Eidgenössisches Amt für Messwesen
Office fédéral de métrologie
Ufficio federale di metrologia
Swiss Federal Office of Metrology

CCL Key Comparison

Calibration of gauge blocks by interferometry

Instructions and technical protocols

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Wabern, 6. April 1998/ Ta

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 September 1997, the Consultative Committee for the Definition of the Metre (CCDM, today called Consultative Committee for Length, CCL) has identified seven key comparisons in the field of dimensional metrology and decided upon the general content, the pilot laboratory and the starting date of each key comparison. In particular, it decided that a key comparison on gauge block measurements by interferometry shall be carried out, starting in spring 1998, with the Swiss Federal Office of Metrology (OFMET) as the pilot laboratory.

The results of this international comparison will contribute and be included to the agreement for establishing the metrological equivalence. The interregional CCL comparison will be combined - where necessary - with regional comparisons following exactly the same scheme. Laboratories participating in both, the interregional and the regional comparisons establish the link between these comparisons and assure their equivalence. The degree of metrological equivalence reported in the above mentioned agreement will therefore not depend on whether the laboratory has participated in the CCL or in a regional comparison.

The procedures outlined in this document are principally intended to allow for a clear and unequivocal comparison of the measurement results and to complete the comparison in the time scale provided for. The procedures are based on experiences made in a preceeding CCDM comparison carried out 1993/1994[1]. Due to the large number of participating laboratories, the time schedule is tight. Therefore particular attention must be attributed to the availability of the laboratory carrying out the calibrations, to transportation and to customs problems. A common way of evaluating and expressing the uncertainty of measurement is particularly important to demonstrate the degree of equivalence between the participating laboratories.

By their declared intention to participate at this key comparison, the laboratories accept the general instructions and the technical protocols written down in this document and commit themselves to follow the procedures strictly.

[1] B.G. Vaucher and R. Thalmann, CCDM Comparison of gauge block measurements, to be published in *Metrologia* 1998.

2. Organisation

According to the rules set up by the BIPM[2] a small group from the provisional list of participating laboratories has drafted the detailed technical protocols. The group is composed of the pilot laboratory (Ruedi Thalmann from OFMET, Switzerland), Jennifer Decker from the NRC, Canada and Nicholas Brown from CSIRO/NML, Australia, all experienced in organizing gauge block comparisons and representing also a regional metrology organisation. The BIPM and the chairman of the WGDM both act as observers of the comparison and will regularly be informed about the progress of the comparison.

2.1 Requirements for participation

According to the WGDM recommendation No.2 (document CCDM/WGDM/97-50b), the participating laboratories should offer this measurement as a calibration service, be willing to participate in a regional comparison in order to provide a link between the interregional and the regional comparisons and have a measurement uncertainty below a certain level. This level shall be fixed to approximately $\pm(0.015\ \mu m + 10^{-7}L)$ standard uncertainty. In addition, it has been paid attention, that the regions are adequately represented.

2.2 Participants

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[2] T.J. Quinn, Guidelines for key comparisons carried out by Consultative Committees, draft of 21. November 1997, BIPM, Paris.

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2.3 Time schedule

The comparison will be carried out in a mixed form, circulation and star-type. After the standards being circulated in a region, they are sent back to the pilot laboratory before the circulation in the next region. Each major region has a local coordinator which helps the regional transportation and customs problems to be solved and the time schedule to be kept within the tight limits. The local coordinator can, if appropriate, organize the regional transportation also in a star-type way. Local coordinators are:

EUROMET	OFMET, CH
NORAMET	NRC, CA
APMP	NML/CSIRO, AU

Each laboratory has one month for calibration, including transportation. With its confirmation to participate, each laboratory has confirmed that it is capable to perform the measurements in the limited time allocated to him. It guarantees, that the standards arrive in the country of the next participant at the beginning of the next

month. If for some reasons, the measurement facility is not ready or customs clearance takes too much time in a country, the laboratory has to contact the coordinator immediately and – according to the arrangement made - eventually to send the standards directly to the next participant before finishing the measurements or even without doing any measurements.

