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MEASUREMENT SYSTEM BASED ON MULTI-WAVELENGTH INTERFEROMETRY FOR LONG GAUGE BLOCK CALIBRATION

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Abstract

This paper shows the result of work of the Institute of Micromechanics and Photonics at Warsaw University of Technology and the Length and Angle Division of Central Office of Measures (GUM) [1] in building an automatic multiwavelength interferometric system with extended measurement range for calibration of long (up to 1 m) gauge blocks. The design of a full working setup with environmental condition control and monitoring systems, as well as image analysis software, is presented. For length deviation determination the phase fraction approach is proposed and described. To confirm that the system is capable of calibrating gauge blocks with assumed accuracy, a comparison between the results of 300 mm length gauge block measurement obtained by using other systems from the Central Office of Measures is made. Statistical analysis proved that the system can be used for high precision measurements with assumed standard uncertainty (125 nm for a length of 1 m). Finally the comparison between our results obtained for a long gauge block set (600 mm to 1000 mm long) and previous calibrations made by the Physikalisch-Technische Bundesanstalt (PTB) [2] is shown.

Keywords: gauge block, multi-wavelength, interferometry.

1. Introduction

One of the basic units of the SI is the metre. It is defined as the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second. This definition has been established in 1983 at the XVII General Measures Conference of Weight and Measures.

Despite the fact that there is a diversity of measurement standards used for length measurements, gauge blocks are still the most popular standards for industrial purposes. Their size tolerance is relatively tight, so the calibration needs to be performed using adequately accurate measuring methods. Gauge blocks of the highest grade of accuracy, called K according to ISO 3650 standard, should be calibrated using the interference method. Because of the difficulties related to such measurements this service is usually performed by National Metrology Institutes (NMIs). The Quantified Degree of Equivalence (QDE) of different countries' measurements results is calculated on the basis of international comparisons of short (up to 100 mm) and long (longer than 100 mm) gauge blocks. The results of these types of comparisons, established by the International Committee for Weights and Measures (CIPM), called K1 and K2, are published on the website of the International Bureau of Weights and Measures (BIPM) Key Comparison Data Base (KCDB) [3]. There are several individual solutions and combinations of measuring systems used by NMIs. Usually the systems used for short and long gauge blocks are different. The former are offered commercially, whereas long gauge block interferometers are designed and built individually. The first well described sophisticated interferometer for long gauge block measurements was

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built in BIPM. It used the exact fractions method and both laser and Krypton lamps as sources of light. [4]. Essential elements of its construction determined the designs of later systems built by some NMIs. Another optical system based on laser light and white light sources was used in MIKES – Finland. [5]. Some later interferometers using the exact fractions method were modernized using the phase-stepping system for more accurate fringe fraction determination [6-7] while others are designed as systems with no wringing on the base plate [8-9].

To preserve an unbroken chain of comparisons, the distance travelled by light has to be transferred into gauge block length. As mentioned above it can be done using an interferometer and measuring the distance between the surface of the gauge block and a reference surface wrung to the rear surface of the gauge block.. However that kind of measurement is complicated due to the big influence of environmental conditions, high requirements for uncertainty and ambiguity in interference order. It is important to monitor temperature, pressure, humidity and concentration of CO_2 in air to correct the used wavelengths [10-12]. Moreover temperature of the gauge block (due to thermal expansion) has to be controlled, appropriate wringing to reference platen, arrangements on supports, weight compensation and other conditions have to be provided to carry out calibrations with all needed requirements[13].

2. Design of the measurement setup

There are three essential parts of the measurement setup: optical, mechanical (with actuators) and environmental condition monitoring and stabilizing system.

