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WHITE LIGHT INTERFEROMETRY: CORRELOGRAM CORRELATION FOR SURFACE HEIGTH GAUGING NOISE STABILITY

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Abstract—Established methods to gauge the surface height by a white light interferometer do not use the full information contained in a correlogram. As the result, the envelope evaluation methods suffer from susceptibility to noise, whereas the phase methods are prone to the "2-pi ambiguity". In the approach of the present paper the surface position is determined via the correlation of the local correlogram with a reference correlogram, thus benefiting from its complete information. As a result, the dispersion by noise is by more than one order of magnitude lower, compared to envelope methods; the 2-pi ambiguity not revealed so far. Another advantage of the suggested method is the immediate availability of a suitability criterion for a local correlogram – the correlation coefficient with the reference correlogram.

Keywords: Interferometr, Surface Topology, Noise Resistance.

I. INTRODUCTION

Among sensor device technologies the white light interferometry (WLI) is established as one of the most popular methods of surface topography evaluation. The challenging problem is false evaluations of the surface height, which are affected by different kinds of noise inevitably appearing during any measurement. On the one hand, there is a continuous search for data evaluation methods that are immune to noise, on the other hand, being aware of error inevitability, one is looking for a possibility to assess the confidence level of the surface height evaluation – on every pixel of the optical field - in order to sort out improper ones [4]. Although the assessment of the confidence level does not prevent appearance of false height estimations, yet it allows preventing false conclusions during a further surface topology analysis.

The WLI data are primarily represented by a set of correlograms from different pixels. There are two commonly recognized ways of correlogram processing to estimate the surface height: the method of the correlogram envelope maximum/centroid calculation and the method of correlogram phase tracking [3, 4]. Both methods have their own advantages and shortcomings: the first is robust when applied to rough torn surfaces but shows higher variations caused by the data noise [5]; the second one, vice versa, is known providing low variations / high reproducibility but cannot be applied to rough surfaces being prone to the 2-pi ambiguity [3]. Disadvantages when applying these methods are actually to be expected - both make use only of a part of the information contained in the signal. The way to go is to involve the complete information in a single evaluation procedure. There are continuous attempts to combine both methods in order to profit from the advantages of both of them [1], yet both kinds of shortcomings remain.

The intention of the present study is to obtain a data evaluation procedure, which uses complete correlogram information, and to obtain improvement in both the noise tolerance and the confidence level assessment. It is suggested to find - in the measured intensity z-distribution – the interval which is most similar to the known reference correlogram of the interferometer. The position of the interval will give the position of the surface and the level of similarity would give the confidence level for this height estimation. This is exactly what is provided by the crosscorrelation function between the measured intensity distribution and the reference correlogram: it gives both the position of maximal resemblance and the level of similarity. Note that this method uses the complete information contained in the correlogram signal: both phase and envelope information, since its complete form is involved in correlation analysis. Thus the noise stability of the correlogram cross-correlation method is expected to be as good as with the phase method, and as in the envelope evaluation methods no phase ambiguity should appear.

In section II a short description of the method is given; the results of a testing of the method by correlogram and noise simulation are given in the subsection "A" of section II; in subsection "B" the results of an application of the method to measurements on smooth surface are presented.

II. REALIZATION OF CORRELOGRAM CORRELATION METHOD AND TESTING OF ITS STABILITY AGAINST NOISE.

The cross-correlation function has been used as the gauge of the correlogram packet position and the level of similarity. The employed normalized cross-correlation function is given by

$$K = \int_{-\infty}^{\infty} I(z) I_0(z+\tau)\,dz \Bigg/ \sqrt{\int_{-\infty}^{\infty} I^2(z)dz \int_{-\infty}^{\infty} I_0^2(z)\,dz}\ , \qquad (1)$$

where I is a measured pixel-correlogram, I_0 is the reference correlogram, z is the interferometer scan coordinate. Of course, the cross-correlation has been calculated on the digitalization net, originally with the step of interferometer frame distance Δz. In fact the MATLAB function *xcov* has been employed to calculate K. The position of absolute maximum of K has been interpreted as the local height of surface relative to that of reference surface which produces the correlogram I_0. The value $Kmax < 1$ (= maximum correlation coefficient) gives the confidence level for the current pixel.

