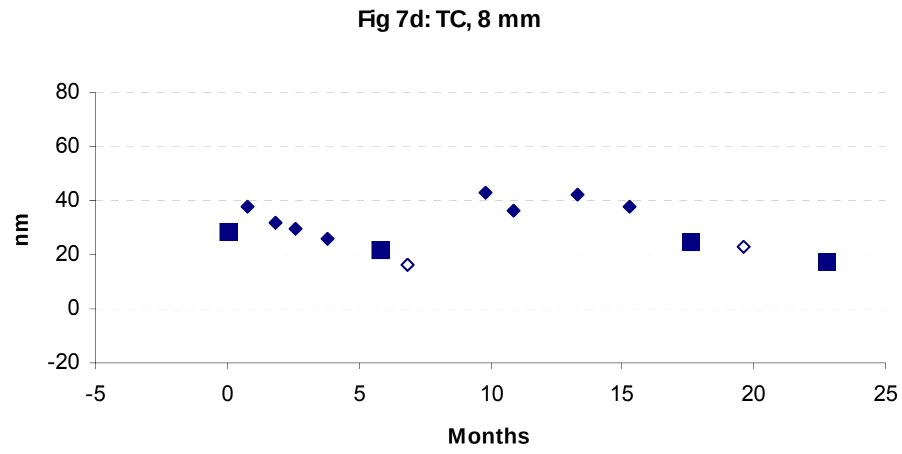


Fig 7d: TC, 8 mm
nm
80
60
40
20
0
-20
-5
0
5
10
15
20
25
Months

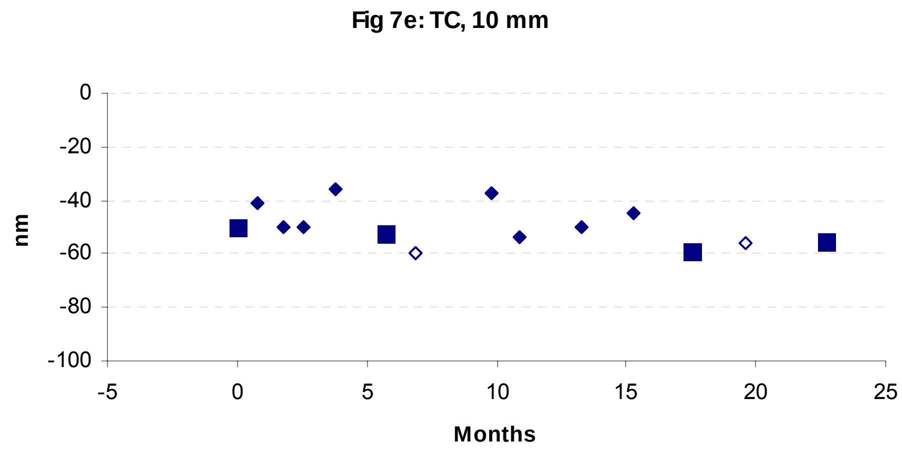


Fig 7e: TC, 10 mm
nm
0
-20
-40
-60
-80
-100
-5
0
5
10
15
20
25
Months

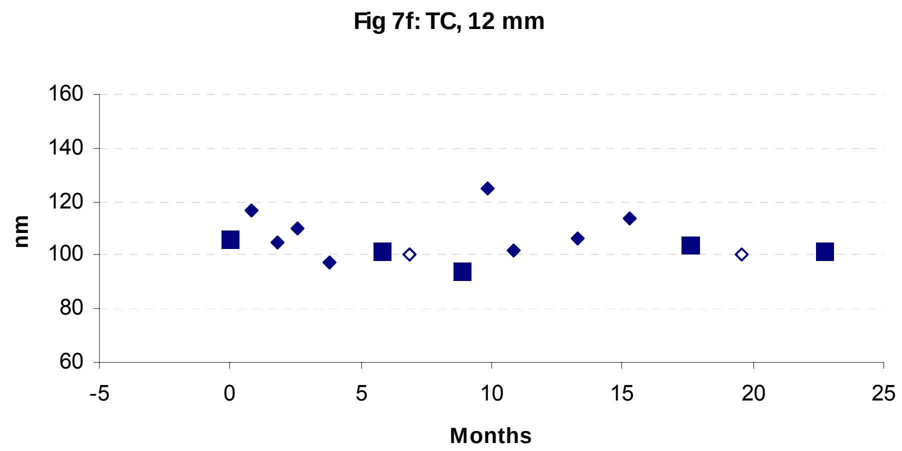
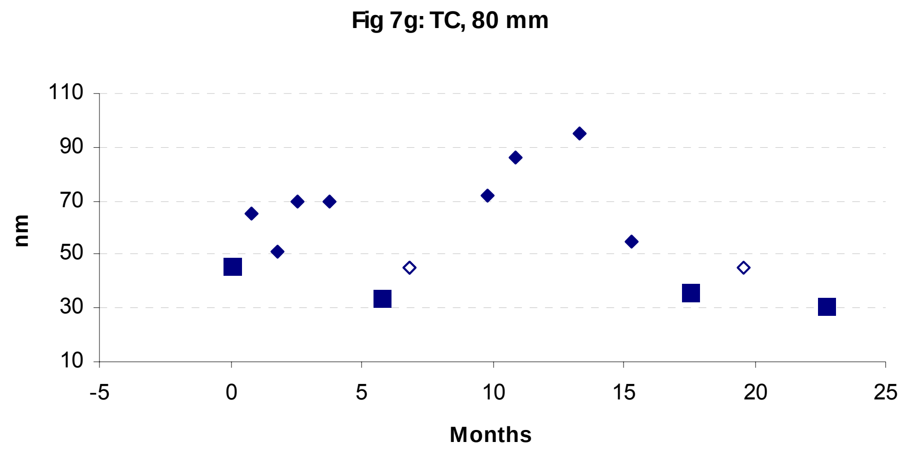


