Fully Automated Measurement of the Modulation Transfer Function of Charge-Coupled Devices above the Nyquist Frequency

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Abstract: The charge-coupled devices used in electron microscopy are coated with a scintillating crystal that gives rise to a severe modulation transfer function (MTF). Exact knowledge of the MTF is imperative for a good correspondence between image simulation and experiment. We present a practical method to measure the MTF above the Nyquist frequency from the beam blocker’s shadow image. The image processing has been fully automated and the program is made public. The method is successfully tested on three cameras with various beam blocker shapes.

Key words: modulation transfer function, point spread function, charge-coupled device, scintillator crystal, beam blocker, transmission electron microscopy, Nyquist frequency, Fourier analysis, aliasing

INTRODUCTION

In electron microscopy, the electrons impinging on the charge-coupled device (CCD) are converted to photons by a scintillating crystal. This results in the ideal image intensity being convolved with a rather broad point spread function (PSF), reducing the contrast. The equivalent in Fourier space is a narrow modulation transfer function (MTF), attenuating higher frequencies. Precise knowledge of the MTF is imperative for a good correspondence between image simulations and experiments (Boothroyd, 1998; Thust, 2009).

The most common technique to estimate the MTF is the knife edge method (Daberkow et al., 1991; de Ruijter, 1995; Weickenmeier et al., 1995; Meyer & Kirkland, 2000). This requires a straight-edged object, placed directly over the CCD, to be illuminated by a parallel electron beam, thus casting its shadow on the CCD. In this way Meyer and Kirkland could retrieve the MTF up to 1.6 times the Nyquist frequency \( n_N \) (Meyer & Kirkland, 2000). However, such a knife edge usually is not in place and needs to be put in temporarily, see for example Meyer et al. (2000). This is not a routine operation because the knife has to be custom made and the vacuum needs to be broken to insert and remove it. Therefore, this technique is experimentally difficult.

Since in electron microscopes a beam blocker is always available, it is experimentally more convenient to measure the MTF from its shadow image. The required data processing is more difficult because these beam blockers have an arbitrary and complex shape. Nevertheless, this has been pioneered in Thust (2009), where the MTF was retrieved up to \( 1.5n_N \). So far this approach involves manual deselection of regions in the diffractogram affected by aliasing, periodic continuation artifacts, and excessive noise. However, this nontrivial task requires a degree of experience surpassing that of a typical operator.

Here we present a method that retrieves the MTF for arbitrarily shaped beam blockers, without manual interference and above \( n_N \). The developed program is available from the corresponding author upon request. In the Image Formation section, the image formation of the shadow image is explained in great detail. In the Materials and Methods section, the image formation is translated to an algorithm for estimating the MTF. In the Results section, the results for three different CCDs with different beam blocker shapes are reported.

Image Formation

Derivations of the image formation in CCDs have appeared previously in de Ruijter (1995) and Meyer and Kirkland (2000), among others. Since further sections of this article strongly rely on a concise notation, a derivation is presented here as well.

The beam blocker is illuminated with a parallel electron beam. The Fresnel fringes caused by diffraction at the edges can be ignored because they are much smaller than the pixel size. A Monte Carlo simulation showed that no electrons penetrate the beam blocker’s edges. Both findings were reported in Thust (2009) and show that the beam blocker provides ideal, infinitely sharp edges. After the electrons have passed the beam blocker and before they hit the scintillator, they form the ideal binary image \( f \).

The transfer through the scintillating crystal convolves \( f \) with a rotationally symmetric PSF \( (psf_\text{ps}) \). The resulting image is subsequently recorded by the CCD. This process of pixelation is mathematically described as a convolution with the shape of an individual pixel \( (psf_\text{px}) \) followed by a multiplication with a comb function \( c \), which consists of an array of Dirac delta functions located on the pixel centers. The recorded image \( h \) can therefore be written as
where \( h \) indicates a convolution product, and \( \cdot \) is a scalar product.

Invoking the convolution theorem (Kak & Slaney, 1988) allows equation (1) to be written in Fourier space as

\[
H = (F \cdot MTF_{sc} \cdot MTF_{px}) \otimes C,
\]

where \( H, F, MTF_{sc}, MTF_{px}, \) and \( C \) are the Fourier transforms of \( h, f, psf_{sc}, psf_{px}, \) and \( c, \) respectively. The function to be measured is \( MTF_{sc}, \) the MTF of the scintillator.

