NPL National Physical Laboratory

EUROMET Key Comparison

EUROMET.L-K2

Calibration of long gauge blocks

(EUROMET Project No. 602)

Final Report - Version: Final

Andrew Lewis, NPL, Teddington, 2 February 2006

Contents

1 Introduction

The metrological equivalence of national measurement standards and of calibration certificates issued by national metrology institutes is established by a set of key comparisons chosen and organized by the Consultative Committees of the CIPM or by the regional metrology organizations in collaboration with the Consultative Committees.

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

The results of this international comparison contribute to the Mutual Recognition Arrangement (MRA) between the national metrology institutes of the Metre Convention [1]. This EUROMET key comparison is linked with the CCL and other RMO comparisons through mutual competence of participating laboratories. Laboratories participating in both the CIPM and the RMO comparisons establish the link between these comparisons and assure their equivalence.

2 Organisation

The protocol document for this comparison and this report have been based on the corresponding documents for key comparison CCL-K2 [2, 3]. The protocol document [4] was issued to all participants at the start of the comparison. A revised version was issued before commencing the second loop artefact circulation, to take into account the replacement of two failed gauge blocks and a revised timetable.

2.1 Participants

All members of EUROMET TC-L were invited to participate. 23 laboratories expressed an interest. The list of participants is given in Table 1.

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Table 1 Participating laboratories.

2.2 Schedule

The comparison was organised in two loops, the first being limited to laboratories able to make direct measurement by interferometry, with the second loop consisting of all other laboratories. The time schedule for the comparison is given in Table 2. Advantage was made of the change to membership of the EU, by scheduling laboratories of some of the new member states to make measurement after 1 May 2004, when they joined the EU. This reduced the carnet cost.

Each laboratory was allowed one month in which to make its measurements and to prepare for transportation to the next participant. The schedule was designed to fit with the preferences of the laboratories for scheduling the measurements and any changes to the schedule, after the start of the circulation, were discussed and agreed among the participants and the TC-L chairman.

Laboratory	Country	Final schedule	Results received
LOOP 1			
NPL	GB	Feb 2002	Feb 2002
SMD	BE	Mar 2002	June 2003
NMi-VSL	NL	Apr 2002	Jan 2003
MIKES	FI	May 2002	June 2002
SP	SE	June 2002	Aug 2002
BEV	AT	July 2002	Sept 2002 Rev. Oct 2002
IPQ	PT	Aug 2002	Jan 2003
METAS	CH	Sept 2002	Oct 2002
CEM	ES	Oct 2002	Nov 2002
IMGC	IT	Nov 2002	Apr 2005*
Pilot	*GB*	*Dec 2002*	*Dec 2002*
PTB	DE	Jan 2003	Mar 2003
LOOP 2			
PTB 2 replacements	DE	Apr 2003	July 2003
Pilot – 2 failed gauges	*GB*	*June 2003*	*June 2003*
Pilot - replacements	*GB*	*July 2003*	*July 2003*
Pilot	*GB*	*Jan 2004*	*Jan 2004*
UME	TR	May 2004	Jul 2004
NCM	BG	Jun 2004	Jul 2004
IMGC	IT	Jul 2004	Apr 2005*
NML	IE	Aug 2004	Aug 2005 Rev. August 2005
CMI	CZ	Sept 2004	Oct 2004
SMU	SK	Oct 2004	Dec 2004 Rev. Sep 2005
OMH	HU	Nov 2004	Mar 2005
INM	RO	Dec 2004	Feb 2005
GUM	PL	Jan 2005	Feb 2005
VNT/VMC	LT	Feb 2005	Mar 2005
LNMC	LV	Mar 2005	Apr 2005
MIRS-LTM	SI	Apr 2005	July 2005
LNE	FR	May 2005	July 2005
Pilot	*GB*	*Jun 2005*	*July 2005*

Shaded = NON EU, thus ATA carnet required on entry/exit of artefacts
Shaded = new EU member after 1 May 2004, ATA carnet was not required

*Table 2 Time schedule of the comparison. 'Final schedule' refers to the latest schedule agreed among the participants. 'Results received' refers to the first date of receipt, by the pilot laboratory, of the official results of the participant (paper or electronic report). * IMGC results sent together (loops 1&2).*

Towards the end of the first loop, significant problems were noticed on two gauge blocks (900 mm and 500 mm S/N 'B'). The CCL linking laboratories (IMGC, NPL and PTB) were asked at this time to attempt measurements of all the gauges, in order to close the first loop. On return of the gauges to the pilot laboratory at the end of loop 1, detailed repeat measurements confirmed the problem. The 500 mm gauge block faces were no longer parallel, showing a variation in length of 470 nm. Similarly the 900 mm gauge block exhibited a variation in length of 580 nm. There was also evidence to suggest that the 500 mm gauge block was changing size (from results received up to that date). It was therefore decided to replace these two gauge blocks before starting loop 2. This resulted in a delay of around 1 year, whilst replacement gauges were supplied (from PTB) and characterised (PTB and NPL). The comparison re-started in April 2004. Apart from the problem at the end of loop 1, the timetable was followed strictly as per the plan.

2.3 Standards

Four gauge blocks made of steel were circulated in each loop. At the end of loop 1, two gauge blocks were replaced. The gauge blocks, which had been kindly donated by JV, PTB and NPL, were selected as having a stable history of measurement and good flatness and variation in length. The gauge blocks were of rectangular cross section, according to international standard ISO 3650 (1998). The thermal expansion coefficient of the gauge blocks had been measured by the pilot laboratory and another laboratory (PTB) before the comparison. The weighted mean of the pilot laboratory and PTB results of expansion measurement (and their calculated uncertainties) were given to the participating laboratories in the technical protocol. The participating laboratories were informed of the nominal length of the gauge blocks, the gauge material (steel), and the pre-determined expansion coefficients.

Loop	**Serial number**	**Nominal length (mm)**	**α (x 10^{-6} K^{-1})**	**α uncertainty (x 10^{-6} K^{-1})**
1 & 2	8728	150	11.407	0.072
1 & 2	AA/71001	500	10.766	0.025
1	B	500	10.510	0.028
1	EM/718	900	11.054	0.020
2	4 PTB 55	500	11.082	0.029
2	PTB 5.13 11/2001	900	10.943	0.022

Table 3 Standards used in the comparison. The uncertainties for the thermal expansion coefficients are given at k = 2. Shaded cells indicate gauges that were replaced at the end of loop 1.

The standards were supplied in a custom made transport case, fashioned from aluminium and steel, containing high density foam, sculpted to make a tight fit with the gauge blocks, to prevent any motion of the gauge blocks and generation of excessive bending forces. The case was designed to be suitable for either cabin or hold transportation. The desire was for cabin transportation (hand carriage) with a fall-back option of transportation in the hold. The gauge blocks were accessible and visible with the lid opened and a pair of chamois gloves were included in case of any request by customs to handle the gauge bocks. The transport case and gauge blocks had a total mass in excess of 10 kg. Despite this being greater than the advertised cabin baggage allowance of many airlines, most airlines involved did not object to the hand carriage of the case in the aircraft cabin, provided they had been informed in advance.

Photo 1 Gauge block transport case

3 Measurement instructions and reporting of results

Before calibration, the gauge blocks had to be inspected for damage of the measurement surfaces. Any scratches, rusty spots or other damage had to be documented by a drawing using forms appended to the instructions.

The measurement quantity was the central length of the gauge blocks, as defined in International Standard ISO 3650. Any laboratory departing from the conditions specified in ISO 3650 had to make the relevant corrections to their measurand. ISO 3650 specifies that the gauge blocks had to be measured by interferometry, in the horizontal position wrung to a flat plate. The measurement result to be reported was the deviation of central length from nominal length, $\Delta l = l - L$. The results of the measurements on both sides (Δl_{left} and Δl_{right}) by wringing each measurement face in turn to the reference flat and the average of the two wringings had to be reported. The measurement results had to be appropriately corrected to the reference temperature of 20 °C using the thermal expansion coefficients given above. Additional corrections (aperture, phase correction) had to be applied according to the usual procedure of the laboratory. In cases where interferometry was not used, the participants were to interpret the instructions and reporting of results accordingly.

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

4 Measurement methods and instruments used by the participants

A wide variety of instruments and techniques were used to make measurements of the gauge blocks. The most important details of these instruments and techniques are reported in Tables 4 and 5.

Approximately one quarter of the 23 participants used direct interferometry on the gauge and platen surfaces. One quarter used some form of dynamic fringe counting interferometry, e.g. using a white light interference as a fiducial. The remaining half of the participants used mechanical comparison techniques, either with reference gauges of a similar size, or with a smaller artefact e.g. a short gauge block used to provide the traceability reference.

In all instruments, with long range interferometry, determination of the refractive index is important. Two techniques were used: direct evaluation of the refractive index by use of an *in situ* refractometer; and calculation of the refractive index based on measurements of air parameters such as temperature, pressure, humidity, and carbon dioxide content, and use of empirical equations.

The variety of measuring instruments and techniques leads to a large range in claimed measurement uncertainty, ranging from a few tens of nanometres, up to several hundred nanometres and indicates that the weighted mean will probably be the best way of determining the key comparison reference value.

Details of the measuring instruments, techniques and conditions are given in Tables 4 and 5.

Lab.	Type of equipment	Traceability route	Measurement method	Platen material	Temperature / °C
NPL	NPL design Twyman-Green phase stepping interferometer.	Frequency stabilized lasers, 633 nm, 543 nm, 612 nm calibrated by iodine stabilized lasers. 633 nm wavelength is reference.	Phase-stepping fringe fractions measurement at three wavelengths. Method of excess-fractions, basing the result on the red wavelength. Refractive index determination via air temperature, pressure, humidity and CO_2 measurements. [6]	Steel	20.031 to 20.081
SMD	NPL-TESA interferometer; Mahr 828 CiM.	150mm: Frequency stabilized lasers, 633 nm, 543 nm; others: Gauge blocks (calibrated at NPL, PTB).	Direct interferometry using exact-fractions; Comparison with similar sized gauge blocks calibrated elsewhere.	Steel	19.980 to 20.249
NMi-VSL	NMi design Michelson interferometer.	Frequency stabilized lasers, 633 nm, 594 nm, 543 nm calibrated by iodine stabilized laser, or using gauges. 633 nm wavelength is reference.	Fringe fractions measured using PZT motion of reference mirror, to align cursors on minima (manual viewing) at 3 wavelengths. Method of excess-fractions, basing the result on the red wavelength. Refractive index determination via air temperature, pressure, humidity and CO_2.	Steel	20 ± 0.048
MIKES	MIKES design fringe counting interferometer.	Zeeman stabilized 633 nm laser, calibrated against iodine standard.	Fringe counting interferometer with moveable mirror. White light used to fiducialize the gauge and platen surfaces. [7]	Steel	19.979 to 20.068
SP	SP-designed Michelson interferometer.	Frequency stabilized lasers, 633 nm, 543 nm. 633 nm laser traceable to iodine reference.	Direct interferometry using exact-fractions.	Steel	20 ± 0.1
BEV	Modified SIP 3002M; Kösters gauge block interferometer (150 mm).	Internal HP interferometer, wavelength calibrated against iodine reference; 633 nm laser calibrated against iodine reference.	Mechanical probing. HP interferometer optics mounted internally. 150 mm also measured in classical Kösters gauge block interferometer. Fringe order determination with Cd wavelengths, fringe fraction determination with red laser.	Quartz (150 mm only)	19.912 to 20.039
IPQ	Modified SIP 3002M.	HP laser interferometer – wavelength calibrated.	Mechanical probing with interferometer distance measurement.	N/A	20.02 to 20.44
METAS	Length comparator based on modified SIP CLP-10.	HP 633 nm laser, calibrated against iodine reference.	Determined from a displacement, measured using high stability plane mirror interferometer. Fiducialization using white light fringes.	Steel	19.977 to 20.019
CEM	Custom built length comparator CEM-TEK 1200.	Comparison against previously calibrated gauge block; HP laser source, calibrated against iodine reference.	Two inductive probes make comparison between standard and test gauge. Travel of probes is monitored with pseudo-Abbe interferometer system. Probed make contact under PZT servo control.	N/A	19.96 to 20.05
IMGC	SIP CLP10A interferometric comparator.	Frequency stabilized laser (633 nm), calibrated by iodine stabilized laser.	Travelling carriage on comparator, measured interferometrically. Fringe fraction evaluation by eye on magnified screen, with white light interferometry used as fiducial indicator.	Steel	19.914 to 20.057
PTB	Kösters-Zeiss interferometric comparator.	Directly via use of iodine stabilized lasers at 633 nm, 612 nm, 515 nm.	Direct interferometry using exact-fractions. [8]	Steel	19.988 to 19.999

UME	1 m gauge block comparator & NPL-TESA GBI (phase stepping).	For GBI, directly via calibrated laser wavelength (633 & 543 nm); for comparator, via PTB calibrated master gauges.	Phase-stepping fringe fractions measurement using direct interferometry at three wavelengths. Comparator uses Mahr inductive probes to compare test gauge against standard gauge.	Steel	19.901 to 20.074
NCM	Custom designed laser interferometer.	633 nm laser calibrated against iodine standard.	White light used for fringe order determination. Laser used for fringe fraction measurement.	Steel	19.907 to 20.084
NML	Federal long gauge block comparator.	Reference gauge blocks.	Comparison against similar sized reference gauges.	N/A	20.0 ± 0.16
CMI	NPL TESA GBI and CMI design Twyman Green interferometer.	633 nm and 543 nm Zeeman lasers, calibrated against iodine reference. Direct use of 3 iodine stabilized lasers.	Standard NPL-TESA fringe fraction and exact fractions technique. For long GBI, performs offline fraction determination using stored two colour interferograms.	Steel	18.75 to 21.12
SMU	SMU design Michelson interferometer.	Frequency stabilized laser (633 nm), calibrated by iodine stabilized laser.	Dynamic fringe counting and interpolation, using white light as fiducial indicator. Refractive index determination via air temperature, pressure, humidity measurements.	Steel	19.924 to 20.048
OMH	SIP 550M, 900 mm: Zeiss ULM3.	Reference gauge blocks calibrated at METAS; HP laser interferometer.	Comparison against similar sized reference gauges.	N/A	19.6 to 20.4
INM	1-D CMM SIP 1000 with TESA comparator.	Standard gauge blocks calibrated by PTB.	Comparison against similar sized reference gauges.	N/A	19.4 to 19.6
GUM	SIP 3002M and HP interferometer.	HP laser wavelength calibrated by iodine reference.	Comparison against 10 mm reference gauge block.	N/A	20.003 to 20.163
VNT/VMC	< 500 mm, horizontal interferometer (ИКПГ); length measuring machine (ИЗМ).	Reference gauge blocks calibrated at Mitutoyo Netherlands.	Comparison against similar sized reference gauges.	N/A	19.8 to 20.2
LNMC	Optical mechanical length measuring machine (ИЗМ-II)	Reference gauge blocks calibrated by MIKES	Comparison against similar sized reference gauges.	N/A	20.0 ± 0.3
MIRS-LTM	Mahr 826	Reference gauge blocks.	Comparison against similar sized reference gauges.	N/A	19.97 to 20.02
LNE	3 m moving carriage, adapted from line scale measurement	Reference gauge block measured by interferometry.	Comparison against 200 mm reference gauge using two probes, with integral line scale fiducials – photoelectric microscope used to set on probe scales.	N/A	19.89 to 20.14

Table 4 Measurement instruments and conditions reported by the participating laboratories.

Lab.	Platen weight compensation method	Phase/roughness correction determination method	Phase correction value(s)	Vertical to horizontal correction	Measurement position (Vertical, Horizontal) and temperature during measurement (°C)				Refractive index determination method
					150 mm S/N 8728	**500 mm S/N AA/71001**	**500 mm B or 4PTB55**	**900 mm S/N EM/7181 or PTB 11/2001**	
NPL	Move supports [6,15]	Not measured	-	-	H 20.040 to 20.048	H 20.031 to 20.042	H 20.036 to 20.081	H 20.034 to 20.038	Birch & Downs
SMD	N/A	Pre-determined (only 150 mm)	-26.2	4 nm	V 20.081 to 20.249	H 19.975 to 20.055	H 19.962 to 20.052	H 19.980 to 20.098	Birch & Downs
NMi-VSL	Move supports	Not measured	-	-	H 20 ± 0.018	H 20 ± 0.033	H 20 ± 0.031	H 20 ± 0.048	Edlen
MIKES	Counterbalance	TIS	-	-	H 19.979 to 20.068	H 19.979 to 20.068	H 19.979 to 20.068	H 19.979 to 20.068	Bönsch & Potulski
SP	Move supports	Not measured	-	-	H 20 ± 0.1	H 20 ± 0.1	H 20 ± 0.1	H 20 ± 0.1	Birch & Downs
BEV	N/A	N/A	+40 nm	$L^2\rho g/2E$	V 20.013 ± 0.058	H 20.099 ± 0.061	H 19.912 ± 0.096	H 20.039 ± 0.056	Birch & Downs
IPQ	N/A	N/A	-	-	H 20.02 to 20.44	H 20.02 to 20.44	H 20.02 to 20.44	H 20.02 to 20.44	N/A
METAS	Counterbalance	Not measured	-	-	H 20.002 to 20.019	H 19.984 to 19.995	H 19.977 to 19.985	H 19.990 to 20.000	Birch & Downs
CEM	N/A	N/A	-	-	H 19.96 to 20.05	H 19.96 to 20.05	H 19.96 to 20.05	H 19.96 to 20.05	Tracking refractometer
IMGC	Counterbalance	Not measured	-	-	H 19.914 to 20.004	H 19.920 to 20.055	H 19.960 to 20.057	H 19.938 to 20.018	Birch & Downs
PTB	Move supports [13]	TIS [14]	-1 to –4 nm	-	H 19.988 to 19.999	H 19.988 to 19.999	H 19.988 to 19.999	H 19.988 to 19.999	Vacuum cell
UME	N/A	Not measured	-	-	H 19.901 to 20.005	H 19.937 to 20.020	H 19.937 to 19.968	H 19.953 to 20.074	Birch & Downs
NCM	Move supports	Not measured	-	-	H 19.954 to 20.064	H 19.940 to 20.084	H 19.907 to 20.054	H 19.930 to 20.050	Refractometer
NML	N/A	N/A	-	-	H 20.0 ± 0.16	H 20.0 ± 0.16	H 20.0 ± 0.16	H 20.0 ± 0.16	N/A
CMI	Counterbalance	N/A	-	-	V 19.967 to 20.068	H 18.75 to 21.12	H 18.75 to 21.12	H 18.75 to 21.12	Decker & Pekelsky

SMU	Move supports	Not measured	-	-	H 20.009 to 20.025	H 20.001 to 20.048	H 20.006 to 20.044	H 19.924 to 20.040	Edlen
OMH	N/A	N/A	-	-	H 19.6 to 20.4	H 19.6 to 20.4	H 19.6 to 20.4	H 19.6 to 20.4	N/A
INM	N/A	N/A	-	-	H 19.4 to 19.6	H 19.4 to 19.6	H 19.4 to 19.6	H 19.4 to 19.6	N/A
GUM	N/A	N/A	-	-	H 20.003 to 20.163	H 20.003 to 20.163	H 20.003 to 20.163	H 20.003 to 20.163	Bönsch & Potulski
VNT/VMC	N/A	N/A	-	-	H 19.8 to 20.2	H 19.8 to 20.2	H 19.8 to 20.2	H 19.8 to 20.2	N/A
LNMC	N/A	N/A	-	-	H 20.0 ± 0.3	H 20.0 ± 0.3	H 20.0 ± 0.3	H 20.0 ± 0.3	N/A
MIRS-LTM	N/A	N/A	-	-	H 19.98 to 20.01	H 19.98 to 20.01	H 19.97 to 20.02	H 19.98 to 20.01	N/A
LNE	N/A	N/A	-	-	H 19.89 to 20.14	H 19.89 to 20.14	H 19.89 to 20.14	H 19.89 to 20.14	Birch & Downs

Table 5 Additional measurement conditions and details reported by the participating laboratories.

Refractive index determination method:
Decker & Pekelsky = Uncertainty Evaluation for the Measurement of Gauge Blocks by Optical Interferometry [5]
Edlen = The refractive index of air [9]
Birch & Downs = Correction to the updated Edlén equation for the refractive index of air [10]
Ciddor = Refractive index of air: new equations for the visible and near infrared [11]
Bönsch & Potulski = Measurement of the refractive index of air and comparison with modified Edlén's formulae [12]
Tracking Refractometer = Refractometer cell used for continuous measurement against known etalon
Vacuum cell = Internal refractometer or vacuum cell for absolute refractive index determination

Phase/roughness method
TIS = Total Integrated Scatter method using integrating sphere [12]
Stack = Traditional ‘stack’ or ‘pack’ method based on gauges wrung separately and as a stack

5 Stability and condition of the gauge blocks

The pilot laboratory, NPL, made interferometric calibrations before the start of the comparison and PTB (who donated the replacement gauge blocks) had some prior information concerning the historic stability of their standards. The pilot laboratory made several interferometric calibrations: at the start of the first loop circulation and before the circulation of the replacement gauges (‘Prelim’), during is official measurement ‘(NPL’), between the first and second loop circulations (‘Interim1’, ‘Interim2’), and at the end of the circulation (‘Final’), always using the same equipment, operator and procedure. NPL made a further measurement of the failed gauges during the time period of the second loop circulation (‘Final’). These interim calibrations included measurement of the central length, flatness and variation in length.

5.1 Central length stability

Figures 1(a) through 1(f) show the measurements of the pilot laboratory used to verify the stability of the gauge blocks’ central length.

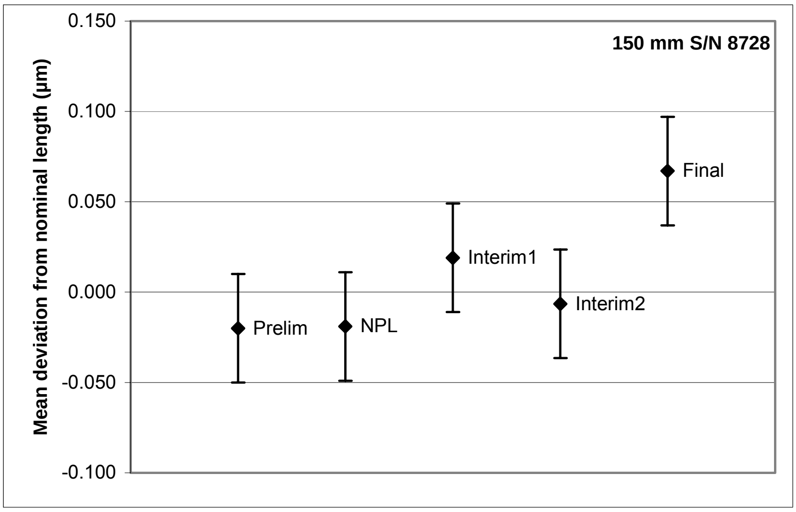

Figure 1(a) Stability of 150 mm gauge block (S/N 8728) during comparison: interferometric length measurements of the pilot laboratory. Uncertainty bars show standard uncertainty (k=1).

