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Abstract. We report on a successful twenty year study, involving a National Metrology Institute and a commercial instrument manufacturer, in the field of gauge block measurement by optical interferometry. The National Physical Laboratory (NPL) has made measurements of length artefacts on its own equipment and on thirty copies of this instrument that are now in use worldwide. Several NPL length artefacts have been measured on all thirty-one instruments including repeated re-measurement of the artefacts on the same equipment at NPL, over a period of twenty years. This pool of data therefore allows for quantitative examination of the temporal stability of these standards as well as the long-term performance of the instruments and of the evolving instrument design. Many of the laboratories which now own these instruments have taken part in international comparisons under the Comité International des Poids et Measures' (CIPM) Mutual Recognition Arrangement (MRA). Combining the data from these key comparisons with the data obtained by NPL allows for a novel analysis - this data can be regarded as coming from an international key comparison, where both the artefact and the measuring instrument are circulated amongst the participants – the remaining variability being due to operator skill at the different laboratories, and the quality of their independent traceability chains.

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(Some figures in this article are in colour only in the electronic version)

1. Gauge blocks

Invented by Johansson in 1896 and in widespread use for more than a century, gauge blocks are still one of the most popular artefacts for disseminating the unit of length, the metre. Gauge blocks are robust, available in several materials, and combinations of gauge blocks from a set can cover the length range from 0.5 mm to 1000 mm in 1 µm increments. Calibration uncertainties of the order of tens of nanometres can be achieved for individual gauge blocks of the highest quality. Gauge blocks of lower quality grades [1-3] may be calibrated by comparing them with high quality gauges, using a mechanical comparator.

At some point in the gauge block traceability chain [4], a comparison is made between the physical length of a gauge block and an optical radiation of known wavelength, ultimately traceable to a realisation of the metre [5, 6]. Typically the wavelength used is that of a stabilized He-Ne laser operating at 633 nm, but other laser and spectral lamp wavelengths are also in common use. This comparison is usually performed as a calibration either at an accredited laboratory or one of the National Metrology Institutes of countries that are signatories of the Metre Convention [7].

The calibration of gauge blocks against an optical wavelength standard is usually performed in a specially designed interferometer. Michelson and Benoit first reported on a comparison between a standard metre bar and the wavelength of red light emitted by cadmium in 1893 [8, 9]. In effect, they performed the reverse experiment to what is now regarded as gauge block interferometry – they calibrated the wavelength using the material standard as a reference. This idea lead to the eventual re-definition of the metre in terms of a spectroscopic wavelength in krypton [10] and finally, to the most recent re-definition of the metre in 1983, in terms of the distance travelled by light in a small fraction of a second. Historically, several designs of interferometer have been used for the measurement of gauge blocks. These generally come from two classes: static interferometers using fringe pattern evaluation [11-13], and, later, moving mirror interferometers using fringe counting and fiducialisation based on short coherence white light fringes [14, 15]. All the interferometer designs measure the length of the gauge block in relation to the wavelength of the light used, providing a clear traceability route to the metre.

2. Gauge block measurement by interferometry

To measure the length of a gauge block in terms of an optical wavelength, several steps are necessary. First, the gauge has to be wrung [16] to a flat plate (platen) of similar material and left to reach thermal equilibrium inside the interferometer. The interferometer measurement beam is then aligned with the gauge block and platen surface normals, either by individual adjustment or by precision tolerancing of the platen mount as part of the interferometer design. After thermal equilibrium has been achieved, usually in a laboratory that is temperature controlled to the standard reference temperature [17] of 20 °C, the measurement process is undertaken.

The model equations [18] used for length determination are as follows. Usually, the reported result is the deviation, d, of the actual gauge block length, l, from the nominal length, L.

$$d = l - L \tag{1}$$

$$d = l_{fit} - L + l_t + l_w + l_\Omega + l_A + l_n + l_G + l_\varphi \tag{2}$$

The parameters of equation 2 are identified and discussed in detail below.

The primary influence parameter, which is then corrected for the effect of non-ideal conditions, is l_{fit}. This is the best-fit solution for gauge block length, based on an analysis technique known as the method of exact fractions [16]. This technique uses measurements at several wavelengths that are then compared against each other over a range of possible solutions, to choose the correct solution corresponding to the gauge block length. If the number of wavelengths used in the interferometer is q, then l_{fit} can be expressed as

$$l_{fit} = \frac{1}{q}\sum_{i=1}^{q}(\kappa_i + F_i)\frac{\lambda_i}{2} \tag{3}$$

where λ_i is the wavelength of light source i, F_i is the measured fringe fraction and κ_i is an integer representing a fringe order. For given values of F_i and λ_i there are an infinite number of solutions for l_{fit}, based on (3). However the method of exact fractions only allows solutions where there is good agreement between the results obtained for different wavelengths. With careful selection of the wavelengths, (3) leads to only one solution, where the results across all wavelengths are sufficiently close to one another, and sufficiently close to the nominal value for l. The nominal value for the gauge block length should be checked, prior to measurement by interferometry, by less accurate mechanical means or from knowledge of previous measurements. The more accurately the wavelengths are known and the more accurately the parameters F_i are measured, the fewer wavelengths are required to guarantee a unique solution close to the nominal length of the gauge block. Note that in the NPL interferometer, after equation 3 has been used to determine the correct solution, the length calculation relies solely on the red laser wavelength, as this has a smaller uncertainty than that of the other laser(s).

The term l_t is the gauge temperature correction, based on ΔT, the departure of the gauge temperature, t_g, from 20 °C and the gauge's coefficient of thermal expansion, α

$$l_t = \Delta T\, \alpha L \tag{4}$$

$$\Delta T = 20 - t_g \tag{5}$$

The term l_w represents the thickness of the wringing film between the gauge and platen surfaces. The gauge block length is defined to include the thickness of one wringing film [1] and so the expectation value of l_w is actually zero. However variability of wringing technique between operators and the different wringing qualities of platens, lead to a variation in the achieved wringing thickness and hence an uncertainty in l_w when comparing different measurements.

A correction, l_Ω, is often necessary to account for the finite aperture size of the interferometer optics causing an obliquity correction [19] and any residual wavefront errors of the optics are collected into the term l_A.

Due to the measurement taking place in air, there is a correction, l_n, for the refractive index, n, of the air to account for the difference between the ambient optical wavelength of the laser light, and the calibrated (vacuum) wavelength

$$l_n = (n - 1)L \tag{6}$$

It is usual to calculate the refractive index, n, from measurement of parameters including the air pressure, p, temperature, t_a and humidity, h, through the use of empirical equations based on the work of Edlén and subsequent re-validations and re-measurements [20].

Geometrical errors of the gauge block which may influence the central length determination, such as imperfect flatness, are accounted for in the term l_G. The difference in surface roughness and complex refractive indices of the platen and gauge block surfaces (which account for the difference in the apparent optical length compared with the mechanical length) are handled by the so-called ‘phase correction’, l_φ.

Thus, in order to measure the length of the gauge block, several parameters need to be measured at the same time, for each wavelength: p, t_a, h, t_g, and F_i. Prior calibration of each vacuum wavelength, λ_i is needed, as well as a sufficiently accurate estimate of l to allow κ_i to be estimated to within a few integer orders. Also, the operator (or result calculation system) needs to have detailed knowledge of l_w, l_A , l_Ω , l_G and l_φ to apply these corrections accurately, or allow for their influence in the uncertainty calculation. In early interferometers, the determination of many parameters was performed visually by the operator – fringe fraction estimation by viewing a static fringe pattern through an eyepiece, reading of analogue instruments for air temperature, pressure and humidity values. Multiple measurements of these parameters were required for each gauge block, requiring constant re-focussing and accommodation of the operator’s eyes. Not surprisingly, the work was tiring and operator-dependent offsets in the results were not uncommon.