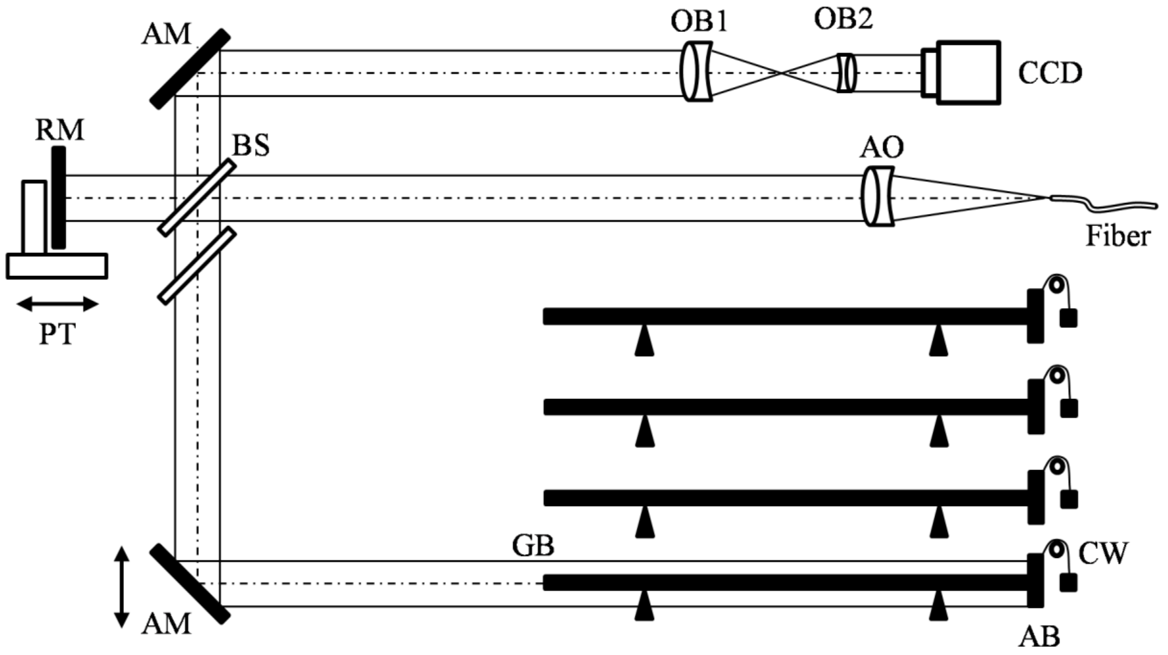

Fig. 1. Scheme of the measurement setup. GB – gauge block, AB wrung platen, CW – counterweight, AM – auxiliary mirrors, BS – beam splitter, RM – reference mirror, PT- piezoelectric transducer, AO – apochromatic objective, OB1-OB2 – imaging lenses.

The optical part is based on the Twyman-Green configuration (see Fig. 1). Light is introduced into the system by multimode fiber with a diameter of 50 µm. Then it is collimated by an apochromatic objective (AO) with a focal length of 502 mm. The diameter of the beam is 50 mm. Correction for four wavelengths, 543.5 nm, 594.1 nm, 611.9 nm and 632.8 nm gives the ability to use different laser sources. Next, the beam is split into two arms by a flat parallel glass plate with half-reflective surface (BS). In the objective arm a second glass plate is used to compensate the optical path length for different wavelengths. Thanks to this, the setup can be easily reconfigured to enable using more than one laser source at the same time. The object beam after being reflected by mirror (AM) illuminates the gauge block under test (GB) with platen (AB) wrung to the rear block's surface. The mirror (AM) is also used to select the measured gauge block. Positioning this mirror along the optical axis allows to measure sequentially up to four gauge blocks. The reference beam illuminates the reference mirror (RM) mounted on a piezoelectric transducer (PT) to perform the phase shifts required by the automatic fringe pattern analysis method (AFPA). Next, the beams reflected by the measured object (GB with AB) and reference mirror (RM) are recombined by the beam splitter (BS) and directed by the mirror (AM) into an imaging afocal system (OB1 and OB2) which is used to conjugate the detector plane with the measured object and fit the beam diameter to the detector matrix size. As a detector, a Grasshopper GRAS-20S4M/C camera made by Point Grey [14] has been used. It provides 16 bit gray depth, pixel size 4.2 µm x 4.2 µm and maximum resolution 1624 x 1224. The camera with water cooling system is shown in Fig. 2.

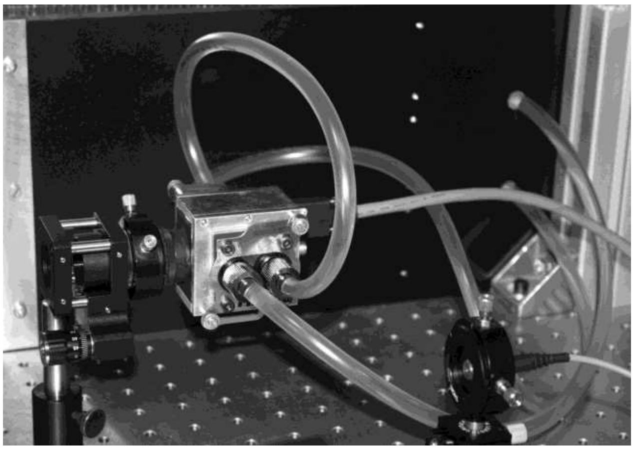

Fig. 2. Grasshopper GRAS-20S4M/C camera with water cooling system mounted.

