Physikalisch-Technische Bundesanstalt (PTB)
Braunschweig und Berlin

Intercomparison of Thermal Expansion Etalons

EUROMET Project 390

Final Report

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Contents

1. Introduction

EUROMET Project 390 covered a comparison of thermal expansion measurements on large material measures of length or bar-shaped bodies carried out in different laboratories. It has been the aim of this project to acquire a general idea of the measurement capabilities, the accuracies achievable and the agreement of such measurements in the different EU countries. The comparison was carried out with the aid of thermal expansion etalons made available by the coordinator (PTB section 5.22B).

2. Description of the comparison etalons

Different types of comparison etalons (gauge blocks, line standards etc.) made of different materials (aluminium, Zerodur, steel, etc.) with different thermal expansion coefficients were used. Their nominal lengths were about 0.5 m.

In detail, the following five etalons were concerned:

Bar number	Material	Bar length (mm)	Cross-section (mm)	Wringable end surfaces	Exp. coeff. (10^{-6} K^{-1})
1	aluminium (Dural)	433.95	20 x 20	no	23
2	steel (gauge block)	500.0	9 x 35	Yes (smaller than'3")	11
3	ceramics (gauge block)	500.0	9 x 35	Yes (smaller than 5")	9
4	Zerodur	501.6	30 x 40	Yes (smaller than I0)	0
5	nickel steel (line standard)	539.2	25 x 30	no	12

3. Modality of the comparison

The comparison was carried out in 1997 and 1998 in the form of an intercomparison. The individual participants had the etalons transported by parcel service.

The intercomparison was carried out among the following metrology institutes: National Physical Laboratory (NPL) in Teddington (GB), Nederlands Meetinstituut VSL B.V. (NMi) in Delft (NL) and Physikalisch-Technische Bundesanstalt (PTB) in Berlin and Braunschweig (D).

Originally, even more institutes in various countries had shown their interest in participating in this intercomparison. However, when the comparison was started they were unable to participate for different reasons. Two PTB sections took part in the comparison measurements, namely section 5.13 "Interferential Length Measurements" in Braunschweig and section 5.22B "Graduations of Length and Angle" in Berlin-Friedrichshagen, which acted as the coordinator.

The work within the scope of this EUROMET Project was carried out by A. Lewis (NPL), G. Kotte and H. Haitjema (NMi), G. Bonsch and R. Mascherek (PTB Braunschweig) and J. Tschirnich and J. Suska (PTB Berlin, coordinator).

The quantity decisive for the comparison was the linear thermal expansion coefficient (TEC) at 20 °C (α_{20}) of the expansion etalons given by the equation $\Delta L(t,20) = L_{P20}[\alpha_{20}(t-20) + \beta(t-20)^2]$ or $\alpha_t = \alpha_{20} + 2\beta(t-20)$, where L_{P20} is the length of the etalon at 20 °C and $\Delta L(t,20)$ the change in the length of the etalon if the etalon temperature changes from 20 °C to t "C. The most important uncertainty components (quantified) and the total uncertainty of α_{20} for the confidence level of 95% (k = 2) were to be given. If possible, the value of the quadratic expansion coefficient β was to be estimated as well.

4. Measurements in the different laboratories

4.1. NPL in Teddington (GB)

The NPL carried out measurements on etalons 2 and 3 in the period from July 23 to August 6, 1997. The measurements were made by means of the primary length bar irterferometer [1] at a series of temperatures inside. This instrument is an absolute interferometer which uses calibrated frequency-stabilized lasers as the light sources.

Length measurements were made using a combination of phase-stepping and multiple-wavelength interferometry. Length measurements are' traceable to the realization of the metre via the calibrated laser wavelengths.

Temperature measurements were made using platinum resistance thermometers and are traceable to ITS-90. The temperature measurements repotted are the mean of two temperatures, measured at each of the supports.

