Comparison of approaches and artefacts in the measurement of detector modulation transfer functions

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In order to investigate the reproducibility of measurements of transmission electron microscope detector modulation transfer functions (MTFs) we measure the MTF of a charge-coupled device (CCD) camera using five different methods. MTFs derived from a sharp edge, a circular aperture and electron holographic interference fringes are found to agree closely with one another. The difficulty of obtaining accurate measurements of MTFs and the potential of using focused electron probes to make direct measurements of MTFs is discussed. We highlight the sensitivity of image contrast after deconvolution to small differences in the measured MTF.

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1. Introduction

The modulation transfer function (MTF) of a detector such as a charge-coupled device (CCD) camera provides a measure of the attenuation of recorded information in a transmission electron microscope (TEM) plotted as a function of spatial frequency. Its accurate measurement is essential for quantitative transmission electron microscopy and is particularly important for quantitative high-resolution electron microscopy (HREM). If lattice fringes are recorded using a relatively high detector spatial frequency, then their contrast can be attenuated by the detector by a factor of 2 or more [1].

Measurements of detector MTFs can be made using either stochastic methods, where the MTF is derived from the attenuation of noise when the detector is illuminated uniformly with electrons [2,3] or deterministic methods, where the MTF is derived from a recorded image of a known intensity distribution [4,5]. Meyer and Kirkland [6] and Niermann et al. [7] have shown that the two methods provide different information about the detector and that only deterministic methods provide the true detector MTF.

There are typically three different contributions to the detector MTF. The first (referred to as the scintillator MTF) is associated with the presence of the scintillator and fibre optics that are used to couple the scintillator to the CCD chip. The second results from the finite size of the CCD elements, while the third is the aliasing effect associated with the finite spacing of the CCD pixels. The second and third components can be calculated if the CCD pixel size and spacing are known.

In this paper, we aim to assess the reproducibility of different methods of measuring detector MTFs. We use five different methods to measure the MTF of a Gatan model 894 2 K (2048×2048 pixel) UltraScan 1000FT CCD detector with 14 μm pixels mounted at the end of a Gatan model 865ER GIF Tridiem imaging filter on an FEI Titan 80-300ST TEM. We compare the MTFs obtained using the different approaches for a microscope accelerating voltage of 300 kV and discuss the reasons why in practice MTFs measured using different methods give different results.

2. Noise method

In the noise method, the detector is illuminated uniformly. As electrons are particles, the input signal is a random distribution of point sources. Scattering of the electrons and light in the scintillator causes the signal from each input electron to be spread over neighbouring pixels, attenuating the noise power spectrum most significantly at high spatial frequencies. Meyer and Kirkland [6] have shown that this method provides not the overall detector MTF, but instead a measure of the statistical properties of the
individual electrons and their trajectories through the scintillator and fibre optics, which they call the noise transfer function (NTF).

We include results obtained using this method both for comparison with the other approaches and because it can be used to provide additional information about the detector (see below).

Twenty images of uniform illumination were collected, each with an average of about 2100 CCD counts. The noise MTF (hereafter referred to as NTF) was determined from each image by using a method similar to that described by Meyer and Kirkland [4], where the mean of all of the images is used for gain-normalisation prior to taking the modulus of the Fourier transform. A smoothed version of the averaged scintillator NTF from these images is shown in Fig. 1, after correcting for the finite pixel size and iteratively correcting for aliasing using a method similar to that used by Meyer and Kirkland [4]. Also shown as a dotted line in Fig. 1 is a corner section (averaged over an arc of width $\pi/20$ rad) of the uncorrected two-dimensional NTF before smoothing to show the effect of the pixel size and aliasing corrections and the level of noise present in the original NTF. The greatest noise is at low spatial frequencies, where the corner section is averaged over fewest pixels.