To control the setup four types of actuators are used. To move the reference mirror, the piezoelectric transducer made by PI [15] with a servo-controller submodule is applied. It works in a feedback loop and provides repeatability of 1 nm in a range of 15 µm. This high accuracy ensures correct work of phase shift algorithms. Axis movement and positioning of auxiliary mirrors (AM) in the objective arm is controlled by a stepper motor conjugated with a linear table. Moreover, the mirror can be rotated around its axis using a servo driver made by Thorlabs. Full adjustment of the setup in the perpendicular axis is realized by tilting the gauge block. Each gauge block lies on two supports placed in Airy points [16]. These supports are made as special hexagonal cases with thermistors located inside, which are used to measure gauge block's temperature. They are mounted on the bench and can be tilted using the servo drivers. Additionally, to assure parallelism of gauge block surfaces, the weight of the reference plate is compensated by a counterweight (CW). The mechanical setup of gauge block supporting and positioning is shown in Fig. 3.

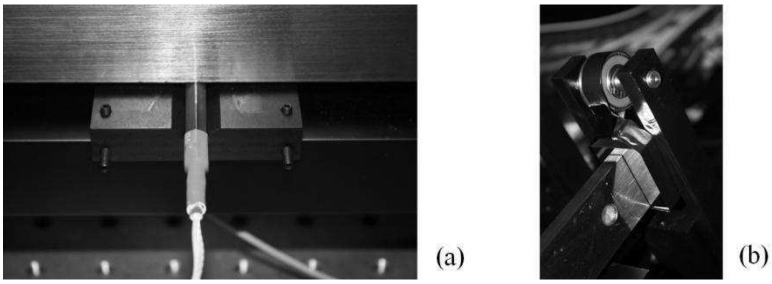

Fig. 3. Gauge block lying on the hexagonal support with thermistor inside (a). Reference plate adhered to the gauge block is hanging on a weight-compensating counterweight (b).

The last moveable part of the system is a fiber shaking device. Due to using coherent light, speckles are produced which disturb the fringe pattern. In order to remove them we simply use a time averaging method realized by shaking the fiber in different directions at different frequencies by a specially designed shaking system. Images with speckle noise and after removing speckles are shown in Fig. 4.

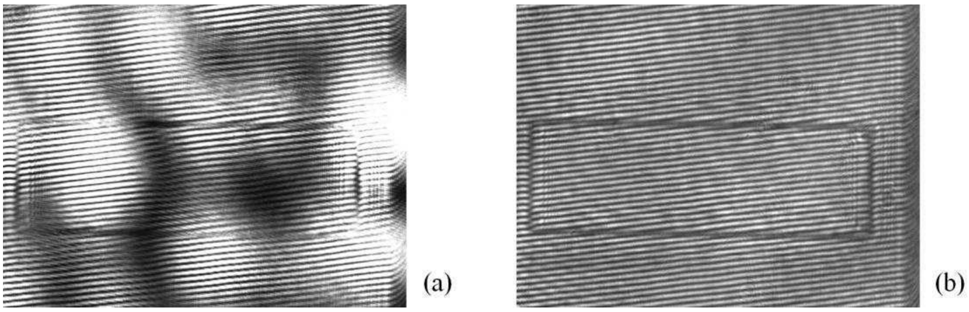

Fig. 4. Fringe pattern of gauge block wrung to platen with visible speckles (a). Fringe pattern of gauge block wrung to platen without speckles after time averaging (b).

