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PRIMARY IMAGING INTERFERENCE MICROSCOPE FOR NANOMETROLOGY

I. Malinovsky, R. S. Franca, I. B. Couceiro, M. S. Lima, C. L. S. Azeredo, C. M. S. Almeida, J. P. Weid *

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

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

Keywords: **Nanometrology, Interference microscopy, AFM, gauge block, interferometry.**

1. INTRODUCTION

Traceable Nanometrology of high accuracy is necessary to provide the quality control basis for nanotechnology. In its broad understanding nanometrology is the science and technology of measurements of the artifacts with nanometric accuracy. Since nanotechnology is playing more and more important role in the industry, it is the task of the metrology to provide better measurements to support this activity. In this respect, nanometrology at National Metrology Institute (NMI) of Brazil, INMETRO, Optical Division (DIOPT) has started with development of high resolution Gauge block interferometry (GBI) about 10 years ago [1-2]. The GBI instrument was successfully characterized and used in several international comparisons. Now the next obvious step is to apply the knowledge in interferometry for measurements of smaller objects like step heights. Interference microscopy (IM) is commonly used for this and it is known to be quite accurate approach for this particular task [3]. Out of several known techniques of nanometrology IM is preferable since it provides direct traceability to wave length standards.

The IM can perform measurement directly relative to wave length standard such as frequency stabilized lasers. Thus, we can use IM for primary calibration of the secondary standards such as step heights. After secondary standard is calibrated it can be used to calibrate vertical axis of the AFM. The final result of this activity, therefore, is to provide AFM measurements traceable to the primary standards of length.

2. EXPERIMENTAL SET UP AND SAMPLES

We have constructed a new system that is Linnik type Interference Microscope based on frequency stabilized laser as a reference wave-length source Fig.1. Construction was made on granite table with intermediate optical breadboard. Most of the opto-mechanical units used are relatively simple components originally manufactured by Newport and NewFocus. Optical beam-splitter of high quality (lambda over 100, from Bernard Hole) was used to provide maximum accuracy of interferometer (due to minimum beam distortion).

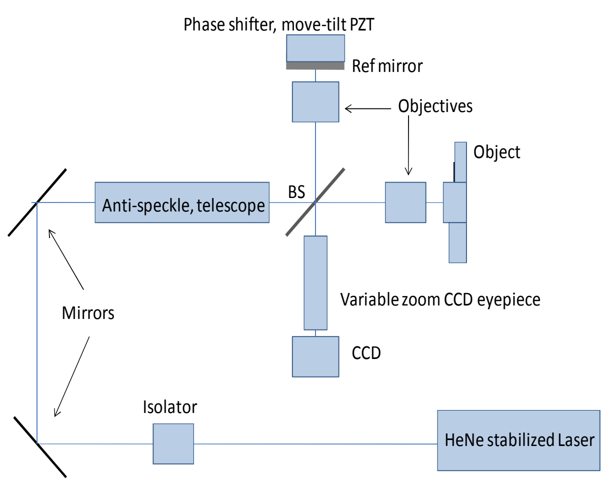

Fig. 1. Set up of Linnik type interferometer, where BS is the high quality 50/50 beam splitter, Object is the step height or master height standard, Objectives are the conformal pair of x10, x20, etc. microscopic objectives. Ref is the reference mirror that is located on phase shifting tilt-move PZT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

Laser light used from He-Ne frequency stabilized laser (SpectraPhysics or Agilent, that is ex-HP). All lasers were calibrated relative primary He-Ne Iodine stabilized laser primary standard, verified via BIPM intercomparison. Fringe pattern is collected by high quality scientific grade digital CCD 1.5 megapixel camera of 12 bits resolution from PCO. Sophisticated zoom eyepiece from Hirox, Japan is used to amplify output interferometric images. The frames are taken by PC and processed with specially developed and tested dedicated fringe pattern processor software (SW). Reference mirror is located on 3 way tilt-move phase shifting unit.