### 3. Aperture method

The aperture method, which is very similar to those used by Nakashima and Johnson [8] and Van den Broek et al. [9] and also used by Erni et al. [10] with modifications, involves deconvoluting an image of an aperture by using a measurement of its shape derived from the aperture image. We used a 1 mm imaging filter entrance aperture, with one of the quadrupoles (the “squareness”) of the imaging filter adjusted to give a slightly elliptical image of the aperture, as shown in Fig. 2a. It is essential that the image of the aperture is not perfectly circular, as the presence of zeros in the Fourier transform of the aperture would give rise to indeterminate spatial frequencies in the MTF if the aperture was exactly circular.

Fig. 2b shows an enlargement of the region marked by a box in Fig. 2a. The image of the edge of the aperture is not sharp primarily due to the detector MTF. An estimate of the true shape of the aperture can be obtained by thresholding the image, as shown in Fig. 2c. However, this estimate is too sharp and jagged, as the real aperture would only partially obscure some of the pixels, resulting in intermediate intensity values. A better estimate of the aperture shape is obtained by oversampling the aperture image using linear interpolation (Fig. 2d) before thresholding (Fig. 2e). This oversampled image is then reduced back to the original size by averaging blocks of pixels (Fig. 2f). The result is an image of how a sharp aperture would look if it were imaged using a CCD detector with a perfect MTF. This method of determining the aperture shape by oversampling is similar to that of Van den Broek et al. [9] but is where our method differs from that of Nakashima and Johnson [8], who used a sub-pixel shifting method to determine their aperture shape. The scintillator MTF can then be obtained by deconvolution. Because the aperture shape image (Fig. 2f) includes the effects of the finite pixel size and aliasing, no further correction for the CCD pixel size or aliasing is required and the MTF obtained is the scintillator MTF.

If a non-circular aperture is used then the two-dimensional MTF obtained by deconvolution can be averaged radially to obtain a one-dimensional MTF, as shown in Fig. 2g. It is necessary to weight with the modulus of the Fourier transform of the aperture during radial averaging to minimise the contribution from the zeros in the Fourier transform of the aperture. The dotted line in Fig. 2g is the average MTF determined from 20 images of the aperture. It is relatively noise-free, especially at low spatial frequencies, with some noise visible at the highest spatial frequencies. The solid line shows the MTF after smoothing with a filter, whose width (and thus amount of smoothing) increases with spatial frequency.

If necessary the process used to determine the MTF can be iterated, with the MTF obtained after each iteration used to deconvolute the original image of the aperture (Fig. 2a) before interpolating, thresholding and averaging blocks of pixels. Iteration gives a better estimate of the shape of the aperture, from which an improved MTF can be obtained.

### 4. Edge method

The edge method is described by Meyer and Kirkland [4] and is similar to the aperture method, in that an image of a sharp mask is recorded. However, the edge is now (nearly) straight and the processing steps used to obtain the MTF are different. Thus, the two methods are considered separately.

A “line spread function” is obtained from an image of a straight edge by differentiation of the image in a direction perpendicular to the edge. However, in order to obtain a good estimate of the higher spatial frequencies of this function, the differentiation must be carried out to sub-pixel accuracy. This requirement can be satisfied if the straight edge is not aligned exactly parallel to the CCD pixels, so that the position of the edge relative to the pixels varies along its length, as described by Meyer and Kirkland [4].

In order to form an image of a straight edge, the metal “blades” in the imaging filter, which are used to shadow the CCD detector when it is used in frame transfer mode, were inserted by reversing the two pneumatic pipes that control their insertion. The use of the blades provides an advantage over using an entrance aperture in that they are positioned immediately in front of the CCD detector, and so are not magnified by a factor of about 10. Thus, the requirement on their sharpness is much less severe.