Fig 7f: TC, 12 mm
nm
160
140
120
100
80
60
-5
0
5
10
15
20
25
Months



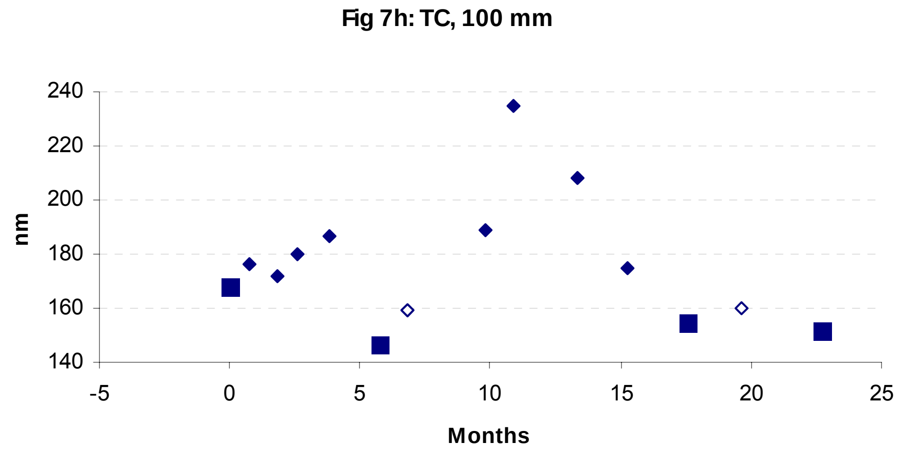


Figure 7a, b, c, d, e, f, g, h. Results in nm versus time (months) for TC gauge blocks. JV (pilot) is marked with a large blue square. PTB is marked with a blue diamond with white inside.

8.2.2 Conclusion

It was decided after the Euromet Length meeting in Dublin in October 2003 that we do not apply any drift corrections to the results. The monitoring of the pilot laboratory indicates a very small drift, and two results from PTB for many of the gauge blocks also verify that the gauge blocks are quite stable.

The monitoring of the pilot laboratory gives a measure of the artefact uncertainty, due to instability of the artefact itself. This uncertainty contribution is calculated as one standard deviation of 3, 4, 5 or 6 measurements at the pilot laboratory. The reason for this uneven number of measurements by the pilot laboratory is that some gauge blocks needed more reconditioning, and the pilot laboratory measured before and after each reconditioning at PTB. One gauge block, steel 7 mm, was once reconditioned at the pilot laboratory as well.

9 Results

9.1 Deviation from nominal length

	Steel gauge blocks : Nominal length in mm									
Laboratory	**0,5**	**1,01**	**4,5*)**	**6*)**	**7**	**8**	**8**)**	**15**	**80**	**100**
JV	-57	-122	-27	85	-52	-16	-5	34	32	-194
MIKES	-56	-100			-46	-1	9	55	61	-168
GUM	-45	-106			-44	7	-6	63	83	-147
CMI	-60	-100			-60	0	0	50	70	-170
IPQ	-38	-82	7		-46	2	11	60	104	-150
PTB	-82	-125	-20	82	-73	-18	-10	42	36	-191
UME	-72	-101	-5	94	-62	-10	1	57	53	-185
INM		-102	-16	96	-72	-4	2	42	32	-152
NCM		-98	-12		-50					-185
E.I.M										