Measurements were made at 6 temperatures in the range 19.9 "C to 29.3 "C. The interferometer features a semi-sealed chamber with active temperature control. The temperature of the chamber was adjusted and the gauges were allowed to stabilize at each temperature following heating. The measurements were performed in the order of increasing temperature.

The measurements at NPL were carried out with utmost care. The same applies to additional measurements of the flatness of the exposed measuring face and the variation in length of the etalons using the same interferometer, which furnished results which were of great interest to the coordinator.

An exact analysis was made of the uncertainty of measurement achieved, based on actual measurement data and their estimated uncertainties (uncertainty at k = 1 for the overall temperature lower than 2 mK and for the overall length smaller than 30 nm).

4.2 NMi in Delft (NL)

At NMi, the expansion measurements were carried out on etalons 1, 2, 3 and 5 in the period from October 1997 to February 1998. Etalon 4 could not be measured because its cross-section was too great. The measurements were made by means of a setup for the measurement of long parallel gauge blocks, whose main components were a Twyman-Green interferometer and three stabilized lasers. The measuring arrangement is described in [2].

A l the etalons were measured as regular gauge blocks. Since etalons 1 and 5 had no optical surfaces, some additional tools were applied (see Fig. 4 of [2]) in order to make it possible to measure them as regular gauge blocks in the interferometer. A ring was attached to both sides of the etalon. A steel optical flat (diameter: 50 mm) mounted in a holder was positioned on the backside of the etalon. The holder was attached to the ring by bolts. Three springs applied the required contact force.

A gauge block in a holder was positioned on the observer side of the etalon. The holder was attached to the ring by bolts. A spherical body was glued on to the gauge block face facing the etalon. The required contact force was applied by a spring. The holder had an opening on both sides of the gauge block, through which the fringes on the optical flat could be observed. Two bolts were used to adjust parallelism between gauge block and optical flat. A normal fringe pattern could thus be observed, allowing the measurements to be carried out in the same way as with a regular gauge block.

The measurements were performed in a rather narrow temperature range (about 2 K for etalons 1, 3 and 5; 3.8 K for etalon 2). The TEC of the etalons was determined on the basis of several length/temperature measurements at each temperature level. Within the respective temperature range (cf. Table 1) 5 to 7 temperature levels were used. The thermal expansion coefficient of the individual etalons was calculated by fitting a quadratic curve to the lengthltemperature points (19 to 26 points) of the respective etalon. The measurements on etalons 1 and 5 were corrected for the length of the attached gauge block and the spherical body and their specific length deviations The measurements lasted for over several months because a relatively high amount of work was required.

The main sources of uncertainty (standard uncertainties,.i.e. at a coverage factor k = 1) associated with the measurements of the expansion coefficients are the change in length (AL = 0.02 pm or $u_{\Delta L} = 1.0\ 10^{-3}\ \alpha_P$ for etalons 1 and 2 and $u_{\Delta L} = 2.0\ 10^{-3}\ \alpha_P$ (α_P in K-') for etalons 3 and 5) and the temperature of the etalons (At = *6* mK or $u_{\Delta t} = 3.2\ 10^{-3}\ \alpha_P$ for etalons 1 and 5, $u_{\Delta t} = 1.7\ 10^{-3}\ \alpha_P$ for etalon 2 and $u_{\Delta t} = 3.0\ 10^{-3}\ \alpha_P$ for etalon 3).

4.3. PTB in Berlin-Friedrichshagen (D)

The measurements in the coordinator's laboratory (PTB1) were carried out in the second quarter of 1997 and the first quarter of 1998 using the so-called alpha measuring device [3, 4]. For the measurements the etalon was placed between the two corner reflectors inside the thermostatically controlled box of this device. The corner reflectors were the main components of a special polarization interferometer.

Length measurements are traceable to the realization of the metre via the red wavelength of a calibrated frequency-stabilized He-Ne laser.