3. NPL Gauge Block Interferometer

In order to reduce the measurement time, remove the operator bias, improve the accuracy and eliminate the occurrence of errors due to operator fatigue, NPL designed and built a new automatic gauge block interferometer [21]. The new instrument took advantage of several technological advances of the mid to late 1980s: instrumentation with standardised computer interfaces (GPIB/IEEE-488), programmable micro computers with instrumentation interfaces, custom-designed image sampling electronics which could work at video frame rates, and NPL-designed turn-key high stability Zeeman-stabilised He-Ne laser systems, which allowed for a reduction in the number of wavelengths required from four to two [22]. The instrument is shown in schematic form in figure 1.

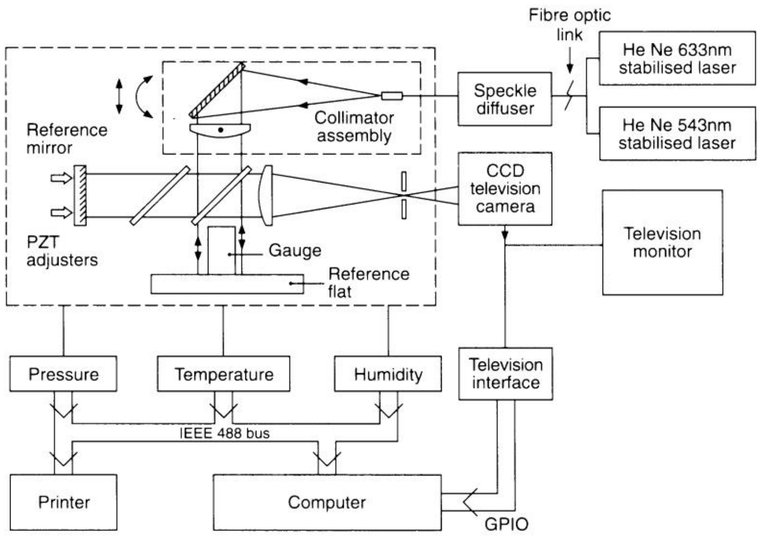

Figure 1 - schema of the NPL gauge block interferometer

After initial prototyping and detailed design within NPL, the instrument and operating software were licensed to Tesa Metrology Ltd. (TML) (now Hexagon Metrology Ltd.). TML sold twenty-two copies of the NPL instrument between 1988 and 1997. Meanwhile, NPL had been developing phase-stepping interferometry for the measurement of long gauge blocks [23-25] and applied this new technology to the existing Gauge Block Interferometer by replacing the computer system and modifying the reference mirror mount to allow for nanometric-precision motion control of the reference mirror. The updated design was also licensed to TML (by then re-named Browne & Sharpe Ltd.) and the first commercial phase-stepping Gauge Block Interferometer was sold in 1999. Other laboratories have since started several programmes of updates to their existing interferometers converting them to use laser light sources and CCD imaging systems [26-28] and also adding phase-stepping technology [29, 30].

A simplified uncertainty budget for the original NPL interferometer, in accordance with international guidelines [31], is given in Table 1, showing the individual components of uncertainty together with the root sum square of these components. The uncertainty budget assumes a typical coefficient of thermal expansion of steel gauge blocks to be 11.7×10^{-6} K^{-1} and the maximum temperature departure from 20 °C to be ± 0.1 °C. In addition to the instrument uncertainty, there is another uncertainty that needs to be considered, which is the uncertainty in performing the phase stack technique (or ellipsometer or scatterometer measurement) used to determine the phase correction. Typically this uncertainty contribution is around 5 nm. A detailed uncertainty calculation also has to take into account the fact that gauge blocks are typically measured twice, once with each of the two faces wrung, and the mean result taken. Several uncertainty components are correlated between the two measurements, whereas others are not. The net effect is a slight reduction in the overall uncertainty sum to 1.35×10^{-7} L in quadrature with 8.8 nm, leading to typical expanded uncertainties of 20 nm (k = 2) for the shortest gauge blocks, to around 40 nm (k = 2) for 100 mm gauge blocks, when measured in the interferometer.

4. Interferometer verification procedure

To date, thirty copies of the NPL automatic instrument have been sold commercially: twenty-two of the original design and eight of the phase-stepping model. A major part of the quality control process for each interferometer is independent inspection of the interferometer's performance by comparison with measurements performed by, and at, NPL. Since the very first instrument was built, a selection of tungsten carbide (TC) and steel (S) gauge blocks in both metric and inch units have been measured on the commercial copies and the NPL reference instruments. These gauges range in size from 1 mm (TC) to 300 mm (S). The gauges were chosen to test all aspects of the interferometer measurement capability, from the measurement of short and long lengths (including temperature compensation), to the measurement of flatness and variation in length. The gauges in inch units were selected as having calibration results dating back many years, showing good stability, and were included to check the numerical conversions to and from these units in the software (several NMIs still measure gauges in inch units for certain customers).

As well as these gauge blocks, several platens of the corresponding material, *i.e.* steel platens for steel gauge blocks, have been set aside. The gauge blocks and platens have not been modified or refurbished in any way over the last twenty years. Since June 1999 the TC gauge blocks have been permanently wrung to the same platens (one small platen per gauge block) and thus the effect of wringing film variation has been removed from repeated measurements of these gauge blocks since that date.

Additionally, two pairs of sub-micrometre 'gauge blocks' have also been manufactured and measured, both by the gauge block interferometers, and other full-field phase-stepping optical testing interferometers. These thin-film 'fringe fraction standards' are in the form of 9×35 mm cross-section step height standards of 100 nm and 200 nm nominal thickness. They were formed by depositing the relevant layer thickness of chromium onto silica and zero expansion glass ceramic optical flats, then over-coating the entire surface (step and substrate) with chromium to produce a very flat, sub-micrometre thickness 'wrung' gauge block-shaped standard. Chromium was chosen as the film and overcoat material as it has a similar reflectance to that of gauge block surfaces, ensuring similar fringe contrast in the interferometer.

The set of gauge blocks in two materials and the thin film standards allowed for separate testing of the length dependent and length independent contributions of the instrumentation errors, and the subsequent permanent wringing of the TC gauges allows for testing of the error sources not-associated with the wringing. The two materials, steel and tungsten carbide have quite dissimilar coefficients of thermal expansion (CTEs), namely 11.7×10^{-6} K^{-1} and 4.2×10^{-6} K^{-1}, respectively, allowing for testing of the thermal expansion compensation capabilities of the instruments.

Table 1. Summation of uncertainty sources (assuming $\alpha = 11.7 \times 10^{-6}$ K^{-1} and $\Delta T = 0.1$ °C). Emboldened values represent quadrature summations of individual components.