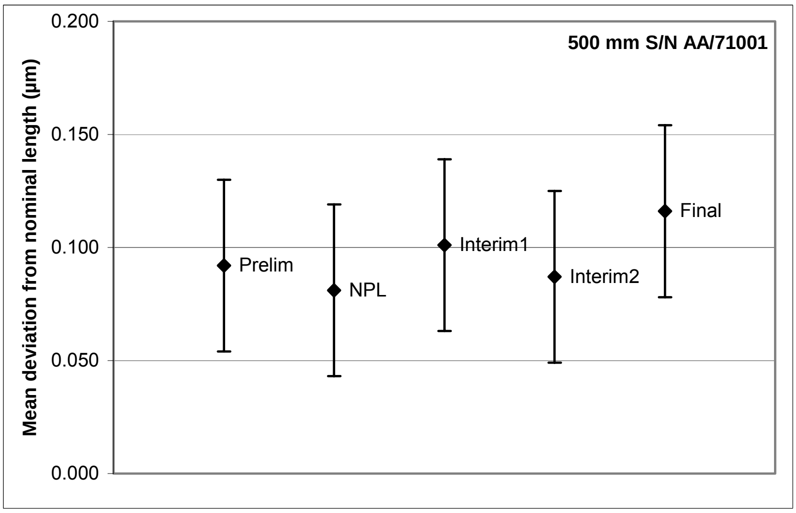

Figure 1(b) Stability of 500 mm gauge block (S/N AA/71001) during comparison: interferometric length measurements of the pilot laboratory. Uncertainty bars show standard uncertainty (k=1).

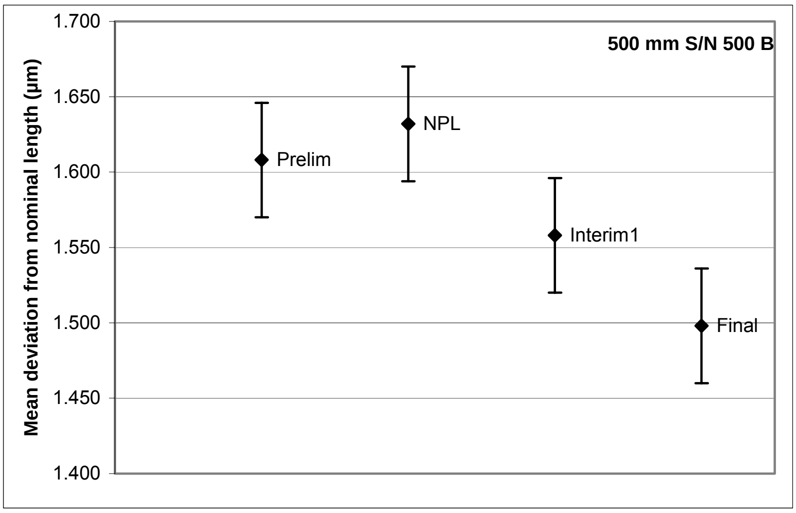

Figure 1(c) *Stability of 500 mm gauge block (S/N 500 B) during comparison: interferometric length measurements of the pilot laboratory. Uncertainty bars show standard uncertainty (k=1).*

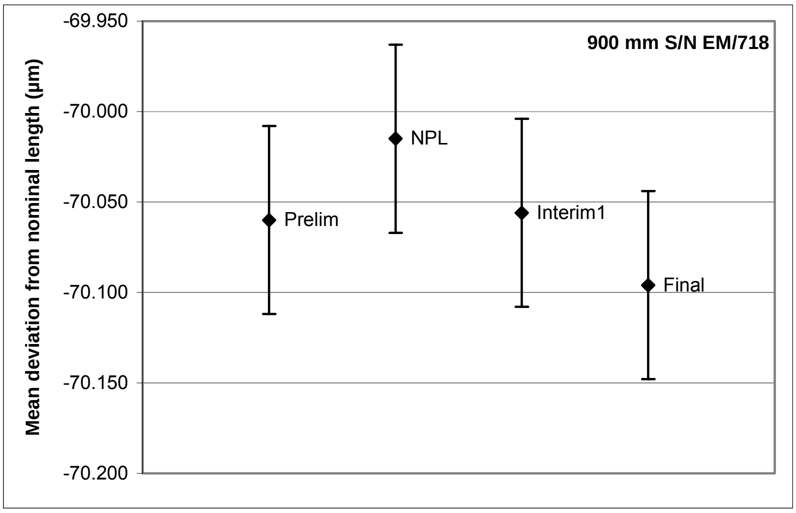

Figure 1(d) *Stability of 900 mm gauge block (S/N EM/718) during comparison: interferometric length measurements of the pilot laboratory. Uncertainty bars show standard uncertainty (k=1).*

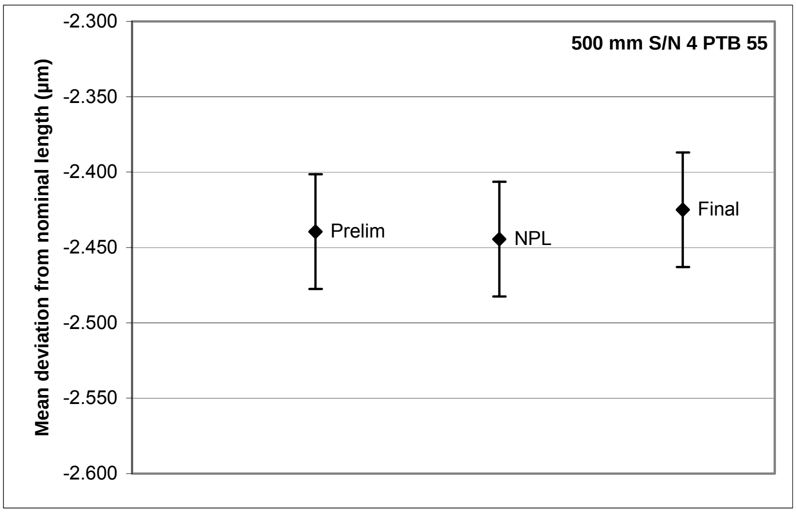

Figure 1(e) *Stability of replacement 500 mm gauge block (S/N 4 PTB 55) during comparison: interferometric length measurements of the pilot laboratory. Uncertainty bars show standard uncertainty (k=1).*

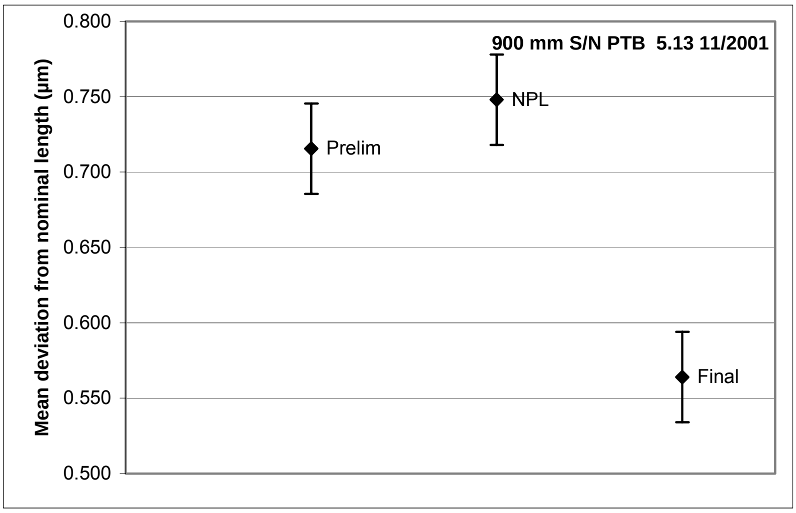

Figure 1(f) *Stability of replacement 900 mm gauge block (S/N 5.13 11/2001) during comparison: interferometric length measurements of the pilot laboratory. Uncertainty bars show standard uncertainty (k=1).*

The uncertainty bars in Figures 1(a) through 1(f) are standard uncertainties of the pilot laboratory's usual measurement technique. Because the same equipment, platens, operator and technique, were used for these measurements, several uncertainty sources will be correlated for the four measurements (*e.g.* phase correction uncertainty) and so in terms of possible changes in length, the uncertainties would be somewhat reduced. The measured overall changes in length (maximum-minimum) for the gauge blocks in Figures 1(a) through 1(f) were: 87 nm, 35 nm, 134 nm, 81 nm, 20 nm and 184 nm, respectively.

The relatively large, nominally linear, change in length of the 500 mm gauge block (S/N 500 B) led to the decision to remove it from the comparison after loop 1 circulation as well as the 900 mm gauge block (S/N EM/718). At that time, the other two gauge blocks seemed stable.

It later appeared that during loop 2, the 150 mm gauge block and the replacement 900 mm gauge block also experienced significant changes in length, according to pilot laboratory results. (This is also suggested by some results of other participants – see §6.1).

In terms of stability of central length, the 500 mm gauges S/N 4 PTB 55 and AA/71001 were the most stable.

5.2 Condition of the gauge blocks

The gauge blocks were essentially free of major damage at the beginning of the comparison. The participating laboratories were asked to document any scratches and other damages on the measurement surfaces by a drawing to be made when receiving the gauge blocks. As the comparison progressed, more scratches appeared on the measurement surfaces of the gauge blocks as well as some marks on the side faces. Some indentations became apparent on the narrow faces close to the Airy points. Copies of the drawings of the measurement faces that were supplied by the participants may be found below (Figures 2(a) to 2(d)). Note that the scanning of the pictures and their transmission to the pilot laboratory has, for some participants, introduced a change in contrast to their pictures.

It is interesting to note the different interpretations of the gauge block surface condition, as reported by the participants in their drawings of the gauge block surfaces. There are clearly some surface defects which are reported by several participants, whereas other defects which are reported by one participant were not reported by later participants. The pilot laboratory is in a unique position of seeing the gauge blocks several times throughout the comparison, as well as seeing the individual reports of the participants. This gives the pilot laboratory the ability to more accurately monitor the damage to the gauge blocks. However the prevalence of deeper scratches later in the comparison may mask the lighter scratching which was apparent at the start, leading to differences of opinion on the surface quality.

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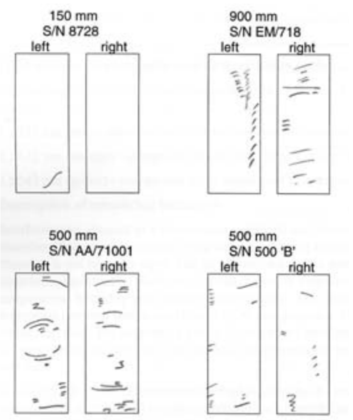
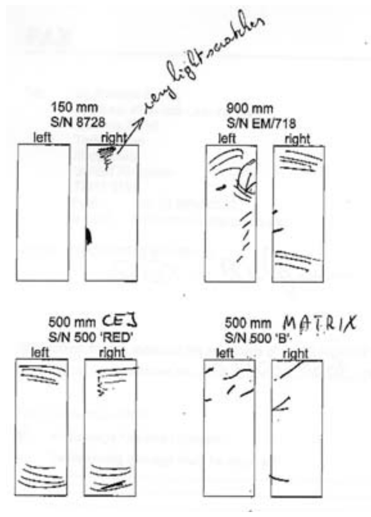
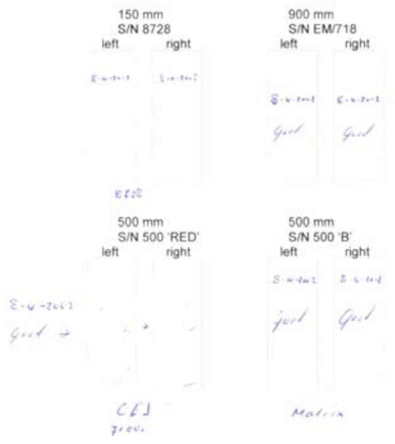
<tr><td></td><td></td><td></td></tr>
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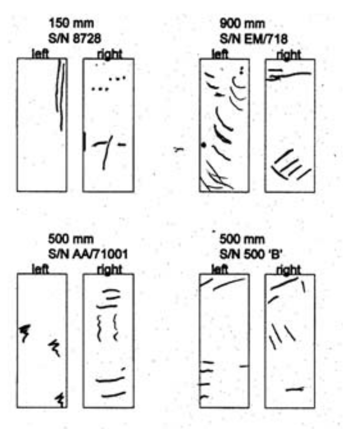
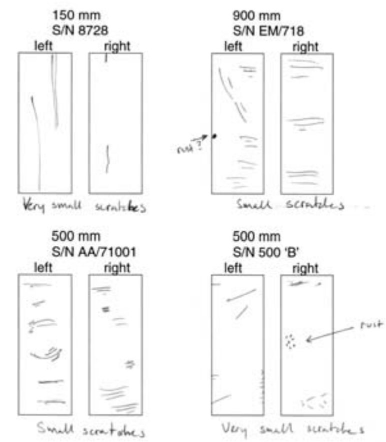
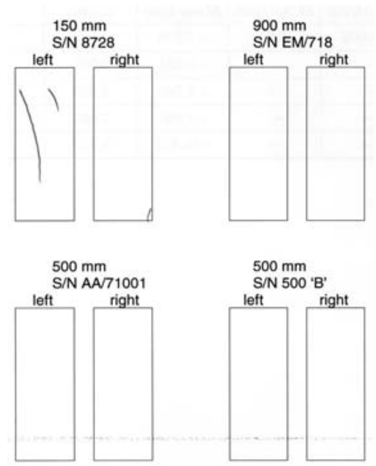
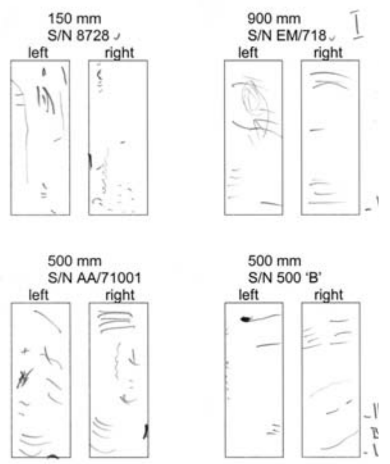
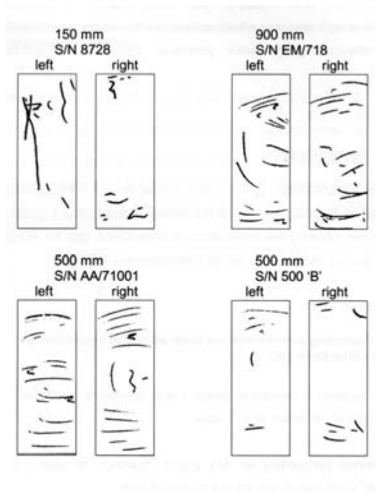
<tr><td></td><td></td><td></td></tr>
<tr><td>IPQ</td><td>METAS</td><td>CEM</td></tr>
<tr><td>No diagram</td><td></td><td></td></tr>
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Figure 2(a) Gauge condition reports received from participants, first part, loop 1.

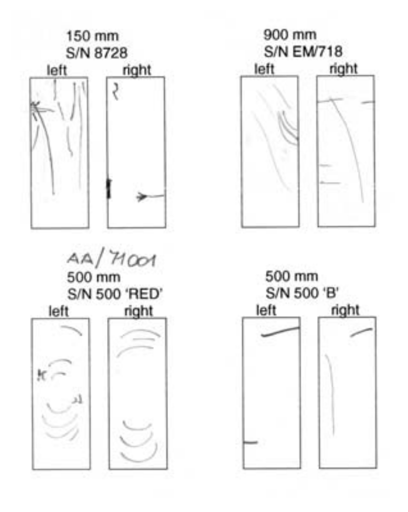
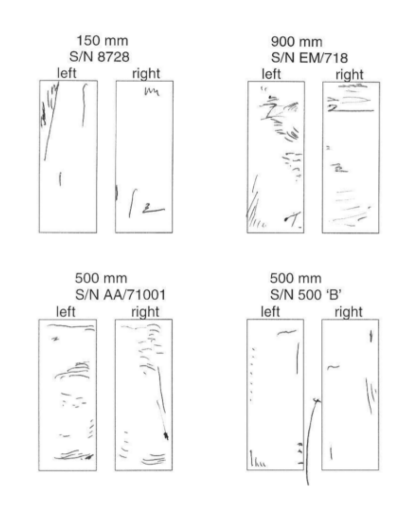
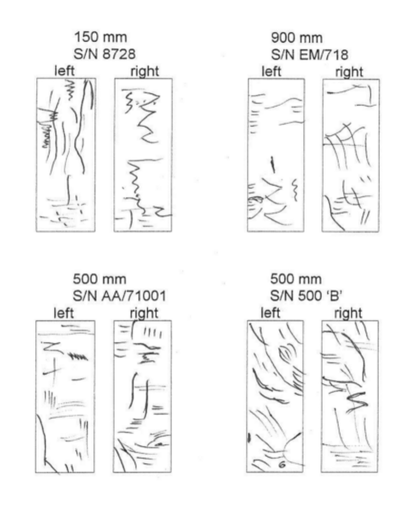
IMGC	PILOT	PTB
		

Figure 2(b) Gauge condition reports received from participants, second part, loop 1.

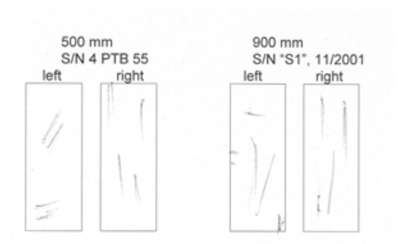
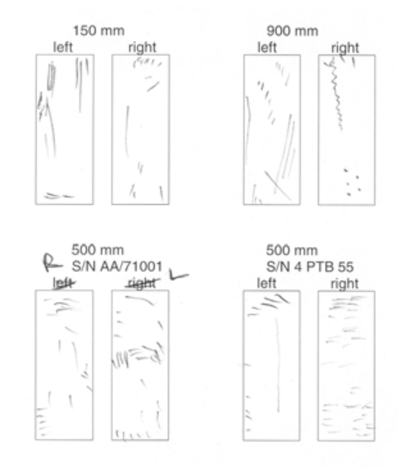
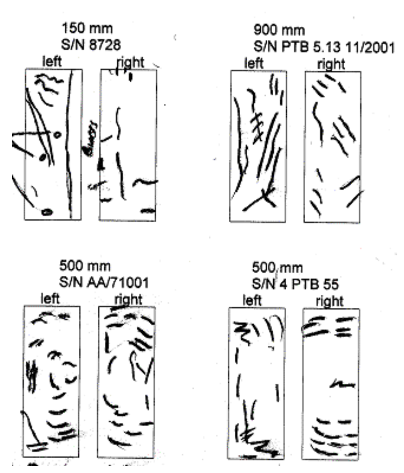
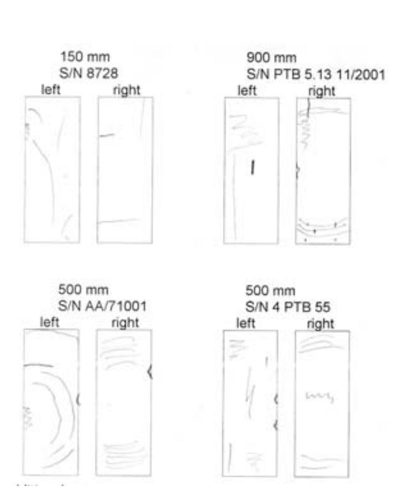
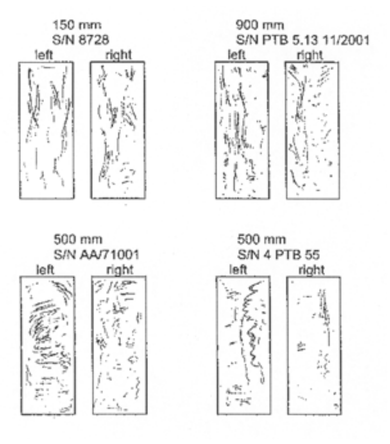
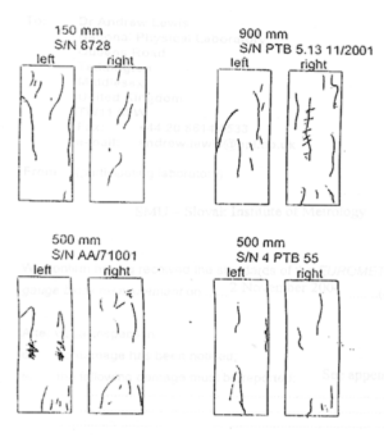
PTB	NPL	UME
		
NCM	**NML**	**CMI**
	No diagram	

Figure 2(c) Gauge condition reports received from participants, first half, loop 2.

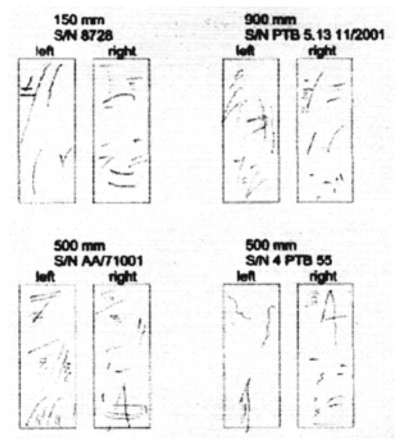
SMU



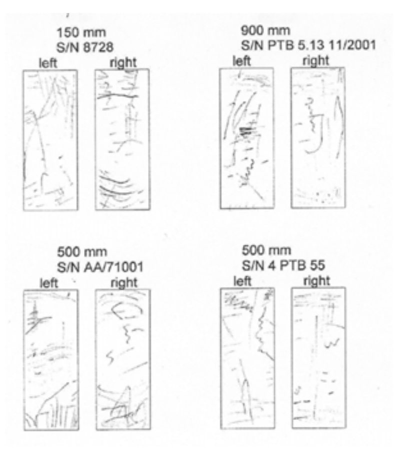
OMH



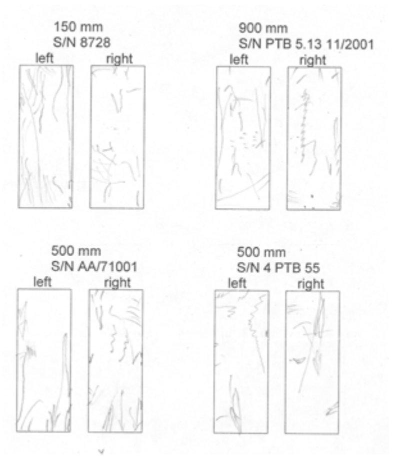
INM



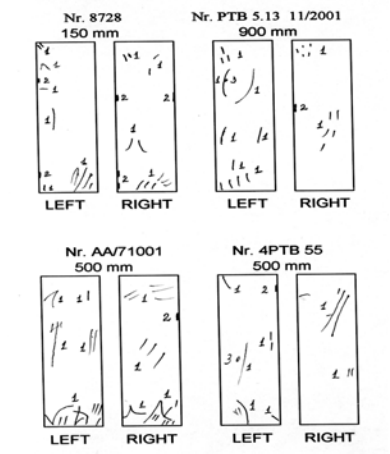
GUM



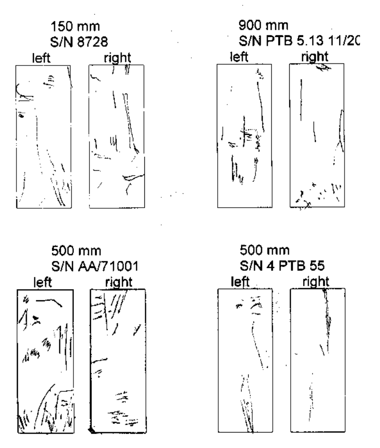
VNT/VMC



LNMC



MIRS



LNE

No diagram

PILOT

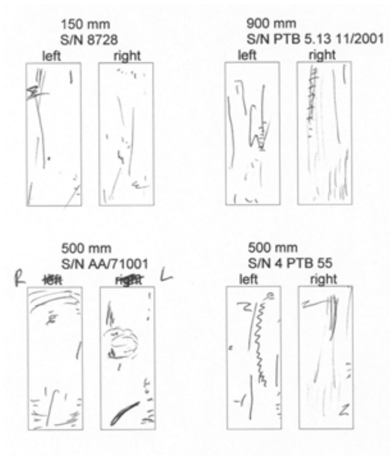


Figure 2(d) Gauge condition reports received from participants, second half, loop 2.