Here, 20 images of uniform illumination were recorded with the blades inserted, followed by 20 images with the blades removed for gain normalisation. One image acquired after gain normalisation is shown in Fig. 3a. The dark areas at the top and bottom of the image are the shadows of the blades. A line profile extracted from the image along a single vertical column of CCD pixels is shown in Fig. 3b. The same scripts that were used by

![Fig. 1. Scintillator NTF calculated from an average of 20 images of noise. Solid line: smoothed scintillator NTF with aliasing removed, corrected for finite pixel size. Dotted line: corner section (averaged over an arc of angular width $\pi/20$ rad) of unsmoothed, two-dimensional detector NTF uncorrected for aliasing and finite pixel size, showing the effect of the aliasing, the pixel size correction and noise.](image-url)
Meyer and Kirkland [4] were used to generate the MTF from the images of the blades. The resulting MTF is shown in Fig. 3c, with the dotted line corresponding to the raw MTF and the solid line the MTF after smoothing. The unsmoothed edge MTF is much noisier than the MTF obtained from the aperture (Fig. 2g).

5. Focused spot

In principle, if the electron beam is focused to a spot that is significantly smaller than the size of a CCD pixel, then an image of this spot can be used to provide the point-spread function directly. In practice, a number of measurements need to be averaged with the spot in different positions relative to the centre of a CCD pixel to account for aliasing. This approach was initially expected to provide very poor results, in part because the dynamic range of the CCD camera is not sufficient to image both the bright centre of a focused spot and the faint scattering away from it. However, it was found to be surprisingly promising.

The spot size required to obtain a reliable image of the point-spread function can be estimated. In order to form a spot that is smaller than approximately 1/3 of the pixel size, for our detector (with 14 μm pixels) the spot must be smaller than ~4 μm on the CCD camera, i.e. smaller than ~400 nm on the TEM screen (assuming 10× magnification in the imaging filter). At a TEM magnification of 4 k, this means that the spot size must be smaller than 0.1 nm at the specimen plane, which is difficult to achieve without using a microscope equipped with both a probe and an image aberration corrector. (This requirement is much less strict for a pre-imaging filter camera.) For a CCD camera mounted at the

![Fig. 2.](image_url)
end of an imaging filter either “EFTEM mode” or a diffraction pattern with a small camera length may then be used. Care must also be taken to ensure that the probe does not have tails with significant intensity.

Fig. 4a shows a magnified image of the central spot of a diffraction pattern recorded using a 100 mm camera length, no specimen, a small selected area aperture and energy filtering. The spot was found to be not as small as ideally required and is also elongated, as a result of limitations in setting the focus and intermediate lens astigmatism as well as possible vibration and streaking from the CCD detector shutter (despite the relatively long exposure time of 1 s).

In principle, the MTF can be found directly from the modulus of the Fourier transform of the image of the spot. However, in practice the background level must be determined from the mean intensity away from the image of the spot (on the assumption that the point-spread function has decreased to a negligible value). This is because the dark current cannot be determined accurately enough from separate dark current images as its mean value changes slightly between each image. Here, the slight astigmatism of the spot meant that only a section of the MTF (of angular width $\pi/20$ rad) was used. The resulting MTF, averaged over three images, is shown in Fig. 4c. As the spot is not small enough, the MTF is underestimated strongly at high frequencies. As a result of this error, the much smaller effect of aliasing was not taken into account here. No significant noise is visible in the MTF even though only three images were averaged because there is no deconvolution stage, which would amplify noise at high spatial frequencies. Although this approach suffers from experimental difficulties, the result could be improved by demagnifying the spot further and focusing and stigmating it more accurately, perhaps by programming a higher magnification imaging filter imaging mode for focusing and a separate lower magnification mode for MTF measurement. Lubk et al. [11] have demonstrated this method for the case of a CCD camera mounted directly beneath the screen where the focused spot is a factor of ten smaller than for our image.
filter CCD camera. The spot method has also been used to characterise CCD detectors for X-rays [12] and infra-red light [13].

