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Intercomparison of Thermal Expansion Measurements

EUROMET Project 275

Final Report

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Contents

1. Introduction

The exact knowledge of the coefficient of thermal expansion is essential for accurate dimensional measurements. Is has obtained additional interest with the discussions concerning an eventual change of the reference temperature for length measurements. Several laboratories (NPL, PTB, OFMET) recently developed dedicated instruments for the measurement of the expansion coefficient.

At the Paris meeting of the EUROMET contact persons for length in November 1992, an intercomparison for the measurement of the expansion coefficient of gauge blocks was decided. Seven laboratories of five national metrology institutes agreed to participate: CH (OFMET), NL (NMi-VSL), DE (2 x PTB Braunschweig, PTB Berlin), UK (NPL), I (IMGC). The OFMET acted as the pilot laboratory. The purpose of the comparison was to ascertain the measurement capabilities of the new instruments and to compare these with the more traditional methods.

Four 100 mm gauge blocks of different material (steel, tungsten carbide, ceramic, and zerodur) were circulated in one loop. The pilot laboratory carried out the measurements before and after the circulation. The expansion coefficient had to be measured at 20°C. Otherwise, no detailed instructions limited the variety of measurement methods. Prior to the comparison, instructions for handling the standards, transportation[1] and data reporting were distributed to the participants (cf. appendix).

2. Participating laboratories and time schedule

Laboratory	**Name**	**Date of measurements**
NMI VSL, Delft	H. Haitjema	November 1993
IMGC, Torino	A. Sacconi M. di Giommo	December 1993
PTB 1, Braunschweig	H. Darnedde	January 1994
PTB 2, Braunschweig	G. Bönsch	February 1994
PTB 3, Berlin	J. Tschirnich J. Suska	March 1994
NPL, Teddigton	B. Hughes	April/May 1994
OFMET, Wabern	R. Thalmann	October 1993, June 1994

Table 1. Participating laboratories and time schedule of the comparison.

For more detailed information about the participants see the measurement instructions in the appendix.

[1] Transportation without ATA carnet worked perfectly well, even if the pilot laboratory does still not belong to the EC.

3. Description of the standards

Four gauge blocks according to ISO 3650 of different material were circulated. The nominal values of the expansion coefficient were obtained from the manufacturers. The nominal length of all four gauge blocks was 100 mm, with deviations from nominal length smaller than 1 µm except for the zerodur gauge block, whose length was 99.9606 mm. The quality and the wringing capability of the measurement faces were good for all but the zerodur gauge block, which was chromium coated on the end faces and showed numerous scratches.

Identification	**Length**	**Grade**	**Manu-facturer**	**Material**	**Nominal value of** a
22'10225	100.00008 mm	K	Cary	steel	11.55 ppm/K
C 1258	100.00034 mm	K	TESA	tungsten carbide	4.2 ppm/K
C 119 21	99.9999 mm	K	TESA	Al_2O_3 ceramics	9.7 ppm/K
AMG 100'3	99.9606 mm	-	?	zerodur	?

Table 2. Gauge blocks used for the comparison.

4. Definition of the coefficient of thermal expansion

The linear coefficient of thermal expansion at the temperature T shall be defined as

$$\alpha_T = \frac{1}{L}\frac{dL}{dT},$$

where L is the length of the material specimen. Since the expansion is not linear, α_T depends on the temperature of the material. In this comparison, the expansion coefficient had to be determined at T = 20° C. The dependence on temperature of α_T can be expressed by a polynomial [1]

$$\alpha_T = a + b \cdot T + c \cdot T^2 + d \cdot T^3 + \ldots$$

An alternative and more common representation is obtained from the Taylor series development of length L

$$L(T) = L_{20}\left(1 + \alpha(T - 20) + \beta(T - 20)^2 + \ldots\right),$$

where α = a, β = b/2 and [T] = °C. The laboratories were asked to determine the linear coefficient $\alpha_{T=20°C}$ and possibly higher order coefficients.

5. Description of the measurement instruments

The participating laboratories were asked to complete a questionnaire describing their measurement method, the instrument and the measurement conditions. The answers are summarised on tables 3 and 4.