The point spread function \( psf_{px} \) is the two-dimensional (2D) block function:

\[
psf_{px}(x, y) = 1, \quad \text{where } |x| < \frac{\Delta}{2} \text{ and } |y| < \frac{\Delta}{2}
\]

\[
0, \quad \text{elsewhere;}
\]

here \( x \) and \( y \) are the real space coordinates and \( \Delta \) is the pixel width. Correspondingly, the function \( MTF_{px} \) is given as (Kak & Slaney, 1988),

\[
MTF_{px}(u, v) = \frac{\sin(\pi u)}{\pi u} \frac{\sin(\pi v)}{\pi v},
\]

where \( u \) and \( v \) are the reciprocal coordinates in units of the sampling frequency \( (\nu_i = \Delta^{-1}). \)

According to Bracewell (1999), \( C \) is a comb function as well, with its Dirac delta functions spaced \( \nu_i \) apart:

\[
C(u, v) = \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} \delta(u - n\nu_s, v - m\nu_s).
\]

Convolution of the spectrum with the function \( C \) causes the so-called aliasing artifact, where frequencies higher than the Nyquist frequency \( (\nu_N = 0.5\nu_s) \) cause additional intensities in the spectrum at frequencies below \( \nu_N. \)

The different stages of the image formation process are illustrated in Figure 1. After the electrons have passed the beam blocker, they form an ideal image: the beam blocker’s edges are sufficiently sharp for the image to be not bandwidth limited. The subsequent passage through the scintillator crystal applies a rotationally symmetric and unknown MTF to the image’s spectrum, thereby attenuating the frequencies up to infinity with \( MTF_{sc}. \) The pixelation further attenuates the spectrum with \( MTF_{px} \) and causes aliasing: the frequencies from above \( \nu_N \) enter the region below \( \nu_N. \) It is important to note that the aliasing takes place only after the spectrum has been attenuated.

**Materials and Methods**

The quantity to estimate is the MTF of the scintillator. This is accomplished by rewriting equation (2) as a matrix transformation such that \( MTF_{sc} \) can be estimated by minimizing the sum of squared differences. The matrix transformation includes the aliasing too, thus allowing the MTF to be estimated for frequencies higher than the Nyquist frequency.

\[
H = (F \cdot MTF_{sc} \cdot MTF_{px}) \otimes C,
\]

where \( H, F, MTF_{sc}, MTF_{px}, \) and \( C \) are the Fourier transforms of \( h, f, psf_{sc}, psf_{px}, \) and \( c, \) respectively. The function to be measured is \( MTF_{sc}, \) the MTF of the scintillator.

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**Image of the Beam Blocker**

The binary image \( f \) of the beam blocker, and its spectrum \( F, \) must be estimated from the measured image \( h, \) since knowledge about the detailed shape of the beam blocker is not available. Furthermore, since the MTF will be estimated up to \( \nu_s, \) \( f \) needs to be sampled with half the sampling distance of the measurements. The \( N \times N \) image \( h \) is upsampled four times in either direction using bicubic interpolation, and subsequently a threshold of half the vacuum intensity is applied; the resulting \( 4N \times 4N \) binary image is called \( g. \) This image is then Fourier transformed to yield the spectrum \( G. \)

The spectrum \( G \) as it is outputted by the numerical Fourier transform in MATLAB has its origin in the upper left corner and coordinates running from \( 0 \) to \( 4\nu_s, \) (see Fig. 2a). The more familiar representation in Figure 2b places the origin in the middle by rearranging the four quadrants (Kirkland, 1998); the frequencies run from \(-2\nu_s \) to \( 2\nu_s. \)

In the next step the frequencies outside the range \([-1\nu_s, 1\nu_s] \times [-1\nu_s, 1\nu_s] \) are discarded; in other words, the hatched areas in Figure 2 are removed. The resulting \( 2N \times 2N \) spectrum is called \( F. \) Since the discarded frequencies cannot cause any aliasing, the severity of the aliasing problem is greatly reduced.

**Transformation Matrix**

Knowledge of the spectrum \( F \) in \([-1\nu_s, 1\nu_s] \times [-1\nu_s, 1\nu_s] \) allows one to model the beam blocker spectrum in \([-0.5\nu_s, 0.5\nu_s] \times [-0.5\nu_s, 0.5\nu_s] \) by multiplying \( F \) with \( MTF_{px} \) and \( MTF_{sc} \) followed by applying the aliasing. The function \( MTF_{px} \) can then be estimated by fitting the model numerically to the measurements \( H. \)
• The attenuation caused by the pixelation is accounted for by multiplying with the $4N^2 \times 4N^2$ diagonal matrix $P$, whose diagonal elements are given by equation (5).
• The $4N^2 \times 4N^2$ diagonal matrix $F_{\text{diag}}$ has the elements of $F$ on its diagonal.
• The matrix $A$ carries out the aliasing by overlaying the four quadrants of the spectrum (when in the representation of Fig. 2a), thus reducing its dimensions to $N \times N$. Then the spectrum is converted to a vector of length $N^2$. The dimensions of $A$ are $N^2 \times 4N^2$.