Table 11a: Steel gauge blocks, deviation from nominal value (in nm).
**) 4,5 mm and 6 mm were included in the second loop only as additional gauges to the set in order to be able to measure the phase correction by stack method. This was necessary because other steel gauges were gradually degrading in wringing quality.*
***) Two 8 mm steel gauge blocks, tabulated with decreasing serial number, id 982413 and id 981491.*

(light grey) *Gauge block not available for measurement*

(dark grey) *Gauge block not measured because of damaged measurement surface*

	Tungsten carbide gauge blocks : Nominal length in mm							
Laboratory	**1,02**	**6**	**7**	**8**	**10**	**12**	**80**	**100**
JV	-1	-20	-17	29	-50	106	46	168
MIKES	10	-11	-14	38	-41	117	65	176
GUM	-4	-22	-13	32	-50	105	51	172
CMI	0	-10	0	30	-50	110	70	180
IPQ	-11	-29	-6	26	-36	97	70	187
PTB	-15	-27	-28	16	-60	100	45	159
UME	8	-11	1	43	-37	125	72	189
INM	8	-24	-21	36	-54	102	86	235
NCM	36	-4	-3	42	-50	106	95	208
E.I.M	5	-9	3	38	-45	114	55	175

Table 11b: TC gauge blocks, deviation from nominal value (in nm).

10 Statistical analysis

10.1 Average deviation and standard deviation; definitions

For each laboratory, the average $< \Delta l >$ of the deviations from the mean over all gauge blocks is calculated as follows:

$$< \Delta l > = \frac{1}{N} \sum (x_j - \bar{x}_j)$$

where x_j is the result for the individual gauge block j and $\bar{x}_j$ is the mean over all laboratories for that gauge block. N = 8 is the number of gauge blocks for each material. Because of wear not all participants could measure all gauges, and because of addition of two steel gauge blocks the number of gauge blocks is not the same for all laboratories.

Similarly, the standard deviation s of the differences $x_j - \bar{x}_j$ is calculated:

$$s^2 = \frac{1}{N-1} \sum_{j=1}^{N} \left((x_j - \bar{x}_j) - < \Delta l > \right)^2$$

The normalised standard deviation s_n is the standard deviation divided by the standard uncertainty u_j given by the laboratory for the individual gauge block j.

$$s_n^2 = \frac{1}{N-1} \sum_{j=1}^{N} \left(\frac{(x_j - \bar{x}_j) - < \Delta l >}{u_j} \right)^2$$

10.2 Results

In the following tables and figures, computed values for $< \Delta l >$, s and s_n are given for each laboratory and gauge block material.

	Steel gauge blocks			TC gauge blocks		
Laboratory	$< \Delta l >$(nm)	s (nm)	s_n (nm)	$< \Delta l >$(nm)	s (nm)	s_n (nm)
JV	-11.4	10.2	0.7	-7.6	6.8	0.4
MIKES	4.9	2.9	0.3	2.3	6.2	0.5
GUM	11.3	10.9	0.6	-6.3	5.0	0.3
CMI	1.9	4.7	0.4	1.1	5.5	0.5
IPQ	18.4	11.6	0.6	-2.9	9.5	0.7
PTB	-18.8	8.6	0.8	-16.4	5.8	0.6
UME	-2.2	7.8	0.5	8.6	4.3	0.3
INM*)	-5.7	10.2	0.6	5.8	20.5	1.0
NCM	-5.8	10.6	0.4	13.6	13.5	0.9
E.I.M				1.8	8.2	0.7

Table 12: Average deviation, standard deviation from mean and normalised standard deviation from mean for all laboratories, steel and TC gauge blocks.
**) 0.5 mm gauge block is not included in the calculation because uncertainty is not reported for this gauge block.*

10.3 Statistical distribution

Figures 8 and 9 show histogram of the normalized deviations from the means of all measurement results. Normalized deviations are obtained by the ratio of the difference of each result with the mean value divided by the standard uncertainty of each individual result.

