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Issues and advantages of gauge block calibration by mechanical comparison

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ABSTRACT

An analysis of gauge block calibrations by mechanical comparison carried out at METAS with several sets of gauge blocks during several years has demonstrated very small variations. It is shown, that under optimum conditions with respect to laboratory environment and instrumental equipment as well as by following a suitable handling and measurement procedure, the contribution in the uncertainty budget added by the mechanical comparison process to the uncertainty of the interferometrically calibrated reference gauge blocks can be very small.

Keywords: Dimensional metrology, calibration of gauge blocks, mechanical comparison

1. INTRODUCTION

As a National Metrology Institute, METAS is providing the traceability for gauge block calibration for accredited calibration laboratories by optical interferometry[1] and by mechanical comparison. Whereas optical interferometry is the primary method for the measurement of gauge blocks and defines the measurand according to the international standard ISO 3650[2], mechanical comparison is a secondary method always based on reference gauge blocks calibrated by optical interferometry.

Although its smaller measurement uncertainty compared to the measurement by comparison, optical interferometry has some drawbacks when used for usual customer calibration: there is a considerable risk for scratching the gauge blocks while wringing, new gauge blocks tend to become shorter by repeated wringing, and the calibration cost is considerably higher due to longer calibration work and higher instrument cost. A further critical point when calibrating customer gauge block sets is the uniformity of the surface roughness. If the individual gauge blocks are not all from the same manufacturing process, an individual phase correction should be applied if a reasonably small uncertainty is to be achieved.

For mainly economic reasons, most of the accredited laboratories in Switzerland prefer their standards being calibrated by comparison. A study on the history of some sets of short gauge blocks that were calibrated several times by METAS has given a strong indication, that the measurement uncertainty attributed so far to the mechanical comparison of gauge blocks $U = \sqrt{(38nm)^2 + (0.5 \cdot 10^{-6} L)^2}$, with $k = 2$ and L the gauge block nominal length ranging from 0.5 mm to 100 mm, was apparently too large and could be considerably reduced, as long as stringent conditions regarding the measurement procedure, the laboratory environment, the equipment used and the quality of the gauge blocks are fulfilled. This fact has been confirmed by the results of an interlaboratory comparison among all laboratories accredited in Switzerland for the calibration of short gauge blocks[3]. In this comparison, 149 of 150 reported results were within ±0.05 µm from the reference value with an average deviation of ±0.015 µm, for some laboratories the deviations were not larger than 0.01 µm. This performance was by far better than could be expected from the reported measurement uncertainties.

A study at the NIST[4] has shown techniques to minimize errors mainly due to thermal effects and probe tip to surface interaction and an uncertainty budget is given with uncertainties that would satisfy most of the customer needs. The purpose of this paper is to give a detailed analysis of the mechanical gauge block comparison process at METAS, motivated by amazingly good historical data presented in the following.

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2. HISTORY STUDY ON SOME SETS OF GAUGE BLOCKS

We have analyzed the calibration results of five sets from different customers of approximately 120 gauge blocks each. The sets have been calibrated three or four times by mechanical comparison at METAS during the past 10 years. This analysis allows us to investigate the variations and the consistency of the METAS gauge block calibration process and to study the stability of the gauge blocks. The different calibrations can be considered to be rather independent because:

- the reference gauge blocks used for mechanical comparison have been replaced entirely about 6 years ago;
- for almost each of the mechanical calibrations observed, the reference values of the standard gauge blocks were obtained from a different calibration by optical interferometry;
- the laboratory has been moved about 2 years ago from an old into a new building with different laboratory conditions.

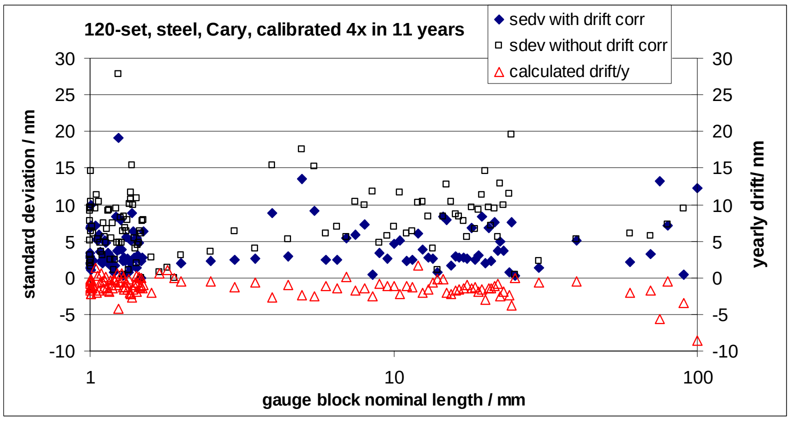
On the other hand, all the measurements have been carried out by one and the same operator and on the same instrument, which has been revised once during the reporting period. It is obvious, that the agreement of the results between different calibrations does not directly relate to the measurement uncertainty. However most of the contributions to the uncertainty (at least all those which can be easily quantified) are uncorrelated between different measurements, which is particularly also the case for the most important contribution, the uncertainty of the reference standards.

