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Meeting-report

The "Platform 9¾ Problem" in Fluctuation Electron Microscopy

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While the existence of a non-integer train station platform in the Harry Potter series is a source of delightful whimsy, the reality of electron detectors registering non-integer electrons can be a headache for electron microscopists worried about non-Poisson noise. Although there is no such thing as ¾ of an electron, when an electron enters a pixel in a direct electron detector, the signal energy can spread into neighboring pixels [1], giving a fractional signal. This seemingly innocent effect is a serious problem for Fluctuation Electron Microscopy (FEM) when attempting to correct Poisson noise in low-fluence experiments [2]. The Poisson distribution applies strictly to countable discrete events.

FEM works by calculating, from images or diffraction patterns, the normalized variance,

$$V(k) = \frac{\langle I^2(k) \rangle}{\langle I(k) \rangle^2} - 1 - \frac{1}{\langle I(k) \rangle}\ , \tag{1}$$

where I is intensity and k is the scattering vector. Angular brackets mean averaging over the position. To align FEM variance results with theory, shorter exposure times have been suggested [3, 4] leading to noisier data. The last term is the Poisson noise correction. Assuming each discrete electron arrival is independent of the others, the statistics of arrivals at each pixel should follow a Poisson distribution:

$$P(I, \langle I \rangle) = \frac{\langle I \rangle^I}{I!} e^{-\langle I \rangle}\ . \tag{2}$$

The variance equals the mean, $\langle I \rangle$. Thus, the normalized variance (dividing by $\langle I \rangle^2$) of the Poisson noise is $1/\langle I \rangle$. For this correction to work, the intensity, $I(k)$, must be *discrete electron counts*. An intensity value of (say) $I = 9.75$ violates the Poisson requirement that I be a discrete integer value.

Figure 1a shows the noise-corrected normalized variance from a 5-nm thickness amorphous silicon sample (1.1-nm probe, at 80 kV), for acquisition times ranging from 1 ms to 256 ms. Diffraction patterns were collected on an Electron Microscope Pixel Array Detector (EMPAD) [1]. Pixel analog-to-digital (ADU) intensities were scaled to electron units by dividing by the appropriate normalization constant (here, that is 151 at 80 kV,) but were not discretized. The noise correction greatly overshoots, especially for the noisiest 1-ms data, resulting in a large negative normalized variance that increases with k. The plot in Figure 1b shows the same data after correcting the EMPAD signal to nearest-integer values (nint). The increasingly negative normalized variance with increasing k is now gone. However, there remains a residual negative offset, that grows with decreasing acquisition time. The origin of this residual offset is not yet identified, but it may be associated with readout noise.

Figure 2 shows typical pixel intensities recorded on the EMPAD detector for the 1-ms acquisition times. Many single- and double-electron arrival events are visible, but the signal is not always confined to one pixel. An electron arriving near the border with a neighboring pixel may share some of the signal with that neighbor if the electron is scattered across the boundary. If a single electron event is scattered over three pixels, with values 0.3, 0.3, and 0.4, none of the nearest-integer values will be 1, and the electron is lost by the nint procedure.

The overcorrection arises because pixels that should have had integer values, tend to record less. This artificially *increases* the correction $1/\langle I \rangle$, but it increases the $\langle I^2(k) \rangle / \langle I(k) \rangle^2 - 1$ term more. On the EMPAD, the nearest-integer values mitigate much of the problem, but not all of it.

Finding the correct correction protocol for the detector noise remains an ongoing topic of our research.

