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NEW APPROACH IN INTERFEROMETRIC LENGTH MEASUREMENTS

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Abstract: Interferometric length measurements without parallax error, based on the phenomenon of the reproducible wringing, are demonstrated. Using reproducible wringing together with the slave-block technique, accuracy level below 1 nm can be obtained for blocks of a few mm length with small flatness deviation. Phase change correction determination with sub-nm uncertainty is achieved for blocks up to 100 mm. Comparing the results of the double-ended method on a transparent reference plate with the reproducible wringing results, measurements without parallax error can be performed in the general case with a nm uncertainty.
Keywords: meter realization, gauge block, Abbe error, uncertainty, interferometry

1 INTRODUCTION

Optical interferometers [1,2], equipped with laser standards with known frequencies [3], are used for practical realization of the SI length unit (the Metre). With these instruments, the length of material artefacts (gauge blocks) [4] is determined in terms of vacuum wavelength of standard radiations [3]. Gauge blocks are commonly used to maintain traceability of length measurements inside the country, and besides, they are regularly used in international comparisons [5].

The standard procedure of the length measurement of a gauge block by optical interferometry [1,4] requires an auxiliary plate to be wrung to one of the faces of the gauge block (Fig. 1). The main physical quantities, associated with the interferometric measurement on a steel plate are shown in Fig. 1. To show a small gap D, which arises between the block and the steel plate at the position of the block centre owing to deviations from flatness of the block surface, the tilt angle of the block and the curvature of the block surface are highly exaggerated. For high quality steel blocks and plates, the tilt angle is typically a small fraction of an arc second, while the effective radius of curvature of a short K-grade gauge block is about 1 km [6]. As the deviations from flatness even for the best, K-grade gauge blocks by an order of magnitude surpass the typical magnitude of block deformations caused by the wringing procedure to a steel plate (that are typically of a few nanometres [8,9]), the area of tight wringing contact usually is somewhat shifted from the block centre, and the gap D appears. Often it is called in literature the excessive wringing film thickness.

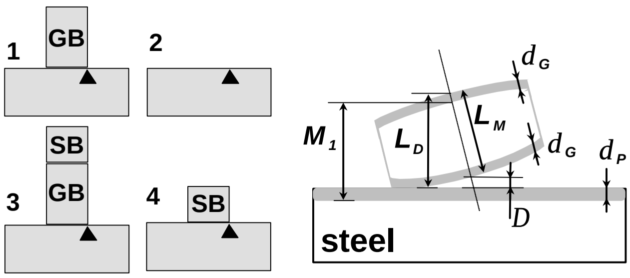

Figure 1. Differential measurements on steel plate (1,2) and of the slave-block method (3,4). Inclination of the block is exaggerated.

For high precision interferometric length measurements, the differential type of measurements [10,8], shown as experiments **1** and **2** in Fig. 1, are preferable. In experiment **1** the length of the block on a steel plate is measured, and then the results of the measurements are corrected on the interferometer optics distortions by measuring the free plate alone at the same position relative to the interferometer optic axis (experiment 2). The corresponding measurement result, denoted $\boldsymbol{M_1}$ (Fig. 1). may be presented as

$$\boldsymbol{M_1} = \boldsymbol{L_M} + D + (d_P - d_G) \qquad (1)$$

where $\boldsymbol{L_M}$ is the length of the block, which will be called below as a *mechanical length* (in order to distinguish it from the *optical length* of the block obtained by the double-sided method on a quartz plate [6,11]); D is an excessive wringing film thickness; d_P and d_G are the phase change values at the optical reflection (expressed in length units) for the surfaces of the plate and of the block, respectively.

The quantities d_P and d_G depend on the roughness values of the plate and the block surfaces and the optical properties of the metals [2]. They characterize the mean penetration depths of the illuminating light into the plate and the block, respectively.

