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Imaging interference microscope for nanometrology

Igor Malinovsky[1], Iakyra B. Couceiro[1] , Ricardo S. Franca[1], Mauricio S. Lima[1], Carlos L. S. Azeredo[1], Clara M. S. Almeida[1], Jean P. von der Weid[2]

[1] *National Metrology Institute of Brazil (INMETRO), Av. N.S. Graças, 50, Xerém, Rio de Janeiro, 25250-020, Brazil*
[2] *Telecommunication Center (CETUC), Catholic University (PUC-Rio), Marquês de S.Vicente, 225 – Gávea, 22453-900, Rio de Janeiro, Brazil*

ABSTRACT
Here we report the development of the primary nanometrology capacity at the National Metrology Institute of Brazil (INMETRO). An interference microscope of the Linnik type has been developed and subjected to optimization and characterization studies. The recording of the fringes is done by an automated CCD system with 2 possible processing approaches: interferometric pattern processing and the phase stepping technique. Current progress in the development of the hardware and software adequate for sub-nanometer resolution of the instrument is reported. A study of systematical errors of the interference microscope has been performed. The instrument is aimed for international key comparisons of step height standards.

Section: RESEARCH PAPER

Keywords: Nanometrology; interference microscopy; AFM; gauge block; step height

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Corresponding author: Igor Malinovsky, e-mail: imalinovski@inmetro.gov.br

1. INTRODUCTION

Traceable nanometrology of high accuracy is a necessary condition for the quality control basis of nanotechnology. In its broad understanding, nanometrology is the science and technology of measurements of the artifacts with nanometric accuracy. Since nanotechnology plays a more and more important role in the industry, it is the task of the metrology to provide better measurements to support the productive activity. In this respect, nanometrology at the National Metrology Institute (NMI) of Brazil, INMETRO, Optical Division (DIOPT) has started with the development of high resolution Gauge block interferometry (GBI) about 10 years ago [1]. The GBI instrument was successfully characterized and used in several international comparisons. The next obvious step now is to apply the knowledge in interferometry for measurements of smaller objects like step heights. Interference microscopy (IM) is commonly used for this task being quite accurate [2]. IM is preferable to several known techniques of nanometrology because it provides direct traceability to wave length standards.

IM can perform measurements directly related to wave length standards such as frequency stabilized lasers. Consequently, IM can be used for calibration of the secondary standards such as step heights. After calibration of secondary standard, it can be used further to calibrate the vertical axis of the AFM. Therefore, the final goal of this work is to provide AFM measurements being traceable to the primary standards of length.

2. EXPERIMENTAL SET UP AND SAMPLES

The optical scheme of the constructed Linnik type Interference Microscope based on a frequency stabilized laser as a reference wave-length source is shown in Figure 1. All components were placed on an optical breadboard which was placed on the top of a granite table. Most of the opto-mechanical units that are used are commercially available components manufactured by Newport and NewFocus. An optical beam-splitter of high quality (lambda over 100, from Bernard Hole) with very low beam distortion was used to provide the highest possible accuracy of the interferometer.

