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Active illumination Focus Variation

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ABSTRACT

Focus Variation (FV) has been successfully employed for the three-dimensional measurement of rough surfaces. The technique relies on scanning the sample under inspection across the depth of focus of a high numerical aperture microscope objective, while computing the local contrast of its surface. Only those samples with sufficient texture will provide a usable axial response to compute its height location, limiting the application of Focus Variation to optically rough surfaces. Active illumination Focus Variation (AiFV) introduces an artificial texture on the field diaphragm position which is superimposed onto the surface. The benefit is a usable axial response, even when scanning an optically smooth surface, while minimizing the evaluation window of the focus operator close to the spatial autocorrelation length of the artificial texture. In this paper, we show the development of an Active illumination Focus Variation on an existing confocal microscope using Microdisplay Scanning technology. We analyzed the performance of AiFV on smooth surfaces with low frequency components, such as traceable Step Height or Type B2 roughness standards. Higher frequency samples such as random direction roughness standards or high-resolution targets are affected by the lateral resolution loss inherent on the AiFV technique. In this paper, we compare the lateral resolution limit of AiFV and Confocal Microscopy with the use of a Siemens Star specimen for a range of microscope objectives with numerical apertures from 0.3 to 0.95. Its influence on the computed ISO 25178 parameters on random surfaces is shown.

Keywords: Focus Variation, Confocal, Three dimensional measurements, Optical inspection

1. INTRODUCTION

In the past few decades, three-dimensional measurement of technical surfaces with optical methods has gained a large portion of the market. Many technologies have been developed, being the most prevalent single point sensors that scan the surface, and imaging sensors that employ a video camera to obtain the height information of all the pixels simultaneously. The most common imaging methods for microscopic measurements are Coherence Scanning Interferometry (CSI), Imaging Confocal Microscopy (ICM), and Focus Variation (FV) [1].

CSI is the most precise of all of them, since its ability to resolve small height deviations, translating into height resolution, merely depends on the coherence length of the light source and the linearity of the Z stage. CSI can achieve height resolution down to 1 nm regardless of the magnification of the objective that is being used. Nevertheless, the requirement for an interferometer setup between the optics of the microscope's objective and the surface under inspection, restricts the overall optical system to relatively low numerical apertures (NA), limiting the technique when measuring optically smooth surfaces with relatively high local slopes. Confocal microscopy overcomes this problem, however, as it uses high numerical aperture objectives, and thus can retrieve signals from much higher slopes than CSI. At the highest NA in air (typically 0.95), a height resolution of 1 nm is achieved, and local slopes up to the optical limit of 72 degrees are measurable. The main drawback of confocal microscopy is that height resolution is dependent on the NA, so that low magnification optics (that have low numerical aperture) yields less height resolution. The technique is therefore bounded on smooth surfaces that have to be measured with low magnification. On optically rough surfaces, confocal microscopy achieves significantly better results in comparison to CSI, but at very high roughness, or even on rough and highly tilted surfaces, it suffers from poor signal. In this particular case, Focus Variation provides the best results, as it is based on the texture present in the bright field image. FV height resolution is difficult to specify, as it depends on the texture contrast, on the algorithm to extract the focus position [2], the NA and the wavelength. Optically smooth surfaces cannot be measured with FV, since no texture is present on the surface, and no focus position can be retrieved. Those surfaces that at a given wavelength and NA appear optically smooth (and are thus not suitable for focus variation), may appear as optically rough when decreasing the wavelength, or the magnification. This is the reason why focus variation is typically suitable with low magnification, since most of the surface then appears as optically rough.

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In this paper, we propose a method that uses the speed and high slopes measurement potential of FV by the use of structured illumination on a confocal microscope arrangement enabling the technique to measure on optically smooth surfaces at the same time that makes possible to evaluate the roughness on these results.

The rest of the paper is organized as follows. on section 2, the method implement Active illumination Focus Variation on an Imaging Confocal Microscope is presented. Section 3 shows the results on real measurements implementing the explored method. Finally, conclusions are shown in section 4.

2. METHODS

2.1 Focus Variation state of the art

There are hundreds of publications analyzing focus operators for the estimation of depth. In [3] a nice overview of 36 shape from focus operators are compared. Most of them rely on the local variations of grey level on a neighborhood of the pixel under evaluation. For those samples with high local contrast and high frequencies, small local operators provide enough information. Nonetheless, if the texture appears at larger scales, it is needed to increase the evaluation window taking the depth estimation of those pixels far away from its real height. Typically, at low magnification (between 2.5X up to 10X) most of the surfaces intended to be measured with focus variation exhibit that high local contrast and small evaluation windows from 3x3 to 7x7 pixels are enough. At higher magnifications, such as 20X to 100X, the same surfaces scale up the texture and the evaluation window is needed to be increased up to 21x21 pixels. Additionally, focus operators are not filling all the pixels with the same strength of signal even for the same evaluation plane, resulting on salt and pepper on the optical sectioned image and an increase of noise on the calculated 3D topography. To avoid such effect, several filters have been proposed such as morphological closing filters, max filters, and Gaussian convolution to smooth local variations. The previous process of assessing depth estimation yields a smooth 3D topography, explaining why focus variation is very good for shape measurements, but not for high resolution or precise roughness evaluation.

