# TECHNICAL SPECIFICATION

# ISO/TS 24597

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# Microbeam analysis — Scanning electron microscopy — Methods of evaluating image sharpness

*Analyse par microfaisceaux — Microscopie électronique à balayage — Méthodes d'évaluation de la netteté d'image*

Reference number
ISO/TS 24597:2011(E)

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ISO/TS 24597 was prepared by Technical Committee ISO/TC 202, *Microbeam analysis*, Subcommittee SC 4, *Scanning electron microscopy (SEM)*.


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# Introduction

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# Microbeam analysis — Scanning electron microscopy — Methods of evaluating image sharpness

## 1 Scope

This Technical Specification specifies methods of evaluating the sharpness of digitized images generated by a scanning electron microscope (SEM) by means of a Fourier transform (FT) method, a contrast-to-gradient (CG) method and a derivative (DR) method.

## 2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 16700:2004, *Microbeam analysis — Scanning electron microscopy — Guidelines for calibrating image magnification*

ISO/IEC 17025:2005, *General requirements for the competence of testing and calibration laboratories*

ISO 22493, *Microbeam analysis — Scanning electron microscopy — Vocabulary*

## 3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 16700 and ISO 22493 and the following apply.

**3.1**
**pixel**
smallest non-divisible image-forming unit on a digitized SEM image

**3.2**
**pixel size**
specimen length, in nanometres, per pixel in an SEM image

NOTE The horizontal and vertical pixel sizes should be same.

**3.3**
**binary SEM image**
converted SEM image in which there are only two brightness levels

**3.4**
**convoluted image**
image obtained by convolution of a binary SEM image with a two-dimensional Gaussian profile

**3.5**
**sharpness factor**
twofold standard deviation ($2\sigma$) of the Gaussian profile used to make a convoluted image

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**3.6**
**image sharpness**
sharpness factor divided by the square root of 2 (i.e. $2\sigma/\sqrt{2}$), the sharpness factor of an SEM image being considered the same as that of a convoluted image produced with a Gaussian profile of standard deviation $\sigma$

**3.7**
**contrast-to-noise ratio**
**CNR**
ratio of $I_A - I_B$ to $\sigma_n$, where $I_A$ and $I_B$ are the image intensities for the object and the background and $\sigma_n$ is the standard deviation of the image noise

**3.8**
**Fourier transform method**
**FT method**
method of evaluating image sharpness by comparing Fourier transform profiles of an SEM image with those of convoluted images

**3.9**
**contrast-to-gradient method**
**CG method**
method of evaluating image sharpness using weighted harmonic mean gradients of the two-dimensional brightness distribution map of an SEM image

**3.10**
**derivative method**
**DR method**
method of evaluating image sharpness by fitting error function profiles to gradient directional-edge profiles of particles in an SEM image

**3.11**
**field of view**
area of a specimen that corresponds to the whole SEM image

# 4 Steps for acquisition of an SEM image

## 4.1 General

For SEM image acquisition, it is important to first adjust the microscope conditions (for example, see Annex B in ISO 16700:2004). Image sharpness is dependent upon (i) the specimen itself, (ii) the structural smoothness of the foreground and the background of the image, (iii) the brightness and contrast and (iv) the contrast-to-noise ratio (CNR). Therefore, follow the procedures described in 4.2 to 4.10 corresponding to the above factors for evaluation of image sharpness by all the three methods described herein. Particular attention must be paid to the adjustment of the electron probe current and the focussing conditions in order to obtain the optimum requirements for brightness and contrast (see 4.6) and contrast-to-noise ratio (see 4.7).

## 4.2 Specimen

At the date of publication of this document, there was no designated certified reference material (CRM). Acceptable results can, however, be obtained using a specimen prepared by the method described in Annex G. Select a specimen with a smooth and flat surface. For evaluations of the image sharpness, choose a part of the specimen which contains circular particles deposited on the substrate. Obtain the desired images at the chosen magnification in accordance with 4.4.

NOTE Material which is sensitive to the electron dose is not suitable for use as a specimen for the evaluation of image sharpness.


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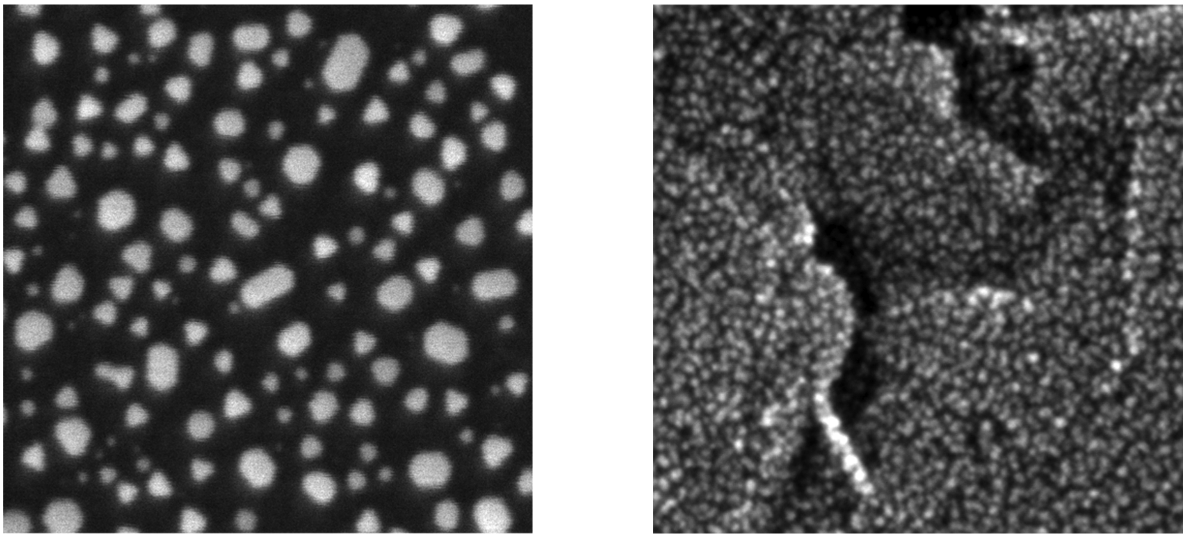
## 4.3 Specimen tilt

Set the specimen tilt angle at 0° (non-tilting condition).

NOTE Errors within ±3° in the tilt angle of the specimen will not affect the evaluation of the image sharpness.

## 4.4 Selection of the field of view

Select the field of view so that it contains a flat and smooth surface because image sharpness varies with the evenness (or rather unevenness) of the surface. Figures 1 a) and b) show acceptable and unacceptable fields of view, respectively. Choose particles extending over several tens of pixels [see Figure 1 a)].



**a) Acceptable image** **b) Unacceptable image**

**Figure 1 — SEM images with a) acceptable and b) unacceptable structured foreground images**

## 4.5 Selection of the pixel size

### 4.5.1 General

Before evaluating the image sharpness, it is necessary to calibrate the image magnification and/or the scale marker in accordance with ISO 16700.

### 4.5.2 Determination of the pixel size from a field of view

The pixel size $L_\mathrm{p}$ (in nm) is determined from the following equation:

$$L_\mathrm{p} = \frac{L_\mathrm{FOV}}{N_\mathrm{p}}$$

where

$L_\mathrm{FOV}$ is the horizontal width of the field of view on an SEM image, in nm;

$N_\mathrm{p}$ is the number of pixels covering the horizontal width of the field of view.

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### 4.5.3 Determination of the pixel size from a scale marker

The pixel size $L_p$ (in nm) is calculated by using a scale marker as follows:

$$L_p = \frac{L_{scale}}{N_{scale}}$$

where

$L_{scale}$ is the "indicator" value (e.g. the nominal value, in nm) of the scale marker;

$N_{scale}$ is the number of pixels covering the length of the scale marker.

### 4.5.4 Conversion of the pixel size

The image sharpness as derived by the methods described herein ($R_{PX}$) is in pixels. Converted to nanometres, the image sharpness $R_L$ is then given by the expression:

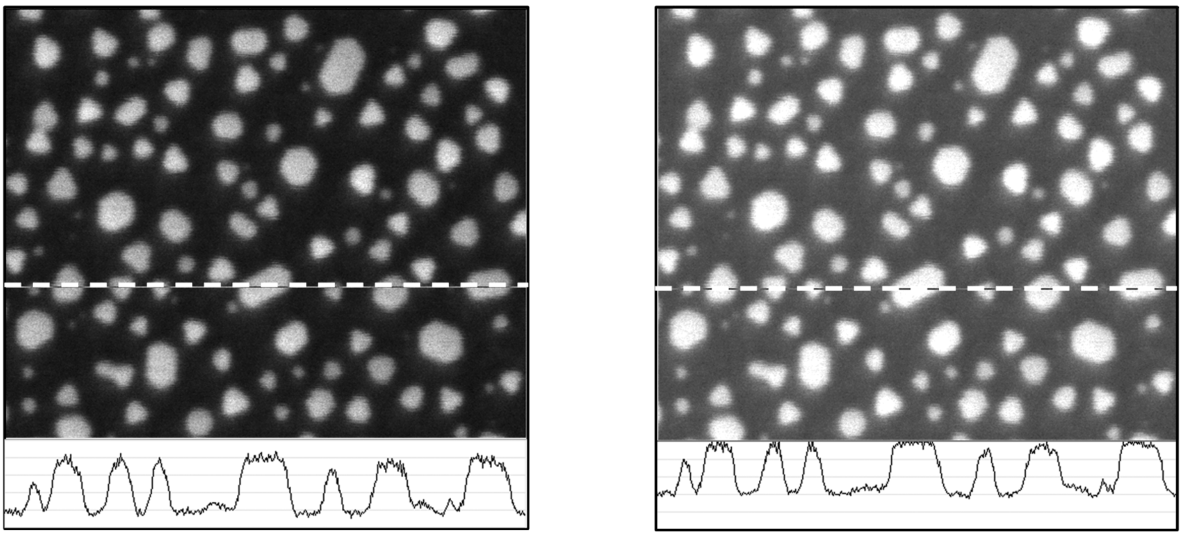
$$R_L = L_p \times R_{PX}$$

where $L_p$ is the pixel size.

Set the pixel size to about 40 % of the expected value of the image sharpness. For example, set the pixel size to 0,8 nm when the image sharpness is expected to be 2 nm.

## 4.6 Brightness and contrast of the image

The signal intensity of the image should be widely distributed. Figures 2 a), b), c) and d) show examples of images with acceptable and unacceptable brightness and contrast. Line profiles corresponding to the dotted lines at the same vertical position in each image are shown for visual guidance.



**a) Acceptable image** **b) Unacceptable (over-saturated) image**

**Figure 2** (*continued*)



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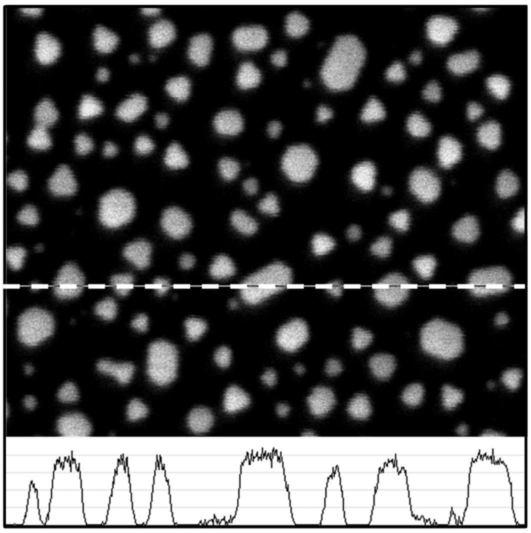
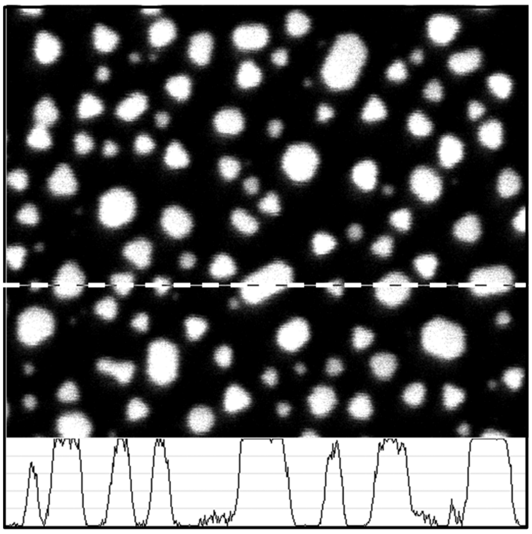


**c) Unacceptable (under-saturated) image**



**d) Unacceptable (over-saturated) image**

**Figure 2 — SEM images with acceptable and unacceptable brightness and contrast**

## 4.7 Contrast-to-noise ratio of the image

The contrast-to-noise ratio (CNR) of the image shall be 10 or larger. Here, the CNR is defined as the ratio of the image contrast $C_{\mathrm{image}}$ to the standard deviation $\sigma_{\mathrm{n}}$ of the image noise (see Figure 3).

$$\mathrm{CNR} = C_{\mathrm{image}}/\sigma_n$$

A procedure for the determination of the CNR ratio is given in Annex A.

Figure 4 shows the simulated appearance of images with CNRs of 5, 10 and 50.

Figure 5 shows examples of SEM images with different CNRs of about 4 and 30.

NOTE In order to obtain SEM images with a good CNR, it is necessary to adjust the probe current and/or the image acquisition time. One should be aware of the fact that variations in the above parameters will affect the results of the image sharpness evaluation.

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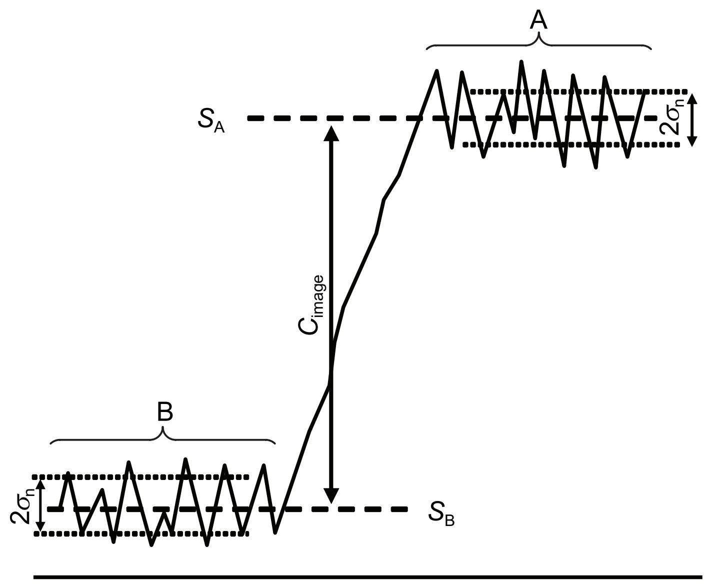
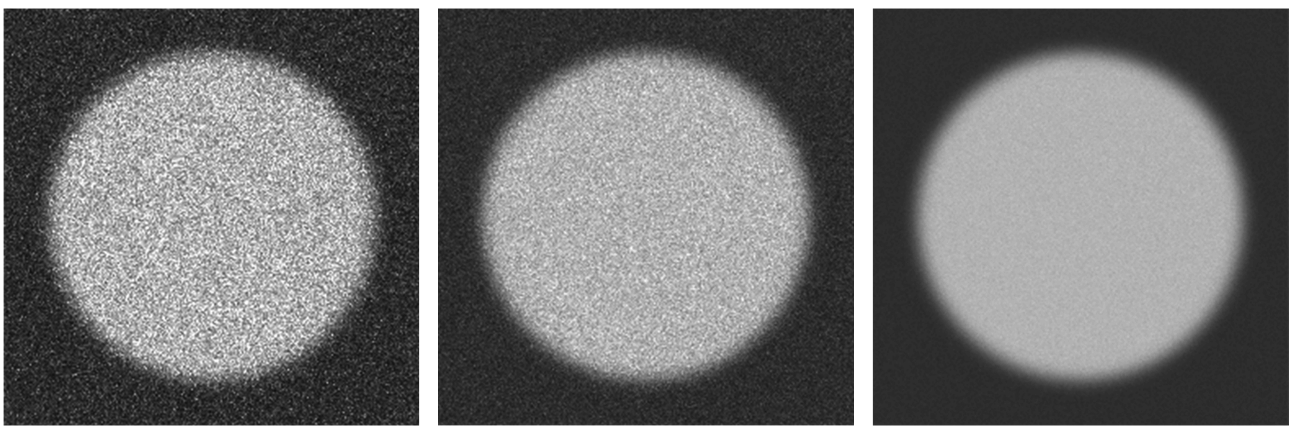



**Key**

A region A

B region B

**Figure 3 — Intensity profile of an image**



**a) CNR = 5** **b) CNR = 10** **c) CNR = 50**

**Figure 4 — Simulated images with different contrast-to-noise ratios**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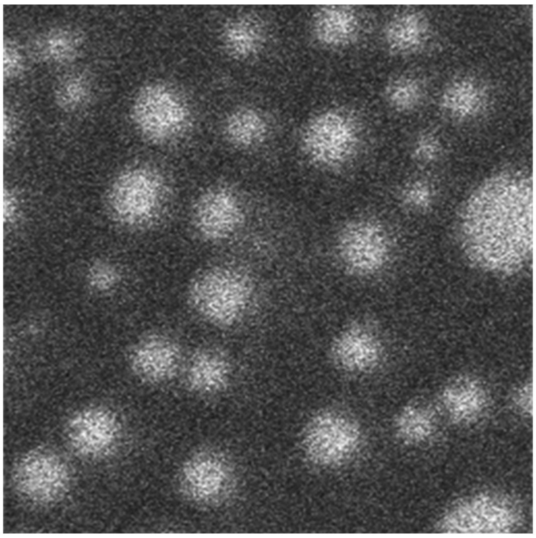
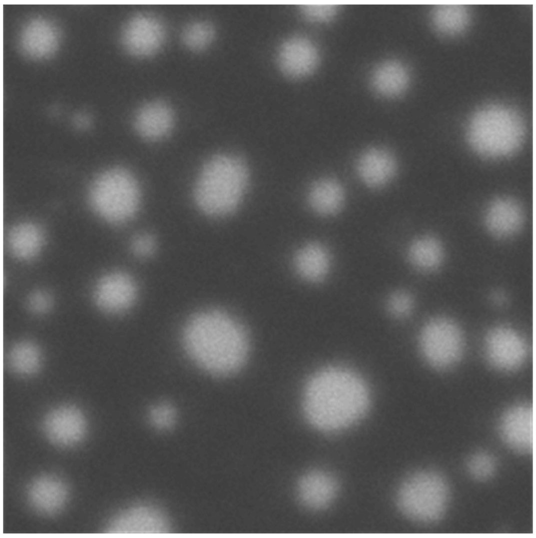


a) Low contrast-to-noise ratio (CNR ≈ 4)



b) High contrast-to-noise ratio (CNR ≈ 30)

**Figure 5 — SEM images with different contrast-to-noise ratios**

### 4.8 Focus and astigmatism of the image

Focus the electron beam as well as possible. Use an image that is as free of astigmatism as possible.