The very important part of the interferometer is the system for stabilizing and controlling environmental conditions. Vibrations are reduced by using an optical table as the basis for other devices and elements. For temperature stabilization a network of pipes with water is mounted around the interferometer (see Fig. 5a). Pipes are arranged in a way which minimizes temperature gradients in the measurement chamber. This means that the first pipe with hottest water lies next to the last pipe with coldest water and so on. The temperature of water is controlled by a thermostat with a resolution of about 0,01 °C for the used volume of liquid. Additionally, as it was mentioned previously (see Fig. 2), the water is provided for the camera cooling system. A housing made of mineral wool cover with aluminum foil has been built over the table. To strengthen the construction and facilitate sealing, mineral wool has been additionally covered by steel plates (see Fig. 5b).

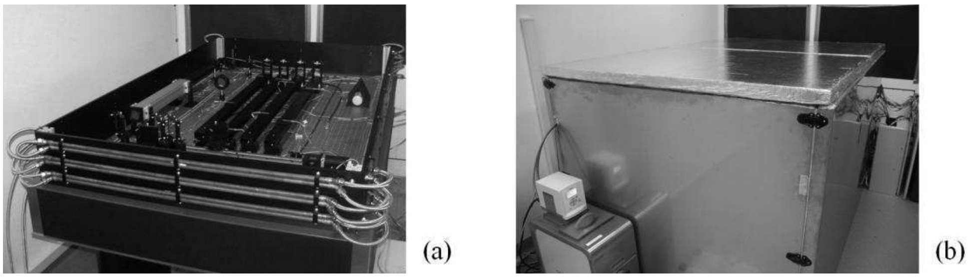

Fig. 5. Interferometer placed on the optical table. The setup is surrounded by pipes with water providing temperature control (a). Housing of the interferometer (b).

During measurements, four main environmental parameters are monitored: temperature, air pressure, humidity and concentration of CO_2. Temperature is monitored by a network of 40 thermistors made by Measurement Specialties (model 44031RC) connected to Keithley's Model 2700 Multimeter [17]. Eight of them are built in hexagonal supports and are used to measure the temperature of gauge blocks. The remaining thermistors are built in cylindrical cases with radial radiators. They are measuring temperature of air at the height of the beam (around 10.5 cm) along the two interferometer arms. To isolate them from the surface of the metal table they are placed on posts made of PTFE (see Fig. 6). Pressure, humidity and concentration of CO_2 are measured using three sensors produced by Vaisala [18]: barometer PTB330, carbon dioxide probe GMP343 and hygrometer MT333.

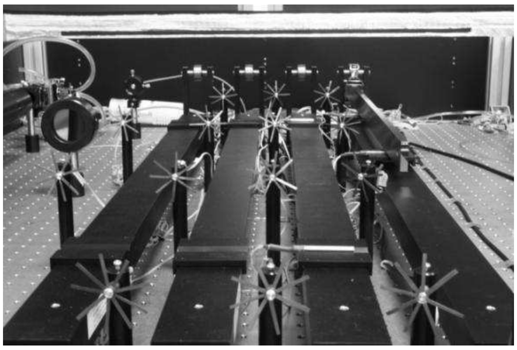

Fig. 6. Network of thermistors for air temperature monitoring.

3. Image analysis and length determination method

Gauge block calibration demands good repeatability and high accuracy. It can be achieved using interferometry. However measurement of objects with high height steps such as gauge blocks is always ambiguous due to unknown interference order. A classical approach to this problem is to measure the shift ε (see Fig. 7a) between fringes obtained on the front surface of the gauge block and the reference plate attached to the rear block surface. This procedure is repeated for different wavelengths and gives a set of fringe fractions $\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_n$ which is unique for a small enough measurement range (but many times greater than the wavelength) [18-20].

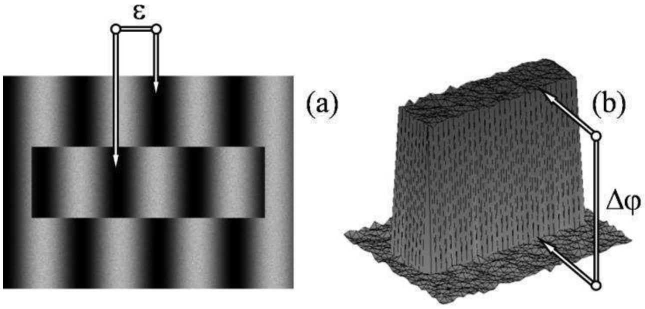

Fig. 7. Fringe shift on simulated fringe pattern (a). 3D image of phase retrieved from the fringe pattern (b).