While we plan that the image pattern fringe processing to be the main method of measurement, we also have included the step phase possibility for additional study of the systematical errors effects. From our previous experience with common GBI, the phase stepping unit can be reliably calibrated "on-flight" within measurement if multiple steps (see detail below) and related fringes are available. Then shifting phase and recording output of the CCD with multiple frames (typically 200 or more) we can use corresponding sinusoidal fit to find exact phase difference for any point of interest.

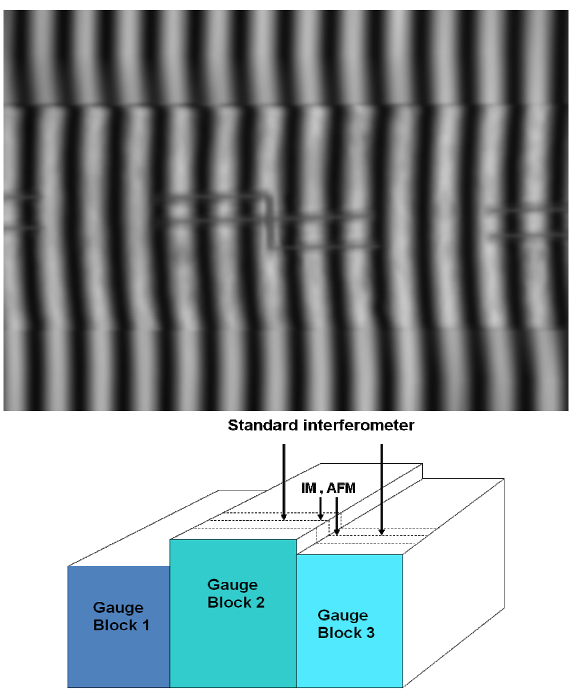

Fig. 2. Interferogram of triple GB standard taken with standatrd Zeiss GBI. On the buttom is the layout of the triple GB step Master Standard.

Simplest method of phase shifting is to apply movement of the reference mirror, but in case of Linnik interferometer it is not really the best solution, because by moving reference mirror the optimum optical path for fringe forming is disturbed. We are planning to use optical wedge for this purpose later on. In here we consider that both image processor and phase step processor have their own advantages and disadvantages. Having both at your disposal makes it possible to perform more detailed investigation.

We used as the secondary Z height standard the Mitutoyo triple step gauge block, Step Master Fig.2. The Step Master is a master secondary standard used for the z-axis (vertical direction) calibration of optical and stylus instruments. The standard is made of interconnected 3 gauge blocks of different heights as shown in Fig.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. Material division of INMETRO (DIMAT) is in the process of production of more common step height standards similar to those used in [3]. They use electron microscope lithography method. We have got quite satisfactory results with secondary standards from DIMAT/INMETRO.

Preliminary study of the reference secondary Step Master standard that have been performed with use of Zeiss interferometer has shown that the artifact exhibits quite flat surfaces of all 3 Gauge blocks. Among the other advantages of this type of secondary standard we should mention high long time stability and negligible roughness difference (known as the phase change correction) between the blocks produced from same material and polished to the same texture finish. The nominal difference of one step was 10 um while in the other was 2 um.

3. FRINGE PATTERN PROCESSING

We have developed 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 multi-parameter iterative fit of the digitized pattern along the vertical line (or several neighboring lines). Prior to the fit it is possible to perform direct / reverse FFT with Gaussian filter in between. This filter is known not to perturb the phase and it is used to remove pixel noise from the interferometric pattern. Additionally pixel noise was removed by averaging several frames to produce the final interferogram used for processing.

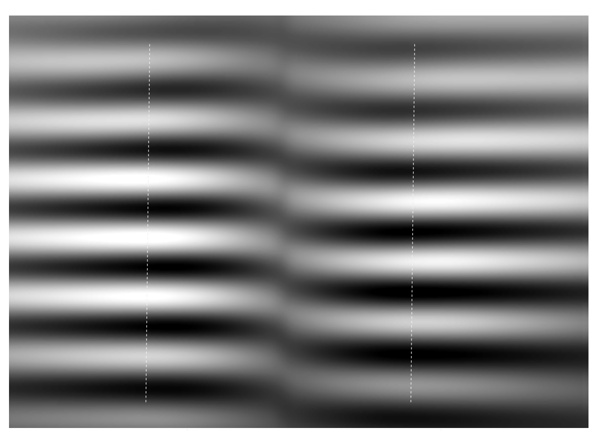

Fig. 3. Fringe pattern for master step height standard taken with Linnik interferometer. The height is about 10 um. Vertical dashed lines are the eye guide to see the areas used to digitize interferometric pattern.