There have been other attempts to avoid the drawbacks of shape from focus for the estimation of weakly textured surfaces. In [4] a method was proposed to us the energy variation across the focus to identify those pixels with weak texture and remove them from the calculations. In [5] a novel method that combines steerable filters with blur estimation provides better assessment of focus position for those texture-less regions.

A good way to get rid of the drawbacks of shape from focus is the combination of several 3D measurement techniques. In [6] a new method of data fusion of Confocal and Focus Variation is proposed to acquire confocal and bright field images simultaneously along the same scan. Both set of images are used to compute the signal quality for every individual pixel and combine the raw data before the computation of the 3D topography. The method is capable to preserve the high lateral resolution of confocal technique for surface regions that have good confocal signal while providing data for other parts of the surface such as those with high local slopes where Focus Variation is more appropriate. This method provides better results than any one of the previously mentioned measuring techniques individually at the cost of higher hardware complexity and computational time.

2.2 Active illumination Focus Variation

Noguchi and Nayar proposed a new method to actively illuminate the surface under evaluation [7]. The pattern proposed on such publication is a chessboard with a period optimized with the numerical aperture, magnification and wavelength. The pattern is placed on the field diaphragm position of the microscope and is uniformly illuminated. The chessboard is projected onto the surface and its reflection is imaged on the observation camera simultaneously with the image of the surface. For those regions with weak texture, or even without, the projected pattern provides local contrast in focus, while for those heavily scattering regions, the pattern is no longer disturbing the original local contrast. In Figure 1 the bright field image of an AIR-B40 roughness calibration specimen from NPL (National Physics Laboratory, Teddington, UK) Bento Box [8] is shown. The surface shape has been engineered to provide traceable results of roughness according to the ISO-25178-200 when measured with an optical profiler. Unfortunately, the surface is optically smooth and Focus Variation cannot provide sufficiently good optical sectioned images. As shown in the center of Fig. 1, a Sum of Modified Laplacian focus operator with a 5x5 window is only giving strong signal for those pixels with the tiny dark spots. The 3D topography result shown on the right of the figure is too noisy for the evaluation of its roughness parameters, making Focus Variation not suitable to be a traceable measuring technique according to the NPL standards.

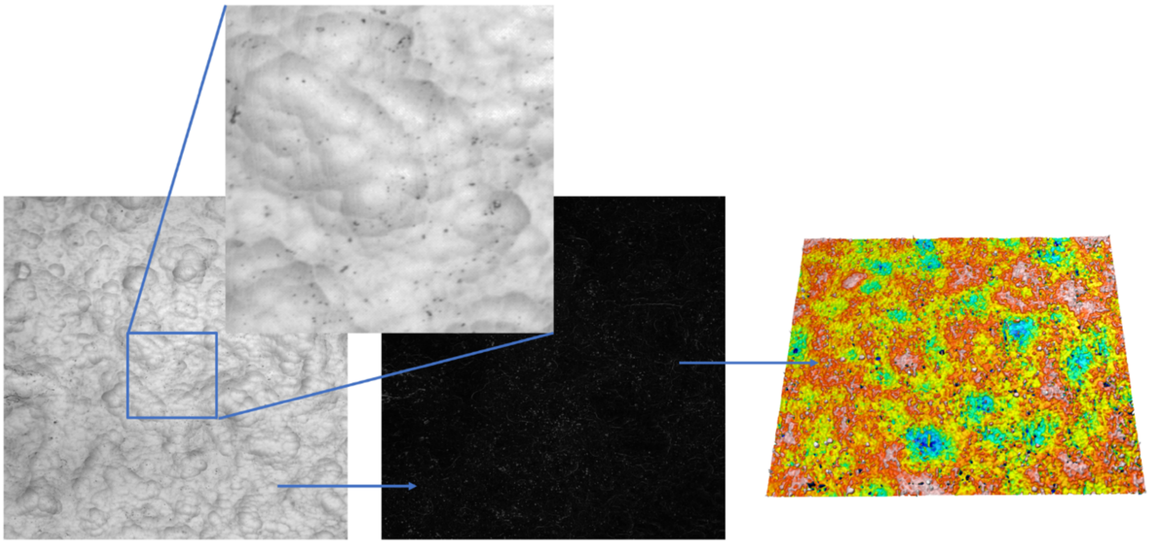

Figure 1: Bright field image of a roughness calibration specimen AIR-B40 from NPL (left), the focus assessment of one evaluation plane with a Sum of Modified Laplacian operator at 3x3 evaluation window (center). Right, the computed 3D topography.

