

Automated gauge block pair length difference calibration and associated uncertainty sources

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Abstract. A reduction for interferometric uncertainties in length difference at gauge block pairs is presented. An automated processing designed to compensate geometric fringe visualization effects and four-alternate wringing technique are used to achieve small combined uncertainties for length difference calibrations, maintaining a good compliance with the EAL-G21 determinations.

1. Introduction

According the EURAMET cg-2 standard [1] the dimensional metrological community must have at their disposal several calibrated standards in form of a gauge block pairs set, to be used as a necessary electromechanical comparator measurement validation tool. The reduced uncertainties considered in this reference are essential prerequisites for these standards and they can be achieved by high-accuracy interferometric methods. Use of automated phase estimation techniques is specially indicated to reduce the measurement uncertainties to the recommended levels.

2. Objective

One of approaches to maintain the quality assessment and extend the traceability chain of the calibration systems is to compare results of same standards obtained with older and updated systems [2]. To avoid operator biases and coarse direct visual observation uncertainties obtained as in the original interferometric system, it was developed an automated image capture computer system. This system was originally based on specific software designed in Visual Basic to process phase information of interferograms that were obtained by an attached high sensitivity astronomical digital camera, with near square aspect ratio (with resolution corresponding to 512 x 512 pixels) and good time exposure control. This last feature allows it to work together with a small luminous flux ¹¹⁴Cd spectral lamp to produce their wavelength references as length standards.

2.1. Interferometric length difference measurements

In differential measurements, as the gauges must be commonly affected by changes of optical paths at the block sides in absolute interferometric techniques, taking a simple numeric subtraction between two absolute lengths of a gauge pair measured in separate moments carry all combined uncertainties due to thermal expansions and air refractive index effects. To avoid that increase of uncertainty values we must measure directly the length difference of both upper surfaces of gauges in a pair by



interferometric methods. This approach allows us to reduce all length-dependant components to sub-nanometer amounts in pairs of similar nominal lengths.

We must compare the phases in fringe patterns of both upper surfaces to estimate their length difference values. But the intrinsically asymmetric nature of geometric point-of-view in comparing lengths from one upper surface center point to another precludes us of using a mean value of two reference points to compensate for slight fringe inclinations as made in absolute symmetrical approaches. In 2000 [3] there was designed a compensation method, consisting in alternating choose of both reference surfaces (“straightening” the fringes over these surfaces) and taking the average of those two measurements, ignoring orientation at base fringes. That can produce a large dispersion sometimes. An estimation error can be directly perceived by inspection at fringe fractions in the figure below:

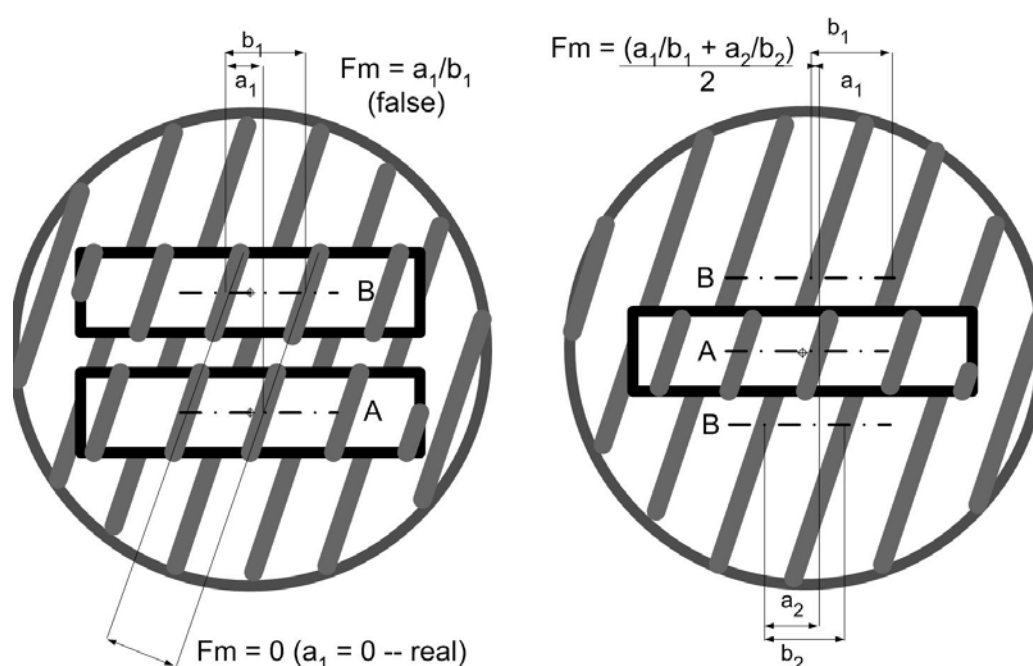


Figure 1. Fraction fringe error due to misalignment of fringe pattern inclination with connecting line of central gauge block points (left image: differential method; right image: absolute method).