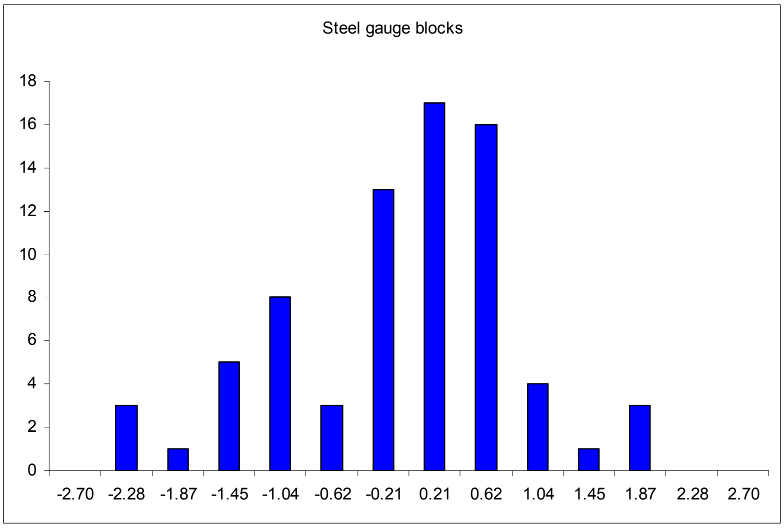


Figure 8: Steel gauge blocks, normalized deviation from mean (standard deviation, s_n=0,91).

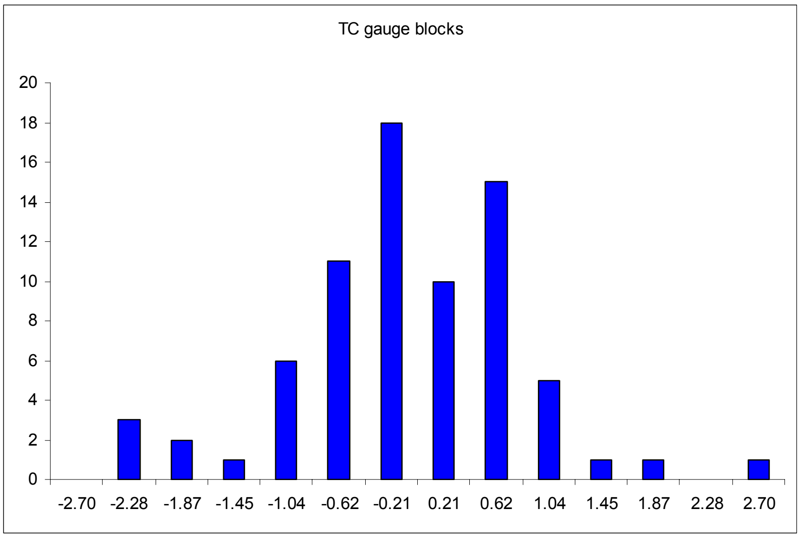


Figure 9: TC gauge blocks, normalized deviation from mean. (standard deviation, s_n = 0,91).

10.4 Statistical consistency

The statistical consistency of a comparison can be investigated by the so-called Birge ratio R_B, which compares the observed spread of the results with the spread expected from the individual reported uncertainties.

The formulas are given in the report from EUROMET Comparison L-K1. The results in a comparison are consistent if $R_B < \sqrt{1+\sqrt{8/(n-1)}}$, n being the number of laboratories reporting one measurement for each gauge block.

Steel	0.5	1.01	4.5	6	7	8	8	15	80	100
u_{in}	4.45	4.05	5.00	5.76	3.95	4.14	4.14	4.26	6.09	6.64
u_{ext}	5.68	4.60	4.77	3.47	3.82	3.13	3.65	3.25	7.69	5.57
R_B	**1.27**	**1.13**	**0.95**	**0.60**	**0.97**	**0.75**	**0.88**	**0.76**	**1.26**	**0.84**
R_B <	**1.47**	**1.41**	**1.50**	**1.62**	**1.41**	**1.44**	**1.44**	**1.44**	**1.44**	**1.41**
TC	1.02	6	7	8	10	12	80	100		
u_{in}	3.72	3.66	3.66	3.69	3.91	3.81	4.97	5.35		
u_{ext}	4.64	2.85	4.18	3.06	2.42	2.73	4.60	5.66		
R_B	**1.25**	**0.78**	**1.14**	**0.83**	**0.62**	**0.72**	**0.93**	**1.06**		
R_B <	**1.39**	**1.39**	**1.39**	**1.39**	**1.39**	**1.39**	**1.39**	**1.39**		

Table 13. Birge ratios, R_B, for measurement results for steel and TC gauge blocks. Critical values for the Birge ratio are red.

From table 20, we see that the data are consistent, because the Birge ratio is smaller than the critical value. For TC gauge blocks, the critical value for the Birge ratio is 1.39 because n = 8, for all gauge blocks. But for steel gauge blocks, the value of n varies.