A significant ‘hack’ mark appeared on the underside face of the 500 mm gauge S/N AA/71001. BEV reported accidental damage to this gauge block, which caused this mark. METAS reported finding indentations similar to ‘hardness tests’ on two gauge blocks. IMGC reported the same conclusion (hardness testing indentations) on the 500 mm gauge S/N 500 B, and a possible clamping mark on the other 500 mm gauge block.

Figure 3 *Side face damage to the 500 mm gauge blocks in the first loop, as photographed by pilot laboratory at end of loop 1.*

Figure 4 *'Hack' mark on the side face of the 500 mm gauge block S/N AA/71001 (loop 2)*

5.3 Stability of flatness and variation in length

Although the participants were not required to measure the flatness or variation in length of the gauge blocks, the pilot laboratory made measurements of these parameters at the start, middle and end of the comparison to check for stability of the gauge blocks. This is important as any change to these values may have an effect on the central length measurement, depending on the measurement technique used.

The pilot laboratory measurements of flatness and variation in length were performed at the same time as the re-measurements of the central length. The measurements were made using a phase stepping technique with an estimated (2 sigma) uncertainty of 30 nm.

Table 6 (overleaf) shows the stability data for the flatness and variation in length, as measured by the pilot laboratory.

Generally, the flatness values of the gauge blocks remained unchanged through the two loops. However several gauge blocks showed an increase in the variation in length occurring during the comparison. The variation in length of the 150 mm gauge block increased by about 200 nm, the three 500 mm gauge blocks changed variation by about 50 nm. More critical were the 300 nm change in variation in length of the 900 mm gauge block used in loop 1 (S/N EM/718) and the 200 to 400 nm change shown by the other 900 mm gauge block. The variation problem with the first loop 900 mm gauge block was communicated to the pilot laboratory by IMGC, and, together with the significant change in length of the 500 mm gauge block (S/N 500 B), led to the decision to remove these two gauge blocks from the comparison and to replace them with alternative gauge blocks.

	150 mm S/N 8728			
	Flatness		Variation	
	Right	Left	Right	Left
Prelim	50	-	286	-
NPL	77	90	286	289
Interim1	43	72	245	323
Interim2	61	85	309	286
Final	74	75	524	450

	500 mm S/N AA/71001			
	Flatness		Variation	
	Right	Left	Right	Left
Prelim	97	-	256	-
NPL	85	83	239	242
Interim1	67	74	231	245
Interim2	75	88	304	312
Final	93	103	310	266

	500 mm S/N 500 B			
	Flatness		Variation	
	Right	Left	Right	Left
Prelim	91	-	183	-
NPL	191	112	225	289
Interim1	78	66	473	399
Final	86	73	390	342

	900 mm S/N EM/718			
	Flatness		Variation	
	Right	Left	Right	Left
Prelim	106	-	228	-
NPL	100	113	230	220
Interim1	103	89	553	583
Final	121	108	519	570

	500 mm S/N 4 PTB 55			
	Flatness		Variation	
	Right	Left	Right	Left
Prelim	129	117	250	268
NPL	348	69	306	221
Final	139	110	320	333

	900 mm S/N PTB 5.13 11/2001			
	Flatness		Variation	
	Right	Left	Right	Left
Prelim	103	106	327	427
NPL	146	90	270	241
Final	84	122	729	649

Table 6 Stability of gauge flatness and variation in length, as determined by the pilot laboratory. Right and left refer to the face which is wrung (corresponding to the length determination, not to the face which is visible). Uncertainty is estimated to be ~30 nm (k=2) for each result.

It should be noted that the two gauge blocks which showed the biggest change in variation in length are the two 900 mm gauge blocks. However the gauge block used in loop 1 (S/N EM/719) became more bent across the end face (i.e. left to right), whereas the other 900 mm gauge block became bent top to bottom, as if a heavy weight had pushed downwards on the middle of the gauge block, whilst supported at the Airy points.

5.4 Overall stability

Overall, the most stable gauge blocks, in terms of both geometry and central length, were the two 500 mm gauge blocks S/N 4 PTB55 (only used in loop 2) and S/N AA/71001, used in both loops. The two 900 mm gauge blocks became bent during their individual loop circulations. This suggests that if future comparisons of long gauge blocks are planned, the maximum length should be limited to 500 mm, in order to avoid excessive damage.

Due to the damage and subsequent replacement of two gage blocks, only two gauge blocks were measured by all the participants: 150 mm and 500 mm S/N AA/71001.

A change in the variation in length or flatness of the end faces may have a direct influence on the measured central length, and so these changes should be accounted for in the uncertainty estimation. Of course, no single participant can observe such changes, since they only make one measurement, and so the uncertainty due to change in artefact geometry is an uncertainty of the artefact, rather than of the participants' measurement processes. This will be considered in a later section (§11.2).

6 Measurement results, as reported by participants

6.1 Deviation from nominal length

In Tables 7(a) through 7(f), all measurement results for the deviation from nominal length for the six gauge blocks are given along with their combined standard uncertainties, as reported by the participants. Results reported are the central deviation from nominal length with the left face wrung (ΔL_{left}),central deviation from nominal length with the right face wrung (ΔL_{right}), and the mean of these results (ΔL_{mean}), for each gauge block, for each laboratory. The standard (k = 1) uncertainty reported by each laboratory is also given, as is the reported effective degrees of freedom (ν_{eff}), if stated, otherwise listed as 'normal'. For laboratories which did not make direct interferometric measurements, the terms *left* and *right* refer to the gauge blocks turned end for end between two sets of measurements. All reported data is rounded to the nearest nanometre. Shaded grey cells indicate pilot laboratory consistency measurements, excluded from its official results, linking laboratory repeat measurements by IMGC and datasets revised after initial submission (BEV, NML). Darker shaded cells are for participants not making measurements in two orientations.∞

UME made measurements of the 150 mm gauge block using both interferometry and comparison techniques. The result made using interferometry (-0.035 ± 0.024 μm) is used in the analysis as it is more accurate (for information, the comparison result was -0.045 ± 0.035 μm).

	150 mm S/N 8728				
	ΔL_{left} (μm)	ΔL_{right} (μm)	ΔL_{mean} (μm)	u_c (μm)	ν_{eff}
Prelim		-0.020	-0.020	0.030	241
NPL	-0.026	-0.011	-0.019	0.030	241
SMD	-0.028	-0.002	-0.015	0.019	33627
NMi	-0.028	-0.025	-0.027	0.018	>158
MIKES	-0.034	-0.021	-0.028	0.017	18
SP	0.008	0.004	0.006	0.018	122
BEV			-0.021	0.065	infinite
BEV2			-0.021	0.065	infinite
METAS	-0.007	-0.002	-0.005	0.021	>100
IPQ			-0.490	0.320	>50
CEM	-0.100	-0.070	-0.080	0.040	242
IMGC	-0.006	0.048	0.021	0.028	65
Interim1	0.013	0.024	0.019	0.030	241
PTB	-0.035	-0.022	-0.029	0.016	48
Interim2	-0.014	0.001	-0.007	0.030	241
UME	-0.030	-0.040	-0.035	0.024	652
NCM	-0.133	-0.148	-0.140	0.032	76
IMGC	0.001	-0.017	-0.008	0.028	65
NML			0.220	0.100	infinite
NML2			0.160	0.100	infinite
CMI	0.010	0.002	0.006	0.029	350
SMU	0.034	0.087	0.062	0.068	32
OMH			-0.05	0.15	normal
INM			0.040	0.120	17
GUM			0.018	0.140	297
VMC			-0.180	0.148	normal
LNMC			0.320	0.190	normal
MIRS			0.010	0.130	normal
LNE			0.060	0.140	332
Final	0.085	0.048	0.067	0.030	241

Table 7(a) Results for the 150 mm gauge block, S/N 8278.

After initial reporting of their result (+0.370 ± 0.080 μm) for the 500 mm gauge block, S/N AA/71001, CEM requested a re-measurement after the pilot informed them of possible problems with this result. The CEM re-measurement was made before the Draft A report was released. The revised result was somewhat shorter at +0.330 ± 0.080 μm, but still a candidate for treatment as an outlier (see §8.5-8.6). Only the revised result (CEM2) is used in the analysis (but with zero weight). BEV and NML revised several results (again before Draft A was issued). Only the corrected, revised results are used in the later analysis. SMU submitted several results for the 500 mm gauge block, serial number 5 PTB 55, none of which were sufficiently close to the KCRV. A further result, SMU4, the mean of all their results obtained with this gauge is closer to the KCRV, and is entered in the results tables (but is zero weighted in the analysis).

	500 mm S/N AA/71001				
	ΔL_{left} (µm)	ΔL_{right} (µm)	ΔL_{mean} (µm)	u_c (µm)	ν_{eff}
Prelim		0.092	0.092	0.038	305
NPL	0.074	0.087	0.081	0.038	305
SMD	0.086	0.083	0.085	0.124	8956
NMi	0.009	0.015	0.013	0.051	>158
MIKES	0.027	0.026	0.027	0.026	15
SP	0.035	0.051	0.043	0.035	329
BEV			0.403	0.141	infinite
BEV2			0.218	0.189	infinite
METAS	0.005	0.027	0.016	0.047	>100
IPQ			-2.480	0.960	>50
CEM	0.320	0.420	0.370	0.080	618
CEM2	0.315	0.346	0.330	0.080	618
IMGC	0.081	0.088	0.085	0.033	104
Interim1	0.091	0.111	0.101	0.038	305
PTB	0.042	0.038	0.040	0.019	86
Interim2	0.076	0.098	0.087	0.038	305
UME			-0.007	0.079	514
NCM	-0.067	-0.073	-0.070	0.076	243
IMGC	0.021	0.010	0.015	0.033	104
NML			0.270	0.390	infinite
NML2			-0.320	0.390	infinite
CMI	0.000	0.009	0.004	0.041	infinite
SMU	0.104	0.111	0.108	0.080	59
OMH			0.170	0.230	normal
INM			0.040	0.242	39
GUM			0.041	0.240	261
VMC			-0.080	0.437	normal
LNMC			0.170	0.270	normal
MIRS			0.090	0.300	normal
LNE			0.140	0.220	556
Final	0.131	0.101	0.116	0.038	305

Table 7(b) Results for the 500 mm gauge block, S/N AA/71001.

	500 mm S/N 500 B				
	ΔL_{left} (µm)	ΔL_{right} (µm)	ΔL_{mean} (µm)	u_c (µm)	ν_{eff}
Prelim		1.608	1.608	0.038	305
NPL	1.639	1.625	1.632	0.038	305
SMD	1.578	1.551	1.565	0.123	8994
NMi	1.576	1.578	1.577	0.051	>158
MIKES	1.624	1.612	1.618	0.026	15
SP	1.609	1.611	1.610	0.035	329
BEV			2.032	0.141	240
BEV2			1.777	0.189	240
METAS	1.592	1.587	1.590	0.046	>100
IPQ			-0.630	0.930	>50
CEM	1.490	1.490	1.490	0.080	618
IMGC	1.570	1.555	1.563	0.033	104
Interim1	1.559	1.557	1.558	0.038	305
PTB	1.463	1.486	1.478	0.036	149
Final	1.488	1.508	1.498	0.038	305

Table 7(c) Results for the 500 mm gauge block, S/N 500 B.

	900 mm S/N EM/718				
	ΔL_{left} (µm)	ΔL_{right} (µm)	ΔL_{mean} (µm)	u_c (µm)	ν_{eff}
Prelim		-70.060	-70.060	0.052	199
NPL	-70.020	-70.009	-70.015	0.052	199
SMD	-70.113	-70.126	-70.120	0.188	42074
NMi	-70.140	-70.129	-70.133	0.091	>158
MIKES	-70.075	-70.085	-70.080	0.041	16
SP	-70.074	-70.069	-70.072	0.058	296
BEV			-69.446	0.255	infinite
BEV2			-69.793	0.284	infinite
METAS	-70.048	-70.067	-70.058	0.077	>100
IPQ			-74.680	1.750	>50
CEM	-70.070	-70.140	-70.110	0.140	553
IMGC	-70.065	-70.034	-70.049	0.042	126
Interim1	0.000	-70.056	-70.056	0.052	199
PTB	-70.163	-70.149	-70.156	0.042	157
Final	-70.138	-70.054	-70.096	0.052	199

Table 7(d) Results for the 900 mm gauge block, S/N EM/718.

	500 mm S/N 4 PTB 55				
	ΔL_{left} (µm)	ΔL_{right} (µm)	ΔL_{mean} (µm)	u_c (µm)	ν_{eff}
Prelim	-2.449	-2.430	-2.440	0.038	305
PTB	-2.453	-2.446	-2.450	0.018	113
NPL	-2.451	-2.438	-2.445	0.038	305
UME			-2.484	0.079	514
NCM	-2.691	-2.657	-2.674	0.075	142
IMGC	-2.515	-2.553	-2.534	0.033	104
NML			0.610	0.390	infinite
NML2			-2.550	0.390	infinite
CMI	-2.515	-2.523	-2.518	0.041	infinite
SMU4	-2.344	-2.391	-2.370	0.102	93
OMH			-2.210	0.230	normal
INM			-2.310	0.243	40
GUM			-2.438	0.250	261
VMC			-1.930	0.437	normal
LNMC			-2.030	0.270	normal
MIRS			-2.470	0.300	normal
LNE			-2.510	0.220	556
Final	-2.413	-2.437	-2.425	0.038	305

Table 7(e) Results for the 500 mm gauge block, S/N 4 PTB 55.

	900 mm S/N PTB 5.13 11/2001				
	ΔL_{left} (µm)	ΔL_{right} (µm)	ΔL_{mean} (µm)	u_c (µm)	ν_{eff}
Prelim	0.713	0.718	0.716	0.052	199
PTB	0.695	0.675	0.685	0.025	67
NPL	0.758	0.738	0.748	0.052	199
UME			0.664	0.137	444
NCM	0.221	0.230	0.226	0.136	145
IMGC	0.619	0.621	0.620	0.042	126
NML					
NML2					
CMI	0.667	0.633	0.649	0.055	infinite
SMU	0.758	0.719	0.741	0.109	206
OMH			0.480	0.390	normal
INM			0.560	0.443	42
GUM			0.968	0.460	239
VMC			0.540	0.688	normal
LNMC			0.660	0.380	normal
MIRS			1.130	0.500	normal
LNE			0.750	0.350	303
Final	0.579	0.548	0.564	0.052	199

Table 7(f) Results for the 900 mm gauge block, S/N 5.13 11/2001.

Figures 5(a) through 5(f) show the ΔL_{mean} results with standard uncertainty bars, plotted individually for each of the gauge blocks. The vertical axis has been scaled to show all measurement points except for those which are severe outliers.

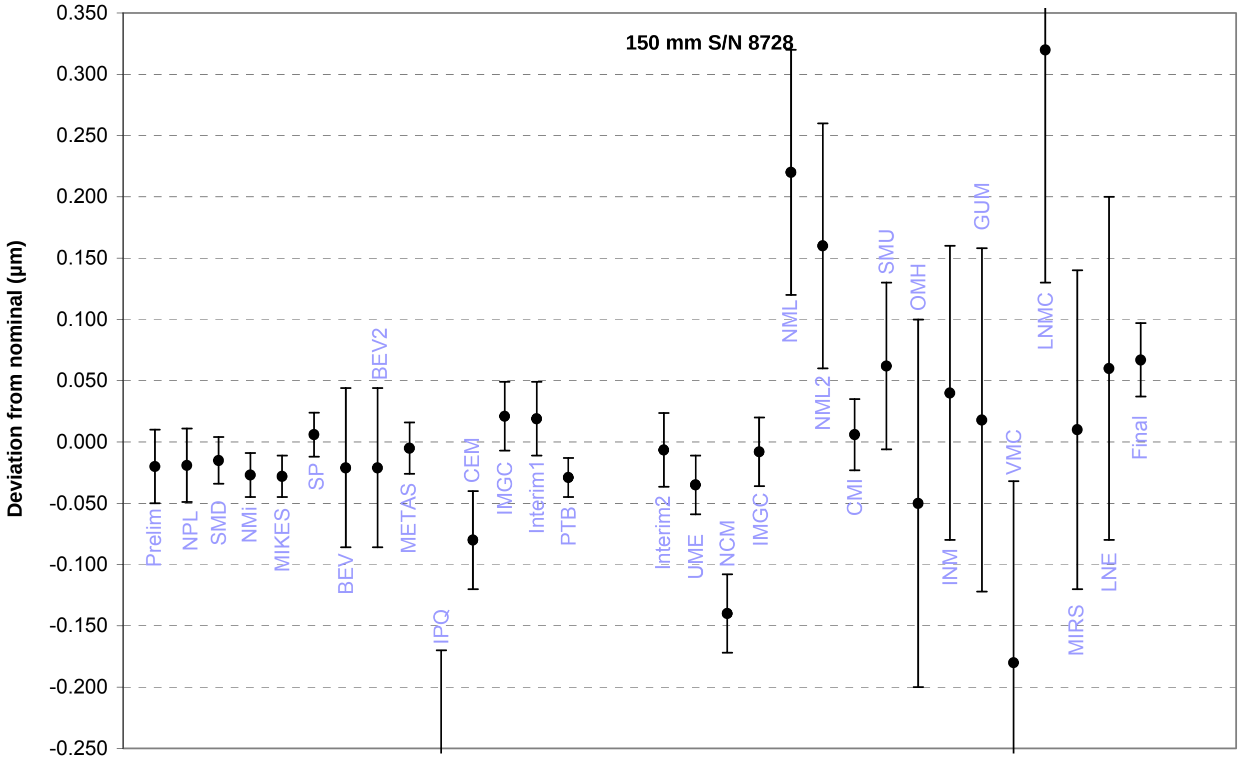


Figure 5(a) Results for the 150 mm gauge block, S/N 8728 (standard uncertainty bars shown).

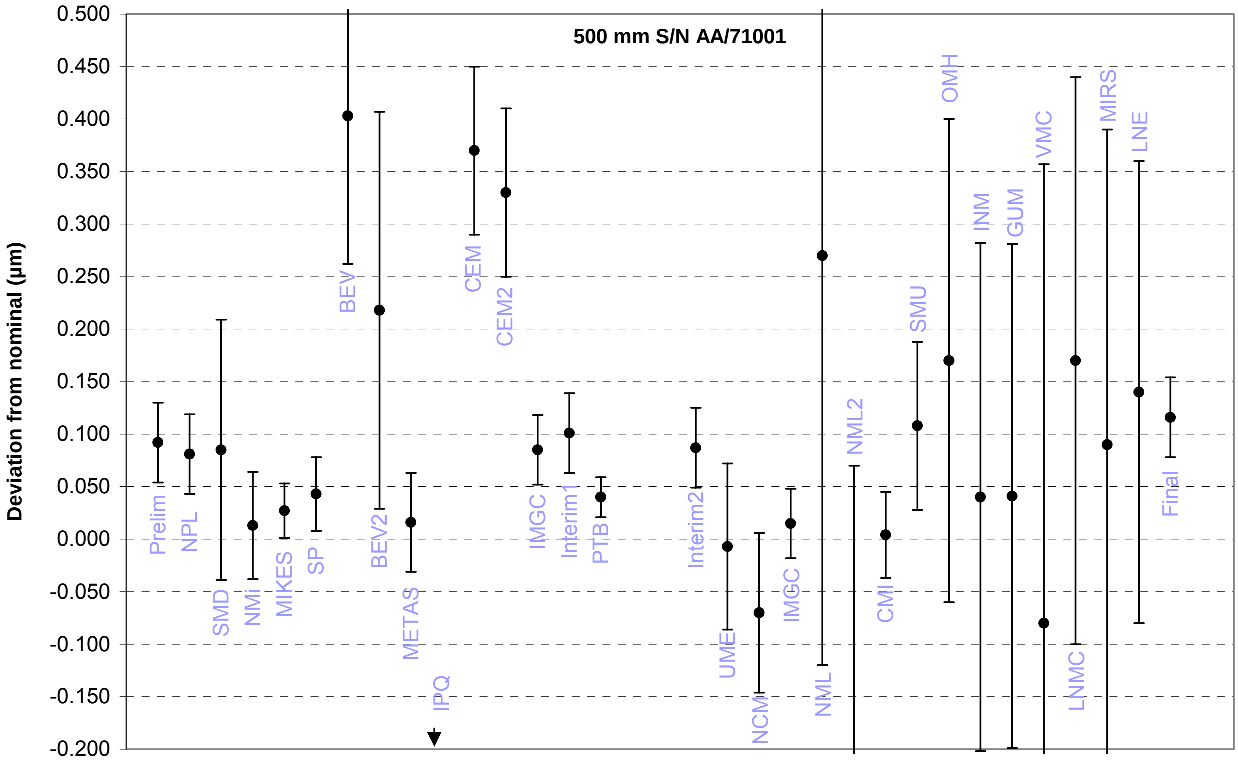


Figure 5(b) Results for the 500 mm gauge block, S/N AA/71001 (standard uncertainty bars shown).

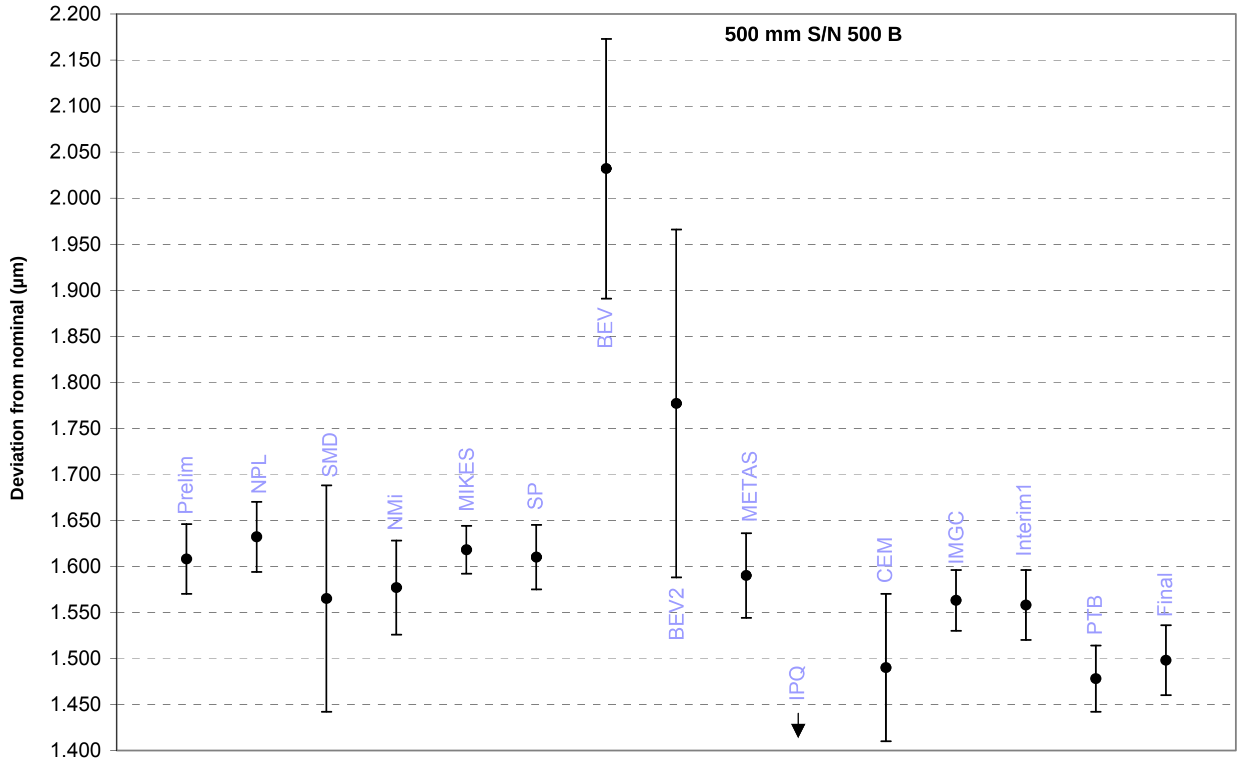


Figure 5(c) Results for the 500 mm gauge block, S/N 500 B (standard uncertainty bars shown).