The five gauge block sets were all made of steel and comprised between 113 and 122 gauge blocks. Four of them were manufactured by Cary, one by Mahr. For each gauge block, an individual linear regression line has been calculated through the four calibration values obtained within a period of roughly 10 years in order to estimate a potential long term drift of the gauge block length. From the linear fit as well as from the arithmetic mean, individual deviations and standard deviations have been determined. The left graphs of Figs. 1a to 1e show for each of the five gauge block sets the observed standard deviations of each gauge block from the linear fit (drift corrected), from the arithmetic mean (without drift correction), as well as the calculated yearly drifts. The histograms in Figs. 1 represent the individual deviations from the linear fit, thus about 480 measurements for each set.

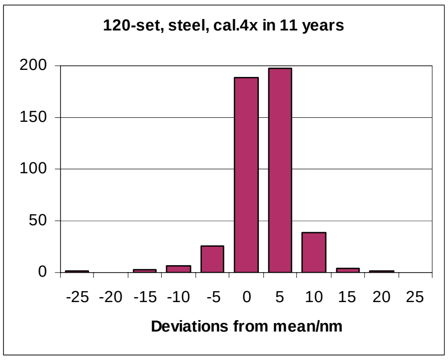
In Table 1, some statistical data extracted from the five investigated gauge block sets are given. The average standard deviations $\langle s \rangle$ are between 4 nm and 8 nm and thus significantly smaller than could be expected from the measurement uncertainty that had been quoted with these calibrations (combined standard uncertainty of 19 nm in the length independent part of the expression given in Section 1). Concerning the yearly drifts of the gauge blocks extracted from the linear regression through typically 4 calibration results within 10 years, the question arises as to whether these are statistically relevant. A simple simulation with random data of 4 calibrations within 10 years has shown that the fitted drift will arbitrarily vary with about 1/6 of the standard deviation of the individual calibrations. Comparing the data of the last column $s(D)$ with the fifth column $\langle s \rangle$ of Table 1 this is in fact about the case, which means that the observed drifts seem to be not significant. Looking at the graphs in Fig. 1 and the values of the average yearly drift $\langle D \rangle$ in the second last column of Table 1, there is however a small, but significant drift of typically -1 nm/year to be observed which is most probably due to wear, because it affects the small as well as the large gauge blocks. However, large drifts of 10 to 20 nm/year, as they were observed in international comparisons and are also allowed by the international standard ISO 3650[2] could not be observed in this study, even for the large gauge blocks. Most of the length changes observed in international comparisons were probably caused by repeated wringing. The gauge blocks observed in this study were never wrung.

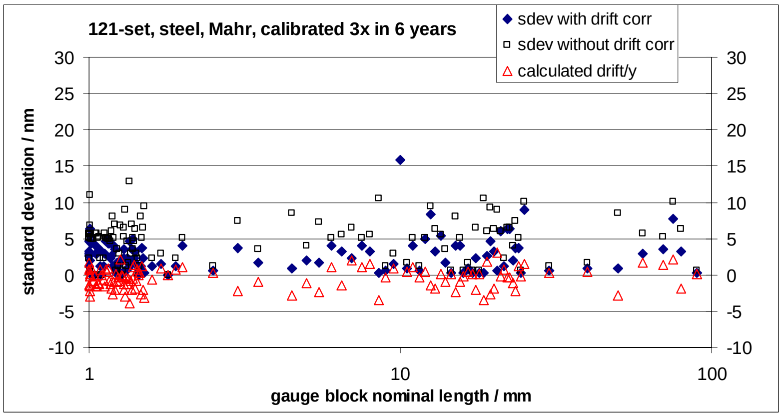
set	no. of gauge blocks	no. of calibrations	manufacturer	$\langle s \rangle$/nm without drift	$\langle s \rangle$/nm drift corr.	$\langle D \rangle$/nm	$s(D)$/nm
a	120	4 x in 11 years	Cary	7.8	4.1	-1.2	1.3
b	121	3 x in 6 years	Mahr	5.2	2.6	-0.7	2.5
c	112	4 x in 10 years	Cary	6.9	4.0	-0.9	1.3
d	122	4 x in 10 years	Cary	6.8	4.8	0	1.5
e	113	3 x in 6 years	Cary	4.1	2.0	-0.7	1.2