The change in the etalon's length was calculated from shift measurements of the interference fringes taking the dilatometer correction for the zero length (ΔL_T = 10 nm) and the change of the air refraction (An = 2 10^{-8}) into account. The temperature of each etalon was measured using two Pt-l00 resistance thermometers; it is traceable to ITS-90 C (At = 2 mK per step). Measurements were carried out in six 10 K temperature steps (1012013014013012011O) in the range from 10 °C to 40 "C. The temperature variation at the temperature levels was 3 mK per hour at most.

The main sources of uncertainty (standard uncertainties, i.e. at a coverage factor k := 1) associated with the measurements of the expansion coefficients are the zero ccrrection ($u_{\Delta LT}$ = (11Lp) 10^{-9} K^{-1} (L_P in m)), the air refraction ($u_{\Delta n}$ = 2 10^{-9} K-') and the temperature of the test piece ($u_{\Delta t}$ = 2 10^{-4} α_P). The complete uncertainty of the phase change is included in the value of the standard deviation s_α of the individual α_{Pt}-points from the linear curve fit line to the a_{pt}-points versus temperature. Based on the results of a great number of earlier measurements the standard deviation amounts to s_α = (8 + 0.2 α_P *c* 6/L_P) 10^{-9} K'' (α_P and L_P in units of 10^{-6} K^{-1} or m) if temperature intervals of 10 K are used.

A calculation of the overall uncertainty of the a_t-values according to [5], at the confidence level of about 95 % (k = 2), was carried out, taking all sources of uncertainties into account. If the number of the temperature levels used is not smaller than 7 (that is to say, 6 of the measured a_t-values) and temperature steps of 10 K are taken, overall uncertainties of $u_{\alpha t}$ = (8+0.4 α_P+5/L_P) 10^{-9} K-' (α_P and L_P in units of 10^{-6} K^{-1} or m) can be reached.

4.4. PTB in Braunschweig (D)

The measurements in section 5.13 (Interferential Length Measurements) of the PTB in Braunschweig (PTB2) on etalons 2 and 3 were carried out in the period from March 4 to April 2, 1998 using the vacuum length comparator [6] for long parallel gauge blocks. The lengths L_P of the etalons were determined by fundamental intsrferometry, for each etalon at five temperatures in the range from 14,9 "C to 25,1 "C. The α_{20}-values and ß-values were calculated from these 5 length/temperature-values respective by using the equation $L_P = L_{P20}(1 + \alpha_{20}(t-20) + \beta(t-20)^2)$, t standing for the Celsius temperature of the International Temperature Scale of 1990 (ITS-90). Laser wavelength standards internationally recommended were used for the length measurements. For the measurements, a plane steel plate had been wrung to the left measuring face of each parallel gauge block (etalons 2 and 3).

5. Measurement results

The measurement results together with the associated uncertainties are presented in Table 1 and Fig. 1. The latter shows the α_{20}-values obtained of etalons 2 and 3 (gauge blocks) in units of 10^{-6} K^{-1} measured by all participating laboratories, together with the u_{α}-values.