### 4.9 Interference from external factors

External factors such as mechanical vibration, distortion by magnetic fields and those listed in Annex B of ISO 16700:2004 affect the image sharpness. Ensure, as far as possible, that the images used are not affected by these factors.

### 4.10 Erroneous contrast

Make sure that the images do not contain erroneous contrast (e.g. contrast due to charging of the specimen).

### 4.11 SEM image data file

The image data, which is directly saved from an SEM, shall be in digital format, with the grey scale at least 8 bits deep. The data file of the image shall be in an uncompressed graphics-file format, e.g. uncompressed bitmap or uncompressed TIF.

Do not use the data obtained from a printed SEM image.

## 5 Acquisition of an SEM image and selection of an area within the image

The procedure described in this clause is common to all those used in this Technical Specification (see Clause 6).

a) Use a specimen prepared by the procedure described in 4.2. Acquire an image, paying attention to the instructions given in 4.3 to 4.10.

b) Select a square area in the SEM image (hereafter referred to as the image) comprising at least $256 \times 256$ pixels. The area shall not have any superimposed extraneous data (e.g. magnification display, scale marker, characters, arrows, etc.).

   Choose an area containing images of preferably non-overlapping particles.

c) Store the selected SEM image in a data file in an uncompressed graphics-file format specified in 4.11.

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# 6 Evaluation methods

## 6.1 General

The evaluation methods described in 6.3 to 6.5 are based on the assumption that the electron beam has a Gaussian profile. Hence the results obtained by these methods do not represent the actual beam size (see Clause E.4). Figure 6 shows a general flow chart for the evaluation of an SEM image, including the common procedure for evaluation of the CNR given in Clause 5.

Basic procedures for obtaining the image sharpness are as follows:

a) Select an SEM image by following Clause 5.

b) Determine the CNR for the selected SEM image (see 6.2) and ensure that it is larger than or equal to 10 before proceeding further.

c) Calculate the sharpness factor $2\sigma$ for the selected SEM image in the frequency space or the real space (depending on method used). Here, the sharpness of an SEM image is determined from an equivalent image produced by convolution of a binary SEM image with a two-dimensional Gaussian profile with a sharpness factor $2\sigma$ (i.e. a twofold standard deviation).

NOTE The calculation procedure depends on the method used.

d) The image sharpness is defined as $k \times 2\sigma$, where $k = 1/\sqrt{2}$ .

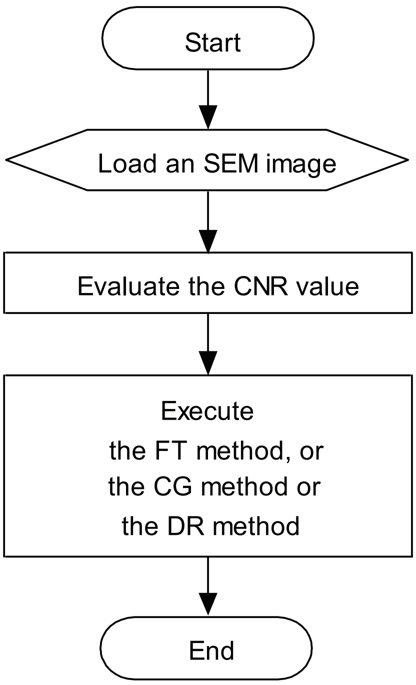


**Figure 6 — General flow chart for the evaluation of an SEM image**



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## 6.2 Contrast-to-noise ratio

The basic concept of the contrast-to-noise ratio (see 4.7) was developed in the medical imaging field. The CNR for the selected SEM image of interest shall be evaluated. Only images with CNR = 10 or larger can be passed on to the next step for evaluating image sharpness. Figure 7 shows a brief flow chart for the CNR evaluation following routines a) and b). Details of the routines are described in Annex A.

If the value of CNR is < 10, discard the SEM image. Acquire a new SEM image with lower noise and carry out the evaluation again.

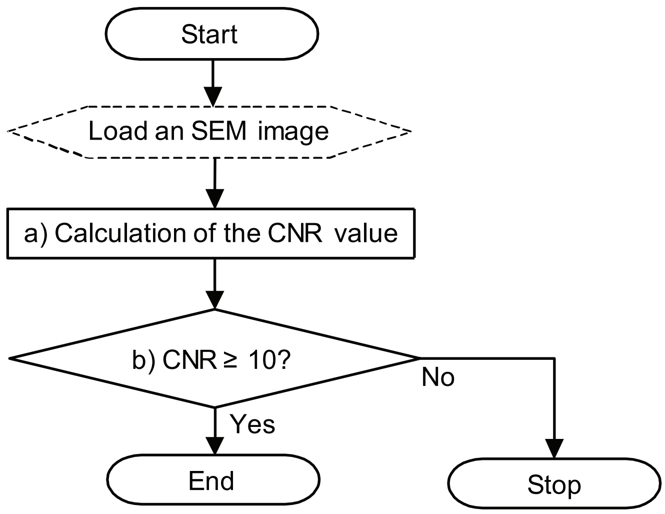


**Figure 7 — Flow chart for the evaluation of the CNR**

## 6.3 Fourier transform (FT) method

For evaluating image sharpness, the Fourier transform (FT) method is used with the spatial frequency components given by the FT of an SEM image. The spatial frequency components of the SEM image are compared with those of the images obtained by the convolution of the binarized SEM image with Gaussian profiles with various sharpness factors $2\sigma$ (see Figures 8 and 9). Details of procedures for the FT method are given in Annex B.

NOTE The signal intensity of an image $I_\mathrm{m}$ is expressed as $I_\mathrm{m}(i, j)$, and the coordinates $i$ and $j$ are chosen as 0, 1, …, $L - 1$ for an image with $x$- and $y$-size $L$ (= 256, 512, …). However, the coordinates $i$ and $j$ are treated as integers ranging from $-L/2$ to $(L/2) - 1$ for the FT pattern.

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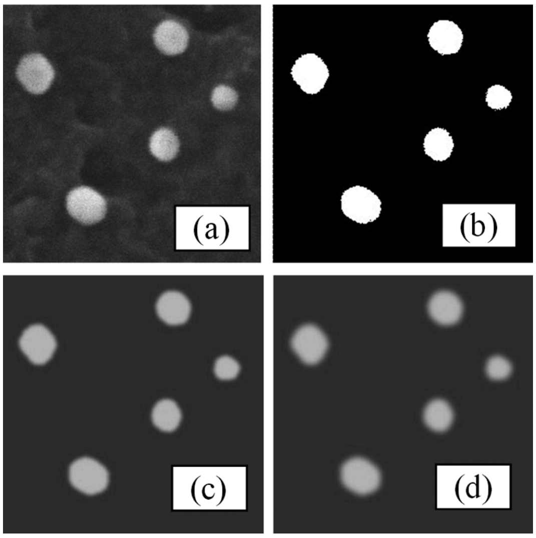
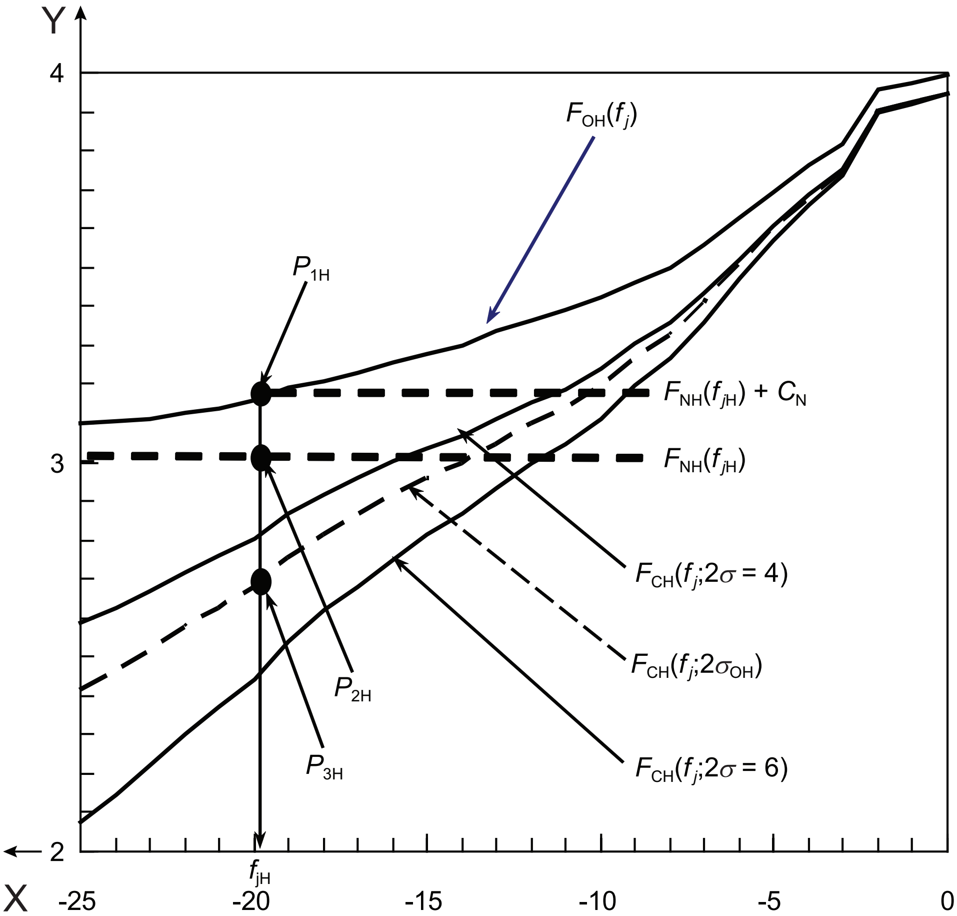



**Figure 8 — (a) a selected SEM image $I_O(i, j)$ with image size $L = 256$, (b) the binarized image $I_B(i, j)$, (c) and (d) the convoluted images $I_C(i, j; 2\sigma)$ with $2\sigma = 4$ pixels and $I_C(i, j; 2\sigma)$ with $2\sigma = 6$ pixels, respectively**




**Key**

X horizontal coordinate $f_j$ (pixels)

Y FT intensity $F_{*H}(f_j)$

$*$ stands for C, N or O.

**Figure 9 — Averaged and smoothed FT curves plotted as common logarithms: $F_{OH}(f_j)$ for the selected SEM image $I_O(i, j)$, and $F_{CH}(f_j; 2\sigma)$ and $F_{CH}(f_j; 2\sigma_{OH})$ for the convoluted images $I_C(i, j; 2\sigma)$ and $I_C(i, j; 2\sigma_{OH})$, respectively**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a) Generation of a convoluted image

1) Generate a filtered image $I_{OF}(i, j)$, processed by the $3 \times 3$ median filter, of a selected SEM image $I_O(i, j)$.

2) Produce a histogram $H(S)$ of $I_{OF}(i, j)$ and then obtain a smoothed histogram $H_s(S)$ by using the moving averages of 9 points. Then calculate $h_s(S) = \log_{10}[H_s(S) + 1]$.

3) Determine $S_L$ and $S_H$ that correspond to the intensities of the substrate and the particles, respectively, and determine a threshold level $(S_L + S_H)/2$ by using $h_s(S)$.

4) Produce a binarized image $I_B(i, j)$ by using $(S_L + S_H)/2$.

5) Add the white noise to the selected image $I_O(i, j)$ by setting $SNR_p$ (signal-to-noise ratio for particles) to 30 for the signal intensity $S = 192$.

6) Generate convoluted images $I_C(i, j; 2\sigma)$ by convolution of the binarized image $I_B(i, j)$ with two-dimensional Gaussian profiles with various sharpness factors $2\sigma = 2\sigma(N)$ beginning with $2\sigma(1) = 1$, where each $\sigma$ corresponds to the standard deviation of the Gaussian distribution and $N$ (=1, 2, …) is the step number.

7) Adjust the intensity of the various convoluted images $I_C(i, j; 2\sigma)$ so that the maximum and the minimum intensities are $S_H$ and $S_L$, respectively.

b) Generation of curves of FT patterns

1) Carry out the FT for the selected SEM image $I_O(i, j)$ and the various convoluted images $I_C(i, j; 2\sigma)$. $G_O(f_i, f_j)$ and $G_C(f_i, f_j; 2\sigma)$ represent the FT patterns corresponding to $I_O(i, j)$ and $I_C(i, j; 2\sigma)$, respectively.

2) Obtain the horizontally averaged-and-smoothed value of $|\mathrm{Re}[G_O(f_i, f_j)]|$ and the vertically averaged-and-smoothed value of $|\mathrm{Re}[G_O(f_i, f_j)]|$ and calculate the curves $F_{OHA}(f_j)$ and $F_{OVA}(f_i)$ by taking the common logarithm of them.

NOTE Re[…] denotes the real part and $|\ldots|$ denotes the absolute value.

3) Obtain the averaged curves of $F_{OH}(f_j)$ and $F_{OV}(f_i)$ by applying the moving averages of 5 points along the horizontal $f_j$ and the vertical $f_i$ directions for the curves $F_{OHA}(f_j)$ and $F_{OVA}(f_i)$, respectively.

4) Obtain the averaged curves $F_{CHB}(f_j; 2\sigma)$ and $F_{CVB}(f_i; 2\sigma)$ for $G_C(f_i, f_j; 2\sigma)$ in a similar manner.

c) Calculation of temporary image sharpness $R_{PXO}$

1) Determine the noise areas for both of the curves $F_{OH}(f_j)$ and $F_{OV}(f_i)$ and then obtain the respective noise functions $F_{NH}(f_j)$ and $F_{NV}(f_i)$ in the noise areas by linear approximation.

2) Calculate the corrected curves $F_{CH}(f_j; 2\sigma)$ and $F_{CV}(f_i; 2\sigma)$ from the averaged curves $F_{CHB}(f_j; 2\sigma)$ and $F_{CVB}(f_i; 2\sigma)$ by using the signal and noise intensities at the origin of $(f_i, f_j)$.

3) Obtain the value $f_i = f_{jC}$ by using $F_{OH}(f_j)$, $F_{NH}(f_j)$ and a specified constant $C_N$ and then calculate the horizontal coordinate $f_{jH}$ from $f_{jC}$ by linear interpolation.

4) From the functions obtained, determine the coordinates of three points, $P_{1H}$ [on the curve $F_{OH}(f_j)$], $P_{2H}$ [on the line $F_{NH}(f_j)$] and $P_{3H}$ [on the curve $F_{CH}(f_j; 2\sigma_{OH})$], lying on a vertical line with horizontal coordinate $f_j$ as shown in Figure 9.

5) Determine the coordinates of the three points $P_{1V}$ [on the curve $F_{OV}(f_i)$], $P_{2V}$ [on the line $F_{NV}(f_i)$] and $P_{3V}$ [on the curve $F_{CV}(f_i; 2\sigma_{OV})$] in a similar manner.

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6) Obtain the sharpness factors $2\sigma_{OH}$ and $2\sigma_{OV}$ by linear interpolation of $2\sigma(N)$ by increasing the step number $N$.