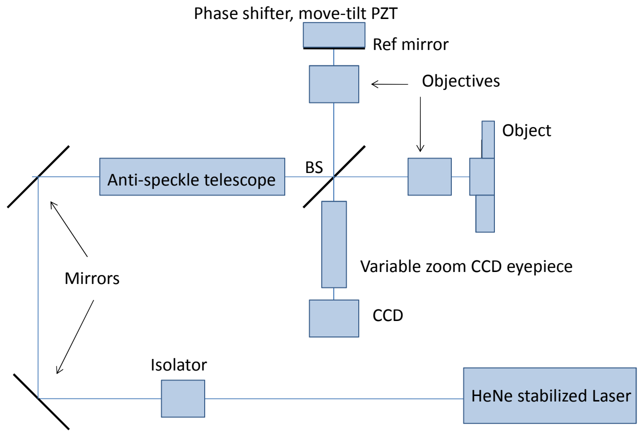
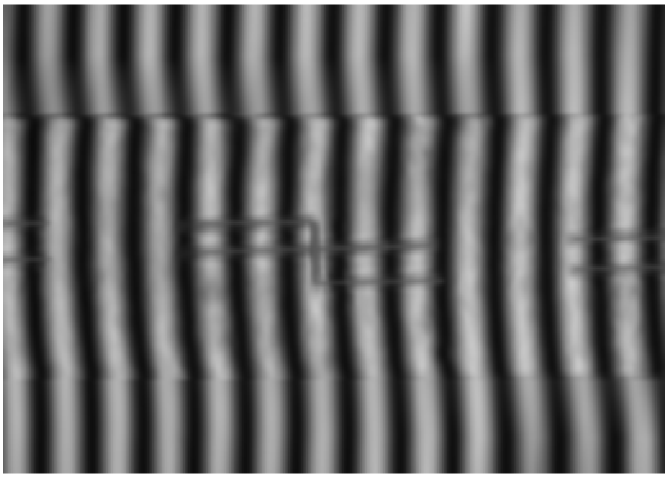


Figure 1. Set up of the Linnik type interferometer, where BS is the high quality 50/50 beam splitter; Object is the step height or master height standard; Objectives are the conformal pairs of x10, x20, etc. microscopic objectives; Ref is the reference mirror located on a phase shifting tilt-move PZT module; Eyepiece is the up to x20 variable zoom optical element.

The employed laser source was a He-Ne frequency stabilized laser (SpectraPhysics or Agilent. All used lasers were calibrated with respect to the primary He-Ne Iodine stabilized laser (primary standard), verified via BIPM intercomparison. Fringe patterns were collected by a high quality scientific grade digital CCD 1.5 megapixel camera of 12 bits resolution from PCO, Germany. A sophisticated zoom eyepiece from Hirox, Japan was used to magnify the output interferometric images. The frames were taken by a PC and processed with specially developed and tested dedicated fringe pattern processor software (SW). The reference mirror was located on a 3-way tilt-move phase shifting unit.

The main measuring method is the interferometric fringe image processing. We also have included into the instrument the phase stepping module which allowed for an additional comparative study of both methods. From our previous experience with common GBI, the phase stepping unit can be reliably calibrated "on-flight" during the measurement if multiple steps and respective fringes are available (see details below). During the measurement we perform phase shifting and simultaneous recording of the CCD output in series of the interferograms (typically 200 or more images). Each pixel in the image corresponds to a certain region (point) on the sample (or on the reference mirror). The frame-by-frame analysis of each pixel of interest provides the corresponding sinusoidal signal that carries the phase information of this particular point (pixel). This output is the so called multiple-step phase shift signal [3]. We fit this signal with the model to extract the phase at each point of interest. We apply the simplest method of phase shifting, i.e. the movement of the reference mirror. However, in case of the Linnik interferometer, it is not really the best solution, because by moving the reference mirror the optimum identical optical path in both arms of the IM is disturbed. We plan to use an optical wedge for this purpose in future studies. In here we consider that both the image processor and the phase step processor have their own advantages and disadvantages. In this work we discuss the advantages and disadvantages of the image processor and phase step processor. Having both at one´s disposal it is possible to perform more detailed investigations.

