Image Restoration using Point Spread Function Deconvolution

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An image can be described as the convolution of an imaging system's point spread function (**PSF**) and the scene being imaged. For a scanning electron microscope (**SEM**), the PSF describes the shape and distribution of the electrons in the electron beam which is scanning the sample. The work of Lifshin et al. and the start-up company Nanojehm has broken new ground for resolution and image quality improvement, showing promise for image deconvolution techniques [1]. Image deconvolution relies on having detailed knowledge of the PSF, which Nanojehm's Aura software is able to determine.

In this study, we report our preliminary findings on the restoration capabilities of Aura software, focusing on the effect of different beam energies [2]. By comparing an average particle to a reference of a perfect particle (see Figure 2), the PSF is determined. With this PSF, we can restore the input nanoparticle image (see Figure 1), or any other image recorded with the same microscope settings (see Figure 3), to its "perfect" form through deconvolution of the PSF and the image.

Our images were taken with a TESCAN MIRA3 field emission scanning electron microscope (**FESEM**). We captured backscattered electron (**BSE**) images of a 19nm gold nanoparticle sample at multiple beam energies, ranging from 3kV to 20kV. At higher voltages, Aura identified many particles in a calibration image, which created a good representation of the average particle. This gave us a better approximation of the PSF's shape. Even when microscope settings were almost ideal, Aura was able to produce a PSF which characterized remaining factors hindering resolution. The original image may already have had good resolution, but Aura provided an extra degree of clarity. At lower voltages, particles were more difficult to distinguish in the calibration image, which led to a less descriptive and noisier average particle. Despite that, Aura's restoration for low beam energy images provided sharper edges and improved resolution. Visualizations from this discussion are shown in Figure 1. As expected, the 20kV electrons form a sharper conical shape than that of the lower energy, 3kV electrons. The blurriness in the 3kV observed image is described by the broader and noisier shape of its PSF.

We imaged the particles in a JEOL transmission electron microscope (**TEM**), and used their measured diameters as our reference data. These measurements of 96 particles gave us diameters of 19.0nm ±1.6nm. For SEM at 3kV, the diameters were too difficult to obtain in the observed image, and in the restored image, 99 particles gave 21.8nm ± 3.3nm. For SEM at 20kV, the observed image with 168 particles gave 20.0nm ± 2.4nm, and the restored image with 168 particles gave 18.1nm ± 2.2nm. The restored images provided measurements within range of the TEM reference data.

In terms of image quality, in both the 3kV and 20kV cases, Aura improved image clarity, which provided more distinct boundaries for measurements. The restored boundaries are blurrier at low beam energies, but the particles are easier to distinguish. Some artifacts were introduced during deconvolution, including dark halos around bright objects, but these become less visible with optimizing the choice of smoothing parameters.

References:

[1] Lifshin, E., *et al*, Microsc. Microanal. **20** (2014), p. 386-7.
[2] The authors acknowledge Nanojehm for the Aura beta unit on loan.