11 Conclusion

In spite of the fact that there were many problems with damage of measuring surfaces of the gauge blocks and that repeated reconditioning of the gauge blocks were necessary, results agree fairly well. Only two E-values are larger than 1: One participant has E = 1.28 for 1.02 mm TC gauge block, and another participant has E = 1.03 for 100 mm TC gauge block. All other E-values are less than 1.

The problem of degradation of the wringing quality of the gauge blocks, and the need for repeated reconditioning of the measurement surfaces of some gauge blocks resulted in many delays in this project. However, the reconditioning work does not seem to have affected the measurement values of the gauge blocks, or made measurement results for this comparison not valid. The 0,5 mm steel gauge block was reported by UME that it was difficult to have a perfect wring in the centre where the measurand for this comparison is defined. Even if some participants have measured close to the centre of this gauge block, avoiding the disrupted interference fringes at the centre, and other participants did measure at the centre (before this problem became visible), the results are good. No laboratories had E-values larger than 1 for this gauge block. All reported results are considered as if they were measured in the centre.

Another problem is to evaluate the drift of the gauge blocks. After the Euromet Length meeting in Dublin in October 2003 it was decided that no drift corrections to the results should be applied. The monitoring of the pilot laboratory indicates a very small drift, and two results from PTB for many of the gauge blocks also verify that the gauge blocks are quite stable. The spread of results at the pilot laboratory calculated as one standard deviation gives rise to an artefact uncertatinty.

All laboratories have reported results on all TC gauge blocks, whereas one laboratory, at the end of the circulation, did not measure any steel gauge blocks because of the bad wringing quality. Some of the steel gauge blocks needed reconditioning already after five participants had finished their measurements. The pilot laboratory then added two extra steel gauge blocks to the set for the rest of the loop. The damage of the gauge blocks is probably caused by repeated wringing trials. To avoid damage of the gauge blocks during a comparison, I think it is necessary to

- select very good surface quality gauge blocks
- limit the number of participants in one project
- limit the number of repeated measurements at each laboratory
- have well trained operators perform the wringing of the gauge blocks

After being measured up to 15 times at 10 different calibration laboratories, 8 out of 20 measurement surfaces (10 steel gauge blocks) are now not possible to give a satisfactory wring. This is an alarmingly high degradation rate. The reason for this can very well be that the measurement instructions did not specify a maximum number of wringing trials for each participant. It is likely that some participants wrung the gauge blocks many times in order to verify their measurement results. If each participant has wrung each measurement surface 3 times (at an average), each measurement surface has been exposed to ca 45 wringing trials. The pilot laboratory has made only one wringing of each measurement surface, but for a few surfaces, two wringing trials were necessary to achieve a satisfactory wring.

12 References

[1] – G-P Vailleau, EUROMET report on L-K1: Calibration of gauge blocks by interferometry, September 19, 2003.

[2] – ISO 5725-2: Accuracy (trueness and precision) of measurement methods and results – Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method.

Appendix 1: Measurement conditions

Laboratory	Make and type of interferometer	Light sources, wavelengths	Method of fringe fraction determination	Refractive index determination	Temperature range / °C Calibration information
MIKES	NPL-TESA Automatic gauge block interferometer, Twyman Green design	HeNe laser, λ = 633 nm HeNe laser, λ = 543 nm			
IPQ	NPL-TESA Automatic gauge block interferometer, Twyman Green design	λ = 632,990 601 9 nm λ = 543,515 367 9 nm	TV line number for fringe minima position. Phase displacement at gauge centre by fitting the fringe numbers on the reference flat to a quadratic form.	Edlén equation with parameters presented in “The refractive index of Air”, Bengt Edlén Metrologia, Vol 2 1966, p 71 – 80.	(20.0 ± 0.3) °C Pt 100 with length 35 mm. u = 5 mK
JV	NPL-TESA Automatic gauge block interferometer, Twyman Green design	HeNe laser, λ = 633 nm calibrated by beat frequency comparison against iodine-stabilsed reference laser. HeNe laser, λ = 543 nm calibrated by Lambdameter and 633 nm reference wavelength	According to computer software – NPL TESA	Edlén’s equation, according NPL TESA interferometer handbook.	Budget: L < 10 mm: 19.8 °C - 20.2 °C L< 25 mm 19.88 °C - 20.15 °C L< 100 mm 19.9 °C - 20.1 °C NPL TESA Pt 100 and and Tinsley thermometer bridge, u = 5 mK
CMI	NPL-TESA Automatic gauge block interferometer, Twyman Green design A.G.I. 300	Frequency stabilized laser RED 633 nm Frequency stabilized laser GREEN 543 nm	According to computer software – NPL TESA	According NPL TESA interferometer handbook	From lowest 19.987 °C to highest 20.168 °C. Difference temp: 2 mK NPL TESA pt thermometers u = 10 mK
E.I.M	NPL-TESA Automatic gauge block interferometer, Twyman Green	Frequency stabilized lasers, wavelength λ = 633 nm	Method of exact fractions, Automatic fringe determination by NPL-TESA	Edlen’s formula, Edlen, Metrologia, vol2, No6, 1966.	Side A: 19.898 °C Side B: 19.978 °C Room temperature:

	design, A.G.I. 1/300	λ = 543 nm	software (D.J. Pugh and K.Jackson, SPIE vol. 656 p.244, 1986)		(20 ± 0.2) °C within several hours. Three Pt100 thermometers (air, platen, gauge block) u = 10 mK.
UME	NPL-TESA Automatic gauge block interferometer, Twyman Green design, FlaP version, phase stepping technique	Two frequencies stabilised HeNe lasers. λ = 633 nm λ = 543 nm	Phase stepping interferometry (five position phase-stepping technique). The computer uses NPL FlaP for control and data acquisition.	Revised Edlen equation by Birch and Downs. Air temp, humidity and pressure is measured.	20 °C ± 0.3 °C. Temperature variation is 0.1 – 0.5 mK/min within the measurement cabinet. Measurement takes ca 1 minute. Pt100 and Tinsley thermometer bridge, Consort 5840E, u = 5 mK.
GUM	Carl Zeiss Jena interferometer, Kösters type	Cd 114 spectral lamp: λ = 644,02480 nm λ = 508.72379 nm λ = 480.12521 nm λ = 467.94581 nm	Automatic interference evaluation by phase stepping interferometry	Modified Edlén's equation: Birch and Downs, Metrologia 31, 1994, 315-316.	Tempeature range for steel: 19.869 °C to 20.124°C. TC: 19.927°C to 20.124°C YSI temperature thermistors and Keithly 2010; u = 10 mK.
INM	Carl Zeiss Jena interferometer, Kösters type	Cd 114 spectral lamp (Resolution 2 of CIPM 1983): At T = 20 °C, P = 101,3 kPa, H = 1,33 kPa: λ = 643.85026 nm λ = 508.58474 nm λ = 479.99360 nm λ = 467.81737 nm	Visual observation of fringe pattern, dedicated interference fringe processing software developed by INM.	Edlen's equation.	Tempeature range for steel: 19.55 °C to 20.35 °C. TC: 19.70 °C to 20.50 °C Glass thermometer (Hg), u = 10 mK
NCM	Carl Zeiss Jena interferometer,	L < 25 mm: He lamp:	Visual interpolation	Modified version of Edlen equation	Temperature within range:

	Kösters type	λ = 667 nm λ = 587 nm λ = 501 nm λ = 492 nm λ = 471 nm λ = 447 nm L < 100 mm: Kr-lamp: λ = 646 nm λ = 587 nm λ = 565 nm λ = 450 nm			19.94 °C to 20.06 °C Liquid in glass thermometer / mercury / with scale division 0.02 °C, u = 10 mK
PTB	Michelson interferometer, modified TSUGAMI, phase-stepping arrangement and active temperature control, automatic evaluation	Wavelength stabilized HeNe lasers at λ = 633 nm λ = 543 nm. Rb stabilized diode laser at λ = 780 nm	Automatic interference evaluation by phase stepping interferometry, computer-aided length determination, topography.	Edlén's formulae, metrologia 35, 133 139 (1998) SPIE Vol. 3477, 62-67, 1998	Steel: 19.981 °C to 19.993 °C TC: 19.986 °C to 19.997 °C Pt-100 sensors with ASL F-25 (AC-instrument) and digital DC multimeter (2 instruments are used simultaneously, u = 5 mK.

Table A1a: Measurement conditions.

	Steel gauge blocks			TC gauge blocks			
Labo-ratory	**material**	**mean (nm)**	**range (nm)**	**material**	**mean (nm)**	**range (nm)**	**Wringing fluid**
MIKES	Steel	-25		Steel	-39		ethanol / paraffin 99:1
IPQ	Steel	-36.6	-40.0 : -34.2	Steel	-56.7	-54.2 : -59.2	-
JV	Steel	-53.7	-59.4 : -55.6	TC	-47.7	-51.2 : -42.0	paraffin
CMI	Steel		-26 : -40	Steel		-29 : -36	No, but some times: CARY
E.I.M	-	-	-	Steel	-22.9		Isopropanol
UME	Steel	+7		Steel	+6		solvent / paraffin 50:1
GUM	Glass		+66.6 : +73.9	Glass		+18.5 : +25.1	No
INM	Glass	+50		Glass	+20		No
NCM	Quartz	+40		Quartz	+20		No
PTB	Steel Crystallin e quartz (0.5 and 1.01 mm)		-4 : 0 +18 : +19	TC and ZK 7 glass (1.02 mm)	+22	-6 : +1	No

Table A1b: Table of the reference flats and values of phase correction in nanometer applied to the measurement results.