7) Calculate the sharpness factor $2\sigma_O$ from $2\sigma_O = (2\sigma_{OH} + 2\sigma_{OV})/2$.

8) Calculate the temporary image sharpness $R_{PXO}$ from $R_{PXO} = 2\sigma_O / \sqrt{2}$ .

d) Calculation of the image sharpness $R_{PX}$

1) Calculate the coefficient $C_F$ from the sharpness factor $2\sigma_O$ used for calibration.

2) Obtain the calibrated sharpness factor $2\sigma_C$ by using the coefficient $C_F$.

3) Evaluate the image sharpness $R_{PX}$ from $R_{PX} = 2\sigma_C / \sqrt{2}$ .

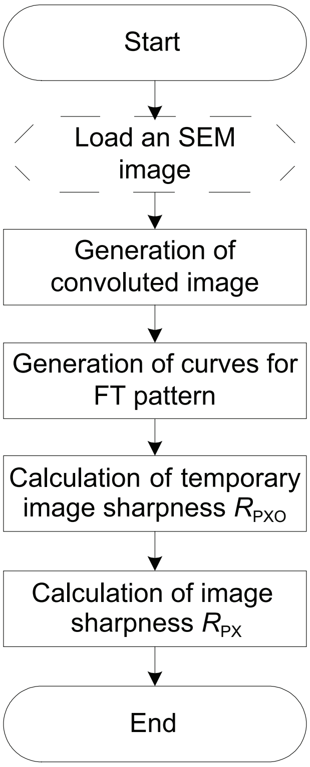


**Figure 10 — Brief flow chart of processes in the FT method**

## 6.4 Contrast-to-gradient (CG) method

The contrast-to-gradient (CG) method is based on the extraction of the intensity gradient at each pixel in the image by fitting a quadratic surface to the $3 \times 3$ area centred at each pixel point [see Figure 11 b)]. The CG image sharpness $R_{CG}$ is inversely proportional to the weighted harmonic mean of the gradients. Finally, the CG image sharpness $R_{CG}$ is converted to the image sharpness $R_{ES}$ using standard images with various sharpness factors $2\sigma$.


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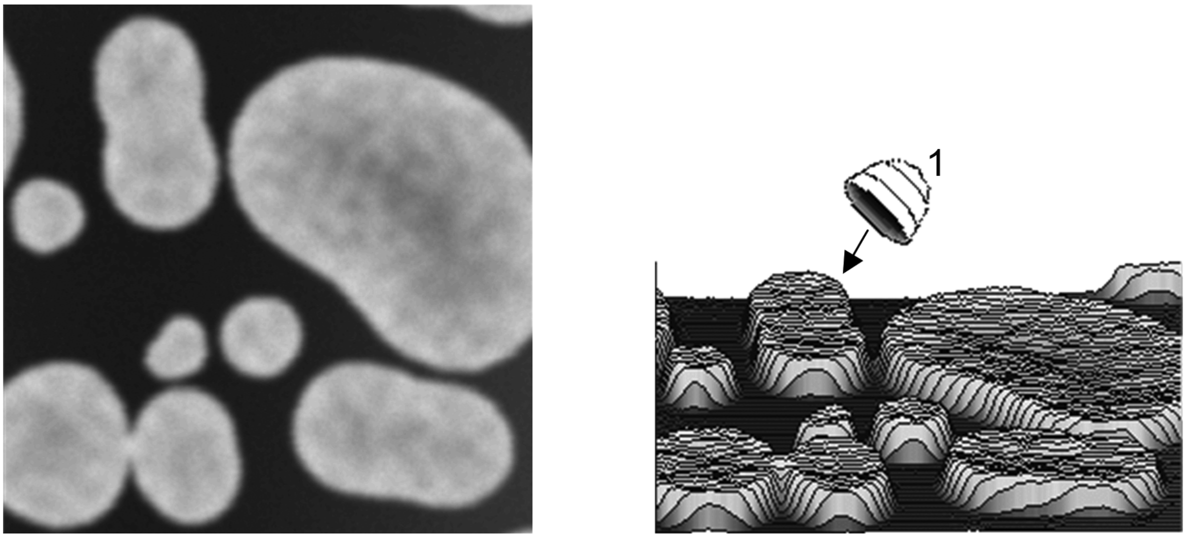


a) Original SEM image

b) Depth image corresponding to the original image, showing a typical quadratic surface fitted to the $3 \times 3$ area centred at a pixel point

**Key**

1 quadratic surface

**Figure 11 — Original SEM image and the fitting of a quadratic surface to the $3 \times 3$ area centred at each pixel point of the corresponding depth image**

The image sharpness has little noise-dependency and is evaluated with the CNR as a given parameter. Figure 12 shows a brief flow chart of the CG method composed of the following routines a) to d). Details of the routines are given in Annex C.

a) Calculation of the CG image sharpness $R_{\mathrm{CG}}$ for the original image

A number of reduced images are generated using reduction factors $r$ equal to 1, 2, 3, 4, 5, 6, 8, 10, 12, 15 and 20. Each reduced image is labelled as a ($1/r$)-size image (1/2-size, 1/4-size, etc.). With the above convention, the ($1/r$)-size image for $r = 1$ is the original image. The image reduction works to reduce the image noise at the cost of image-sampling frequency. In routine b) given below, the following four kinds of sharpness are calculated: local sharpness, directional sharpness, directionally averaged sharpness and CG image sharpness. The first three kinds of sharpness are calculated for each reduced image. The last kind of sharpness, which characterizes the image, is determined from curves of $R$ and $\Delta R/R$ vs $r$, where $\Delta R$ is the fluctuation in $R$.

1) Local sharpness

In each image, the local sharpness at any pixel $(i, j)$ is calculated as follows:

$$R_{\mathrm{p}}(i, j;\ \theta) = 2\Delta C/g(i, j;\ \theta)$$

where

$\Delta C$ is the threshold contrast;

$g(i, j;\ \theta)$ is the local gradient with directional information $\theta$.

The local gradient is found by fitting a quadratic surface over a $3 \times 3$ pixel area centred at each pixel $(i, j)$. The fitting error $\Delta g$ provides the fluctuation in $R_{\mathrm{p}}$, i.e. $\Delta R_{\mathrm{p}}$.

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2) Directional sharpness

The directional sharpness $R_k$, defined as the weighted harmonic mean of the local sharpness in the $k$th sector of azimuth angle $\theta$ in the image, is calculated. The values of $\Delta R_k/R_k$ are also calculated using $\Delta R_\mathrm{p}/R_\mathrm{p}$.

3) Directionally averaged sharpness

The directionally averaged sharpness $R$, defined as the root mean square of $R_k$, is calculated. The values of $\Delta R/R$ are also calculated using $\Delta R_k/R_k$.

4) CG image sharpness

The CG image sharpness $R_\mathrm{CG}$ is defined as follows. Graphs of $R$ and $\Delta R/R$ vs $r$ are drawn, where $R$ and $\Delta R/R$ are the values of $R_r$ and $\Delta R_r/R_r$ when $r = 1$, for all the reduced images. The reduction value $r_\mathrm{min}$ at which $\Delta R/R$ is a minimum is then found. The CG image sharpness $R_\mathrm{CG}$ is defined as $R$ at $r = r_\mathrm{min}$. The CG image sharpness is considered to be a reliable sharpness because $\Delta R/R$ is at a minimum. It is inherently influenced by the amount of noise.

b) Generation of standard images and calculation of their CG image sharpness $R_\mathrm{CG}$

Standard images are blurred images formed by convoluting a binary SEM image with Gaussian profiles having different known sharpness factors $2\sigma$ and adding the Gaussian random noise so that the contrast-to-noise ratio of the standard image is equal to that of the original SEM image.

c) Calibration of the conversion constants $A$ and $B$

The conversion constants $A$ and $B$ vary with both the structure and size of the SEM image and the image noise. So the constants are calibrated for each SEM image evaluated, using the standard images with different known sharpness factors $2\sigma$.

d) Conversion of the $R_\mathrm{CG}$ value to the image sharpness $R_\mathrm{ES}$ using the calibrated constants $A$ and $B$

$$R_\mathrm{ES} = k \times 2\sigma$$

where

$k = 1/\sqrt{2}$;

$2\sigma$ is the sharpness factor, given by

$$2\sigma = A \times R_\mathrm{CG} + B$$

Here, the image sharpness $R_\mathrm{ES}$ shows little noise-dependency and is evaluated with the CNR value as a given parameter.


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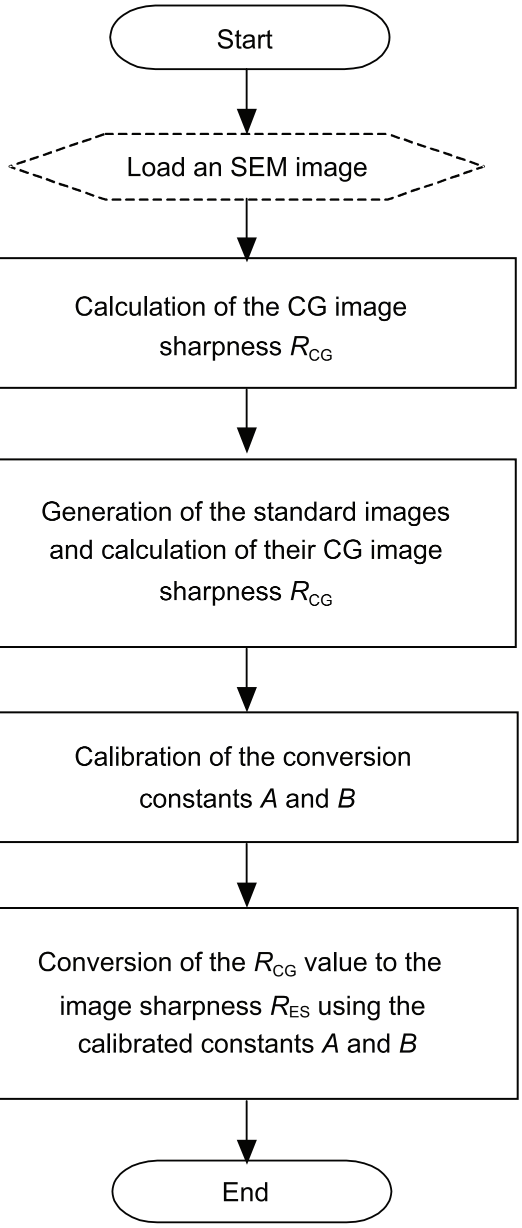


**Figure 12 — Brief flow chart of the CG method**

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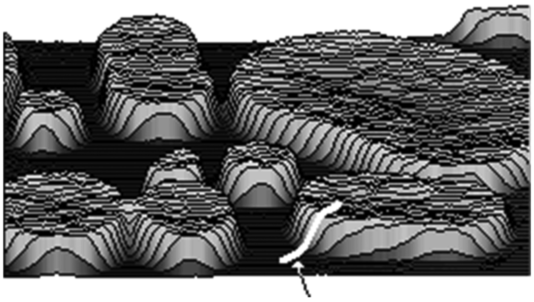
## 6.5 Derivative (DR) method

The derivative method is based on the extraction of edge profiles and the fitting of error functions to them. The method is built on the fact that the sharpness of edges relates to a parameter defined by the Rayleigh-Abbe criterion. Thus the method can determine the edge sharpness. To do this, edge profiles are modelled as error functions. If the point-spread function is assumed to be a Gaussian profile, the profile of an edge in an SEM image can be approximated by an error function. This error function is fitted to all the extracted profiles in the image (see Figure 13). From their average, the sharpness factor, which is, by definition, related to the image sharpness, is derived.




**Key**

1 error function fitting

**Figure 13 — Basic concept of the derivative (DR) method**

Figure 14 shows a brief flow chart of the DR method composed of the following routines a) to d). Details of the routines are given in Annex D.

a) Generation of a binary mask image $M(x, y)$

1) The gradient magnitude $G_M(x, y)$ is computed by convoluting the original image with first-order derivative Gaussian profiles of standard deviation $\sigma$ equal to 2 pixels.

2) A binary image $B(x, y)$ is computed from $G_M(x, y)$, based on a two-mean threshold.

3) A binary mask image $M(x, y)$ is computed by cleaning up $B(x, y)$ by a one-iteration binary-closing operation. Then all object pixels that are close to the image borders are set to zero and all objects that contain little pixels are discarded.

b) Generation of an edge position map $E(x, y)$

1) An edge location image $P_L(x, y)$ is computed by convoluting the original image with first- and second-order derivative Gaussian profiles of standard deviation $\sigma$.

2) A binary mask $M_1(x, y)$ is computed from the maximum value of $[P_L(x, y) - |P_L(x, y)|]$, based on a two-mean threshold within $M(x, y)$.

3) An initial binary edge map image $E_1(x, y)$ is computed by skeletonization from the result of the one-iteration binary-closing operation carried out on $M_1(x, y)$.

4) An edge position map $E(x, y)$ is computed from $E_1(x, y)$ by considering only positions along a contour that are separated from each other by a distance of at least 10 pixels.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c) Extraction of the edge profiles $P_j(x, y)$ and fitting of an error function

1) The normalized gradient $G_\mathrm{N}(x, y)$ is computed for all positions of $E(x, y)$, based on the normalization of $G_\mathrm{M}(x, y)$.

2) The sub-pixel profile positions $P_{\mathrm{S}i}(x, y)$ are calculated from the initial edge positions given by $E(x, y)$ along both directions of $G_\mathrm{N}(x, y)$ for a total of 41 positions with a pitch of 0,5 pixels.

3) The sub-pixel intensity values $P_j(x, y)$ at $P_{\mathrm{S}i}(x, y)$ are retrieved from the original image at the profile positions by cubic interpolation.

4) An error function is fitted to each $P_j(x, y)$ and the edge sharpness $s_j$ is calculated and stored.

d) Calculation of image sharpness $R_\mathrm{DR}$

1) The overall edge sharpness $s$ is calculated as the average of the edge sharpnesses of all the edge slopes determined.

2) The image sharpness $R_\mathrm{DR}$ is calculated as $R_\mathrm{DR} = \sqrt{2}s$ .

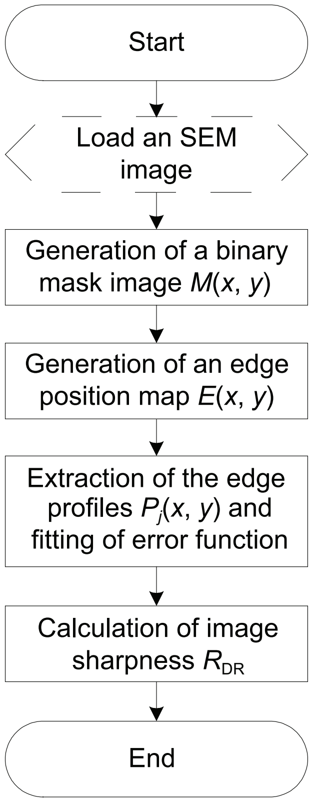


**Figure 14 — Brief flow chart of the DR method**

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# 7 Test report

## 7.1 General

The test report prepared by the laboratory shall be accurate, clear and unambiguous, and in accordance with the specific instructions in the evaluation methods described in this Technical Specification.

In addition to the results of the evaluation, the information prescribed in 5.10.2 of ISO/IEC 17025:2005 shall be supplied. The results may be reported in a simplified way, subject to the written agreement of an external client or by mutual understanding with internal clients. Information prescribed in 5.10.2 of ISO/IEC 17025:2005 which is not reported to the client shall be readily available in the laboratory which carried out the tests.

## 7.2 Contents of test report

The test report shall include the items given below and any other relevant information which could affect any of the results reported therein (an example of a test report is given in Annex H):

a) a title for the test report;

b) the name and address of the laboratory;

c) an identification number for the test report;

d) name and address of the client where relevant;

e) identification of the method used (i.e. ISO/TS 24597, FT method, CG method or DR method);

f) the name of the manufacturer, the name of the model and the serial number of the instrument used;

g) the name(s) of the reference material(s) used;

h) the specific operating values of the accelerating voltage (in kV), the working distance (in mm) and the magnification set, as well as any additional information, if considered necessary (imaging mode, scan speed, etc.);

i) the original SEM image(s), corresponding image size(s) and data files with file name(s), selected image file name(s), binary SEM image files with file name(s) and their image sizes (number of pixels);

j) the name of the person conducting the evaluation;

k) the date and time of the evaluation;

l) the name(s), function(s) and signature(s) of the person(s) authorizing the evaluation certificate;

m) where relevant, a statement to the effect that the results relate only to the items tested.

The data files of the original SEM images and the selected SEM images used in obtaining the reported results shall be kept for a specified mandatory period.

Laboratories issuing a test report shall specify that the report shall only be reproduced in full and with the written permission of the laboratory.


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# Annex A
(normative)

# Details of contrast-to-noise ratio (CNR)

This annex provides details of the evaluation of contrast-to-noise ratio (CNR). A flow chart of the CNR evaluation is given in Figure A.1.