Lab.	Method	Temp. Sensors	Position of gauge block
NMI VSL	Absolute length measurement with Kösters Zeiss gauge block interferometer using usual method of exact fringe fractions. Gauge block inside messing box (120 mm)[3], opened at the upper side to enable the interferometric measurement. Temperature controlled with thermostatic heater/cooler on bottom and three side walls of the box.	1 Pt 100 on gauge block	upright, wrung on base plate
IMGC	Absolute length measurement with Hilger&Watts gauge block interferometer using usual method of exact fringe fractions. Temperature control through laboratory air conditioning.	2 Pt 100 on gauge block	upright, all gauge blocks wrung onto a common base plate
PTB1	Absolute length measurement with Kösters vacuum wavelength comparator for gauge blocks [2] using usual method of exact fringe fractions. Temperature controlled with thermostatic heater/cooler of the walls of the box.	Pt 25	horizontally supported in the Airy points
PTB2	Length measurement with mechanical gauge block comparator (remote controlled) in clima box [3]. Comparison with thermal expansion standard (PTB1 calibrated) of possibly the same material, except for the ceramic gauge block, which was compared with a steel standard.	Pt 100	upright
PTB3	Dedicated instrument: specimen mechanically contacted between two corner cube reflectors of laser interferometer inside thermostatically controlled box [4].	Pt 100	horizontally supported in the Airy points
NPL	Dedicated instrument: length measurement using Fizeau interferometer likewise NPL/TESA interferometer; gauge blocks inside electrically heated oven [5].	Pt 100	upright, wrung on base plate
OFMET	Dedicated instrument: vacuum interference dilatometer. Gauge block on thermally isolating support inside a thermostatically (water) controlled copper cylinder. Within vacuum chamber, temperature change only through radiation. Length measurement using HP differential plane mirror interferometer with electronic phase meter and non-linearity compensation.	3 thermistors clamped on gauge block	upright, wrung on base plate

Table 3. Measurement methods and instruments.

On table 4 some information about the temperature changes are summarised. The stabilisation time might not be directly comparable from one laboratory to the other, since the applied criteria for the necessary temperature stability during the measurements are not the same. Regarding the total measurement time, note that some laboratories are able to measure several specimens at the same time, whereas others measure only one at a time.

Lab.	Temp. intervals and range	Temp. stabili-sation time	Temp. stability	Total meas. time
NMI VSL	9 points, 16 to 24 °C	100 min.	0.01 °C	1.5 day for one gauge block
IMGC	5 points, 18 to 22 °C	15 h	0.004 °C / min.	2.5 days for all gauge blocks
PTB1	3 points, 15 to 25 °C	always left for 24 h	< 0.001 °C	3 days for one gauge block
PTB2	2 points, 15 and 25 °C	140 min., but al-ways left for 24 h	< 0.01 °C	3 days for one gauge block
PTB3	7 points in 5 °C intervals	10 h, but always left for 24 h	< 0.005 °C	7 days for one gauge block
NPL	6 points, 20 and 37 °C	4 h, but always lest for 24 h	0.01 °C	3 days for one gauge block
OFMET	7 points, 10 and 30 °C	10 to 15 h	< 0.01 °C	3 to 5 days for one gauge block

Table 4. Characteristic temperature changes and settling times of the different measurement apparatus used.

6. Measurement results

Lab.	Steel 22 10225	Tungsten carbide C 1258	Ceramic C 119 21	Zerodur AMG 100 3
OFMET1	11.57 ± 0.04	4.28 ± 0.03	9.32 ± 0.07	-0.04 ± 0.02
NMI VSL	11.53 ± 0.08	4.22 ± 0.07	9.31 ± 0.11	-0.07 ± 0.06
IMGC	11.56 ± 0.1	4.27 ± 0.09	9.39 ± 0.1	-0.04 ± 0.07
PTB1	11.612 ± 0.014	4.295 ± 0.014	9.38 ± 0.014	-0.026 ± 0.014
PTB2	11.61 ± 0.07	4.25 ± 0.06	9.37 ± 0.07	-0.01 ± 0.04
PTB3	11.53 ± 0.12	4.28 ± 0.12	9.33 ± 0.14	
NPL	11.57 ± 0.09	4.26 ± 0.07	9.22 ± 0.09	-0.08 ± 0.06
OFMET2	11.587 ± 0.026	4.277 ± 0.014	9.345 ± 0.055	-0.018 ± 0.005

Table 5. Measurement results (in ppm/K) and associated measurement uncertainty (k=2).

