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The development of the spatially correlated adjustment wavelet filter for atomic force microscopy data

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ABSTRACT

In this paper a novel approach for the practical utilization of the 2D wavelet filter in terms of the artifacts removal from atomic force microscopy measurements results is presented. The utilization of additional data such as summary photodiode signal map is implemented in terms of the identification of the areas requiring the data processing, filtering settings optimization and the verification of the process performance. Such an approach allows to perform the filtering parameters adjustment by average user, while the straightforward method requires an expertise in this field. The procedure was developed as the function of the Gwyddion software. The examples of filtering the phase imaging and Electrostatic Force Microscopy measurement result are presented. As the wavelet filtering feature may remove a local artifacts, its superior efficiency over similar approach with 2D Fast Fourier Transformate based filter (2D FFT) can be noticed.

1. Introduction

Near field microscopy is a dynamically developing diagnostic method since three decades. Its popularity still increases, as the there is a continuous progress in a number of measurement modes and data it delivers [1,2]. On the other hand, the complexity of acquired data sometimes makes it difficult to interpret [3]. Therefore, the advanced algorithms for data processing and imaging are continuously developed in order to improve the analysis tasks [4–6]. Despite the imaging techniques optimization effort, one has to take into account the presence of various artifacts, which may introduce additional interpretation uncertainty [7,8]. The artifacts identified during the data analysis should be removed, as they may confuse the readers of the published results as well as can be taken into account by the data processing software while some statistical factors are calculated.

The most popular commercial and home-made AFM systems base on the setups with optical detection of the probe displacement, containing the laser and quadruple photodiode [9,10]. The major advantage of such a solution is relatively low price of the probes, satisfying force detection sensitivity [11] and automated aligning [12]. On the other hand, the interference issue caused by periodic features present on the surface of the sample is a significant drawback [13]. It is due to the fact, that used light wavelength approx. 650 nm is reflected not only by the probe, but also by the surface.

It should be underlined, that a number of alternative solutions in terms of the probe displacement detection have been successfully tested and used: piezoresistor-based [14], capacitance sensing [15], tuning fork- cantilever combined probes [16], interferometer detection [17], tunneling current [18] or the charge measurement [19]. Kassies et al. proposed the laser diode current modulation in order to avoid such an issues [20]. Also, the optical setups with 1.3 μm wavelength have been recently introduced into market in order to reduce the impact of the interference [21]. Nevertheless the presence of the above described artifacts has to be reduced by means of data filtering, as the majority of typical setups still may deliver distorted results.

As the interference phenomena is periodic, specific wavy features reveal the presence of the artifact. In order to remove it, one can use 2D Fast Fourier Transformate (2D FFT), which provides high selectivity in terms of the spatial frequency [22,23]. One can, however, face the presence of features only partially covering the image, which can not be easily removed with 2D FFT filtering, as such an approach may introduce a significant distortions of the

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rest of the image unaffected by the artifact. As the alternative, the two dimensional wavelet transform filtering feature can be utilized, as it allows to perform local features removal. Some examples of such filters utilization were already demonstrated [24,25].

It should be underlined, that wavelet filter was not delivered to the users in commercial or free AFM processing software releases so far. One of the major reasons may be the much more difficult adjustment procedure of such a feature than in case of the 2D FFT filter. Therefore, basing on earlier successful implementation of maps-correlated approach where additional measurement signal was used to adjust the filter settings [26], we have developed similar solution using wavelet algorithms.

1.1. Solution development

The filtering procedure was developed basing on the Gwyddion software [27,28], which is an Open Source project. It is one of the most popular freeware programs among AFM users, at it delivers a wide spectra of analysis and data representation tools [29–32]. Its continuous development provides new features as well as the data import filters for recently released AFM instruments. The open architecture of the software allowed to implement the filtering feature based on the wavelet transform and inverted wavelet transform of the two-dimensional set of data acquired using atomic force microscopy.