Uncertainty component $u(x_i)$	**Source**	**Standard uncertainty** $u(x_i)$	**Sensitivity coefficient** $c_{x_i} = \frac{\partial f}{\partial x_i}$	**Length uncertainty** $u_i(d) = \lvert c_{x_i} \rvert \times u(x_i)$
$u(l_{fit})$	Reference laser frequency Laser frequency drift Laser frequency stability Fringe fraction estimation	2.5×10^{-11} 1.0×10^{-8} 1.0×10^{-9} 1 nm	L L L 1	$2.5 \times 10^{-11}\,L$ $1.0 \times 10^{-8}\,L$ $1.0 \times 10^{-9}\,L$ 1 nm
$\boldsymbol{u_c(l_{fit})}$		**1.0×10^{-8}** **1 nm**	L 1	**$1.0 \times 10^{-8}\,L$** **1 nm**
$u(l_t)$	PRT calibration PRT drift Temperature gradient Bridge accuracy Gauge block CTE	0.005 °C 0.002 °C 0.010 °C 0.003 °C 5.8×10^{-7}	$\alpha \times L$ $\alpha \times L$ $\alpha \times L$ $\alpha \times L$ $\theta \times L$	$5.9 \times 10^{-8}\,L$ $2.3 \times 10^{-8}\,L$ $1.2 \times 10^{-7}\,L$ $3.5 \times 10^{-8}\,L$ $5.8 \times 10^{-8}\,L$
$\boldsymbol{u_c(l_t)}$				**$1.5 \times 10^{-7}\,L$**
$\boldsymbol{u(l_w)}$	**Wringing variation**	**5 nm**	**1**	**5 nm**
$u(l_\Omega)$	Obliquity effect Source size	5.8×10^{-9} 8.7×10^{-9}	L L	$5.8 \times 10^{-9}\,L$ $8.7 \times 10^{-9}\,L$
$\boldsymbol{u_c(l_\Omega)}$		**1.1×10^{-8}**	$\boldsymbol{L}$	**$1.1 \times 10^{-8} L$**
$\boldsymbol{u(l_A)}$	**Wavefront error**	**5.2 nm**	**1**	**5.2 nm**
$u(l_n)$	Edlen equation Air temperature Air pressure Air humidity Air CO_2 concentration	1.0×10^{-8} 0.024 °C 0.12 mbar 0.15 °C DP 100 ppm	L $9.3 \times 10^{-7}\,L$ $2.7 \times 10^{-7}\,L$ $3.5 \times 10^{-8}\,L$ $1.5 \times 10^{-10}\,L$	$1.0 \times 10^{-8}\,L$ $2.2 \times 10^{-8}\,L$ $3.2 \times 10^{-8}\,L$ $5.4 \times 10^{-9}\,L$ $1.5 \times 10^{-8}\,L$
$\boldsymbol{u_c(l_n)}$		**4.3×10^{-8}**	$\boldsymbol{L}$	**$4.3 \times 10^{-8}\,L$**
$\boldsymbol{u(l_G)}$	**Flatness errors of gauge**	**1 nm**	**1**	**1 nm**
$u(l_\varphi)$	Complex refractive index Surface roughness	2° 5.8 nm	λ/720° 1	1.8 nm 5.8 nm
$\boldsymbol{u_c(l_\varphi)}$		**6.0 nm**	**1**	**6.0 nm**
	OVERALL SUM (k = 1)			**$1.6 \times 10^{-7}\,L$** **9.5 nm**

For each commercial copy sold, the gauge block and thin film samples were measured at NPL and then inside the test instruments whilst located at TML. One 25 mm gauge block, measured on the first two interferometers, became damaged and was not used again and the 50 mm tungsten carbide gauge was only introduced in 1995. In June 1993 the standard 4 inch steel gauge was unavailable and was substituted. The fringe fraction standards were manufactured and first used in 1993, and were replaced by higher quality copies in 1999. Apart from these changes, all gauges have been measured on all instruments over the last twenty-year period, including multiple measurements at NPL on the two NPL instruments (NPL has copies of both the original and phase-stepping versions of the interferometer). The measurement date for each instrument is shown in table 2. Identification by serial number (S/N) allows for comparison of results in figure 2 through figure 7 with the key comparison analysis in section 6 of the paper.

Table 2. Measurement date for each instrument.

S/N	01	02	03	04	05	06	07	08	09	10
Test Date	Nov 1988	Nov 1988	Jun 1989	Nov 1989	Nov 1990	Nov 1990	Dec 1990	Aug 1991	Aug 1991	Oct 1991
S/N	11	12	13	14	15	16	17	18	19	20
Test Date	Apr 1993	May 1993	Jun 1993	Oct 1993	Jul 1994	Aug 1994	Sep 1995	Oct 1995	Nov 1995	Jan 1997
S/N	21	22	23	24	25	26	27	28	29	30
Test Date	Jun 1997	Nov 1999	Nov 1999	Feb 2000	Jan 2002	Oct 2003	Nov 2003	Sep 2004	Oct 2004	Oct 2007

5. Results of twenty years of measurements

5.1. Stability of gauge blocks

Figures 2 through 7 show the results obtained for a selection of gauge blocks and fringe fraction standards with the poorest stability - results for other items are similar to each other and are excluded for brevity. These figures include error bars representing expanded uncertainty (k = 2). Measurements made at NPL are marked with solid squares and solid uncertainty bars, and measurements on the test instruments are shown with empty circles and dashed uncertainty bars. The uncertainties are similar to those given in table 1, except the variation in wringing film thickness term, $u(l_w)$, and the phase correction term, $u_c(l_\varphi)$ have been excluded from measurements of the TC gauges after June 1999 (the gauges are permanently wrung). Uncertainties for test instrument results are increased in some cases, reflecting the actual temperature stability at the time of measurement.

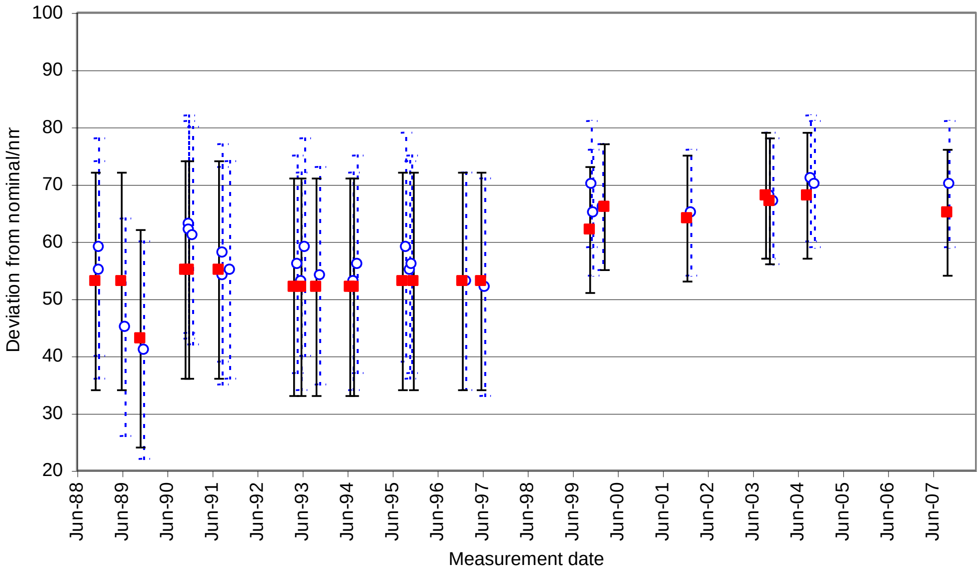

Figure 2. Measurement history for the 6 mm tungsten carbide gauge block. Error bars show expanded uncertainty (k = 2).