Appendix 2: Determination of reference values

Consistency of results and outliers

Some reported measurement results seems to be inconsistent with other results, and may change the estimate and specially reference values.

Grubbs' test

Grubbs test has been applied on the smallest and largest value of the sets of data according to ISO 5725-2:1994 and report EUROMET.L-K1. No outliers or stragglers were identified for steel or TC gauge blocks, because the statistics G_{max} and G_{min} are both less than both Grubbs 99 % critical value and Grubbs 95 % critical value. See tables A2a for steel gauge blocks and A2b for TC gauge blocks.

	0.5 mm	1.01 mm	4.5 mm	6 mm	7 mm	8 mm	8 mm	15 mm	80 mm	100 mm
max	-38	-82	7	96	-44	7	11	63	104	-147
min	-82	-125	-27	82	-73	-18	-10	34	32	-194
G max	1.286	1.704	1.603	0.993	1.087	1.354	1.484	1.240	1.732	1.323
G min	1.711	1.626	1.241	1.066	1.516	1.467	1.415	1.608	1.032	1.232
GRUBBS 95 %	2.126	2.215	1.887	1.481	2.215	2.126	2.126	2.126	2.126	2.215
GRUBBS 99 %	2.274	2.387	1.973	1.496	2.387	2.274	2.274	2.274	2.274	2.387

Table A2a: Grubbs test for values of steel gauge blocks. No outliers are identified, and also no stragglers.

	1.02 mm	6 mm	7 mm	8 mm	10 mm	12 mm	80 mm	100 mm
max	36	-4	3	42	-31	124	95	235
min	-15	-29	-28	16	-60	97	45	159
G max	2.275	1.484	1.376	1.291	1.819	1.924	1.831	2.275
G min	1.328	1.414	1.784	2.169	1.541	1.343	1.201	1.169
GRUBBS 95 %	2.290	2.290	2.290	2.290	2.290	2.290	2.290	2.290
GRUBBS 99 %	2.482	2.482	2.482	2.482	2.482	2.482	2.482	2.482

Table A2b: Grubbs test for values of TC gauge blocks. No outliers are identified, and also no stragglers.

Reference values

Note: The results of the pilot laboratory contribute only once to the calculation of the reference values, namely the first measurement.

Arithmetic mean

The arithmetic mean value x_{ref} is calculated by the average of all measurement values x_i.

$$x_{ref} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad \text{(A1)}$$

The arithmetic mean does not take into account the uncertainty of the individual results contributing to the reference value. The standard uncertainty $u(x_{ref})$ of the arithmetic mean can either be determined by the application of the error propagation law, i.e. by taking into account the uncertainties $u(x_i)$ of the individual results [Eq. (A2a)], or by the spread of the results, i.e. by the standard deviation divided by the square root of the number n of results contributing to the mean [Eq. (A2b)]. See tables A2c and A2d.

$$u(x_{ref}) = \frac{1}{n}\sqrt{\sum_{i=1}^{n} u^2(x_i)} \qquad \text{(A2a)}$$

$$u(x_{ref}) = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}(x_i - x_{ref})^2} \qquad \text{(A2b)}$$

Uncertainty of the difference between results and the reference values

For the arithmetic mean approach, the expanded uncertainty $U(\Delta x)$ is given by

$$U(\Delta x) = 2\sqrt{(1-\frac{2}{n})u^2(x_i) + \frac{1}{n^2}\sum_{j=1}^{n} u^2(x_j) + u^2_{artefact}} \qquad \text{(A3)}$$

Compared to equation (A8) in reference [1], we have here included also the artefact uncertainty calculated from the spread of results (one standard deviation) at the pilot laboratory. However, because the measurements at the pilot laboratory extended over a much longer period of time than the actual comparison, an observed drift of the gauge blocks observed by the pilot contributes too much to the artefact uncertainty. The artefact uncertainty is consequently reduced by a fraction equal to 0,77. Artefact uncertainties are summarized in table A2e.