The length of the block in accordance with the present definition [4] will be denoted L_D and is shown also in Fig. 1. It is known to include the excessive wringing film thickness [4], and the corresponding expression for L_D may be written as

$$L_D = L_M + D. \tag{2}$$

Comparison of equations (1) and (2) shows that the interferometric measurement result M_1 is equal to the length of the block L_D, only if the surface textures for the block and the plate are the same, i.e. d_G is equal to d_P. This equality should be confirmed experimentally in each high-precision length measurement. If d_G is not equal to d_P, then the experimentally obtained phase change correction $r = (d_G - d_P)$ [1,5,7] should be applied to the measurement result M_1 to obtain the length of the block in accordance with the definition [4].

For the blocks of a few mm nominal length, the largest uncertainties of the interferometric length measurement are associated with wringing and with the phase change correction errors [7]. In accordance with [7], the typical standard deviations for both factors are ~6 nm for high quality blocks. Here we report new methods, which are based on the recently observed phenomenon of reproducible wringing [8,.9,11], that dramatically decrease the above mentioned sources of uncertainties and result in sub-nanometre accuracy level in some cases [12,13].

2 MEASUREMENTS WITHOUT ABBE ERRORS

The key feature of the approach described below is the absence of the Abbe errors, which are usually present in the standard interferometric length measurement. The two types of Abbe errors are shown in Figs. 2a and 2b. The first type of Abbe (parallax) error, which can be corrected in a reasonably good way, is associated with the parallax p between the measurement line m_1 (shown as dashed line in Fig. 2) and two reference lines r_1 and r_2 intersecting the reference plate. The first-order Abbe error is cancelled out in the standard interferometric length measurement, as the mean value of the phases of the beams propagating along the reference lines r_1 and r_2 are compared with the phase of the beams propagating along the measurement line m_1. But the higher-order terms are present, and they are caused by the curvature of the plate (d_p Abbe error in Fig. 2a), and by the curvature of the wave-fronts of the beams in the interferometer due to always present small optic distortions. By using the differential measurements **1** and **2** in Fig. 1, the sum of these Abbe errors can be very accurately taken into account for short blocks with nominal lengths in the range of 2-10 mm [9].

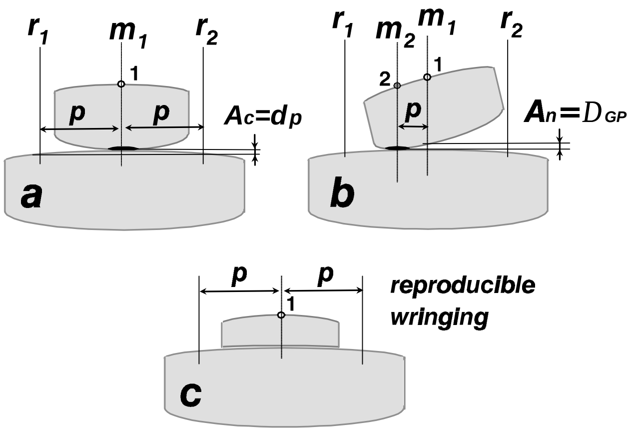

Figure 2. Correctable (a) and non-excluded (b) Abbe offsets in the interferometric measurement.

The other type of Abbe error, which is usually present in the standard length measurement, is the excessive wringing film thickness D (Fig. 1). It arises when the measurement line m_1 (Fig. 2) is shifted from the line m_2 passing through the centre of the tight wringing contact [9]. As the effective radius of curvature for a short block is about 1 km, to detect the actual position of the tight wringing is quite difficult.

Nevertheless, interferometric measurements without Abbe errors has been demonstrated for high-quality gauge blocks, using the reproducible wringing technique [8,9,11]. In [9,11] it has been shown that for gauge blocks with 2-10 mm nominal lengths and with small (a few nm) flatness deviations in the central area, it is possible to realize the wrings, which are reproducible to ~0.1 nm uncertainty level. Special experiments reported in [8,9] show that for the reproducible wrings the excessive wringing film thickness is approaching zero. The main features of reproducible wringing are schematically shown in Fig. 2c, where a thin block is slightly deformed by the wringing forces, so that it follows the shape of much more rigid steel plate. Using the differential measurements **1** and **2** in Fig.1,