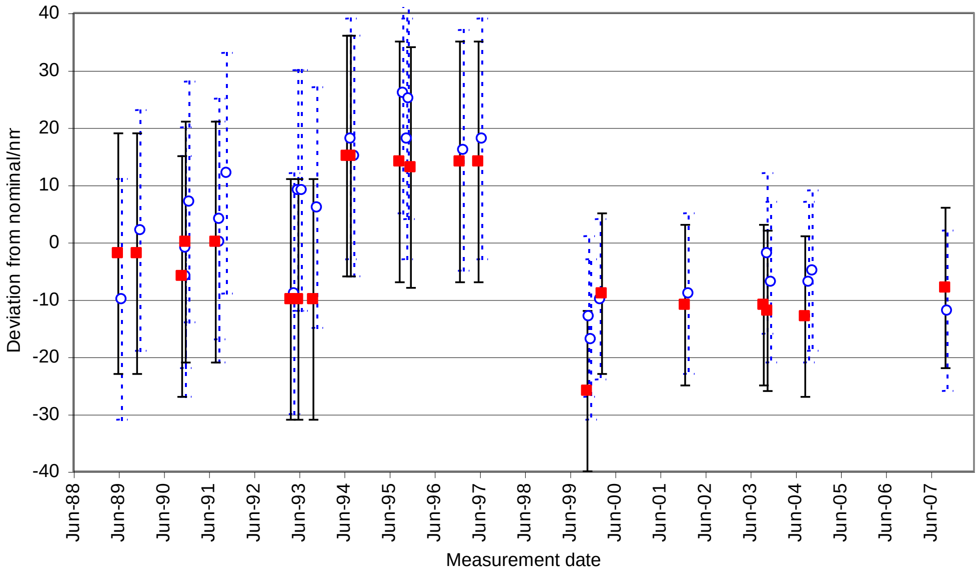

Figure 3. Measurement history for the 25 mm tungsten carbide gauge block. Error bars show expanded uncertainty (k = 2).

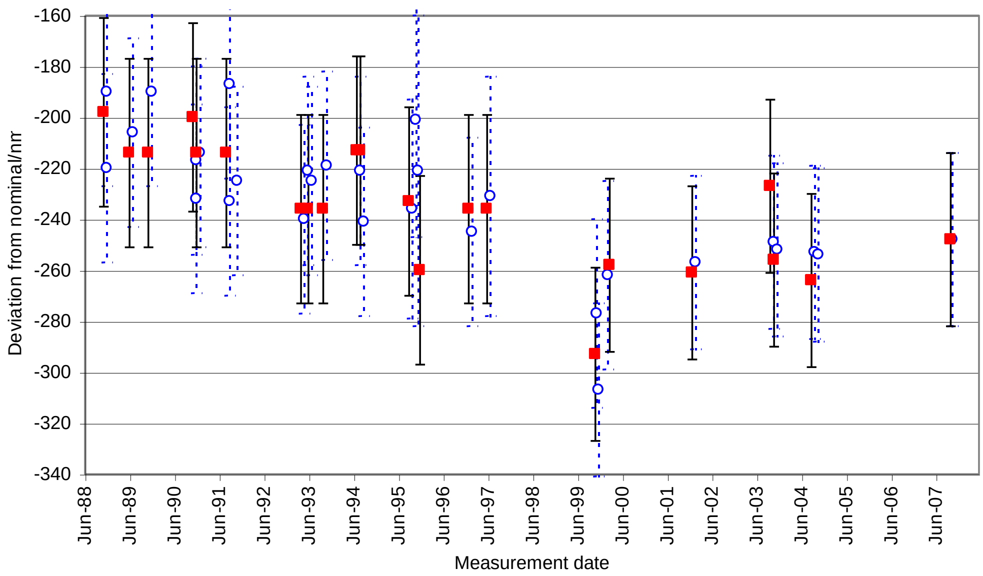

Figure 4. Measurement history for the 100 mm tungsten carbide gauge block. Error bars show expanded uncertainty (k = 2).

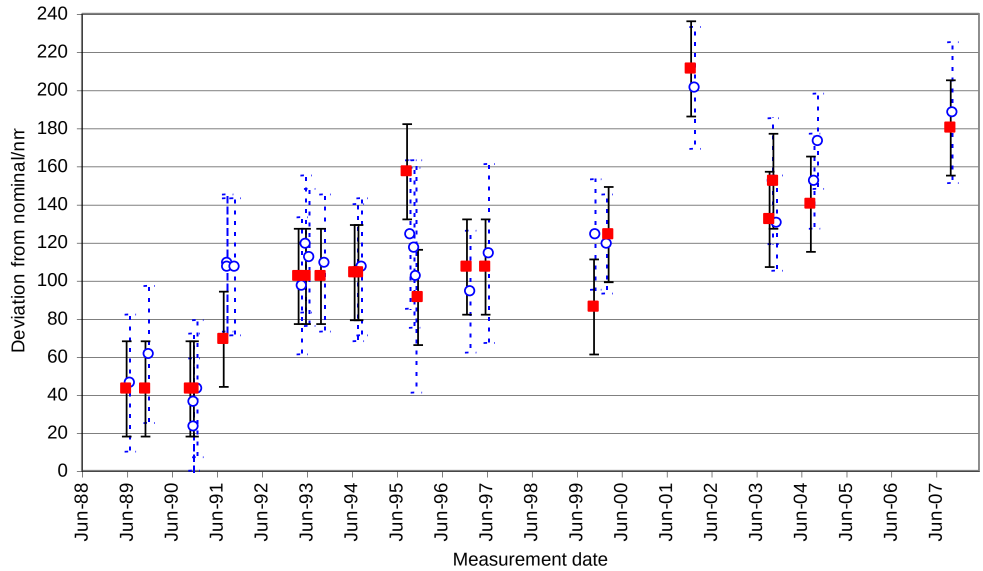

Figure 5. Measurement history for the 2 inch steel gauge block. Error bars show expanded uncertainty (k = 2).

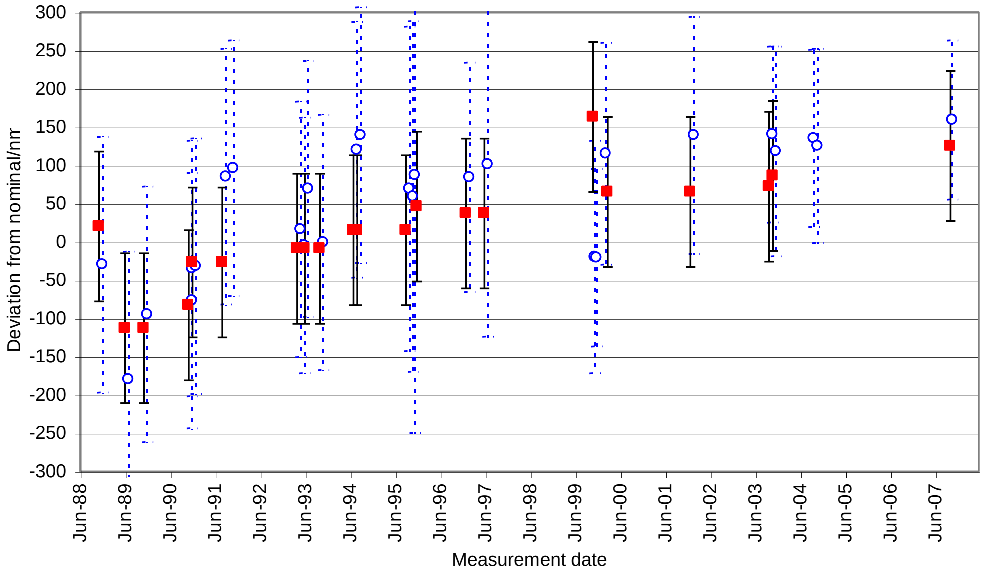

Figure 6. Measurement history for the 300 mm steel gauge block. Error bars show expanded uncertainty (k = 2).

