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LETTER TO THE EDITOR

Author's reply to Dr G Bönsch's Letter to the Editor

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Abstract
Deviations from flatness of the gauging surfaces of material artefacts do not practically affect the results of new parallax-free methods of length measurements based on optical differential measurements (DM). The surface texture deformations, resulting from the wringing procedure of a gauge block to a reference plate and defined for the wringing contact without an excessive wringing film thickness, are highly reproducible and can be included in the definition of the mechanical length of a block without any tangible increase in the total uncertainty.

A series of papers [1–10], presented at numerous International Conferences [1, 2, 7–10] and published in *Metrologia* [4, 6] and *Applied Optics* [3, 5], deals with basic advances in interferometric length measurements. These include *new methods* in optical length measurements (such as the calibrated double-sided method [6, 7, 10] or a precise method for optical phase and phase change measurements [4, 5]), *new concepts* (such as reproducible wringing (RW) [1, 3] or wringing texture deformations [8, 10]), as well as *new length specifying parameters* (such as mechanical length L_M [4, 9], optical length L_{OPT} [1, 6] and physical length of a gauge block [8, 10]). In the recently published Letter to the Editor by Dr G Bönsch (PTB) [11] we find some criticism of our studies reported in [4, 6]. Below we show that solutions to the main problems raised in [11] can be found within the series [1–10].

First, we cannot agree with the basic statement of the abstract in [11] saying that

> 'Among the effects limiting the attainable uncertainty level, the elastic deformation of the gauge block by the wringing process has to be included in the evaluation model and to be appropriately taken into account in the uncertainty budget.'

In accordance with the presently valid International Standard [12], the length of a gauge block is defined in a wrung condition to a reference plate, so that the effect of one wringing is already included in the length of a gauge block (p 11 in [12]). So, the extra uncertainty component dealing with the wringing deformation of the gauge block is incompatible with [12], or with the definition of L_M [4, 5, 9], which is also defined in the wrung condition.

Table 1. Uncertainty budget for mechanical length measurement of a 2 mm tungsten carbide block.

Source	Its standard deviation	Corresponding standard uncertainty/nm
Laser frequency	2×10^{-9}	$2 \times 10^{-3} L$
Block temperature	1.5 mK	$17 \times 10^{-3} L$
Dilatation coefficient	5×10^{-8}/°C for $\Delta T = 150$ mK	$7.5 \times 10^{-3} L$
Air pressure	10.7 Pa	$27 \times 10^{-3} L$
Air temperature	10 mK	$9.6 \times 10^{-3} L$
Humidity	1%	$8.5 \times 10^{-3} L$
Edlen equation	1.6×10^{-8}	$16 \times 10^{-3} L$
Aperture and obliquity correction		$4 \times 10^{-3} L$
Wringing reproducibility	0.05 nm for 2 DM	0.32
Phase change correction measured for both surfaces	0.05 nm	0.1
Fringe fraction determination	0.045 nm for 4 wrings	0.07
Wringing deformation of the reference plate	—	0.1

Second, we demonstrate below that the evaluation of the uncertainty budget for L_M, given by the combination of the RW and slave block techniques [5, 9], does contain all the main influencing parameters. It is in agreement with the

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standard procedure of evaluation described in [12–15] and is not affected by the principal experimental 'finding' of [11]—'the two length values obtained for wringing on both sides of the gauge block'. The corresponding budget is presented as table 1 for the case when the measured 2 mm block is located above the 5 mm slave block (see figure 9 in [5]). The first seven influencing factors give the contributions proportional to the length of a block L, measured in millimetres. The standard deviations (σ-values) presented here were estimated at the time of writing the article [5]. These factors characterize the interferometer [1], and for a 2 mm gauge block they give the expanded uncertainty [13] of 0.16 nm for a 95% confidence level. Rows 9–12 in table 1 describe the length-independent factors of the budget, associated with the experimental studies of a specific 2 mm tungsten carbide (TC) block [5]. Wringing uncertainty evaluation is given by row 9. As usual [14, 15], the effect of flatness deviations of the block surfaces (or the influence of the surface topography as it is called in [11]) is estimated by the reproducibility of the length measurements corresponding to the wrings to both block surfaces. As follows from experiments ***a***, ***e*** and ***b***, ***f*** in figure 9 in [5], wringing reproducibility to both faces of the 2 mm block is within 0.1 nm, both for the wrings to a reference plate (***a***, ***e***) and to a 5 mm TC block (***b***, ***f***) of the same set. The corresponding σ-value for the wringing reproducibility presented in the table is 0.05 nm. Thus, the effect of topography, which is illustrated in [11] by figure 1, is not observed in this case, typical for RW. As pointed out in [5], the agreement of the length values to a small fraction of a nanometre for wrings to both sides of a block is the first test for RW.