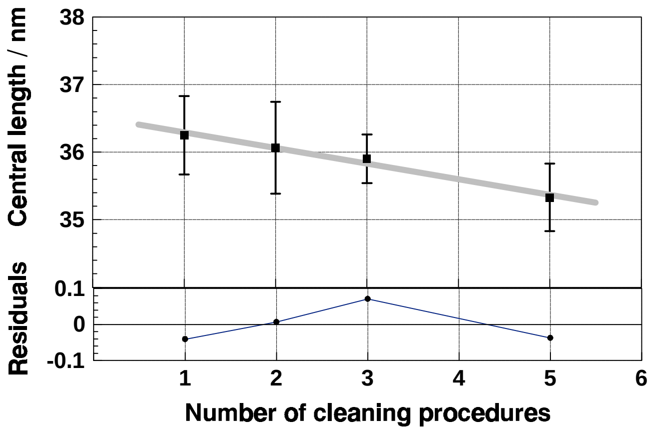

Figure 3. Length decrease of a block as a function of the number of cleaning procedures. Residuals are the deviations from the linear trend

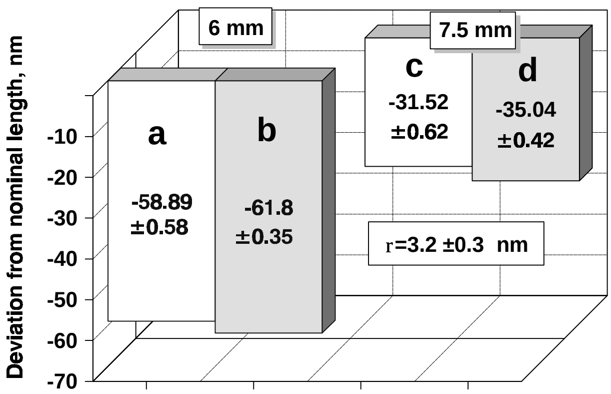

Figure 4. Length L_D measured in accordance with definition (**a,c**) and length corrected on interferometer optics and plate curvature (**b,d**).

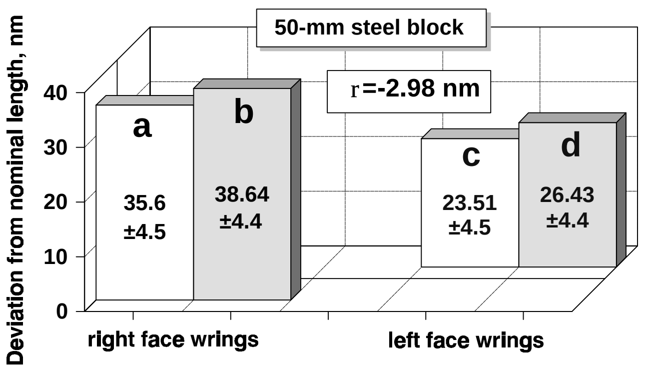

Figure 5. Length L_D in accordance with definition (**a,c**) and length corrected on interferometer optics and plate curvature (**b,d**). (See text for details).

for the reproducible wrings we obtain the measurement results, which are free from parallax errors [6]. When the measurements are performed with accurately specified laser interferometer, a significant improvement in the reproducibility of the interferometric length measurement is achieved. In Fig.3 we show the central length measurements of the specially selected 6-mm block under the conditions of reproducible wringing. The decrease of the length of the block (-0.23 nm/cleaning), which is caused by the cleaning procedure introduced in the laboratory practice by E.Engelhard about 25 years ago, is clearly detected. To demonstrate it in a more obvious way, a doubled cleaning was used before the fourth wring. The standard deviation for the experimental points (shown as squares) relative to the linear regression line is 0.045 nm, corresponding to the random uncertainty interval (at 95% confidence level) of the differential measurement of about 0.14 nm