Figure 2 presents the same sample at exactly the same conditions of Fig. 1 but using the technique described by Noguchy and Nayar. The sample has been illuminated actively with a chessboard placed on the field diaphragm of the microscope. The optically smooth surface is now showing high local contrast for those regions in focus, while the out of focus regions simultaneously defocus the chessboard. The optical section computed with a 5x5 Sum of Modified Laplacian is shown in the middle. This optical section remembers a confocal image. The computed 3D topography shown on the right has enough quality to evaluate the roughness parameters according to the ISO-25178. Obtained results are in concordance with the values provided by the calibration certificate.

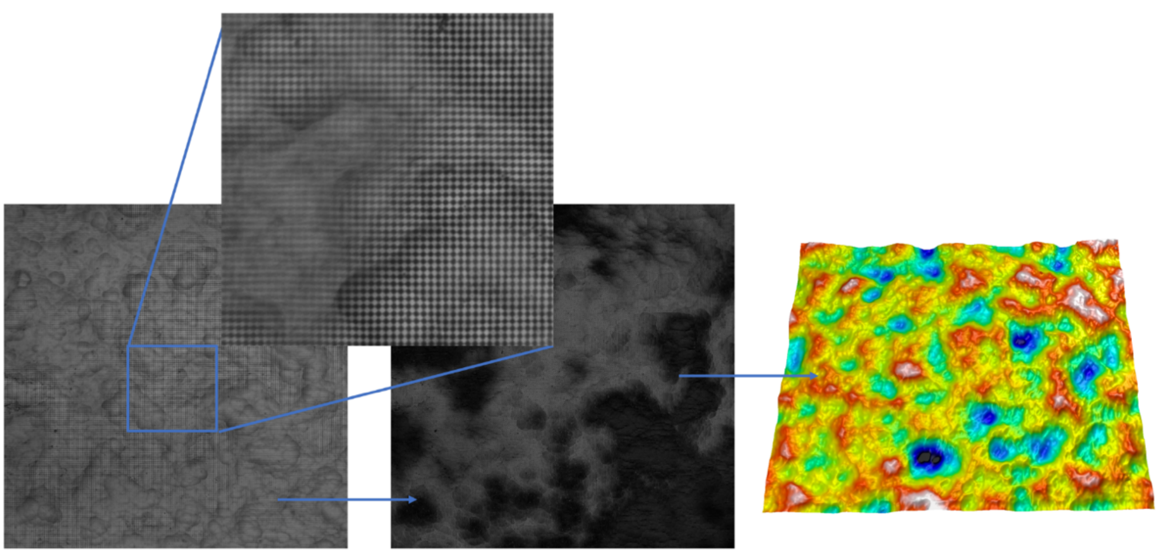

Figure 2: Same sample and same evaluation conditions as in Fig. 1, but with an optically superimposed artificial texture. Right, the computed 3D topography.

2.3 AiFV on a Confocal Microscope

There are several arrangements that provide a microscope the capability of making optically sectioned images. According to the ISO25178-607 [9] there are mainly three different technologies: laser scan, disc scan, and microdisplay scan confocal microscopes. A laser scan confocal microscope uses a laser as a light source illuminating a pinhole that is projected onto the surface under inspection. The light reflected or scattered from the surface is imaged back to a second pinhole, called confocal aperture, which is responsible to filter out the light that reflected outside the depth of focus of the objective. The beam is scanned in a raster scan manner to cover a desired field of view. In a disc scanning confocal microscope, a disc with a pattern of opaque and transparent regions, usually a large number of pinholes or slits, is imaged onto the surface. A light source illuminates the required area on the disc needed to fill the desired field of view. The light reflected from the surface is imaged back through the same pattern, providing the light rejection. The pattern is imaged onto a camera where a confocal image is recorded. In both confocal arrangements, the illumination and observation light path does not allow to record a bright field image. To solve this problem on commercial instruments (which require a bright field image for sample manipulation), both arrangements incorporate a second light source and a beam splitter before the pupil of the microscope's objective that allows bright field illumination and observation through a dedicated camera. In contrast, a microdisplay scan confocal microscope, as shown in Figure 3, can use the same illumination and observation optical paths to acquire a confocal and bright field image [10].