NOTE The explanation applies to an image with $L = 512$ or 256 and 8 bits in the grey scale for ease of understanding.

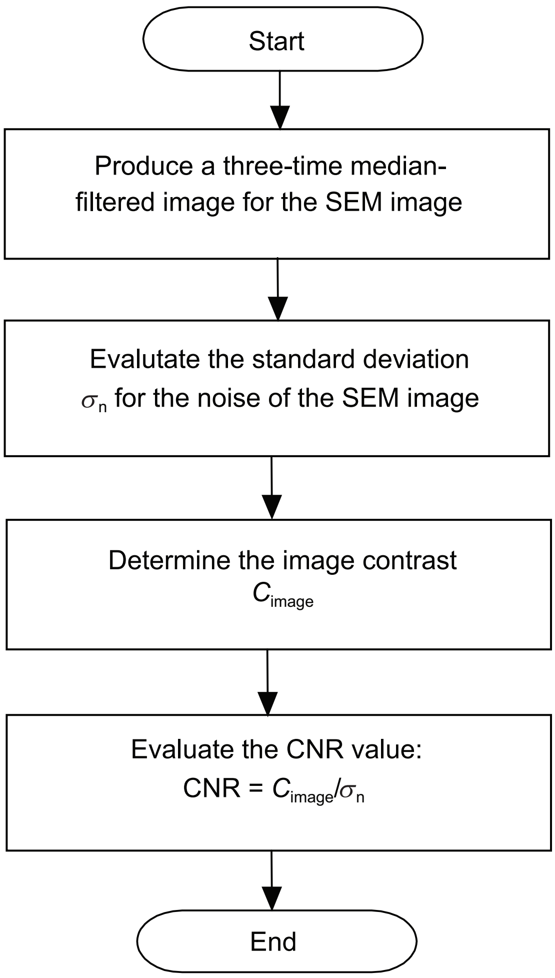


**Figure A.1 — Flow chart of the CNR evaluation**

a) Produce a median-filtered image by carrying out (unweighted $3 \times 3$) median filtering three times sequentially for the SEM image. The filter matrix is a $3 \times 3$ matrix. Hereafter, the resultant image will be called a three-time median-filtered image.

NOTE 1 The principle of $3 \times 3$ median filtering is shown in Figure A.2. The median filtering is calculated by first sorting the intensities of the pixels in the $3 \times 3$ square into ascending (or descending) order and then replacing the pixel intensity $I(i, j)$ at pixel $(i, j)$ with the middle (or fifth) pixel intensity.

NOTE 2 Any pixel position of the image is expressed as $(i, j)$, where $i$ (and $j$) = 0, 1, 2, …, and $i_{max}$ (and $j_{max}$).



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NOTE 3 Both $i_{max}$ and $j_{max} = 511$ (or 255) (depending on the pixel size of the original SEM image, namely 512 × 512 or 256 × 256).

NOTE 4 Edge pixels are processed in a special way for median filtering (see the end of this annex).

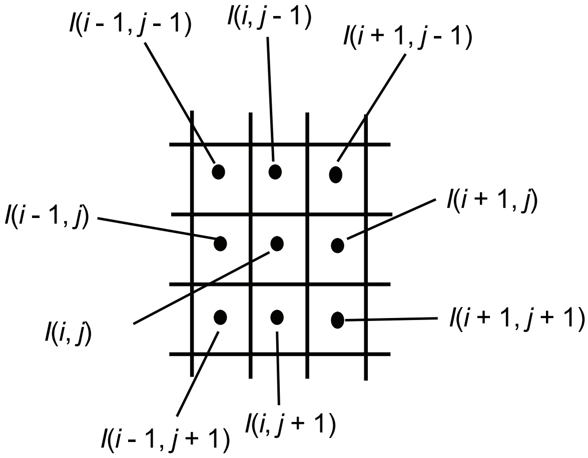


**Figure A.2 — The principle of 3 × 3 median filtering: the figure shows the pixel $(i, j)$ concerned and its neighbouring pixels in the 3 × 3 square**

b) Evaluate the standard deviation $\sigma_n$ of the image noise:

$$\sigma_n = \sqrt{\frac{\sum_{j=0}^{j_{max}} \sum_{i=0}^{i_{max}} [I_{med}(i,j) - I(i,j)]^2}{(i_{max}+1)\times(j_{max}+1)}} \tag{A.1}$$

where $I_{med}(i, j)$ and $I(i, j)$ are the pixel intensities at pixel position $(i, j)$ of the three-time median-filtered and SEM images, respectively.

NOTE The denominator $(i_{max} + 1) \times (j_{max} + 1)$ corresponds to the total number of pixels in the median-filtered region (see Figure A.3).

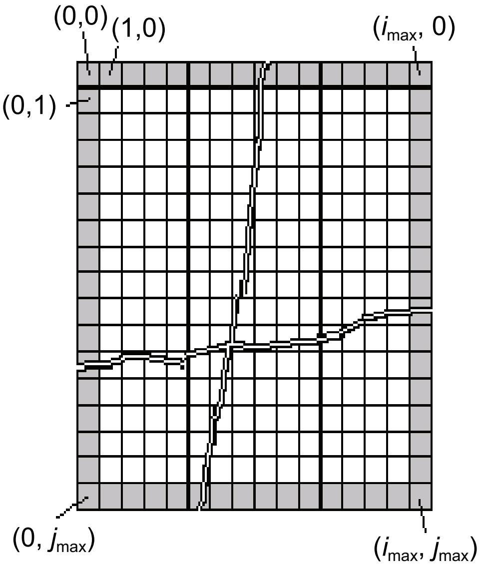


**Figure A.3 — Intensities of a three-time median-filtered image**



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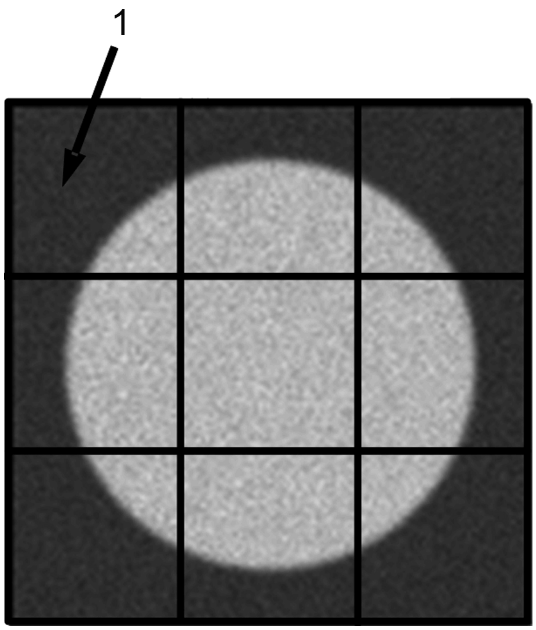
c) Determine the image contrast $C_{\mathrm{image}}$.

1) Divide the three-time median-filtered SEM image into nine (or $3 \times 3$) segment-images as shown in Figure A.4.

NOTE The $i$ (or $j$) region is divided into three ranges from 1 to 170, 171 to 340 and 341 to 510 for $i_{\mathrm{max}}$ (or $j_{\mathrm{max}}$) = 511 and from 1 to 84, 85 to 169 and 170 to 254 for the image of $i_{\mathrm{max}}$ (or $j_{\mathrm{max}}$) = 255.

2) For each segment $s$, make a sequence of increasing or decreasing intensity as shown in Figure A.5.

3) For each segment $s$, compute $z_{\mathrm{max,av},s}$ by arithmetically averaging the first to $q$th elements of the descending intensity sequence and compute $z_{\mathrm{min,av},s}$ by arithmetically averaging the first to $q$th elements of the ascending intensity sequence. Here, $q$ is an integer that corresponds to 0,2 % of the number of elements in the sequence. The minimum value of $q$ is 1.




**Key**

1 segment-image

**Figure A.4 — Nine segment-images**

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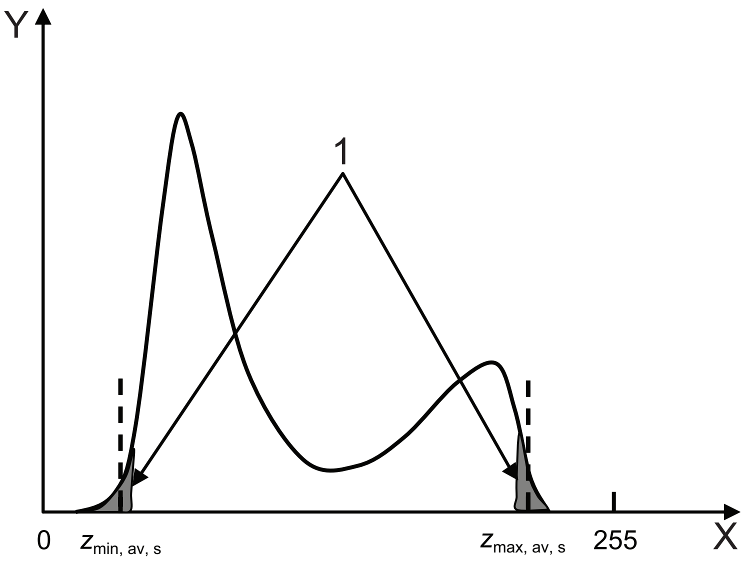


**Key**

X intensity level

Y number of elements

1 0,2 % of the number of elements in the sequence

**Figure A.5 — Intensity sequence for segment-image** $s$

4) Determine the threshold intensity $z_{\text{threshold},s\text{-av}}$ as follows:

$$z_{\text{threshold},s\text{-av}} = [\text{Maximum}\ (z_{\text{max,av,0}}, z_{\text{max,av,1}}, \cdots, z_{\text{max,av,8}}) + \text{Minimum}\ (z_{\text{min,av,0}}, z_{\text{min,av,1}}, \cdots, z_{\text{min,av,8}})]/2 \quad \text{(A.2)}$$

5) Determine the averages $\text{Av}z_{\text{max,av},s}$ and $\text{Av}z_{\text{min,av},s}$ from the following equations:

$$\text{Av}z_{\text{max,av},s} = \text{Average (only for } z_{\text{max,av},s} > z_{\text{threshold},s\text{-av}}) \text{ of } (z_{\text{max,av,0}}, z_{\text{max,av,1}}, \cdots, z_{\text{max,av,8}}) \quad \text{(A.3)}$$

$$\text{Av}z_{\text{min,av},s} = \text{Average (only for } z_{\text{min,av},s} < z_{\text{threshold},s\text{-av}}) \text{ of } (z_{\text{min,av,0}}, z_{\text{min,av,1}}, \cdots, z_{\text{min,av,8}}) \quad \text{(A.4)}$$

6) Calculate the temporary contrast $C_{\text{temp}}$ of the image from the following equation:

$$C_{\text{temp}} = \text{Av}z_{\text{max,av},s} - \text{Av}z_{\text{min,av},s} \quad \text{(A.5)}$$

7) Determine the image contrast $C_{\text{image}}$ by correcting $C_{\text{temp}}$ using a correction term $k_{\text{corr}} \times \sigma_{\text{n}}$, where $k_{\text{corr}} = 1{,}38$ (empirical value), as follows:

$$C_{\text{image}} = C_{\text{temp}} - k_{\text{corr}} \times \sigma_{\text{n}} \quad \text{(A.6)}$$

d) Evaluate the CNR value of the SEM image as follows:

$$\text{CNR} = C_{\text{image}}/\sigma_{\text{n}} \quad \text{(A.7)}$$

The values of $\text{Av}z_{\text{max,av},s}$ and $\text{Av}z_{\text{min,av},s}$ shall be in the ranges $245 \geqslant \text{Av}z_{\text{max,av},s} \geqslant 170$ and $80 \geqslant \text{Av}z_{\text{min,av},s} \geqslant 10$ (for 8 bits in the grey scale), respectively. If the values are not in their corresponding ranges, discard the SEM image.


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**3 × 3 median filtering:**

$$F_{\mathrm{OUT}}(i, j) = M_{\mathrm{ED}}[F_{\mathrm{IN}}(i-1, j-1), F_{\mathrm{IN}}(i-1, j), F_{\mathrm{IN}}(i-1, j+1), F_{\mathrm{IN}}(i, j-1), F_{\mathrm{IN}}(i, j), F_{\mathrm{IN}}(i, j+1), F_{\mathrm{IN}}(i+1, j-1), F_{\mathrm{IN}}(i+1, j), F_{\mathrm{IN}}(i+1, j+1)]$$

where

$F_{\mathrm{IN}}(i, j)$ is the input image data for $511 \geqslant i, j \geqslant 0$ (for an SEM image with 512 × 512 pixels);

$F_{\mathrm{OUT}}(i, j)$ is the 3 × 3 median-filtered data.

The median-filtering function $M_{\mathrm{ED}}(a_1, a_2, \ldots, a_N)$ sorts the values $a_n$ ($n = 1, 2, \ldots, N$) into ascending order and finds the median value for odd values of $N$ or the mean value of the ($N$/2)th and [($N$/2) + 1]th values in the series for even values of $N$.

NOTE If $i - 1 < 0$, $i + 1 > 511$, $j - 1 < 0$ or $j + 1 > 511$, discard the corresponding $F_{\mathrm{IN}}(\ldots, \ldots)$ and carry out $M_{\mathrm{ED}}[\ldots\ldots]$.

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# Annex B
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# Details of the Fourier transform (FT) method

## B.1 General

This annex provides details of the procedure used for the Fourier transform (FT) method.

Figure B.1 shows an example of an SEM image.

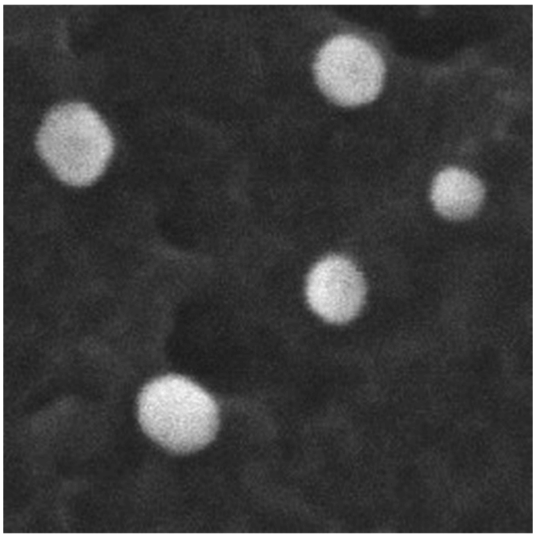

**Figure B.1 — Example of an SEM image**

## B.2 Generation of convoluted images

a) Prepare a filtered image $I_{OF}(i, j)$, processed three times sequentially by the unweighted $3 \times 3$ median filter, of a selected SEM image $I_O(i, j)$ by using the procedure described in B.6.1.

b) Produce a histogram $H(S)$ (where $S = 0, 1, 2, 3, \ldots, 255$) of the filtered image $I_{OF}(i, j)$.

c) Obtain a smoothed histogram $H_s(S)$ from $H(S)$ by applying the procedure in B.6.2, using the window of nine points. Then calculate $h_s(S) = \log_{10}[H_s(S) + 1]$.

d) Obtain two signal intensities $S_L$ and $S_H$ from the smoothed histogram. Then determine a threshold value $S_T$ by the following procedure:

1) Find the maximum values of $h_s(S)$, $h_s(S_1)$ and $h_s(S_2)$, in the intervals [0, 127] and [128, 255], respectively, which satisfy the following conditions:

$h_s(S_1 - 16) < h_s(S_1)$ and $h_s(S_1 + 16) < h_s(S_1)$;

$h_s(S_2 - 16) < h_s(S_2)$ and $h_s(S_2 + 16) < h_s(S_2)$;

$96 < S_2 - S_1$, $h_s[(S_1 + S_2)/2] < h_s(S_1) - 0{,}02$ and $h_s[(S_1 + S_2)/2] < h_s(S_2) - 0{,}02$.


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Then set $S_1$ to $S_L$ and set $S_2$ to $S_H$ and go to step 3). Otherwise, go to step 2).

If $S_1 - 16 < 0$ or $255 < S_2 + 16$, use $h_s(0)$ or $h_s(255)$ instead of $h_s(S_1 - 16)$ or $h_s(S_2 + 16)$, respectively.