Table 1. Summary of some statistical history data for each of the gauge block sets. $\langle s \rangle$ denotes the average standard deviation (with or without drift correction), $\langle D \rangle$ is the average drift and $s(D)$ is the standard deviation of the fitted drifts.

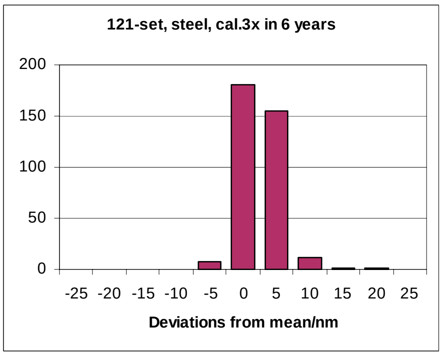

120-set, steel, Cary, calibrated 4x in 11 years
sedv with drift corr
sdev without drift corr
calculated drift/y
standard deviation / nm
yearly drift/ nm
30
25
20
15
10
5
0
-5
-10
1
10
100
gauge block nominal length / mm

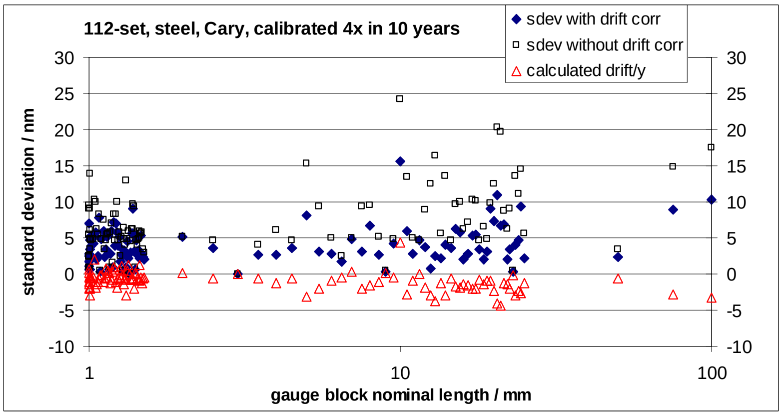
(a)


120-set, steel, cal.4x in 11 years
200
150
100
50
0
-25
-20
-15
-10
-5
0
5
10
15
20
25
Deviations from mean/nm

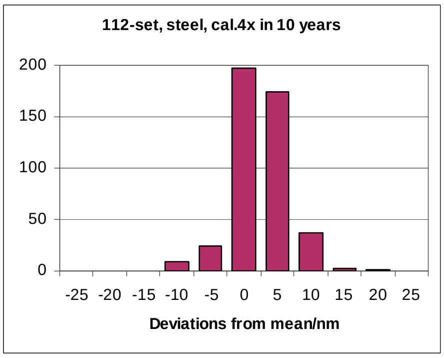

121-set, steel, Mahr, calibrated 3x in 6 years
sdev with drift corr
sdev without drift corr
calculated drift/y
standard deviation / nm
30
25
20
15
10
5
0
-5
-10
1
10
100
gauge block nominal length / mm

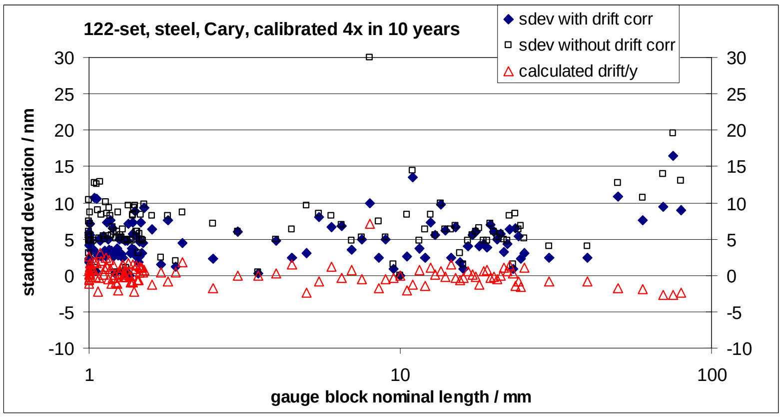
(b)