In the next step, we combined the reproducible wringing technique with the well-established British slave-block method [14], which is shown schematically as experiments **3** and **4** in Fig. 1. If the wringing of the slave block (SB) is reproducible, then the result of differential measurement **3,4** in Fig.1, denoted $\boldsymbol{M_S}$, gives the length of the block $\boldsymbol{L_D}$ strictly in accordance with the definition [4]:

$$\boldsymbol{M_S} = \boldsymbol{L_D} = \boldsymbol{L_M} + D. \qquad (3)$$

If for the wrings of the measured block (GB) to the plate D=0, then the length $\boldsymbol{L_D}$ coincides with $\boldsymbol{L_M}$. From the equations (1) and (3) it follows that for the reproducible wringing of the slave block the difference between the two differential measurements **3,4** and **1,2** gives the phase change correction $r = (d_G - d_P)$.

The corresponding results are presented in Figs.4-6. In Fig.4 we show the results obtained for selected 6-mm and 7.5-mm TESA steel blocks. Lighter blocks in Figs. 4-6 (cases ***a,c***) show the values of length in accordance with the definition, that are obtained by the slave-block method, while the darker ones (***b,d***) are the values, obtained by differential measurements **1,2**. The differences between the results ***a,b*** and ***c,d*** give the values of the phase change correction r for the blocks relative to the steel plate. Assuming polishing of the blocks to be equal, we find that the value of the correction r for these blocks is 3.2 ± 0.3 nm.

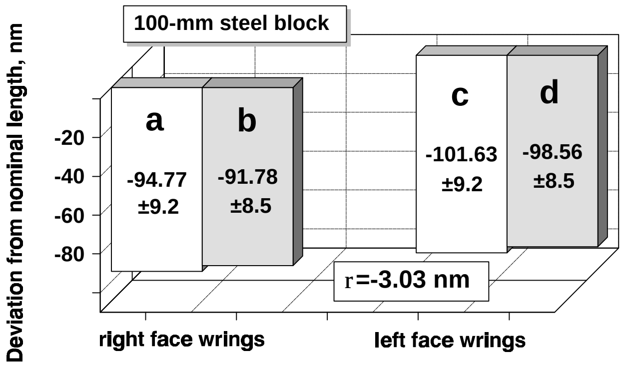

Figure 6. Length L_D in accordance with definition (**a,c**) and length corrected on interferometer optics and plate curvature (**b,d**).

Then we extended the application of the method to longer blocks. In Figs. 5-6 we show the measurement results of 50-mm and 100-mm Cary blocks. Here, only the wrings of the slave, 8-mm Cary block were reproducible. Due to the surface irregularities of the measured blocks, the measurement results contain some excessive wringing film thickness. As a result of important difference in the variations from flatness for the block surfaces, the length measurement results corresponding to opposite faces of the block are also different. For the 50-mm block the difference between the results ***a*** and ***c*** (Fig. 5) is ~12 nm. It is far beyond the random uncertainty of the method that is ~1 nanometre. The values of the differential measurements ***a,b*** (-3.04 nm) and ***c,d*** (-2.92 nm) are amazingly close to each other, indicating that the wrings of the 8-mm slave block are reproducible. So, the differential measurements ***a,b*** and ***c,d*** give the phase change correction values for the corresponding surfaces of the block. Similar results were obtained for the 100-mm block (Fig. 6). The phase change correction for both faces were close to –3.0 nm (-2.99 nm and -3.07 nm). The length difference corresponding to the wrings to opposite faces of the block was about 6.9 nm.