We used the Mitutoyo triple step gauge block (Step Master) as the secondary Z height standard. The Step Master is a master



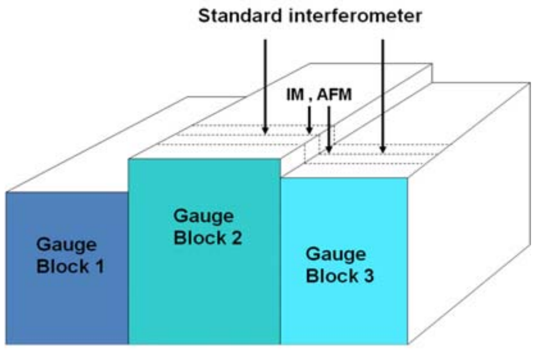


Figure 2. Interferogram of triple GB standard taken with standard Zeiss GBI. On the bottom, is the layout of the triple GB step Master Standard.

secondary standard used for the z-axis (vertical direction) calibration of optical and stylus instruments. The standard is made of three interconnected gauge blocks of different heights as shown in Figure 2. The choice of this particular standard was carefully considered from the point of view that it is the only artifact that can be measured by both classical Michelson type GB interferometry and microscopic methods such as AFM and IM. The Materials Division of INMETRO (DIMAT) is in the process of production of more common step height standards similar to those used in [2]. They use the electron microscope lithography method. We have got quite satisfactory results with secondary standards from DIMAT/INMETRO.

Preliminary studies of the reference secondary Step Master standard, performed with a Zeiss interferometer, have shown that the artifact exhibits quite flat surfaces of all three Gauge blocks. Among the other advantages of this type of secondary standard we should mention high long time stability and negligible difference in surface roughness (known as the phase change correction) between the blocks produced from the same material and polished to the same texture finish. The nominal height differences between gauge blocs 1 and 2 (GB step), and between gauge blocs 2 and 3 were 10 µm and 2 µm respectively.

3. FRINGE PATTERN PROCESSING

We have developed a set of software tools suitable for fringe image processing, phase shifting interferometry and post processing data visualization. The main software (SW) module of fringe pattern processing is based on a multi-parametric iterative fit of the digitized pattern along the vertical line (or several neighboring lines). Prior to the fit, it is possible to perform a direct / reverse FFT combined with a Gaussian

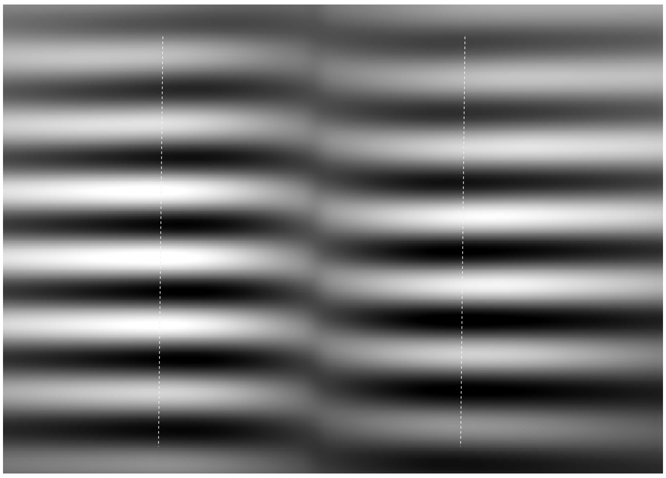


Figure 3. The fringe pattern of 10 µm GB step taken with the Linnik interferometer. Vertical dashed lines are the eye guides of the regions (trajectories) used to digitize the interferometric pattern.

filter. This filter does not perturb the phase and it is used to remove pixel noise from the interferometric pattern. In addition, pixel noise was removed by averaging of several frames to produce the final interferogram used for processing.

The model sine function has the following fit parameters: amplitude, offset, phase, frequency, phase modulation and amplitude modulation. A minimization criterion is least square difference between measured data and a model function. By analyzing the fringe pattern along several lines instead of just two, one can find out the topography of the master step GB object.

Previously it has been shown that using our fringe processing algorithm the resolution of the interferometer can be as high as 0.1 nm (about λ/6000) or better. The accuracy of the measurement is determined by the quality of the GB and it can be as good as 1 nm [1, 4]. Figures 3 and 4 show the quality of the fringe pick-up and the fit using our algorithm. It is worth noting here that pixel and intensity (bits) resolution as well as stability/uniformity of the CCD is quite essential for obtaining good results.