3. Measurement results

The first report presented in [3] was obtained from good surface quality gauge block pairs, measured through visual estimation. Those results were good enough to validate a new calibration service. The original software measurement techniques were initially aimed to be used in absolute interferometric gauge block calibrations, but there were afterwards directly adapted to perform differential measurements.

A posterior study for estimation of uncertainty component due to dispersion obtained after measurements of some wrings at both blocks of a pair was made by changing position/wringing of only one block at a time, alternating and inverting sides (but not its wringing surface) to produce four independent geometric configurations in relative positions over same wringing surfaces as shown in figure 2. The base fringes were maintained strictly vertical to avoid huge misaligning effects. That should barely compensate for minimal asymmetric flatness deviations and effects of positional wringing. The original proposal was take two measurements each wringing, inverting the reference surface to reduce the misalignments effects, as shown before in figure 1.

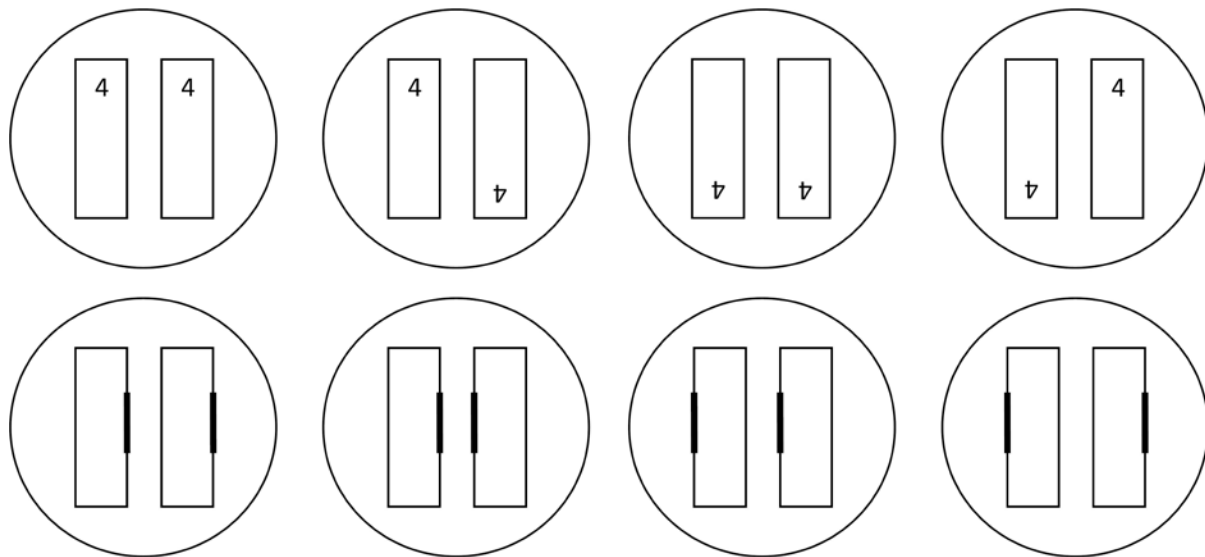


Figure 2. Upper view of four positional wrings for a complete measurement of the length difference of a gauge block pair; Row above: 4 mm gauge block pair; Row below: 100 mm gauge block pair (similarly for blocks larger than 6 mm) – Lateral body inscriptions depicted as thick traces.

3.1. Phase estimation software for difference measurements

In order to reduce the uncertainty component due to visual estimation of the fringe fractions an automated method was developed based on interferometric image processing obtained from a CCD camera, as used in absolute gauge-block length calibrations. This method just allowed user-controlled channel definitions, because both parallel 1D interferogram channels must cross the central point of upper surfaces in both gauges to perform length difference calibrations. The phase estimation was originally based on simple maxima enhancement skeletonizing methods and direct pixel counts between maxima to estimate the phase difference between both channels.

The figure 3 below shows the main window of the software developed in Visual Basic for automated phase difference estimations in four different wavelengths, obtained from the ^{114}Cd spectral lamp as length reference. The information of fraction fringes in more than one wavelength is essential to determine length deviations in nominal lengths (or difference in lengths) that are much larger than half wavelength as defined in [4] and a numerical coincidence of four lengths must be achieved, combined as in equation (1) below.

$$L = (N_i + f_i) \frac{\lambda_i}{2} \quad (1)$$

Where N_i is the integer number of half wavelengths ($\lambda_i/2$) contained in the length L and the f_i is the fractional fringe read, for each sequenced wavelength selected.