2) Obtain the maximum value $S_A$ and the minimum value $S_B$ of the signal intensity $S$ so that the sum of the histogram intensity for $H_s(S)$ in each of the intervals $[0, S_A - 1]$ and $[S_B + 1, 255]$, respectively, is closest to 0,2 % (but less than 0,2 %) of $L^2$. Then, calculate two signal intensities $S_L$ and $S_H$ as follows:

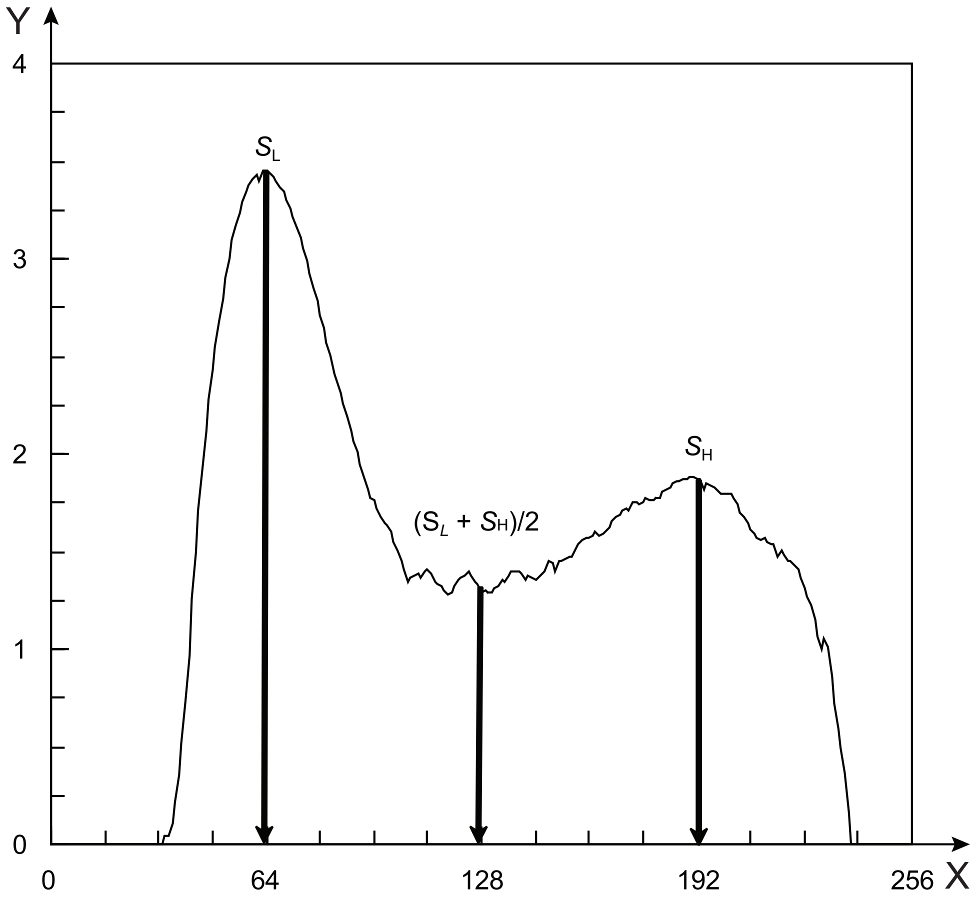
$$S_L = S_A + C_R\sqrt{S_A} \quad \text{and} \quad S_H = S_B - C_R\sqrt{S_B}$$

where $C_R = (S_B - S_A)/128$

3) Calculate the threshold value $S_T$ (see Figure B.2) as follows:

$$S_T = (S_L + S_H)/2$$

e) Obtain a binarized image $I_B(i, j)$ by applying the threshold value $S_T$ (see Figure B.3).




**Key**

X signal intensity $S$ (from 0 to 255)

Y $h_s(S)$ (logarithmic values)

**Figure B.2 — Example of a smoothed histogram**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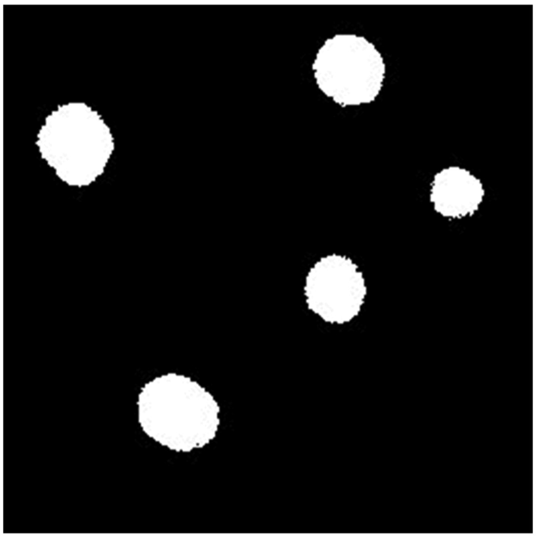

**Figure B.3 — Example of a binarized image** $I_B(i, j)$

f) Add the white noise to the selected image $I_O(i, j)$ so that the effect of weak correlated noise is neglected, as follows:

1) Set $SNR_p$ (signal-to-noise ratio for particles) to 30 for the signal intensity $S = 192$ and calculate the noise intensity $s_n(i, j)$ for the selected image intensity $I_O(i, j)$ as follows:

$$s_n(i, j) = [I_O(i, j) \cdot S]^{1/2} / \mathrm{SNR_p} = [I_O(i, j) \cdot 192]^{1/2} / 30$$

2) Obtain the intensity $I_{ON}(i, j)$ of the noisy image as follows:

$$I_{ON}(i, j) = I_O(i, j) + s_n(i, j) \cdot r_G$$

where $r_G$ is a random value which obeys the normal distribution with a mean value of 0 and a standard deviation of 1.

NOTE This is done by setting $I_{ON}(i, j; 2\sigma)$ to 0 if $I_{ON}(i, j; 2\sigma) < 0$ and setting $I_{ON}(i, j; 2\sigma)$ to 255 if $255 < I_{ON}(i, j; 2\sigma)$.

3) Set $I_{ON}(i, j)$ to $I_O(i, j)$.

g) Generate convoluted images $I_C(i, j; 2\sigma)$ by using the convolution of the binarized image $I_B(i, j)$ with two-dimensional Gaussian profiles $I_G(i, j; 2\sigma)$ having various sharpness factors $2\sigma$, given by

$$I_G(i, j; 2\sigma) = \exp\left[-\frac{1}{2\sigma^2}(i^2 + j^2)\right]$$

where $\sigma$ is the standard deviation of the Gaussian distribution.

1) Set the sharpness factor $2\sigma(N = 1)$ to 1 as the initial step. During the evaluation process, $2\sigma(N)$ is increased in the following way:

if $1 \leqslant N \leqslant 8$, then $2\sigma(N) = N$;

if $9 \leqslant N$, then $2\sigma(N) = 2^{Q+1} + 2^{Q-1} \cdot (N - 4Q)$.



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where $Q$ is the integer part of $N/4$ $(N = 4Q + \text{remainder})$.

NOTE $N$ is the step number. The maximum values of $N$ and $2\sigma(N)$ are $24 + 4[(\log_2 L) - 8]$ and $L/2$, respectively.

2) Compute the Fourier transform pattern $G_B(f_i, f_j)$ of the binarized image $I_B(i, j)$.

3) Compute the Fourier transform pattern $G_G(f_i, f_j; 2\sigma)$ of the Gaussian profile $I_G(i, j; 2\sigma)$ with a sharpness factor $2\sigma$ equal to $2\sigma(N)$ for the $N$th step in a similar manner.

4) Calculate the product of $G_B(f_i, f_j)$ and $G_G(f_i, f_j; 2\sigma)$:

$$G_{BG}(f_i, f_j; 2\sigma) = G_B(f_i, f_j) \cdot G_G(f_i, f_j; 2\sigma)$$

5) Obtain the image $I_{BG}(i, j; 2\sigma)$ from $G_{BG}(f_i, f_j; 2\sigma)$ by applying the inverse Fourier transform.

6) Obtain the convoluted images $I_C(i, j; 2\sigma)$ (see Figure B.4) as follows:

$$I_C(i, j; 2\sigma) = \frac{S_H - S_L}{\max[|I_{BG}(i, j; 2\sigma)|]} |I_{BG}(i, j; 2\sigma)| + S_L$$

where the mathematical symbol | … | means "the absolute value of" and max[…] means "the maximum value of".

**a)** $2\sigma = 2$ pixels

**b)** $2\sigma = 4$ pixels

**c)** $2\sigma = 6$ pixels

**Figure B.4 — Examples of convoluted images $I_C(i, j; 2\sigma)$ with image size $L = 256$**

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## B.3 Generation of curves of FT patterns

The following procedures a), c), d) and e) are performed once for the selected SEM image $I_O(i, j)$ when the step number $N = 1$.

a) Compute the Fourier transform pattern $G_O(f_i, f_j)$ of the image $I_O(i, j)$.

b) Compute the Fourier transform pattern $G_C(f_i, f_j; 2\sigma)$ of the convoluted image $I_C(i, j; 2\sigma)$.

c) Take the real part $\mathrm{Re}[G_O(f_i, f_j)]$ of $G_O(f_i, f_j)$ and then take the absolute value $|\mathrm{Re}[G_O(f_i, f_j)]|$ of the real part $\mathrm{Re}[G_O(f_i, f_j)]$.

d) Obtain the vertically averaged value and the horizontally averaged value of $|\mathrm{Re}[G_O(f_i, f_j)]|$. Then calculate their common logarithms as follows:

$$F_{\mathrm{OHA}}(f_j) = \log_{10}\left\{\varepsilon + \frac{1}{L}\sum_{p=-L/2}^{(L/2)-1} |\mathrm{Re}[G_O(p, f_j)]|\right\}$$

$$F_{\mathrm{OVA}}(f_i) = \log_{10}\left\{\varepsilon + \frac{1}{L}\sum_{q=-L/2}^{(L/2)-1} |\mathrm{Re}[G_O(f_i, q)]|\right\}$$

where

$\varepsilon$ is taken as $10^{-20}$ to avoid $\log_{10}0$ occurring;

$L$ is the image size.

e) Calculate a smoothed horizontal curve $F_{\mathrm{OH}}(f_j)$ from $F_{\mathrm{OHA}}(f_j)$ by applying the procedures in B.6.2, using a window of five points in the interval $[-L/2, (L/2) - 1]$ of $f_j$.

Obtain a smoothed vertical curve $F_{\mathrm{OV}}(f_i)$ from $F_{\mathrm{OVA}}(f_i)$ in a similar manner.

f) Take the real part $\mathrm{Re}[G_C(f_i, f_j; 2\sigma)]$ of $G_C(f_i, f_j; 2\sigma)$ and then take the absolute value $|\mathrm{Re}[G_C(f_i, f_j; 2\sigma)]|$ of the real part $\mathrm{Re}[G_C(f_i, f_j; 2\sigma)]$.

g) Obtain the vertically averaged value and the horizontally averaged value of $|\mathrm{Re}[G_C(f_i, f_j; 2\sigma)]|$. Then calculate their common logarithms as follows:

$$F_{\mathrm{CHA}}(f_j; 2\sigma) = \log_{10}\left\{\varepsilon + \frac{1}{L}\sum_{p=-L/2}^{(L/2)-1} |\mathrm{Re}[G_C(p, f_j; 2\sigma)]|\right\}$$

$$F_{\mathrm{CVA}}(f_i; 2\sigma) = \log_{10}\left\{\varepsilon + \frac{1}{L}\sum_{q=-L/2}^{(L/2)-1} |\mathrm{Re}[G_C(f_i, q; 2\sigma)]|\right\}$$

h) Calculate a smoothed horizontal curve $F_{\mathrm{CHB}}(f_j; 2\sigma)$ from $F_{\mathrm{CHA}}(f_j; 2\sigma)$ by applying the procedures in B.6.2, using a window of five points in the interval $[-L/2, (L/2) - 1]$ of $f_j$.

Calculate a smoothed vertical curve $F_{\mathrm{CVB}}(f_i; 2\sigma)$ from $F_{\mathrm{CVA}}(f_i; 2\sigma)$ in a similar manner.


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## B.4 Calculation of temporary image sharpness $R_{PXO}$

The following procedures a) to f) are performed once for the selected SEM image $I_O(i, j)$ when the step number $N = 1$.

a) Calculate the slope $m_H$ and the intercept $b_H$ by the least-squares method described in B.6.3 to obtain a linear function which approximates to the smoothed curve $F_{OH}(f_j)$ in the interval [$-L/2$, $-(L/4) - 1$] of $f_j$.

Calculate the slope $m_V$ and the intercept $b_V$ of the smoothed curve $F_{OV}(f_i)$ in the interval [$-L/2$, $-(L/4) - 1$] of $f_i$ in a similar manner.

b) Determine the noise functions as follows:

$$F_{NH}(f_j) = m_H \cdot f_j + b_H$$

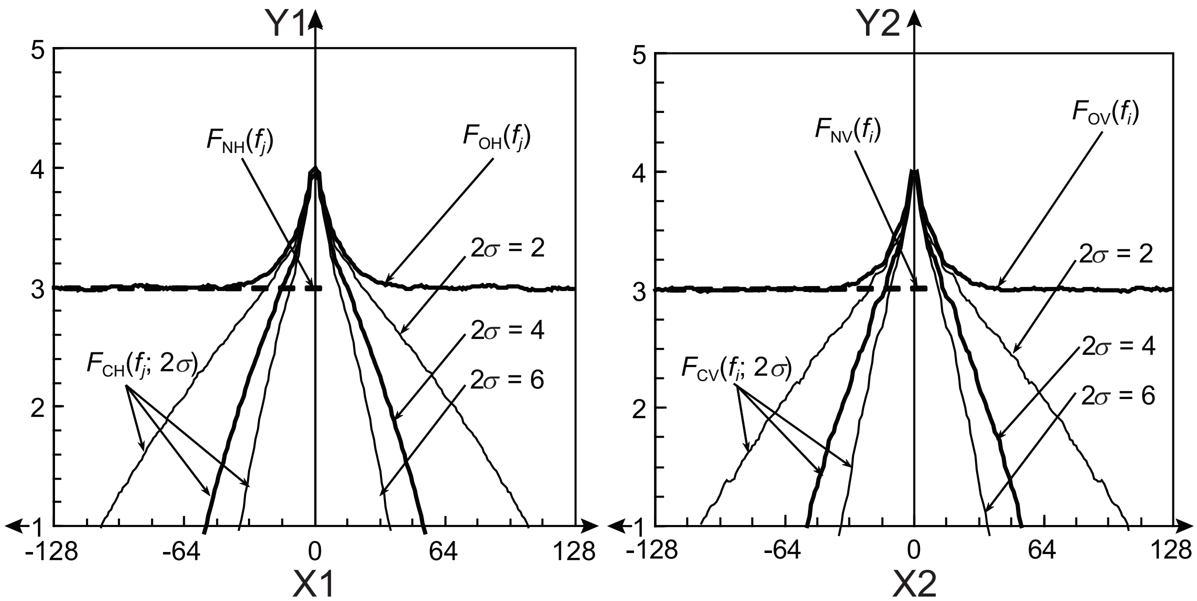
$$F_{NV}(f_i) = m_V \cdot f_i + b_V$$

c) Calculate the corrected curves $F_{CH}(f_j; 2\sigma)$ and $F_{CV}(f_i; 2\sigma)$, using the signal and noise intensities at the origin of $(f_i, f_j)$, as follows:

$$F_{CH}(f_j; 2\sigma) = F_{CHB}(f_j; 2\sigma) - [F_{CHB}(0; 2\sigma) - \log_{10}(10^{F_{OH}(0)} - 10^{b_H})]$$

$$F_{CV}(f_i; 2\sigma) = F_{CVB}(f_i; 2\sigma) - [F_{CVB}(0; 2\sigma) - \log_{10}(10^{F_{OV}(0)} - 10^{b_V})]$$

To verify the computation, it is recommended that graphs of $F_{OH}(f_j)$ and $F_{CH}(f_j; 2\sigma)$ be drawn for the horizontal direction and graphs of $F_{OV}(f_i)$ and $F_{CV}(f_i; 2\sigma)$ be drawn for the vertical direction, as shown in Figure B.5.




**Key**

X1 horizontal coordinate $f_j$ (pixels)

Y1 FT intensity $F_{*H}(f_j)$

X2 vertical coordinate $f_i$ (pixels)

Y2 FT intensity $F_{*V}(f_i)$

$*$ stands for C, N or O.

**Figure B.5 — Examples of averaged and smoothed curves for the FT patterns in the horizontal and the vertical directions**

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d) Obtain the horizontal coordinate $f_j = f_{j\mathrm{H}}$ as follows:

1) Set the parameters $A$ and $B$ as

$$A = F_{\mathrm{OH}}(f_j) \text{ and } B = F_{\mathrm{NH}}(f_j) + C_{\mathrm{N}}$$

where $C_{\mathrm{N}}$ is the contribution factor determined from the convoluted image in the Fourier space and is given by

$$C_{\mathrm{N}} = \log_{10}(1 + a_{\mathrm{N}} + \Delta a_{\mathrm{N}})$$

where

$a_{\mathrm{N}} = 0{,}5$;

$\Delta a_{\mathrm{N}} = -\,0{,}05$ (empirical value).

2) Set $f_j = -\,L/2$ as the initial value, then increase $f_j$ until the condition $A < B$ changes to $A \geqslant B$. Set $f_j = f_{j\mathrm{C}}$ for this change.