In order to compare measurement with Atomic Force Microscopy (AFM) we have measured the same secondary master standard using a commercial Witec Alpha 300 AFM. AFM measurements cannot cover the large XY area of the GB step (the maximum area in our case was 100x100 µm). In addition, because of a slight curvature of blocks, it is desirable to compare several measurements performed in different places of the standard along the step direction.

Figure 5 shows a typical comparative plot of two data sets obtained in two different locations. For detailed comparison of

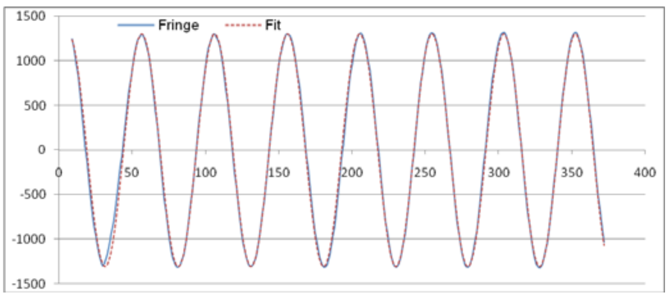


Figure 4. Variation of the experimental (solid) and calculated (dash) fringes intensity as a function of pixel number. Typical relative differences between the experimental and calculated intensities are less than 1%.

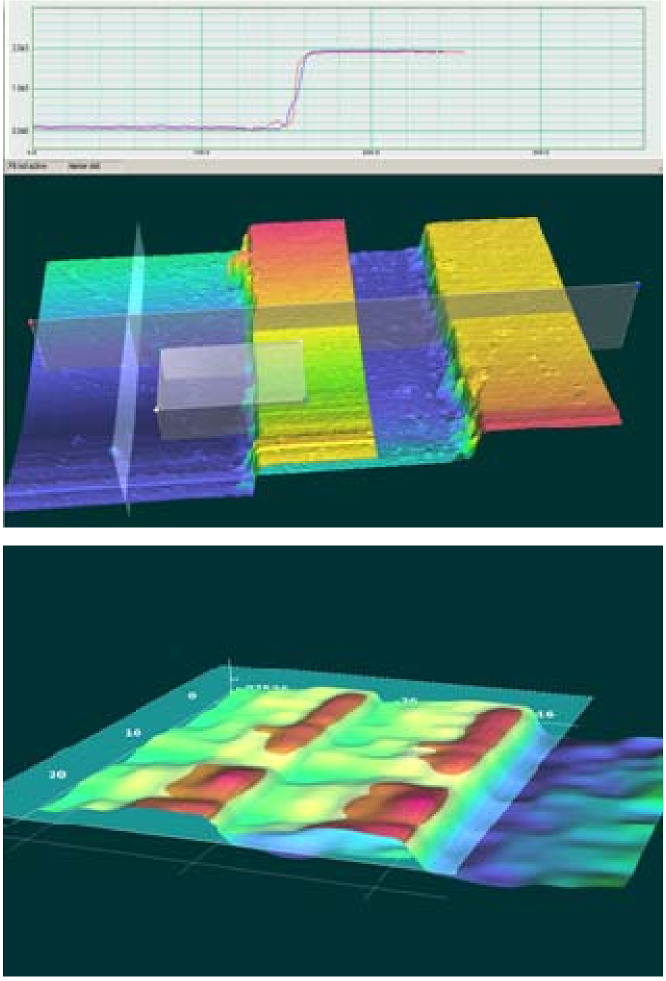


Figure 5. Comparison of the data with AFM in 3D mode. An interactive cube is used to select the area of interest for parameter calculation. Planes are set to define the cross-section of the 3D AFM image and the respective 2D plots (upper figure). The lower image shows the Z intersection plane which is used for detailed comparison of surface topography of two measurements (left and right surfaces in the lower picture).

the different measurements we have developed dedicated 3D software that allows a visualization of several surfaces in one screen with interactive virtual reality style rotation, pan and zoom.