121-set, steel, cal.3x in 6 years
200
150
100
50
0
-25
-20
-15
-10
-5
0
5
10
15
20
25
Deviations from mean/nm

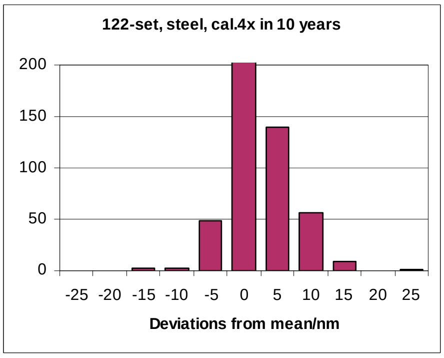

112-set, steel, Cary, calibrated 4x in 10 years
sdev with drift corr
sdev without drift corr
calculated drift/y
standard deviation / nm
30
25
20
15
10
5
0
-5
-10
1
10
100
gauge block nominal length / mm

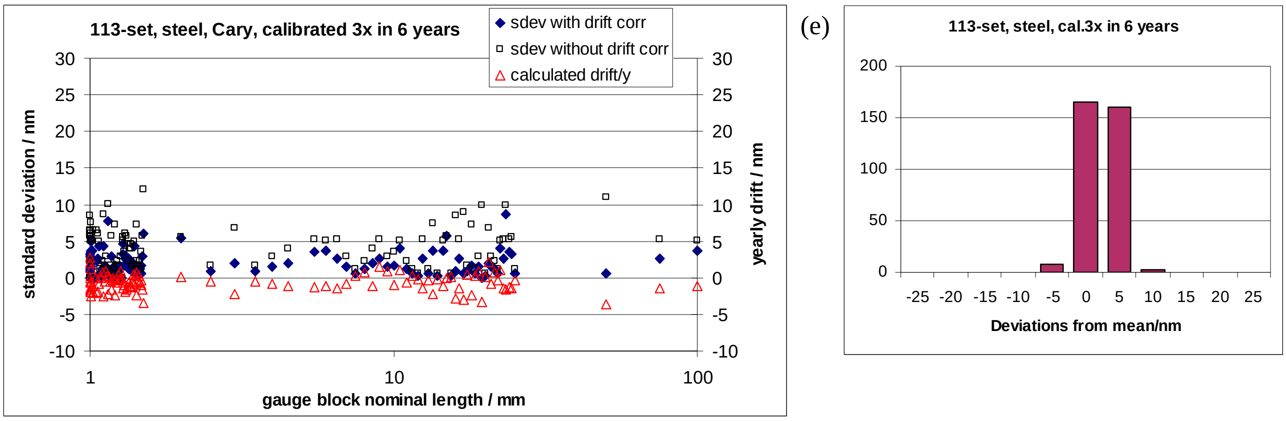
(c)


112-set, steel, cal.4x in 10 years
200
150
100
50
0
-25
-20
-15
-10
-5
0
5
10
15
20
25
Deviations from mean/nm


122-set, steel, Cary, calibrated 4x in 10 years
sdev with drift corr
sdev without drift corr
calculated drift/y
standard deviation / nm
30
25
20
15
10
5
0
-5
-10
1
10
100
gauge block nominal length / mm

(d)


122-set, steel, cal.4x in 10 years
200
150
100
50
0
-25
-20
-15
-10
-5
0
5
10
15
20
25
Deviations from mean/nm



Figures 1a..e: Observed standard deviations of calibrations of five gauge block sets, calculated from deviations to mean and to a drift compensating linear regression, calculated drift per year, and histogram of the deviations to linear regression.

The sixth column of Table 1 shows the average standard deviation with respect to the drift corrected data. Correcting for the drift removes one degree of freedom. The above mentioned simulation showed that on completely random data the drift corrected standard deviation will be about 80% of the standard deviation without correction. The ratio of column six to column five is considerably smaller which is another indication, that the drift correction is not entirely insignificant.