3) Calculate the horizontal coordinate $f_{j\mathrm{H}}$ as follows:

$$f_{j\mathrm{H}} = \frac{F_{\mathrm{NH}}(f_{j\mathrm{C}}) + C_{\mathrm{N}} - [F_{\mathrm{OH}}(f_{j\mathrm{C}} - 1) + m_{\mathrm{H}}]}{F_{\mathrm{OH}}(f_{j\mathrm{C}}) - [F_{\mathrm{OH}}(f_{j\mathrm{C}} - 1) + m_{\mathrm{H}}]} + (f_{j\mathrm{C}} - 1) \text{ for } A - B > 10^{-4}$$

$$f_{j\mathrm{H}} = f_{j\mathrm{C}} \text{ for } A - B \leqslant 10^{-4}$$

4) Determine at $f_j = f_{j\mathrm{H}}$ the coordinates of the point $P_{1\mathrm{H}}$ on the curve $F_{\mathrm{OH}}(f_j)$ for the original image, the point $P_{2\mathrm{H}}$ on the linear function $F_{\mathrm{NH}}(f_j)$ for the noise and the point $P_{3\mathrm{H}}$ on the curve $F_{\mathrm{CH}}(f_j;\, 2\sigma_{\mathrm{OH}})$ for the convoluted image as follows:

$$P_{1\mathrm{H}}\colon\ (f_{j\mathrm{H}}, F_{\mathrm{NH}}(f_{j\mathrm{H}}) + C_{\mathrm{N}})$$

$$P_{2\mathrm{H}}\colon\ (f_{j\mathrm{H}}, F_{\mathrm{NH}}(f_{j\mathrm{H}}))$$

$$P_{3\mathrm{H}}\colon\ (f_{j\mathrm{H}}, F_{\mathrm{NH}}(f_{j\mathrm{H}}) + \log_{10} a_{\mathrm{N}})$$

e) Obtain the vertical coordinate $f_i = f_{i\mathrm{V}}$ using $f_i = f_{i\mathrm{C}}$ in a similar manner.

Then determine at $f_i = f_{i\mathrm{V}}$ the coordinates of the point $P_{1\mathrm{V}}$ on the curve $F_{\mathrm{OV}}(f_i)$ for the original image, the point $P_{2\mathrm{V}}$ on the linear function $F_{\mathrm{NV}}(f_i)$ for the noise and the point $P_{3\mathrm{V}}$ on the curve $F_{\mathrm{CV}}(f_i;\, 2\sigma_{\mathrm{OV}})$ for the convoluted image (see Figure B.6) as follows:

$$P_{1\mathrm{V}}\colon\ (f_{i\mathrm{V}}, F_{\mathrm{NV}}(f_{i\mathrm{V}}) + C_{\mathrm{N}})$$

$$P_{2\mathrm{V}}\colon\ (f_{i\mathrm{V}}, F_{\mathrm{NV}}(f_{i\mathrm{V}}))$$

$$P_{3\mathrm{V}}\colon\ (f_{i\mathrm{V}}, F_{\mathrm{NV}}(f_{i\mathrm{V}}) + \log_{10} a_{\mathrm{N}})$$



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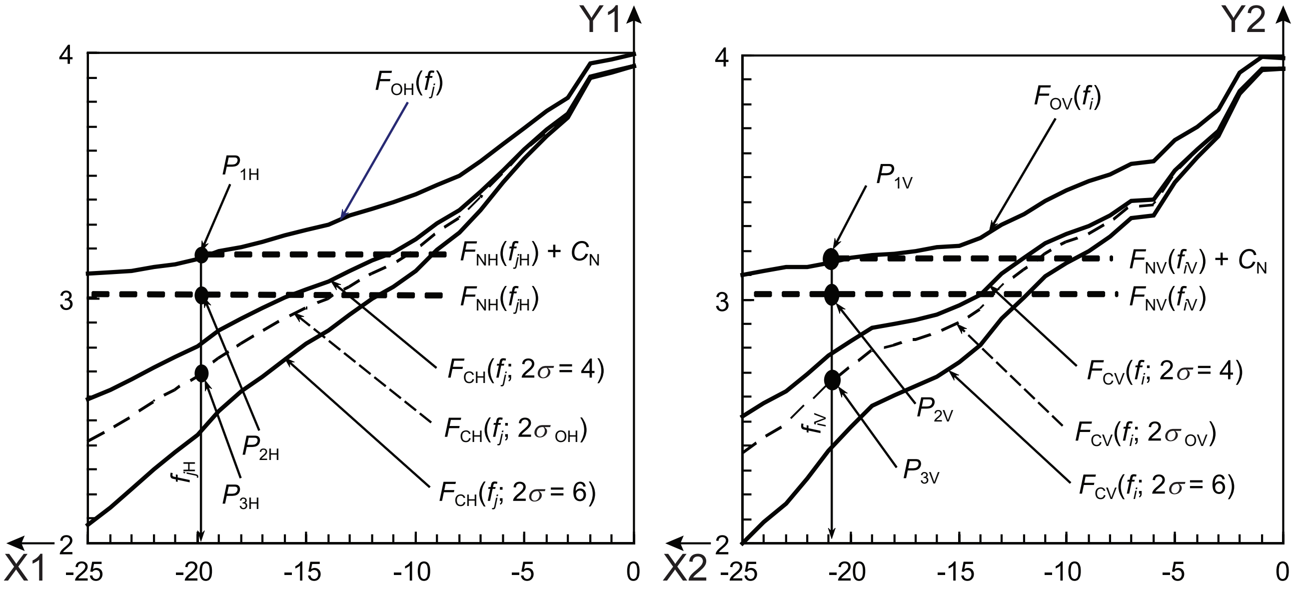


**Key**

X1 horizontal coordinate $f_j$ (pixels)

Y1 FT intensity $F_{*H}(f_j)$

X2 vertical coordinate $f_i$ (pixels)

Y2 FT intensity $F_{*V}(f_i)$

$*$ stands for C, N or O.

**Figure B.6 — Graphs showing the points $P_{1H}$, $P_{2H}$, $P_{3H}$, $P_{1V}$, $P_{2V}$ and $P_{3V}$**

f) Calculate the values of $F_{CH}(f_{jH};\ 2\sigma)$ and $F_{CV}(f_{iV};\ 2\sigma)$ at $f_j = f_{jH}$ and $f_i = f_{jV}$, respectively, using linear interpolation, as follows:

$$F_{CH}(f_{jH};2\sigma) = [F_{CH}(f_{jC};2\sigma) - F_{CH}(f_{jC} - 1;2\sigma)] \cdot [f_{jH} - (f_{jC} - 1)] + F_{CH}(f_{jC} - 1;2\sigma)$$

$$F_{CV}(f_{iV};2\sigma) = [F_{CV}(f_{iC};2\sigma) - F_{CV}(f_{iC} - 1;2\sigma)] \cdot [f_{iV} - (f_{iC} - 1)] + F_{CV}(f_{iC} - 1;2\sigma)$$

g) Find the step numbers $N = N_{OH}$ and $N = N_{OV}$ for the sharpness factors $2\sigma(N_{OH}) = 2\sigma_{HL}$, $2\sigma(N_{OH} - 1) = 2\sigma_{HU}$, $2\sigma(N_{OV}) = 2\sigma_{VL}$ and $2\sigma(N_{OV} - 1) = 2\sigma_{VU}$ as follows:

1) Stop the evaluation if either of the following inequalities is satisfied for the initial convoluted image with $2\sigma(N = 1) = 1$. Otherwise, go to step 2).

$$F_{CH}(f_{jH};\ 1) \leqslant F_{NH}(f_{jH}) + \log_{10} a_N \text{ or } F_{CV}(f_{iV};\ 1) \leqslant F_{NV}(f_{iV}) + \log_{10} a_N$$

It is recommended that a message be generated at termination. This termination is caused when the sharpness factor $2\sigma_{OH}$ or $2\sigma_{OV}$ of the selected image $I_O(i, j)$ is less than 1 pixel or the image is irregular.

2) Find the step numbers $N = N_{OH}$ and $N = N_{OV}$ which satisfy the following conditions by increasing the step number $N$ and then repeat the procedures from Clause B.2 f) 1) to the present step.

$$F_{CH}(f_{jH};2\sigma_{HL}) \leqslant F_{NH}(f_{jH}) + \log_{10} a_N \leqslant F_{CH}(f_{jH};2\sigma_{HU})$$

$$F_{CV}(f_{iV};2\sigma_{VL}) \leqslant F_{NV}(f_{iV}) + \log_{10} a_N \leqslant F_{CV}(f_{iV};2\sigma_{VU})$$

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h) Calculate $2\sigma$ by linear interpolation as follows:

$$2\sigma_{\mathrm{OH}} = \frac{[F_{\mathrm{NH}}(f_{j\mathrm{H}}) + \log_{10} a_{\mathrm{N}}] - F_{\mathrm{CH}}(f_{j\mathrm{H}}; 2\sigma_{\mathrm{HU}})}{F_{\mathrm{CH}}(f_{j\mathrm{H}}; 2\sigma_{\mathrm{HL}}) - F_{\mathrm{CH}}(f_{j\mathrm{H}}; 2\sigma_{\mathrm{HU}})}(2\sigma_{\mathrm{HL}} - 2\sigma_{\mathrm{HU}}) + 2\sigma_{\mathrm{HU}}$$

$$2\sigma_{\mathrm{OV}} = \frac{[F_{\mathrm{NV}}(f_{i\mathrm{V}}) + \log_{10} a_{\mathrm{N}}] - F_{\mathrm{CV}}(f_{i\mathrm{V}}; 2\sigma_{\mathrm{VU}})}{F_{\mathrm{CV}}(f_{i\mathrm{V}}; 2\sigma_{\mathrm{VL}}) - F_{\mathrm{CV}}(f_{i\mathrm{V}}; 2\sigma_{\mathrm{VU}})}(2\sigma_{\mathrm{VL}} - 2\sigma_{\mathrm{VU}}) + 2\sigma_{\mathrm{VU}}$$

NOTE The values of $2\sigma_{\mathrm{OV}}$ and $2\sigma_{\mathrm{OH}}$ are similar in magnitude to each other for an image with a low level of astigmatism.

i) Obtain the sharpness factor $2\sigma_{\mathrm{O}}$ as follows:

$$2\sigma_{\mathrm{O}} = (2\sigma_{\mathrm{OH}} + 2\sigma_{\mathrm{OV}})/2$$

j) Obtain the temporary image sharpness $R_{\mathrm{PXO}}$ before calibration as follows:

$$R_{\mathrm{PXO}} = k \cdot 2\sigma_{\mathrm{O}}$$

where $k$ is $1/\sqrt{2}$.

## B.5 Calculation of image sharpness $R_{\mathrm{PX}}$

a) Calculate the coefficient $C_{\mathrm{F}}$ by using the following formulae:

1) If $2\sigma_{\mathrm{O}} < 3$ or $11 \leqslant 2\sigma_{\mathrm{O}}$, then $C_{\mathrm{F}} = 1$.

2) If $3 \leqslant 2\sigma_{\mathrm{O}} < 4{,}1$, then

$$C_{\mathrm{F}} = b_0 + b_1/2\sigma_{\mathrm{O}}$$

where $b_0 = 0{,}401\ 42$ and $b_1 = 1{,}795\ 74$.

3) If $4{,}1 \leqslant 2\sigma_{\mathrm{O}} < 11$, then

$$C_{\mathrm{F}} = c_3(2\sigma_{\mathrm{O}})^3 + c_2(2\sigma_{O})^2 + c_1(2\sigma_{\mathrm{O}}) + c_0$$

where $c_3 = 1{,}489\ 79 \times 10^{-4}$, $c_2 = -6{,}646\ 10 \times 10^{-3}$, $c_1 = 9{,}638\ 83 \times 10^{-2}$ and $c_0 = 5{,}456\ 65 \times 10^{-1}$.

b) Obtain the calibrated sharpness factor $2\sigma_{\mathrm{C}}$ as follows:

$$2\sigma_{\mathrm{C}} = C_{\mathrm{F}} \cdot 2\sigma_{\mathrm{O}}$$

NOTE The coefficient $C_{\mathrm{F}}$ ranges from 0,839 4 to 1. Examples of the sharpness factor before and after calibration are shown in Figure B.7 and Figure B.8, respectively, for simulated images such as those in Figure 4 using a Gaussian profile with $2\sigma = 4$ and 10 pixels.

c) Obtain the calibrated image sharpness $R_{\mathrm{PX}}$ as follows:

$$R_{\mathrm{PX}} = k \cdot 2\sigma_{\mathrm{C}}$$

where $k$ is $1/\sqrt{2}$.


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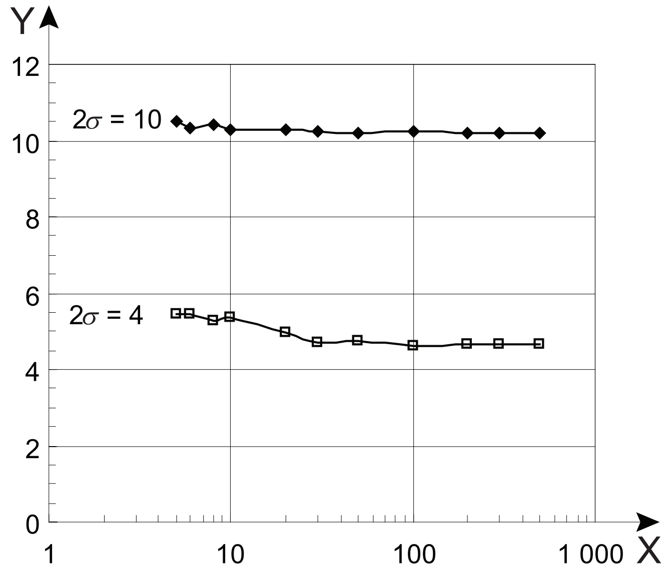
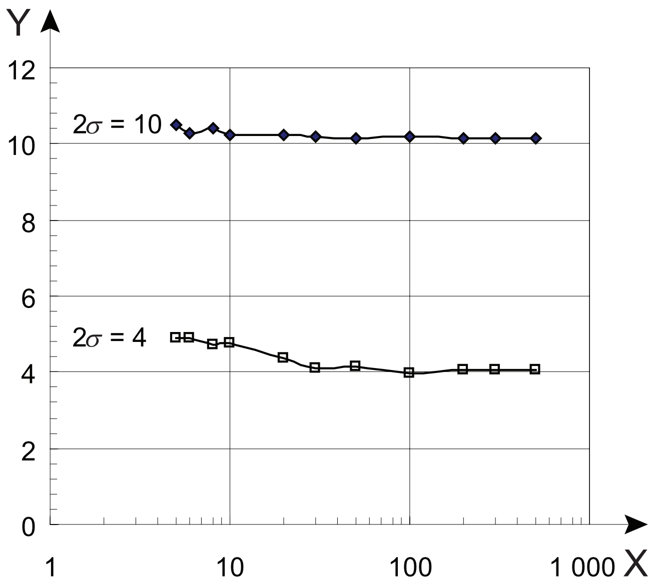



**Key**

X signal-to-noise ratio for particles $SNR_p$

Y measured sharpness factor $2\sigma_O$ (pixels)

**Figure B.7 — Example of measured sharpness factor $2\sigma_O$ before calibration**




**Key**

X signal-to-noise ratio for particles $SNR_p$

Y calibrated sharpness factor $2\sigma_C$

**Figure B.8 — Example of calibrated sharpness factor $2\sigma_C$ (calibrated using the coefficient $C_F$)**



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## B.6 Calculation sub-procedures

### B.6.1 3 × 3 median filter

Define the function $M_{ED}(a_1, a_2, \ldots, a_N)$ which sorts the values $a_n$ ($n = 1, 2, \ldots, N$) into ascending order and find the median value for odd $N$ as well as the mean value of the ($N$/2)th and [($N$/2) + 1]th values for even $N$. Let $F_{IN}(i, j)$ be the input image data for $0 \leqslant i, j \leqslant L - 1$. The output data $F_{OUT}(i, j)$ processed by the 3 × 3 median filter can then be derived as follows:

$$F_{OUT}(i, j) = M_{ED}[F_{IN}(i-1, j-1), F_{IN}(i-1, j), F_{IN}(i-1, j+1), F_{IN}(i, j-1), F_{IN}(i, j), F_{IN}(i, j+1), F_{IN}(i+1, j-1), F_{IN}(i+1, j), F_{IN}(i+1, j+1)]$$

NOTE If $i - 1 < 0$, $i + 1 > L - 1$, $j - 1 < 0$ or $j + 1 > L - 1$, discard the corresponding $F_{IN}(\ldots, \ldots)$ and carry out $M_{ED}[\ldots\ldots]$.

