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ADVANCES AND NEW TECHNIQUES IN LENGTH MEASUREMENTS BY OPTICAL INTERFEROMETRY

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Abstract: Studies of a long gauge block Kösters interferometer, performed at INMETRO, and the results of the CIPM Key Comparison CCL-2 show that the uncertainty in realization of the SI length unit achieved with this type of instrument in the range of 500 mm is ~1 part in 10^8. Basic advances in philosophy and techniques of high-precision temperature measurements, realized in Brazil in the last few ears, permit to reduce crucially the uncertainty of length measurements by optical interferometry and to reach the Nanometrolgy regime in artifacts with nominal lengths above 100 mm. New measurement and calibration techniques give an opportunity to realize the temperature measurement of a particular point on the GB surface inside the interferometer with a total uncertainty below 0.1 mK, realizing the measurement without the contributions of the temperature gradient in the GB and velocity error. The demonstrated reproducibility in length measurements of 100-mm steel gauge block is at the level of 58 pm.

Keywords: accuracy, interferometry, temperature.

1. LONG GAUGE BLOCK MEASUREMENTS WITH KÖSTERS INTERFEROMETER

Though laser interferometers (similar to HP5519A Model) are widely used in traceable dimensional measurements, the most accurate realization and the dissemination of the SI length unit in all advanced countries is performed through measurements of gauge blocks (GB) in terms of wavelengths of standard radiations by optical interferometry. Absolutely outstanding contribution in the field belongs to W. Kösters, who in 1920 developed the method for length measurements of Johansson end standards (now usually called as GB) by optical interferometry [1], proposed the existing nowadays the length definition of the material length standard, a later developed the interferometer [2,3], which for many decades has been used for the most accurate realization of the SI length unit. An idea about the present state-of- the-art in length measurements at highest level give the results of recent CIPM Key Comparison CCL-K2 [4], presented in Fig.1. As it follows from Fig.1, the most consistent data were presented by the INMETRO team both from the point of view of the reproducibility of measurement results and their proximity to the reference values of the Comparison. The other important feature of the INMETRO contribution is the correctness of the evaluation of the uncertainty budget of the comparator, resulting in small E_n-values (See Tables 10a in [4]), showing the deviation of the reported results relative to the reference values of the Comparison, that is divided by the uncertainty value estimated by the laboratory.

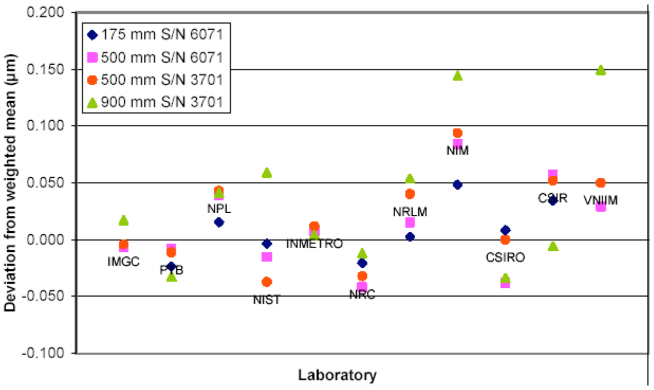

Fig.1. Results of the 12 leading National Metrology Institutes in the Key Comparison CCL-K2.

Before Key Comparison, our studies of the temperature measuring system of Kösters interferometer [2,3], belonging to INMETRO, revealed a systematic type of offsets of about 1.5-2 mK. So, the combined standard uncertainty for 500 mm blocks was estimated to be 20 nm in report of INMETRO to the pilot laboratory. This estimation was proved by the results of CCL-K2, revealing the differences of +7 nm and +12 nm relative to the Reference values of the CCL-K2, which correspond to two 500-mm blocks used in the Comparison. Relatively recently, we completed the first metrology study and the certification [5] of the temperature measuring system of our Kösters interferometer. This study confirmed the existence of the length dependent systematic bias of ~2 mK in the instrument. After applying the corresponding correction (-12 nm) to the INMETRO data of Fig.1, we find that the accuracy of our Kösters interferometer, with the properly certified temperature measuring system, reaches the level of ~$1x10^{-8}$ in measurements of 500-mm blocks. So, we can say that the efforts of the length experts in 11 World leading National Metrology Institutes, participating in the Key Comparison

CCL-K2, prove the validity of H. Darnedde's evaluation [3] of the accuracy of Kösters interferometer.

2. ADVANCES IN LENGTH MEASUREMENTS BY OPTICAL INTERFEROMETRY

The recent progress in length measurements by optical interferometry, achieved at INMETRO, is related to the new approach in temperature measurements of gauge blocks [5,6]. The special techniques in calibration of platinum resistance thermometers (PRT) and the realization of temperature measurements by pairs of calibrated PRT, both provide the temperature measurement of a material artifact without devastating contribution of temperature gradients in the artifact and without the velocity error, associated with the time delays in propagation of heat waves inside interferometer. The importance of temperature measurements for gauge block measurements stems from the fact that the contribution of the uncertainty due to temperature measurements is equal to the sum of all other uncertainties in Kösters interferometer [3], and the average value of the uncertainty for 500-mm blocks in Fig.1 is equal to 52 nm [4]. From this data we evaluate that the mean value of the uncertainty in temperature of gauge blocks, achieved at 12 leading NMIs, is about 6 mK.

The key feature of our new approach is the precise calibration of resistance thermometers under the real experimental conditions, so that that the calibrated thermometer measures the temperature of the block surface. The calibration procedure is realized in two stages. In the first stage, we calibrate the temperature response of the sensor in a specially developed double Dewar system (DDS) [6] by realizing several slow heating and cooling procedures under well controlled conditions, thus eliminating the velocity error contribution in temperature measurement, which is associated with the finite time of propagation of the heat signal in the experimental set-up.