6. Electron holographic interference fringes

This method is different from the previous methods, in that it in principle measures the MTF directly. The CCD is illuminated with sinusoidal electron holographic interference fringes, whose contrast is measured over a range of different magnifications [14]. The contrast of the fringes incident on the CCD detector must be the same at all magnifications, so that the measured fringe contrast depends only on the detector MTF. Parameters such as biprism voltage and incident beam convergence must all be kept unchanged.

48 Holograms (2 per magnification step) with no specimen present were acquired, over an indicated magnification range of 1.4 M to below 24 k, with the lowest magnifications achieved by reducing the strength of the diffraction lens at a nominal magnification of 24 k. Two of the holograms are shown in Fig. 5a and b. Fourier transforms of the images (or portions of the images when the fringes covered less than the whole CCD) were calculated and the fringe contrast obtained from the sum of the intensity around the point in the Fourier transform corresponding to the fundamental fringe spacing.

Four attempts were required to obtain a good enough set of holograms, in which the fringe contrast remained constant throughout the measurement series, involving a careful choice of biprism voltage, beam intensity and exposure time. The large range of magnifications required, combined with the necessity of keeping the illumination conditions constant, meant that the lower magnification images had much greater intensities than the higher magnification images. It was decided not to vary the exposure time substantially to compensate for this change in intensity in order to ensure that factors such as biprism instability

Fig. 4. (a) Enlarged image of a focused electron beam recorded directly on the CCD detector. The squares are the individual CCD pixels. (b) Point spread function measured directly as a line trace through the spot in (a) in its narrowest direction (marked by arrow in (a)). (c) Unsmoothed scintillator MTF (corrected for finite pixel size, aliasing was negligible) derived from the average of three images of focused spots.
and drift, which would result in lower fringe contrast for longer exposure times, remained constant.

The measurements of fringe contrast are plotted in the form of an MTF in Fig. 5c. Over most of the frequency range the change in fringe contrast reproduces the expected form of the MTF. However, for the very lowest spatial frequencies (0.0089 pixels$^{-1}$ and below, corresponding to fringe spacings greater than 110 pixels) the fringe contrast reaches a maximum and then decreases. It is possible that this behaviour is caused partially by an increase in exposure time from 2 s to 4 s for the highest three magnifications. However, this explanation is unlikely to account for the anomalous measurements. Instead, it is possible that the dark current was not compensated correctly, making the average intensity higher than it should be and affecting the lower intensity images most severely. Alternatively, the holographic fringe contrast may depend on magnification at the highest magnifications used.

As the true contrast of the holographic fringes before attenuation by the detector point spread is unknown, an arbitrary scaling factor must be used to match the fringe contrast to the MTFs measured using the other methods (see below).

7. Comparison of measured MTFs

Fig. 6a shows a comparison of the MTFs measured using the five methods described above. Fig. 6b shows the same measurements with the vertical scale enlarged to show the measurements recorded at the highest spatial frequencies more clearly.
Fig. 6 shows that the noise method provides a different MTF to the other measurement methods, and is consistently higher than the other MTFs for all but the lowest spatial frequencies. This difference has been discussed by Meyer and Kirkland [6] and Niermann et al. [7] and is associated with the fact that the noise method measures the properties of individual electrons and not the average MTF of many electrons. In other words, each electron may be scattered sideways in the scintillator, resulting in a relatively sharp area of light emission (which itself will consist of individual photons) at some distance from the point where the electron first hit the scintillator. The NTF measures the average shape of this area of light emission but does not take into account the further blurring caused by each electron being scattered in different directions and by different amounts.

An important parameter is the detection quantum efficiency (DQE), which varies with spatial frequency and is defined as the square of the ratio between the measured signal to noise ratio and the input signal to noise ratio [6,15]. Meyer and Kirkland [6] have shown that the DQE can be obtained from the ratio between the detector MTF and the NTF. Our DQE measurement, obtained using the aperture MTF and shown in Fig. 7, drops rapidly between spatial frequencies of 0 and 0.05 pixels$^{-1}$ and then decreases less rapidly. This trend is consistent with that reported by Meyer and Kirkland [6] and suggests that for a typical spatial frequency of
-0.25 used to record HREM images (corresponding to about half of the Nyquist frequency) the signal to noise is decreased by a factor of nearly 2 by the CCD detector.