3. DESCRIPTION OF THE GAUGE BLOCK COMPARATOR AT METAS

The gauge block comparator used at METAS is of the usual design with two inductive measurement probes touching the gauge blocks to be compared on the top and the bottom surface, as scetched in ISO 3650. The model Cary IVC 153 is based on a heavy cast iron stand, fabricated by Cary, Switzerland (Fig. 2). The two inductive probes (MET 8) have a measurement range of ±200 µm, the electronic indicator instrument (Cary Labor) provides a digital resolution of 0.01 µm. The hard metal measurement anvils have a diameter of 2.5 mm and a tip radius of 8 mm. The measurement force is about 0.3 N for the upper probe and 0.15 N for the lower probe.

The reference gauge blocks and the gauge blocks under test are disposed before measurement on cast iron plates for temperature stabilisation (Fig. 2). For the measurement on the comparator, the gauge blocks are resting on a flat ribbed steel plate. The exact positioning of the gauge blocks is guaranteed by a stencil mounted above the ribbed plate (Fig. 3). The placement of the gauge blocks between the probes is made by a patented roller bearing table, where a mechanism retracts the lower probe while moving. This has the advantage, that the gauge blocks do not slide on the plate but move with the plate and can thus not be damaged while moving. The comparison sequence A-B-A-B-A-B-A-B-A between


Figure 2. Gauge block comparator at METAS.

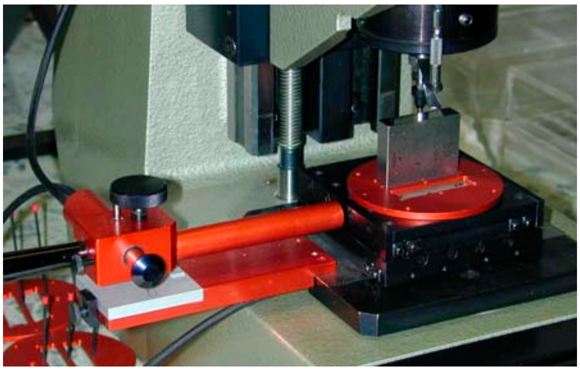


Figure 3. Gauge block positioning system.

touching the reference gauge block A and the device under test B gives an average of 5 respectively 4 measurements, compensated for linear drift.

We have three complete sets of grade K reference gauge blocks of different material, which are all calibrated on the automatic NPL-TESA gauge block interferometer at METAS. This allows for the calibration of steel, tungsten carbide and ceramic gauge blocks with high accuracy, without being affected by problems due to the comparison of dissimilar materials. The performance of the gauge block comparator is checked regularly according to the EA technical guidance document[5].

4. ANALYSIS OF THE MEASUREMENT PROCESS

In the following, the measurement process shall be investigated by a detailed analysis of the different contributions affecting the uncertainty of the gauge block comparison. As will be seen, the by far largest contribution is the calibration uncertainty of the reference gauge block. Further contributions are due to the comparator instrument, the measurement anvils, geometry errors of the gauge blocks and all the effects related to temperature.

4.1 Reference gauge blocks

The best measurement capability at METAS for the calibration of steel gauge blocks by optical interferometry has been estimated to $U = \sqrt{(19nm)^2 + (0.2 \cdot 10^{-6} L)^2}$. A further contribution to the uncertainty in mechanical gauge block calibration is the potential drift of the standards. Although in section 2 it has been shown, that the drift of gauge block is usually very small, the history of our reference gauge blocks is rather short. From two interferometric calibrations within a five years interval, the observed length changes were in the average –5 nm within 5 years and distributed in an interval of 13 nm (2 sigma). Although the major part of this is most probably due to the uncertainty of the interferometric measurement, it has in the worst case to be interpreted as a length drift. Combining linearly the average and the random part of the drift results in a possible length change of 2.3 nm/y, which is still much smaller than the maximum permissble length change of ±(20 nm + $0.25 \cdot 10^{-6} \cdot L$)/year, as allowed for according to ISO 3650[2].

4.2 Gauge block comparator

The uncertainty contribution of the gauge block comparator is given by the disperion of measurements, the digital resolution and geometry errors:

- Repetive measurements of gauge blocks of various lengths between 1 mm and 100 mm, applying the measurement sequence explained in section 3, have resulted in a standard deviation of the measured gauge block length difference of 3 nm.

- In many cases, the digital value of the indication does not change during a measurement sequence, resulting in fact in a zero dispersion, hence the digital resolution of 0.01 µm of the indicator instrument has to be taken as part of the uncertainty, corresponding to a standard uncertainty of 0.5·10/sqrt(3) nm = 2.9 nm.