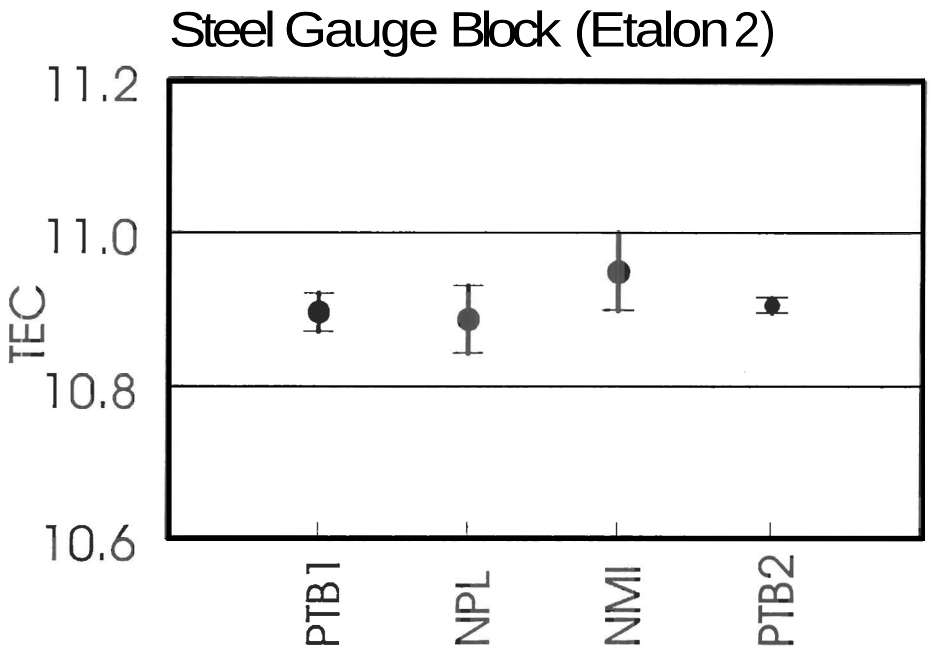
The comparison shows satisfactory agreement, expressed as the difference between the largest and the smallest value, which is 0.062 10^{-6} K-' for etalon 2 (steel) and 0.092 10^{-6} K^{-1} for etalon3 (ceramics).

With the exception of etalon 5 whose measurement was somewhat difficult because a line standard was concerned and only two laboratories were able to participate, the expansion coefficients α_{20} and β measured by the different institutes approximately agree within the range of the uncertainties of measurement stated by the individual laboratories.

All laboratories which were able to carry out the measurements in a somewhat larger temperature range also tried to estimate the quadratic expansion coefficients β and have achieved overall uncertainties of measurement of less than $5x10^{-9}$ K^{-2}.

Insti-tution	Etalon No.	Measured (monthlyear)	Range of t used ("C)	α_{20} (10^{-6} K^{-1})	β (10^{-9} K^{-2})	u_α (k=2)	u_β (k=2)
PTB1	1	5/97	10 to 40	22.257	11.9	0.030	3.0
NMi	1	11/97	18.9 to 20.9	22.27		0.15	
PTB 1	1	3/98	10 to 40	22.245	12.3	0.030	3.0
PTB1	2	5/97	10 to 40	10.897	6.2	0.025	2.5
NPL	2	7/97	19.9 to 29.3	10.888	8.36	0.044	4.69
NMi	2	12/97	18.7 to 22.5	10.95		0.05	
PTB2	2	3/98	15 to 25	10.907	6.0	0.010	3
PTB1	3	4/97	10 to 40	9.206	5.5	0.025	2.5
NPL	3	7/97	19.9 to 29.3	9.178	8.13	0.044	4.64
NMi	3	1/98	18.8 to 21.0	9.12		0.08	
PTB2	3	3/98	15 to 25	9.212	10	0.010	3
PTB1	3	4/98	10 to 40	9.199	6.0	0.025	2.5
PTB1	4	4/97	10 to 40	-0.010	-1.0	0.020	2.0
PTB1	4	3/98	10 to 40	-0.003	-1.3	0.020	2.0
PTB1	5	5/97	10 to 40	11.451	4.2	0.025	2.5
NMi	5	2/98	19.0 to 21.0	11.70		0.08	
PTB1	5	4/98	10 to 40	11.457	4.24	0.025	2.5