This approach became the basis for our analysis method. The easiest and more accurate way to analyze fringe patterns is to do it in the phase domain (see Fig. 7b). So, the first step is obtaining a phase image of the measured object. It can be done by using one of the automatic fringe pattern analysis methods. The eight-point phase shifting algorithm with approximation of the Hanning window [21-22] which minimizes the phase error caused by phase-shift miscalibration has been proposed. The exemplary phase map modulo 2π with marked areas for further analysis of phase fraction is presented in Fig. 8.

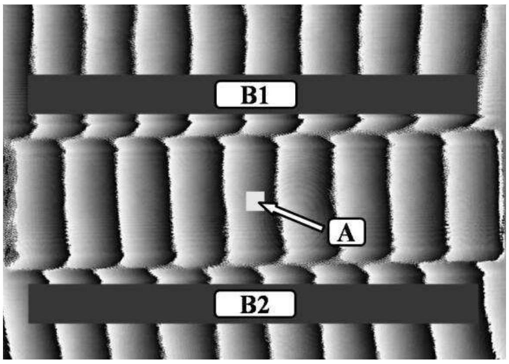

Fig. 8. Phase map modulo 2π obtained from 11.5 mm gauge block calibration. Two bigger areas marked on the reference block and one small on the center of the gauge block have been used to make phase fraction calculations.

From this phase map the phase fraction can be calculated as the phase difference between the central point of the gauge block surface (marked by square A) and the surface of the reference block (areas B1 and B2). First, these areas are unwrapped using a spanning tree algorithm with weight of sum of absolutes of real and imaginary parts of phase. Then the average value of $\varphi 1$ from all pixels inside area A is calculated. Rectangles B1 and B2 represent areas which are used for finding the parametric representation of the reference surface. After unwrapping, the least squares method is used to find best fitted planes in areas B1 and B2. However we are able to find slopes of planes but not their location on the z axis due to unknown interference order. These two areas are separated the by gauge block due to a limited field of view. It forces us to make this step of calculations individually for each plane. As the result, two values of phase φ_{2a} and φ_{2b} on the bottom surface of the gauge block are obtained (see Fig. 9).

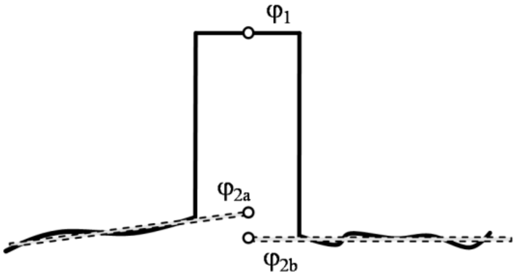

Fig. 9. Dotted lines represent planes fitted to the left and right side of the reference surface. Points φ_{2a} and φ_{2b} are values of phase calculated using fitted planes. Point φ_1 is the value of phase obtained from the top surface of the gauge block.

Then each value is being moved to the $<0, 2\pi)$ domain by adding or subtracting integer multiples of 2π. If the difference between φ_{2a} and φ_{2b} is less than π we can calculate φ_2 as a simple average of φ_{2a} and φ_{2b}. Otherwise we should add π to the average to shift planes into the same interference order (we assume that the error in obtaining phase from two different areas should be smaller than π). Next the phase fraction $\Delta\varphi$ is calculated as the difference between φ_2 and φ_1 again moved to the $<0, 2\pi)$ domain. The procedure described above has to be repeated for each wavelength used in the measurement. Moreover, the length of each wavelength has to be corrected using Edlen's formula [10-12]. Then the central length l of the gauge block can be written as:

$$l=\left(N_1+\frac{\Delta\phi_1}{2\pi}\right)\frac{\lambda_1}{2}=\left(N_2+\frac{\Delta\phi_2}{2\pi}\right)\frac{\lambda_2}{2}=\ldots=\left(N_k+\frac{\Delta\phi_k}{2\pi}\right)\frac{\lambda_k}{2}. \tag{1}$$

Unfortunately, because unknown integer multiplies wavelength Ni there is no possibility to unambiguously determine length *l*. To do this we proposed and applied the following procedure. First, the range *(l-x, l+x)* in which we are going to find all sets of $N_1, N_2, \ldots, N_k$ is defined. It has to satisfy inequality (2):

$$l-x\le\left(N_i+\frac{\Delta\phi_i}{2\pi}\right)\frac{\lambda_i}{2}\le l+x. \tag{2}$$