The relation between the experimentally measured σ-value obtained for a fixed number of measurements, or degrees of freedom ν, and the uncertainty interval, measured at the 95% confidence level, can be found from table G.2 in [13]. For two independent measurements ($\nu = 1$), the coefficient value t_p in this table is 12.71, and the uncertainty interval, obtained by multiplication of the experimentally measured σ-value by the coefficient t_p, is equal to ± 0.64 nm. Half of it is presented in table 1 as a σ-value of a normal distribution, describing the wringing process of the 2 mm block.

Row 10 deals with the precise measurements of optical phase change corrections performed for the 2 mm and 5 mm TC blocks, using the effect of RW. The results of the measurements, presented as figures 9 and 10 in [5], show that the optical phase value for the 2 mm block is higher than that of the 5 mm block by 0.1 nm. This difference characterizes the measurements for both sides of the blocks. To ensure a proper safety margin, we consider that the uncertainty of this correction is equal to the whole effect (i.e. 0.1 nm). So, the corresponding σ-value in the table is shown as 0.1 nm.

The evaluation of the fringe fraction determination is based on the measurement results of wringing reproducibility of a short steel block to a steel plate, shown as figure 1 in [4]. As noted on page 123 there, the σ-value characterizing the spread of experimental points relative to the trend, describing the cleaning procedure of the surface, is 0.045 nm. For four independent data points ($\nu = 3$), the t_p coefficient is 3.18 [13], and the total uncertainty interval is 0.14 nm. Half of this value gives a safe estimate of the uncertainty of the σ-value for the fringe fraction determination, corresponding to the averaging procedure over four interferograms with gradually increasing phase shift between them [3]. We recall here that the ultimate resolution of our comparator was measured to be 0.05 nm for a 100 mm block, giving a resolution below 1×10^{-9} [1].

The problem of application corrections for wringing deformation of a steel reference plate, posed in [11], has already been solved in [5]. The corresponding contribution is evaluated as row 12. The solution is to use a modified stack (figure 2 in [5]) when a measured block is located above a relatively thick slave block, which is wrung to a much more rigid reference plate. Bending wringing deformations for blocks and plates were studied in [5]. The deformation magnitude shows a cubic dependence on the thickness of a sample (figure 4 in [5]). So, the slave block, 2.5–3 times thicker than the measured block, gives the necessary level of reduction of the plate perturbations, since for a 2 mm block the bending deformations of the plate are already less than 1 nm. Local surface deformations of the plate, observed outside the wringing contact, have been studied in [1]. In accordance with figure 8 in [1] their magnitude is within 1.5 nm. They are determined by the wringing contact between the slave block and the plate, and their effect is practically completely eliminated by the differential measurement of the slave block method, that is, by experiments 3, 5 in figure 2 of [5]. The possible residuals were estimated in [5] as 0.2 nm ($\sigma = 0.1$ nm in table 1).

The expanded uncertainty of the L_{M} measurement of the 2 mm block, following from table 1 and calculated in accordance with [13], is in the sub-nanometre range (0.73 nm).