- Any error in the geometry of the comparator, affecting the length comparison, may be detected when interchanging or rotating the two gauge blocks. Experimental tests have resulted in a maximum difference of 2 nm, taken as the half width of a rectangular distribution und thus corresponding to a standard uncertainty of 1.2 nm. Any residual Abbe or cosine errors are included in this value.

Combining the above contributions results in a standard uncertainty due to the mechanical comparator of 4.3 nm.

4.3 Gauge block variation in length

The accuracy of positioning the gauge blocks on the measurement table is limited by the play of the gauge block when placed in the stencil. This has been measured to be at maximum 0.4 mm, taken as the full width of a rectangular distribution and thus resulting in a standard uncertainty of the position of 0.12 mm. With the maximum permissible variation in length for grade K gauge blocks of 70 nm, according to ISO 3650, the standard uncertainty in the measured gauge block length due to positioning errors amounts to less than 1 nm.

4.4 Measurement anvils

The error of indication (including the calibration factor and the linearity) of the upper inductive probe is checked by measurement of gauge block pairs with a known length difference of 5 µm and 10 µm. The lower probe is checked with the help of a U-shaped special gauge block which is measured in both positions, with the groove upwards and downwards[5]. The deviation turned out to be smaller than 0.3% of the value. Obviously the probes are used only in a very limited measurement range, given by the deviation from nominal value of the gauge blocks to be compared. A statistical evaluation of the roughly 600 gauge blocks involved in this study yields a standard deviation of the length deviations of 56 nm, independent of the gauge block length, thus close to the tolerance limit for grade 0 gauge blocks. Multiplying this value with the error of indication of 0.3% and a factor of sqrt(2), taking into account, that in a comparison always two gauge blocks are involved, results in a standard uncertainty of 0.24 nm, thus negligible.

The question arises as to the elastic or plastic deformation of the anvils and the gauge block surface due to the measurement force. As it has been pointed out elsewhere[4], the spherical end of the tips will always show after some use a flat part due to wear or plastic deformation. Figure 4 shows a microscope image of the spherical end face (radius 8 mm) of our upper probe. The small dark circle in the middle is a flat with about 0.1 mm diameter, corresponding to a permanent deformation of 200 nm in the apex. According to Hertz'ian deformation, a hard metal sphere with 8 mm radius would result for the measurement force of 0.3 N in an elastic deformation of 60 nm when touching a steel gauge block. It is therefore very unlikely that such an anvil with a small flat will produce any non-reproducible deformation while probing.

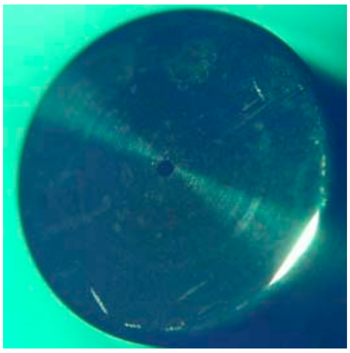


Figure 4. Spherical end face of the probe tip with small flat in the center.

4.5 Temperature effects

4.5.1 Laboratory temperature

The laboratory is temperature stabilized at 20 °C. The room temperature is continuously monitored by an indpendent data logger recording the air temperature at a distinct place within the room every 10 min. It has been measured to stay during one month within a span of less than 0.2 °C with a standard deviation of 0.017 °C. This may reflect the performance of the air temperature stabilization system, but not the real situation near the gauge block comparator, which will be much more influenced by the operator. What finally counts is the temperature of the gauge blocks during comparison. We do usually not measure directly the gauge block temperature, but at each measurement the temperature of the cast iron platens where the gauge blocks are disposed before measurement. A statistical evaluation on the 10 jobs (including 400 measured gauge blocks) performed this year so far has given an average temperature of 20.003 °C with a span of 0.1 °C and a standard deviation of 0.026 °C (see histogram in Fig.5).

