Fourier-Ring Correlation Resolution for Time-Resolved Measurement in Charged Particle Microscopy

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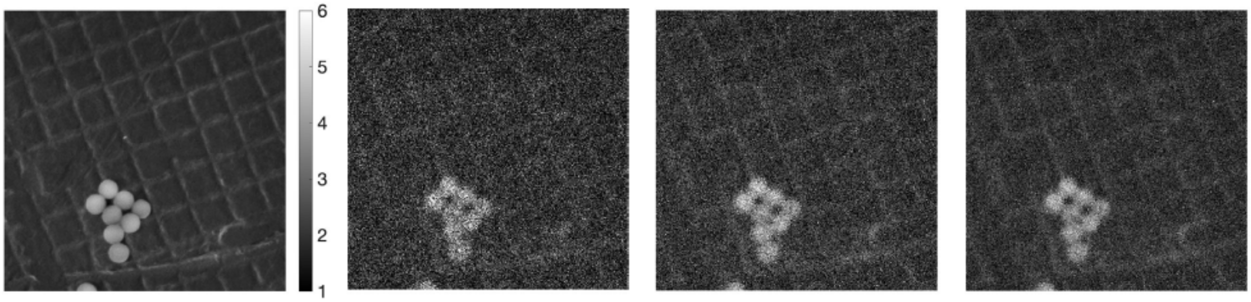
Time-Resolved Measurement (TRM) has been proposed as a method to improve charged particle microscopy. Under the assumption of direct secondary electron (SE) detection, TRM has been shown to reduce the mean-squared error (MSE) of estimation of SE yield η [1,2] and to give robustness to beam current variation [3]. In this work, we translate increased accuracy in η estimation into increased imaging resolution by numerically analyzing the performance of TRM using Fourier Ring Correlation (FRC). FRC is a method commonly used for determining the resolution of electron microscopic (EM) reconstructions [4,5]. It is the normalized correlation between the Fourier transforms of two independent reconstructions of the sample, as a function of spatial frequency. Resolution is defined as the inverse of the highest spatial frequency at which the FRC is above a predefined threshold [6]. This study is valuable to quantify the advantages of TRM in charged particle microscopy.

We evaluated the performance of three estimators for η using Monte Carlo simulation:

1. The conventional η estimator, which divides the number of detected SEs by the average dose λ, the expected number of incident ions within the pixel dwell time
2. The oracle estimator, which divides the number of detected SEs by the number of incident ions. Since the number of incident ions cannot be precisely known, this estimator is not practical but it serves as a theoretical limit on the performance of implementable estimators.
3. The maximum likelihood (ML) estimator, which estimates η as the value that maximizes the joint likelihood of the number of detected SEs and the number of clusters of detected SEs.

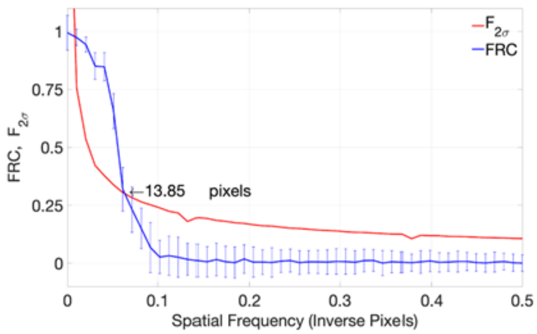
To analyze the performance of these estimators, we used a real SEM image of nanoparticles on a carbon mesh of size 600-by-600 pixels, shown in Figure 1(a), to generate synthetic images for each estimator. We scaled the pixel values of the ground truth image such that η lay between 1 to 6 for all pixels, to reflect the usual range of η in focused-ion beam (FIB) microscopy. We chose a scan step size of 2 ground truth pixels to simulate the coarseness of the beam scan compared to the ground truth. The incident beam was modeled with a Gaussian distribution centered on each scan location, with a standard deviation of 5 pixels and average dose of 10. We chose a beam standard deviation larger than the step size to simulate the image resolution being limited by beam size/interaction volume rather than by scan grid density. The simulated images are shown in Figure 1(b)-(d). The ML estimate shows more of the ground truth details compared to the noisier conventional image. To quantify this difference, we found the MSE between a Gaussian filtered, downsampled version of the ground truth and reconstructed images. The MSE values were 0.68 for conventional, 0.46 for ML and 0.26 for oracle images.

To calculate the FRC resolution of each estimate, we synthesized ten images for each estimator using the scan step and beam profile described above. Using the resulting 45 image pairs for each estimator, we calculated FRC curves shown in Figure 2. The solid blue curve for each estimator is the mean FRC as a function of spatial frequency across all 45 image pairs, and the error bars are the standard deviations of these values. We estimated resolution from these FRC curves by looking at their intersection with the $F_{2\sigma}$ curve [5], which represents a 2σ upper significance level on the FRC being equal to 0. We found the resolution to be 13.85 pixels for conventional, 11.38 pixels for ML, 10.39 pixels for the oracle image. These results show similar advantages of TRM compared to conventional imaging as the analysis of MSE in [2]. Having established the possible resolution gain with FRC through simulations, we are now working to demonstrate improved resolution from experimental data [7].

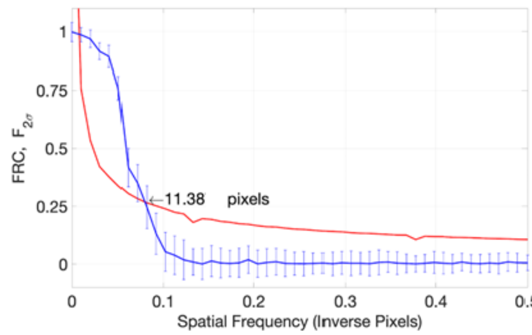


(a) Ground truth (b) Conventional (c) ML (d) Oracle

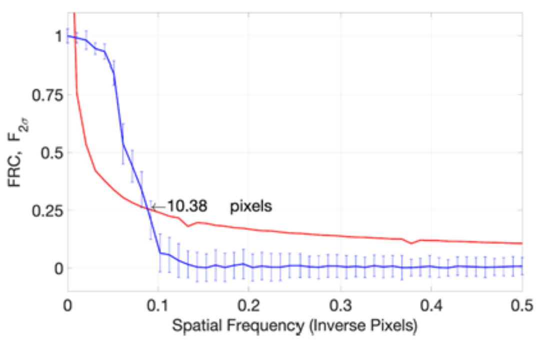
Figure 1: Simulation of time-resolved imaging. Color bar shows range of SE yields for all panels.



(a) Conventional



(b) ML



(c) Oracle

Figure 2: Evaluation of resolution for conventional imaging and TRM. Fourier-ring correlation curves (solid blue) for (a) conventional estimator, (b) ML estimator, and (c) oracle estimator.

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