A reliable estimate of the contribution of the length-independent part of the uncertainty expression for the interferometric length measurement [7,13] can be obtained from the spread of measurement results obtained by the method. If we assume polishing of all faces of these two blocks to be same, then we can estimate the higher limit of the contribution of the length-independent part of the uncertainty expression presented in [13] for the described method, which includes two independent wrings of the slave block (one is to the measured block, the other is to the plate). We have four independent measurement results for the phase change correction r (i.e.-3.04; -2.92; -2.99 and –3.07 nm). The corresponding standard deviation s is 0.057 nm. From the table G2 in [15] we find that for the degrees of freedom equal to 3, the corresponding coefficient k in the table is equal to 3.18 for 95% confidence level. To obtain the corresponding sigma–value of the normal distribution, describing the length-independent part of the combined uncertainty expression [12], the standard deviation value of 0.057 nm should be multiplied by 3.18/2, and we obtain ~0.09 nm (length-independent part of the expression for the combined uncertainty [13]). The contribution of the length-dependent part of the uncertainty expression gives ~0.31 nm for the 8-mm block we used as a slave one. From these contributions, we find that the expanded uncertainty [15] for the phase change correction measurements should be expected to be 0.65 nm for the 95% confidence level. Thus, the over-all uncertainties for the differential measurements ***a,b*** and ***c,d*** are less than 1nm, while the length values difference obtained for the wrings to different faces of the 50-mm block is ~12 nm. The observed length variations are related to the accuracy limitations of the present length definition [4], which includes the excessive wringing film thickness of a measured block to the reference plate. When the surface deviations from flatness are significantly different for the block faces, then the values of the wringing film thickness are not equal for different faces, and the corresponding length values also vary.

3 DOUBLE-SIDED INTERFEROMETRIC MEASUREMENTS

The demonstrated above accuracy limitations of the presently accepted definition of the length of a block [4] can be removed, if we realize the measurements without the wringing film error and exclude the excessive wringing film thickness from the definition of the length of a block. Below we shall use the mechanical length of the block L_M (Fig. 1a), specified as a perpendicular distance between the mechanical surfaces of the artefact, as a more suitable parameter in comparison with L_D that supports higher accuracy level in length measurements. Below we shall show how to realize this approach in practice.

First, we shall describe how to measure very accurately the optical length of a gauge block [11]. The key features of this method is that measurement results do not contain Abbe errors and correspond to *a free, unperturbed artefact*. The technique represents some improvement of the

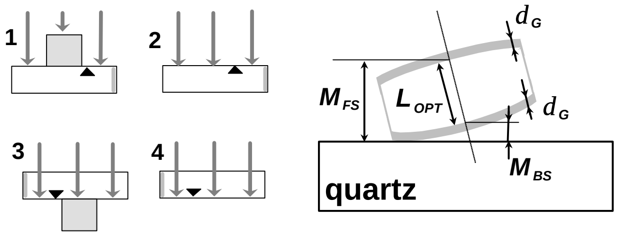

Figure 7. High precision measurements of the double-sided method on a quartz plate.

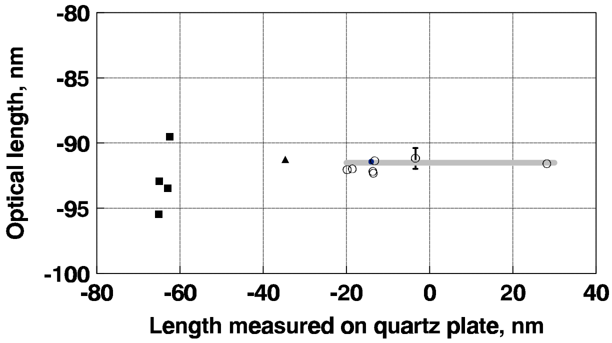

Figure 8. Measured optical lengths of the block versus the increasing separation of the upper block surface M_{FS} from the plate. Circles correspond to measurements with oil layer. (See text for other details).

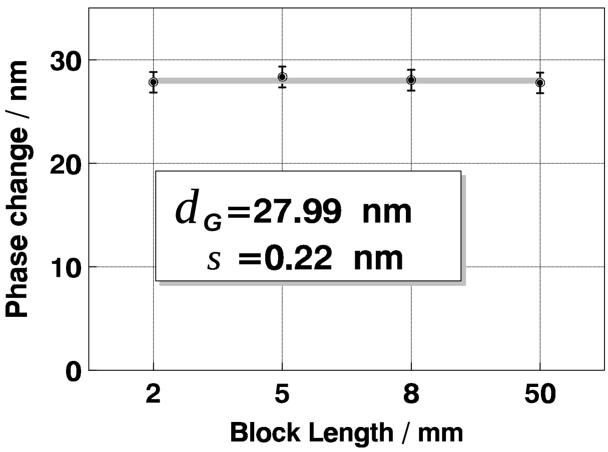

Figure 9. Phase change values, obtained for steel blocks of different nominal lengths.