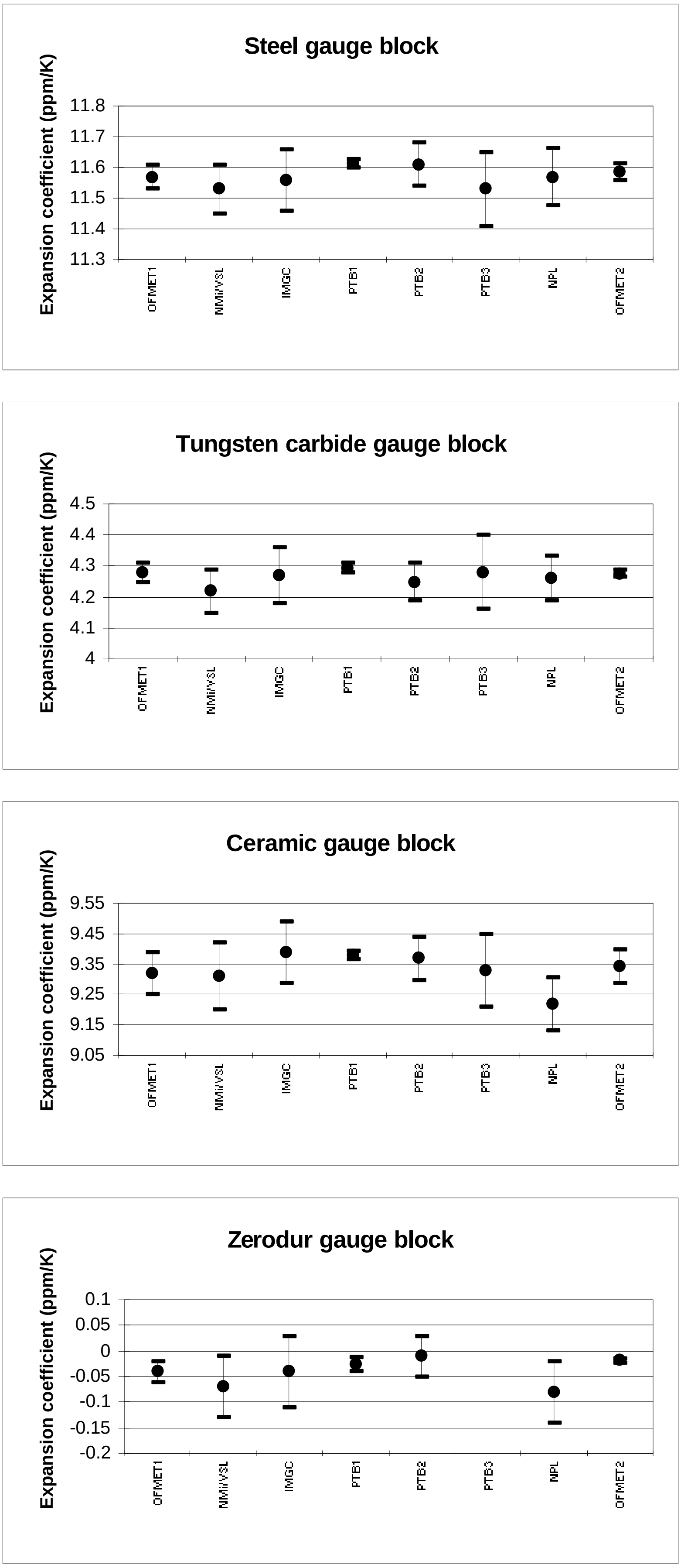


Fig.1. Measurement results with uncertainty intervals.

Discussion: The comparison shows satisfactory agreement between the measurement results of α. No attempt has been made to find a reference value, also it does not seem to make sense to calculate the average value. However, for all standards, a value can be found which is contained in all uncertainty intervals of the different laboratories (except for one measurement of the ceramic gauge block). The agreement expressed as the difference between the largest and the smallest value is 0.08 ppm/K for steel, 0.075 ppm/K for tungsten carbide, 0.17 ppm/K for ceramic, and 0.07 ppm/K for zerodur. The agreement between the two laboratories claiming the smallest uncertainty (PTB1 and OFMET) is 0.025, 0.018, 0.025, and 0.008 ppm/K for the four standards, respectively. Note that some systematic differences between the laboratories become obvious from the four figures 1 (PTB1 has always the highest value, NMI/VSL and NPL on the other hand contribute rather small values).

Some laboratories reported also results of the quadratic expansion coefficient β, or the second term b = 2 β of the polynomial representation of α_T. For those who did not report these values but a sufficient number of length measurements at different temperatures, the coefficient was determined from a quadratic polynomial fitted through the measurements, as described by the last equation of section 4. These results are marked with an asterisk *. All measurements were taken with the same weight. For the values put into parentheses (), the quadratic fit parameter was not significative. Most laboratories did not report uncertainties for this quadratic coefficient. The uncertainties of OFMET take only type A uncertainties into account. The results for steel and zerodur can be compared with those reported by Birch [6]: $1.18 \cdot 10^{-8}$ K^{-2} and $-0.09 \cdot 10^{-8}$ K^{-2}, respectively.

