Restoration of noisy Scanning Tunneling Microscope images

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Abstract

We have compared and improved several implementations of the Wiener filter to remove noise effects from Scanning Tunneling Microscope images.

We have found that the implementation of Weisman et al. [6], using the noise model of Stoll et al. [2], provides the best performance on both simulated and real STM images.

1: Introduction

Since its invention by Binnig and Rohrer in 1981 [1], the Scanning Tunneling Microscope (STM) has proved to be a very useful instrument for surface science. A STM images the height of a surface on atomic scale, by measuring the current of tunneling electrons between the tip of the microscope and the surface, when a voltage difference is applied between them. Variations in the tunneling current are imaged by the STM as variations of the height of the surface.

Unfortunately, images made with a STM suffer from various distortions. We have found that the internal noise of the STM is the main source of distortion of STM images made in air. This distortion is characterised by long stripes in the scan direction, and has been characterised as so-called *1/f*-noise [2]. This type of noise is strongly correlated and has a self-similar frequency distribution. The removal of this internal *1/f*-like noise from STM images is the main goal of the research presented here.

2: Image acquisition models applied to STM

To model the acquisition of a STM image, we have assumed that the internal STM noise $n(x,y)$ is additive and non-correlated with the "true" image $f(x,y)$ of the surface,

$$g(x,y) = f(x,y) + n(x,y), \tag{1}$$

where $g(x,y)$ is the observed STM image. We have used the mean square error as a criterion to minimise the difference between the restored image $\hat{f}(x,y)$ and the true image $f(x,y)$. The optimal linear restoration filter, given $g(x,y)$, is then known as the *Wiener smoothing filter* [3] , which is given by

$$W(u,v) = \frac{F(u,v)F^*(u,v)}{F(u,v)F^*(u,v) + N(u,v)N^*(u,v)} = \frac{1}{1 + \frac{S_{nn}(u,v)}{S_{ff}(u,v)}}, \tag{2}$$

where $F(u,v)$ and $N(u,v)$ are the Fourier transforms of respectively the true image and the noise. $S_{ff}(u,v)$ denotes the power spectrum of the true image, $S_{nn}(u,v)$ of the noise. The restored image is given by

$$\hat{F}(u,v) = W(u,v)G(u,v), \tag{3}$$

with $\hat{F}(u,v)$ the Fourier transform of the restored image and $G(u,v)$ of the observed image. Since the power spectrum of the true image and the noise are in general not known, one has to use an estimate or a model of them. We have compared two models of the noise power spectrum with real noise measurements, and tested five estimations of the true power spectrum on simulated images.

From experiments [2], Stoll and Marti have found that the power spectrum of STM noise is determined by *1/f*-like noise at low frequencies. They believe that this noise is caused by very slow unintentional motion of the tip perpendicular to the scan direction and by the electronic components of the STM's feedback system. Based on these assumptions they model the noise power spectrum as,

$$S_{nn}(u,v) = \frac{A}{\left[u^2 + (v/2L_x)^2\right]^{\frac{\beta}{2}}}, \tag{4}$$

where L_x is the number of points per scan line. They argue that the effect of *1/f*-like noise is much more pronounced in the *v*- than in the *u*-direction, which is in contradiction with the model of Park and Quate [4], who modelled the noise power spectrum as A/u^{β}. From our own noise measurements [5] we have found that the model of Stoll and Marti describes real STM noise more accurately than the model of Park and Quate.

To restore STM images, Stoll and Marti have used the following implementation of the Wiener smoothing filter,

$$W(u,v) = \frac{1}{1+\dfrac{\alpha A}{\left[u^2+\left(v/2L_x\right)^2\right]^{\frac{\beta}{2}}}}, \qquad (5)$$

in which the true power spectrum is modelled with the constant $1/\alpha$. We have estimated this power spectrum, by using equation [1], as the difference between the observed image and the noise model of Stoll and Marti. This leads to the following formulation of the Wiener smoothing filter [5],

$$W(u,v) = \begin{cases} 1-\dfrac{\dfrac{A}{\left[u^2+\left(v/2L_x\right)^2\right]^{\frac{\beta}{2}}}}{G(u,v)G^*(u,v)} & \text{if } W(u,v) > 0 \\ 0 & \text{otherwise} \end{cases}, \qquad (6)$$

Finally, we have tested a modified version of the Wiener filter proposed by Weisman et al. [6][5],

$$W(u,v) = \frac{1}{1+\dfrac{\dfrac{\alpha A}{\left[u^2+\left(v/2L_x\right)^2\right]^{\frac{\beta}{2}}}}{G(u,v)G^*(u,v)}}, \qquad (7)$$

in which we have used the noise model of Stoll and Marti instead of the model of Park and Quate.

3: Simulations with the Wiener filter

In our tests with simulated and real STM images, we have mainly used graphite as a test surface. Mizes et al.[7] show that STM images of graphite are well approximated by a summation of three cosine waves oriented at 120° angles.

Since a good physical model for the internal STM noise is lacking, we have used a simple method to simulate *1/f*-like noise. The $1/f^{\beta}$-noise was generated by inverse Fourier transforming a function with a $1/f^{\beta/2}$ amplitude and a uniformly distributed random phase (fig. [1], right).