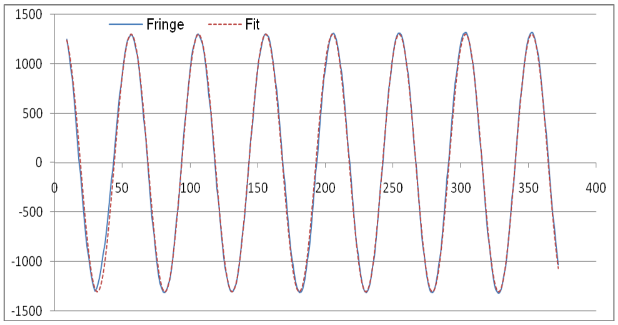

Fig. 4. Quality of the fringe (solid) and the fit (dash). Typical difference in most of the pattern is less than 1% almost invisible. Pixel number on X axis, the relative intensity of the CCD image on Y axis.

The fit function is sinusoidal with following parameters: Amplitude, offset, phase, frequency, phase modulation and amplitude modulation. A minimization criterion is least square difference between measured data and a model function. Analyzing fringe pattern along several lines instead of just 2 we can figure out topography of the master step GB object.

It has been previously 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. While the accuracy of the measurement is determined by the quality of the GB and it might be as good as 1 nm [1, 2]. In Fig. 3 we demonstrate the quality of the fringe pick-up and fitting with our algorithm (see Fig.4). In here we note that both pixel and intensity (bits) resolution as well as stability/uniformity of 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 commercial Witec Alpha 300 AFM. Measurements with AFM cannot be done using large area of the step. Also since blocks are slightly curved, typically it is desirable to compare several measurements done in different places of the standard moving along the step direction.

In Fig.5 we show typical comparison for data from 2 different locations. For detailed comparison of the different measurements we have developed dedicated 3D Software that permits visualization of several surfaces in one screen with interactive virtual reality style rotation, pan, zoom. Several mouse driven measurement tools are instrumental for analysis of the intersection areas and volumes. All together this approach makes it easy data drill down and detailed comparison of the features of interest. Some screen shots are presented in Fig.5.

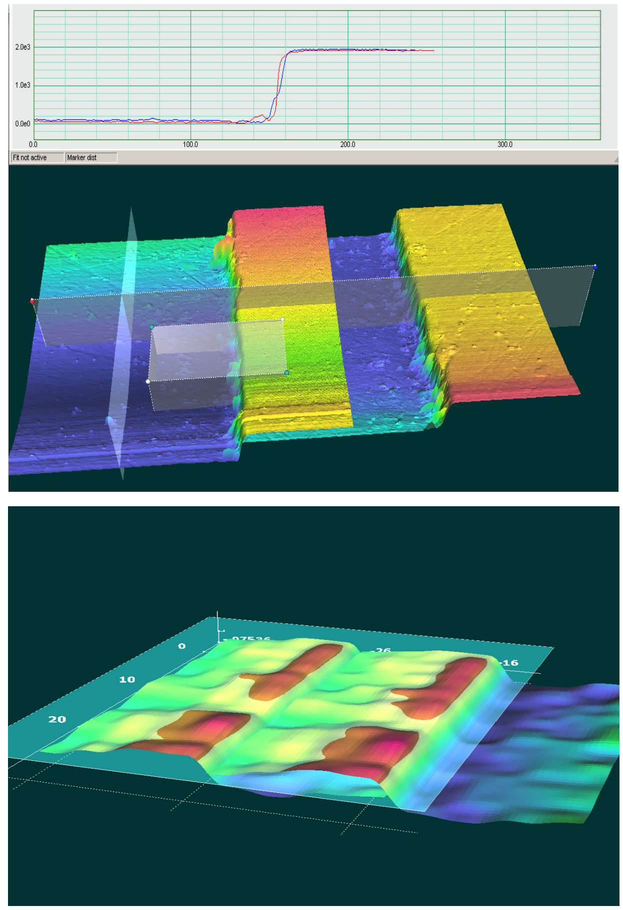

Fig. 5. Comparison of the data with AFM comparator 3D mode. Interactive Cube is used to mark the area of interest for parameter calculation. Planes are set to read intersection with corresponding 2D plots (upper part). At lower image Z intersection plane is used for detailed map comparison between 2 measurements.