Next, for each set of phase fractions, the arithmetic mean from li values is calculated as:

$$l_{avg}=\frac{l_1+l_2+\ldots+l_k}{k}. \tag{3}$$

Then the geometric mean Δl of deviations from lavg is calculated as:

$$\Delta l=\sqrt{\left(l_{avg}-l_1\right)^2+\left(l_{avg}-l_2\right)^2+\ldots+\left(l_{avg}-l_k\right)^2}. \tag{4}$$

Values of $l_1, l_2, \ldots, l_k$ *for* which Δl is a minimum (in perfect conditions equal to zero) are the basis to calculate gauge block length as lavg. The last step is to recalculate l_{avg} into l_{avg20} at 20 ºC. It can be done using (5) or expanded equation with higher orders accounted.

$$\Delta l_{avg20}=\frac{\Delta l_{avg}}{\alpha(t-20°C)}, \tag{5}$$

where α is the thermal expansion coefficient and t is the temperature of the measured gauge block.

Using this approach we have to be aware of some difficulties during real measurement. First of all we assume that the platen is perfectly flat. According to the definition of gauge block length [13] this assumption is correct. However in reality the approximation of the platen surface as a plane causes an error in the result. Analysis from previous works [23] shows that we could reduce this error by subtracting the phase map obtained from the reference flat surface. Still the most proper approach and more consistent with the definition is to use areas limited to the nearest neighborhood of the gauge block. Flatness in this area is closer to flatness under the gauge block while remaining errors can be taken into account as an element of uncertainty analysis.

The second problem is to choose the range *(l-x, l+x)* in which we will find only one combination of phase fractions. Simulations show that in perfect conditions this range is equal to the least common multiple of wavelengths of the used laser source. However due to errors in obtaining a phase (camera noise, calibration of piezoelectric transducer…) we have to limit this range. For an assumed 2% error with two wavelengths λ_1=633 nm and λ_2=543 nm, the measurement range is 1900 nm [24]. To make sure that phase in our setup can be obtained with required accuracy we have made a short-term stability test using a flat mirror with flatness about λ/50. Using a mirror makes the test independent from the influence of changes of environmental conditions and gives the ability to check the repeatability of obtaining phase. Results of 100 measurements of phase obtained in a 6 h period are shown in Table 1. The standard deviation of measurements corresponds to 0.6% error for half of 633 nm wavelength. It gives us an over 99% probability that our setup has sufficient accuracy of obtaining phase for a measurement range equal to 1900 nm.

Table 1. Results of phase measurement repeatability

Mean value of phase	Standard deviation	Maximum deviation
0.206 rad	0.034 rad	0.081 rad
3.3%	0.6%	1.3%

4. Tests of the system

Preliminary tests of the setup made using short gauge blocks proved that results obtained using the presented system are comparable with results from other systems [23]. To be sure that we are able to measure long gauge blocks (up to 1 meter) we have decided to make a comparison with other methods and setups used in the Central Office of Measures. First, as the test object we used a 300 mm long gauge block made by KOBA [25]. The exemplary fringe pattern obtained for this gauge block in our measurement system is shown in Fig 10.

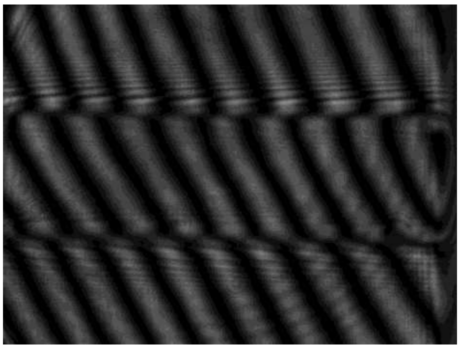

Fig. 10. Fringe pattern obtained during measurement of a 300mm long gauge block.

As reference, five other setups were used: automatic laser interferometer GBI 300, gauge-block interferometer based on one stabilized laser and a white-light source (UKI01) constructed in GUM, Mechanical Comparator with two sensors TESA UPC and Length measuring machine with laser interferometer SIP 3002M using two different gauge blocks as reference (10 mm length and same length as the measured gauge block). The uncertainty of multiwavelength interferometer (MI) has been estimated using the evaluation of uncertainty of other interferometers and was described in previous papers [23, 26-27]. Expanded uncertainty (k=2) for a 300 mm gauge block is U=113 nm. The results of 300 mm gauge block calibration with uncertainty obtained from each setup are shown in Fig. 11. Each result is calculated as the average length from measurements of both sides of the gauge block. It can be easily noticed that results are comparable and the spread between them is relatively low.