Stability of the gauge blocks can be determined from the NPL measurement results, which have been made using the same equipment throughout. The NPL interferometers have not been altered or moved over this period and the only changes made were the re-calibrations of the ancillary sensors. Most of the measurements were made using the same operator. Examination of the available data shows that most gauge blocks are very stable - figures 2 through 6 show the gauges with the poorest stability. There appears to be a long term increase in length of two of the steel gauge blocks: the 2 inch gauge block has lengthened by approximately +5 nm/year, and the 300 mm gauge block has exhibited lengthening of approximately +10 nm/year. Less certain, is a possible contraction of the 100 mm tungsten carbide gauge block of around -2 nm/year. All these length changes appear to be slowing with time, *i.e.* the stability improves with age. The steel gauge blocks were manufactured several decades before these measurements were started and were expected to be stable. The instability is due to any residual austenite, left in the bulk material at the end of the manufacturing and hardening process, being transformed into martensite. This transformation process results in a net increase in volume leading to elongation of the gauge block [32, 33]. The length change is difficult to predict as it depends on the specific details of the heat treatment that was used for each individual gauge block. It should also be noted that the steel gauge blocks are not, and have never been, permanently wrung to a platen. Each measurement of the 2 inch, 4 inch and 300 mm steel gauge blocks requires a new wring to be made, leading to increased variation in the results.

The 6 mm TC gauge shows a +10 nm step change between June 1997 and November 1999. The 25 mm TC gauge shows a +25 nm step between October 1993 and July 1994 and -25 nm step between June 1997 and November 1999. These step changes correspond to changes in platens, showing that the variability in the wringing thickness and/or phase correction are of this order. Since November 1999 the TC gauges have remained permanently wrung to platens.

Table 3 summarises the results for each gauge block in terms of the maximum difference between a test instrument and the NPL reference result obtained at around the same time, as well as the standard deviation of the results. There is a clear length dependent trend for both the difference and the standard deviation, as well as a material dependency – the differences for the steel gauges are generally twice those for tungsten carbide gauges of a similar size. This may be a result of thermal effects due to the higher coefficient of thermal expansion of steel. The higher standard deviation for the steel gauges is likely to be due to repeated re-wringing of these gauges.

Table 3. Summary of gauge measurement result statistics.

Material	Nominal length	Maximum difference / nm	Standard deviation / nm
TC	1 mm	5	2.6
TC	3 mm	12	4.5
TC	6 mm	8	3.4
TC	25 mm	19	6.5
TC	50 mm	21	10.6
TC	100 mm	39	17.6
S	2 inch	40	21.2
S	4 inch	74	28.3
S	300 mm	184	74.3

The results for fringe fraction samples FF2 and FF3 (not shown) indicate almost no change since the resolution of the fringe fraction result recorded at the time was only 0.01 fringe (3.2 nm). With the advent of the phase-stepping software, measurements of fringe fraction samples FFA and FFB have been recorded with 0.001 fringe resolution. The NPL measurements (figure 7) show that these are stable within 6 nm. Because these standards are so thin, their measurement is unaffected by changes in temperature, refractive index, laser wavelength or alignment. Neither are they subject to phase correction nor wringing variation. They are of interest because they test the fringe fraction measurement capability of the interferometer (image processing, optical wavefront quality, data fitting).

During the twenty-year period, the ancillary instrumentation of the NPL interferometers (the pressure, humidity and temperature sensors, the laser wavelengths, PRTs, reference resistors) have been re-calibrated at least ten times and the uncertainty associated with those instruments is included in the uncertainty evaluations.

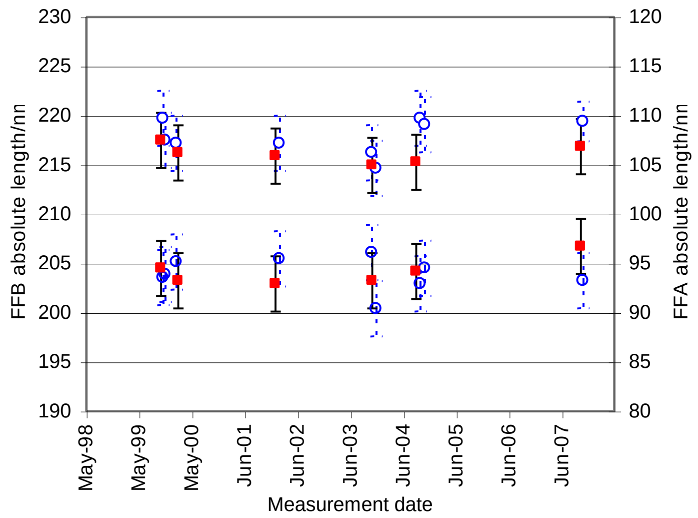

Figure 7. Measurement history for fringe fraction standards FFA (upper series) and FFB (lower series). Error bars show expanded uncertainty (k = 2).

5.2. Verification of interferometers

As well as showing the stability of the gauges (by viewing just the NPL data), figures 2 through 7 also show how well the measurements on the test instruments compare with the reference measurements at NPL, made at almost the same time. The results for all gauges, measured by all test instruments, show agreement with the NPL results well within the combined uncertainties of both instruments and over 95 % of the differences are within the uncertainty of either instrument. The instruments can be compared with each other only by individual comparison against the NPL instrument, because the gauge blocks were not sufficiently stable over the twenty-five year period to allow for direct comparison between early and later results on the same gauge block. The results, in terms of difference from the NPL instrument result obtained at the same time, were averaged across all instruments to give a mean difference for each gauge block. Each instrument's deviation from the mean difference can be considered as representing the measurement error, for that gauge, obtained by the instrument. The mean differences themselves can be regarded as being equal to the measurement error of the NPL instrument, *i.e.* a mean difference of 5 nm indicates the NPL instrument has a measurement error of –5 nm. The deviation from mean difference, for each gauge block, is given for each instrument, in table 4. The values in table 4 represent the best estimates of the measurement error for each instrument, for each measured gauge block.

6. A virtual key comparison ?

To date, sixteen of the interferometers, which are now owned and operated by national metrology institutes, have taken part in international key comparisons of gauge block measurement by interferometry, organised under the CIPM's Mutual Recognition Arrangement [34]. Reports on comparisons CCL-K1, EUROMET.L-K1, EUROMET.L-K1.1, APMP.L-K1, APMP-L.K1.1 and SIM.L-K1 are published and available from the Key Comparison Database [35].

Table 4. Individual instrument performance, given as deviation from mean result of all instruments (referred to NPL instrument). A star (*) indicate a gauge that was not measured on a particular instrument.

Nominal length	1 mm	3 mm	6 mm	25 mm	50 mm	100 mm	50.8 mm	101.6 mm	300 mm
S/N	Deviation from mean difference / nm								
00	-0.4	-1.4	-2.4	-5.8	-4.7	-1.3	-5.5	-7.9	-27.1
01	*	*	-0.4	*	*	6.7	*	*	-77.1
02	*	*	3.6	*	*	-23.3	-5.5	-7.9	*
03	-4.4	-11.4	-10.4	-13.8	*	6.7	-2.5	-0.9	-94.1
04	-5.4	-3.4	-4.4	-1.8	*	22.7	12.5	-34.9	-9.1
05	-2.4	-3.4	5.6	-5.8	*	-33.3	-25.5	22.1	20.9
06	1.6	2.6	4.6	-0.8	*	-18.3	-12.5	7.1	-21.1
07	1.6	2.6	3.6	1.2	*	-1.3	-5.5	-23.9	-32.1
08	0.6	-4.4	-3.4	-5.8	*	-20.3	34.5	-10.9	84.9
09	-0.4	2.6	0.6	-1.8	*	25.7	32.5	33.1	*
10	-3.4	10.6	-2.4	6.2	*	-12.3	32.5	-37.9	95.9
11	-2.4	2.6	1.6	-4.8	*	-5.3	-10.5	23.1	-2.1
12	4.6	7.6	-1.4	13.2	*	13.7	11.5	2.1	-23.1
13	2.6	6.6	4.6	13.2	*	9.7	4.5	*	50.9
14	0.6	2.6	-0.4	10.2	*	15.7	1.5	-9.9	-19.1
15	0.6	-5.4	-1.4	-2.8	*	-9.3	-5.5	-33.9	77.9
16	2.6	-3.4	1.6	-5.8	*	-29.3	-2.5	-17.9	96.9
17	-1.4	0.6	3.6	6.2	7.3	-4.3	-38.5	15.1	26.9
18	-1.4	-1.4	-0.4	-1.8	4.3	30.7	-45.5	-5.9	16.9
19	2.6	1.6	0.6	6.2	-7.7	37.7	5.5	66.1	13.9
20	-3.4	-5.4	-2.4	-3.8	-15.7	-10.3	-18.5	-41.9	19.9
21	-3.4	-1.4	-3.4	-1.8	-18.7	3.7	1.5	-30.9	36.9
22	2.6	-0.4	5.6	7.2	16.3	14.7	32.5	33.1	-210.0
23	2.6	-1.4	0.6	3.2	-0.7	-15.3	*	-2.9	-211.0
24	0.6	-3.4	-2.4	-6.8	0.3	-5.3	-10.5	-24.9	22.9
25	2.6	1.6	-1.4	-3.8	11.3	2.7	-15.5	55.1	46.9
26	-1.4	5.6	-2.4	3.2	11.3	-23.3	14.5	25.1	40.9
27	-0.4	-3.4	-2.4	-0.8	-0.7	2.7	-27.5	-19.9	4.9
28	3.6	1.6	0.6	0.2	3.3	9.7	6.5	2.1	21.9
29	-0.4	-0.4	-0.4	2.2	3.3	8.7	27.5	23.1	11.9
30	-0.4	-0.4	2.6	-9.8	-13.7	-1.3	2.5	-9.9	6.9