As two of the gauge pairs defined by [1] have length differences of circa $10\text{ }\mu\text{m}$ and $5\text{ }\mu\text{m}$, this sequence combination of fringe readings should be performed to achieve the unequivocal values of length deviation measurements.

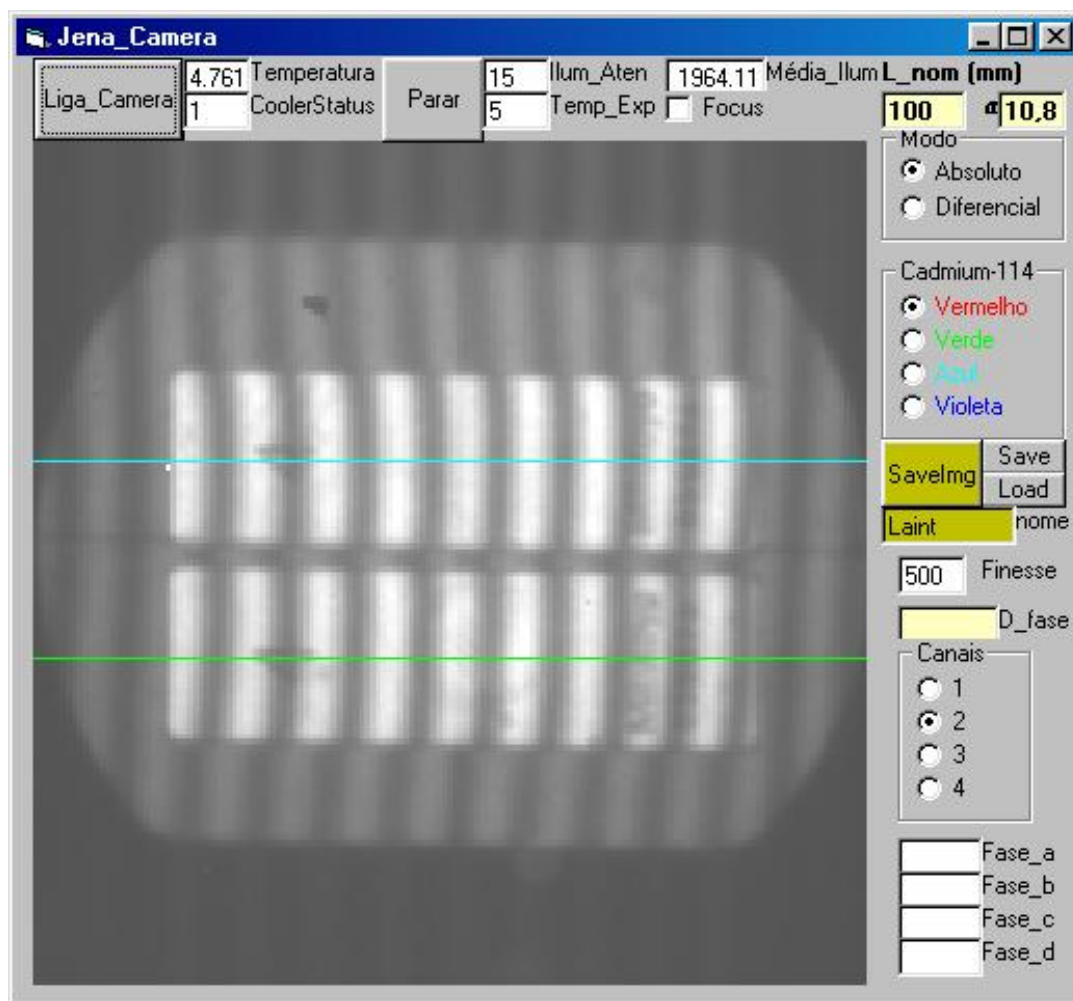


Figure 3. Measurement and inspection main window of software designed to estimate phase differences in interferograms. The image inside shows a monochromatic interferogram taken from a 4 mm steel gauge block pair wrung on a quartz plate, seen from above.

After the first automated method for phase estimation was implanted, the older calibration procedure was refurbished, replacing the “composite” result of two measurements, i.e. resulting from the operation $((A-B) - (B-A))/2$ described in [3], by taking one valid measurement only. A special cautious must be taken in maintaining the base fringes as orthogonal as possible to avoid huge misaligning effects. Below, in table 1, there are depicted a set of main uncertainty components used in a typical uncertainty budget of a pair difference length calibration by interferometric method. The fraction fringe estimation uncertainty component presented here is derived from the pixel count method and it has a value more than 2 times smaller than uncertainties due to the older visual estimations.

Table 1. Updated Uncertainty Budget for length difference of gauge blocks with similar nominal length (in this case: 100 mm).