4. PHASE SHIFTING METHOD

We have used hardware and developed procedures suitable for detailed analysis of phase shifting technique. Our phase shifting unit is based on quite sophisticated 3 degree of freedom tilt-move stage. Each element is independently programmed via 24 bits digital to analog converter (DAC) generated signal that is amplified with low noise 3 channel HV amplifier. This way we can program independently all kind of movements trying to compensate on nonlinear effects of the PZT. We move reference mirror with 100 or more (typically 200) equal distance intervals. At each point the full intergerogram is taken and saved into memory of the PC. After process is done, it is possible to process interferometric image stack at each point vs. distance of movement such as to reconstruct the phase for the whole measured surface. Further, to remove vibration related noise, we normally take several interferograms, averaging at each position of phase-shifter. To improve exactness of the phase step we can optionally make several back-forward positioning at each Z position averaging intergerograms. This improvement actually demonstrated the best scans we obtained so far. Each individual scan produces intrferometric fringe line of about 3-5 fringes at each pixel (or area of pixels) of the field of view. Each line is fitted with an algorithm similar to the one shown in Fig.4. Normally we use not single pixel, but some neighboring pixel area to average out the pixel-to-pixel noise.

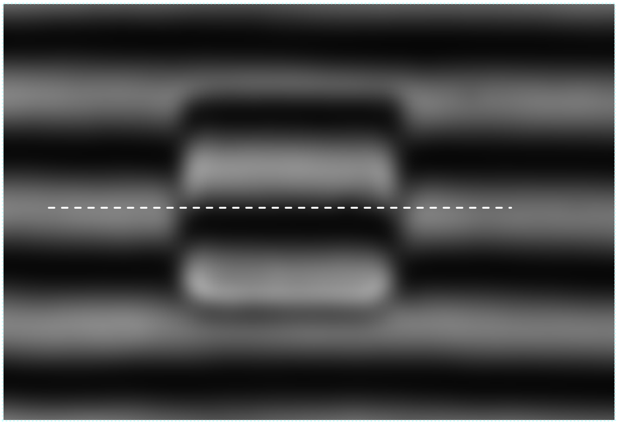

Fig. 6. Fringe pattern for 100 nm Al step height 30x30 um XY size taken with Linnik IM. Gaussian 2D filtering was applied. The horizontal dashed line is the eye guide to see the area used to provide the measurement.

Alternatively, it is possible to process individual interferograms the way described above. Thus, we have an opportunity to compare both algorithms: fringe pattern and pure phase shifting method.

The experience shows that after all above precautions the signal to nose ratio permits some 0.1 nm resolution (or better) of the system. This has been confirmed by multiple repeatability testes.

5. STUDY OF THE SYSTEMATICAL ERRORS

One of the most important and difficult tasks of the primary comparators is detailed characterization of the instrument and uncertainty evaluation. This task implies measurement of the systematical errors of the instrument. While Carl Zeiss interferometer was studied in this respect [4,5] 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 measurement of the length during changes of environment conditions such as temperature. Our interferometer is fully automated and permits this tipe of measurements.

The systematic drift is shown in Fig. 7. Length is measured together with simultaneous temperature measurements. The correlation was expected and observed. We attribute temperature related drift with possible changes in optical path of the measured or reference part of the interferometer. Dilatation of standard itself can create similar effect.