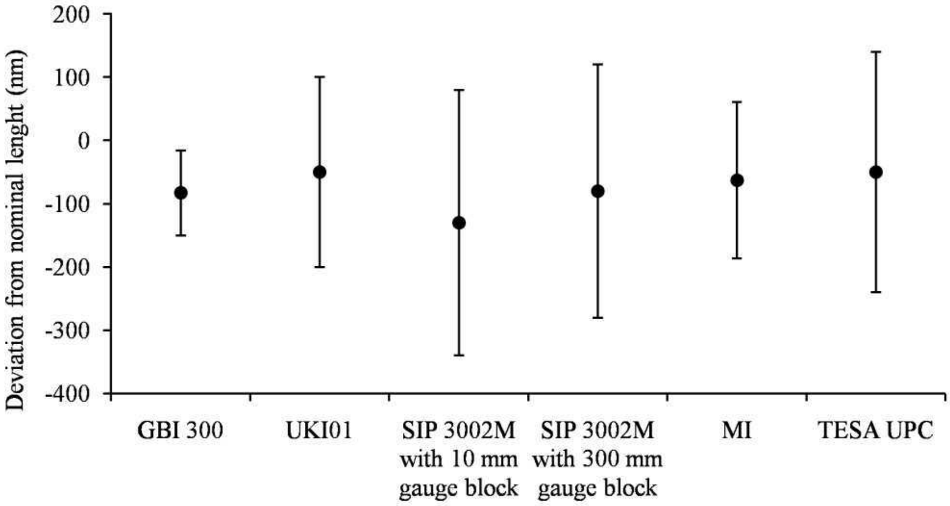

Fig. 11. Results of calibrations of a 300 mm long gauge block with marked expanded uncertainty for each setup.

However it is important to check if this spread is statistically significant. To check statistical consistency of obtained results the value of En for all of them can be calculated.

$$E_n = \frac{x_i - \bar{x}_w}{2\sqrt{u^2(x_i) - u_{\text{int}}{}^2(\bar{x}_w)}}, \tag{6}$$

where $u(x_i)$ is the standard uncertainty, $\bar{x}_w$ the weighted mean and $u_{int}(\bar{x}_w)$ is internal standard deviation. The expected value of En should be less than 1 for a coverage factor k=2. To expand the analysis, the statistical consistency of the comparison can be checked. It can be made using a Birge ratio test which compares the observed spread of the results with spread expected from individual uncertainties. The Birge ratio can be calculated as in (7).

$$R_B = \frac{u_{ext}(\bar{x}_w)}{u_{\text{int}}(\bar{x}_w)}. \tag{7}$$

External standard deviation u_{ext} can be calculated as in (8):

$$u_{ext}(\bar{x}_w) = \sqrt{\frac{1}{n-1} \frac{\sum_{i=1}^{n} \frac{(x_i - \bar{x}_w)^2}{u^2(x_i)}}{\sum_{i=1}^{n} \frac{1}{u^2(x_i)}}} \tag{8}$$

For a coverage factor k=2 the comparison is consistent if the Birge Ratio satisfies the following inequality:

$$R_B < \sqrt{1 + \sqrt{\frac{8}{n-1}}}. \tag{9}$$

If the Birge Ratio would indicate that the comparison may not be consistent, we should eliminate the result with the largest value of E_n from the comparison. This procedure should be repeated until we find the largest dataset which satisfies (9).

The results of statistical analysis of data obtained by different measurement systems are shown in Table 2. Values of most important parameters like En and Birge ratio show that all results, as well as the whole comparison, are statistically consistent. It leads to the conclusion that results obtained from our setup are on the same level as results obtained in other certified setups from the Central Office of Measures.

Table 2. Comparison of results for a 300 mm long gauge block.

