

## The MTF & DQE of Annular Dark Field STEM: Implications for Low-dose Imaging and Compressed Sensing

Lewys Jones<sup>1,2</sup> and Clive Downing<sup>2</sup>

<sup>1</sup> School of Physics, Trinity College Dublin, Ireland.

<sup>2</sup> Advanced Microscopy Laboratory, Centre for Research on Adaptive Nanostructures and Nanodevices (CRANN), Dublin, Ireland.

Annular dark-field imaging in the scanning transmission electron microscope (ADF-STEM) is a hugely useful incoherent imaging mode, yielding monotonically increasing mass / thickness contrast facilitating quantitative compositional mapping, atom-counting, structure-solving and even unstained biological-imaging [1]. With increasing interest in beam-sensitive materials, many people would like to perform ultra-low-dose imaging or compressed-sensing (CS). Unfortunately, some CS implementations require complex blankers/mask/shutters and may require expensive instrument modification; fast-scanning on the other hand should in principle be available to everyone.

Nearly all installed ADF detectors follow the same basic design comprising; a scintillator, light-pipe, PMT, amplifier and a digitiser outputting in arbitrary uncalibrated units [2]. While the scintillator material itself may have an afterglow of only some tens of nanoseconds, the combined assembly has a decay constant of the order of 1.7-3 $\mu$ s which becomes significant in some cases [3,4]. Scanning with dwell-times faster than this decay introduces issues such as increased background and loss of contrast, streaking in real-space and a diffuse noise band in Fourier-space [5]. In spite of these problems, previous literature has shown that PMT based detectors are in fact sensitive to even single electron signals [3,4,6], unfortunately they are also highly inhomogeneous in their collection efficiency [7].

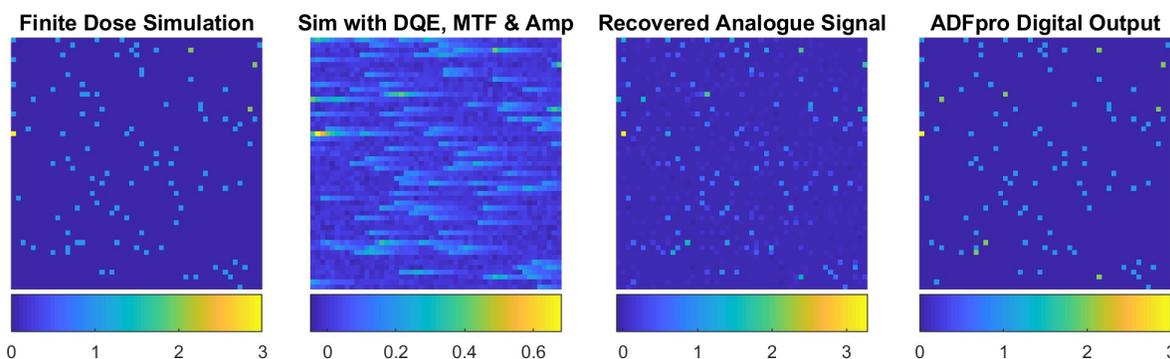
One solution to this is to ask whether we can form an image using these signals using a pulse read-out? Such an image would record the arriving electron as a single impact-event rather than a streak (perfect MTF), the results would be digital rather than analogue, and all electrons would be recorded with equal sensitivity (perfect DQE). The integer nature of the resulting image signal would also directly benefit quantitative contrast (fractional-beam) studies, statistical image analysis, and compressed-sensing / image-inpainting.

In this presentation, we will present a new tool to generate realistic noise realisations from ADF image-simulations. This tool registers *each* electron of a finite dose passing through the sample, to the detector (incorporating afterglow), and onward to amplifiers with realistic thermal and electronic noise (Figure 1). This tool is verified against previous experimental observations of the behaviour of fast-scanned images [5], and is used to explore the modulation transfer function (MTF) of ADF-STEM for various dwell-times (Figure 2).