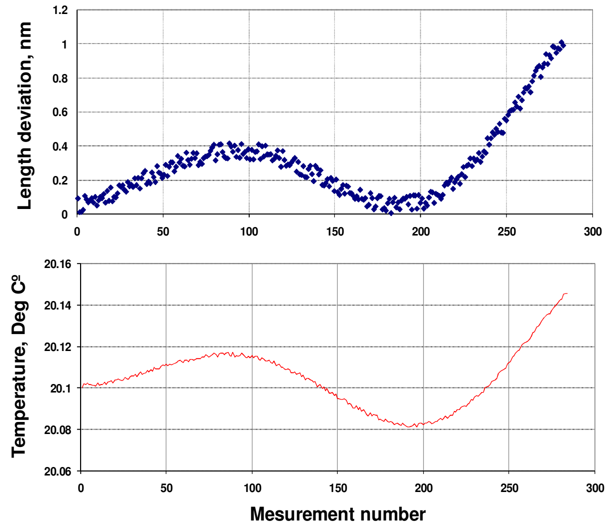

Fig. 7. Correlation of the temperature drift with measured length. About 300 measurements have been performed during several hours of continuous read out.

The most serious errors of Linnik type of the interferometers is known to be misalignment of the reference and measuring shoulders. While our interferometer software permits to control misalignments we have developed simple but very efficient self-calibration procedure. In this procedure we measure step and immediately after that calibrate the fringe pattern on 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. It the surface of the gauge block is flat this in ideal case will remove misalignment error.

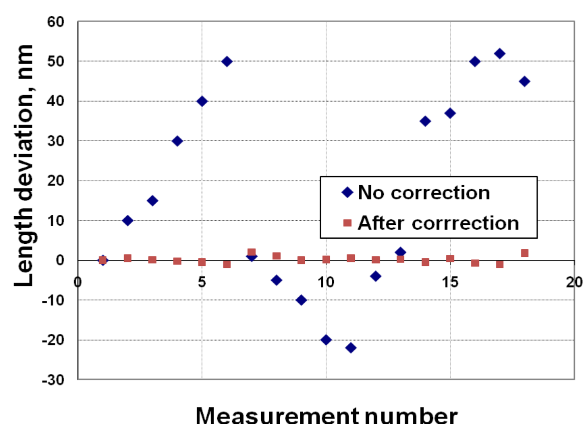

Fig. 8. Misalignment error of the interferometer. Several measurements are the non-corrected (diamonds) and after correction (squares). Standard deviation of the corrected values is about 0.7 nm. That was results of interferometric image processing method.

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

We have performed several measurements deliberately slightly misaligning interferometer. Some of the results are presented in Fig. 8. The typical spread of misaligned data was about 100 nm. While after applying the correction from self-calibration procedure above the data spread was within 1 nm, that gives a good indication of the prospects of the instrument under construction.

6. RESULTS AND DISCUSSION

In general, it is not easy to compare the results of different type of the instruments because each has its own advantages and restrictions. In case of the step GB main restriction is on area measured. While step GB is quite flat in the areas recommended by Mitutoyo for measurement, it is not that flat close to edges of the block. And those are exactly the only areas where microscopic instrumentation can be used. Using Carl Zeiss interferometer closest approximation to the edge is about 0.3 mm restricted by pixel size of the camera and diffraction at the edges of blocks. Reliable results from AFM we achieved with XY range of about 50 um. And as usual 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 up to better accuracy.

Interesting results were obtained with phase step method. Here we did observe much better reproducibility of the output, as compared with interferometric pattern processor. Study of systematical errors (due to nonlinear effects in PZT, for example) is ongoing job in our lab.

Quite important to note that 2 different approaches in processing demonstrated close agreement in final results (typically within about 1 nm)

The results were in agreement within 2-3 nm with data obtained by Mitutoyo GBI, Linnik interferometer and Zeiss interferometer. But the difference between interferometric and AFM measurements was a bit higher up to 20 nm in worst case. Those errors we associate at this moment with problems of AFM instrument.

In here one should recall that this type of measurements of relatively big step is the difficult case of errors accumulation in simple AFM instruments without additional interferometers for on-flight recalibration. Because nonlinear PZTs always increase errors with increase of range (Z range in this case). So, in general we were satisfied with these preliminary results. Obviously, commercial AFM of this kind is itself not an easy instrument and should be studied for systematic errors, especially in large ranges.

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