Setup	Deviation from nominal length [µm]	Standard uncertainty [µm]	E_n	Birge Ratio
GBI 300	-0.083	0.034	-0.17	0.35
UKI01	-0.05	0.075	0.18	
SIP 3002M[a]	-0.130	0.105	-0.27	
SIP 3002M[b]	-0.080	0.100	-0.02	
TESA UPC	-0.050	0.095	0.14	
MI	-0.059	0.056	0.16	

[a] SIP 3002M with 10 mm gauge block
[b] SIP 3002M with 300 mm gauge block

5. Comparison of the results of calibrations carried out in PTB and GUM

A final test of our measurement system has been made using a set of long gauge blocks. The set consisted of five gauge blocks 600 mm, 700 mm, 800 mm, 900 mm and 1000 mm long. Each gauge block was previously calibrated two times by Physikalisch-Technische Bundesanstalt (PTB) laboratories. The first calibration was made in 2006 using a precise interferometer similar to the one used in GUM (MI). In addition, thermal expansion coefficients and deviations from flatness of gauge block surface were measured. A second calibration was made in 2011 by comparison.

Using the interferometer in GUM (MI) final results were calculated as the average value from calibrations of a gauge block wrung to the left and right side. Moreover calibration for each side was repeated up to four times. The comparison between results obtained by PTB and GUM for a 1000 mm gauge block is shown in Fig 12.

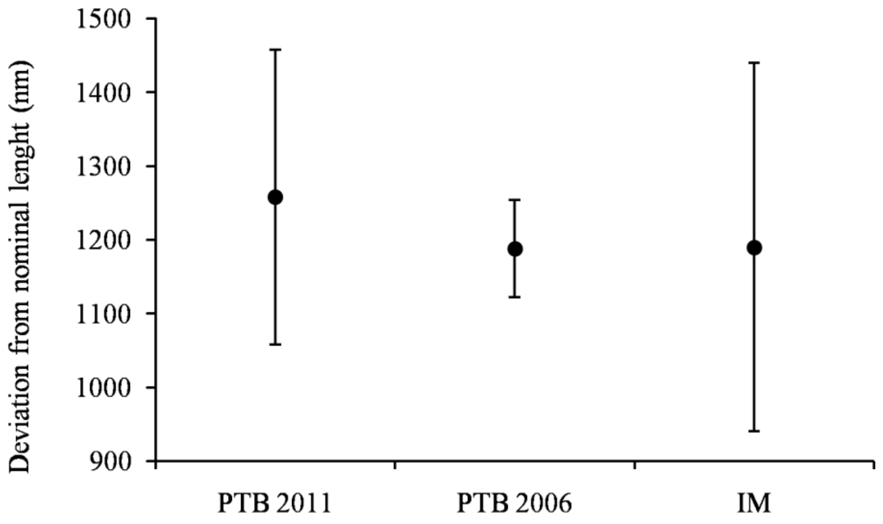

Fig. 12. Results of 1000 mm long gauge block calibrations with marked expanded uncertainty for each setup.

Results for the remaining gauge blocks are presented in Table 3. Considering the fact that all obtained deviations from nominal length are very close and are approximately in the range of the assumed standard uncertainty, it can be concluded that results obtained using the MI system are correct and comparable to other systems.

Table 3. Comparison of long gauge block deviations from the nominal length. Results are in nm with corresponding expanded uncertainty *U(d)*.

Nominal length	PTB 2011		PTB 2006		MI	
	Deviation [nm]	*U(d)* [nm]	Deviation [nm]	*U(d)* [nm]	Deviation [nm]	*U(d)* [nm]
600 mm	431	140	388	45	390	144
700 mm	609	150	488	49	510	174
800 mm	1297	200	1222	55	1270	204
900 mm	603	160	501	60	475	228
1000 mm	1258	200	1188	66	1190	250

6. Conclusions

In the paper a measurement system based on multiwavelength interferometry for calibration of long gauge blocks is described. Optical and mechanical designs of the setup have been presented. Moreover, the image analysis method and length deviation determination procedure have been presented. It has been noted that parameters like phase calculation uncertainty and flatness of the platen are crucial for obtaining a wide measurement range and repeatability of results. To confirm that the presented setup is capable of calibrating gauge blocks with high accuracy we have made comparisons with other certified systems from the Central Office of Measures. Statistical analysis proved that the presented system can be used for high precision measurements. Finally, results of long gauge block calibrations obtained by PTB with those obtained using the MI system have been presented. All experiments carried out confirmed that long gauge blocks can be calibrated with the assumed uncertainty.

7. Acknowledgements

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