Region	**Laboratory**	**Country**	**Date**
EUROMET	OFMET	CH	March 1998
	PTB	DE	April 1998
	NPL	UK	May 1998
	BNM / LNE	FR	June 1998
Pilot Lab	OFMET	CH	July 1998
NORAMET	NRC	CA	August 1998
	NIST	USA	September 1998
	CENAM	MX	October 1998
Pilot Lab	OFMET	CH	November 1998
COOMET	VNIIM	SU	January 1999
Pilot Lab	OFMET	CH	February 1999
APMP	NML/CSIRO	AU	March 1999
	NRLM	JP	April 1999
	KRISS	KR	May 1999
	NIM	CN	June 1999
Pilot Lab	OFMET	CH	August 1999

2.4 Transportation

Transportation is on each laboratory's own responsibility and cost. The standards are packed in a plastic box (dimensions 53x40x27 cm^3) ready to be shipped. Inside this box, the gauge blocks are disposed in a wooden box with serial numbers written such, that they can be inspected easily by customs. The package is accompanied by an ATA carnet. The carnet shall always be shipped with the package, never inside the box, but apart. **Please be certain, that when receiving the package, you also receive the carnet!** The box can be shipped with any appropriate carrier, preferably using a fast mail service such as DHL.

You are kindly asked to inform the pilot laboratory and the local coordinator by Fax immediately after receiving the gauge blocks using the fax form in the annex.

Immediately after having completed the measurements, the pack has to be sent to the next participant. It is advisable to prepare and organize this transportation beforehand. Please inform again the coordinator and the next laboratory by fax or e-mail about date of shipment, transportation company and possibly flight details.

2.5 Unpacking, Handling, Packing

The package contains the following items:
- one wooden box with 20 gauge blocks
- temperature data logger
- 1 copy of measurement instructions
- ATA carnet, apart from the package

After receiving the package, the standards have to be inspected carefully for any damage, scratches or rust. **The gauge blocks must be handled with care!** Any damage has to be communicated to the pilot laboratory. **The measurement surfaces should never be relapped or polished!** Damaged gauge blocks are not going to be replaced. Try to calibrate also gauge blocks judged to be damaged if there is no risk for damaging the platens used for wringing the gauge blocks.

After the measurements, the gauge blocks have to be cleaned and **greased**. Ensure that the content of the package is complete before shipment. Use always the original package.

2.6 Financial aspects, Insurance

Each participating laboratory covers the costs for the measurements, transportation and eventual customs formalities as well as for any damages that may have occurred within its country. The overall costs for the organisation and for the devices are covered by the organising pilot laboratory. The pilot laboratory has no insurance for any loss or damage of the standards during transportation.

3. Description of the Standards

The package contains 10 gauge blocks of steel and 10 gauge blocks of tungsten carbide. The gauge blocks are of rectangular cross section, according to the international standard ISO 3650. The thermal expansion coefficient of the gauge blocks has been measured by the pilot laboratory (measurement uncertainties are stated as standard uncertainty).

Steel gauge blocks:

Identification	Nominal length (mm)	Expansion coeff. (10^{-6} K^{-1})	Manufacturer
2’10282	0.5	11.52 ± 0.1	CARY
3’23288	1.01	11.52 ± 0.1	CARY
21’23584	1.1	11.52 ± 0.1	CARY
1’0071	6	11.52 ± 0.1	CARY
16’0087	7	11.52 ± 0.1	CARY
7’0103	8	11.52 ± 0.1	CARY
18’23395	15	11.52 ± 0.1	CARY
24’23259	80	11.56 ± 0.03	CARY
7’23260	90	11.72 ± 0.03	CARY
29’23539	100	11.52 ± 0.03	CARY

Tungsten carbide gauge blocks:

Identification	Nominal length (mm)	Expansion coeff. (10^{-6} K^{-1})	Manufacturer
9’2605	0.5	4.24 ± 0.1	CARY
20’23289	1	4.24 ± 0.1	CARY
10’20632	1.01	4.24 ± 0.1	CARY
20’20987	1.1	4.24 ± 0.1	CARY
2’22685	6	4.24 ± 0.1	CARY
24’95598	7	4.24 ± 0.1	CARY
19’22087	8	4.24 ± 0.1	CARY
B 32364	80	4.26 ± 0.02	Select
H 580223-00	90	4.25 ± 0.02	-
B 32365	100	4.27 ± 0.02	Select

4. Measurement instructions

Before calibration, the gauge blocks have to be inspected for damage of the measurement surfaces. Any scratches, rusty spots or other damages have to be documented by a drawing using the appropriate form in the annex (A2, A3).

Measurement item is the central length of the gauge blocks, as defined in the International Standard ISO 3650. The gauge blocks have to be measured by interferometry, in their vertical position wrung to a flat plate. The central length of a gauge block is the perpendicular distance between the centre point of the free measuring surface and the plane surface of an auxiliary plate of the same material and surface texture upon which the other measuring surface has been wrung. The measurement result to be reported is the deviation of central length from nominal length, $\Delta l = l - L$. The results of the measurements on both sides (Δl_{left} and Δl_{right}) by wringing each measurement face in turn upon the reference flat and the average of the two wringings have to be reported on the table in the annex A1 (“left” refers to the measurement surface left to the marking on the side face of gauge blocks longer than 6 mm or to the non-marked measurement surface).

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

5. Measurement uncertainty

The uncertainty of measurement shall be estimated according to the *ISO Guide for the Expression of Uncertainty in Measurement*. In order to achieve optimum comparability, a mathematical model containing the principal influence parameters for gauge block calibration by interferometry shall be given in the following.[3] The participating laboratories are encouraged to follow this model as closely as possible, however adapted to their instruments and procedures.
The length of a gauge block measured by interferometry and fringe fraction determination is described by

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

where:

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

L nominal length of the gauge block;

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

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

F_i fractional part of fringe order;

λ_i vacuum wavelengths of the different light sources used;

n index of refraction of the air;

Δt_g = (20 - t_g) is the difference of the gauge block temperature t_g in °C during the measurement from the reference temperature of 20 °C;

α linear coefficient of thermal expansion of the gauge block;

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

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

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

f is the focal length of the collimating lens;

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

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

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

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

[3] J.E. Decker and J.R. Pekelsky, Uncertainty Evaluation for the Measurement of Gauge Blocks by Optical Interferometry, to be published in *Metrologia* **34**(4) or **34**(5).

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

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

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

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

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

The participants are required to report their measurement uncertainty budget in the table of the annex A4, the format according to the example below. Some indicated standard uncertainties, in particular $u(n)$, $u(\delta l_\Omega)$ or $u(\Delta l_\Phi)$, might be based on a separate calculation, which can be added to the report. ν_i is the number of degrees of freedom of $u(x_i)$, ν_{eff} is the effective number of degrees of freedom of $u_c(l)$.

Example:
(Please note, that this is only an example and does not claim to be neither complete nor correct).

x_i	$u(x_i)$	ν_i	$c_i = \partial l/\partial x_i$	$u_i(l)$ / nm
λ_1	$5\cdot10^{-9}$	100	L	$0.005\cdot10^{-6}\,L$
λ_2	$2\cdot10^{-8}$	100	L	$0.02\cdot10^{-6}\,L$
F_i (i = 1,2)	0.02 fringe	10	$(\lambda/2)/\sqrt{2}$	4.2
n	$1.8\cdot10^{-7}$	100	L	$0.18\cdot10^{-6}\,L$
t_g	0.01 °C	100	$\alpha\cdot L$	$0.11\cdot10^{-6}\,L$
α *	$0.5\cdot10^{-6}$ °C^{-1}	100	$\overline{\Delta t}_g \cdot L$	$0.05\cdot10^{-6}\,L$
δl_Ω	10^{-8}	100	L	$0.01\cdot10^{-6}\,L$
s (as part of Δl_s)	5 µm	100	$(s/8f^2)\cdot L$	$0.002\cdot10^{-6}\,L$
δl_A	3 nm	100	1	3
δl_G	2.5 nm	100	1	2.5
δl_w	6 nm	100	1	6
Δl_Φ	5 nm	10	1	5