### B.6.2 Moving average with window of width $2n + 1$

Let $F_{IN}(r)$ be the input original function of integer $r$ ($r = s, s + 1, s + 2, \ldots, s + m$) in the interval $[s, s + m]$. The output function $F_{OUT}(r)$ processed by the moving average with a window of width $2n + 1$ ($n = 1, 2, 3, \ldots$) is obtained as follows:

1) If $s \leqslant r < s + n$, set $t = r - s$ (= 1, 2, 3, …, $n - 1$) and calculate $F_{OUT}(r)$ as follows:

$$F_{OUT}(r) = \frac{1}{t+1+n} \sum_{k=-t}^{n} F_{IN}(r+k)$$

2) If $s + n \leqslant r < s + m - n$, calculate $F_{OUT}(r)$ as follows:

$$F_{OUT}(r) = \frac{1}{2n+1} \sum_{k=-n}^{n} F_{IN}(r+k)$$

3) If $s + m - n < r \leqslant s + m$, set $t = (s + m) - r$ (= 0, 1, 2, 3, …, $n - 1$) and calculate $F_{OUT}(r)$ as follows:

$$F_{OUT}(r) = \frac{1}{n+1+t} \sum_{k=-n}^{t} F_{IN}(r+k)$$

### B.6.3 Linear approximation by the least-squares method

Let $F_{IN}(r)$ be the input original function of integer $r$ ($r = s, s + 1, s + 2, \ldots, s + m$) in the interval $[s, s + m]$. The output result is the slope $m_{OUT}$ and the intercept $b_{OUT}$ at the vertical axis. The calculation method is as follows:

a) Calculate the mean of $r$ from:

$$\overline{r} = \frac{1}{m+1} \sum_{r=s}^{s+m} r = \frac{1}{m+1}\left[\frac{1}{2}(s+m)\cdot(s+m+1) - \frac{1}{2}(s-1)s\right]$$

b) Calculate the mean of $F_{IN}(r)$ from:

$$\overline{F} = \frac{1}{m+1} \sum_{r=s}^{s+m} F_{IN}(r)$$


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c) Calculate the variance of $r$ from:

$$\sigma_r{}^2 = \frac{1}{m+1}\sum_{r=s}^{s+m}(r-\overline{r})^2$$

d) Calculate the covariance of $r$ and $F_{\mathrm{IN}}(r)$ from:

$$\sigma_{rF} = \frac{1}{m+1}\sum_{r=s}^{s+m}(r-\overline{r})\left[F_{\mathrm{IN}}(r)-\overline{F}\right]$$

e) Obtain the slope $m_{\mathrm{OUT}}$ and the intercept $b_{\mathrm{OUT}}$ at the vertical axis from the following equations:

$$m_{\mathrm{OUT}} = \frac{\sigma_{rF}}{\sigma_r{}^2}$$

$$b_{\mathrm{OUT}} = \overline{F} - m_{\mathrm{OUT}} \cdot \overline{r}$$

NOTE The approximately linear equation $F = F(r)$ processed by the least-squares method is given by:

$$F - \overline{F} = m_{\mathrm{OUT}} \cdot (r - \overline{r})$$



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## B.7 Flow charts for the procedures described in Clauses B.2 to B.5

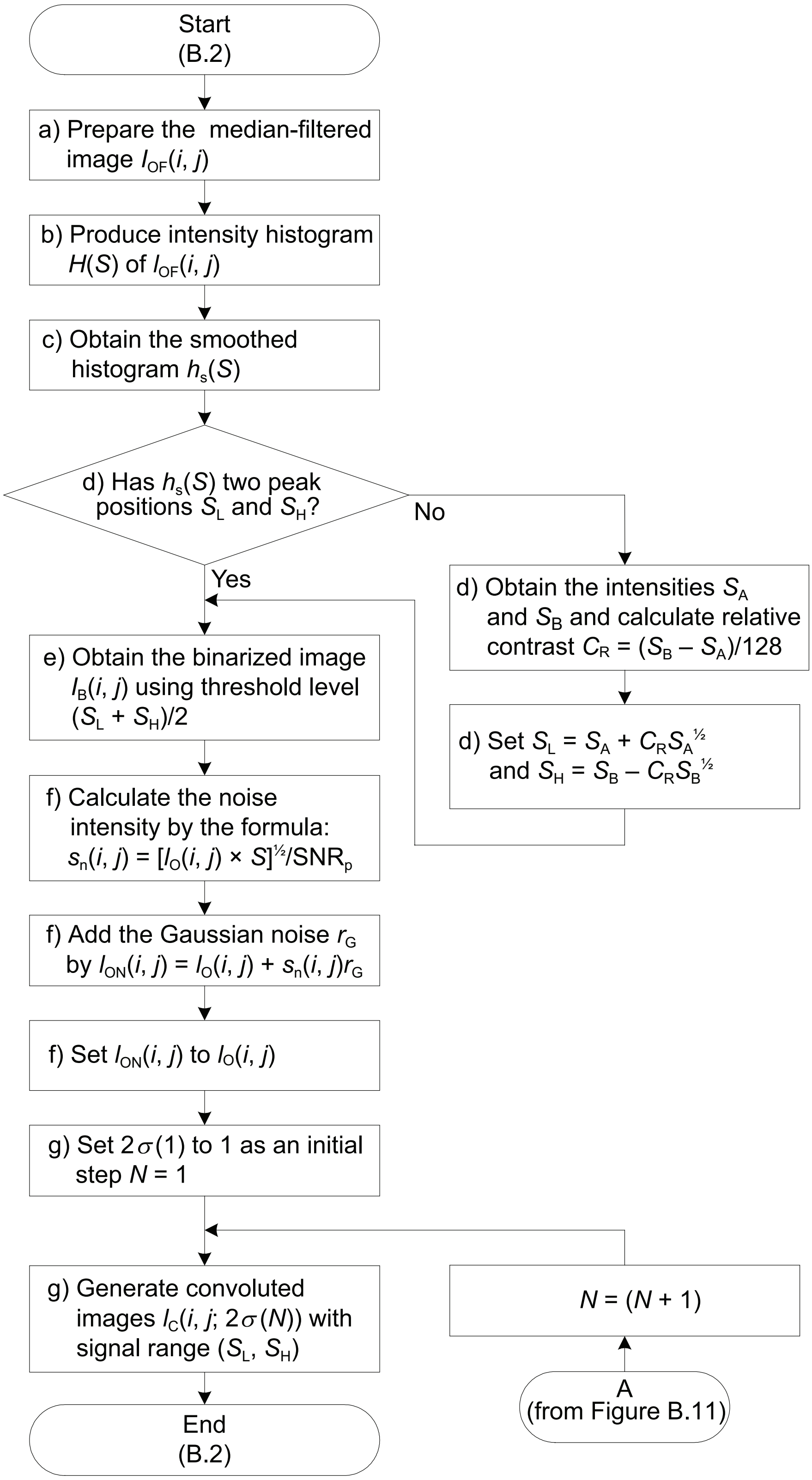


**Figure B.9 — Flow chart for the procedure described in Clause B.2**


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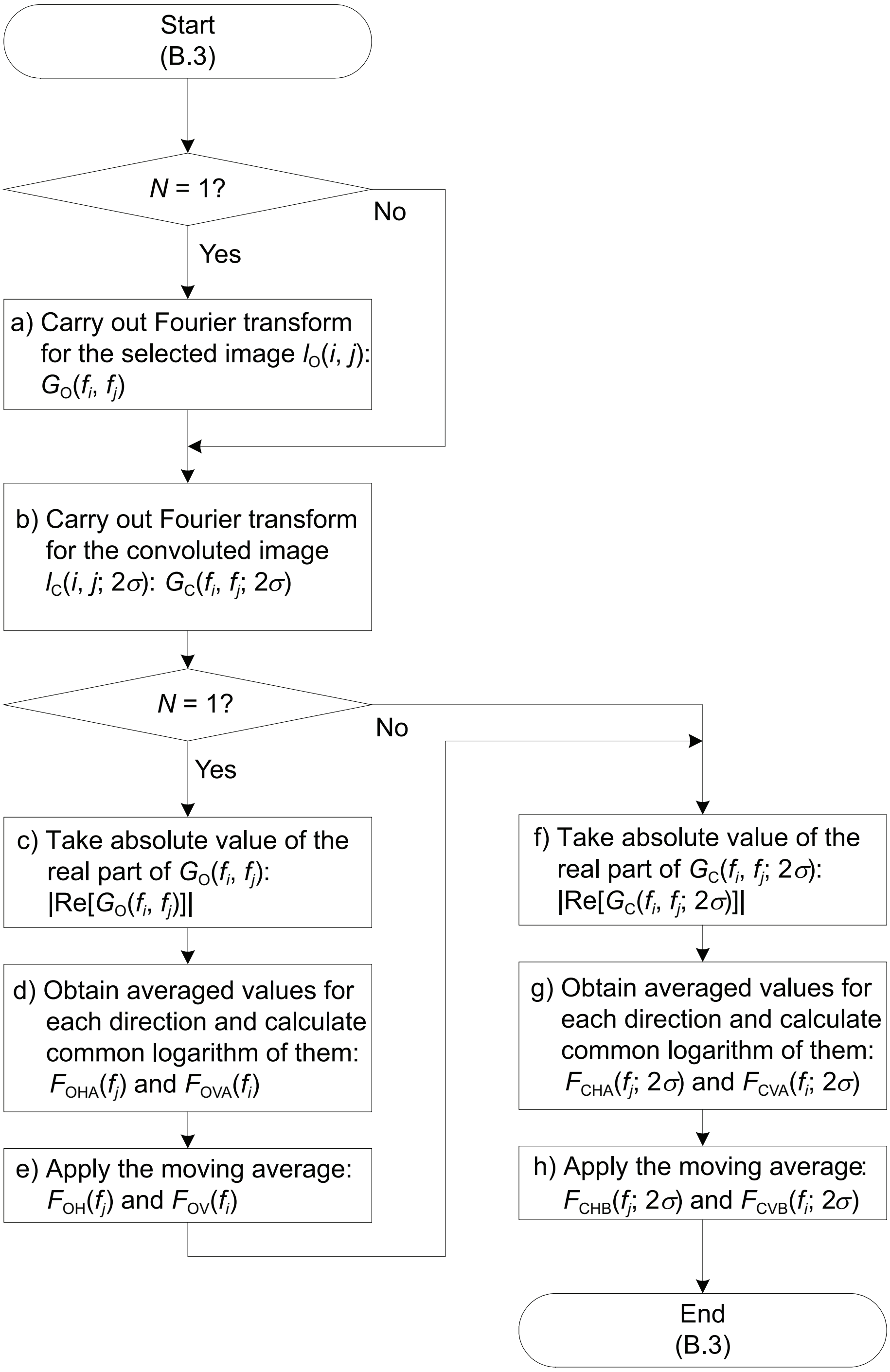


**Figure B.10 — Flow chart for the procedure described in Clause B.3**

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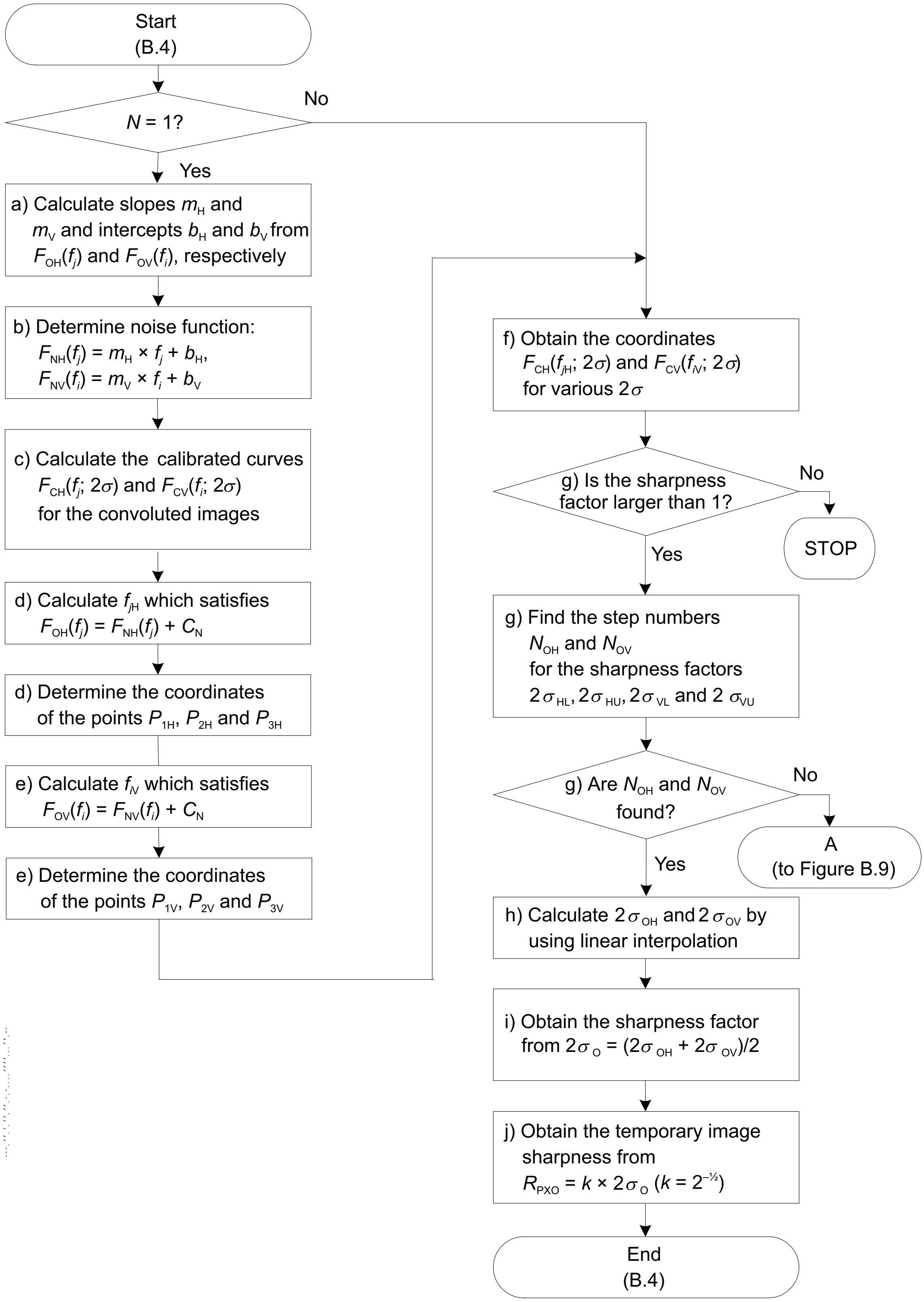


**Figure B.11 — Flow chart for the procedure described in Clause B.4**


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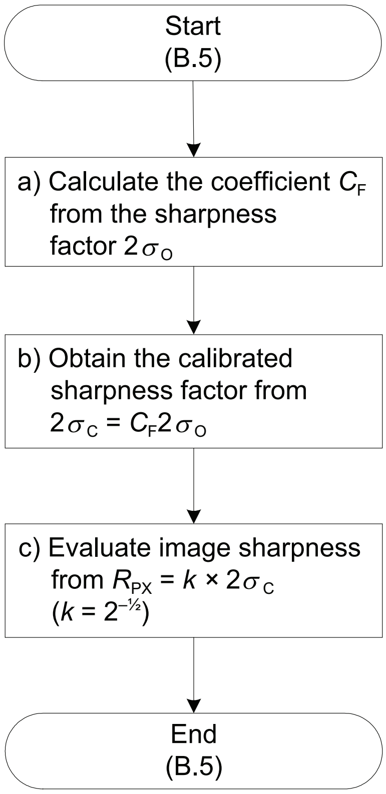


**Figure B.12 — Flow chart for the procedure described in Clause B.5**


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# Annex C
(normative)

# Details of the contrast-to-gradient (CG) method

## C.1 General

This annex provides details of the procedure used for the contrast-to-gradient (CG) method described in 6.4 and Figure 12.

NOTE The explanation applies to an image with $L = 512$ or 256 and 8 bits in the grey scale for ease of understanding.

## C.2 Calculation of the CG image sharpness

### C.2.1 Flow charts

A flow chart of the routine is given in Figure C.1. In this routine, there are three subroutines: a) generation of reduced-size images referred to as (1/$r$)-size images, b) calculation of the directionally averaged sharpness $R_r$ and c) calculation of the CG image sharpness $R_{CG}$. Flow charts of the second and the third subroutines are given in Figure C.2 and Figure C.3, respectively.