Whereas the NTF is of little use for deconvoluting images for quantitative measurements of contrast, it can be useful for estimating the information limit of a high-resolution image. Fig. 8 shows a diffractogram determined by calculating the modulus squared of the Fourier transform of a lattice image of Si acquired close to [110], displayed after dividing by the NTF. The fact that the background noise now has a constant value can be seen in the highest spatial frequency regions of the diffractogram. Any parts of the diffractogram that have higher values than this constant background level must be associated with information in the image. In Fig. 8, information from amorphous Si is transferred linearly to about 0.14 nm (arrowed), thus determining the information limit. Spots from the Si lattice fringes are also present to about twice this value, as expected from non-linear interference. This approach can be applied provided the image intensity is sufficiently high for the camera dark current noise to be negligible when compared to the statistical electron noise. Grob et al. [16] have also use the NTF as a means of comparing TEM CCD cameras.

The aperture and holography measurements agree well except at the lowest spatial frequencies (Fig. 6). In contrast, the edge and aperture methods agree well at low spatial frequencies, but slightly less well at higher spatial frequencies, with the edge MTF being slightly higher than the MTF from the aperture method. These two methods might be expected to give the same results as they both involve measuring the sharpness of the image of an edge. A possible explanation for this difference (assuming insufficiently sharp masks can be ruled out) is that the amount of noise in the edge measurement (resulting from the differentiation step in the calculation) increases with spatial frequency, as seen from the dotted line in Fig. 3c. The edge MTF is thus much more noisy at high spatial frequencies than the aperture MTF and thus the smoothed edge MTF is likely to be correspondingly less accurate at these frequencies.

For typical high-resolution applications, where the highest spatial frequency present is usually no greater than 0.25 pixels⁻¹, the edge, aperture and holography MTFs are similar to each other. For example, at a spatial frequency of 0.25 pixels⁻¹ the edge method MTF has a value of 0.19 while the hologram and aperture MTFs have values of 0.16 and 0.17, respectively. For higher spatial frequencies, this difference is larger. For example, the difference between the three methods is close to 60% at 0.5 pixels⁻¹. The magnitude of this difference was unexpected. Indeed, it is not yet clear whether any of the methods has provided an accurate value for the MTF at the highest spatial frequencies. We would expect the aperture and holography MTFs to be the most accurate as they agree most closely with each other.

Whereas the focused spot method was not expected to work at all due to the limited dynamic range of the CCD detector, the primary limitation was instead found to be the ability to obtain a small enough focused electron probe. In Fig. 6 (and particularly in Fig. 6b) the focused spot MTF can be seen to provide the least noisy MTF despite being shown with no smoothing and averaged over only a small fraction of the two-dimensional MTF owing to the non-symmetric shape of the probe. An MTF obtained from a more accurately focused spot and averaged over the full two-dimensional MTF would be even less noisy and the method is much easier to implement on the CCD detector below the viewing magnification of the imaging filter [11]. Our results also demonstrate that this method is limited to CCD cameras where a sufficiently small focused spot can be obtained.

8. Deconvolution using measured MTFs

Two examples are now used to compare the effect of deconvolution using the different measured MTFs. Because the MTF measured using electron holography is sampled at only discrete points and is similar to the aperture MTF, it is not included in this comparison.

