Characterization of 16 MegaPixel CMOS Detector for TEM

by Evaluating Single Events of Primary Electrons

WITHIN THE LAST TWO DECADES, CCD cameras (Charge Coupled Device) turned out to be an important tool for image recording in TEM. In 2008, 2009 and 2011 TVIPS introduced 64, 16 and 4 MegaPixel cameras (TemCam-F816, TemCam-F416 and TemCam-F216) based on CMOS technology (Complementary Metal Oxide Semiconductor). These cameras have squared pixels with a large size of 15.6 μm that is mandatory for fiber optic coupled cameras. The sensor area is divided into 1024×1024 pixels areas, which can be addressed individually.

Two different image acquisition modes are available: Rolling Shutter (RS) and Correlated Double Sampling (CDS) modes. For low noise and high sensitivity single image acquisition, the CDS mode leads to an extremely high sensitivity allowing a clear detection of single primary electrons. For fast readout the sensor can be operated in the RS mode where every pixels line is first readout and then reset. Frame rates of up to 8.5 fps at 1k×1k or 4×1k and 4.5 fps at 2k×2k can be achieved using RS mode. The camera delivers 1 fps at full resolution and 2 fps at 2k×2k, using the low noise CDS mode. This is about five times faster than up-to-date 4k multi-port CCD cameras.

We present here a procedure which allows determining sensitivity and resolution of highly sensitive cameras. This method is based on calculation of the Point Spread Function (PSF) using Single Electron Events (SEE).

1. General remarks

In order to get the highest sensitivity, all TVIPS cameras are fiber optically coupled to a scintillator that allows to generate a large number of photons for each impinging electron. The general scheme of cameras is shown on fig. 1.

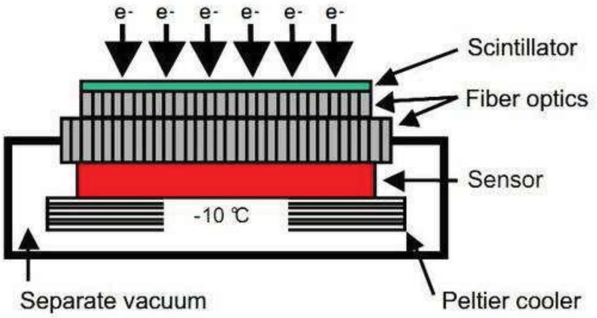

Fig. 1: Typical setup for high sensitivity cameras.

The main characteristics of TEM cameras[1,2] can be described as follows:

- Sensor: Number of pixels, pixel size, optical coupling
- Dynamic range: maximum signal/read-out noise
- Linearity: proportional signal response
- Sensitivity: counts per primary electron
- Resolution: Modulation Transfer Function (MTF)
- Signal-to-Noise Ratio (SNR) for single electrons: Sensitivity/readout noise
- Noise characterization: Detection Quantum Efficiency (DQE) combines resolution and sensitivity

2. Detection of Single Electron Events (SEE)

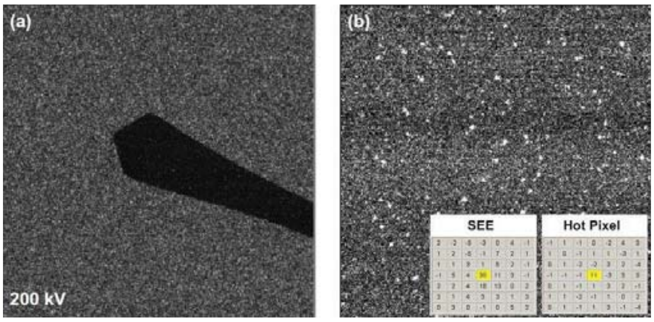

Fig. 2: (a) 1024×1024 pixels sub area of a 4k×4k image acquired with F416 at medium dose with the beamstop in the center position; (b) 256×256 pixels sub area of a 4k×4k image acquired at a very low electron dose. Separated single electron events are clearly visible which have been used for calculation of the PSF. Insets show gray value distributions of a typical separate SEE and a typical hot pixel which is discarded by the software (kernel size: 7×7 pixels).