Uncertainty Components	$u(x_i)/nm$	c_i	$u(l)/nm$
Fraction fringe estimation	0.02	132.5	2.60
Wringing (2x)	2.90	1.414	4.10
Flatness/Parallelism (2x)	2.80	1.414	4.00
Software resolution	0.58	1.000	0.58
Dispersion (best 4 meas.)	2.50	1.000	2.50
Wavefront errors	3.00	1.000	3.00
Total Expanded Uncertainty: U=15 nm (k=2)			

The “best-case” expanded uncertainty, as shown in last row of table 1, is in fair agreement with declared CMC PTB pairs calibration uncertainty at BIPM database (10-14 nm, $k = 2$). To achieve such reduced values some homogeneity assumptions were taken in account, as the similarity at standards material features of both gauge-blocks of one pair. The uncertainties components due to slight differences of expansion coefficients and surface finishing were deemed as negligible. Also the complete temperature stabilization of standards and measurement system was assumed, to avoid the occurrence of thermal gradients inside and between the blocks or along the optical paths.

3.2. Review of Uncertainty Components

Some doubled components presented in table 1, as those due to wringing and flatness/parallelism, are composed of similar effects in both blocks of the pair. The first one took in account both wringing films between gauge blocks and wringing platen and the second one is due to respective maxima deviations of geometrical tolerances. As a common source we can inspect the software length resolution. This component is due to the steps taken by a fitting error function at the length deviation calculus, that is designed to compare ideal model results to the actual four independent fraction fringe readings (from different wavelengths). The wavefront error is another common factor caused by optical effects at optical paths and elements inside the interferometric measurement apparatus. The quoted dispersion “type A” or reproducibility component is obtained after the four differential measurements taken in different positional wrings, as presented in figure 2.

Further reductions in some of its greater components are yet to be expected. For example, that due to “flatness/parallelism” component, originally estimated in abstract dependence of maxima gauge block class tolerances and centering definitions as defined in [5], can be computed with the actual features of each individual pair. A wavefront error compensation for each interferometer type can be also implemented in automated form, measuring good reference standard surfaces as software image compensators before measuring the gauge pair. A finer step search size can be chosen to produce a direct reduction in the software length resolution component. Better fringe estimation algorithms, as suggested before, can still reduce its respective uncertainty component fivefold by using commercial phase step systems [6] or more than tenfold by using sophisticated Fourier or recent stochastic methods. In [7] it was described a possible further upgrade of the phase estimation software by adopting evolutionary computation methods and preprocessing techniques of noise reduction. This upgrade can reduce further the global uncertainty values for many types of interferometric calibrations.

Some the before deemed “negligible” uncertainties components were recently updated from results of tests made on the same measurement system: The asymmetric uncertainty contribution of second wringing of the pair (3.1 nm) was revealed to be only slightly different of the before adopted, obtained from the homogeneity assumption (2.9 nm for both wrings). The new composition of effects from first and second wringing at uncertainty budget was similar as the previous value used. A study over the uncertainty component due to the phase differences between surfaces of blocks purchased from same

manufacture and made from same material (steel) and delivered within short time intervals was estimated to be around 0.98 nm. The component due to difference length variations within the assumed temperature measuring range of the interferometry laboratory could not be experimentally discriminated from other uncertainty effects and we can, therefore, still consider all temperature inhomogeneities as negligible.

4. Discussions and conclusions

Actual interferometric differential measurements systems must take into account some geometric and material constraints in order to attain expanded uncertainties of circa 15 nm for each gauge block pair length calibration.

A visual old-fashioned observation and estimation of fringe fractions was clearly inappropriate for accurate measurement of fringe fractions commonly found in differential measurements. Therefore, an automated image capture system was developed in Inmetro. That system combined a new developed approach, using a dispersion component produced by four-wrining positional compensation technique, with the compensated geometric misalignments and algorithmic automated estimations of fringe fractions. Those practices allowed the Interferometry Lab in Inmetro to calibrate high-accuracy dimensional standards as prime quality grade K or 00 gauge-block pairs towards uncertainty levels there are in better conformity to EURAMET cg-2 [1], and with lower uncertainty values than could be achieved by composing their individual gauge length measurements. This technique allows us to reach fairly similar values to the uncertainty values declared in PTB, the german National Metrology Institution where originally the idea for this kind of interferometric measurements was developed, aiming to establish a fair maintenance of the dimensional traceability chain, and in order to follow good metrological standards.

As future developments for this interferometric system were designed an accurate and low-uncertainty evolutionary algorithm for phase estimation as described in [7], and an upgrade of digital camera system together with its operating software, added to an advanced optical capture system. With these upgrades, the calibration services could achieve good compliance with the best metrological practices [1] and good traceability towards more technological and advanced applications [8].

5. References

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