The combined standard uncertainty is $u_c(l) = \sqrt{(9.7\,\text{nm})^2 + (0.22\cdot10^{-6}L)^2}$

For L = 0.5 mm: u_c = 9.7 nm with ν_{eff} = 81
For L = 100 mm: u_c = 24 nm with ν_{eff} = 251

* Note that the treatment of $u(\alpha)$ is not rigurously correct, since the expectation value of Δt_g is zero. This term should therefore be treated as a second order term in Eq.(4). In the simplified example above, an average deviation Δt_g from 20°C of 0.1°C has been assumed.

6. Reporting

The quality of the measurement surfaces of the gauge blocks, the measurement results, instrument descriptions and a detailed evaluation of the uncertainty of measurement have to be reported using the forms enclosed in the annex. Handwritten notes are sufficient.

The measurement report forms in the annex of this document are sent by e-mail (Word document) to all participating laboratories. It would be appreciated if the report forms (in particular the results sheet) could be completed by computer and sent back electronically to the coordinator. **In any case, the signed report must also be sent in paper form by mail.** In case of any differences, the paper forms are considered to be the valid version.

The reports shall be sent **within six weeks** after completing the measurements to the pilot laboratory. No information about differences of the reported results with respect to others will be communicated before the completion of the comparison, unless large deviations of particular laboratories with respect to the preliminary reference results obtained by the pilot laboratory have been observed. In the latter case the laboratory in question will be contacted.

Within 3 months after completion of the circulation, the pilot laboratory will prepare a first draft report and send it to the participants for comment. Subsequently, the procedure outlined in the BIPM Guidelines will be followed.

Measurement results:

Steel gauge blocks:

Id. no.	nom. length	central length (**deviation** from nominal length)			uncert. (1σ)	eff. deg. of freedom
	L (mm)	Δl_{left} (µm)	Δl_{right} (µm)	Δl (µm)	u_c (nm)	ν_{eff}
2'10282	0.5					
3'23288	1.01					
21'23584	1.1					
1'0071	6					
16'0087	7					
7'0103	8					
18'23395	15					
24'23259	80					
7'23260	90					
29'23539	100					

Tungsten carbide gauge blocks:

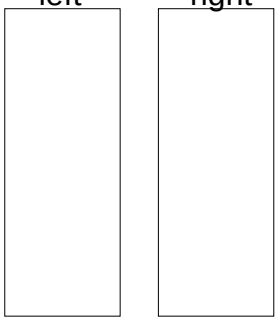
Id. no.	nom. length	central length (**deviation** from nominal length)			uncert. (1σ)	eff. deg. of freedom
	L (mm)	Δl_{left} (µm)	Δl_{right} (µm)	Δl (µm)	u_c (nm)	ν_{eff}
9'2605	0.5					
20'23289	1					
10'20632	1.01					
20'20987	1.1					
2'22685	6					
24'95598	7					
19'22087	8					
B 32364	80					
H 580223-00	90					
B 32365	100					

Laboratory: .....

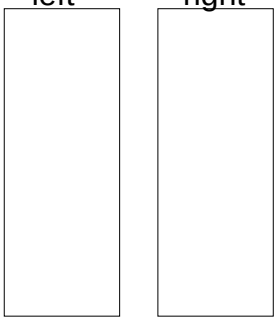
Date:..... Signature:.....