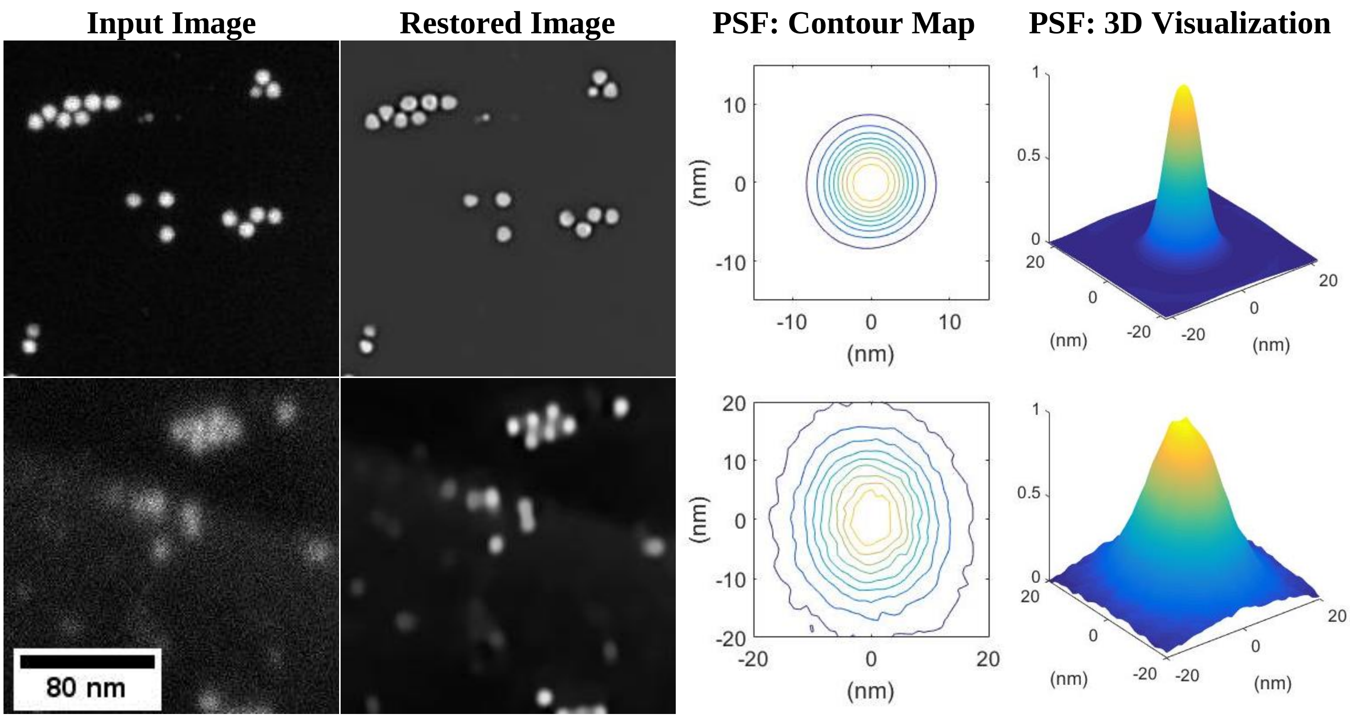

Figure 1. Comparison of Aura Processing at Different Beam Energies. The top row of images corresponds to a 20kV beam, while the bottom row corresponds to a 3kV beam. The input image and restored image columns use the same scale bar as shown in the bottom leftmost image. The PSFs show lowest to highest elevations as dark blue to light yellow, respectively.

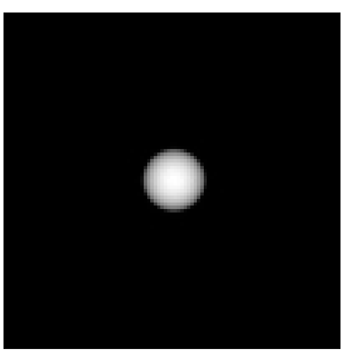

Figure 2. Generated Reference Particle. This 19nm particle was theoretically calculated by Nanojehm.

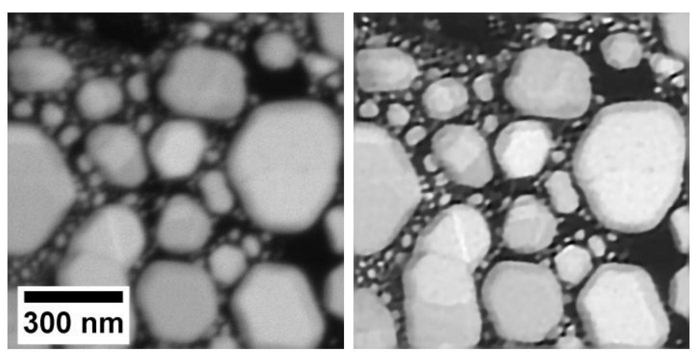

Figure 3. 617 Gold Standard. The image on the left was taken with the same operating conditions as the 3kV nanoparticles shown in Figure 1, bottom leftmost image. The image on the right is the restored image, which used the PSF determined for 3kV in Figure 1, bottom rightmost image. Both images shown here have the same scale.