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Iterative filtering algorithm for denoising HR(S)TEM micrographs

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HR(S)TEM micrographs are usually superimposed with different kind of noise, such as counting noise and scanning noise etc. Removal of noise from a micrograph therefore is an important task in electron microscopy. It is possible, more often necessary, to quantitatively compare the denoised and recorded images by their difference (residual), which is considered to be the noise. We have compared the performance of low-pass, Wiener, and our developed iterative filters by examining their residuals for noise reduction in HR(S)TEM micrographs.

Low-pass filtering is one of the simplest way to reduce high special frequency noise in atomic-resolution HR(S)TEM micrographs. Figure 1 shows the results of a Gaussian low-pass filtered HAAD-STEM micrograph of a $SrTiO_3$ thin film at [001] zone-axis. The peak attenuation is evidently seen in the residual image and its line profiles (Figure 1c), which hinders faithful quantification of the peak intensity. The Wiener filter and background subtraction filters can effectively reduce peak attenuation.[1] However, these filters tend to have artifacts when variation of background or nonperiodic defects are present in the images (Figure 2). To solve these problems we have developed an iterative filtering algorithm that can efficiently reduce noise in HR(S)TEM micrographs without noticeable artifacts even in the presence of variation of background and defects.

Reduction of peak attenuation has been reported by low-pass filtering to the 1D input signal and its residual.[2] To eliminate peak, background, and defects attenuation we applied the low-pass and wiener (or background subtraction) filters iteratively to the recorded 2D HR(S)TEM images and their residuals respectively. Figure 3 shows the results from the filtered HAAD-STEM image with 15 iterations. The high special frequency noise from iterative filtering has quite similar features to the Wiener filtering in quantitative sense as seen from the line profiles of the residuals (Figure 2b and 3b). The iterative filter performs as efficiently as Wiener filter in removing the high special frequency noise and reduce the so-called scanning noise. However, the advantage of the iterative filter over Wiener filter is without the artifact of low special frequency background ground attenuation. This is because that the signal with special frequency around zero is less touched in the iterative filtering algorithm (Figure 3c). The residual appears to follow a Gaussian distribution with an average value of zero (Figure 3c, inset). The signal-to-noise ratio (SNR) of the recorded image can be estimated from the standard deviation of the denosied image to that of the residual, which turns out to be 1.5 for Figure 1a).

Though the presented example is a HAADF-STEM image with variation of background, the iterative filtering method appears to perform well in denoising other kind of high-resolution electron micrographs, such as HRTEM, EFTEM, BF-STEM micrographs, even when defects are present.

1. R. Kilaas, J. Microscopy 190 (1998), p. 45.
2. J. McNames and B. Goldstein, Acoustics, Speech, and Signal Processing (ICASSP), IEEE International Conference, (2002), p. II-1529-II-1532.
3. We kindly acknowledge the financial support from the Deutsche Forschungsgemeinschaft (SFB 917).