Steel gauge blocks	Nominal value (mm)	**0.5**	**1.01**	**4.5**	**6**	**7**	**8**	**8**	**15**	**80**	**100**
	Number of labs	7	9	6	4	9	8	8	8	8	9
Ref. value x_{ref}	Formula A1	-58.6	-104.0	-12.2	89.3	-56.1	-5.0	0.3	50.4	58.9	-171.3
$u(x_{ref})$	Formula A2a	4.9	4.4	5.3	6.1	4.3	4.5	4.5	4.7	7.1	8.1
$u(x_{ref})$	Formula A2b	6.1	4.6	5.3	3.9	3.9	3.4	2.7	3.8	9.8	6.5

Table A2c

TC gauge blocks	Nominal value (mm)	**1.02**	**6**	**7**	**8**	**10**	**12**	**80**	**100**
	Number of labs	10	10	10	10	10	10	10	10
Ref. value x_{ref}	Formula A1	3.6	-16.7	-9.8	33.0	-47.3	108.2	65.5	184.9
$u(x_{ref})$	Formula A2a	4.0	4.0	4.0	4.0	4.2	4.3	5.9	6.6
$u(x_{ref})$	Formula A2b	4.7	2.9	3.5	2.7	2.5	2.8	5.5	7.4

Table A2d

Table A2c / A2d: Reference values and associated standard uncertainties (in nm) for steel gauge blocks and for TC gauge blocks.

Steel gauge blocks	Nominal value (mm)	**0.5**	**1.01**	**4.5**	**6**	**7**	**8**	**8**	**15**	**80**	**100**
	u(artefact)	9.2	5.4	4.9	9.0	10.0	6.7	5.1	2.6	12.4	8.5
TC gauge blocks	Nominal value (mm)	**1.02**	**6**	**7**	**8**	**10**	**12**	**80**	**100**		
	u(artefact)	5.3	3.0	4.6	3.6	3.0	3.5	5.0	6.9		

Table A2e: Summary of artefact uncertainty calculated as one standard deviation of all measurements by the pilot laborator, reduced by a fraction 0,77 due to the fact that the pilot laboratory measured over a longer time interval than the actual comparison.

Appendix 3: Comparison of results to the reference values

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

Table A3a

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

Table A3b

Table A3a / A3b. Differences of measured lengths (Δx) of steel and TC gauge blocks with respect to the reference values and expanded uncertainties of these differences according to equations (A1) and (A3). No drift correction has been applied. All results are in nm.

Steel gauge blocks	0.5 mm	1.01 mm	4.5 mm	6 mm	7 mm	8 mm	8 mm	15 mm	80 mm	100 mm
JV	0.05	0.67	0.58	0.15	0.13	0.40	0.20	0.66	0.58	0.47
MIKES	0.10	0.18			0.36	0.17	0.40	0.23	0.05	0.09
GUM	0.37	0.06			0.31	0.34	0.18	0.38	0.51	0.50
CMI	0.05	0.18			0.14	0.21	0.01	0.02	0.26	0.03
IPQ	0.71	0.87	0.75		0.32	0.25	0.41	0.34	0.87	0.39
PTB	0.87	0.93	0.38	0.29	0.63	0.58	0.49	0.44	0.67	0.62
UME	0.41	0.11	0.28	0.17	0.19	0.18	0.03	0.27	0.15	0.36
INM		0.06	0.13	0.24	0.50	0.03	0.06	0.32	0.49	0.32
NCM		0.22	0.01		0.19					0.21
E.I.M										

Table A3c

TC gauge blocks	1.02 mm	6 mm	7 mm	8 mm	10 mm	12 mm	80 mm	100 mm
JV	0.16	0.12	0.26	0.15	0.10	0.08	0.57	0.45
MIKES	0.29	0.28	0.19	0.24	0.31	0.42	0.02	0.27
GUM	0.22	0.16	0.09	0.03	0.08	0.09	0.39	0.33
CMI	0.16	0.33	0.45	0.14	0.13	0.09	0.13	0.12
IPQ	0.58	0.49	0.14	0.27	0.42	0.41	0.10	0.04
PTB	0.89	0.59	0.97	0.95	0.57	0.45	0.87	0.94
UME	0.16	0.23	0.41	0.39	0.41	0.65	0.22	0.12
INM	0.16	0.27	0.40	0.11	0.25	0.20	0.48	1.03
NCM	1.28	0.54	0.27	0.35	0.10	0.06	0.58	0.37
E.I.M	0.05	0.32	0.51	0.20	0.09	0.23	0.38	0.33

Table A3d

Table A3c / A3d: E-values for steel gauge blocks and TC gauge blocks calculated from table A3a and A3b, $E = |\Delta x| / U(\Delta x)$. No drift correction has been applied.