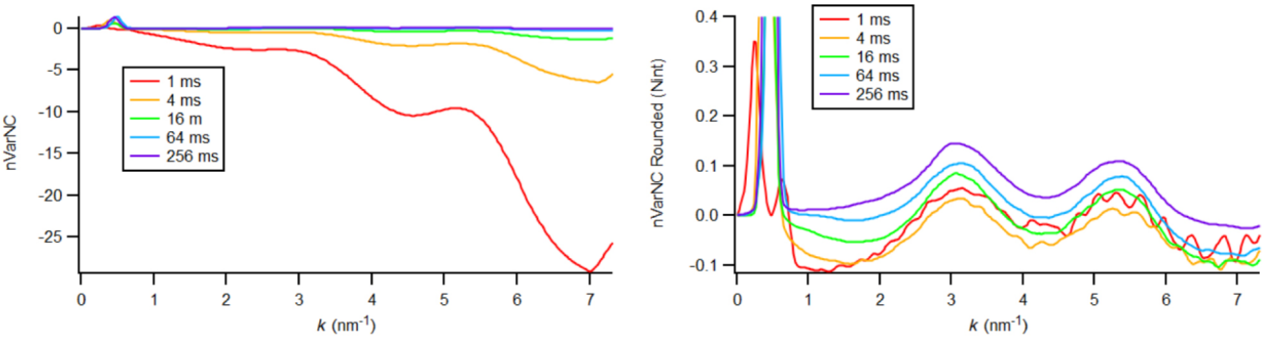

Figure 1: A comparison of different methods for obtaining the normalized variance from noisy diffraction data. Left: the normalized variance using float values, after applying the noise correction (last term in Equation (1)). Right: the normalized variance after nearest-integer rounding (nint operation) of the float intensity values. There remains an approximately constant negative offset.

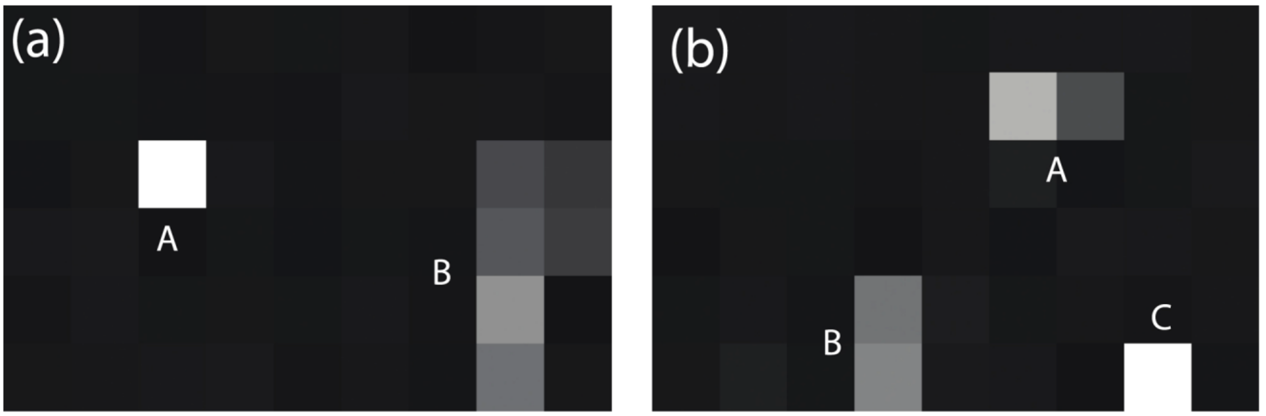

Figure 2: Expanded views of discrete electron arrival events in the EMPAD. (a) The bright pixel A registers a normalized value of 1.01 –a single electron arrival event confined to one pixel. The patch of six pixels, B, has a total intensity of 0.2618+0.1815+0.3204+0.2077+0.5563+0.4223=1.95..., almost certainly two electrons. However, no single pixel has enough signal to record as a single electron using the nint protocol. (b) A shows two pixels with values 0.6683+0.2746=0.942. The brighter pixel will register nint (0.6683) = 1 and nint (0. 2746) = 0, correctly recording one electron overall. B shows two pixels with values 0.4238+0.4989=0.9227. Both will return nint values of 0, losing the electron. C is a single pixel with a value of 1.02 and nint correctly records it as a one-electron event. All three are single electron events yet manifest themselves differently.

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