Certainly, the scan discretization interval of interferometer Δz produces a too rough net: the surface has to be localized much more accurately. Therefore an interpolation of intermediate points has been performed producing a net 10 times more dense. In this study a proper interpolation has been performed to keep the spectrum of the function unchanged by the interpolation. Specifically, digital Fourier transform of the original function is performed; the present harmonics are kept unchanged, but supplemented with harmonics of higher frequencies and zero amplitude; finally the reverse transformation produces the function on the dense net. It can be proven that such an interpolation of the correlograms followed by the calculation of their crosscorrelation gives the same result as the primary calculation of cross-correlation on the rough net followed by the interpolation. The latter variant lowers computation costs, and being much more effective, has been used in present study. Further accuracy elevation is achieved by the parabolic interpolation on the three points near the maximum of K. A. Simulation

A simulation has been carried out in order to obtain the surface height assessment at different noise levels. The correlograms have been simulated on a digitalization net z_i just as the harmonic modulated with the Gaussian envelope:

$$I_i = Aexp\{-log(2)\ [(z_i - z_0)/W_\lambda]^2\} \times cos[(2\pi/\lambda_0)(z_i - z_0)] + \sigma_{noise} rand(i),$$

where A is an arbitrary amplitude; z_0 is the position of the correlogram maximum, W_λ is half-width of the correlogram; λ_0 is its main frequency, σ_{noise} is the noise dispersion, *rand* is the function producing normally-distributed random values with zero mean value and the unit dispersion. Thus, white noise has been used, not in complete correspondence with the distortion noise produced by surface inhomogeneities which reveal themselves mainly in additional phase shifts [2], but representing well the instrumental noise. Figure 1, (a)-(c) shows how the noise of different level distorts the correlograms.

The correlogram corruption grows from a slight disturbance at the relative level of 0.01 to a very substantial packet spoiling at the 0.1-level and to complete correlogram distraction at the level 0.3. Following values have been used for the simulation: Δz = 40 nm; λ_0 = 300 nm; $W_\lambda = 2\lambda_0$. For the presented correlogram correlation (CC) method the correlogram without noise has been used as reference correlogram

For the comparison with the results of the correlogram correlation method the signal envelopes have been calculated using the known formula of square summation of correlogram with its Hilbert transform [4]. The two most common methods to determine the correlogram position have been used: the parabolic approximation of half-height. envelope followed by the determination of its maximum and the calculation of the half-height envelope centroid. No filtration of the envelope [2] has been applied relying on the averaging which is automatically provided by these two envelope evaluation methods owing to usage of the complete half-height envelope.

As expected, the height determination has been exact at zero noise level by all the tested methods. The mean values of deviations of height estimation from the height z_0 specified in (1) calculated as the average over 1000 repetitions. These deviations appearing when using the correlogram and the two envelope evaluation methods are presented in Figure 2.

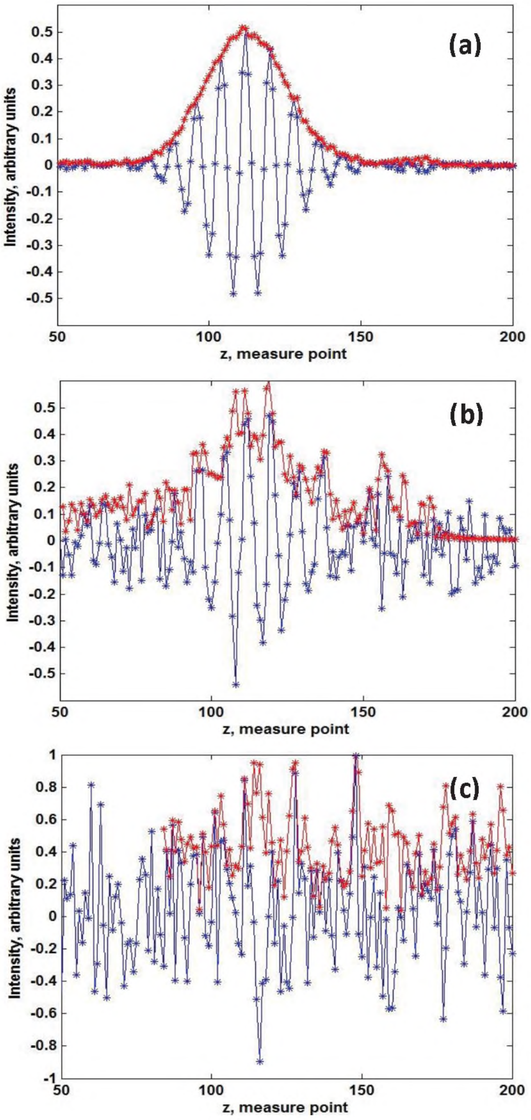
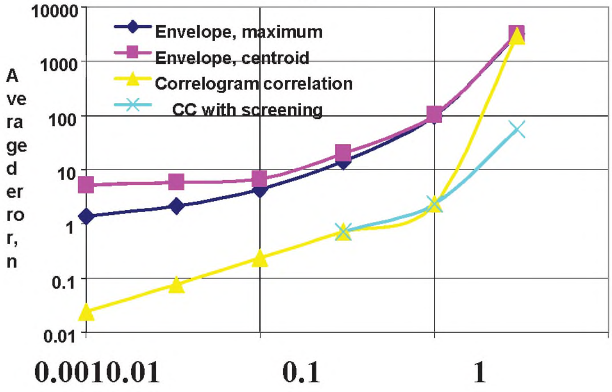