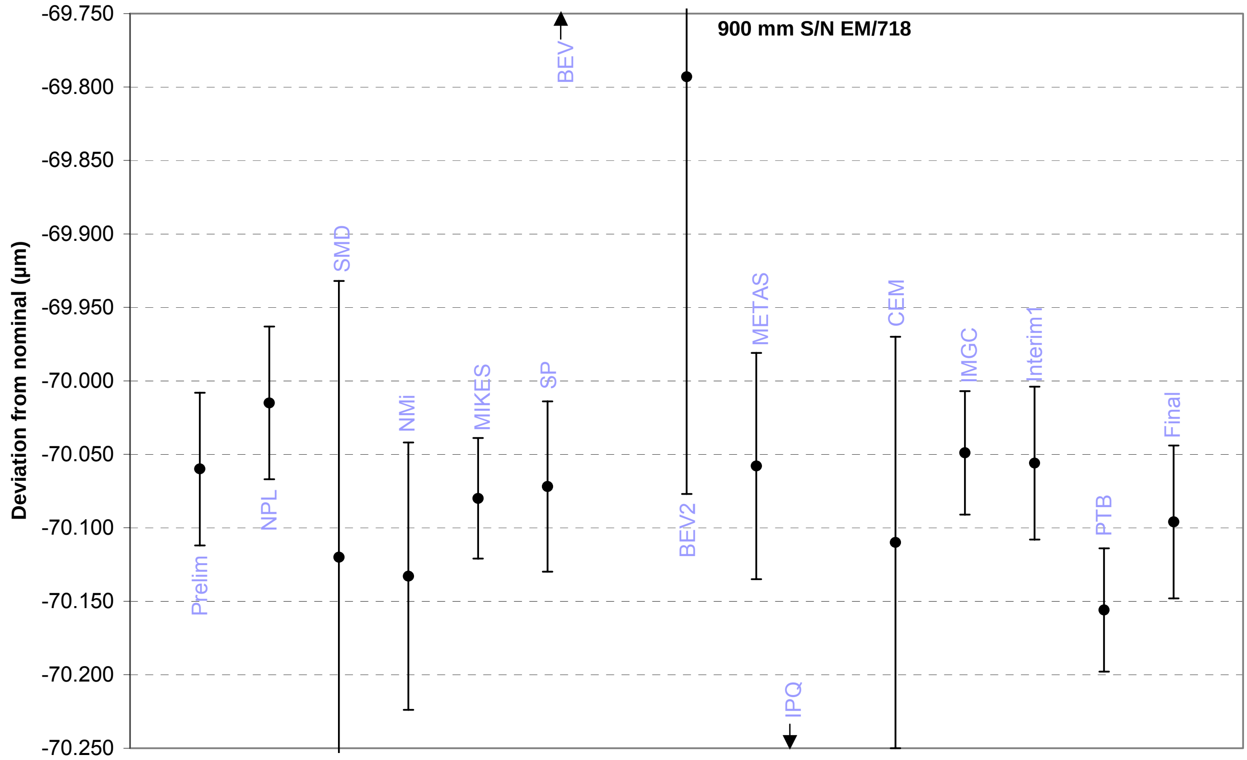


Figure 5(d) Results for the 900 mm gauge block, S/N EM/718 (standard uncertainty bars shown).

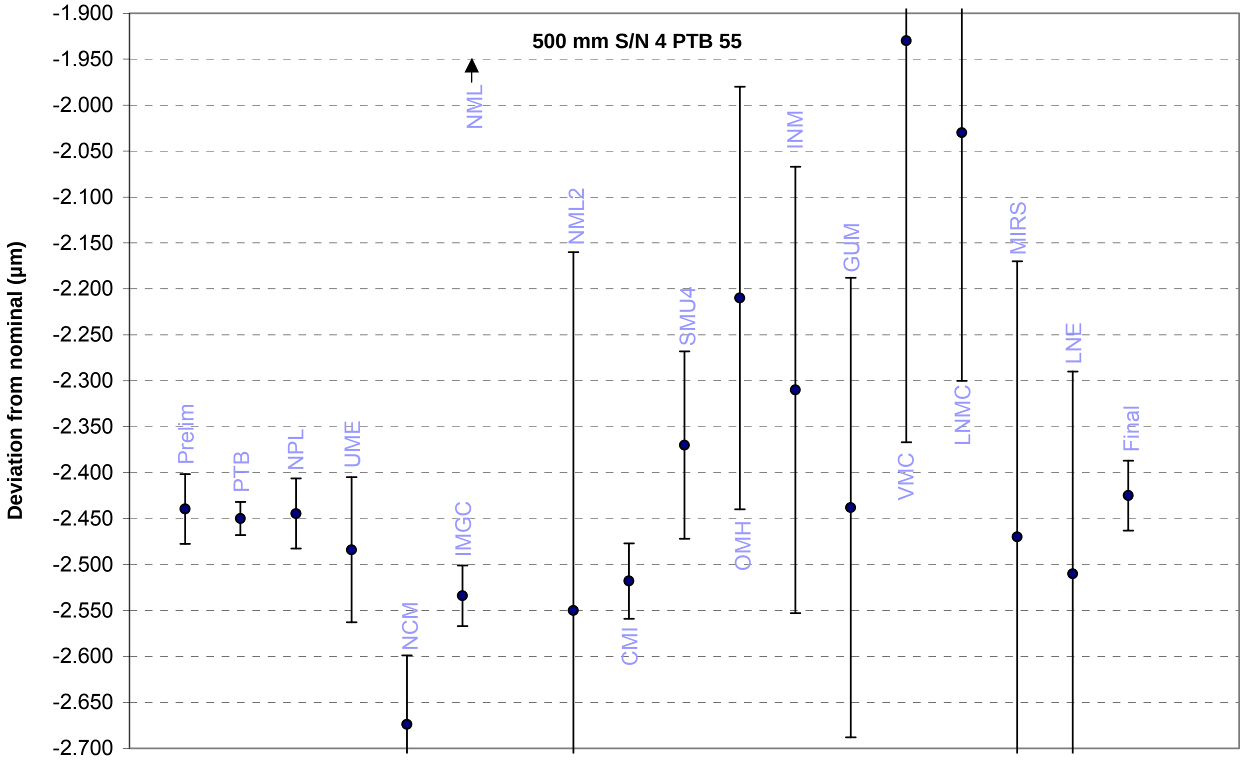


Figure 5(e) Results for the 500 mm gauge block, S/N 4 PTB 55 (standard uncertainty bars shown).

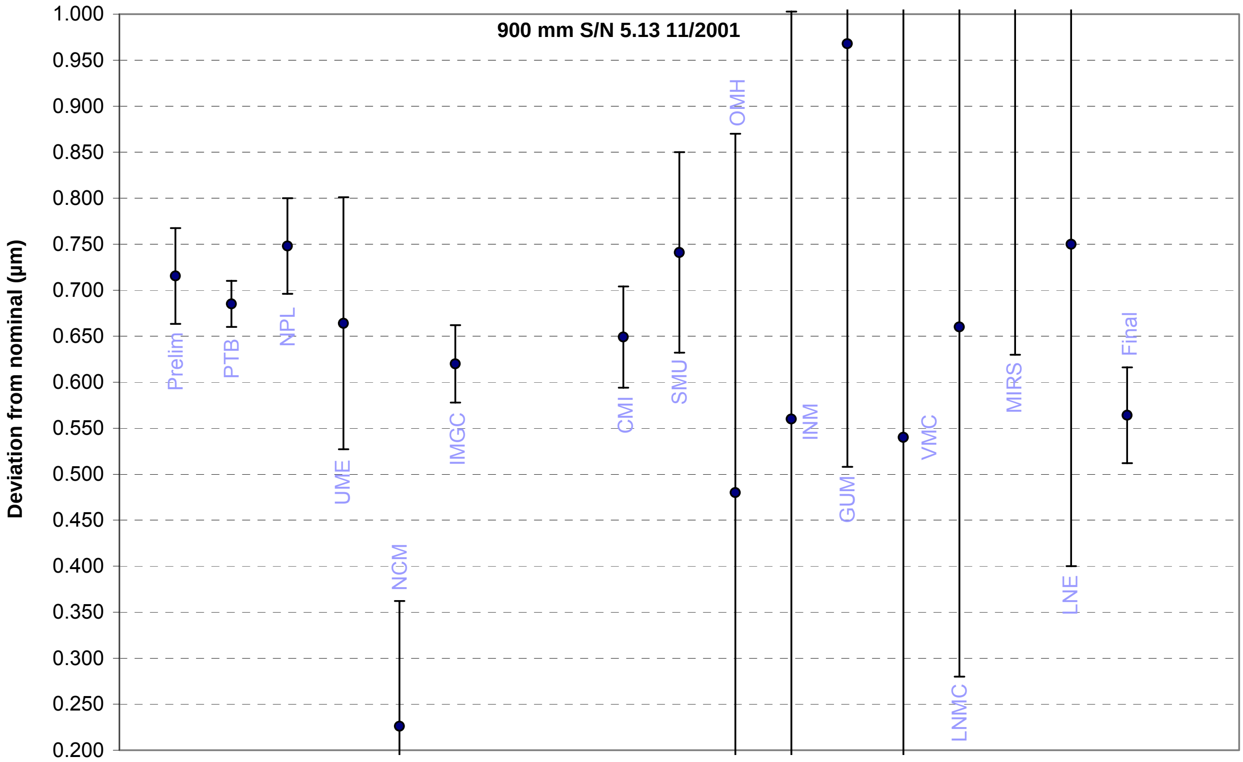


Figure 5(f) Results for the 900 mm gauge block, S/N 5.13 11/2001 (standard uncertainty bars shown).

6.2 Difference between left and right wringing

The laboratories were requested to measure the gauge blocks with both the left and the right measurement surface wrung and to report the results from the individual wringings and the mean. Table 8 shows the differences between the two wringings (or sets of measurements) of all laboratories for all gauge blocks, separately. Note that several laboratories did not perform measurements with both faces independently wrung, or without the gauges turned around so these laboratories do not report results in Table 8, or Figure 6. Also, not all gauge blocks were measured by every laboratory, as only two gauge blocks were common to both loops.

Nominal	150 mm	500 mm	500 mm	900 mm	500 mm	900 mm
S/N	8728	AA/71001	500 B	EM/718	4 PTB 55	PTB 5.13 11/2001
	$\Delta L_{left} - \Delta L_{right}$ (nm)	$\Delta L_{left} - \Delta L_{right}$ (nm)	$\Delta L_{left} - \Delta L_{right}$ (nm)	$\Delta L_{left} - \Delta L_{right}$ (nm)	$\Delta L_{left} - \Delta L_{right}$ (nm)	$\Delta L_{left} - \Delta L_{right}$ (nm)
NPL	-15	-13	14	-11		
SMD	-26	3	27	13		
NMi	-3	-6	-2	-11		
MIKES	-13	1	12	10		
SP	4	-16	-2	-5		
METAS	-5	-22	5	19		
CEM	-30	-31	0	70		
IMGC	-54	-7	15	-31		
Interim1	-11	-20	2			
PTB	-13	4	-23	-14		
pilot			-20	-84	-19	-5
PTB					-7	20
Interim2	-15	-22			-13	20
UME	10					
NCM	15	6			-34	-9
IMGC	18	11			38	-2
CMI	8	-9			8	34
SMU	-53	-7			47	39

Table 8 Differences between left and right wringing for all four gauge blocks (ΔL_{left} - ΔL_{right}),with the result given in nm. Dark grey shading for gauges not in that loop, light grey where the NMI did not submit two individual results (due to measuring technique).

The values given in Table 8 are plotted in Figure 6.

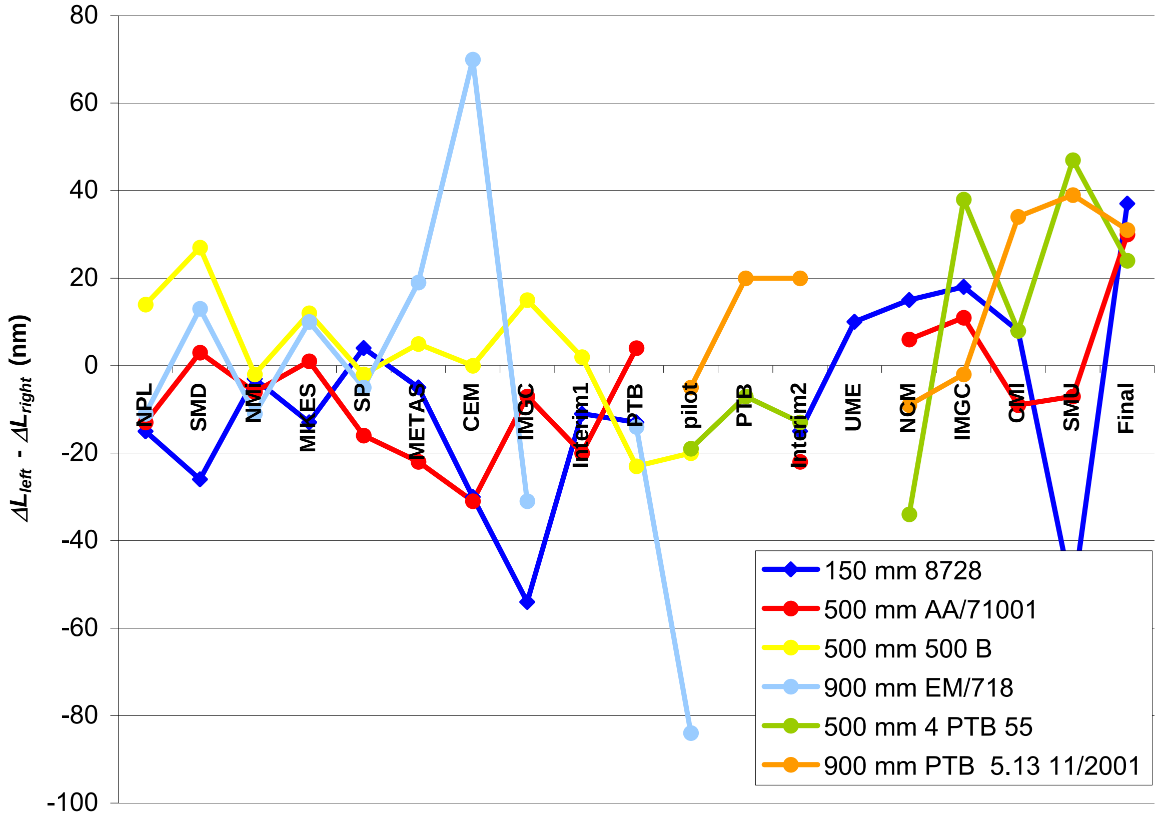


Figure 6 *Difference between Δl_{left} and Δl_{right} (nm). Missing points or names indicate no second orientation measurement for that gauge block or NMI.*

In an ideal comparison, there would be no change in the difference between measurements made of each gauge block in the two orientations, and the above graph would therefore show a horizontal line for each data series. Correlations between data series would suggest common geometrical errors across the range of artefacts concerned, e.g. a concave measuring face at one end or problems with measuring techniques. Changes in values as the comparison progressed would suggest either changing artefact geometry or difference in measuring technique or skill between the NMIs concerned. Gauge block 500 mm 'B' appears to have been quite stable, but with a general trend. There are two large changes visible in the results from CEM, followed by a significant change in the 900 mm gauge block 'EM/718' between CEM and the pilot laboratory, after which it was withdrawn from the remainder of the comparison. Laboratory SMU's results for the 500 mm '4 PTB55' and the 150 mm gauge block show some possible differences from the prevailing trends.

7 Measurement uncertainties

7.1 Model equations

The participants were asked in the technical protocol of the comparison to estimate the uncertainty of measurement according to the *ISO Guide for the Expression of Uncertainty in Measurement* [16]. An example mathematical model [5] was given and the participants were encouraged to use this model as closely as possible to allow for a detailed comparison of all the uncertainties. However, since a variety of measurement techniques have been used, in many cases the uncertainties are not given according to this model. This therefore makes a detailed analysis of the uncertainty contributions rather difficult, when all results are considered together.

Instead, two types of model equations are used for the uncertainty analysis: measurement by interferometry; measurement by comparison.

In Tables 9 and 10, the uncertainty contributions are summarized for all laboratories, according to the best applicable model. The numerical values are standard uncertainties given in nanometres. The length dependent terms are written in italic letters and were calculated for a gauge block length of 500 mm. In the last row, the combined standard uncertainty has been calculated by a simple quadratic sum. This might not necessarily be identical to the combined uncertainty quoted by the laboratory for the 500 mm gauge blocks, because they might have used further contributions, correlations and second order terms, which are not given in the table.

7.2 Measurement by interferometry

The uncertainties in the determination of the following model parameters were taken into account by the majority of the participants making measurements by direct interferometry:

λ_i vacuum wavelengths of the different light sources used;

F_i fractional part of fringe order;

n index of refraction of the air;

Δt_G difference of the gauge block temperature from the reference temperature of 20 °C;

α linear coefficient of thermal expansion of the gauge block;

δl_Ω obliquity correction for the shift in phase resulting from the angular alignment errors of the collimating assembly;

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

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

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

δl_w length attributed to the wringing film;

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

Model parameter	NPL	SMD*	NMi	MIKES	SP	BEV	METAS	CEM	IMGC	CMI	NCM	SMU	PTB
λ_i	*5*	*1.0**	*12.5*	*2*	*0*	*1.5*	*0.6*	*1*	*2*	*0*	*4.4*	*6*	*0*
F_i	0.9	3.0	5.4	2	5	5	2.6	22.5	18	8	3.2	63	6
n	*18.2*	*8.7**	*16.5*	*10.8*	*19.2*	*23.6*	*24.4*	*17*	*14*	*7.6*	*31.6*	*15*	*5*
Δt_G	*14.5*	*23.7**	*40.5*	*17.5*	*23*	*113*	*31.1*	*55*	*12.5*	*20*	*60.5*	*38*	*5.4*
α	*0.14*	*4.3**	*16.5*	*1*	*2.5*	*1.3*	*0.1*	*14.5*	*0.5*	*0.1*	*0.8*	*0.3*	*.15*
δl_Ω	*0.8*	*46**	*1*	*6*	*6*	*0*	*1.4*	*0*	*0*	*2.5*	*0*	*4*	*1.5*
Δl_s	*0*	*0.3**	*0.5*	*1*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0.5*
δl_A	0.5	2.3	3	5	2.5	0	0	2.1	4	28	11	6	5
δl_G	20	1.7	2	10	3	2.9	19.3	3.2	1	15	4.5	10	8
δl_w	5	5.1	4	8	4.5	0	5.8	0	10	5	10	6	10
Δl_Φ	20	7.0	5	5	4.5	0	14.5	0	17	10	8	20	3
other	0	0	0	0	0	80	0	52	0	6.1	27.3	8	7
u_c	**38**	**54**	**51**	**27**	**32**	**141**	**47**	**81**	**33**	**42**	**76**	**80**	**19**

Table 9 *Standard uncertainties (in nm) quoted for a 500 mm gauge block, by the different laboratories making interferometric measurements, for the uncertainty contributions given in the model of the technical protocol, and combined uncertainty calculated from these values. The quadrature summed standard uncertainties (u_c) have been rounded up to the nearest nm. (* SMD uncertainties scaled from supplied values for 150 mm for completeness, though 300 mm is their limit for measurement vertically by interferometry).*

7.3 Measurement by comparison

The uncertainties in the determination of the following model parameters were taken into account by the majority of the participants making measurements by comparison:

λ_i vacuum wavelengths of the different light sources used;

n index of refraction of the air;

Δt_{Gt} difference of the test gauge block temperature from the reference temperature of 20 °C;

Δt_{Gr} difference of the reference gauge block temperature from the reference temperature of 20 °C;

α_t linear coefficient of thermal expansion of the test gauge block;

α_r linear coefficient of thermal expansion of the reference gauge block;

δl_G correction accounting for flatness deviation variation in length of the gauge block & centering;

δl_Ω correction for alignment errors of the measuring system;

l_r length of the reference gauge block;

σ_l spread in the results;

δ_m machine uncertainty.

Model parameter	SMD	IPQ	UME	NML	OMH	INM	GUM	VNT/VMC*	LNMC*	MIRS	LNE
λ_i	*0*	*0*	*0*	*0*	*0*	*0*	*0.7*	*0*	*0*	*0*	*0*
n	0	43	0	0	0	0	12.9	0	0	0	35
Δt_{Gt}	*65*	*1000*	*40.5*	*166*	*73*	*160*	*106*	*166**	*163**	*125*	*172*
Δt_{Gr}	*66*	*0*	*40.5*	*0*	*160*	*85*	*0*	*0*	*0*	*0*	*42.5*
α_t	*0.2*	*6*	*18*	*30*	*3*	*0*	*1*	*47.2**	*70**	*60*	*6*
α_r	*1.1*	*0*	*29*	*0*	*10*	*100*	*0*	*0*	*0*	*40*	*0*
δl_G	12.0	11.1	2.9	4	8	6.2	12.8	11.2	21	0	0
δl_Ω	*24.4*	0	0	0	82	30	30.4	0	0	31	0
l_r	59.9	14.4	35.5	342	100	44	17	572	46.5	150	71
σ_l	11	0.15	4.5	36	37	0	5	210.2	20	0	85
δ_m	50.2	0	17.2	29	50.2	0	2.9	80	173	45	4
other	0	0	0	29	58	118	44	0	3	0	35
$\boldsymbol{u_c}$	**125**	**1002**	**78**	**386**	**235**	**245**	**122**	**639**	**254**	**215**	**215**

Table 10 Standard uncertainties (in nm) quoted for a 500 mm gauge block, by the different laboratories making mechanical comparison measurements, for the uncertainty contributions given above, and combined uncertainty calculated from these values. The quadrature summed standard uncertainties (u_c) have been rounded up to the nearest nm (VNT/LMC and LNMC uncertainties scaled from supplied values for 900 mm and 150 mm gauge blocks, respectively).*

Examination of Tables 9 & 10 shows that the uncertainty due to the coefficient of thermal expansion, (α_g, α_t), is very small, compared to other sources of uncertainty. This is presumably due to *a priori* knowledge of these coefficients, through their determination by the pilot laboratory and another laboratory before the start of the comparison. In hindsight, this allows laboratories with poor temperature control to achieve uncertainties which are better than would normally be achievable with 'unknown' customer gauges.

For the majority of participants, the largest source of uncertainty is due to the uncertainty in the determination of the gauge block temperature (Δt_G , Δt_{Gt}). This uncertainty is multiplied by the gauge block coefficient of thermal expansion which is approximately 10^{-5} K^{-1}. In order, therefore, to reduce this uncertainty below 10 nm (for a 500 mm gauge block) requires temperature measurement with an uncertainty below 2 mK, which is quite difficult to achieve.

For some participants making mechanical comparison, the other largest uncertainty source is the uncertainty of the reference gauge block length (l_r). Better calibration of the reference gauge blocks would lead to a reduced overall uncertainty.

8 Analysis of the reported results

The reported measurement results are now analysed by simple statistical means to allow identification of any significant bias or outliers, and to investigate the statistical distribution of the results.