As yet, these comparisons have not been numerically linked, however for the purposes of this paper, a linking has been performed by simply aligning the reference values of all the regional comparisons with that of the CCL-K1 comparison on a gauge-by-gauge basis. In such a way, the graphs showing degrees of equivalence are plotted on a single graph, with a common zero for the ordinate axis. This process was proposed in the final report [36] for comparison CCL-K1.

Examination of the reports of the relevant comparisons has shown that gauges of slightly different nominal lengths have been chosen and whilst some comparisons have included gauge blocks in steel and tungsten carbide materials, others have omitted the tungsten carbide gauges or used ceramic gauges instead. However, the following artefacts were common across the majority of comparisons: steel gauges of 0.5 mm, 8 mm and 100 mm nominal lengths and tungsten carbide gauges of 1.01 mm (or 1.02 mm for the case of the EUROMET.L-K1.1 comparison), 8 mm and 100 mm nominal lengths. Figures 8 to 13 show the results obtained from the key comparison measurements of these gauge blocks, analysed as detailed above.

Each result, plotted in figures 8 to 13 has an associated 'modified' value, marked with a horizontal bar. These are the key comparison results, corrected by an amount equal to the deviation from the mean instrument result, as reported in table 4. In this way, any bias due to the instrument should be removed. Examining figures 8 to 13 shows that correction of possible instrument bias improves approximately one third of the results, one third are unchanged and one third are made worse (larger degree of equivalence). This is to be expected, as the differences between instruments reported in table 4 include effects due to random sources (such as wringing quality). Of the six results which have degrees of equivalence greater than their expanded (k = 2) uncertainty, only two are improved sufficiently, such that, after bias correction, the degree of equivalence is less that its associated uncertainty.

Comparing figures 8 to 13 with the data in table 4, shows that some interferometers have performed worse in the key comparisons, even after possible bias correction, than when they were initially compared with the NPL reference instruments. The exact reasons for this would require detailed investigation, by each NMI, of its own measurement procedure and sensor re-calibration accuracy, which are beyond the scope of this paper, however another possible cause has been identified. All key comparison reports describe damage that occurred to gauges during the measurement/transportation cycle and, in several comparisons, participants were unable to measure some gauges due to an inability to wring satisfactorily. It is likely that the degraded wringing quality is adversely affecting some NMIs' results.

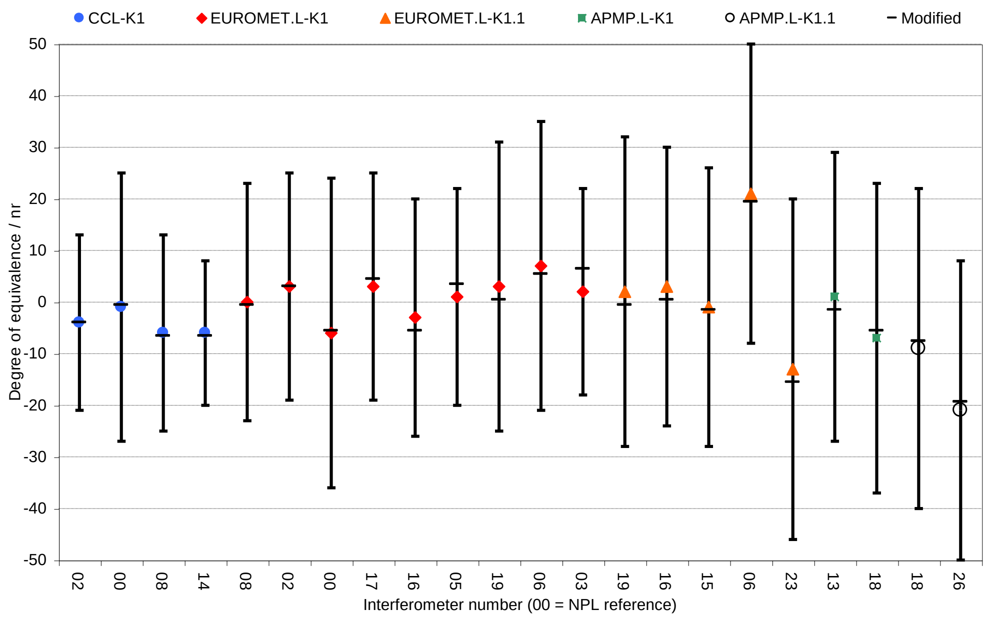

Figure 8. Key comparison measurement results for 0.5 mm steel gauge blocks. Degrees of equivalence and their expanded uncertainties (k = 2).

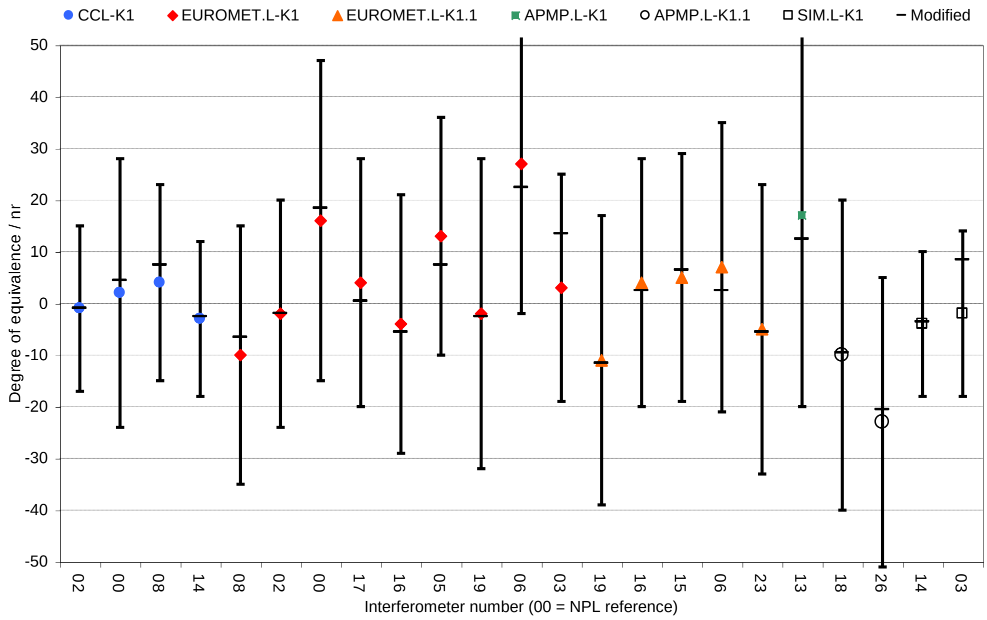

Figure 9. Key comparison measurement results for 8 mm steel gauge blocks. Degrees of equivalence and their expanded uncertainties ($k = 2$).