Fig. 9a shows the 000 disc of an energy-filtered convergent beam pattern acquired from [110] Si, recorded on the same CCD detector as was used for the MTF measurements. Fig. 9b–e shows the effect of deconvolution on the convergent beam pattern in Fig. 9a. Deconvolution was performed by Fourier transforming the CCD image, dividing it by an image that was weighted radially by the MTF and then back-transforming. No attempt was made to

Fig. 7. Spatial-frequency-dependent DQE normalised to the DQE at zero spatial frequency calculated for a Gatan 2 K CCD detector at 300 kV from the ratio of the aperture MTF (Fig. 2g) to the NTF (Fig. 1).

Fig. 8. Diffractogram of a high-resolution image of amorphous and crystalline Si after dividing by the NTF uncorrected for aliasing. This approach results in a constant noise background, allowing the information limit to be estimated, here 0.14 nm (marked with an arrow).
deconvolute the effect of the finite size of the CCD pixels and so the deconvoluted images represent those that would be obtained on a CCD detector with perfect image transfer to the CCD chip but with the intensity averaged over the area of each CCD pixel. For accurate comparison with simulations, the effect of the finite size of the CCD pixels would need to be included in the simulations.

The aperture and edge MTFs give similar results (Fig. 9b and d), while the spot MTF results in considerable high-frequency noise (Fig. 9c). (The noise at spatial frequencies above about 0.5 pixels\(^{-1}\) is enhanced by more than 100×.) Unsurprisingly, the disc deconvoluted using the NTF (Fig. 9e) shows less contrast and less noise than any of the other deconvoluted discs.

A more quantitative comparison of the effect of the different MTFs can be seen in Fig. 10, in the form of linescans obtained across the middle of each 000 convergent beam disc averaged perpendicular to the linescan over the distance marked in Fig. 9a. After deconvolution using each of the MTFs, the bright areas are increased in intensity by about 10% and the dark areas are correspondingly decreased in intensity, showing the importance of deconvolution for the quantitative interpretation of convergent beam patterns. An indication of the reliability of the deconvolution procedure is that the darkest areas of the convergent beam pattern should not go below the mean phonon background intensity outside the discs (here about 100 counts) and certainly not below

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**Fig. 9.** (a) Central disc of an energy-filtered Si [110] CBED pattern recorded at a camera length of 60 mm. An area 301 pixels square from the original 2048 pixel square image is shown. Subsequent images show the same area after deconvoluting using MTFs derived from the (b) aperture, (c) spot, (d) edge and (e) noise methods (NTF). The speckly appearance of (c) is due to the over-enhancement of noise at the highest spatial frequencies. All images are shown on the same intensity scale with black and white corresponding to 0 and 10,000 counts respectively.
zero counts. This criterion is satisfied by the aperture, edge and noise methods, but less equivocally by the spot deconvolution method (Fig. 10b). The edge of a convergent beam disc should also be sharp if the condenser aperture is perfectly in focus. Here, Fresnel fringes can be seen around the edge of the disc. After deconvolution, the intensity outside the disc should decay smoothly, following the intensity distribution expected for Fresnel diffraction. This is the case for the aperture and edge methods (Fig. 10a and c), whereas the spot method (Fig. 10b) results in rather abrupt decay and even goes slightly below the background level, due to over-enhancement of the high spatial frequencies. In contrast, the intensity at the edge of the disc deconvoluted using the noise method decays too slowly, as the noise method over-estimates the MTF (and thus underestimates its effect during deconvolution) for the higher spatial frequencies.

Here, only the aperture and edge methods provide deconvoluted convergent beam discs that are consistent with the expected intensity distribution. The resulting intensity distributions are almost identical and differences between them are close to the level of noise in the final convergent beam patterns.

A second example is provided by deconvoluting an energy-filtered lattice image of Si acquired near [110]. The image shows one strong set of 111 lattice fringes and faint half-spacing 222 lattice fringes (Fig. 11a). The 111 lattice fringes have a spatial frequency of 0.095 pixels\(^{-1}\) (corresponding to a wavelength of 10.5 pixels), while the 222 fringes have a spatial frequency of 0.19 pixels\(^{-1}\) (5.25 pixel wavelength).