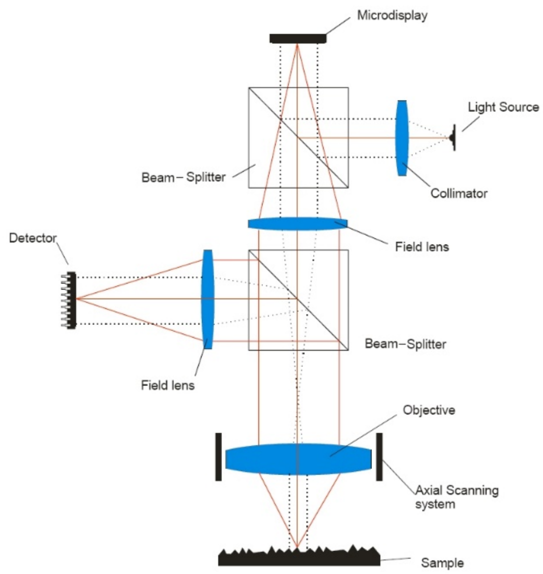

Fig 3: Optical schematic of a microdisplay scan confocal microscope compatible with Active illumination Focus variation.

A light source is collimated and directed onto a spatial light modulator located on the field diaphragm position of the microscope. The modulator is of reflective type, and it can be based on FLCoS (ferroelectric liquid crystal on silicon) or DMD (digital micromirror device). Each pixel of the microdisplay is imaged onto the surface, and by the use of a field lens, the surface and the microdisplay are simultaneously imaged onto a camera. To recover the same performance of a laser scan microscope, a single pixel of the modulator is switched on (behaving as reflective), while all the other are switched off. A single point of the surface is illuminated, and the corresponding single pixel of the camera is recording the signal. Optical sectioning light rejection is achieved by the fact of recording the signal of a single pixel of the camera, which is behaving as a confocal aperture pinhole and detector simultaneously. A raster scan of all the pixels of the microdisplay creates a confocal image in the same way a laser scanning system is doing. Parallel illumination and signal recording can be achieved by switching on a set of equally distributed pixels, slits or any other pattern that restricts the amount of illumination. Switching on all the pixels of the microdisplay and simply recording a single image of the camera easily recovers a bright field image, while switching on one every two pixels on a row, creates a chessboard like pattern. The chessboard can be scaled by switching one, two or more adjacent pixels of the microdisplay to adapt to the Numerical Aperture, magnification, and wavelength. Typically, a 2x2 pixels chessboard is usable for magnifications from 2.5X up to 50X, while higher magnifications require 3x3 or even 4x4 adjacent pixels.

Figure 4 shows the result of measuring with Active illumination Focus Variation and confocal the previous roughness calibration specimen shown in Figures 1 and 2. The image on the left shows the same result as in Fig. 2 by computing the 3D topography from a set of actively illuminated images and a Sum of Modified Laplacian focus operator with a 5x5 pixel window and a 20X 0.45NA objective. On the right, the same surface at the same location is measured with confocal technique. It is clearly shown that the confocal topography is able to preserve the high frequency components of the tiny details of the surface due to its nature to provide high lateral resolution. Medium and lower frequencies are well preserved on the AiFV measurement. On this particular case, the height parameters shown in Table 1 of the ISO25178-200 evaluated on both topographies have a good accordance due to the fact that the tiny high frequency details are not relevant to the evaluation.

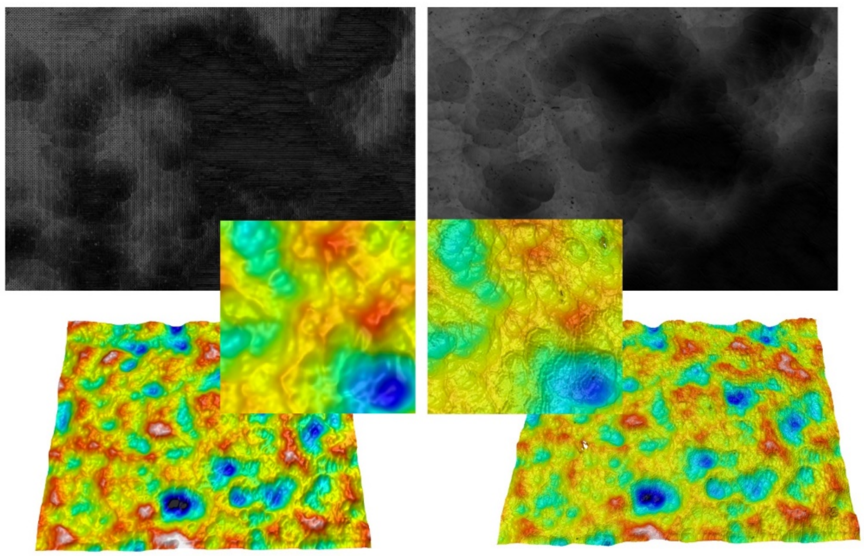

Figure 4: Left, optical section by applying a Sum of Modified Laplacian with a window of 5x5 pixels on an actively illuminated surface with a 20X 0.45 NA objective, and its corresponding computed 3D topography. Right, a confocal image at the same height location and its computed 3D topography.