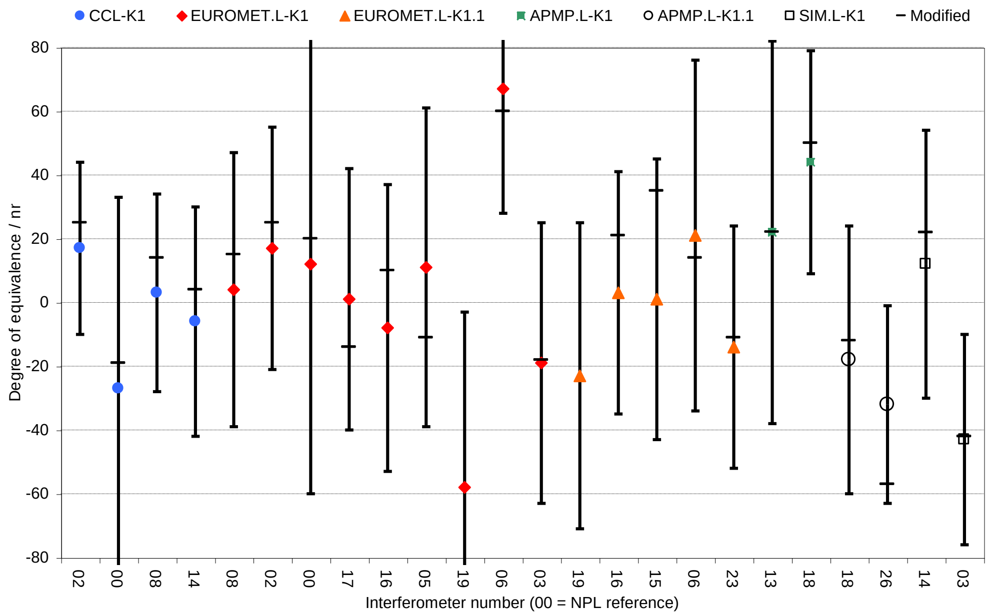

Figure 10. Key comparison measurement results for 100 mm steel gauge blocks. Degrees of equivalence and their expanded uncertainties ($k = 2$).

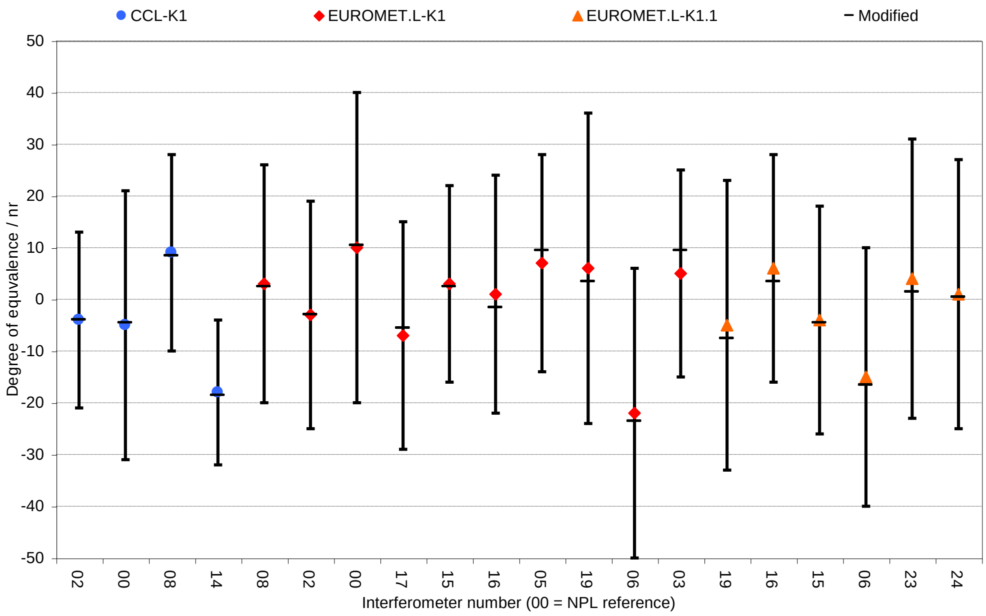

Figure 11. Key comparison measurement results for 1.01 mm (or 1.02 mm) tungsten carbide gauge blocks. Degrees of equivalence and their expanded uncertainties (k = 2).

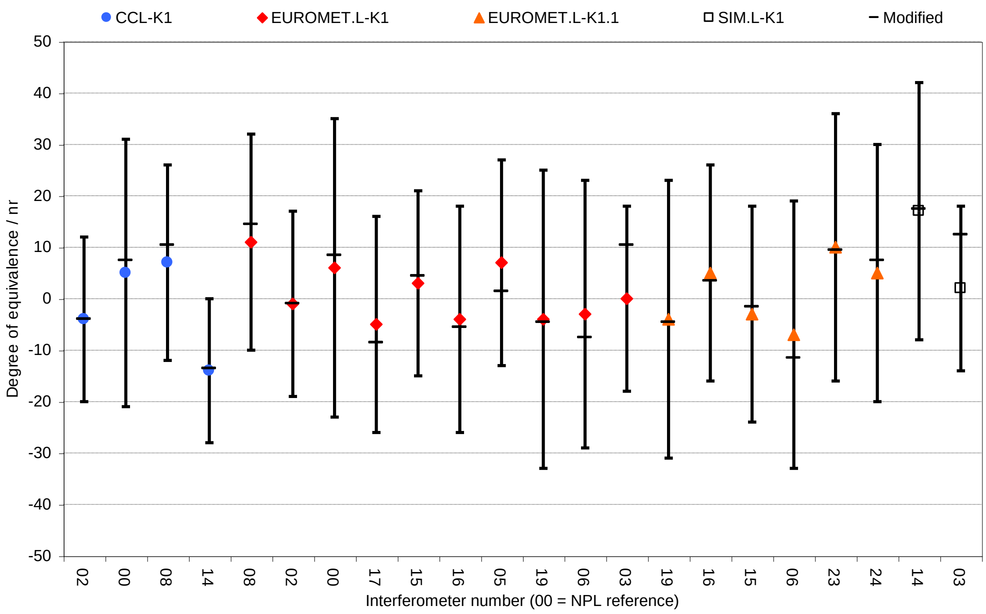

Figure 12. Key comparison measurements for 8 mm tungsten carbide gauge blocks. Degrees of equivalence and their expanded uncertainties (k = 2).