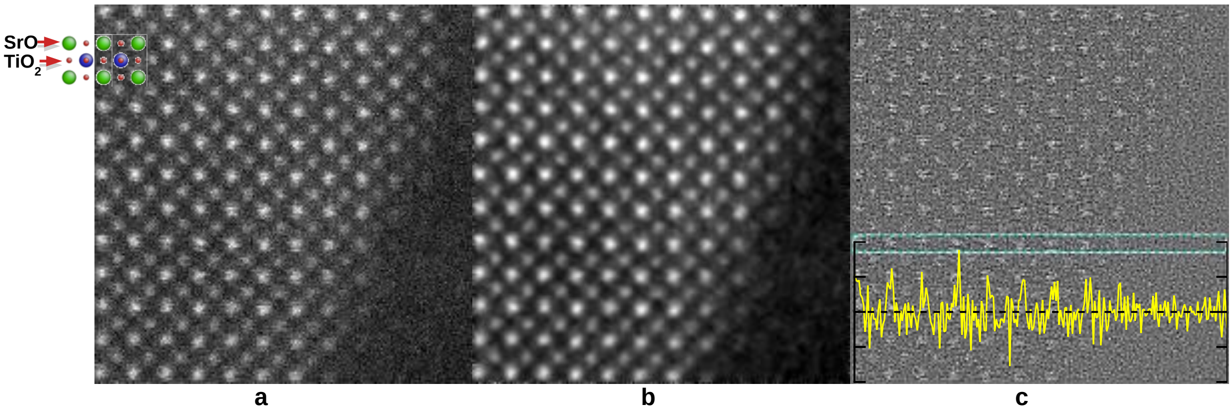

Figure 1. a) HAAD-STEM image of a $SrTiO_3$ film at [001] zone-axis, the dark area at the right side is the amorphous part at the edge of the lamellar, b) low-pass filtered image using a 5×5 Gaussian kernel, c) difference of the recorded and filtered images, inset: line profile of the framed area in horizontal direction.

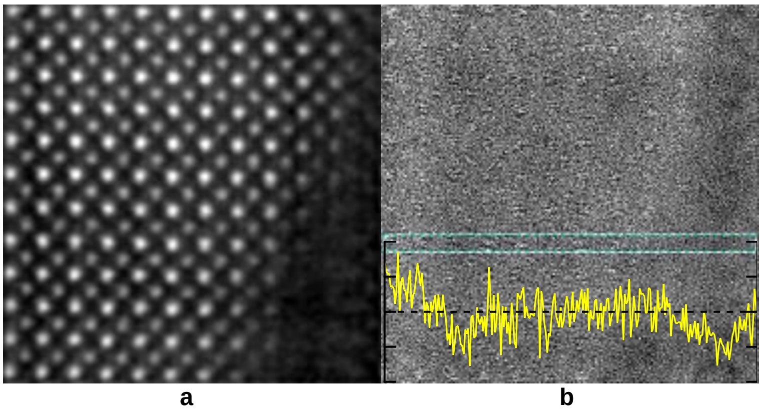

Figure 2. a) Wiener filtered image of Figure 1a), b) difference of the recorded and filtered images, inset: line profile of the framed area in horizontal direction. Background subtraction filter gives quite similar results**.**

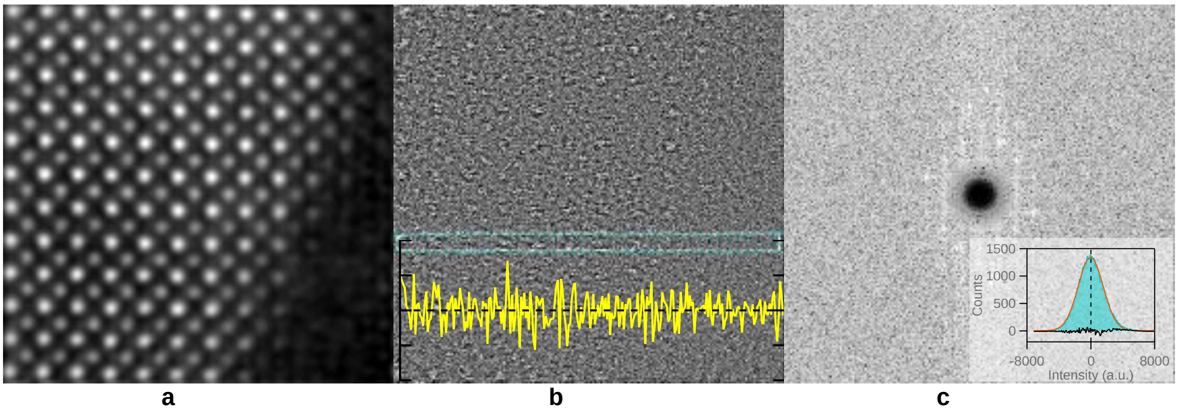

Figure 3. a) Iterative filtered image of Figure 1a), b) difference of the recorded and filtered images, inset: line profile of the framed area in horizontal direction, c) FFT of the difference image, inset: histogram of b).