From Tables 7(a) though 7(f) and Figures 3(a) through 3(f) it is clear that the uncertainties quoted by the participants are different from one participant to another, and that the uncertainties depend on the length of the gauge block being measured. Thus analysis via use of the simple arithmetic mean as an estimator of the true mean is not suitable and instead, the weighted mean should be used. This approach requires that the participants have made correct estimates of their uncertainty of measurement otherwise a too low uncertainty will place undue emphasis on the result of that particular laboratory.

8.1 Derivations

For each laboratory, i, which measures each gauge block, j, let the measured deviation from nominal size (after making all required corrections) be denoted x_{ij}. The number of laboratories, I, is 23 and the number of gauge blocks, J, is 6. Since the six gauge blocks are six physically different length artefacts with six different lengths, thermal expansion coefficients, material properties *etc*, it is reasonable to expect that the data x_{ij} come from six separate populations (one per gauge block) and so analysis should be on a gauge-by-gauge basis. Note that not all laboratories measured all gauge blocks.

Thus, for a particular gauge block, j :

Each laboratory reports a measured value, x_i , and its associated standard uncertainty $u(x_i)$.

The normalised weight, w_i , for the result x_i is given by:

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

where the normalising factor, C, is given by:

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

Then the weighted mean, $\bar{x}_w$, is given by:

$$\bar{x}_w = \sum_{i=1}^{I} w_i \cdot x_i \tag{3}$$

The uncertainty of the weighted mean can be calculated as either the so-called internal or external standard deviation, $u_{\text{int}}(\bar{x}_w)$ and $u_{ext}(\bar{x}_w)$, respectively. The internal standard deviation is based on the estimated uncertainties $u(x_i)$ as reported by the participants, whereas the external standard deviation is the standard deviation of the spread of the actual results, x_i, weighted by the uncertainties $u(x_i)$:

$$u_{\text{int}}(\bar{x}_w) = \sqrt{\frac{1}{\sum_{i=1}^{I}\left(\frac{1}{u(x_i)}\right)^2}} = \sqrt{C} \tag{4}$$

$$u_{ext}(\bar{x}_w) = \sqrt{\frac{1}{(I-1)} \cdot \frac{\sum_{i=1}^{I} w_i (x_i - \bar{x}_w)^2}{\sum_{i=1}^{I} w_i}} \tag{5}$$

Substituting (1) into (5) gives:

$$u_{ext}(\bar{x}_w) = \sqrt{\frac{1}{(I-1)} \cdot \frac{\sum_{i=1}^{I} \frac{1}{[u(x_i)]^2}(x_i - \bar{x}_w)^2}{\sum_{i=1}^{I} \frac{1}{[u(x_i)]^2}}} \quad (6)$$

After deriving the weighted mean and its associated uncertainty, the deviation of each laboratory's result from the weighted mean is determined simply as $x_i - \bar{x}_w$. The uncertainty of this deviation is calculated as a combination of the uncertainties of the result, $u(x_i)$, and the uncertainty of the weighted mean. In this case, the uncertainty of the weighted mean is taken as $u_{\mathrm{int}}(\bar{x}_w)$. The uncertainty of the deviation from the weighted mean is given by equation (7), which includes a minus sign to take into account the correlation between the two uncertainties (it would be a plus sign if dealing with uncorrelated uncertainties, such as when comparing data from two separate laboratories).

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

Values for the weighted mean, internal and external standard deviations, deviation from weighted mean and its corresponding uncertainty and are calculated for each gauge block, and reported in Tables 11(a) through 11(f).

8.2 Analysis using E_n values

A check for statistical consistency of the results with their associated uncertainties can be made by calculating the E_n value for each laboratory, where E_n is defined as the ratio of the deviation from the weighted mean, divided by the uncertainty of this deviation:

$$E_n = \frac{x_i - \bar{x}_w}{\sqrt{[u(x_i)]^2 - [u_{int}(\bar{x}_w)]^2}} \quad (8)$$

E_n values for each laboratory have been calculated and are also reported in Tables 11(a) through 11(f).

8.3 Birge ratio test

The statistical consistency of a comparison can also be investigated by the so-called Birge ratio R_B [17], which compares the observed spread of the results with the spread expected from the individual reported uncertainties.

The application of least squares algorithms and the χ^2-test leads to the Birge ratio:

$$R_B = \frac{u_{ext}(\bar{x}_w)}{u_{int}(\bar{x}_w)} \quad (9)$$

The Birge ratio has an expectation value of R_B = 1, when considering standard uncertainties. For a coverage factor of k = 2, the expectation value is increased and the data in a comparison are consistent provided that

$$R_B < \sqrt{1 + \sqrt{8/(I-1)}} \quad (10)$$

where I is the number of laboratories. As different numbers of laboratories measured the individual gauge blocks, there are 3 separate values of R_B to use For the cases I = 23, 15, 11, a value of R_B < 1.27, 1.33, 1.38, respectively, indicates consistency (for k = 2).

8.4 Results of all participants

Tables 11(a) through 11(f) present the analysis of the results for the six gauge blocks, as described in sections 8.1 through 8.3, with displayed values rounded to the nearest nanometre.

150 mm S/N 8728						
LAB	x_i (µm)	$u_c(x_i)$ (µm)	w_i	$x_i - x_w$	$u(x_i - x_w)$ (µm)	$E_{n\,(k=2)}$
NPL	-0.019	0.030	0.042	0.001	0.029	0.023
SMD	-0.015	0.019	0.105	0.005	0.018	0.149
NMi	-0.027	0.018	0.117	-0.007	0.017	-0.197
MIKES	-0.028	0.017	0.131	-0.008	0.016	-0.242
SP	0.006	0.018	0.117	0.026	0.017	0.779
BEV2	-0.021	0.065	0.009	-0.001	0.065	-0.005
METAS	-0.005	0.021	0.086	0.015	0.020	0.382
IPQ	-0.490	0.320	0.000	-0.470	0.320	-0.734
CEM	-0.080	0.040	0.024	-0.060	0.040	-0.755
IMGC	0.021	0.028	0.048	0.041	0.027	0.757
PTB	-0.029	0.016	0.148	-0.009	0.015	-0.293
UME	-0.035	0.024	0.066	-0.015	0.023	-0.316
NCM	-0.140	0.032	0.037	-0.120	0.031	-1.905
NML2	0.160	0.100	0.004	0.180	0.100	0.903
CMI	0.006	0.029	0.045	0.026	0.028	0.465
SMU	0.062	0.068	0.008	0.082	0.068	0.608
OMH	-0.050	0.150	0.002	-0.030	0.150	-0.099
INM	0.040	0.120	0.003	0.060	0.120	0.252
GUM	0.018	0.140	0.002	0.038	0.140	0.137
VMC	-0.180	0.148	0.002	-0.160	0.148	-0.540
LNMC	0.320	0.190	0.001	0.340	0.190	0.896
MIRS	0.010	0.130	0.002	0.030	0.130	0.117
LNE	0.060	0.140	0.002	0.080	0.140	0.287
weighted mean, x_w	-0.020					
C	3.788E-05					
$u_{int}(x_w)$	0.0062					
$u_{ext}(x_w)$	0.0078					
R_B	1.2608					

Table 11(a) Data analysis for measurements of the 150 mm gauge block, S/N 8728, showing deviations from weighted mean, and associated uncertainties. Also shown is the Birge ratio for this data set, R_B ,and the individual E_n values.

500 mm S/N AA/71001						
LAB	x_i (µm)	$u_c(x_i)$ (µm)	w_i	$x_i - x_w$	$u(x_i - x_w)$ (µm)	$E_{n\ (k=2)}$
NPL	0.081	0.038	0.077	0.036	0.037	0.487
SMD	0.085	0.124	0.007	0.040	0.124	0.160
NMi	0.013	0.051	0.043	-0.032	0.050	-0.325
MIKES	0.027	0.026	0.165	-0.018	0.024	-0.388
SP	0.043	0.035	0.091	-0.002	0.033	-0.036
BEV2	0.218	0.189	0.003	0.173	0.189	0.457
METAS	0.016	0.047	0.051	-0.029	0.046	-0.321
IPQ	-2.480	0.960	0.000	-2.525	0.960	-1.315
CEM2	0.330	0.080	0.017	0.285	0.079	1.794
IMGC	0.085	0.033	0.102	0.040	0.031	0.633
PTB	0.040	0.019	0.309	-0.005	0.016	-0.172
UME	-0.007	0.079	0.018	-0.052	0.078	-0.335
NCM	-0.070	0.076	0.019	-0.115	0.075	-0.767
NML2	-0.320	0.390	0.001	-0.365	0.390	-0.469
CMI	0.004	0.041	0.066	-0.041	0.040	-0.523
SMU	0.108	0.080	0.017	0.063	0.079	0.394
OMH	0.170	0.230	0.002	0.125	0.230	0.271
INM	0.040	0.242	0.002	-0.005	0.242	-0.011
GUM	0.041	0.240	0.002	-0.004	0.240	-0.009
VMC	-0.080	0.437	0.001	-0.125	0.437	-0.144
LNMC	0.170	0.270	0.002	0.125	0.270	0.231
MIRS	0.090	0.300	0.001	0.045	0.300	0.074
LNE	0.140	0.220	0.002	0.095	0.220	0.215
weighted mean, x_w	0.045					
C	1.116E-04					
$u_{int}(x_w)$	0.0106					
$u_{ext}(x_w)$	0.0124					
R_B	1.1729					

Table 11(b) Data analysis for measurements of the 500 mm gauge block, S/N AA/71001, showing deviations from weighted mean, and associated uncertainties. Also shown is the Birge ratio for this data set, R_B ,and the individual E_n values.

500 mm S/N 500 B						
LAB	x_i (µm)	$u_c(x_i)$ (µm)	w_i	$x_i - x_w$	$u(x_i - x_w)$ (µm)	$E_{n\ (k=2)}$
NPL	1.632	0.038	0.120	0.050	0.036	0.696
SMD	1.565	0.123	0.011	-0.017	0.122	-0.071
NMi	1.577	0.051	0.066	-0.005	0.049	-0.055
MIKES	1.618	0.026	0.256	0.036	0.022	0.794
SP	1.610	0.035	0.141	0.028	0.032	0.425
BEV2	1.777	0.189	0.005	0.195	0.189	0.516
METAS	1.590	0.046	0.082	0.008	0.044	0.086
IPQ	-0.630	0.930	0.000	-2.212	0.930	-1.190
CEM	1.490	0.080	0.027	-0.092	0.079	-0.585
IMGC	1.563	0.033	0.159	-0.019	0.030	-0.320
PTB	1.478	0.036	0.133	-0.104	0.034	-1.558
weighted mean, x_w	1.582					
C	1.728E-04					
$u_{int}(x_w)$	0.0131					
$u_{ext}(x_w)$	0.0191					
R_B	1.4515					

Table 11(c) Data analysis for measurements of the 500 mm gauge block, S/N 500 B, showing deviations from weighted mean, and associated uncertainties. Also shown is the Birge ratio for this data set, R_B ,and the individual E_n values.

900 mm S/N EM/718						
LAB	x_i (µm)	$u_c(x_i)$ (µm)	w_i	$x_i - x_w$	$u(x_i - x_w)$ (µm)	$E_{n\,(k=2)}$
NPL	-70.015	0.052	0.133	0.066	0.048	0.680
SMD	-70.120	0.188	0.010	-0.039	0.187	-0.105
NMi	-70.133	0.091	0.043	-0.052	0.089	-0.293
MIKES	-70.080	0.041	0.214	0.001	0.036	0.012
SP	-70.072	0.058	0.107	0.009	0.055	0.081
BEV2	-69.793	0.284	0.004	0.288	0.283	0.508
METAS	-70.058	0.077	0.061	0.023	0.075	0.153
IPQ	-74.680	1.750	0.000	-4.599	1.750	-1.314
CEM	-70.110	0.140	0.018	-0.029	0.139	-0.105
IMGC	-70.049	0.042	0.204	0.032	0.037	0.425
PTB	-70.156	0.042	0.204	-0.075	0.037	-1.003
weighted mean, x_w	-70.081					
C	3.601E-04					
$u_{int}(x_w)$	0.0190					
$u_{ext}(x_w)$	0.0223					
R_B	1.1765					

Table 11(d) *Data analysis for measurements of the 900 mm gauge block, S/N EM/718, showing deviations from weighted mean, and associated uncertainties. Also shown is the Birge ratio for this data set, R_B ,and the individual E_n values.*

500 mm S/N 4 PTB 55						
LAB	x_i (µm)	$u_c(x_i)$ (µm)	w_i	$x_i - x_w$	$u(x_i - x_w)$ (µm)	$E_{n\,(k=2)}$
PTB	-2.450	0.018	0.529	0.024	0.012	0.956
NPL	-2.445	0.038	0.119	0.029	0.036	0.408
UME	-2.484	0.079	0.027	-0.010	0.078	-0.067
NCM	-2.674	0.075	0.030	-0.200	0.074	-1.357
IMGC	-2.534	0.033	0.157	-0.060	0.030	-0.996
NML2	-2.550	0.390	0.001	-0.076	0.390	-0.098
CMI	-2.518	0.041	0.102	-0.044	0.039	-0.571
SMU4	-2.370	0.102	0.016	0.104	0.101	0.512
OMH	-2.210	0.230	0.003	0.264	0.230	0.574
INM	-2.310	0.243	0.003	0.164	0.243	0.337
GUM	-2.438	0.250	0.003	0.036	0.250	0.071
VMC	-1.930	0.437	0.001	0.544	0.437	0.622
LNMC	-2.030	0.270	0.002	0.444	0.270	0.823
MIRS	-2.470	0.300	0.002	0.004	0.300	0.006
LNE	-2.510	0.220	0.004	-0.036	0.220	-0.083
weighted mean, x_w	-2.474					
C	1.714E-04					
$u_{int}(x_w)$	0.0131					
$u_{ext}(x_w)$	0.0161					
R_B	1.2281					

Table 11(e) *Data analysis for measurements of the 500 mm gauge block, S/N 4PTB55, showing deviations from weighted mean, and associated uncertainties. Also shown is the Birge ratio for this data set, R_B ,and the individual E_n values.*

900 mm S/N PTB 5.13 11/2001						
LAB	x_i (µm)	$u_c(x_i)$ (µm)	w_i	$x_i - x_w$	$u(x_i - x_w)$ (µm)	$E_{n\,(k=2)}$
PTB	0.685	0.025	0.517	0.015	0.017	0.423
NPL	0.748	0.052	0.119	0.078	0.049	0.796
UME	0.664	0.137	0.017	-0.006	0.136	-0.023
NCM	0.226	0.136	0.017	-0.444	0.135	-1.648
IMGC	0.620	0.042	0.183	-0.050	0.038	-0.663
CMI	0.649	0.055	0.107	-0.021	0.052	-0.205
SMU	0.741	0.109	0.027	0.071	0.108	0.329
OMH	0.480	0.390	0.002	-0.190	0.390	-0.244
INM	0.560	0.443	0.002	-0.110	0.443	-0.125
GUM	0.968	0.460	0.002	0.298	0.460	0.324
VMC	0.540	0.688	0.001	-0.130	0.688	-0.095
LNMC	0.660	0.380	0.002	-0.010	0.380	-0.014
MIRS	1.130	0.500	0.001	0.460	0.500	0.460
LNE	0.750	0.350	0.003	0.080	0.350	0.114
weighted mean, x_w	0.670					
C	3.230E-04					
$u_{int}(x_w)$	0.0180					
$u_{ext}(x_w)$	0.0198					
R_B	1.0991					

Table 11(f) *Data analysis for measurements of the 900 mm gauge block, S/N 5.13 PRB 11/2001, showing deviations from weighted mean, and associated uncertainties. Also shown is the Birge ratio for this data set, R_B ,and the individual E_n values.*

Five of the six analysis tables [11(a) through 11(f)] show a Birge ratio less than the critical values enumerated in §8.3, indicating that the data is consistent with the stated uncertainties. The critical Birge ratio value is exceeded for the 500 mm S/N 500 B gauge block. Plotting the E_n values as a histogram, in Figure 7, allows identification of possible outliers, as well as giving a graphical view of the distribution of the data.

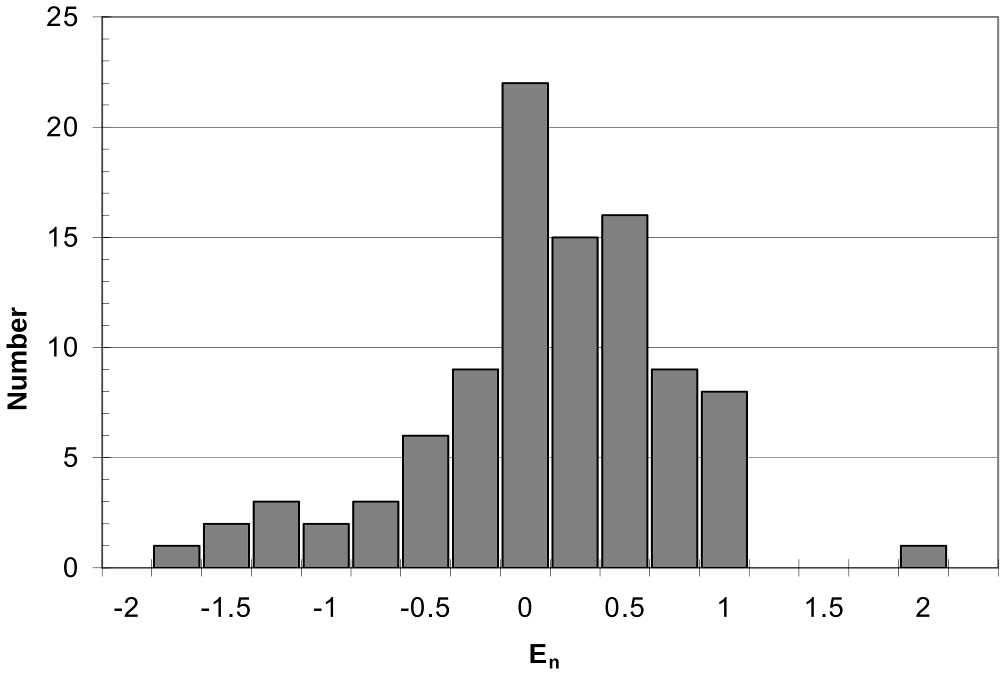


Figure 7 *Histogram of E_n values (at k = 2) from the whole 98 element dataset of deviation from weighted mean, based on measurement results and standard uncertainties reported by the participants.*

As can be seen in Figure 7, the data is clustered into two 'groups', the larger group with E_n values from -1.75 to +1.00 and a single result with E_n value around +2.0. There are 9 results with | E_n | > 1.000, whereas one would expect 5% (about 5 of the 98) of the E_n values to be outside the range –1 to +1. There are therefore 4 results which, statistically, may be outliers. Examination of the data in Tables 11(a) through 11(f) shows that this small group of data corresponds to the results of several laboratories, but notably contains 3 of the 4 results for IPQ, 3 of the results for NCM, 1 for CEM and 2 for PTB. The two results from PTB with | E_n | > 1 correspond to the last official results on the two gauge blocks that were removed from the circulation due to damage. The PTB results lie very close to the final results of the pilot laboratory for these two gauge blocks (see Figures 5(c) and 5(d)). This indicates that the PTB results for these two gauge blocks were probably correct. Therefore the suspicion is that the gauges had changed size before they reached PTB. IMGC reported excessive variation in length of these two gauges, so the change had happened before the gauges reached IMGC. The measurement techniques of CEM and IPQ would not necessarily detect such damage. METAS reported no gauge block geometry problems and their interferometric measurement technique would detect if the gauges showed excessive variation in length. So the conclusion is that these two gauge blocks became damaged somewhere between leaving METAS, and arriving at IMGC. Therefore the 2 anomalous results of PTB are explained immediately by artefact changes.

8.5 Result revision or withdrawal

Separately, IPQ communicated that their measuring system was still being developed and planned modifications had not been completed at the time of participation. They measured the gauge blocks but decided, when submitting that the results were not representative of their measuring system and asked to withdraw their participation. This confirms the above hypothesis that the IPQ results were possible outliers. They are hereby removed from all remaining analysis.

After receiving the original results from BEV, CEM, NCM, NML and SMU, the pilot noticed that some of these results were far from the average of the other data so far submitted and asked them to check their calculations (as required under CCL-WGDM guidance rules on key comparisons). BEV, CEM, NCM, NML and SMU were not informed of the sign or magnitude of any problem. BEV re-calculated their results with a more detailed analysis of the temperature variations at the time of measurement. These results are given as 'BEV2' in the above sections. NML did likewise and found some thermal corrections which had not been performed correctly. Their revised results are given as 'NML2'. NCM and CEM checked their results but could find no apparent errors, so their results remain unchanged. SMU submitted 3 sets of results for the 500 mm gauge block (4 PTB 55) before Draft A, and one set after seeing Draft A. The sets submitted before the KCRV was known were in very poor agreement with the KCRV (ΔL_{mean} = -2.187, -2.283, -2.573 µm). The fourth result, a mean of several measured values, is in agreement within the KCRV uncertainty overlap and is shown in the analysis. However, because SMU could not definitively pick the correct answer (fringe order ambiguity) it is prudent to zero weight their result for this gauge block.

After draft B2 had been issued, NMi-VSL submitted additional data for the 500 mm gauge block S/N AA/71001, which they had overlooked during earlier analysis. This data has been incorporated into their results, but the change in their overall result for this gauge block was only –2 nm. The change is so small that it has no impact on the KCRV for this gauge block, the only changes being some minor alterations to the E_n values for this gauge block for all participants.

For brevity, only the revised results (where submitted) are used in the remaining analysis. After all the results had been sent to the pilot laboratory and detailed analysis was performed, only one of the CEM results remained outside the | E_n | > 1 range. CEM requested and were granted a re-measurement of one gauge block, but the new result (CEM2) still appears as an outlier, though it is somewhat closer that their original result, to the KCRV.

In order to process the data in a rigorous way, outliers should be excluded from contributing to the weighted mean. After withdrawal of the IPQ results, the 7 candidates for status of outlier based on statistical analysis are: 2 PTB results on the withdrawn gauges; 3 results from NCM; one result from SMU and one result from CEM.

8.6 Analysis of results, outliers excluded from weighted mean

As discussed in section 8.5, ten results were identified as possible outliers (9 results with | E_n | > 1 plus the SMU4 result) and discussion with the laboratories concerned, or re-measurement of the gauge by the pilot laboratory, has confirmed this analysis for 6 of the results (the CEM2 plus 3 NCM results remain unexplained). It is possible that these outlying results are biasing the weighted mean values and contributing to uncertainties which cause the E_n values of some other participants to be greater than expected.

Therefore, in order to progress with more accurate analysis of the data, the analysis of section 8.4 is repeated, but with all outlying data points excluded from the determination of the weighted mean and the IPQ results withdrawn completely. The results of this analysis are presented in Table 12(a) through Table 12(f) and in Figure 8. Displayed results are rounded to the nearest nanometre.