The following are the steps[3] used for determining every single event:

- At very low intensities (1 e^-/300 pixels), single electron events are clearly visible and well separated. See fig. 2(b).
- All separated SEE can automatically be localized, as shown on fig. 3, using a specially developed software taking the following paramenters into account:
  - Upper threshold: 50 counts
  - Lower threshold: 2 counts, corresponding to camera readout noise

  - A mask with a kernel size of 7×7 pixels is used to find the local maxima (Pixel$_{max}$).
  - Hot pixels and X-ray events can be localized and discarded by the software if the average value of the next neighbour pixels of Pixel$_{max}$ is lower than 3 counts, as shown on fig. 2(b).

- All single events are expanded in a 16×larger image by a bi-cubic spline interpolation and the centers of gravity (COG) are calculated. The events are averaged using the individual COG, as shown on fig. 4. This averaged SEE is the Point Spread Function (PSF).
- The modulus of the PSF Fourier transform gives the MTF, shown on fig. 5. Due to the interpolation, this MTF is already aliasing corrected.

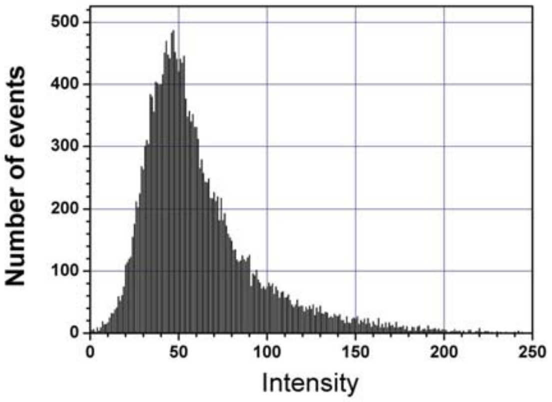

Fig. 3: Histogram of integrated signals generated by over 12000 detected SEE. The center of gravity of the histogram (54 counts) is a direct measure of the camera sensitivity. The standard method to calculate sensitivity gives 35 counts, using the current density of the viewing screen.

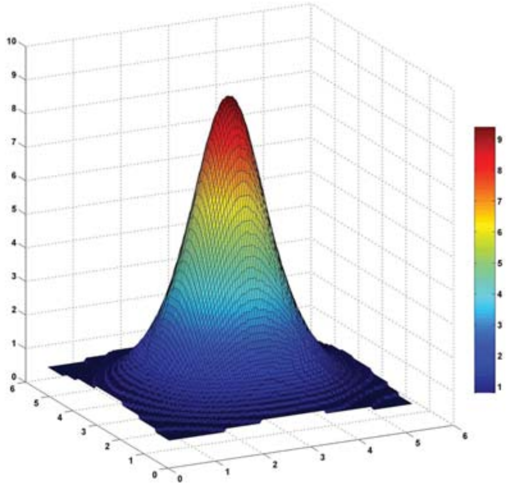

Fig. 4: Averaged 3D plot of the point spread function using more than 12000 single electron events, 16× over-sampled by bi-cubic spline interpolation before.

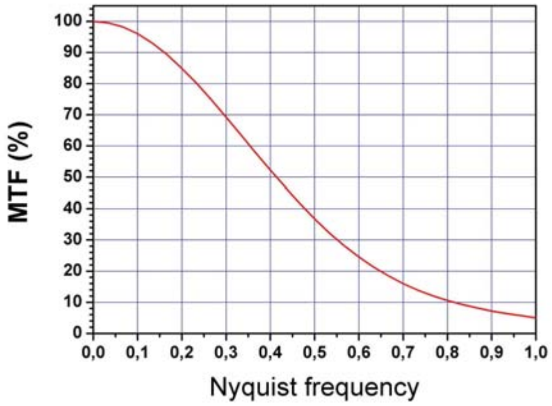

Fig. 5: Modulation transfer function (aliasing corrected).

3. Determination of the MTF from the edge spread function

Here is the general procedure used for determining the MTF using a physical edge placed above the scintillator. While used in many places and accepted as a standard method, it is demanding in terms of skill and time. On the other hand, it still remains the only method available for cameras that cannot detect single electron events.

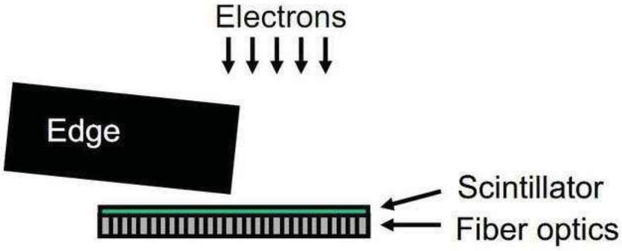

Fig. 6: Schematics of the edge for determining the MTF.