The same image after deconvolution using the four different MTFs is shown in Fig. 11b–e. The deconvoluted images are noisy, owing to the low average number of counts per pixel in the original image (~150). For the image deconvoluted using the spot MTF (Fig. 11c), the image is so noisy that the lattice fringes are difficult to see. In contrast, the NTF-deconvoluted image (Fig. 11e) shows less noise, but does not fully correct the image. Both the visibility of the lattice fringes and the noise level look very similar in the aperture and edge deconvoluted lattice images (Fig. 11b and d), as the MTFs have very similar values at the spatial frequencies of the lattice fringes.

A more quantitative comparison of the lattice fringe amplitudes is shown in Fig. 12, in which each of the deconvoluted images in Fig. 11b–e has been projected parallel to the lattice fringes for comparison with the projection of the original lattice image (Fig. 11a), which is shown as a dotted line in each figure. Deconvolution using the aperture and edge MTFs gives almost identical lattice fringe contrast, with the 111 lattice fringe amplitude increased by a factor of 2.63 using aperture deconvolution and 2.59 using edge deconvolution and the 222 lattice fringe amplitude increased by factors of 4.35 and 4.17 respectively for the two methods. The difference between the 222 fringe contrasts after aperture and edge deconvolution shows that apparently small differences between the methods for measuring MTFs can be significant when quantitative comparisons are needed. Spot deconvolution (Fig. 12b) overcompensates for the MTF, while NTF deconvolution (Fig. 12d) underestimates the effect of the MTF. The importance of using a correctly measured MTF can be seen in the relative contrast of the 111 and 222 lattice fringes. In the original projected image (Fig. 12, dotted lines) the 222 fringes are not visible. They only become visible after deconvolution and their

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**Fig. 10.** Line profiles obtained from the centres of CBED patterns projected over 20 pixels (marked in Fig. 9a), for MTFs deconvoluted using the (a) aperture, (b) spot, (c) edge and (d) noise methods (NTF). In each case, the dotted line shows the same section obtained from the original CBED pattern for comparison.
contrast relative to the 111 fringes depends greatly on the deconvolution method chosen.

The measured decrease in the contrast of the Si 111 lattice fringes due to the MTF (by a factor of ~2.6) is similar to the typical factor of about 3 by which experimental energy-filtered lattice fringe contrast is lower than in simulations (the “Stobbs factor”) [17,18]. It has been suggested that deconvolution by the MTF resolves this problem [19]. However, while the detector MTF does indeed make a significant contribution to reducing image contrast, many quantitative image comparisons already take the detector MTF into account and are still left with a significant mismatch between experimental and simulated lattice fringe contrast [20–22].

9. Conclusions

The measurement and compensation of the MTF of a detector used to record TEM images, diffraction patterns or energy-loss spectra is essential for any work involving the quantitative measurement of intensities or contrast levels, even when the features of interest are relatively slowly varying across the field.

Fig. 11. (a) Energy-filtered Si lattice image recorded near [110] at a magnification of 34 k showing (111) fringes (spacing 0.314 nm). An area of size 256 pixels is shown. Subsequent images show the same area after deconvoluting with the (b) aperture, (c) spot, (d) edge MTFs and (e) NTF. All images are shown on the same intensity scale, with black and a white corresponding to 0 and 500 counts, respectively.
of view, as in convergent beam patterns. Accurate deconvolution is particularly important for quantitative comparisons of high-resolution lattice images with simulations. The measurement of a sufficiently accurate and noise-free MTF requires the use of a sharp enough mask. However, discrepancies between MTFs calculated using different masks are still observed at the highest spatial frequencies. Surprisingly, the best MTF measurements may result in the future from the simplest method, involving the direct measurement of the recorded shape of a focused probe, if the probe can be focused to a size that is significantly smaller than the size of a CCD pixel. The present results highlight the need for great care when measuring and applying MTFs to recorded intensities.

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