150 mm S/N 8728						
LAB	x_i (µm)	$u_c(x_i)$ (µm)	w_i	$x_i - x_w$	$u(x_i - x_w)$ (µm)	$E_{n\ (k=2)}$
NPL	-0.019	0.030	0.044	-0.003	0.029	-0.059
SMD	-0.015	0.019	0.109	0.001	0.018	0.016
NMi	-0.027	0.018	0.121	-0.011	0.017	-0.339
MIKES	-0.028	0.017	0.136	-0.012	0.016	-0.393
SP	0.006	0.018	0.121	0.022	0.017	0.639
BEV2	-0.021	0.065	0.009	-0.005	0.065	-0.042
METAS	-0.005	0.021	0.089	0.011	0.020	0.264
CEM	-0.080	0.040	0.025	-0.064	0.040	-0.816
IMGC	0.021	0.028	0.050	0.037	0.027	0.670
PTB	-0.029	0.016	0.154	-0.013	0.015	-0.456
UME	-0.035	0.024	0.068	-0.019	0.023	-0.419
NCM	-0.140	0.032	0.000	-0.124	0.031	-1.983
NML2	0.160	0.100	0.004	0.176	0.100	0.880
CMI	0.006	0.029	0.047	0.022	0.028	0.381
SMU	0.062	0.068	0.009	0.078	0.068	0.573
OMH	-0.050	0.150	0.002	-0.034	0.150	-0.115
INM	0.040	0.120	0.003	0.056	0.120	0.232
GUM	0.018	0.140	0.002	0.034	0.140	0.120
VMC	-0.180	0.148	0.002	-0.164	0.148	-0.556
LNMC	0.320	0.190	0.001	0.336	0.190	0.884
MIRS	0.010	0.130	0.002	0.026	0.130	0.098
LNE	0.060	0.140	0.002	0.076	0.140	0.270
weighted mean, x_w	-0.016					
C	3.935E-05					
$u_{int}(x_w)$	0.006					
$u_{ext}(x_w)$	0.006					
R_B	0.932					

Table 12(a) Data analysis for measurements of the 150 mm gauge block, S/N 8728, with data from one participant excluded from the weighted mean as an outlier and one result withdrawn, showing deviations from weighted mean, and associated uncertainties. Also shown is the Birge ratio for this data set, R_B ,and the individual E_n values.

500 mm S/N AA/71001						
LAB	x_i (µm)	$u_c(x_i)$ (µm)	w_i	$x_i - x_w$	$u(x_i - x_w)$ (µm)	$E_{n\,(k=2)}$
NPL	0.081	0.038	0.079	0.040	0.036	0.553
SMD	0.085	0.124	0.007	0.044	0.124	0.179
NMi	0.013	0.051	0.044	-0.028	0.050	-0.278
MIKES	0.027	0.026	0.168	-0.014	0.024	-0.289
SP	0.043	0.035	0.093	0.002	0.033	0.035
BEV2	0.218	0.189	0.003	0.177	0.189	0.470
METAS	0.016	0.047	0.051	-0.025	0.046	-0.270
CEM2	0.330	0.080	0.000	0.289	0.079	1.824
IMGC	0.085	0.033	0.104	0.044	0.031	0.709
PTB	0.040	0.019	0.315	-0.001	0.016	-0.022
UME	-0.007	0.079	0.018	-0.048	0.078	-0.305
NCM	-0.070	0.076	0.020	-0.111	0.075	-0.736
NML2	-0.320	0.390	0.001	-0.361	0.390	-0.463
CMI	0.004	0.041	0.068	-0.037	0.040	-0.463
SMU	0.108	0.080	0.018	0.067	0.079	0.424
OMH	0.170	0.230	0.002	0.129	0.230	0.281
INM	0.040	0.242	0.002	-0.001	0.242	-0.001
GUM	0.041	0.240	0.002	0.000	0.240	0.001
VMC	-0.080	0.437	0.001	-0.121	0.437	-0.138
LNMC	0.170	0.270	0.002	0.129	0.270	0.240
MIRS	0.090	0.300	0.001	0.049	0.300	0.082
LNE	0.140	0.220	0.002	0.099	0.220	0.226
weighted mean, x_w	0.041					
C	1.136E-04					
$u_{int}(x_w)$	0.011					
$u_{ext}(x_w)$	0.008					
R_B	0.707					

Table 12(b) Data analysis for measurements of the 500 mm gauge block, S/N AA/71001, with data from one participant excluded from the weighted mean as an outlier and one result withdrawn, showing deviations from weighted mean, and associated uncertainties. Also shown is the Birge ratio for this data set, R_B ,and the individual E_n values.

500 mm S/N 500 B						
LAB	x_i (µm)	$u_c(x_i)$ (µm)	w_i	$x_i - x_w$	$u(x_i - x_w)$ (µm)	$E_{n\,(k=2)}$
NPL	1.632	0.038	0.138	0.033	0.035	0.468
SMD	1.565	0.123	0.013	-0.034	0.122	-0.139
NMi	1.577	0.051	0.077	-0.022	0.049	-0.224
MIKES	1.618	0.026	0.295	0.019	0.022	0.436
SP	1.610	0.035	0.163	0.011	0.032	0.172
BEV2	1.777	0.189	0.006	0.178	0.188	0.472
METAS	1.590	0.046	0.094	-0.009	0.044	-0.103
CEM	1.490	0.080	0.031	-0.109	0.079	-0.692
IMGC	1.563	0.033	0.183	-0.036	0.030	-0.603
PTB	1.478	0.036	0.000	-0.121	0.033	-1.827
weighted mean, x_w	1.599					
C	1.994E-04					
$u_{int}(x_w)$	0.014					
$u_{ext}(x_w)$	0.011					
R_B	0.790					

Table 12(c) Data analysis for measurements of the 500 mm gauge block, S/N 500 B, with data from one participant excluded from the weighted mean as an outlier and one result withdrawn, showing deviations from weighted mean, and associated uncertainties. Also shown is the Birge ratio for this data set, R_B ,and the individual E_n values.

900 mm S/N EM/718						
LAB	x_i (μm)	$u_c(x_i)$ (μm)	w_i	x_i - x_w	$u(x_i - x_w)$ (μm)	$E_{n\ (k=2)}$
NPL	-70.015	0.052	0.167	0.046	0.047	0.484
SMD	-70.120	0.188	0.013	-0.059	0.187	-0.158
NMi	-70.133	0.091	0.055	-0.072	0.088	-0.407
MIKES	-70.080	0.041	0.269	-0.019	0.035	-0.272
SP	-70.072	0.058	0.135	-0.011	0.054	-0.103
BEV2	-69.793	0.284	0.006	0.268	0.283	0.473
METAS	-70.058	0.077	0.076	0.003	0.074	0.020
CEM	-70.110	0.140	0.023	-0.049	0.138	-0.177
IMGC	-70.049	0.042	0.257	0.012	0.036	0.164
PTB	-70.156	0.042	0.000	-0.095	0.036	-1.313
weighted mean, x_w	-70.061					
C	4.525E-04					
$u_{int}(x_w)$	0.021					
$u_{ext}(x_w)$	0.012					
R_B	0.563					

Table 12(d) Data analysis for measurements of the 900 mm gauge block, S/N EM/718, with data from one participant excluded from the weighted mean as an outlier and one result withdrawn, showing deviations from weighted mean, and associated uncertainties. Also shown is the Birge ratio for this data set, R_B ,and the individual E_n values.

500 mm S/N 4 PTB 55						
LAB	x_i (μm)	$u_c(x_i)$ (μm)	w_i	x_i - x_w	$u(x_i - x_w)$ (μm)	$E_{n\ (k=2)}$
PTB	-2.450	0.018	0.555	0.019	0.012	0.792
NPL	-2.445	0.038	0.125	0.025	0.036	0.345
UME	-2.484	0.079	0.029	-0.015	0.078	-0.096
NCM	-2.674	0.075	0.000	-0.205	0.074	-1.389
IMGC	-2.534	0.033	0.165	-0.065	0.030	-1.078
NML2	-2.550	0.390	0.001	-0.081	0.390	-0.104
CMI	-2.518	0.041	0.107	-0.049	0.039	-0.632
SMU4	-2.370	0.102	0.000	0.099	0.101	0.490
OMH	-2.210	0.230	0.003	0.259	0.230	0.564
INM	-2.310	0.243	0.003	0.159	0.243	0.328
GUM	-2.438	0.250	0.003	0.031	0.250	0.062
VMC	-1.930	0.437	0.001	0.539	0.437	0.617
LNMC	-2.030	0.270	0.002	0.439	0.270	0.814
MIRS	-2.470	0.300	0.002	-0.001	0.300	-0.002
LNE	-2.510	0.220	0.004	-0.041	0.220	-0.093
weighted mean, x_w	-2.469					
C	1.798E-04					
$u_{int}(x_w)$	0.013					
$u_{ext}(x_w)$	0.013					
R_B	0.957					

Table 12(e) Data analysis for measurements of the 500 mm gauge block, S/N 4 PTB 55, with data from 2 participants excluded from the weighted mean as outliers, showing deviations from weighted mean, and associated uncertainties. Also shown is the Birge ratio for this data set, R_B ,and the individual E_n values.

900 mm S/N PTB 5.13 11/2001						
LAB	x_i (µm)	$u_c(x_i)$ (µm)	w_i	$x_i - x_w$	$u(x_i - x_w)$ (µm)	$E_{n\ (k=2)}$
PTB	0.685	0.025	0.526	0.007	0.017	0.197
NPL	0.748	0.052	0.122	0.070	0.049	0.716
UME	0.664	0.137	0.018	-0.014	0.136	-0.052
NCM	0.226	0.136	0.000	-0.452	0.135	-1.677
IMGC	0.620	0.042	0.186	-0.058	0.038	-0.768
CMI	0.649	0.055	0.109	-0.029	0.052	-0.281
SMU	0.741	0.109	0.028	0.063	0.107	0.292
OMH	0.480	0.390	0.002	-0.198	0.390	-0.254
INM	0.560	0.443	0.002	-0.118	0.443	-0.134
GUM	0.968	0.460	0.002	0.290	0.460	0.315
VMC	0.540	0.688	0.001	-0.138	0.688	-0.100
LNMC	0.660	0.380	0.002	-0.018	0.380	-0.024
MIRS	1.130	0.500	0.001	0.452	0.500	0.452
LNE	0.750	0.350	0.003	0.072	0.350	0.103
weighted mean, x_w	0.678					
C	3.287E-04					
$u_{int}(x_w)$	0.018					
$u_{ext}(x_w)$	0.012					
R_B	0.657					

Table 12(f) Data analysis for measurements of the 900 mm gauge block, S/N PTB 5.13 11/2001, with data from one participant excluded from the weighted mean as an outlier, showing deviations from weighted mean, and associated uncertainties. Also shown is the Birge ratio for this data set, R_B ,and the individual E_n values.

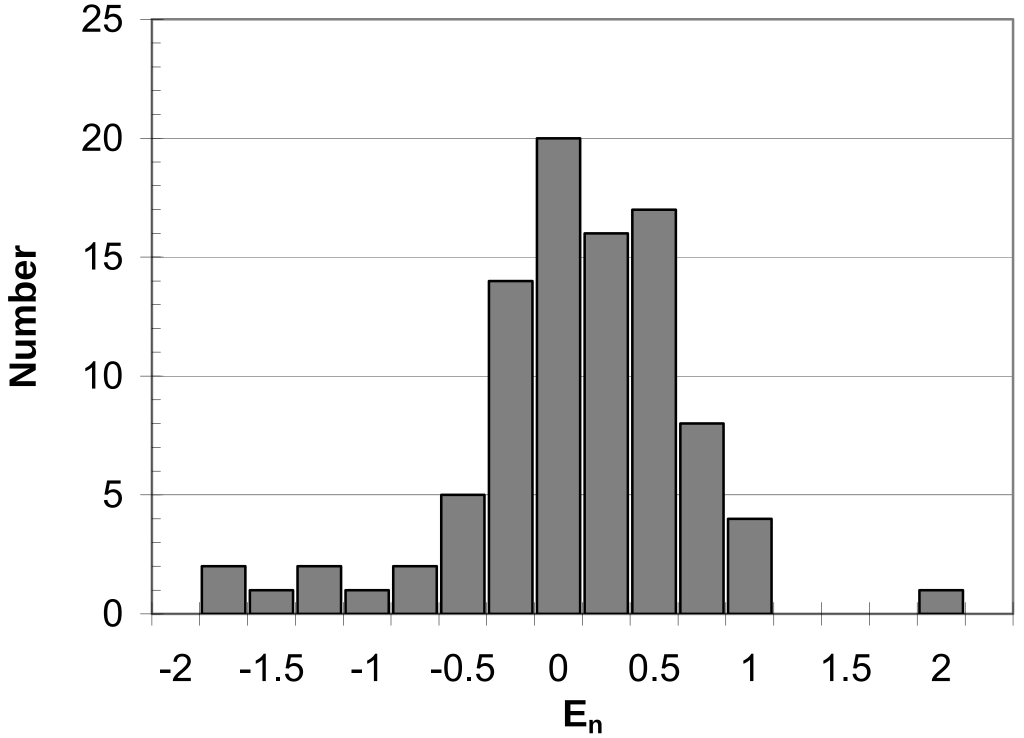


Figure 8 Histogram of E_n values (at k = 2) from the dataset of deviation from weighted mean, based on measurement results and standard uncertainties reported by the participants, after withdrawal of 4 results and zero weighting of 7 outlier results (94 results remaining).

Examination of Tables 12(a) though 12(f) shows that the Birge ratios for the six sets of data have all decreased and are all below the critical values of 1.07, 1.33 and 1.34, re-calculated according to formula (10) in §8.3, with reduced participant numbers of 22, 15 and 10, respectively. Based on the Birge ratios, it appears that overall, the uncertainty estimates are now in better agreement with the observed spread in data, with a possible over-estimation of some uncertainties.

Examination of the data underlying Figure 8 indicates that for 86 of the remaining 94 results, *i.e*. 91%, the E_n ratio (at k = 2) has a magnitude less than or equal to 1. This compares favourably with the expectation of 95% of the results being within the stated uncertainties, at k = 2. Figure 8 also shows that the mean of the E_n values is close to zero (actually –0.022), the median is –0.002.

A summary of all of the measurement data is represented in Figure 9, as deviation from weighted means (it is difficult to include uncertainty bars in this plot).

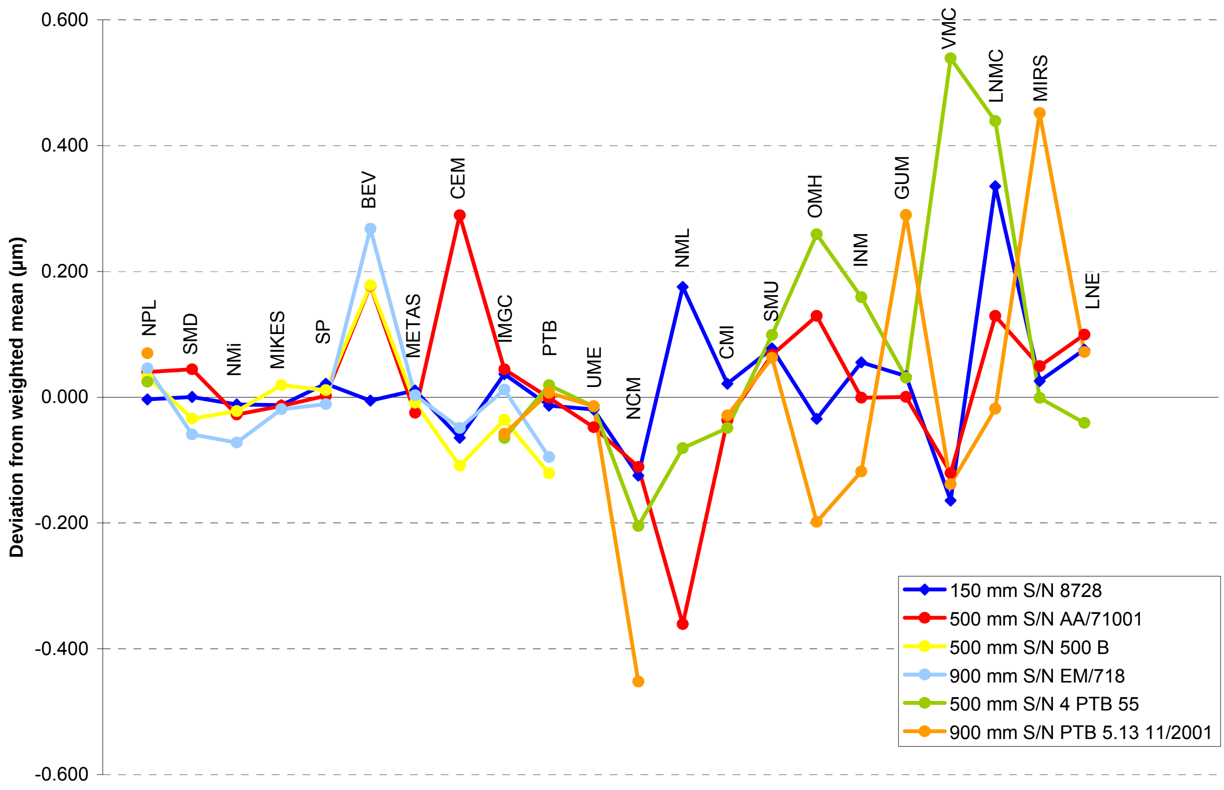


Figure 9 Laboratory deviations from weighted means.

8.7 Discussion of results

Excluding outliers, the total spread of the whole set of results, over the four gauge blocks is about 600 nm, with most of the participants reporting results which agree within ± 200 nm, which represents good agreement for relatively long dimensional artefact calibrations. In some part, this may be due to the availability of pre-determined thermal expansion coefficients for the artefacts. For example, one 900 mm gauge block had a nominal expansion coefficient (according to ISO 3650) of 11.5 ± 0.5 x 10^{-6} K^{-1} whereas its determined value was 10.943 x 10^{-6} K^{-1}, a difference of 0.557 x 10^{-6} K^{-1}. For the laboratories which reported the largest temperature deviation from 20 °C of up to 1.25 °C, this difference could have contributed an additional error of 626 nm. Future comparisons should take this into account, and pre-determined values of parameters such as thermal expansion coefficient should not be routinely available, if the purpose of the key comparison is to test participants' ability to measure 'unknown' artefacts from customers.

With regard to Figure 9, there may be evidence for systematic deviations of several laboratories, with respect to each other. Whilst the variations in the results for each particular laboratory are generally within the specified uncertainties (which are difficult to show clearly in the graph), there are some possible trends which can be observed. For example, laboratories NPL, BEV and SMU generally measure longer, whereas laboratories PTB, METAS, CEM, NCM, and VMC generally measure shorter. These differences may be due to factors such as phase correction determination or compensation of the support position, vertical rather than horizontal measurement, refractive index determination or wringing effects. These are now examined.

8.7.1 Phase correction

Although the specification standard ISO 3650 requires that “*Corrections shall be made to the calculations for significant influences; e.g. : … surface texture and optical phase changes on the reflection of the light wave*”, *i.e.* the so called ‘phase correction’, only one participant (PTB) fully performed this correction (SMD used pre-determined phase values). Some other participants were not able to perform experiments to determine this correction and, instead, made no correction but expanded their uncertainty to take this into account. These laboratories reported that this was the usual procedure at their institutes when offering this measurement service for customers. Other laboratories making measurements by mechanical comparison would have used calibrated master gauge blocks as their length traceability reference. In theory, the calibration results for these standard gauge blocks should already been corrected for phase changes, by the laboratory making the reference calibration. However, the report for key comparison CCL-K2 showed that only 3 of its 12 participant laboratories make a phase correction, so it is possible that biases due to phase change could be present in the results of some participants in this EUROMET comparison, due to their reliance on reference calibrations from other NMIs. However, for the majority of the participants in this EUROMET comparison, the size of the phase correction is quite small compared with other sources of uncertainty.

8.7.2 Vertical or horizontal measurement

Only the 150 mm gauge block was measured vertically, by three laboratories (SMD, BEV, CMI). None directly reported making a correction from the vertical to horizontal states, however theory predicts the correction to be only 4 nm. The results of the three laboratories which made measurements with the gauges standing vertically are very close to the reference value line. Subsequently SMD confirmed it had indeed made a 4.23 nm correction, but had not mentioned this, as it was normal procedure. The effect is minimal.

8.7.3 Compensation of platen weight

Four participants reported that the weight of the platen was compensated by a counterbalance system, whereas four other participants moved the supports instead. Both sets of participants are equally distributed above and below the reference line.

8.7.4 Compensation for refractive index

There is no observed correlation between reported result and the method used to determine the refractive index correction.

8.8 Further discussion

Figure 9 shows information about the measurements of all six gauge blocks, linked through the determined weighted means, allowing some analysis of length dependent and length independent errors. The fact that the coefficient of thermal expansion was given for all four gauge blocks means one of the largest length dependent sources of error has been significantly reduced. Other potentially large length dependent error sources for those using interferometric measurement techniques are also well controlled: use of standard and well known equations for refractive index determination, stabilized laser sources for measurement wavelengths. This is reflected in the clustering of data in Figure 9, where deviations from weighted mean values are, for many participants that used interferometry, grouped in clusters spanning approximately 50 nm, or less. However the centres of the clusters differ from each other by more than 50 nm, in many cases, indicating uncontrolled length independent errors. There may also be indications of uncontrolled length dependent errors for one or two participants.

8.9 Normalised differences between laboratories

Because there is some question concerning the correctness of choosing a reference value when it is suspected that there may be non-symmetrically distributed uncorrected biases in some results, e.g. phase correction, an alternative analysis is to examine only normalised differences between laboratories’ results. The normalised difference takes into account the fact that the uncertainties of the two laboratories are uncorrelated and therefore the normalised difference between laboratories i and j, is given by

$$\hat{d}_{ij} = \frac{x_i - x_j}{\sqrt{[u(x_i)]^2 + [u(x_j)]^2}} \tag{11}$$

These values are given, for information, in Tables 13(a) though 13(f). A value with magnitude less than 2 indicates the differences are commensurate with the stated uncertainties, for a k = 2 coverage factor.