- A polished edge is placed about 2 mm above the scintillator. It is tilted about 10° in order to minimize the influence of scattered electrons from the edge.
- For aliasing correction, the recorded image has been expanded in a 16× larger image with a bi-cubic spline interpolation.
- 100 line profiles have been averaged perpendicularly to the recorded edge. The result is the Edge Spread Function (ESF) shown on fig. 7A.
- The derivative of the ESF is the Line Spread Function (LSF) shown on fig. 7B.
- The modulus of the Fourier transform is the MTF, on fig. 7C.

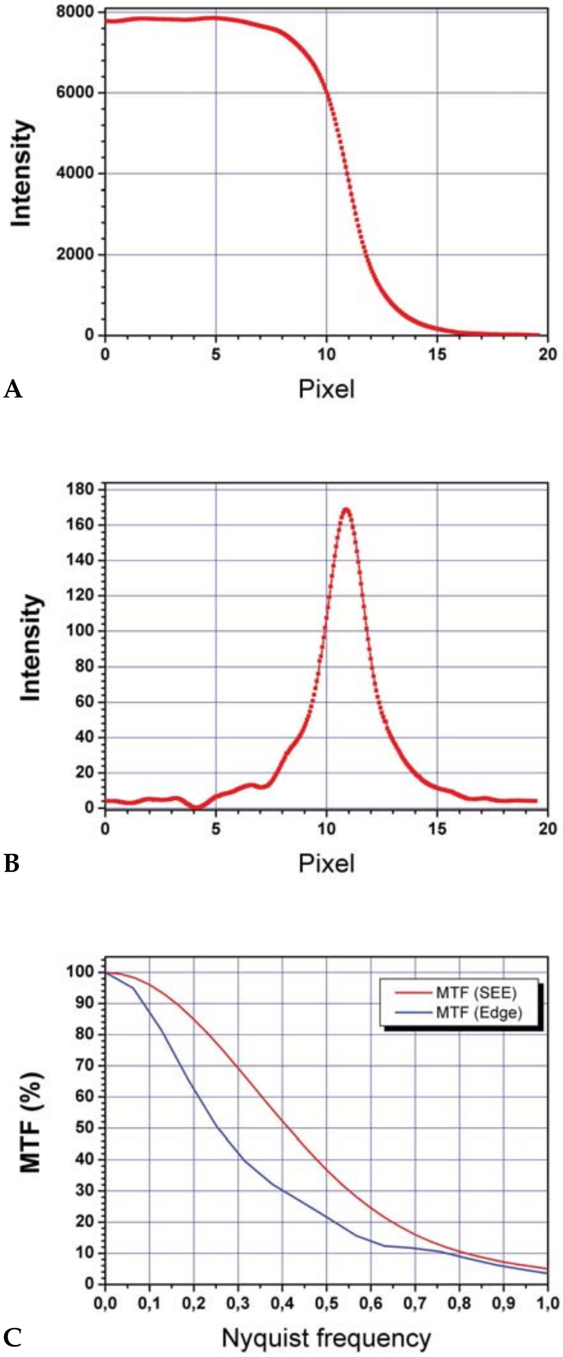

Fig. 7: A: Averaged Edge Spread Function over 100 line profiles. B: Line Spread Function. C: comparison of Modulation Transfer Function determined by the edge and SEE method.

4. Determination of the Noise Transfer Function (NTF)

The basic idea[4] for determining the NTF can be expressed as follows:

- The signal transfer generally deteriorates more quickly than the noise transfer with increasing spatial frequency.
- This is due to additional noise introduced by stochastic electron scattering shown on fig. 8.
- Signal transfer determined by area illuminated by many electrons impinging on the same single incident point.
- Simple calculation: Rotational line scan of a power spectrum from an evenly illuminated flatfield corrected image.

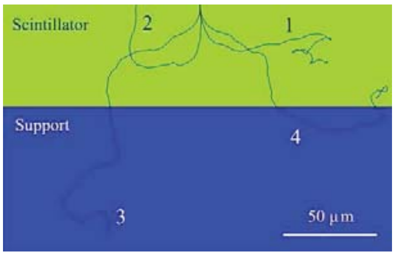

Fig. 8: 4 simulated trajectories of 200 keV electrons in a glass-backed 50 μm YAG scintillator[4].