Table 1. Roughness parameters of the AIR-B40 roughness calibration specimen from NPL

Parameter	**Certified value (nm)**	**Expanded uncertainty (nm)**	**Confocal (nm)**	**AiFV (nm)**
Sa	790.7	26.3	788.4	785.3
Sq	1008.1	21.6	1005.2	1001.2
Sz	7437.6	439.7	7415	7421

3. RESULTS

3.1 Roughness measurements

Active illumination Focus Variation is capable of measuring 3D topographies of optically smooth surfaces, opening the possibility to optical profilers to use such technique to be traceable to national standards through the measurement of calibration specimens. Most of them, such as traceable step height or type B2 roughness standards are manufactured on a flat and stable substrate like glass or silicon. Additionally, a chromium layer around 100 nm is typically deposited on top of the surface to increase reflectivity. Figure 5 shows the measured profile with Confocal and AiFV of a Type B2 roughness standard Mahr (Göttingen, Germany) PRN-3 made on a glass substrate. Calibrated values from the certificate are Ra=0.88

µm with PV of 3.0 µm. Both measurements are on agreement and consistent with the certified values. As in the results shown in Fig. 4 and Table 1, the PRN-3 specimen is a low frequency sample on which the higher frequencies are not relevant and thus not affecting the evaluation of the roughness parameters. Additionally, the filtering process according to the ISO4278 for the evaluation of the profile roughness values, states that a short cut-off filter must be applied, further smoothing out the high frequencies present on such calibration specimen.

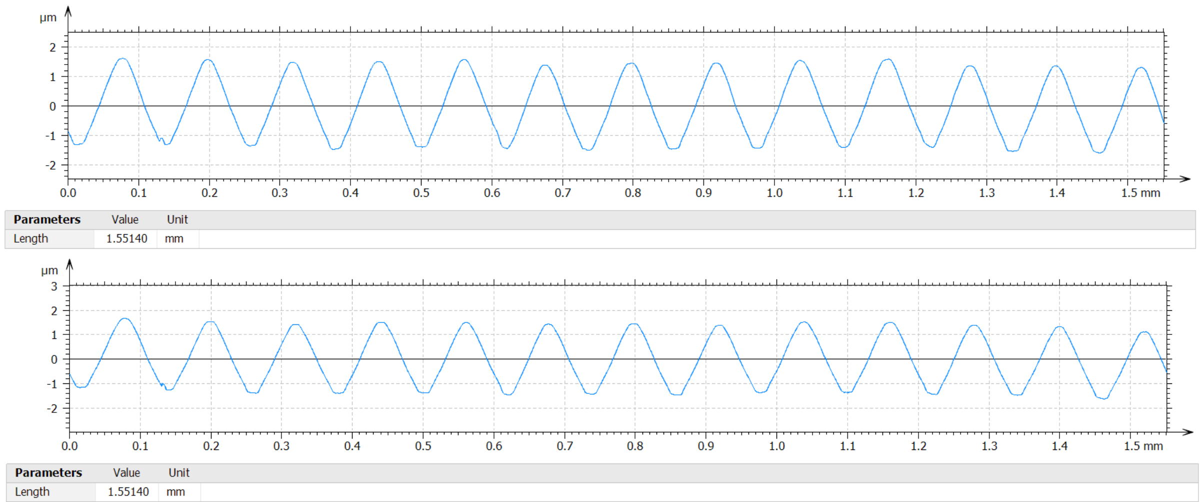

Figure 5: 2D profile of Mahr PRN-3 roughness calibration specimen with Confocal (top) and Active illumination Focus Variation (bottom) with a 20X 0.45NA objective.

Other roughness calibration specimens intended for 3D optical profilers exhibit a random type surface texture, such as the one analyzed in Fig. 4, with high, medium, and low frequencies. AiFV starts to be compromised for those samples where surface texture has a correlation length close to the evaluation window of the focus operator and the optically projected artificial texture. In order to show that limit, we took a roughness calibration specimen from Simetrics GmbH (Limbach-Oberfrohna, Germany) type ARS-c3 with Sa=0.29 µm and a correlation length close to 3.5 µm. Figure 6 shows the 3D measurement with a 50X 0.8NA objective with confocal (left) and Active illumination Focus Variation (right). The smoothing effect shown in the figure will be affecting the roughness parameters on such specimen, since the high frequency components on such case are close to the lateral resolution limit imposed by the technique.