150 mm S/N 8728																						
	NPL	SMD	NMi	MIKES	SP	BEV2	METAS	CEM	IMGC	PTB	UME	NCM	NML	CMI	SMU	OMH	INM	GUM	VMC	LNMC	MIRS	LNE
NPL	0.00	0.11	-0.13	-0.26	0.71	-0.03	0.38	-1.22	0.97	-0.29	-0.42	-2.76	1.71	0.60	1.09	-0.20	0.48	0.26	-1.07	1.76	0.22	0.55
SMD	-0.11	0.00	-0.21	-0.51	0.80	-0.09	0.35	-1.47	1.06	-0.56	-0.65	-3.36	1.72	0.61	1.09	-0.23	0.45	0.23	-1.11	1.75	0.19	0.53
NMi	0.23	0.46	0.00	-0.04	1.30	0.09	0.80	-1.21	1.44	-0.08	-0.27	-3.08	1.84	0.97	1.27	-0.15	0.55	0.32	-1.03	1.82	0.28	0.62
MIKES	0.26	0.51	0.02	0.00	1.37	0.10	0.85	-1.20	1.50	-0.04	-0.24	-3.09	1.85	1.01	1.28	-0.15	0.56	0.33	-1.02	1.82	0.29	0.62
SP	-0.71	-0.80	-0.57	-1.37	0.00	-0.40	-0.40	-1.96	0.45	-1.45	-1.37	-3.98	1.52	0.00	0.80	-0.37	0.28	0.09	-1.25	1.65	0.03	0.38
BEV2	0.03	0.09	-0.07	-0.10	0.40	0.00	0.23	-0.77	0.59	-0.12	-0.20	-1.64	1.52	0.38	0.88	-0.18	0.45	0.25	-0.98	1.70	0.21	0.52
METAS	-0.38	-0.35	-0.37	-0.85	0.40	-0.23	0.00	-1.66	0.74	-0.91	-0.94	-3.53	1.61	0.31	0.94	-0.30	0.37	0.16	-1.17	1.70	0.11	0.46
CEM	1.22	1.47	0.78	1.20	1.96	0.77	1.66	0.00	2.07	1.18	0.96	-1.17	2.23	1.74	1.80	0.19	0.95	0.67	-0.65	2.06	0.66	0.96
IMGC	-0.97	-1.06	-0.78	-1.50	-0.45	-0.59	-0.74	-2.07	0.00	-1.55	-1.52	-3.79	1.34	-0.37	0.56	-0.47	0.15	-0.02	-1.33	1.56	-0.08	0.27
PTB	0.29	0.56	0.03	0.04	1.45	0.12	0.91	-1.18	1.55	0.00	-0.21	-3.10	1.87	1.06	1.30	-0.14	0.57	0.33	-1.01	1.83	0.30	0.63
UME	0.42	0.65	0.13	0.24	1.37	0.20	0.94	-0.96	1.52	0.21	0.00	-2.63	1.90	1.09	1.35	-0.10	0.61	0.37	-0.97	1.85	0.34	0.67
NCM	2.76	3.36	1.78	3.09	3.98	1.64	3.53	1.17	3.79	3.10	2.63	0.00	2.86	3.38	2.69	0.59	1.45	1.10	-0.26	2.39	1.12	1.39
NML2	-1.71	-1.72	-1.64	-1.85	-1.52	-1.52	-1.61	-2.23	-1.34	-1.87	-1.90	-2.86	0.00	-1.48	-0.81	-1.16	-0.77	-0.83	-1.90	0.75	-0.91	-0.58
CMI	-0.60	-0.61	-0.53	-1.01	0.00	-0.38	-0.31	-1.74	0.37	-1.06	-1.09	-3.38	1.48	0.00	0.76	-0.37	0.28	0.08	-1.23	1.63	0.03	0.38
SMU	-1.09	-1.09	-1.02	-1.28	-0.80	-0.88	-0.94	-1.80	-0.56	-1.30	-1.35	-2.69	0.81	-0.76	0.00	-0.68	-0.16	-0.28	-1.49	1.28	-0.35	-0.01
OMH	0.20	0.23	0.14	0.15	0.37	0.18	0.30	-0.19	0.47	0.14	0.10	-0.59	1.16	0.37	0.68	0.00	0.47	0.33	-0.62	1.53	0.30	0.54
INM	-0.48	-0.45	-0.51	-0.56	-0.28	-0.45	-0.37	-0.95	-0.15	-0.57	-0.61	-1.45	0.77	-0.28	0.16	-0.47	0.00	-0.12	-1.15	1.25	-0.17	0.11
GUM	-0.26	-0.23	-0.30	-0.33	-0.09	-0.25	-0.16	-0.67	0.02	-0.33	-0.37	-1.10	0.83	-0.08	0.28	-0.33	0.12	0.00	-0.97	1.28	-0.04	0.21
VMC	1.07	1.11	0.97	1.02	1.25	0.98	1.17	0.65	1.33	1.01	0.97	0.26	1.90	1.23	1.49	0.62	1.15	0.97	0.00	2.08	0.96	1.18
LNMC	-1.76	-1.75	-1.75	-1.82	-1.65	-1.70	-1.70	-2.06	-1.56	-1.83	-1.85	-2.39	-0.75	-1.63	-1.28	-1.53	-1.25	-1.28	-2.08	0.00	-1.35	-1.10
MIRS	-0.22	-0.19	-0.26	-0.29	-0.03	-0.21	-0.11	-0.66	0.08	-0.30	-0.34	-1.12	0.91	-0.03	0.35	-0.30	0.17	0.04	-0.96	1.35	0.00	0.26
LNE	-0.55	-0.53	-0.58	-0.62	-0.38	-0.52	-0.46	-0.96	-0.27	-0.63	-0.67	-1.39	0.58	-0.38	0.01	-0.54	-0.11	-0.21	-1.18	1.10	-0.26	0.00

500 mm S/N AA/71001																						
	NPL	SMD	NMi	MIKES	SP	BEV2	METAS	CEM2	IMGC	PTB	UME	NCM	NML	CMI	SMU	OMH	INM	GUM	VMC	LNMC	MIRS	LNE
NPL	0.00	0.03	-0.52	-1.17	-0.74	0.71	-1.08	2.81	0.08	-0.97	-1.00	-1.78	-1.02	-1.38	0.30	0.38	-0.17	-0.16	-0.37	0.33	0.03	0.26
SMD	-0.03	0.00	-0.41	-0.46	-0.33	0.59	-0.52	1.66	0.00	-0.36	-0.63	-1.07	-0.99	-0.62	0.16	0.33	-0.17	-0.16	-0.36	0.29	0.02	0.22
NMi	1.07	0.54	0.00	0.24	0.49	1.05	0.04	3.34	1.19	0.50	-0.21	-0.91	-0.85	-0.14	1.00	0.67	0.11	0.11	-0.21	0.57	0.25	0.56
MIKES	1.17	0.46	-0.11	0.00	0.37	1.00	-0.20	3.60	1.38	0.40	-0.41	-1.21	-0.89	-0.47	0.96	0.62	0.05	0.06	-0.24	0.53	0.21	0.51
SP	0.74	0.33	-0.23	-0.37	0.00	0.91	-0.46	3.29	0.87	-0.08	-0.58	-1.35	-0.93	-0.72	0.74	0.55	-0.01	-0.01	-0.28	0.47	0.16	0.44
BEV2	-0.71	-0.59	-0.90	-1.00	-0.91	0.00	-1.04	0.55	-0.69	-0.94	-1.10	-1.41	-1.24	-1.11	-0.54	-0.16	-0.58	-0.58	-0.63	-0.15	-0.36	-0.27
METAS	1.08	0.52	-0.02	0.20	0.46	1.04	0.00	3.38	1.20	0.47	-0.25	-0.96	-0.86	-0.19	0.99	0.66	0.10	0.10	-0.22	0.56	0.24	0.55
CEM2	-2.81	-1.66	-2.14	-3.60	-3.29	-0.55	-3.38	0.00	-2.83	-3.53	-3.00	-3.62	-1.63	-3.63	-1.96	-0.66	-1.14	-1.14	-0.92	-0.57	-0.77	-0.81
IMGC	-0.08	0.00	-0.56	-1.38	-0.87	0.69	-1.20	2.83	0.00	-1.18	-1.07	-1.87	-1.03	-1.54	0.27	0.37	-0.18	-0.18	-0.38	0.31	0.02	0.25
PTB	0.97	0.36	-0.21	-0.40	0.08	0.94	-0.47	3.53	1.18	0.00	-0.58	-1.40	-0.92	-0.80	0.83	0.56	0.00	0.00	-0.27	0.48	0.17	0.45
UME	1.00	0.63	0.14	0.41	0.58	1.10	0.25	3.00	1.07	0.58	0.00	-0.57	-0.79	0.12	1.02	0.73	0.18	0.19	-0.16	0.63	0.31	0.63
NCM	1.78	1.07	0.57	1.21	1.35	1.41	0.96	3.62	1.87	1.40	0.57	0.00	-0.63	0.86	1.61	0.99	0.43	0.44	-0.02	0.86	0.52	0.90
NML2	1.02	0.99	0.81	0.89	0.93	1.24	0.86	1.63	1.03	0.92	0.79	0.63	0.00	0.83	1.08	1.08	0.78	0.79	0.41	1.03	0.83	1.03
CMI	1.38	0.62	0.07	0.47	0.72	1.11	0.19	3.63	1.54	0.80	-0.12	-0.86	-0.83	0.00	1.16	0.71	0.15	0.15	-0.19	0.61	0.28	0.61
SMU	-0.30	-0.16	-0.64	-0.96	-0.74	0.54	-0.99	1.96	-0.27	-0.83	-1.02	-1.61	-1.08	-1.16	0.00	0.25	-0.27	-0.26	-0.42	0.22	-0.06	0.14
OMH	-0.38	-0.33	-0.60	-0.62	-0.55	0.16	-0.66	0.66	-0.37	-0.56	-0.73	-0.99	-1.08	-0.71	-0.25	0.00	-0.39	-0.39	-0.51	0.00	-0.21	-0.09
INM	0.17	0.17	-0.10	-0.05	0.01	0.58	-0.10	1.14	0.18	0.00	-0.18	-0.43	-0.78	-0.15	0.27	0.39	0.00	0.00	-0.24	0.36	0.13	0.31
GUM	0.16	0.16	-0.10	-0.06	0.01	0.58	-0.10	1.14	0.18	0.00	-0.19	-0.44	-0.79	-0.15	0.26	0.39	0.00	0.00	-0.24	0.36	0.13	0.30
VMC	0.37	0.36	0.20	0.24	0.28	0.63	0.22	0.92	0.38	0.27	0.16	0.02	-0.41	0.19	0.42	0.51	0.24	0.24	0.00	0.49	0.32	0.45
LNMC	-0.33	-0.29	-0.53	-0.53	-0.47	0.15	-0.56	0.57	-0.31	-0.48	-0.63	-0.86	-1.03	-0.61	-0.22	0.00	-0.36	-0.36	-0.49	0.00	-0.20	-0.09
MIRS	-0.03	-0.02	-0.24	-0.21	-0.16	0.36	-0.24	0.77	-0.02	-0.17	-0.31	-0.52	-0.83	-0.28	0.06	0.21	-0.13	-0.13	-0.32	0.20	0.00	0.13
LNE	-0.26	-0.22	-0.50	-0.51	-0.44	0.27	-0.55	0.81	-0.25	-0.45	-0.63	-0.90	-1.03	-0.61	-0.14	0.09	-0.31	-0.30	-0.45	0.09	-0.13	0.00

500 mm S/N 500 B										
	NPL	SMD	NMi	MIKES	SP	BEV2	METAS	CEM	IMGC	PTB
NPL	0.00	-0.52	-0.42	-0.30	-0.43	0.75	-0.70	-1.60	-1.37	-2.94
SMD	0.52	0.00	0.07	0.42	0.35	0.94	0.19	-0.51	-0.02	-0.68
NMi	0.86	-0.09	0.00	0.72	0.53	1.02	0.19	-0.92	-0.23	-1.59
MIKES	0.30	-0.42	-0.32	0.00	-0.18	0.83	-0.53	-1.52	-1.31	-3.15
SP	0.43	-0.35	-0.25	0.18	0.00	0.87	-0.35	-1.37	-0.98	-2.63
BEV2	-0.75	-0.94	-0.88	-0.83	-0.87	0.00	-0.96	-1.40	-1.12	-1.55
METAS	0.70	-0.19	-0.10	0.53	0.35	0.96	0.00	-1.08	-0.48	-1.92
CEM	1.60	0.51	0.59	1.52	1.37	1.40	1.08	0.00	0.84	-0.14
IMGC	1.37	0.02	0.11	1.31	0.98	1.12	0.48	-0.84	0.00	-1.74
PTB	2.94	0.68	0.76	3.15	2.63	1.55	1.92	0.14	1.74	0.00

	900 mm S/N EM/718									
	NPL	**SMD**	**NMi**	**MIKES**	**SP**	**BEV2**	**METAS**	**CEM**	**IMGC**	**PTB**
NPL	0.00	-0.54	-0.56	-0.98	-0.73	0.77	-0.46	-0.64	-0.51	-2.11
SMD	0.54	0.00	-0.05	0.21	0.24	0.96	0.31	0.04	0.37	-0.19
NMi	1.13	0.06	0.00	0.53	0.57	1.14	0.63	0.14	0.84	-0.23
MIKES	0.98	-0.21	-0.25	0.00	0.11	1.00	0.25	-0.21	0.53	-1.29
SP	0.73	-0.24	-0.29	-0.11	0.00	0.96	0.15	-0.25	0.32	-1.17
BEV2	-0.77	-0.96	-0.97	-1.00	-0.96	0.00	-0.90	-1.00	-0.89	-1.26
METAS	0.46	-0.31	-0.34	-0.25	-0.15	0.90	0.00	-0.33	0.10	-1.12
CEM	0.64	-0.04	-0.09	0.21	0.25	1.00	0.33	0.00	0.42	-0.31
IMGC	0.51	-0.37	-0.40	-0.53	-0.32	0.89	-0.10	-0.42	0.00	-1.80
PTB	2.11	0.19	0.11	1.29	1.17	1.26	1.12	0.31	1.80	0.00

	500 mm S/N 4 PTB 55														
	PTB	**NPL**	**UME**	**NCM**	**IMGC**	**NML**	**CMI**	**SMU4**	**OMH**	**INM**	**GUM**	**VMC**	**LNMC**	**MIRS**	**LNE**
PTB	0.00	0.13	-0.42	-2.90	-2.23	-0.26	-1.52	0.77	1.04	0.57	0.05	1.19	1.55	-0.07	-0.27
NPL	-0.13	0.00	-0.45	-2.73	-1.78	-0.27	-1.31	0.68	1.01	0.55	0.03	1.17	1.52	-0.08	-0.29
UME	0.42	0.45	0.00	-1.74	-0.58	-0.17	-0.38	0.88	1.13	0.68	0.18	1.25	1.61	0.05	-0.11
NCM	2.90	2.73	1.74	0.00	1.71	0.31	1.83	2.40	1.92	1.43	0.90	1.68	2.30	0.66	0.71
IMGC	2.23	1.78	0.58	-1.71	0.00	-0.04	0.30	1.53	1.39	0.91	0.38	1.38	1.85	0.21	0.11
NML2	0.26	0.27	0.17	-0.31	0.04	0.00	0.08	0.45	0.75	0.52	0.24	1.06	1.10	0.16	0.09
CMI	1.52	1.31	0.38	-1.83	-0.30	-0.08	0.00	1.35	1.32	0.84	0.32	1.34	1.79	0.16	0.04
SMU4	-0.77	-0.68	-0.88	-2.40	-1.53	-0.45	-1.35	0.00	0.64	0.23	-0.25	0.98	1.18	-0.32	-0.58
OMH	-1.04	-1.01	-1.13	-1.92	-1.39	-0.75	-1.32	-0.64	0.00	-0.30	-0.67	0.57	0.51	-0.69	-0.94
INM	-0.57	-0.55	-0.68	-1.43	-0.91	-0.52	-0.84	-0.23	0.30	0.00	-0.37	0.76	0.77	-0.41	-0.61
GUM	-0.05	-0.03	-0.18	-0.90	-0.38	-0.24	-0.32	0.25	0.67	0.37	0.00	1.01	1.11	-0.08	-0.22
VMC	-1.19	-1.17	-1.25	-1.68	-1.38	-1.06	-1.34	-0.98	-0.57	-0.76	-1.01	0.00	-0.19	-1.02	-1.19
LNMC	-1.55	-1.52	-1.61	-2.30	-1.85	-1.10	-1.79	-1.18	-0.51	-0.77	-1.11	0.19	0.00	-1.09	-1.38
MIRS	0.07	0.08	-0.05	-0.66	-0.21	-0.16	-0.16	0.32	0.69	0.41	0.08	1.02	1.09	0.00	-0.11
LNE	0.27	0.29	0.11	-0.71	-0.11	-0.09	-0.04	0.58	0.94	0.61	0.22	1.19	1.38	0.11	0.00

	900 mm S/N PTB 5.13 11/2001													
	PTB	**NPL**	**UME**	**NCM**	**IMGC**	**CMI**	**SMU**	**OMH**	**INM**	**GUM**	**VMC**	**LNMC**	**MIRS**	**LNE**
PTB	0.00	1.09	-0.15	-3.32	-1.33	-0.60	0.50	-0.52	-0.28	0.61	-0.21	-0.07	0.89	0.19
NPL	-1.09	0.00	-0.57	-3.59	-1.91	-1.31	-0.06	-0.68	-0.42	0.48	-0.30	-0.23	0.76	0.01
UME	0.15	0.57	0.00	-2.27	-0.31	-0.10	0.44	-0.45	-0.22	0.63	-0.18	-0.01	0.90	0.23
NCM	3.32	3.59	2.27	0.00	2.77	2.88	2.95	0.61	0.72	1.55	0.45	1.08	1.74	1.40
IMGC	1.33	1.91	0.31	-2.77	0.00	0.42	1.04	-0.36	-0.13	0.75	-0.12	0.10	1.02	0.37
CMI	0.60	1.31	0.10	-2.88	-0.42	0.00	0.75	-0.43	-0.20	0.69	-0.16	0.03	0.96	0.29
SMU	-0.50	0.06	-0.44	-2.95	-1.04	-0.75	0.00	-0.64	-0.40	0.48	-0.29	-0.20	0.76	0.02
OMH	0.52	0.68	0.45	-0.61	0.36	0.43	0.64	0.00	0.14	0.81	0.08	0.33	1.03	0.52
INM	0.28	0.42	0.22	-0.72	0.13	0.20	0.40	-0.14	0.00	0.64	-0.02	0.17	0.85	0.34
GUM	-0.61	-0.48	-0.63	-1.55	-0.75	-0.69	-0.48	-0.81	-0.64	0.00	-0.52	-0.52	0.24	-0.38
VMC	0.21	0.30	0.18	-0.45	0.12	0.16	0.29	-0.08	0.02	0.52	0.00	0.15	0.69	0.27
LNMC	0.07	0.23	0.01	-1.08	-0.10	-0.03	0.20	-0.33	-0.17	0.52	-0.15	0.00	0.75	0.17
MIRS	-0.89	-0.76	-0.90	-1.74	-1.02	-0.96	-0.76	-1.03	-0.85	-0.24	-0.69	-0.75	0.00	-0.62
LNE	-0.19	-0.01	-0.23	-1.40	-0.37	-0.29	-0.02	-0.52	-0.34	0.38	-0.27	-0.17	0.62	0.00

Tables 13(a) to 13(f) Normalised differences between laboratories' results. Yellow shading indicates |normalised difference| > 2, indicating non-equivalence at 95% confidence level.

9 Conclusions

From the EUROMET.L-K2 long gauge block key comparison, the following conclusions can be drawn:

- From the start of the comparison, the time taken to perform all the measurements, including transportation, was much longer than originally planned, namely 38 months (27 originally planned). The timetable was adjusted after the end of the first loop to allow for characterisation and preparation of two replacement gauge blocks. This caused a delay of about 1 year between the two loops.

- The CCL linking laboratories (NPL, PTB and IMGC) had an excessive work load in this comparison due to the necessity to measure not only the initial set of four gauge blocks, but also the two replacement gauges. There was also a need to link the two loops by repeated measurement of some gauge blocks. These laboratories are thanked for their efforts and perseverance in bringing this comparison to a conclusion.

- Both 900 mm gauge blocks suffered damage during the comparison, as did half of the 500 mm gauge blocks. Future comparisons should be limited to 500 mm maximum length and contain several gauges of long lengths, as ‘spares’, with only some gauges being measured at any one time.

- The decision to organise the participating laboratories into two loops was very reasonable. The majority of the laboratories using interferometry were in loop 1, with the remainder of the participants in loop 2. The intention was to use the same artefacts in both loops, however only half of the artefacts were used in both loops: two gauge blocks were unique to loop 1 and two other gauge blocks were unique to loop 2. This comparison therefore serves as a useful prototype for future EUROMET comparisons where multiple loops are planned, using different artefacts.

- Overall, the comparison has been successful. Considering the large number of participants, with a wide variety of measuring instruments and uncertainties, taking such a long time to complete, it is noteworthy that there were relatively few results which were considered as outliers.

- One participant withdrew their results (equipment still being developed at the time) and three participants modified their results after initial submission (these happened before the Draft A report was prepared).

- The close agreement of many results may be due to the inclusion in the protocol document of pre-determined values for the linear coefficient of thermal expansion for the supplied gauge blocks. This allowed laboratories to make accurate corrections for any measurements performed at temperatures away from the standard temperature of 20 °C. Whilst this helps ensure a uniformity of results, it does not reflect a typical measurement for a customer, where the expansion coefficient is not known by the laboratory other than the nominal value attributed to the gauge block material. Thus the results of this comparison may represent an over-optimistic view of the mutual equivalence of the services offered by the participants. At the September 2000 meeting of the CCL-WGDM it was decided that in any future comparisons, no ‘additional’ data such as thermal expansion coefficients would be supplied. Only data that would normally be available to a customer or calibration laboratory would be included in the protocol document. However the pilot laboratory would perform a check that the artefacts complied with any specification standards, in respect of any such data.

- The reliability of the weighted mean, or other estimators of the true value of the measurands has been discussed. Non-symmetrically distributed, uncorrected biases to some results (phase corrections) are thought to be possible explanations for some laboratories’ differences from each other, particularly for laboratories that made interferometric measurements. When examining deviation of results from weighted mean results, this fact should be taken into account. The use of bilateral comparisons between two laboratories’ results is expected to be more robust, as possible biases of the reference value (weighted mean) have no influence.

- The principal aim of this key comparison has been to determine the degree to which results of measurement of long gauge blocks made by a selection of NMIs can be deemed to be ‘equivalent. This has been tested by measurement of six almost-unknown long gauge blocks, using techniques normally used by each participant for such measurements. This has resulted in a set of data which can be used by the metrology community to gain insight into degrees of equivalence of NMI measurements of long gauge blocks. However one should also try to maximise the scientific value of this comparison, It would be useful for each participant to examine their results and measurement processes in light of this report, and seek explanations for any significant offsets of their results from those of other laboratories.

10 Acknowledgements

The pilot laboratory would like to acknowledge the kind assistance, and willingness to fund the necessary travel, of all the colleagues in the participating laboratories for helping this comparison to run so smoothly. Also beneficial to the successful completion of the comparison was the assistance afforded by all the airlines which were kind enough to allow hand carriage of the gauge case in their aircraft.

Particular thanks are also due to PTB and JV for kindly donating several of the long gauge blocks that were used in this comparison.

The CCL linking laboratories, NPL, PTB and IMGC are gratefully thanked for their additional work undertaken to cope with replacement of half of the travelling standards of the comparison.

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11 References

[1] CIPM, Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes, 1999, BIPM.

[2] A. Lewis, National Physical Laboratory (NPL), Technical Protocol document, key comparison CCL-K2 (2001).

[3] A. Lewis, CCL-K2: Long gauge block measurement by interferometry: Final Report, 2003 *Metrologia* **40** 04004.

[4] A. Lewis, National Physical Laboratory (NPL), Technical Protocol document, key comparison EUROMET.L-K2 (2002), and revision (2004).

[5] J. E. Decker and J.R. Pekelsky, Uncertainty Evaluation for the Measurement of Gauge Blocks by Optical Interferometry, *Metrologia* **34,** 479-493 (1997).

[6] A. J. Lewis, Measurement of length, surface form and thermal expansion coefficient of length bars up to 1.5 m using multiple-wavelength phase-stepping interferometry, *Meas. Sci. Technol*., **5**, 694-703 (1994).

[7] E. Ikonen & K. Riski, Gauge block interferometer based on one stabilized laser and a white light source, *Metrologia*, **30**, 95-104 (1993).

[8] H. Darnedde, High-precision calibration of long gauge blocks using the vacuum wavelength comparator, *Metrologia,* **29**, 349-359 (1992).

[9] B. Edlen, The refractive index of air, *Metrologia*, **2**, 71-80 (1966).

[10] K. P. Birch & M. J. Downs, Correction to the updated Edlén equation for the refractive index of air, *Metrologia*, **31**, 315-316 (1994).

[11] P. E. Ciddor, Refractive index of air: new equations for the visible and near infrared, *Appl. Opt*., **35**, 1566 –1573 (1996).

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

[13] F. Beyer-Helms, Biegung von Endmaßen bei horizontaler Lagerung auf Scheiden, *PTB Mitteilungen*, 25-30 and 124-130 (1967).

[14] G. Bönsch, Interferometric calibration of an integrating sphere for determination of the roughness correction of gauge blocks, *Proc. SPIE*, **3477**, 152-160 (1998).

[15] D. C. Williams, The parallelism of a length bar with an end load, *J. Sci. Instrum*., **39**, 608-610 (1962).