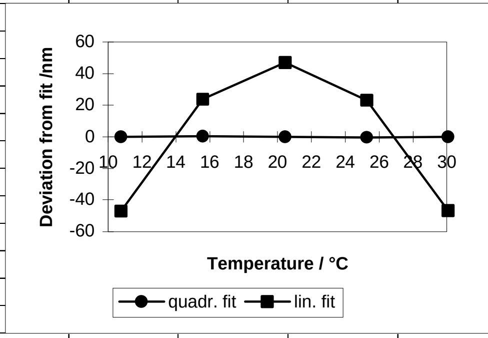
Lab.	Steel 22 10225	Tungsten carbide C 1258	Ceramic C 119 21	Zerodur AMG 100 3
NMI VSL	1.1	(0.95)	(-0.6 *)	(1.2 *)
IMGC	1.5 *	(6.1 *)	(-0.6 *)	(-1.2 *)
PTB1	0.8 ± 0.5	0.4_5 ± 0.5	0.3 ± 0.5	-0.2 ± 0.5
NPL	1.2 *	0.4 *	1.3 *	(0.0 *)
OFMET2	1.01 ± 0.01	0.39 ± 0.01	0.57 ± 0.02	-0.1 ± 0.01

Table 6. Measurement results of the quadratic coefficient β of thermal expansion in 10^{-8} K^{-2}. The values marked with * have been calculated by the pilot laboratory from raw measurement data.

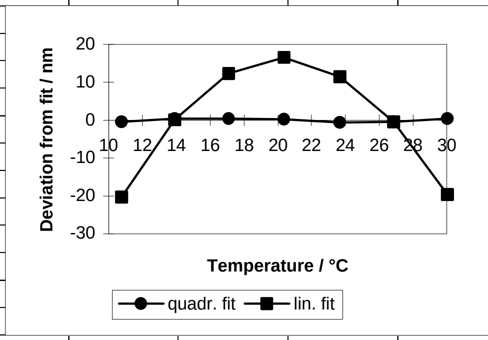
7. Measurements of the pilot laboratory

On the four following graphs, the measurements of the pilot laboratory are represented. Each table comprises the measurement temperatures, the measured length change, the linear and the quadratic polynomial fit through the measurement points together with the residuals in (length deviation). The residuals show, that the quadratic expansion coefficient is highly significative and that a further, cubic term would be to small to be significative.

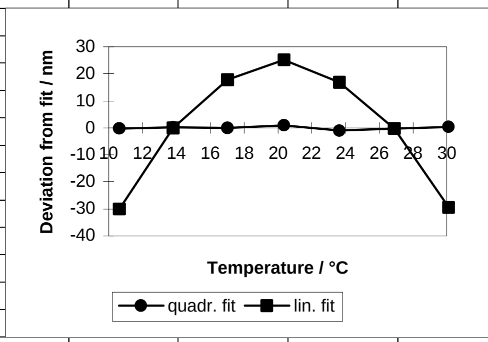
Gauge block:		Steel, 22'10225			
Length:	100				
T / °C	dL / µm	quad fit	resid./ nm	lin fit	resid./ nm
10.7756	-22.3749	-22.375	-0.2	-22.422	-47.1
15.591	-16.862	-16.862	0.3	-16.838	23.8
20.4336	-11.27	-11.270	0.0	-11.223	47.1
25.2652	-5.6434	-5.644	-0.3	-5.620	23.0
30.0718	0	0.000	0.2	-0.047	-46.8
			0.257268		7720.733
		L0	-11.7726	L0	-11.7257
		a	1.15871	a1	1.159565
		b	0.00101		
		alpha	11.587		11.596
		beta	0.0101		



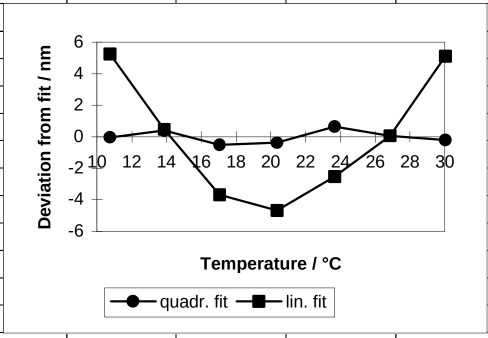
Gauge block:		tungsten carbide, C 1258			
Length:	100				
T / °C	dL / µm	quad fit	resid./ nm	lin fit	resid./ nm
10.7589	0	0.000	-0.4	-0.020	-20.4
13.9012	1.3241	1.324	0.3	1.324	0.1
17.0832	2.6735	2.674	0.4	2.686	12.3
20.3746	4.0777	4.078	0.3	4.094	16.5
23.659	5.4882	5.488	-0.6	5.500	11.5
26.8481	6.8647	6.864	-0.4	6.864	-0.4
30.0417	8.2505	8.251	0.4	8.231	-19.6
			1.228288		1358.284
		L0	3.917753	L0	3.933943
		a	0.427599	a1	0.427908
		b	0.00039		
		alpha	4.276		4.279
		beta	0.0039		