Inspection of the measurement surfaces, steel gauge blocks

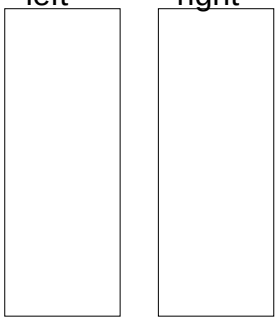
0.5 mm
S/N 2’10282
left right



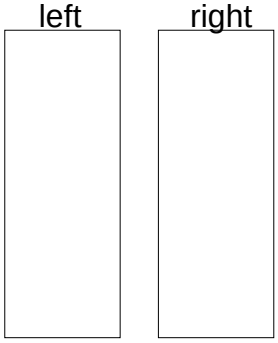
1.01 mm
S/N 3’23288
left right



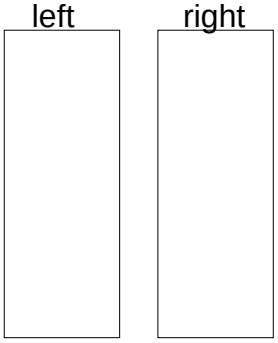
1.1 mm
S/N 21’23584
left right



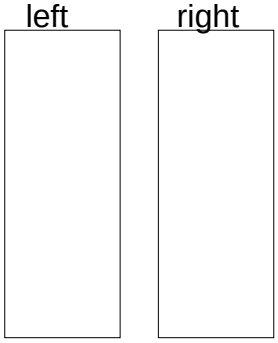
6 mm
S/N 1’0071
left right



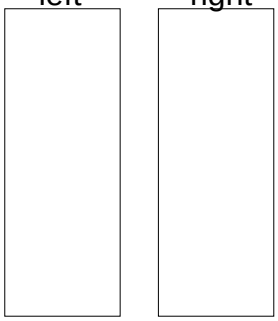
7 mm
S/N 16’0087
left right



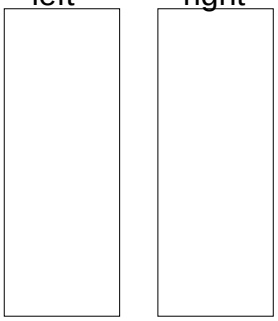
8 mm
S/N 7’0103
left right



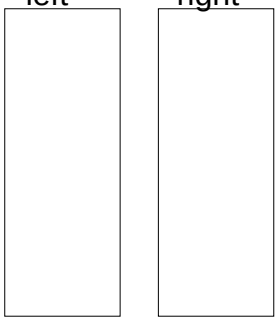
15 mm
S/N 18’23395
left right



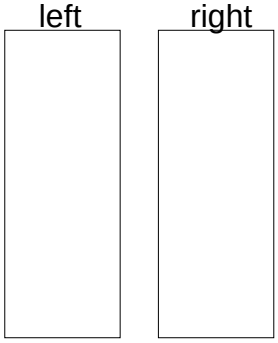
80 mm
S/N 24’23259
left right



90 mm
S/N 7’23260
left right



100 mm
S/N 29’23539
left right

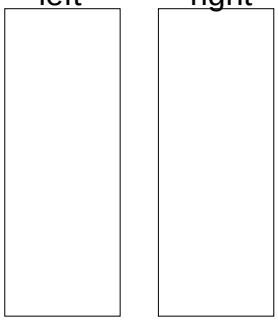


Laboratory: .....

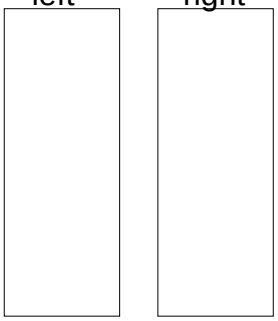
Date:..... Signature:.....