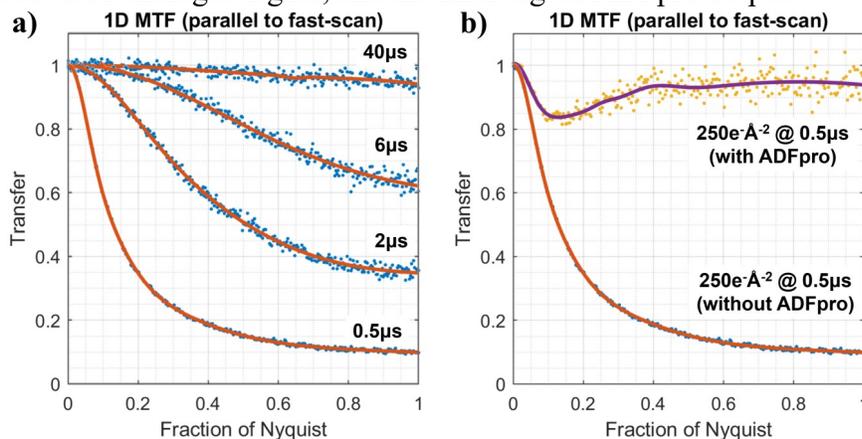
We then propose, and demonstrate using both simulations and experiment (Figure 3), a new method for operating an ADF detector in a pulse read-out mode (which we call ADFpro) using dwell-times of 0.5 $\mu$ s and 0.2 $\mu$ s. The detector's quantum efficiency is evaluated indirectly through the evaluation of image pixel-value histograms but also directly using ADF-detector sensitivity maps. The limitations of this approach will be presented, as well as the implications for ultra-low-dose imaging and for compressed-sensing / image-inpainting using such fully digital data.

References:

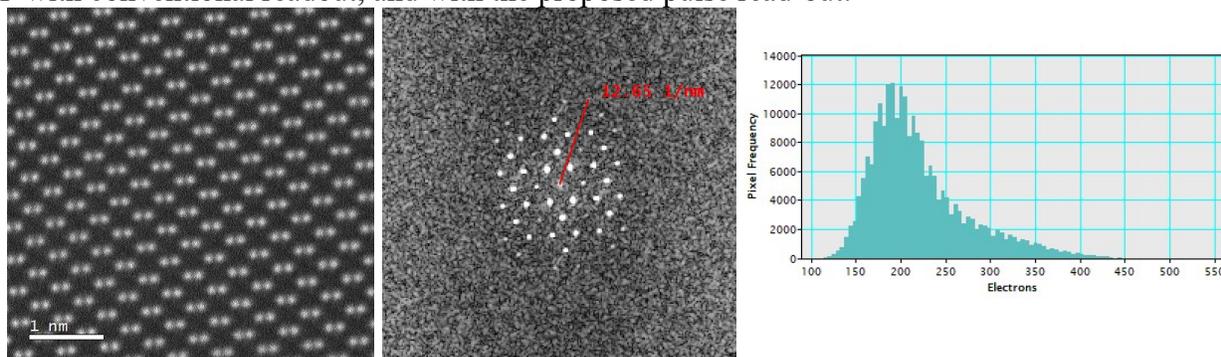
- [1] L. Jones, IOP Conf. Ser. Mater. Sci. Eng. **109** (2016), p. 12008.
- [2] E. J. Kirkland and M. G. Thomas, Ultramicroscopy **62** (1996), p. 79.
- [3] F. F. Krause *et al*, Ultramicroscopy **161** (2016), p. 146.
- [4] X. Sang and J. M. LeBeau, Ultramicroscopy **161** (2016), p. 3.
- [5] J. P. Buban *et al*, J. Electron Microsc. (Tokyo). **59** (2010), p. 103.
- [6] R. Ishikawa, A. R. Lupini, S. D. Findlay, and S. J. Pennycook, Microsc. Microanal. **20** (2014), p. 99.
- [7] K. E. Macarthur, L. B. Jones, and P. D. Nellist, J. Phys. Conf. Ser. **522** (2014).



**Figure 1.** Simulated testing of the ADFpro method; (from left), an enlargement from a finite dose ( $250e^{-}/\text{\AA}^2$ ) ADF simulation of [110] oriented Si, the simulation including effects of DQE, MTF & thermal noise, the recovered analogue signal, and the final digital ADFpro output.



**Figure 2.** (a) Calculated 1D-MTFs for ADF images with various indicated dwell-times. (b) the 0.5µs MTF with conventional readout, and with the proposed pulse read-out.



**Figure 3.** (left) Experimental ADFpro image of [110] Si single-crystal, (sum of 100 ADFpro frames), (centre) diffractogram of same, and (right) histogram of pixel values with calibrated units of electrons.