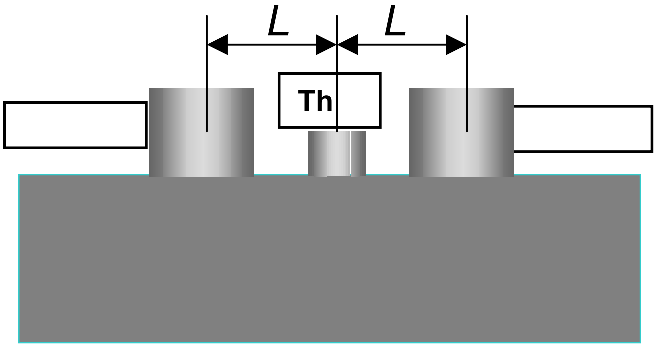

Fig.2. Thermometers configuration for precise calibration, and precise temperature measurement of a particular point on the GB surface.

The effect of thermal gradients in the experimental set-up, which usually sets the accuracy limitations to calibration procedure, is eliminated by the reciprocal exchange of the positions of the calibrated and reference thermometers inside the DDS. In the final stage of calibration, we precisely measure the self-heating effect of the calibrated thermometer directly on the gauge block surface using the specially developed double-channel synchronous detection technique [4,5]. The self-heating (SH) effect of the thermometer is measured with the help of an auxiliary temperature sensor, located on the block surface (Fig.2). As the SH value is shown to depend on the distance from the calibrated thermometer and the thermal flux conditions existing in the gauge block [5], the SH measurements has to be repeated for the inversed position of the PRT relative to auxiliary sensor [8]. Then the resistance thermometer, calibrated in this way, measures the temperature of the gauge block surface at the point, occupied by the auxiliary sensor in the calibration procedure. But it occurs only in the case when *there is no velocity error*, so that the temperature rate is close to zero at the time of measurement, and *there is no temperature gradient*.

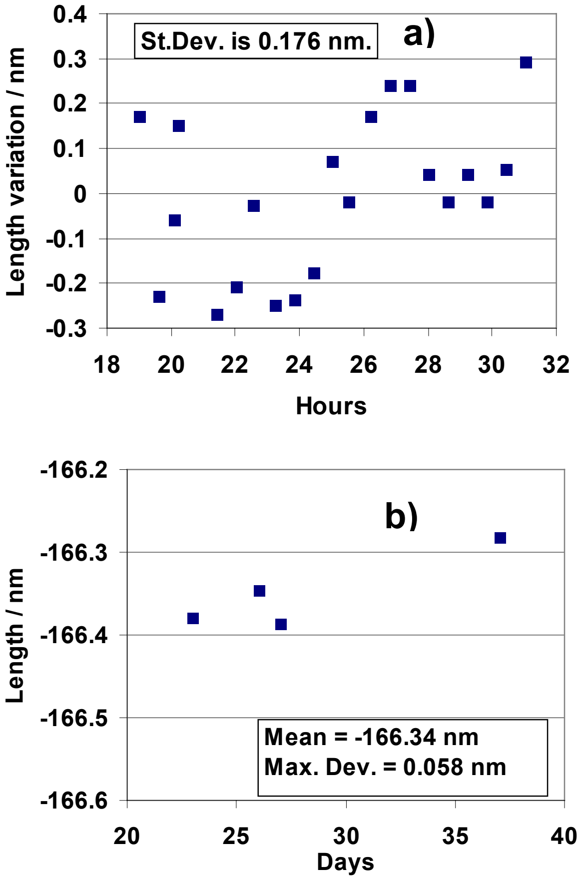

Fig.3. Stability of the length measurements of a 100-mm steel gauge block in the night-time series (Fig.3a) and the reproducibility of the mean length value in such series on a two weeks time interval (Fig.3b).

To realize in practice temperature measurements without the velocity error [5,7] and with the suppression of the thermal gradient effects [8], we install a pair of calibrated thermometers with the auxiliary sensor between them (Fig.2). We keep the configuration of the calibration procedure in the following interferometric length measurements, in order not to change the temperature distribution produced by resistance thermometers. In case of our short gauge block interferometer, when the axial gradient in GB is very small (see Fig.8 in [8]) , we can put calibrated sensors symmetrically on the upper and lower side surfaces of the gauge block. In this case, the couple of calibrated resistance thermometers give the temperature on the block axis, thus realizing “mode matching” between resistance thermometry and optical interferometry.

The key feature of this measurement procedure is that the measured temperature on the axis is not affected (in the first approximation) by thermal gradients in the block and the velocity error. In Fig.3 we show the results of length measurements of our 100-mm Frank steel gauge block in the comparator equipped with the new temperature measuring system. The standard deviation in a 12 hours series of night-time measurements with a regular phase shift between consecutive interferograms, is 0.176 nm (Fig.3a). When plotting the mean values of the block length in such long series, we obtain the reproducibility of length measurements shown in Fig.b. For two weeks time interval, the maximum deviation from the mean value is 0.058 nm, demonstrating the agreement between the measurements of the resistance and optical thermometers at the level of less than 50 μK in the case, when the gauge block temperature variations inside the instrument reached the value of 80 mK and the change of the vertical temperature gradient in the artifact was about 0.8 mK.

When comparing this reproducibility value with the typical values of Fig.1, one can realize what a progress has been realized at INMETRO towards the regime of Nanometrology in length measurements.

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