Inspection of the measurement surfaces, tungsten carbide gauge blocks

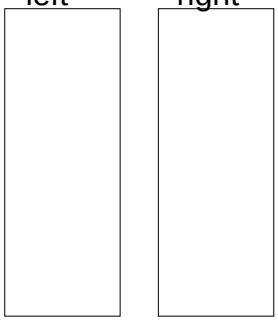
0.5 mm
S/N 9’2605
left right



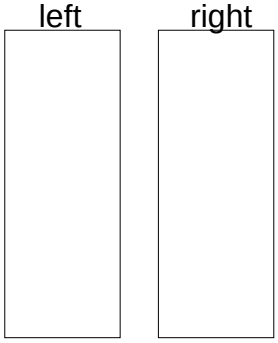
1 mm
S/N 20’23289
left right



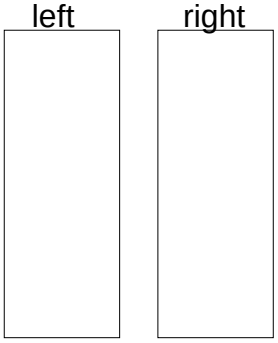
1.01 mm
S/N 10’20632
left right



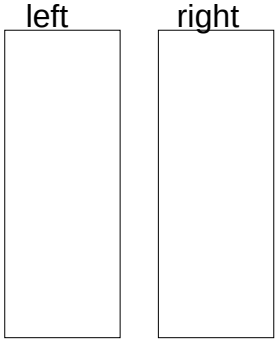
1.1 mm
S/N 20’20987
left right



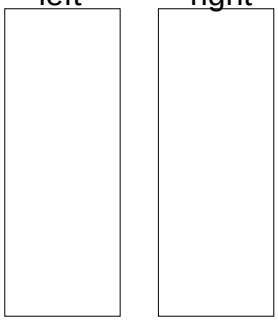
6 mm
S/N 2’22685
left right



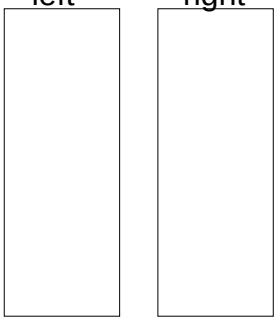
7 mm
S/N 24’95598
left right



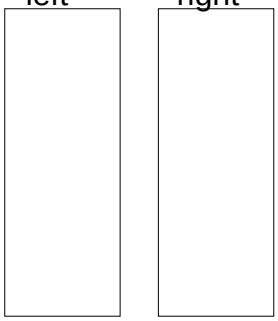
8 mm
S/N 19’22087
left right



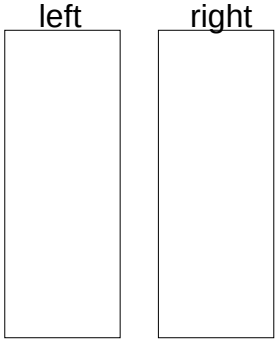
80 mm
S/N B 32364
left right



90 mm
S/N H 580223-00
left right



100 mm
S/N B32365
left right



Laboratory: .....

Date:..... Signature:.....

Description of the measurement instrument

Make and Type of interferometer .....

.....

.....

.....

.....

.....

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

.....

.....

.....

.....

Method of fringe fraction determination: .....

.....

.....

.....

.....

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

.....

.....

.....

.....

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

.....

.....

.....

Phase correction:

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

Laboratory: .....

Date:..... Signature:.....

Uncertainty of measurement

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

Combined standard uncertainty: $u_c(l) =$

Laboratory: .....

Date:..... Signature:.....

Telefax Telefax Telefax Telefax Telefax

To: **Swiss Federal Office of Metrology**
R. Thalmann
Lindenweg 50
CH-3003 Bern- Wabern, Switzerland
Fax: ++41 31 323 32 10
e-mail: Rudolf.Thalmann@eam.admin.ch

From: (participating laboratory)

We confirm having received the standards of the *CCL key comparison on gauge block measurement* on .....(date).

After visual inspection

no damage has been noticed.

the following damage(s) must be reported:

.....
.....
.....
.....

Date: Signature:

....