Equation (7) can be solved by minimizing the sum $S$ of squared differences between the left- and the right-hand side:

$$S = \sum_{i=1}^{N^2} ((T \text{MTF}_{sc})_i - H_i)^2. \tag{9}$$

This is possible, for example, with the function “lsqmin” in MATLAB. Since $T$ and $H$ are complex, the result $\text{MTF}_{sc}$ becomes complex too, thereby doubling the number of unknowns to $2K$. However, since $\text{psf}_{sc}$ is real and $\text{MTF}_{sc}$ is rotationally symmetric by construction, the imaginary part of $\text{MTF}_{sc}$ is zero (Pinsky, 2002). Indeed, preliminary experimental results yielded imaginary components well below $10^{-15}$ for all frequencies. To keep the number of unknowns down to $K$, the optimization is performed separately on the real and the imaginary parts of $T$ and $H$, and the two results are averaged.

The values of the spectrum $H$ typically drop exponentially with the frequency. The terms of $S$ corresponding to the higher frequencies therefore exert relatively low influence on the value of $S$, despite the fact that they are more numerous. The MTF will therefore be estimated wrongly for higher frequencies. This is mended by multiplying the terms of $S$ with weights that approximately undo the exponential behavior and that are inversely proportional to the absolute value of the frequency. In this way, every frequency range exerts approximately the same influence on $S$.

### Periodic Boundaries

The numerical Fourier transform uses periodic boundaries in real space. This amplifies the contribution of frequencies around $\nu_N$, stemming from the artificial sharp edges between the opposing boundaries. One might expect that this poses no problem because this artifact occurs at both sides in equation (2), i.e., in $F$ and in $H$. However, the relative contribution of the higher frequencies is larger in $H$ because the lower frequencies have been damped by the MTF before the artifact occurs, whereas in $F$ no damping has taken place. This results in an overestimated MTF around $\nu_N$.

To deemphasize the effects of the periodic boundary conditions, $h$ and $f$ are multiplied with a window function $w$ that is zero at the edges of the image. This is equivalent to a convolution in Fourier space:

$$H \otimes W = (F \cdot \text{MTF}_{sc} \cdot \text{MTF}_{px}) \otimes C \otimes W, \tag{10}$$

$$= ((F \otimes W) \cdot \text{MTF}_{sc} \cdot \text{MTF}_{px}) \otimes C. \tag{11}$$
where $W$ is the Fourier transform of $w$. Equation (11) becomes exact if $W$ is an even function and if $F_{\text{MTF}}$. $MTF_{px}$ is linear over the width of $W$; in other words, the approximation is better for narrow $W$. The sinc window,

$$\sin \left( \frac{\pi x}{\Delta (N-1)} \right) \sin \left( \frac{\pi y}{\Delta (N-1)} \right),$$

with $0 \leq x \leq \Delta (N-1)$

and $0 \leq y \leq \Delta (N-1),$

(12)

fulfills both requirements. In practice, $w$ is not applied to $f$, but to the fourfold upsampled and thresholded image $g$.

Better behavior at low frequencies is observed if the image average is subtracted before applying $w$ and re-added afterward, such that the edges taper off to the average image value instead of zero.

### Simulations

The reliability of the method is assessed with the aid of computer simulations. The mathematics of the image formation as laid out in the previous sections stems from the physics of the detector system, such as, for example the electron scattering in the scintillator. In this section, the mathematics involved is taken as a given, since it has been confirmed elsewhere (for example in Daberko et al., 1991 and Meyer & Kirkland, 1998) with the aid of Monte Carlo simulations. The goal of the simulations in this section is to test the MTF estimation method, given that the mathematical assumptions are valid. The head of a beam blocker is modeled as a disk supporting half an ellipse. First, a $5N \times 5N$ image is made, the vacuum intensity is set to $I/16$, and Poisson noise is applied. The MTF is modeled as an exponentially decaying function

$$MTF_{sc}(u,v) = \exp \left( -\frac{\sqrt{u^2 + v^2}}{\alpha} \right).$$

(13)

For $\alpha = 0.20$ the MTF has an intensity of 0.082 at $\nu_N$, which is a realistic value. After the MTF has been applied, an edge of width $N/2$ is removed from around the image to dispose of artifacts induced by the periodic boundary conditions. Finally, the pixelation process is simulated by a $4 \times 4$ binning. This results in an $N \times N$ image with an average of $I$ electrons per pixel in the vacuum (see Fig. 3).