Several mouse driven measurement tools are available for the analysis of the intersection areas and volumes Altogether, the proposed approach to data analysis allows one to examine in depth the obtained data in a comparative and selective way, as exemplified in Figure 5.

4. PHASE SHIFTING METHOD

We have developed procedures suitable for a detailed analysis of the phase shifting technique. The phase shifting unit is based on a comprehensive 3-DOF tilt-move stage. Each element is independently programmed via a 24 bits digital-to-analog converter (DAC) generating signals from -10 V to +10 V, and amplified with a low-noise 3-channel HV amplifier. After amplification, the signal is suitable for PZT operation (-100 V to +100 V). In this way, we can program independently all kind of movements aiming at compensation of nonlinear effects of the PZT.

We move the reference mirror with 100 or more (typically 200) equal distance intervals. At each mirror position the full

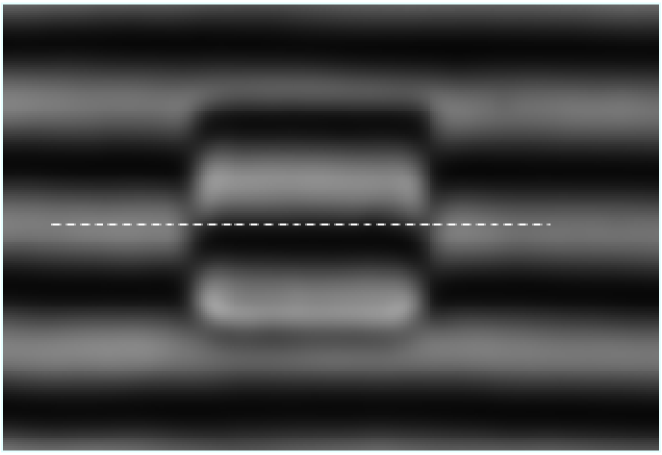


Figure 6. Fringe pattern of 100 nm aluminium step height taken with the Linnik IM. The XY size of the square height is about 30x30 µm. Gaussian 2D filtering was applied to the whole image. The horizontal dashed line is the eye guide for the line area used to provide the measurement.

interferogram is taken and saved into the memory of the PC. After having finished this process, it is possible to process the interferometric image stack at each surface point in order to reconstruct the phase for the whole measured surface. Further, to remove vibration related noise, we normally take several interferograms, averaged at each position of the phase-shifter. To improve the exactness of the phase step we can optionally make several back-forward mirror positionings to average the interferograms. These improvements resulted in the best scans obtained so far.

Each individual scan typically produces several interferometric fringe lines that correspond to a pixel (or area of pixels) position. Each line is fitted with an algorithm similar to the one shown in Figure 4. Normally, we do not use a single pixel, but rather a few neighboring pixels to average out the pixel-to-pixel noise [5]. Alternatively, it is possible to process individual interferograms in the way described hereinabove. Consequently, one has an opportunity to compare both algorithms: the fringe pattern and the pure phase shifting method.

The results obtained show that after all above precautions the signal to noise ratio permits a 0.1 nm (or even better) resolution of the system. This conclusion has been confirmed by multiple repeatability tests (see examples in Figure 7).

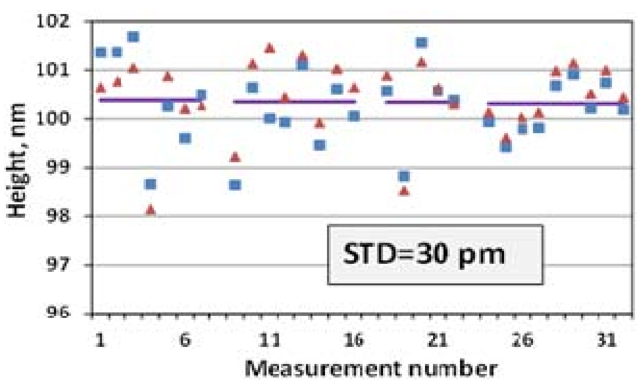


Figure.7. Reproducibility of the corrected phase step readings. Data were taken during a period of about 4 weeks. The data sets correspond to different alignments of the interferometer. Lines are the means of each series. Standard deviation between means in the series is about 30 pm.