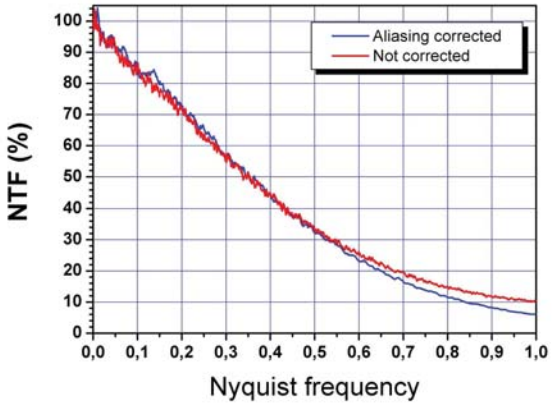

Fig. 9: NTF at 200 keV, aliasing correction was performed by bi-cubic spline interpolation.

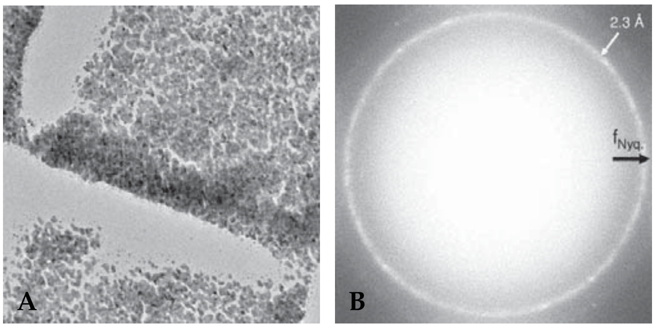

Fig. 10: A: 4k×4k image of a cross grating replica. B : Corresponding power spectrum, showing clearly the 0.23 nm gold lines close to $f_{Nyq.}$ at a dose of 290 e$^-$/Å^2 .

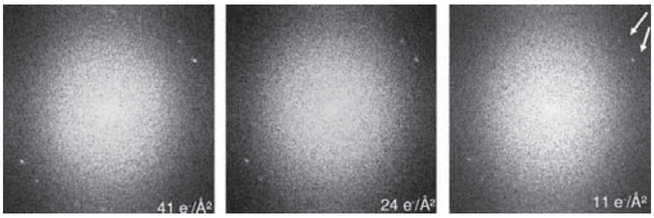

Fig. 11: Power spectra of sub areas at different doses clearly showing some 0.23 nm gold lines close to Nyquist frequency even at extremely low dose conditions.

5. Gold reflections at different doses

As an alternative method to the DQE we have used a direct way to demonstrate the spatial resolution under different low dose conditions, as illustrated on fig. 10 and 11.

- Cross grating replica is an ideal specimen for comparison of resolution against dose.
- The magnification was chosen such that the 0.23 nm gold lines appear close to Nyquist frequency $f_{\mathrm{Nyq.}}$.
- All images were taken at our JEM-2010 (LaB$_6$, total mag. 130,000×, 200 kV).

6. Summary

- A new method for determination of resolution and sensitivity has been presented and compared with standard methods.
- No additional devices (e.g. edge above the scintillator, Faraday cup) are needed, because the signal of single electron events (SEE) are used directly for determination directly.
- In this example of a very fast (1 s readout of a full 4k image) and extremely sensitive TemCam-F416, the dose series demonstrates a high resolution at Nyquist frequency even under extremely low dose conditions. Therefore this camera is an ideal recording device for cryo microscopy in life as well as material science: diffraction, energy filter imaging, spectroscopy, etc.

7. References

1: I. Daberkow, K.-H. Herrmann, L. Liu, W.D. Rau: *Performance of electron image converters with YAG single-crystal and CCD sensor*, UM 38 (1991) 215-223.

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3: I. Daberkow, M. Stumpf and H.R. Tietz: *Detection of Single Primary Electrons allowing Easy and Accurate Characterizaton of CCD Cameras for TEM*, ICEM 16 (2006) I, 189R.

4: R. Meyer, A. I. Kirkland: *The effects of electron and photon scattering on signal and noise transfer properties of scintillators in CCD cameras used for electron detection*, UM 75 (1998) 23-33.

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