Figure 1. Correlogram corruption at different noise levels: (a) – noise dispersion is 0.01 of the double correlogram amplitude; (b) – 0.1; (c) – 0.3. The red lines show the unfiltered envelope.



Noise level

Figure 2. Mean deviation of the calculated surface height from the true value employing the envelope methods and the correlogram correlation (CC). (Concerning the screening see the enumeration below, d)).

Following conclusion can be drawn from the data of Figure 2:

a) For white noise the deviation of the correlogram correlation method is approximately 1.5 orders of magnitude below the errors produced by the envelope methods.

b) In practice the noise levels of about 0.1 are not rare. At these levels the errors of envelope methods are already inacceptable while that of CC are still just about 2-3 nm.

c) It is known that the deviations of the phase method are about 7 times smaller than that of envelope methods [4]. Here the inaccuracy of CC is still lower.

d) Within the CC method the confidence estimation is readily available, and can be used to screen out the worst corrupted correlograms when calculating the mean value of surface height. Such a screening has been performed, and the result is given in Figure 2. The threshold maximal correlation coefficient with the reference correlogram here has been 0.5. All correlograms of lower correlation have been omitted. Moreover, the height deviation values produced by the remaining correlograms have been weighted for the averaging; the maximal correlation coefficients with the reference correlogram have been used to get the weights. Up to the noise level of 0.1 the error level is practically the same as that of pure CC, but at the noise level 0.3 the error is still moderate (56 nm) while other methods fail completely.

The deviations from unity of the averaged correlation coefficients obtained by the CC for the noise levels of 0.03, 0.10, 0.30, are correspondingly: 0.018, 0.16, 0.63. The values of coefficients at the lower noise level are practically indistinguishable from 1.

B. Measurement on smooth surface

For a validation with experimental data a measurement on polished Si wafer has been evaluated. The Mirau interferometer, Breitmeier Messtechnik GmbH, with the interferometer objective Nikon CF IC EPI of x10 magnification has been employed for this measurement. The frame area of the objective is 0.66x0.89 mm^2. The low CCD camera resolution of 518x692 pixels has been chosen in order to keep data amounts reasonable. The LED light source has a spectrum energy distributed in the range of 8.5 - 12.8 μm^{-1}. The sampling step size of 40 nm, minimal for the instrument, has been chosen. A typical correlogram is shown in Figure 3, on the top. On the bottom of the figure the correlogram which has been chosen to be the reference one for the CC method is depicted. The reference correlogram is already devoid of the mean level and slope and shortened in length, in order to exclude surplus noise.