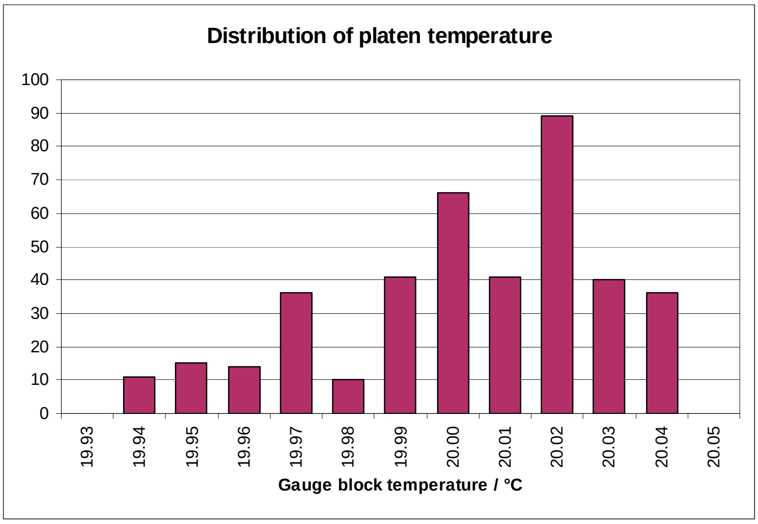


Figure 5. Platen temperature during 400 measurements in 5 months.

4.5.2 Acclimatisation

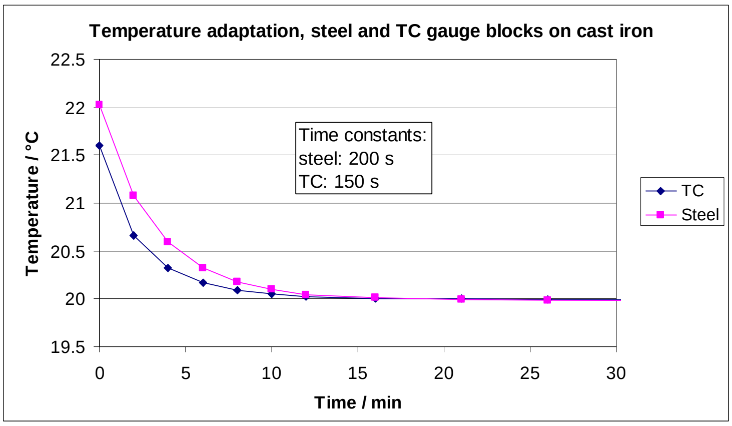


Figure 6. Temperature recording of gauge blocks while acclimatisation.

We have investigated the acclimatisation time needed for the gauge blocks to stabilize in temperature when brought in the laboratory. Two steel and one tungsten carbide 100 mm gauge blocks were first kept for at least one day in a room at 23 °C. Using three thermistors the gauge block temperature was then recorded after bringing the gauge blocks in the laboratory. One steel and one tungsten carbide block were placed on the cast iron plate, while the second steel gauge block was placed on a thermally insulating surface. Figure 6 shows the temperature recordings. The plots were fitted with an exponential function, from which resulted time constants of 200 s for steel and 150 s for tungsten carbide on cast iron, whereas the steel gauge block on a thermally insulating surface had a time constant of 36 min (not shown in the Figure). This shows that when gauge blocks are disposed in the laboratory on an appropriate surface, waiting before measurement for more than one hour is largely sufficient.

4.5.3 Temperature difference between DUT and standard

In a next experiment, the temperature and the length difference of two 100 mm steel gauge blocks were recorded after placement on the comparator, i.e. after taking the two gauge blocks from the steel plate and putting them on the comparator for comparison measurement. Figure 7 shows the temperature of the two gauge blocks during 1 hour after handling, at the same time the steel plate temperature was monitored. The figure shows that the temperature changes by almost 0.1 °C. This is due to a temperature gradient between the steel plate and the comparator, most probably due to different light exposure. Such temperature gradients are inavoidable in all laboratories. After somewhat less than an hour, the two gauge blocks have reached within the digital resolution of the thermometer of 0.01 °C the same, stable temperature. Even more important is the measured length difference during this settling time, as shown in Fig.8. Again, it takes almost one hour until the length difference has reached a stable value, which differs by about 20 nm from the value measured a few minutes after handling. A further test has shown, that the length difference between the gauge blocks does not change when they are interchanged between front and back position on the comparator. So there seems to be no significant difference in temperature between the two gauge blocks after the settling time on the comparator. These tests have shown, that at least the long gauge blocks have to be diposed on the comparator for a sufficient settling