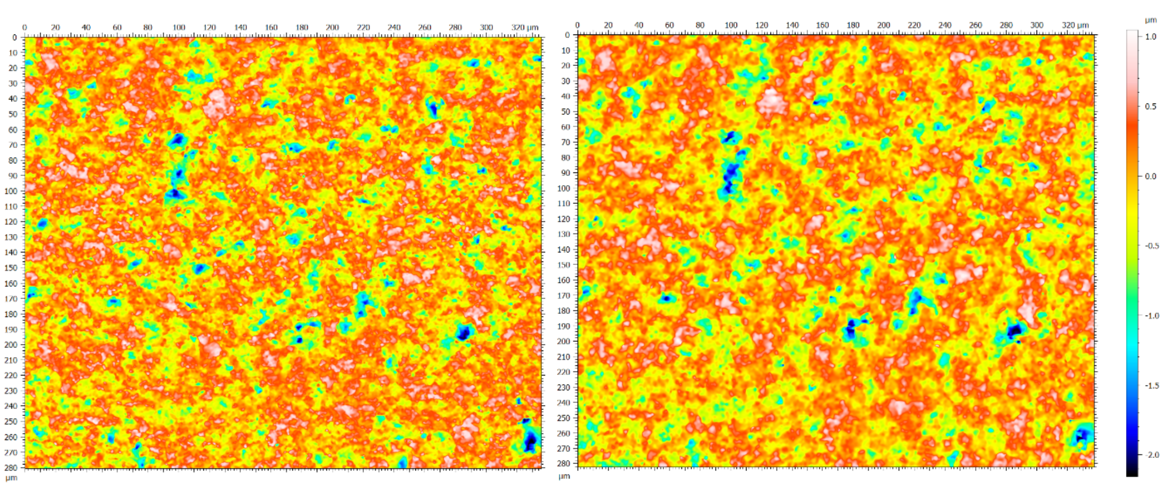

Figure 6: 3D topography of areal roughness standard Simetrics ARS-c3 with confocal (left) and AiFV (right).

3.2 Lateral resolution

The ability to preserve high frequency details of the surface is dependent on three different factors: first, the magnification and numerical aperture of the objective; second, the pixel size of the camera and field lens magnification factor and the evaluation window of the focus operator; third, the pixel size and pattern period of the chessboard and the magnification factor of the field lens that projects the image of the microdisplay onto the surface. Table 2 shows such parameters from 10X to 150X magnification range. The values are obtained for a 0.5X field lens and a 5x5 evaluation window. The diffraction limit is shown as a reference.

Table 2: projected chessboard pattern period, evaluation window at the object plane, and diffraction limit according to Rayleigh criteria at 532 nm wavelength for different magnifications.

Magnification	Chessboard pattern period (µm)	Evaluation window size (µm)	Diffraction limit at 0.532 nm (µm)
10X	7.2	6.9	1.1
20X	3.6	3.45	0.7
50X	1.4	1.38	0.4
100X	0.7	0.69	0.36
150X	0.47	0.46	0.34

The previous measurement shown in Fig. 6 in combination with Table 2 shows that surface details smaller than the chessboard pattern period, or window evaluation size would not be resolved. The roughness values, both height related parameters and lateral related parameters, will be affected by system magnification. Figure 7 shows the result of measuring Sa (surface roughness) and Sal (surface autocorrelation length) on the sample shown in Fig. 6 for both, confocal (black dots) and AiFV (red dots). It is shown that the Sa and Sal values are achieved with a 100X or higher magnification for the confocal measures, while for AiFV the values are never getting to its correct values, even they get close to them. A 50X magnification is still providing close results for confocal, but not trustable in AiFV.

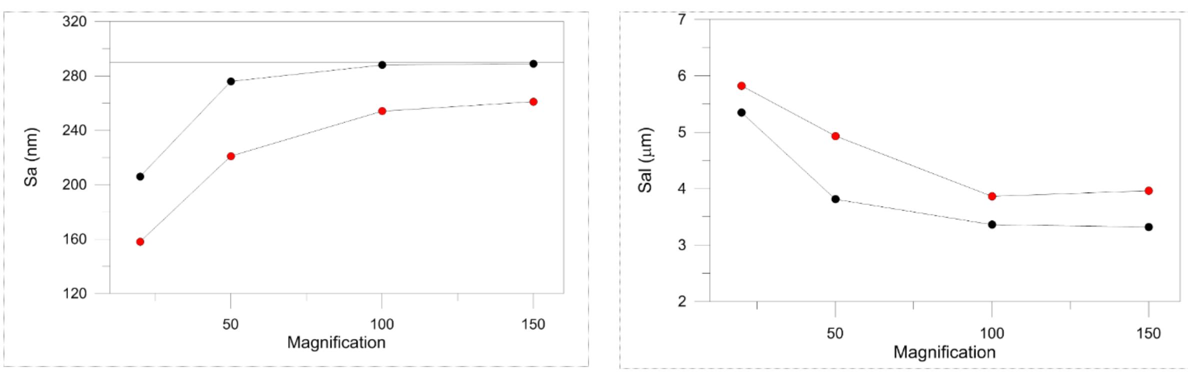

Figure 7: roughness (Sa) and autocorrelation length (Sal) for several magnifications. Black dots: confocal. Red dots: AiFV measurements.