Table 1



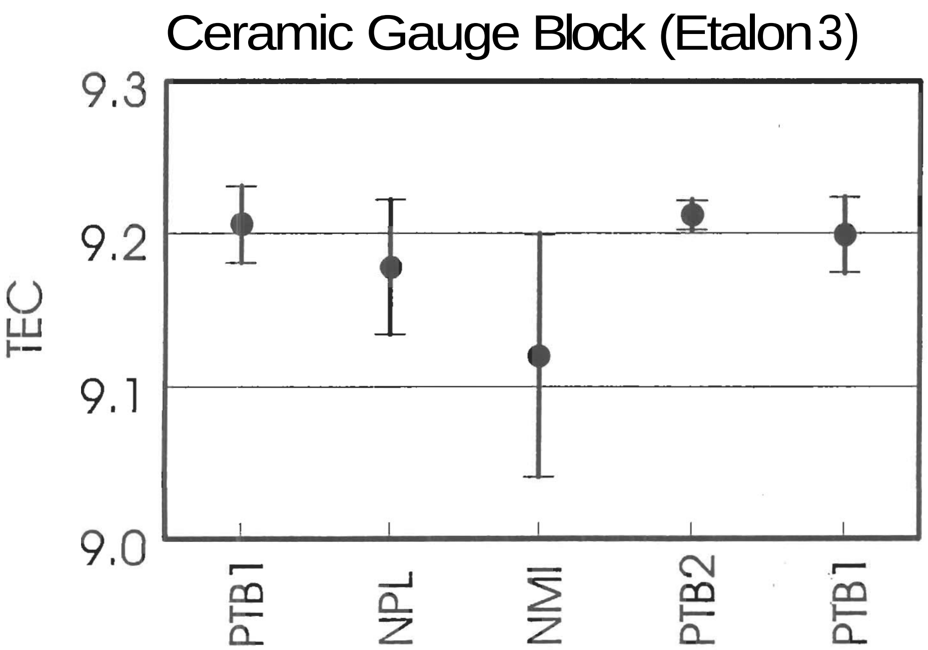


Figure 1: TEC-values at 20 °C (in units of 10E-6/K) and their uncertainties (k=2) received by the different laboratories in temporal sequence of measurements

6. Conclusions

EUROMET Project 390 has shown that only very few institutions in Europe are in a position to carry out precise measurements of the thermal expansion of length standards or bar-shaped bodies with lengths ranging from 200 mm to 1.2 m. Only very special test pieces which meet special requirements for material, end surfaces, line marks etc. can usually be measured, or great effort must be spent, for example by the mounting of mirrors, to change existing test pieces into objects if the kind required.

The reason for this is that no special measuring devices are available for the determination of the TEC and that, therefore, existing length measuring devices are used for thermal expansion measurements. The time and effort to be spent on such measurements is, therefore, considerable, and the temperature ranges which can be used are relatively small.

The PTB's alpha measuring device is specially designed for expansion measurements. It allows expansion measurements of a more universal. kind to be carried out, i.e. no special requirements must be met with regard to the end surfaces, th3 material or the provision of marks (e.g. lines); at the same time, a relatively wide temperature range can be used.

As only few institutes participated in the comparison described here, no final statement can be made concerning the agreement achievable inside Europe in measurements of this kind. It can, however, be concluded that in the measurement of the thermal expansion coefficient at 20 °C agreement of about $1 \cdot 10^{-7}\ K^{-1}$ can be achieved with high probability. It appears that insufficiently thermostating of the test pieces and the fact that the temperature ranges that can be used are too small are the decisive uncertainty factors. A worldwide comparison using similar or even the same test pieces seems desirable because the number of participating countries or institutes would then be considerably greater which would allow much more precise information on the quality level reached in such measurements.

The five expansion etalons used in the comparison of the linear expansion coefficients that were measured have been deposited at PTB section 5.22B and can, upon request, be made available at any time to EUROMET countries for comparison measurements. This is the reason why Table 1 also shows the results of the measurements of etalon 4 although only the pilot laboratory (PTB1) was in a position to carry out measurements on it.

Acknowledgement

The coordinator would like to thank NPL and NMi for the good cooperation and for the trouble taken to carry out the measurements and to draw up the very informative reports.

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