The result for $I = 100$ and $N = 512$ is given in Figure 4a. The MTF is estimated faithfully, also for frequencies above $0.5 \nu_N$. The noise in the image translates as noise on the MTF, especially for frequencies larger than $0.5 \nu_N$. In Figure 4b no noise has been applied and the estimate now exhibits digital noise only. A slight systematic underestimation is observed due to aliasing from frequencies with absolute values larger than $3 \nu_N$, that are still present in the spectrum $F$. These aliased frequencies are absent from $H$ because the exponentially decaying MTF has suppressed them almost completely.

The MTF is estimated up to $0.99 \nu_N$ instead of $1 \nu_N$ to avoid numerical difficulties. The number of channels $K$ in which the MTF is estimated can be set by the user; in this article it is chosen as 199.

![Figure 3](image3.png)

**Figure 3.** Simulated shadow image. The beam blocker is modeled as a disk supporting half an ellipse and the MTF as an exponentially decaying function. The image is $512 \times 512$, and the number of electrons per pixel in the vacuum is 100 on average.

![Figure 4](image4.png)

**Figure 4.** Estimation of the MTF from a simulated shadow image. a: The average number of electrons per pixel in the vacuum is 100. The MTF is estimated faithfully, also for frequencies beyond $\nu_N$. The noise in the image translates as noise on the MTF. b: Estimate from a noise-free simulation. The estimated MTF exhibits only digital noise. A slight systematic underestimation is observed due to aliasing artifacts.

All matrices in equation (8) are large, with the number of elements proportional to $KN^2$ or $N^4$. However, these matrices are sparse and the number of nonzero elements is proportional to $N^2$. The implementation has exploited this to limit the computer memory usage. The number of nonzero elements of the resulting matrix $T$ equals $3.0N^{2.0}$. 

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RESULTS

Experimental shadow images are recorded on three different CCDs:

1. \(2k \times 2k\) Gatan UltraScan 1000 CCD camera (Gatan, Inc., Pleasanton, CA, USA) of 14 \(\mu m\) pixel size at IFP at the University of Bremen, with an electron energy of 300 keV
2. FEI Eagle 2\(k\) HR camera (FEI Company, Hillsboro, OR, USA) with 30 \(\mu m\) pixel size at EMAT at the University of Antwerp, with an electron energy of 200 keV
3. \(1k \times 1k\) Gatan Model 694 Slow-Scan Camera with a 24 \(\mu m\) pixel size at EMAT at the University of Antwerp, with an electron energy of 300 keV.

Since these CCDs are fitted to three different microscopes, they are shadowed with different beam blockers. To reduce the noise, the MTF is estimated from repeated measurements and then averaged. The gain reference and the dark reference have been taken in the beginning of the series. The gain reference was obtained from ten repeated measurements in the vacuum with illumination and recording time identical to that used for the shadow images. The dark reference has been taken at the same recording time as well. The images are displayed in Figure 5. Note that CCD 3 is mounted on a Gatan Imaging Filter (GIF) and that the 0.6 mm entrance aperture was used as a beam blocker. The unprocessed result of the algorithm is shown in Figure 6. For CCD 1 and 2, it was sufficient to carry out the fit in a square region containing just the beam blocker’s head.

For CCD 1, 16 repeated measurements have been made. The MTF of a CCD of the same type has been characterized previously in Thust (2009) and agrees with our result: both the rapid drop-off at low frequencies and the low level at \(\nu_N\) are reproduced here.

For CCD 2, 100 repeated measurements have been made. No reference for its MTF was found, but there is no reason to assume that our findings are less trustworthy in this case.

The MTF of CCD 3 has been found from 100 repeated measurements. It has the same characteristic shape as CCD 1, but since the pixels are larger, the drop-off occurs at higher frequencies (expressed in \(\nu_s\)).

Postprocessing

In Figure 7 it is shown that the MTF of CCD 1 exhibits a discontinuity at the origin. This artifact could be reproduced in the test images by adding a constant background to the measurements, thereby strongly suggesting that it is caused by an imperfect dark reference, possibly due to afterglow of the scintillating crystal.

The effect of a constant background is twofold. First of all, the dc component of the MTF will be overestimated. This effect spreads out to neighboring channels because of the convolution in Fourier space implied by the sine-window [see equation (11)]. Second, the binary image \(g\) of the beam blocker will be scaled wrongly, leading to a wrongly scaled MTF.