In order to search for the lateral resolution limit of Active illumination Focus Variation, we used the method described in [11]. We used a Siemens Star from the Bento Box (NPL). Figure 8 shows the result of measuring the 3D topography of such specimen with a 20X (top) and 50X (bottom) with confocal and AiFV. It is clearly shown the superior performance of a confocal microscope to preserve lateral dimensions and thus higher frequencies. Nevertheless, AiFV is also capable of performing well up to a certain frequency limit. To assess such limit, the Siemens star has been measured with a range of objectives from 20X to 150X. Figure 9 shows the result of the lateral resolution limit for confocal (black dots), AiFV (red dots), and half the diffraction limit (blue dots) as a reference value. Taking into account these results, it can be stated that a 20X objective is capable of resolving down to 1 µm structures on optically smooth surfaces with AiFV technique.

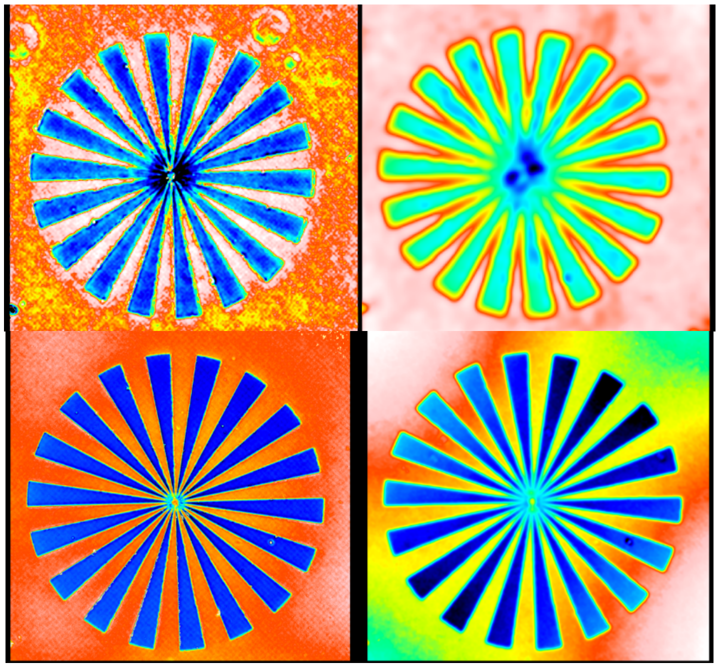

Figure 8: Siemens star measured with a 20X 0.45NA (top) and 50X 0.8NA (bottom) and confocal (left) and AiFV (right).

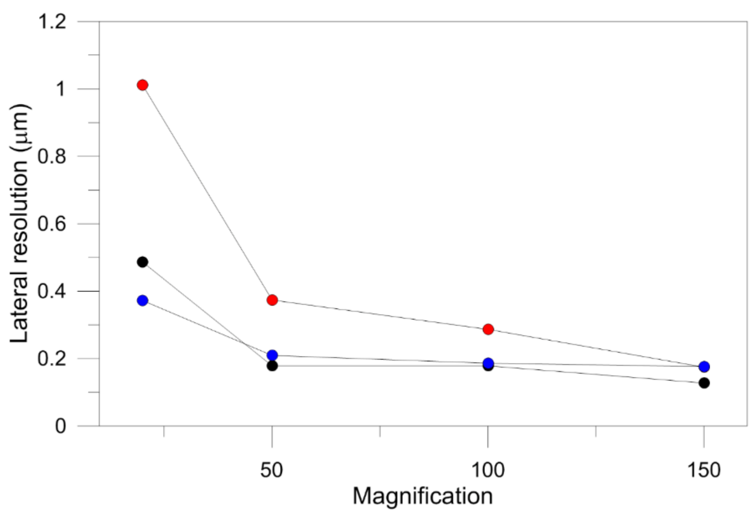

Figure 9: Lateral resolution derived from the Siemens star method for objectives magnification ranging from 20X to 150X. Black, confocal; Red, AiFV; Blue, half the diffraction limit.

3.3 Real examples

The following figures from 10 to 12 show the capability of AiFV to measure real surfaces in comparison to conventional Focus Variation and Confocal techniques. Refer to the figure captions for a brief description of the results.