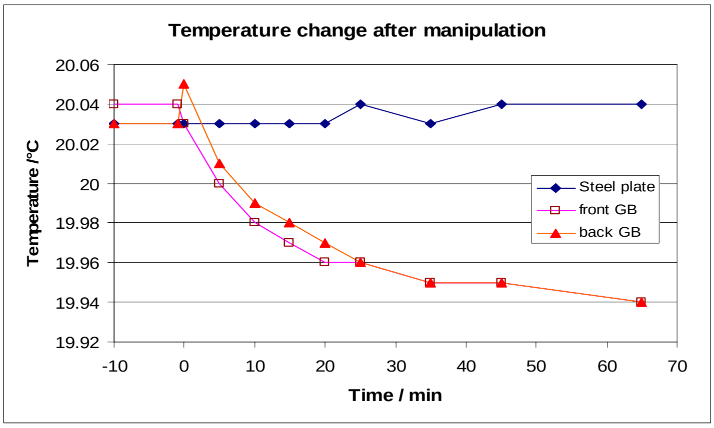


Figure 7. Temperature settling of gauge blocks after handling.

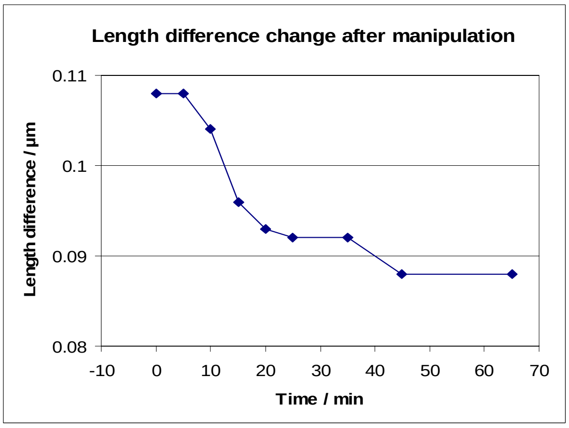


Figure 8. Measured length difference of gauge blocks after handling.

time before measurement, when very high accuracy is to be achieved. We usually measure a series of small gauge blocks, prepare a pair of long gauge blocks, wait for at least one hour, and then continue the measurements.

5. OPTIMIZED UNCERTAINTY BUDGET

Based on the contributions discussed above, a new uncertainty budget has been established:

Description	X_i	$u(x_i)$	c_i	$u_i(y)$	$u_i(y)$
Calibration of reference gauge block	l_s	9.4 nm	1	9.4 nm	-
	l_s	$9.6 \cdot 10^{-8} \cdot l$	1	-	$9.6 \cdot 10^{-8} \cdot l$
Drift since last calibration (2 years)	δl_D	4.6 nm	1	4.6 nm	-
Gauge block comparator (incl. repeatability)	δl	4.3 nm	1	4.3 nm	-
Gauge block positioning, variation in length	δl_v	1 nm	1	1 nm	-
Measurement anvils (error of indication)	δl_a	0.3 nm	1	0.3 nm	-
Temperature difference between gauge blocks	δt	0.005 °C	$\alpha \cdot l$	-	$5.7 \cdot 10^{-8} \cdot l$
Difference to reference temperature 20 °C	Δt	0.06 °C	$\Delta\alpha \cdot l$	-	$4.9 \cdot 10^{-8} \cdot l$
Combined standard uncertainty	u_c			**11.3 nm**	$\mathbf{12.2 \cdot 10^{-8} \cdot l}$

This results in an expanded measurement uncertainty of $U = \sqrt{(23nm)^2 + (0.25 \cdot 10^{-6} L)^2}$,which in fact is only slightly larger than the uncertainty of the interferometrically calibrated standards. We are fully aware of the fact, that this uncertainty estimation seems to be rather optmistic and is certainly only achievable under optimum conditions, with good quality gauge blocks and – most important – only when taking sufficient time for temperature settling before measurement of each gauge block. This is obviously not possible in an industrial environment, where a reasonable throughput of calibrated items has to be achieved.

6. CONCLUSIONS

A statistical analysis of the values of several hundred gauge blocks which were calibrated regularly during the past ten years by mechanical comparison has shown, that the calibration process is apparently much better than thought so far. A detailed evaluation has shown, that with high quality gauge blocks, a good laboratory environment, a stable comparator allowing for a good repeatability and by waiting a sufficiently long time (at least 30 min) before measuring a pair of long gauge blocks, a measurement uncertainty can be obtained, which is only a few nm larger than the uncertainty of the interferometrically calibrated reference standards. This allows for providing the traceability to secondary accredited laboratories by mechanical comparison rather than by interferometry, which is much more economic and has in addition the advantage, that the gauge blocks need not to be wrung for calibration and thus will likely be more stable.

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