5. STUDY OF THE SYSTEMATIC ERRORS

One of the most important and difficult tasks of the primary comparators is a detailed characterization of the instrument for the subsequent uncertainty evaluation. This task implies measurement of the systematic errors of the instrument. While the Carl Zeiss interferometer was already studied in this respect [4], the new Linnik interferometer investigation and characterization is ongoing work of our laboratory.

The important information concerning possible drifts of the interferometer read out can be obtained by automatic continuous measurements of the length during changes in environmental conditions such as temperature. Our interferometer is fully automated and permits this type of measurements.

The systematic drift is shown in Figure 8. The correlation was expected and observed. We attribute temperature induced drift to possible changes in optical path of the measuring or reference part of the interferometer. Dilatation of the standard itself can create similar drift.

The most serious errors of the Linnik type interferometers is known to be misalignment of the reference and measuring arms [2]. As our interferometer software permits to control misalignments, we have developed a simple but very efficient self-calibration procedure. In this procedure we measure the GB step and immediately after that calibrate the fringe pattern on the reference flat surface of the gauge block. We can optionally use flat surfaces of both gauge blocks in the master standard to perform such self-calibration. If the surface of the gauge block is flat this, in the ideal case, will remove misalignment errors.

The idea of self-calibration of the interferometer relative to the flat part of the surface is valid for both the image processing and the phase step method. We applied this idea in both methods to obtain the final results of this work.

We have performed several measurements on an interferometer with deliberately slight misalignment. Some of the results are presented in Figure 9.

The typical spread of misaligned data was about 100 nm. While after applying the correction according to the above self-

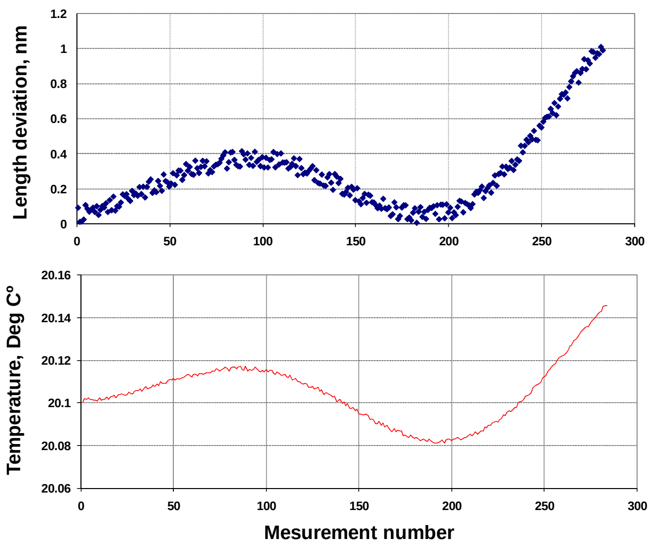


Figure 8. Correlation of the temperature induced drift with measured length. The data are composed of about 300 measurements performed during several hours of continuous read out.