Gauge block:		ceramic, C 119 21			
Length:	100				
T / °C	dL / µm	quad fit	resid./ nm	lin fit	resid./ nm
10.6328	0	0.000	-0.2	-0.030	-30.1
13.8182	2.9629	2.963	0.2	2.963	0.0
17.0332	5.9658	5.966	-0.1	5.984	17.8
20.3683	9.092	9.093	1.0	9.117	25.2
23.6517	12.1853	12.184	-1.1	12.202	16.9
26.8696	15.226	15.226	-0.3	15.226	-0.3
30.095	18.2858	18.286	0.4	18.256	-29.6
			2.502609		3018.674
		L0	8.747049	L0	8.771166
		a	0.934892	a1	0.935302
		b	0.000571		
		alpha	9.349		9.353
		beta	0.0057		



Gauge block:		zerodur, AMG 100'3			
Length:	100				
T / °C	dL / µm	quad fit	resid./ nm	lin fit	resid./ nm
10.7411	-0.0189	-0.019	0.0	-0.014	5.2
13.8749	-0.0192	-0.019	0.4	-0.019	0.5
17.0611	-0.0202	-0.021	-0.5	-0.024	-3.7
20.3487	-0.0245	-0.025	-0.4	-0.029	-4.7
23.6585	-0.032	-0.031	0.7	-0.035	-2.5
26.832	-0.0397	-0.040	0.1	-0.040	0.1
30.0237	-0.0499	-0.050	-0.2	-0.045	5.1
			1.057341		95.35693
		L0	-0.02434	L0	-0.02861
		a	-0.00154	a1	-0.00161
		b	-0.0001		
		alpha	-0.015		-0.016
		beta	-0.0010		



8. Measurement uncertainty

The participants were asked to state the uncertainty of measurement according to the ISO guide and to detail, if possible, the various components contributing to the combined uncertainty. Table 7 summarises the principal error contributions and the corresponding standard uncertainties of those laboratories who reported these data. The numbers in normal characters refer to steel, the *italic* characters to zerodur.

Type of uncertainty	**OFMET**	**u_s** $10^{-8}K^{-1}$	**VSL**	**u_s** $10^{-8}K^{-1}$	**IMGC**	**u_s** $10^{-8}K^{-1}$	**PTB 3**	**u_s** $10^{-8}K^{-1}$	**NPL**	**u_s** $10^{-8}K^{-1}$
Uncertainty of LS-Fit		0.38 *0.16*		1.3 *2.1*		1.0 *0.7*		7 *7*		
Interfer. length measurement	1.5 nm	0.09 *0.09*			12 nm	3 *3*		4 *4*	8.5 nm	0.5 *0.5*
Air refractive index	--	--		2.7 *2.1*	2 nm	0.5 *0.5*		2 *2*	1.5 nm	
Material temp. meas./calibr.	5 mK	0.41 *0*	17 mK	2.4 *0.2*	14 nm *3 nm*	3.5 *0.8*		2 *2*	5 mK	
Gauge block temp. gradient	<15 mK <40 mK	1.2 *0*			9 nm *6 nm*	2.2 *1.6*			<25 mK	
U (k=2) steel ***U (k=2)*** *zerodur*	$2.7 \cdot 10^{-8}$ K^{-1} *$0.4 \cdot 10^{-8}$ K^{-1}*		$8 \cdot 10^{-8}$ K^{-1} *$6 \cdot 10^{-8}$ K^{-1}*		$10 \cdot 10^{-8}$ K^{-1} *$9 \cdot 10^{-8}$ K^{-1}*		$12 \cdot 10^{-8}$ K^{-1} *$12 \cdot 10^{-8}$ K^{-1}*		$9 \cdot 10^{-8}$ K^{-1} *$6 \cdot 10^{-8}$ K^{-1}*	

Table 7. Estimated contributions to the uncertainty of measurement for the example of a 100 mm steel and zerodur specimen. PTB1 and PTB2 reported only the expanded uncertainty given in table 5.

9. Conclusions

The conclusions shall be up to the participants...
The author would like to thank all participants for their contributions, for keeping so well the time schedule and for their prompt measurement reports. The four standards remain available to the participants and to other laboratories for further measurements and comparisons.

10. Literature

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