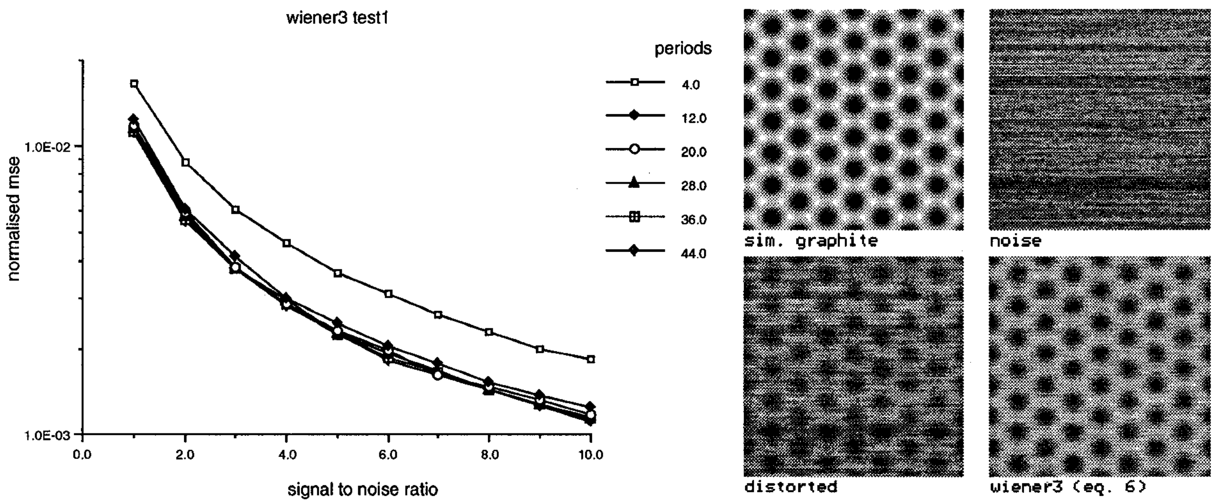

Figure 1: The left picture shows the normalised mse between the true image and restored image of our Wiener implementation (eq. 6) as function of the signal to noise ratio between the true image and the noise for different numbers of the period of the graphite lattice, with a constant β of 1.50. The right image shows the filter performance of our Wiener implementation, with the true image (upper left), the noise realisation (upper right), the distorted image (down left) and the filter output (down right). The signal to noise ratio is 1.0, β 1.0 and the number of lattice periods is 8.0. The normalised mse of the filtered image is 0.095.

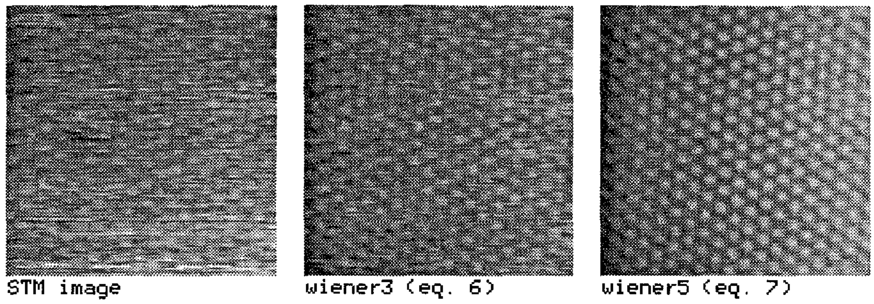

Figure 2: Wiener filtering of a real STM image. A STM image of graphite is shown, wiener3 denoted our implementation, wiener5 the modified filter of Weisman et al. with the filter parameter α of 25.0.

We have tested five Wiener filter implementations: the ideal Wiener filter (eq. [2]), the ideal filter with the noise model of Stoll et Marti (to test this noise model), the implementation of Stoll and Marti, our implementation and the modified Weisman filter.

The performance of these Wiener filters have been tested as function of the signal-to-noise (SNR) ratio between the true image and the noise. The SNR ratio is determined by the noise amplitude A, the β of $1/f^{\beta}$-noise, and the period P of the graphite image. We have varied A, β and P so that they represent the range of these variables in real STM images.

The performance of the Wiener filters have been determined by calculating a *normalised mean square error*, which is the mean square error between the restored and the true image, divided by the average power of the true image.

From our tests [5] with the ideal Wiener filter, we conclude that the additive *1/f*-noise is well suppressed in the simulated graphite images. The second filter gives only a slightly worse performance than the first one. Thus, the parametric model of Stoll for the power spectrum which is used in this filter, is a good model to describe the noise power spectrum. The performance of our Wiener implementation and the modified filter of Weisman et al. give good results, reducing the amount of noise from 1.0% down to 0.1% of the original amount of noise (fig 1, left). The filter of Stoll et al. only reduces this amount by half.

5: Restoration of real STM images

We have applied our Wiener filter and the modified Weisman implementation of the Wiener filter to real STM images. We have found that the stationary tip images describe the noise in the real images qualitatively well, but that they underestimate the total power of the noise. We have therefore assumed that the shape of the noise has been conserved in real images, and have fit the amplitude of the noise on the spectra of real STM images.

The results of the two Wiener filter implementations differ from what we would have expected from the simulations. The modified filter of Weisman et al. has performed significantly better then our implementation (fig. 2). We have found that this difference in performance can be explained by the deviations of the STM-noise from the *1/f*-noise model of Stoll. These deviations of real STM-noise are, apparently, larger than our simulated *1/f*-noise.

References

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