methods described in [8,11]. It consists of two differential measurements performed on a crystalline quartz plate (Fig. 7). The experiments **1,2** are performed from the side of the block, which is wrung to the gauging surface of the plate (marked by a dark triangle in Fig. 7). As a result of a differential measurement **1,2** the visible separation M_{FS} of the upper face relative to the two reference points on the plate is obtained. The difference, in comparison with experiments in [11], is that a relatively thick oil film, having the same refraction index as the material of the plate is being used to wring the block to a crystalline plate. For the oil thickness of several tens of nanometers, the deformations of the block caused by wringing forces are shown to be very small. On the other hand, the differential measurement **3,4** performed through the plate gives the visible separation of the lower surface of the block M_{BS} relative to the same reference points on the plate. The important feature is that a *linear* interferometric measurement, i.e. the measured optical path is to be divided by the refraction index of oil in order to obtain the separation M_{BS} of the lower face of the block from the plate surface. In contrast with [10] no Fizeau type interference is arising in this case. The difference between the two differential measurements **1,2** and **3,4** in Fig. 7 gives the optical length of the block L_{OPT} [6,11], which is defined as

$$L_{OPT} = (L_M - 2d_G) \tag{4}$$

In Fig.8 we show the optical length measurements of a 5-mm block, performed by the above described method, as a function of a separation of the front surface of the block M_{FS} relative to the quartz surface. The gradual increase of the separation M_{FS} is caused by a slightly penetrating oil into the wringing contact, as in experiments described in [11]. The corresponding experimental points are marked with circles. For the separation values M_{BS} in the range of 45-90 nm, when the gap between the block and the plate is completely filled with oil, the standard deviation for the measured values of the optical length is 0.4 nm, only. The corresponding mean value of the optical length is -91.99 nm. The value is in agreement with the optical length measurement result (-91.26 nm), which was obtained by the method described in [11,13]. This result was obtained for the *air gap* of about 30 nm between the block and the plate. In Fig. 9 this result is marked with a triangle. The optical lengths, measured with oil in a dynamic mode (circles), were compared with a stationary type of measurement in oil for an independent wringing of the measured block. The result of this measurement, corrected on the additional cleaning procedures, was –91.75 nm and is shown in Fig.9 as a dark dot. The reproducibility of these data points differ dramatically from the results of measurements with air gap [11,13], when the normal, relatively tight type of wringing to the same quartz plate is realised. The corresponding points in Fig.9 are marked with filled squares and show only the variation in time of the measurement results owing to slow plastic deformations of the quartz surface [11], caused by the wringing forces.

The proposed double-sided method can be used for high precision measurements of the mechanical length of the block L_M, which is free from Abbe errors. The comparison of equations (3) and (4) shows that *for reproducible wringing of the measured block* the difference between the slave-block method and the double-sided method gives the sum of values of the phase changes at the optical reflection for the two faces of the block. The corresponding measurements results are shown in Fig.9, where the half difference between the slave- block and double-sided methods is presented. All the wrings in these experiments of the 2-mm, 5-mm, 8-mm Cary blocks as well as the wring of the 50-mm steel block (experiment ***c*** in Fig. 5) to the same Cary plate were reproducible. The mean measured value of the phase change d_G for the surface texture of the Cary blocks is found to be 27.99 nm. The standard deviation, describing the spread of the data points obtained by the two methods free of Abbe errors, is 0.22 nm !

In conclusion we are to note that after determination of the phase change value d_G for the reference blocks, for which the reproducible wrings of the blocks to steel plates are possible, the mechanical length L_M of an arbitrary block can be found from the measurements of the optical length of the block. The optical length determined by the described double-sided method is to be by summed with the doubled value of the phase change d_G. The needed value of the phase change for the block can be precisely determined from the corresponding values of the reference blocks and the phase change correction r, accurately measured by the slave block method relative to the reference blocks, as outlined in the previous section.

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