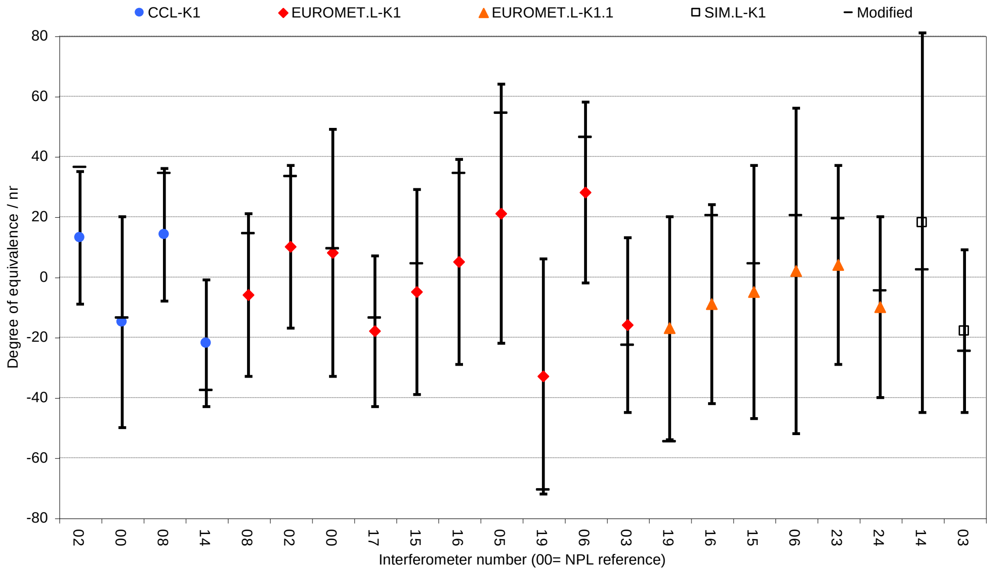

Figure 13. Key comparison measurement results for 100 mm tungsten carbide gauge blocks. Degrees of equivalence and their expanded uncertainties (k = 2).

The previous analysis of figures 2 through 6 and the contributions listed in table 1 show that the three biggest contributions to measurement uncertainty are, respectively, thermal expansion, the phase correction and the wringing thickness variation. These are also the three least-controllable aspects of the instrument performance after delivery to the customer, with the latter two being completely dependent on operator skill. It is therefore quite natural to expect a larger variation in key comparison results than encountered in the initial inspections performed by NPL. Nevertheless, figures 8 to 13 show a total of 133 results, obtained from a selection of interferometers, some of which are now over twenty years old, with only six results (5%) outside the k = 2 uncertainty bounds. This shows that not only are the independent traceability chains used at the individual NMIs operating correctly, with skilled operators (and associated quality systems), but that the instruments continue to perform within specification.

7. The future for gauge blocks

Gauge blocks have been in use for just over one hundred years. Gauge block interferometers have been the primary tool for gauge block calibration for the last half-century and the NPL designed automatic instruments have existed for twenty-five years. At this combined 100-, 50- and 25-year anniversary, the future of gauge blocks and gauge block interferometers, in their current form, should be reviewed. Recent advances in laser interferometers and scale-based metrology have led to the development of very accurate long-range gauge block comparators, and micro Coordinate Measuring Machines with sub-micrometre uncertainty [37-39]. Rather than requiring a full set of 122 gauge blocks to cover the 0.5 mm to 100 mm range, use can be made of long range comparators and micro-CMMs to make measurements, with reference to gauge blocks of a reduced selection of lengths (such as a small set comprising 5 mm, 25 mm, 50 mm, 75 mm and 100 mm gauges). Some articles [40, 41] have highlighted issues concerning the gauge block traceability hierarchy. Recently there has been a suggestion [42] to replace gauge blocks with ‘end standards’ – solid artefacts where the length is defined as a point-to-point distance between the end faces, with no wringing necessary. This would allow for a wider range of materials to be used (thereby matching the CTE with that of typical work pieces) and removes the wringing thickness from the definition of the gauge block length, which better serves the needs of users who no longer wring gauges together.

However, the current definition of the length of a gauge block, which requires the gauge to be wrung, serves a more fundamental purpose – it minimises the error due to mis-alignment with the measuring axis (cosine error) when the gauge is being calibrated. The specification standards [1-3] place reasonably tight specifications on the squareness between the measuring face and side faces (around five to ten arc minutes). But these are not sufficient to allow the side faces to be used as datums, to define the measuring line, if one wishes to achieve better than 1 part in10^6 error due to mis-alignment, (gauge block interferometers typically achieve overall measurement uncertainties three times better than this). By aligning the gauge block in the interferometer such that the fringes on the platen (and/or the gauge surface) are opened out to less than a few fringes in the field of view, guarantees the alignment to better than 0.1 arc minutes, making the error due to mis-alignment negligible. Point-to-point contact, especially over extended ranges, cannot easily match this accuracy of alignment. Even with reduced gauge block set sizes, there is still a need to transfer the unit of length (realised as a wavelength) to at least one of these gauges and this is best performed in a dedicated interferometer.

There are no length metrology tools which achieve relative uncertainties lower than those offered by interferometers, and the calibration of gauge blocks by interferometry achieves the lowest relative uncertainty of all dimensional artefact calibration. However to achieve this accuracy requires careful alignment, thermal control and refractive index compensation. If gauge blocks are to evolve to meet the ever increasing need for more accurate calibration artefacts, then the three biggest uncertainty sources need to be tackled – thermal expansion, wringing variability and phase correction, and the surface quality of gauges must also be improved. Interferometric dilatometry [43-48], with the ability to achieve small uncertainties in the calibration of gauge block CTE values, is well understood, though many NMIs no longer offer this service on a routine basis and the cost per gauge block is quite high. Phase correction values can be determined to small uncertainties through the use of interferometric [49-50] scatterometer [51] or ellipsometer methods [52]. This leaves the errors due to the variation in the wringing thickness. As shown in this paper, gauge blocks that are permanently wrung exhibit significantly smaller measurement uncertainties and better reproducibility of measurement. It is not that the gauges are wrung that is key, but that they are never re-wrung. For some applications, permanently wrung gauge blocks (step-height standards) would be suitable, however the majority of applications require bi-directional measurement and this will require gauge blocks with opposing faces which can be probed. The next generation of such gauge blocks should not base their defined length on point-to-point contact but instead, they should be based on interferometric measurement between the measurement surfaces whilst the gauge is in the un-wrung state. This will necessitate interferometric measurement from both ends, simultaneously – so-called ‘double ended interferometry’. Some tentative investigations of this technique have already been attempted [53-55], but there remain several problems to be addressed.

Double-ended interferometry requires two phase corrections to be applied, one for each end face, so the accuracy of determining the phase corrections must be improved by at least a factor of √2 if the doubly-applied correction is not to increase the overall measurement uncertainty. In addition, double-ended interferometry requires the collimated full-field measurement beam to be split, to image both ends of the gauge simultaneously. This requires either several additional mirrors or beam splitters to split and steer the beams, or a significant shearing of the beam. These place more stringent tolerances on the surface quality of the optics as well as a need for increased spatial coherence across the field. Nevertheless, as reported in other experiments [56] such high quality optical performance is achievable and bi-directional measurements of opposing surfaces can be made with nanometre level uncertainty. It may even be possible to use a comparator based on bi-directional probing by Atomic Force Microscopes [57].

8. Conclusions

The performance of thirty-one gauge block interferometers over a period of twenty-five years has been examined by measuring several reference artefacts in all of the instruments. This has shown the performance of all instruments to be comparable and stable over time. The reference artefacts have been shown to be stable, within the tolerances set out in the respective specification standard [1], though, over the long term, length changes are visible, especially in the longer steel gauges. Several of the interferometers have taken part in international key comparisons where they have shown continued performance within the uncertainty budgets constructed by their NMI owners. These interferometers offer dimensional artefact calibration services with some of the smallest relative uncertainties offered worldwide. However, the basic properties of gauge blocks are now the limiting factors preventing these robust, popular length standards from achieving the smaller uncertainties necessary for use in the near future. By re-defining the length of the gauge blocks to be that in the un-wrung state, improving their surface quality (reduced roughness) and constructing higher quality double-ended interferometers for their measurement, gauge blocks can continue to serve as physical length artefacts at improved levels of accuracy.

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