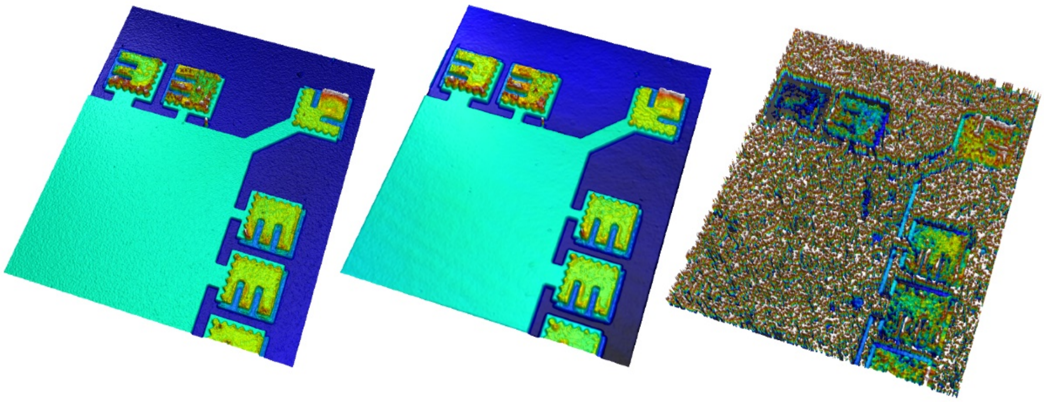

Figure 10: MEM. Measured with a 20X0.45NA. Confocal (left), AiFV (center), and conventional FV (right).

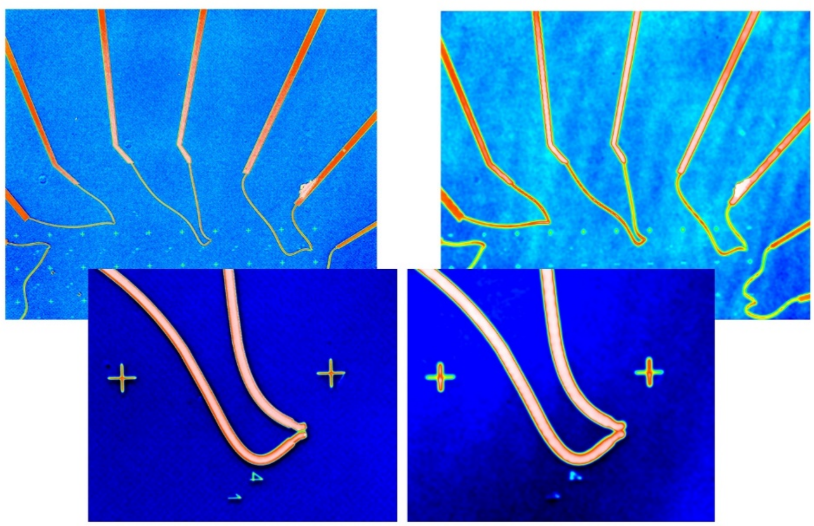

Figure 11: MEM. Measured with a 50X0.8NA. Confocal (left), AiFV (right).

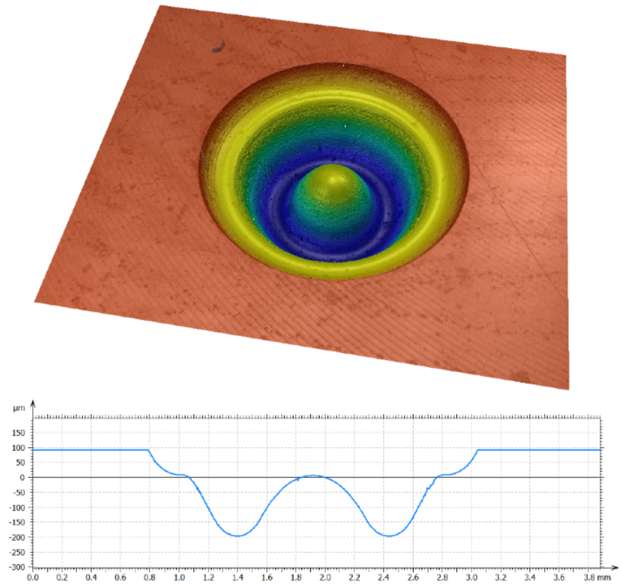

Figure 12: Diamond turned optical lens, measured with AiFV and 10X0.3NA objective.

4. CONCLUSIONS

We have shown the benefits and the limits of conventional focus variation technique for the measurement of optically smooth surfaces such as those present on traceable calibration specimens for the calibration of instruments according to ISO standards. To get rid of the limitations, we have implemented an Active illumination Focus Variation approach compatible with a Microdisplay Scan confocal microscope. With such arrangement, we have shown the capability to measure optically smooth surfaces with results very similar to the ones achieved with confocal microscopy. We have also shown the effects of loss in lateral resolution by measuring areal roughness standards with high frequency, and we have evaluated the limits with a Siemens Star to ascertain the lateral resolution limit. We concluded that AiFV is a good measuring technique rivalling confocal microscopy on those surfaces where small structures are less relevant than medium to low frequencies. Cristina (than?)

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