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Improved SEM Image Resolution Through the Use of Image Restoration Techniques

Eric Lifshin[1], Yudhishthir P. Kande[l] Richard L. Moore[2] and Siwei Lyu[3]
[1.] College of Nanoscale Science and Engineering, University at Albany, State University of New York, Albany, NY, USA
[2.] RLM2 Analytical, Albany, NY, USA
[3.] Department of Computer Science, University at Albany, State University of New York, Albany, NY, USA

Improving spatial resolution has been a major goal of scanning electron microscope (SEM) development since the first commercial instrument was introduced in the mid-1960s. While the early SEMs had resolutions in the 25 to 50 nm range when operated around 20 KV, more recently available microscopes can provide resolutions around 1 nm even below 1 KV. Critical to this development were improved electron optics including more advanced electron guns, lenses and aberration correctors to produce the smallest possible electron probes. High performance comes, however, with increased cost and it is unclear as to just what the next steps will be to obtain still better resolution. The need for a small probe is based on the fact that as magnification is increased the pixel size must be decreased such that the probe size is approximately equal to the pixel size, and thus information is unique to each pixel. If the probe size is larger than the pixel size then oversampling and blurring occurs.

In situations where oversampling occurs computational algorithms based on deconvolution and regularization provide an alternative path to resolution improvement rather than further electron optical advances to decrease probe size. The approach is based on the concept that the observed image can be viewed as a convolution of the true image with the point spread function (PSF) that describes the distribution of electrons in the probe striking the sample. The actual image formation process will be more complicated, however, because the image is a map of a particular emitted signal and should be characterized by an excitation volume PSF not just the probe PSF. Fortunately, for secondary electron (SE) emission, mean free path may be small relative to the probe PSF and in many cases the probe PSF can be used to approximate the emission distribution. The image formation process can then be described by the following equation:

$$I'[x,y] = PSF[i,j] \otimes I[x,y] + k[x,y] \quad (1)$$

where $I'[x,y]$ is the matrix describing the intensity of the measured signal as a function of the position x, y, in the image, $I[x,y]$ the true image, $PSF[I,j]$ is the point spread function, $k[x,y]$ is the noise at each pixel and $\otimes$ is the convolution operator. In the image processing literature [1] it is common practice to re-state equation (1) as:

$$I_c = AI_t + k \quad (2)$$

Here the m by n matrices $I'[x,y]$, $I[x,y]$, and $k[x,y]$ are replaced by $m*n$ by 1 column vectors and $PSF[i,j]$ is replaced by the $m*n$ by $m*n$ block circulant matrix A. In this form equation (2) becomes

$$I_c = AI_t + k \quad (3)$$

Where A^{-1} is the pseudo-inverse of A and the second term $A^{-1}k$ is commonly referred to as the inverse noise term. If this term is large compared to $A^{-1}I_c$ than the problem is considered ill-posed and it may be impossible to get an acceptable solution for I_t. This is a major reason why in the past this method was generally found to be unsuitable for SEM restoration. Today, however, significant improvements in available algorithms as well as the greater availability of much higher computer speeds and large storage capacities suggest that the computational approach to image restoration may be of real value. As an example, the method known as Tikhonov regularization can be used to give a best fit for I_t through the following minimization:

$$\min_{I_t}\{\|I_c - AI_t\|^2 + \alpha^2 \|DI_t\|_2^2\} \quad (4)$$

where α and D are regularization parameters. We have determined that the value of A can be calculated by the use of two carefully registered low noise images, one with pixel resolution I_t and one at the same magnification with the beam significantly larger than the pixel size I_c. This idea is based on a concept proposed by Liddle, et. al. [2]. Once A is determined, it can be used with equation 4 to determine I_t. An example of this procedure is given in figure 1. The estimated resolution improvement in the restored image is at least 3X based on visual comparisons of images taken with different probe sizes. This paper will look at the history, present research and future opportunities for SEM restoration.

References:

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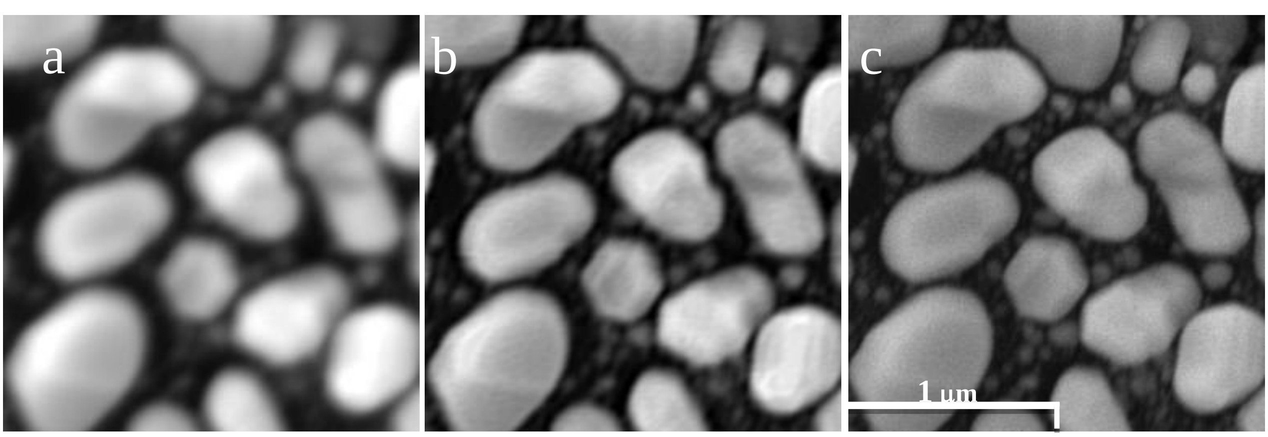

Figure 1. Restored gold standard SEM image obtained with LaB6 source: (a) a blurred image obtained with a beam size of 41nm, (b) the restored image (c) a pixel level resolution image obtained with beam size of 6.2 nm.

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