The effect of surface topography outlined in [11] is not new. The internationally accepted procedure of taking it into account is the performance of measurements for wrings to both surfaces [14, 15], considering the mean value to be the length of the artefact [14]. In our papers the effect was studied both for the convex/convex gauging surfaces (see figures 6 and 10 in [5]) and for concave/convex surfaces (figures 11 and 12 in [5]). To improve the accuracy of measurements, the calibrated double-sided method (CDSM) was developed [6, 7, 10], which reduced the wringing uncertainty dramatically. In the general case [7], it requires 20 interferometric measurements or 10 differential measurements (DM), a high-resolution comparator, and two reference blocks permitting realization of RW. CDSM consists of three stages. Two DM are needed to find L_{OPT} of a measured block (see figure 1 and table 1 in [4]), four DM for finding the optical phase change value δ for a reference block (see figure 9 in [7]), and four DM for measuring, for both faces, the difference in δ values between the measured and the reference blocks (see figures 10 and 9 in [5]). Though CDSM is quite complicated, it offers the possibility of measurement of the excessive wringing film thickness [4, 5] for the wrings to concave surfaces, as demonstrated in [7] for the concave surface shown in figure 12(*a*) in [5]. It is worthy of note that the excessive wringing film thickness, which is included in the length definition [12], has never been measured by the standard method of optical interferometry [12, 14]. It should also be emphasized that all the stages of CDSM are insensitive to topography effects. First, the results of the double-sided method [1] are not sensitive to it. This is demonstrated experimentally by figure 8

[1], where a standard deviation of 0.18 nm is obtained for the wrings to both sides of a 30 mm block, while for the standard interferometric method the corresponding spread was 10 nm. Second, the L_M measurement for reference blocks is free from the topography effect (see row 9 in table 1) and, so, the δ measurement for them is not affected by topography. Third, high-precision measurements of the δ correction can be performed for concave/convex blocks with a σ-value of only ~0.05 nm, as demonstrated by figures 11 and 12 in [5]. So, we come to the conclusion that the effect of topography does not exist in the new parallax-free methods [4–7].

We are to note also that wringing surface texture deformations, mentioned in [11], have been measured for the first time in [10]. For TC blocks, for which texture deformations are determined much more accurately than for steel blocks [10], they have the value of 3 nm. This level of deformations corresponds to the tight wringing contact [5] and describes the maximum level of texture deformations existing between surfaces of the same texture. So, texture deformations are much smaller than gauge block typical flatness deviations [12]. As a result of the extremely high level of reproducibility of length measurements in case of RW (see table 1), these deformations can be included in the definition of L_M without any tangible loss of accuracy.

The conclusion in [11] about 'the perfect wringing over the complete measuring face' for the measurements on steel plates is based on the naked-eye observation of 'a particular shine on the plate after the gauge block has been removed'. Quite different results are obtained when using high-resolution interferometers and DM of parallax-free methods. In this case inhomogeneity of the wringing contact between steel blocks and plates is unambiguously detected [5]. As follows from the experiment showing the parallax-free type of measurements for RW (figure 3 in [5]), the tight wringing contact covers only a small portion of the gauging surface, having dimensions of about 3 mm × 4 mm even for specially selected blocks with small flatness deviations. Due to this the effect of RW has been observed only recently [1, 2], when a method has been found to localize the position of the tight wringing contact close to the centre of the gauging surface, though the gauge blocks have been used for almost a century.

The accusation in [11] that we use the 'rigid-body model' is absolutely groundless. In [4] there is a paragraph (p 126), describing the condition for RW and saying:

> 'If a short block (nominal length 3 mm to 8 mm) is chosen, having a uniformly polished face without scratches and with deviations in flatness of a few nanometres at the centre, reproducible wringing can therefore be achieved—the wringing forces deform the block so that it follows the shape of the much more rigid steel plate.'

Also, figure 7(*a*) in [5] illustrates the block deformations in the case of RW. Finally, the theoretical analysis presented in [5] does include the effect of texture wringing deformations, as is shown in [8, 10]. It follows from equation (3) in [10] that in the case of RW the relation between gauge block parameters L_M and L_{OPT} is given by the expression

$$L_M = L_{OPT} + 2\delta_S + \delta^*_{R,1} + \delta^*_{R,2} \tag{1}$$

where δ_S is the skin depth value for the block material, and $\delta^*_{R,1}$, $\delta^*_{R,2}$ are the roughness values for both block surfaces measured under the condition of tight wringing contact, that is, for the highest level of texture deformations. High-precision measurements of the optical phase change value δ under this condition are described in detail in [10]. The other result of the analysis [10] is that the values of length are the same for the standard and modified slave block configurations [5], if the surface textures of the blocks in the stacks are the same. Experimental confirmation of this basic result is presented by measurements (a) and (b) of figure 8 in [5].

We advise our colleagues to take much more seriously the results of scientific studies in the laboratory, which have demonstrated very accurate measurements in recent international comparisons, including the SIM.4.2 Comparison and the Key Comparison of BIPM CCL-K2.

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