[16] BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML *Guide to the expression of uncertainty in measurement* (1995)

Appendix 1: Key Comparison Reference Values & their uncertainties

11.1 KCRVs and their uncertainties

In order to satisfy the requirements of the Mutual Recognition Arrangement, the so-called ‘Key Comparison Reference Values’ have been evaluated according to the method described in section 8 of the main document, *i.e.* the weighted mean is determined and the deviations from the weighted mean are then calculated. Data identified as outliers are excluded from the determination of the weighted mean. This method requires that the individual uncertainties from the laboratories were estimated according to a common approach (which should be the case, since all participants were requested to estimate the uncertainties according to the *ISO Guide*). If this is not the case, a single "wrong" value with a strongly underestimated (too small) uncertainty could strongly influence or even fully determine the weighted mean. On the other hand, a high quality measurement with overestimated uncertainty would contribute only a small amount to the reference value. The uncertainty of the weighted mean is based on the internal standard deviation of the contributing results.

Note that the results of the pilot laboratory contribute only once to the calculation of the reference values, namely its official measurement result. This excludes the preliminary, interim and final ‘stability’ measurements of the gauge blocks, performed by the pilot laboratory.

Serial number	Nominal length (mm)	Reference Value (nm)	Uncertainty in Reference Value (nm)
8728	150	-16	7
AA/71001	500	41	11
500B	500	1599	15
4 PTB 55	500	-2469	14
EM/718	900	-70061	22
PTB 5.13 11/2001	900	678	19

Table 14 Key Comparison Reference Values and associated standard uncertainties (in nm). The internal standard deviation is used for determination of the uncertainty. The Key Comparison Reference Values represent the measured deviation from nominal size for the six gauge blocks used in the comparison.

It should be noted that there are several arguments presented in the main text of this report that indicate that the Key Comparison Reference Values may not be totally reliable estimators of the true values of each measurand, due to unknown, non-symmetric bias of some results. Even if such biases could be determined and corrected for, the Key Comparison Reference Values would have no significance in terms of the SI other than as the best estimates of the sizes of the six gauge blocks which were used in this comparison.

11.2 Artefact uncertainties

When calculating the degree of equivalence for each participant, it is necessary to consider additional sources of uncertainty, other than the uncertainty in the KCRV and the participant’s uncertainty. Due to correlations between the participants’ results and the weighted mean, the (k = 2) uncertainty of the difference from the weighted mean is usually given by

$$U(\Delta l) = 2\sqrt{u^2(x_i) - u^2(\overline{x}_{ref})} \qquad (8)$$

where $u(x_i)$ and $u(\overline{x}_{ref})$ are the standard uncertainties of the laboratory result x_i and the reference value $\overline{x}_{ref}$. Although this is statistically correct, it fails to take into account the uncertainties associated with the artefacts, such as stability, accumulation of damage, *etc*. When performing calibrations for customers, these artefact-based errors are not included in any uncertainty analysis as the calibrations only determine ‘on the day’ values’ and no allowance is made for subsequent drift, damage or misuse. However in a comparison such as EUROMET.L-K2 with an extended timescale, and measurements by a relatively large number of laboratories, artefact stability and the effects of damage accumulated during the circulation must be taken into account when comparing participants’ results with the reference values.

This report therefore proposes the use of a third uncertainty component, $u(\bar{x}_{artefact})$, which is estimated from artefact performance in the comparison and other expert knowledge, and is therefore not correlated with the two other uncertainty components.

Possible contributions to the artefact uncertainty are:

- secular change in gauge block central length during the comparison;
- change in gauge block geometry (flatness, variation in length);
- accumulation of damage to wringing surfaces of gauge blocks affecting the wringing property;
- constraints imposed by the comparison (stabilisation timescales etc);
- change in phase correction due to surface wear;
- additional uncertainties, not normally considered significant enough to compensate for (*e.g.* pressure differentials between laboratories).

11.2.1 Secular change in length of gauge block

It is known that gauge blocks can exhibit a change in length, even if left undisturbed (see for example F. H. Rolt, *Gauges and Fine Measurements*, Macmillan, London, (1929), Chapter 10). Although the gauge blocks were specially selected as having a long history of stability, the artefacts of EUROMET.L-K2 have been transported around the world, subject to different temperatures and pressures (in transit) and to mechanical vibration. It is therefore reasonable to expect some change in length of the gauge blocks due to stress relief in the bulk material. The best estimator of this change in length is through the measurements of the pilot laboratory, before, during and after the circulation of the artefacts. The measured changes in length of the four gauge blocks are give in Table 15. It is difficult to estimate the uncertainty of this measurement as it depends on the wringing properties of the surfaces, but the best estimate standard uncertainty is the quadrature sum of ± 7 nm and ± 2×10^{-8} *L*. This is based on the pilot laboratory's measurement uncertainty, taking account of uncertainties which are common to all four measurements.

Serial number	Nominal length (mm)	Change in length (nm)	Standard uncertainty (nm)
8728	**150**	87	8
AA/71001	**500**	35	13
500B	**500**	134	13
4 PTB 55	**500**	20	13
EM/718	**900**	81	20
PTB 5.13 11/2001	**900**	184	20

Table 15 Measured changes in central length, as determined by the pilot laboratory.

All measured apparent changes in length are outside the k = 1 uncertainty of the pilot laboratory and all but 1 are outside the k = 2 uncertainty, i.e. the changes are probably statistically significant. For the purposes of determining the artefact uncertainty, this contribution will be treated as a rectangular distribution, of half width 43.5, 17.5, 67, 10, 40.5 and 82 nm, for the six gauge blocks, resulting in standard uncertainties of 26, 11, 39, 6, 24 and 48 nm, respectively.

11.2.2 Change in gauge block geometry

The changes in central length in section 11.2.1 already include the effect of any changes in surface geometry on central length. Of the two measured parameters, the change in flatness is likely to have the larger effect as it affects the wringing quality. Assuming that the laboratories were able to measure at the centre of the face, those that used a wrung platen will have an error caused by imperfect wringing at the wrung face of the gauge block. Previous work (G. Bönsch, *Proc. SPIE*, **3477**, 199-210 (1998)) has shown a typical error of 12 nm in the central length measurement of a gauge block caused by a flatness error of approximately 70 nm. The largest change in flatness of the six EUROMET.L-K2 gauge blocks was 24 nm for the 150 mm gauge block, which was already displaying a flatness error of ~50 nm. Therefore one could estimate that the change in flatness could contribute an additional length measurement error of the order of 4 nm. This value is well within the length changes detailed in section 11.2.1 and so no additional error term is proposed.

11.2.3 Damage to wringing surfaces

During the comparison, the surface quality was observed to become degraded due to repeated wringing causing scratching of the surface. No attempt was made to re-lap the surfaces, so it must be assumed that the wringing quality changed during the comparison. This was also reported by some participants. However, the pilot laboratory made measurements at the start and end of the comparison, using the same platens, so any change in length due to changes in surface quality should already be present in the data in section 11.2.2, so no further uncertainty component is proposed.

11.2.4 Constraints imposed by protocol

The only change from normal operating procedure required by the protocol document was for completion of all actions, including unpacking, preparation, measurement, packing and onwards transportation, within a 1 month timescale. This may have led to some participants using a shorter stabilisation time than usual. Work by Decker et al (J. E. Decker, *Metrologia,* **38**, 269-272 (2001)) has indicated the possibility of temporary length instability at the $1 \times 10^{-8}\,L$ level for a period of up to 5 days after transportation. However, after this period, the length of the gauge block was stable. No information is available concerning stabilisation times used by participants, however the need to make two measurements (different wrings) would indicate that the second measurement at least would be performed with the gauge block in a stable configuration. Also, it is anticipated that participants would have made several measurements of the gauge blocks, and averaged the results. Therefore it is unlikely that this uncertainty component is any greater than $\sim 5 \times 10^{-9}\,L$. Taking this as the full width of a rectangular distribution, leads to a standard uncertainty of $1.5 \times 10^{-9}\,L$.

11.2.5 Change in phase correction due to wearing of surfaces

The pilot laboratory made measurements at the start and end of the comparison, using the same wrung platens, so any change in length due to changes in phase correction should already be present in the data in section 11.2.1, so no further uncertainty component is proposed.

11.2.6 Additional uncertainties

Although the protocol document requested that all measurement be corrected to the condition of standard atmospheric pressure (101 325 Pa), only one laboratory (BEV) performed this correction because for most participants, it is usually very small compared to other corrections. However, as some participants are based at institutes at different altitudes, when comparing results between laboratories at the highest level of accuracy, the effects of pressure on the gauge block compression should be considered. Strictly, this should be a parameter for each laboratory's uncertainty budget, and the correction can be easily calculated (see for example H. Darnedde, *Metrologia,* **29**, 349-359 (1992)). Unless participants experienced sever pressure differences from standard atmosphere (as was the case for one participant in the CCL-K2 comparison) then no further uncertainty component is proposed.

11.2.7 Summary of artefact uncertainties

Combining the additional uncertainties described above, gives the following artefact based standard uncertainties for the six gauge blocks used in EUROMET.L-K2:

Serial number	Nominal length (mm)	Artefact-based standard uncertainty (nm)
8728	**150**	27
AA/71001	**500**	12
500B	**500**	40
4 PTB 55	**500**	7
EM/718	**900**	25
PTB 5.13 11/2001	**900**	49

Table 16 Summary of artefact-based standard uncertainties.

Appendix 2: Comparison with reference values

Table 17 shows the differences Δl of measured lengths with respect to the Key Comparison Reference Values and the expanded (*k* = 2) uncertainties $U(\Delta l)$ of these differences calculated by

$$U(\Delta l) = 2\sqrt{u^2(x_i) - u^2(\bar{x}_{ref}) + u^2(x_{artefact})} \tag{9}$$

where $u(x_i)$, $u(\bar{x}_{ref})$ and $u(x_{artefact})$ are the standard uncertainties of the laboratory result x_i, the reference value $\bar{x}_{ref}$, and the artefact, $x_{artefact}$.

Laboratory	150 mm 8728	500 mm AA/71001	500 mm 500 B	900 mm EM/718	500 mm 4 PTB 55	900 mm PTB 5.13 11/2001
NPL	**-4** ± 80	**40** ± 77	**33** ± 107	**45** ± 107	**24** ± 73	**69** ± 138
SMD	**0** ± 65	**44** ± 249	**-34** ± 257	**-60** ± 377		
NMi	**-12** ± 64	**-28** ± 103	**-22** ± 127	**-73** ± 184		
MIKES	**-13** ± 63	**-14** ± 53	**19** ± 91	**-20** ± 86		
SP	**21** ± 64	**2** ± 71	**11** ± 102	**-12** ± 119		
BEV	**-6** ± 141	**177** ± 379	**178** ± 386	**267** ± 569		
METAS	**10** ± 67	**-25** ± 95	**-9** ± 119	**2** ± 156		
CEM	**-65** ± 96	**289** ± 161	**-109** ± 177	**-50** ± 282		
IMGC	**36** ± 77	**44** ± 67	**-36** ± 100	**11** ± 88	**-65** ± 62	**-59** ± 124
PTB	**-14** ± 62	**-1** ± 40	**-121** ± 104	**-96** ± 88	**19** ± 27	**6** ± 104
UME	**-20** ± 71	**-48** ± 159			**-15** ± 157	**-15** ± 289
NCM	**-125** ± 83	**-111** ± 153			**-205** ± 149	**-453** ± 287
NML	**175** ± 207	**-361** ± 781			**-81** ± 780	
CMI	**21** ± 78	**-37** ± 83			**-49** ± 79	**-30** ± 143
SMU	**77** ± 146	**67** ± 161			**99** ± 203	**62** ± 236
OMH	**-35** ± 305	**129** ± 461			**259** ± 460	**-199** ± 786
INM	**55** ± 246	**-1** ± 485			**159** ± 486	**-119** ± 891
GUM	**33** ± 285	**0** ± 481			**31** ± 500	**289** ± 925
VMC	**-165** ± 301	**-121** ± 875			**539** ± 874	**-139** ± 1379
LNMC	**335** ± 384	**129** ± 541			**439** ± 540	**-19** ± 766
MIRS	**25** ± 266	**49** ± 601			**-1** ± 600	**451** ± 1005
LNE	**75** ± 285	**99** ± 441			**-41** ± 440	**71** ± 706

Table 17 *Differences of measured lengths with respect to the weighted mean reference values and the expanded uncertainties (k = 2) of these differences (nm). The uncertainties have been rounded up to the nearest nm. Grey cells are for artefacts not available to or measurable by the NMI. Blue cells are CCL-K2 linking laboratories. Results in red do not agree with the KCRV within their k = 2 uncertainties. Two PTB results are in green as although they disagree with the KCRV, this is due to artefact instability, confirmed by the pilot laboratory. The SMU4 result for the 4 PTB 55 gauge requires further investigation (see report).*

Once again, it should be noted that there are several arguments presented in the main text of this report that indicate that the Key Comparison Reference Values may not be totally reliable estimators of the true values of each measurand, and therefore each laboratory's deviations from these reference values should be interpreted with this in mind.

Figures 10(a) through 10(f) show the graphs of degrees of equivalence for the six gauge blocks.

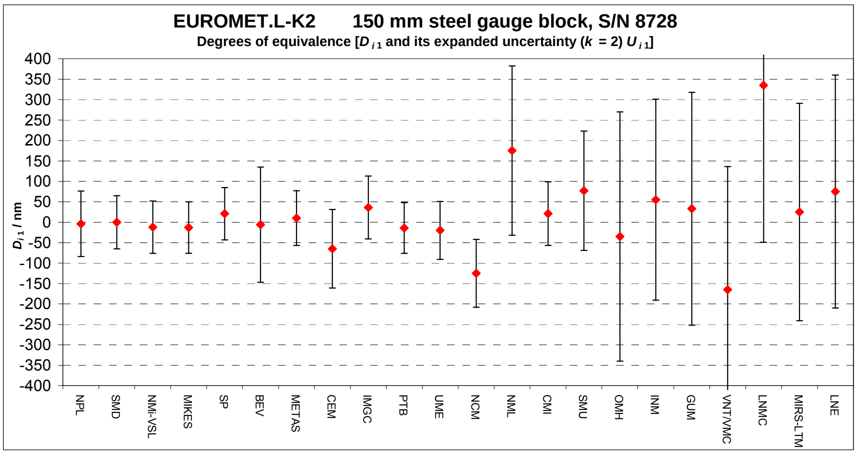

Figure 10(a) Degrees of equivalence for the 150 mm gauge block, S/N 8728, and their expanded (k=2) uncertainties.

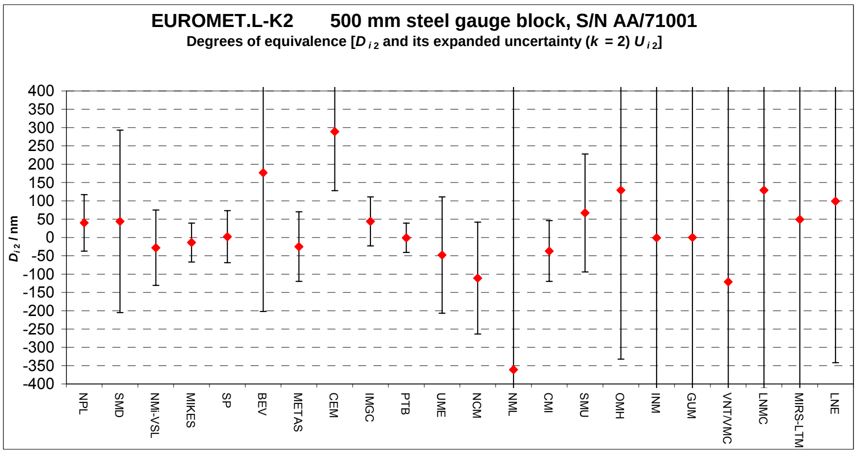

Figure 10(b) Degrees of equivalence for the 500 mm gauge block, S/N AA/71001, and their expanded (k=2) uncertainties.

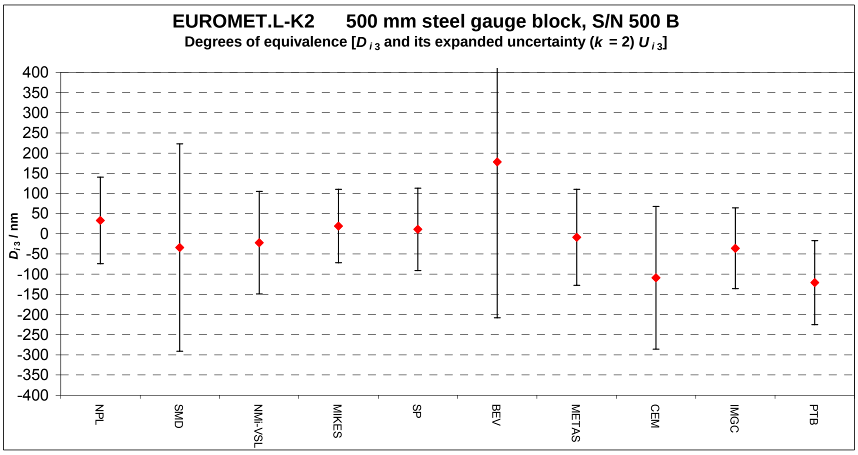

Figure 10(c) Degrees of equivalence for the 500 mm gauge block, S/N 500 B, and their expanded (k=2) uncertainties.

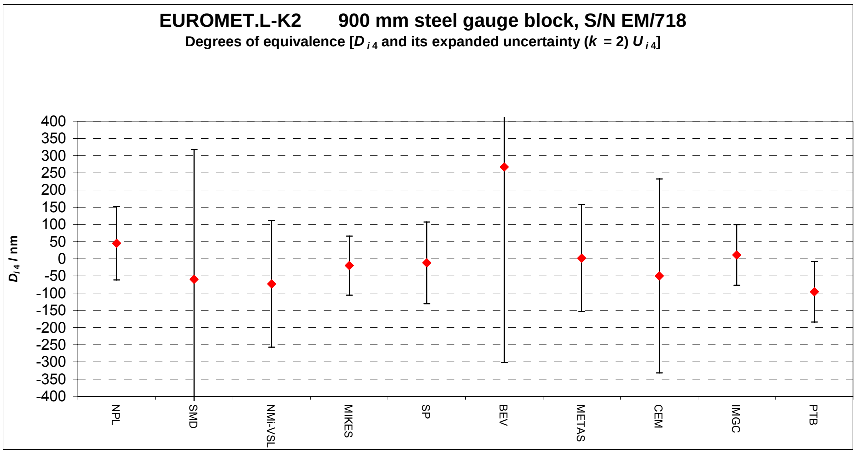

Figure 10(d) Degrees of equivalence for the 900 mm gauge block, S/N EM/718, and their expanded (k=2) uncertainties.

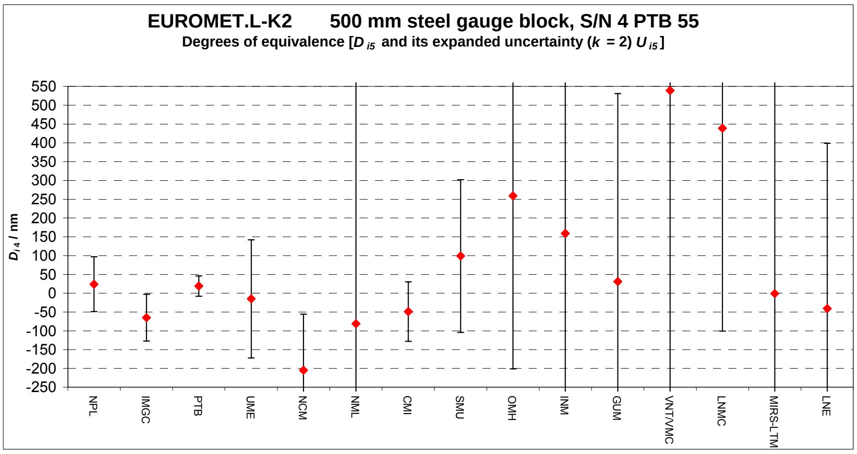

Figure 10(e) Degrees of equivalence for the 500 mm gauge block, S/N 4 PTB 55, and their expanded (k=2) uncertainties.

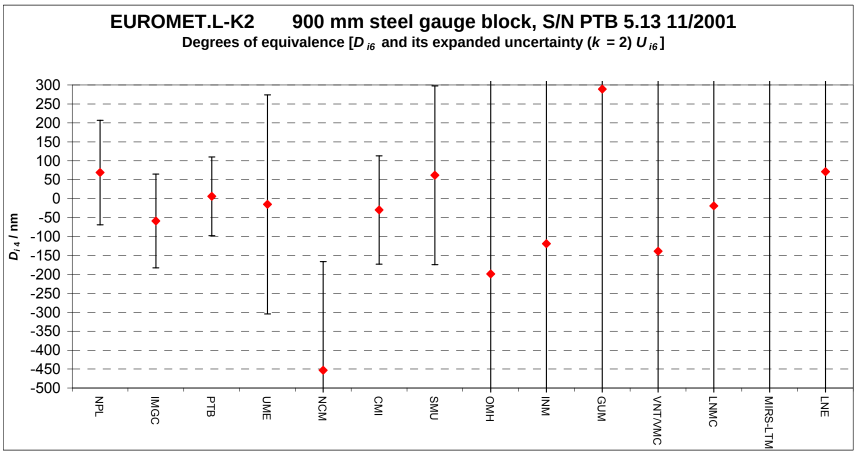

Figure 10(f) Degrees of equivalence for the 900 mm gauge block, S/N PTB 5.13 11/2001, and their expanded (k=2) uncertainties.

The calculation of the mutual degrees of equivalence between pairs of laboratories is not recommended for comparisons involving several material standards, since many sets of values would have to be calculated. The mutual degrees of equivalence would be given by $D_{ij} = (x_i - x_j)$ and the expanded uncertainty $U(D_{ij})$ of this difference for two laboratories participating in the same comparison, and by $D_{ij} = (D_i - D_j)$ and its expanded uncertainty $U(D_{ij})$ for two laboratories participating in distinct comparisons, where D_i and D_j are the degrees of equivalence of the two laboratories, in the two different comparisons.

However, one can see that Tables 13(a) through 13(d) give the normalized mutual degrees of equivalence, $D_{ij}/U(D_{ij})$ for bilateral comparisons of laboratories' results.

Appendix 3: Transfer of reference values to RMO key comparisons

When trying to link CCL and RMO artefact based key comparisons in dimensional metrology, the application of the concept of transferring the key comparison reference value to a second, independent comparison, turns out to be difficult. Not only does the reference value not have the importance of a realisation of an SI unit but also a rigorous transfer of a numerical reference value would necessitate the introduction of metrologically meaningless corrections and lead to an undue increase in the uncertainty of the regional reference value used to express the degree of equivalence. The RMO and CCL comparisons would then not have equal status, contrary to the expectations of the MRA.

An alternative is to adjudge that the proper link between two comparisons is established by an expert judgement of the results of the participants common to both comparisons, taking into account their degrees of equivalence for all standards of the two comparisons. This follows one of the recommendations of the 2001 CCL-WGDM meeting concerning artefact based key comparisons in dimensional metrology.

Furthermore, the 2002 CCL-WGDM meeting announced that it would formally recommend that artefact based Key Comparisons in Dimensional Metrology would not use a numerical link between the CCL Key Comparison and the corresponding RMO Comparisons. Instead, the link would be based on competences demonstrated by the participants which took part as linking NMIs in the Key and RMO Comparisons. If these linking NMIs were judged to have performed competently in both comparisons then the comparisons were to be regarded as equivalent. The judgement of the competence is the responsibility of the WGDM.

The WGDM also recommended to no longer run the CCL level of key comparisons in dimensional metrology, and to replace them by CCL authorised RMO key comparisons, using participation from outside the organising RMO.

These recommendation was approved by the CCL during its meeting in September 2003.