DQE measurement for TEM detectors: from the key parameter to an ambiguous estimate

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Background incl. aims

Nowadays, the performance of CMOS electron detectors for transmission electron microscopes (TEM) are mainly compared by means of a unique parameter, the detective quantum efficiency (DQE). This parameter is largely promoted by camera providers, and is given as a unique number while it is known to strongly depend on the electron dose. In addition, the DQE calculation method may influence the result, as it will be presented in this study. Consequently, several DQE values can be found for one detector, and one should wonder if a unique DQE is the correct figure of merit for electron detectors.

One aim of this work is to demonstrate that the most commonly used method to calculate the DQE leads to strong uncertainties. To achieve this goal, measurements are conducted on an electron detector and a model is developed. Then, the second aim is to provide recommendations and trustable alternatives for detector comparisons.

Methods

The DQE depends on the spatial frequency w and is generally expressed as a component DQE(0) at the spatial frequency (0) times components depending on the spatial frequency, as in the following:

$$DQE(w)=DQE(0)xMTF(w)^2/NTF(w)^2$$

where MTF is the modulation transfer function and NTF the noise transfer function. MTF and NTF are well established so this work focuses on the DQE(0) calculation.

DQE(0) can be estimated by means of the full calculation of the various noise sources, including the shot noise, the gain variance "σg", the Fano noise "F", the dark current "DC" and the readout noise "NRO":

$$DQE(0)=g^2/(g^2\ (1+F)+\sigma g^2+(t\cdot DC+NRO^2)/n\_i\ )$$

where "n_i" is the number of incident electrons, "g" is the detector gain, "t" the integration time

The gain is extracted thanks to a comparison between the integrated electrons and the beam current measured with a Faraday cap, and the gain variation is estimated from the spatial variance of a flat field picture. While these measurements are not too complex, it is much more difficult to measure the Fano noise. It can be estimated with the standard deviation of simulated deposited energy distributions. Then, the readout noise and the

dark current are measured from several acquisitions performed in dark condition.
Since several years, a simplified method has been preferred for the DQE(0) estimation, and relies on the direct measurement of the detector output noise by means of the spatial variance of a flat field image. However, in this case, the large electron hole distribution generated by the beam is spread between pixels and the spatial variance is underestimated. To solve this issue, McMullan proposed in 2009 to extract the spatial variance on binned pixels, for which a saturation is achieved if the binning number is large enough. This method is referred as the McMullan method subsequently.

Results

A Gatan-Rio-16 camera mounted on a JEOL-2100 FEG microscope is used for this study. This detector being an indirect one, the Fano noise is due to the scintillator and is estimated at 0,25. The electron dose is chosen in order to achieve the half full well capacity of the detector. For n_i=107, DQE(0)_FullCalculation=0.79 and DQE(0)_McMullan=0.62.

These two results are quite different and it is supposed that the McMullan method over-estimates the output noise and therefore gives a lower DQE(0). With the intention to demonstrate it, a simple model is built, based on the generation of a shot noise and a gain variation leading to a similar noise distribution acquired with the Gatan-Rio-16 camera. For this purpose, the standard deviation of the noise is adapted is order to get an extracted variance identical to the measured one. In addition, a Gaussian blur is added with the intention to simulate the electron spread over the pixels and is parametrized in a way to get the same saturation of the variance according the binning number. The resulting noise distribution does not match the measured one which is much more extended and show pixels with much higher noises.

Actually, the McMullan method requires to subtract two flat field pictures in order to remove dead and saturated pixels, and the fixed pattern noise which avoid a correct variance saturation. However, it is necessary to consider other defective pixels, such as the hot pixels with a higher gain. These defective pixels are not removed by the subtraction of two flat field images and may distort the variance extraction. To demonstrate it, the previous model is modified and one population of hot pixels is introduced. The hot pixels ratio and gain are adjusted in order to obtain a noise distribution similar to the one measured with the Gatan-Rio-16. A hot pixel density of 6×10^(-4) with a high gain of 30 lead to a noise distribution comparable with the experiment, and the spatial variance extracted with hot pixels is 50% higher compared to the one extracted without hot pixels (see the figure 1).
Therefore, it is demonstrated that the commonly used McMullan method leads to an underestimation of the DQE(0) because of hot pixels. Other

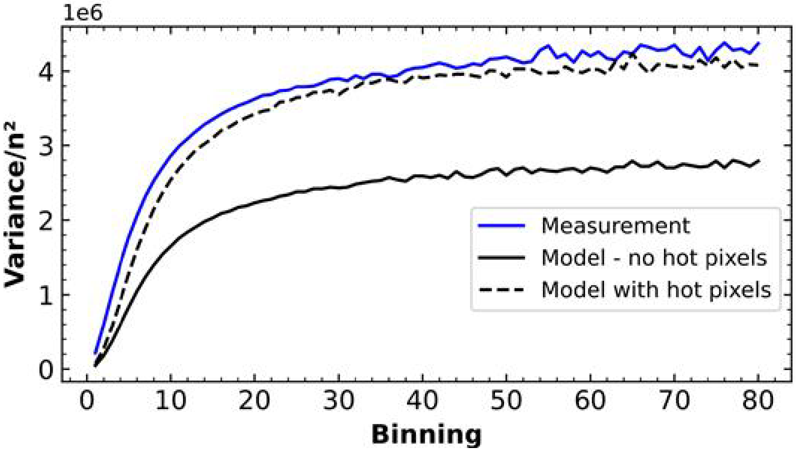
limitations are found and discussed, based on the fact that the noise is distributed on a statistical population of hot pixel which may give different results at every DQE measurement.

Consequently, the DQE(0) should not be used as a unique number for the detector comparison because it depends on the electron dose, on the experimental condition and on the used method. In order to fairly compare detectors, it is therefore recommended to use other parameters clearly defined and measurable: the gain for an information on the sensibility, the MTF for the spatial resolution and the dark current for the radiation hardness.

Conclusion

The DQE(0) is measured on a commercial camera with two methods and it comes that the McMullan method, largely preferred by the camera providers, leads to large uncertainties. By means of a model, it is demonstrated that detector hot pixels induce an over-estimation of the output noise leading to the DQE under-estimation with the McMullan method.
The DQE suffering from large uncertainties it is recommend to use the gain, the MTF and the dark current for fair comparisons between detectors.

Graphic:



Keywords:

DQE; simulation; electron detector, TEM

Reference:

- G. McMullan, et Al., “Detective quantum efficiency of electron area detectors in electron microscopy,” Ultramicroscopy, vol. 109, no. 9, pp. 1126–1143, 2009.

- O. Marcelot, et Al., “Limitations and Drawbacks of DQE Estimation Methods Applied to Electron Detectors”, accepted for publication in Oxford Microscopy, 2024.