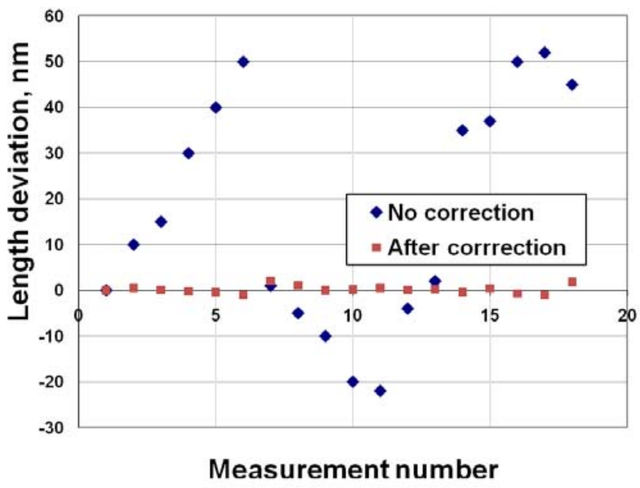


Figure 9. Misalignment error of the interferometer. Non-corrected measurements (diamonds) are shown together with the respective data after correction (squares). Standard deviation of the corrected values is about 0.7 nm. This particular data was obtained with the interferometric image processing method.

calibration procedure the data spread is within 1 nm. This shows the benefit of the self-calibration method and the prospects of the instrument under construction.

The obliquity or aperture error was estimated theoretically from the geometry of the optical set-up of our IM. With our NIKON PLAN x10 long focus microscopic objectives the maximum angle of incidence on the sample is about 20 degrees, which is significantly decreased by the camera lens x20 eye-piece. The eye-piece restricts the aperture; as a result, the angles of incidence decrease correspondingly. Estimations of the effective angle of incident give values of about 3 to 4 degrees. This means that the possible obliquity error, as calculated from standard interferometry formulae, is about 80-90 pm on a 100 nm height step. In order to check experimentally these estimations, we have restricted the entrance aperture of the IM down to about 2.5 degrees using a variable diaphragm at the entrance of the IM interferometer. The measurements of the length of the 100 nm step artifact have been performed according to the procedure described above with and without diaphragm. The result shows that the obliquity error is non-detectable within 100 pm uncertainty. Therefore, we consider that for k=2 the uncertainty associated to this particular error type is not higher than 0.2 nm. This is well within the targeted final IM uncertainty.

6. RESULTS AND DISCUSSION

In general, a comparison of the results of the different types of instruments is not straightforward because each instrument has its own advantages and restrictions. Phase- shifting method has itself certain problems in terms of errors [5]. In case of the step GB, the main concern is the measured area. While the step GB is quite flat on the probed areas recommended by Mitutoyo, it is not that flat close to edges of the block which are exactly the only regions where microscopic instrumentation can be used. By using the Carl Zeiss interferometer, closest approximation to the edge cannot be less than a certain distance because: i) a line thickness of several pixels is required for the analysis, ii) diffraction at the edge of the GB distorts the interferogram making interpretation uncertain. In our case, the minimum approximation to the edge preserving quality of the fringe was about 0.3 mm. Reliable results from AFM were achieved with an XY range of about 50 μm. Usually, the repeatability of all instruments was better than 1 nm, which indicates that all of them can be, in principal, calibrated or studied for systematic errors to even better accuracy.

Interesting results were obtained with the phase step method. Here we have observed much better reproducibility of the output, as compared with the interferometric pattern processor (see Figure 7). Study of systematic errors as, for example, due to nonlinear effects in the PZT is currently the ongoing research activity in our lab.

The results obtained were in agreement within 2-3 nm between the data obtained by the Mitutoyo GBI, the Linnik interferometer and the Zeiss interferometer. Nevertheless, the difference between the interferometric and the AFM measurements was a bit higher, up to 20 nm in the worst case. We attribute these discrepancies, for the moment, to possible problems of AFM instrument.

One should recall that the systematic errors of the AFM are significant for a large step height. Metrological AFM is used to remove those errors. Due to the nonlinearity of the PZTs the error increases with increasing range (Z range in this case). In general, we were satisfied with the obtained results. Obviously, a commercial AFM of this kind is by itself not an easy instrument and should be studied for systematic errors, especially in large scan ranges.

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