The wavelet transform decomposes the signal into mutually orthogonal set of wavelets, which is the key difference from the continuous wavelet transform (CWT), or in case of the discrete time series – usually called discrete-time continuous wavelet transform (DT-CWT) [33,34]. The wavelet can be implemented from a scaling function which describes its scaling properties. The scaling functions must be orthogonal to its discrete translations. Therefore it implies some mathematical conditions on them which are mentioned everywhere, e.g. the dilation equation [28]

$$\phi(x)=\sum_{k=-\infty}^{\infty} a_k\phi(Sx-k) \tag{1}$$

where S is a scaling factor (usually chosen as 2). In addition, the area between the function must be normalized and scaling function must be ortogonal to its integer translates, i.e.

$$\int_{-\infty}^{\infty}\phi(x)\phi\left(x+l\right)dx=\delta_{0,1} \tag{2}$$

After introducing some more conditions (as the restrictions above does not produce unique solution) we can obtain results of all this equations, i.e. the finite set of coefficients a_k which define the scaling function and also the wavelet. The wavelet is obtained from the scaling function as

$$\psi(x)=\sum_{k=-\infty}^{\infty}\left(-1\right)^k a_{N-1-k}\psi(2x-k) \tag{3}$$

where N is an even integer. The set of wavelets forms an orthonormal basis which is used to decompose the signal. It should be mentioned, that usually only few of the coefficients a_k are nonzero which simplifies the calculations.

It should be underlined, that unlike in 2D FFT filtering, where spatial frequencies identification and removal can be trained relatively easily, the wavelet-based filters are more complicated in terms of practical use. Therefore one needs the assistance in order to select appropriate spatial frequencies and to remove unwanted features of the image. Therefore the idea of the multiple-signal supported wavelet filter adjustment was developed and tested. The diagram showing the idea of the filter utilization is presented in Fig. 1. The developed feature provides the filter settings adjustment using the summary diode signal map (I stage), and once the filter adjustment is done, the filtering of the image containing specific data (signal) is performed using previously tuned parameters (II stage)..

The specific processing modules are described below. The

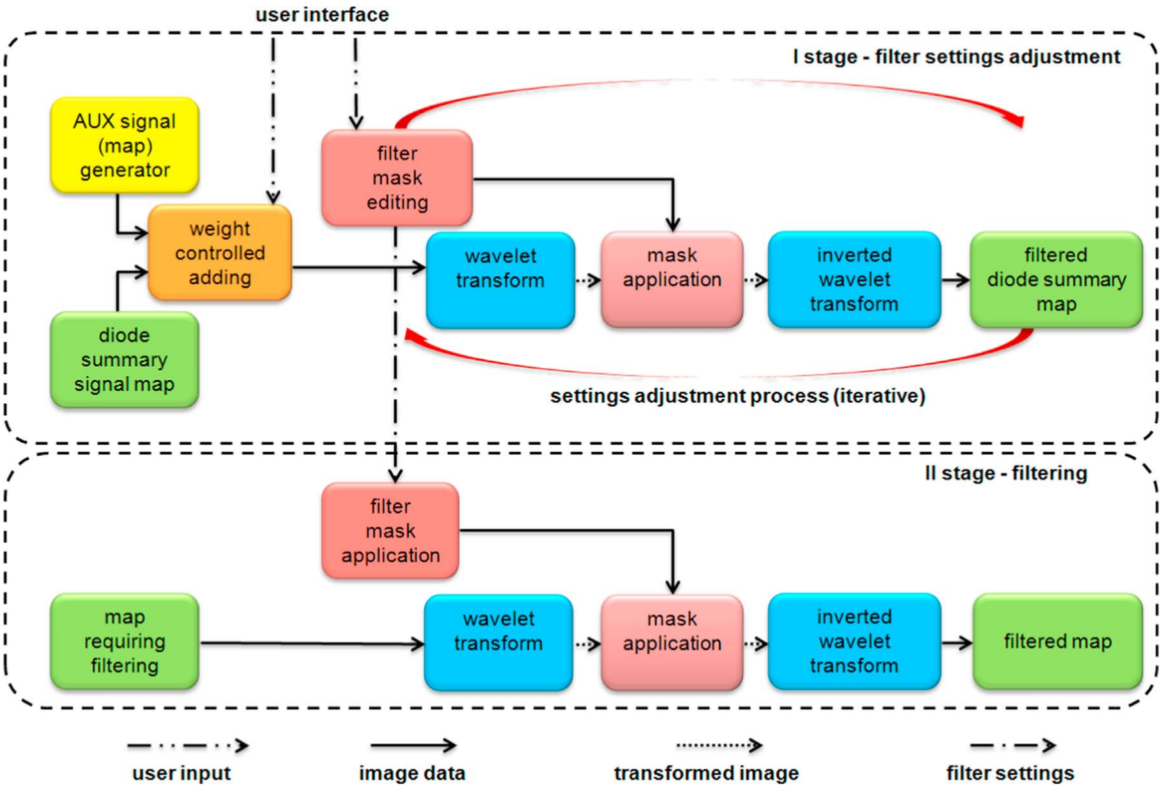

Fig. 1. The diagram representing the utilization of the summary diode signal-supported in terms of the adjusting the wavelet filter settings.