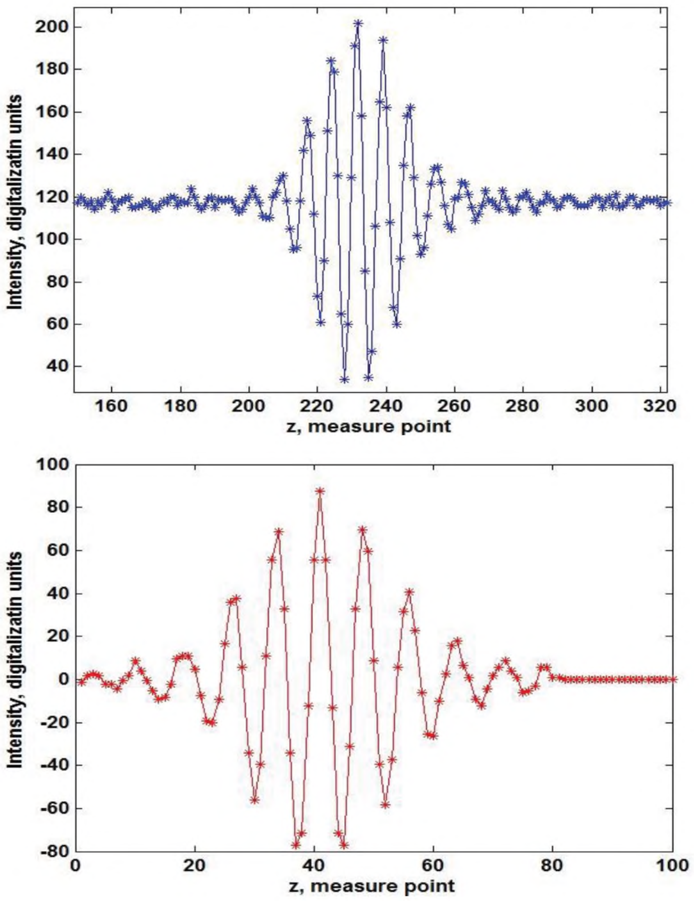


Figure 3. A typical correlogram measured on smooth surface (picture above) and the correlogram used as the reference correlogram (below).

Comparing the correlogram pictures in Figure 3 with those of the simulation, the noise level can be roughly estimated to be about 0.02. The evaluated distributions of surface heights along a stretch of the optical field are illustrated in Figure 4.

The height dispersion provided by the envelope maximum estimation method is 5.6 nm that provided by the envelope centroid method – 9.6 nm and of the CC method it is 0.45 nm. Thus, the CC demonstrates an accuracy 12 times higher, than that of the envelope method. The dispersions found correspond well to the results of the simulation given in Figure 2, assuming the estimated noise level is in the vicinity of 0.02.

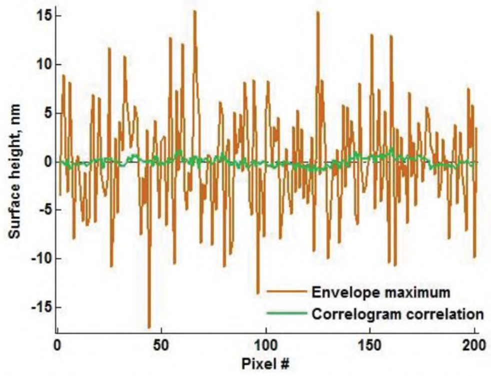


Figure 4. Surface heights obtained by envelope and correlogram correlation methods on a smooth Si surface along a line segment of the optical field.

The CC method is expected to have an additional advantage: its dispersion seemingly contains also a fraction of the real surface height variation. This part in the height dispersion of the envelope method is negligible. Therefore there is no correlation between the height profiles measured using both methods: their correlation coefficient amounts just to 0.08. Notice that the accuracy difference between CC and the envelope method again exceeds the accuracy of phase method as compared to the accuracy envelope method [4].

For a practical realization of the CC method a reference correlogram is needed. It should be measured on a smooth surface of the material in question and then properly averaged over a set of pixels. A doubt arises when thinking about using the CC method because of an allegedly high computation time for the cross-correlation function. But if done employing the very quick procedure of the fast Fourier transform (direct and reverse), it is, in fact, not time expansive. Moreover, the procedure can be further developed, say, resettled in the frequency domain in order to get a still quicker performance.

III. CONCLUSION AND FUTURE WORK

The introduced correlogram correlation method uses the complete information contained in the correlogram and thus is supposed to have a noise resistance not lower, than that of the phase method. At the same time it is not supposed to exhibit a phase ambiguity. The first supposition is confirmed in the present study with the help of simulations and a measurement on a smooth surface: the accuracy of the CC method exceeds that of the envelope method by more than one order of magnitude. The confirmation of the absence of an ambiguity is a matter of further research, involving the evaluation of measurements on rough surfaces and possibly simulations. It is demonstrated that the CC method can be used, when analyzing data with a noise level at which the employment of the envelope estimation methods is impossible.

Another advantage of the method is that it automatically provides a measure of the fitness of pixel's correlogram for further evaluations – the coefficient of correlation with a reference correlogram. This confidence parameter can be used for further surface structure evaluations. It is shown here that its application allows height evaluation even from very corrupted correlograms.

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МОДЕЛИРОВАНИЕ ТЕРМИЧЕСКОГО НАГРЕВА ВЕЩЕСТВА ЭЛЕКТРОМАГНИТНЫМ ИЗЛУЧЕНИЕМ

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