These two effects are inseparable and can only be undone heuristically. The first channels of the MTF, starting from the third, are fitted to the sum of a Gaussian function and an exponentially decaying function. It can be seen from Figure 7 that this is a near perfect description. The MTF is then adjusted by replacing the values of the first two channels with the fitted curve and by rescaling with a factor equal to the inverse of the curve’s value in the origin. The rescaling factor of CCD 1 is 1.020. The same artifact has been observed in the other CCDs too, albeit less severe: for CCD 2 and CCD 3 the rescaling factor is 0.987 and 1.003, respectively.
Negative MTF Values

The binary image $g$ of the beam blocker is obtained by first performing a fourfold bicubic upsampling and then a threshold of half the vacuum intensity $I$. However, this threshold value is only correct if the beam blocker’s edge is straight over the extent of the PSF. In the 2D case, the value of 0.5$I$ is a compromise that is too low for convex parts of the beam blocker and too high for concave parts. In Figure 8 three examples of errors introduced by the threshold are given for CCD 1. It is seen that the finer details disappear. This artifact is therefore likely to affect the higher frequencies of the MTF.

The extent of this effect is investigated with the aid of a test image based on the beam blocker and the MTF of CCD 1. As binary beam blocker image $g$, the fourfold upsampled and thresholded experimental shadow image is used. For the MTF, the fit of the sum of a Gaussian function and an exponentially decaying function to the experimental MTF is used. No noise is applied. The result of estimating the MTF from this test image is shown in Figure 9.

Comparing the results of Figure 6a and Figure 9 shows that the MTF becomes negative around $0.8\nu_N$ in both cases. The effect is less pronounced in the test image because much of the higher frequencies had already disappeared upon construction of the image $g$ for the test image. Nevertheless, this test result shows that the errors introduced in the thresholding are the likely cause of the negative values in the MTF of CCD 1.

DISCUSSION

The shape of the MTF below $\nu_N$ of CCD 1 corresponds well to the findings in Thust (2009). Both the rapid drop-off at

Figure 6. The MTFs extracted from the investigated CCDs.

a: MTF of CCD 1. b: MTF of CCD 2. c: MTF of CCD 3.

Figure 7. Detail of the MTF of CCD 1 around the origin. Note the artifact in the first two channels. The solid line is the fit with a sum of a Gaussian function and an exponentially decaying function.

Figure 8. Three details from the beam blocker of CCD 1. Note how the thresholding step fails to bring out the finer details.
low frequencies and the low value around $\nu_N$ is reproduced here. Furthermore, the shape corresponds well to the shape of the MTF of CCD 3, which is produced by the same manufacturer. There is no reason to assume that the estimate of MTF of CCD 2 is any less trustworthy.

The negative values of the MTF of CCD 1 and 2 above 0.8$\nu_s$ are likely caused by the thresholding, as explained in the Negative MTF Values section. Optimizing the threshold value is of no use because convex and concave parts of the beam blocker require different threshold values. Close inspection of the beam blocker of CCD 3 learns that its edges are much smoother than that of CCD 1 and 2. As a result, the estimate of its MTF is well behaved up to 0.99$\nu_s$.

Figure 7 shows that the MTF of CCD 1 and 3 is described well by the sum of a Gaussian function and an exponentially decaying function. This means that the PSF of the scintillator is the sum of a Gaussian function and a Lorentzian function (Abramowitz & Stegun, 1972).

We found that acquiring the dark reference only in the beginning of the series is sufficient. The error this introduces is small and can be compensated (see the Postprocessing section).

**SUMMARY**

The CCDs used in electron microscopy are coated with a scintillating crystal that gives rise to a severe MTF. In this article we summarize the image formation in the CCD and explain how the linear transformation between the MTF and the Fourier transform of the shadow image can be constructed. The MTF is then found by minimizing the sum of squared differences. The corresponding author has implemented this method in the MATLAB program “MTF Estimate,” which is available upon request.

This approach has two advantages over previous approaches. First of all, no dedicated beam blocker—typically a knife edge—has to be installed; the shadow image of the default beam blocker suffices. Second, the linear transformation is constructed and solved completely autonomously, thereby eliminating the need for manual interference.

Since the linear transformation takes the aliasing into account as well, the MTF is estimated above the Nyquist frequency ($\nu_N$).

This method is tested successfully on three different CCDs with various beam blocker shapes. The maximum frequency for which the MTF can be estimated reliably depends on the smoothness of the beam blocker. For CCD 1 and 2, the MTF was estimated up to 1.6$\nu_N$ (0.8$\nu_s$), and for CCD 3 up to 1.98$\nu_N$ (0.99$\nu_s$).

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