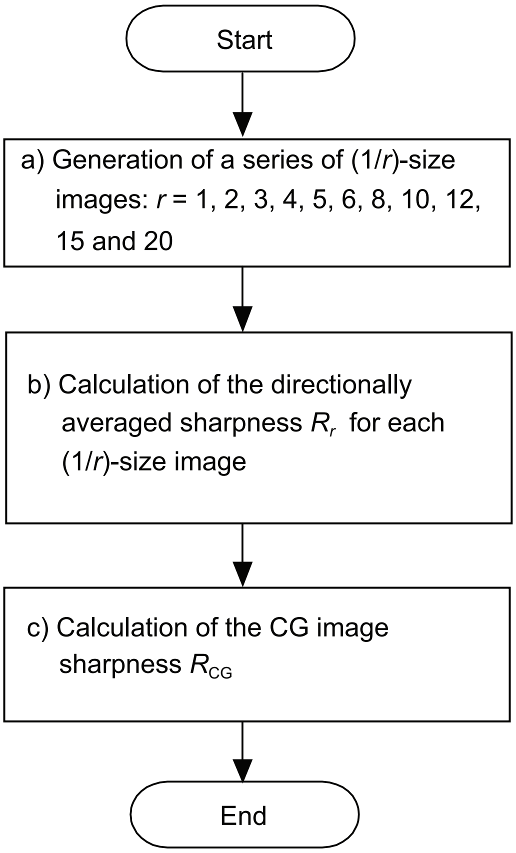


**Figure C.1 — Flow chart for calculation of the CG image sharpness**


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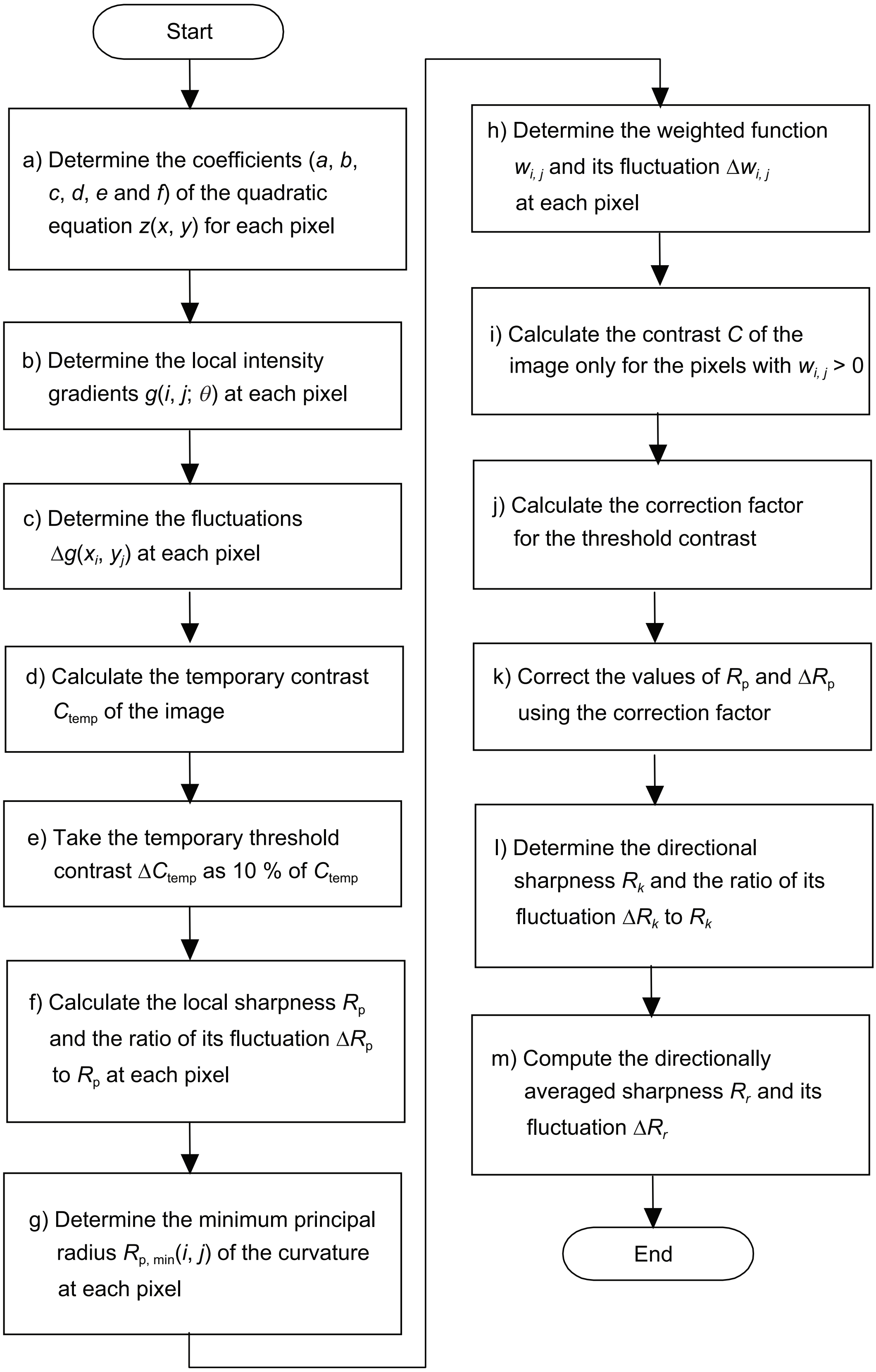


**Figure C.2 — Flow chart for subroutine b)
(calculation of the directionally averaged sharpness) in Figure C.1**

--`,,```,,,,````-`-`,,`,,`,`,,`---

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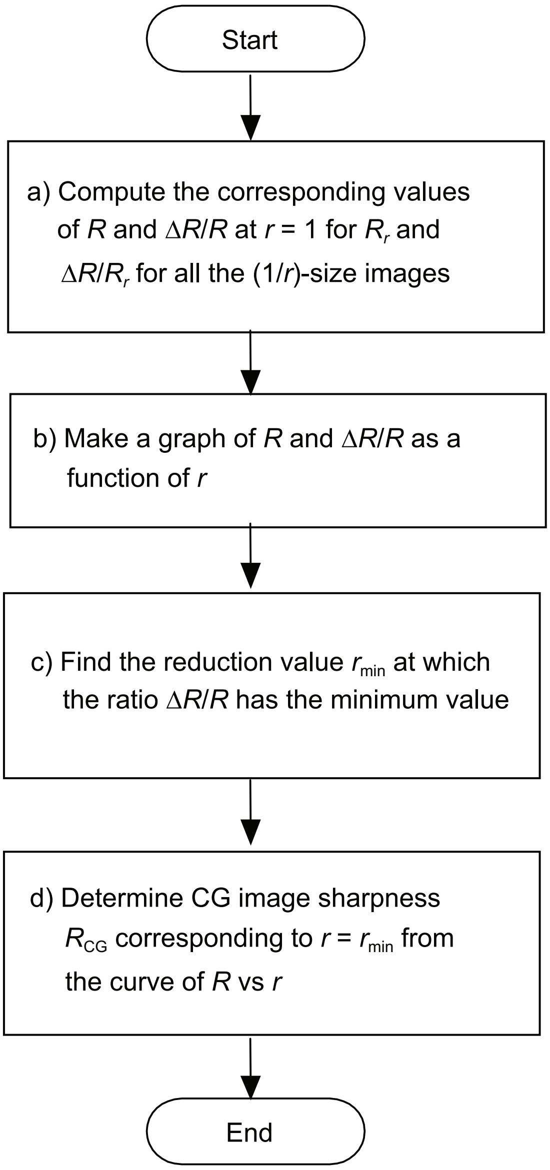


**Figure C.3 — Flow chart for subroutine c) (calculation of the CG image sharpness) in Figure C.1**

### C.2.2 Generation of the (1/$r$)-size images

This subroutine generates a series of (1/$r$)-size images from the original SEM image, where $r$ = 2, 3, 4, 5, 6, 8, 10, 12, 15 and 20. Hereafter, the (1/$r$)-size image when $r$ = 1 means the original image in order to make the description simple (see Figure C.4).

Generate the (1/$r$)-size images, obtaining the pixel intensity $I_r(i, j)$ by averaging the pixel intensities $I(p, q)$ in the original image as follows:

$$I_r(i, j) = \mathrm{Round}\left\{\left[\sum_{p=ir}^{ir+r}\sum_{q=jr}^{jr+r} I(p, q)\right] \Big/ (r \times r)\right\} \quad \text{for } i \text{ (and } j) = 0, 1, \ldots, i_{\max} \text{ (and } j_{\max}) \tag{C.1}$$

NOTE 1 Any pixel of the image is expressed as $(x_i, y_j)$, where $i$ (and $j$) = 0, 1, 2, …, $i_{\max}$ (and $j_{\max}$).


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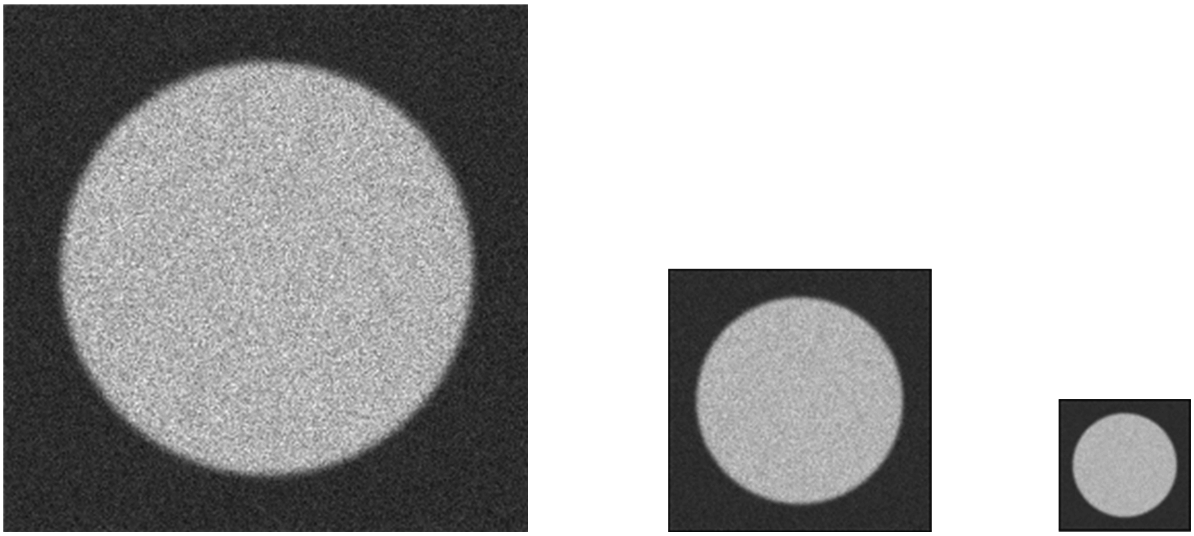
NOTE 2 Both $i_{max}$ and $j_{max}$ = Int($512/r$) – 1 [or Int($256/r$) – 1] (depending on the pixel size of the original SEM image, i.e. 512 × 512 or 256 × 256). Here, Int($x$) is an integer function of $x$, e.g. Int(100,8) = 100.

NOTE 3 Round($x$) is a function yielding the rounded value of $x$, e.g. Round(12,4) = 12 and Round(12,5) = 13.



**a) Original image (1/1)** **b) 1/2-size image** **c) 1/4-size image**

**Figure C.4 — Original image, 1/2-size image and 1/4-size image**

## C.2.3 Calculation of the directionally averaged sharpness

This subroutine calculates the directionally averaged sharpness $R_r$ for each ($1/r$)-size image as follows.

a) For each pixel $(i, j)$, determine the coefficients ($a$, $b$, $c$, $d$, $e$ and $f$) of the quadratic equation $z(x, y)$ so that the fitting error $S_{error}(i, j)$ in the 3 × 3 pixel area is minimized:

$$z(x, y) = a(i, j)\, x^2 + b(i, j)\, y^2 + c(i, j)\, xy + d(i, j)\, x + e(i, j)\, y + f(i, j)$$
$$\text{for } i \text{ (and } j) = 1, 2, \ldots, i_{max} - 1 \text{ (and } j_{max} - 1) \tag{C.2}$$

$$S_{error}(i, j) = \left\{ \sum_{p=-1}^{+1} \sum_{q=-1}^{+1} \left[ I_r(i+p, j+q) - z(p, q) \right]^2 \right\} \Big/ (3 \times 3) \tag{C.3}$$

The 3 × 3 operators to determine the coefficients $a$, $b$, $c$, $d$, $e$ and $f$ are given by:

$$a:\ (1/6)\begin{bmatrix} 1 & -2 & 1 \\ 1 & -2 & 1 \\ 1 & -2 & 1 \end{bmatrix} \quad b:\ (1/6)\begin{bmatrix} 1 & 1 & 1 \\ -2 & -2 & -2 \\ 1 & 1 & 1 \end{bmatrix} \quad c:\ (1/4)\begin{bmatrix} -1 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & -1 \end{bmatrix}$$

$$d:\ (1/6)\begin{bmatrix} -1 & 0 & 1 \\ -1 & 0 & 1 \\ -1 & 0 & 1 \end{bmatrix} \quad e:\ (1/6)\begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ -1 & -1 & -1 \end{bmatrix} \quad f:\ (1/9)\begin{bmatrix} -1 & 2 & -1 \\ 2 & 5 & 2 \\ -1 & 2 & -1 \end{bmatrix} \tag{C.4}$$

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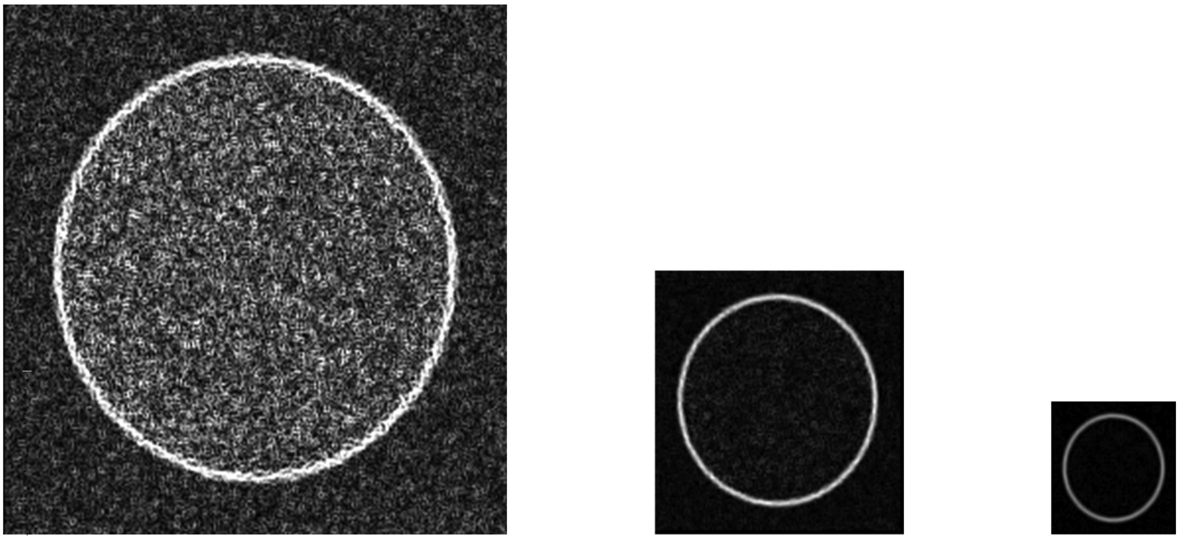
b) For each pixel, determine the local intensity gradients $g(i, j; \theta)$ by calculating the first partial-differential coefficients $\partial z/\partial x$ and $\partial z/\partial y$.

$$g(i, j; \theta) = [g_x^2(i, j) + g_y^2(i, j)]^{1/2} \quad \text{for } i \text{ (and } j) = 1, 2, \ldots, i_{\max} - 1 \text{ (and } j_{\max} - 1) \tag{C.5}$$

The angular information on the gradients is given by

$$\theta = \tan^{-1}(g_y/g_x), \quad g_x(i, j) = (\partial z/\partial x)_{x=0} = d(i, j) \quad \text{and } g_y(i, j) = (\partial z/\partial y)_{x=0} = e(i, j) \tag{C.6}$$

NOTE Images of local intensity gradients corresponding to the $(1/r)$-size images at $r = 1$, 2 and 4, for example, are shown in Figure C.5.



**a) Original image (1/1)** **b) 1/2-size image** **c) 1/4-size image**

**Figure C.5 — Distributions of the local intensity gradient**

c) Determine the fluctuations $\Delta g(i, j)$ in $g(i, j; \theta)$ at each pixel as follows:

$$\Delta g(i, j) = [S_{\text{error}}(i, j)/6]^{1/2} \quad \text{for } i \text{ (and } j) = 1, 2, \ldots, i_{\max} - 1 \text{ (and } j_{\max} - 1) \tag{C.7}$$

d) Determine the temporary contrast $C_{\text{temp}}$ of the calculated-$z$ image, in which the pixel intensities are rounded integers in $z(0, 0)$, i.e. $f(i, j)$. The calculation procedures for $C_{\text{temp}}$ are the same as those for the image temporary contrast given in steps 1) to 6) in Annex A, item c), except that the calculated-$z$ image is used instead of the three-time median-filtered SEM image.

e) Take the temporary threshold contrast $\Delta C_{\text{temp}}$ as

$$\Delta C_{\text{temp}} = 0{,}1 \times C_{\text{temp}} \tag{C.8}$$

f) Calculate the local sharpness $R_{\text{p}}(i, j; \theta)$ and the ratio of its fluctuation $\Delta R_{\text{p}}(i, j; \theta)$ to $R_{\text{p}}(i, j; \theta)$ at each pixel $(i, j)$ from the following equations:

$$R_{\text{p}}(i, j; \theta) = 2\Delta C_{\text{temp}}/g(i, j; \theta) \tag{C.9}$$

$$\Delta R_{\text{p}}(i, j; \theta) = R_{\text{p}}(i, j; \theta)\,[\Delta g(i, j)/g(i, j; \theta)] \quad \text{for } i \text{ (and } j) = 1, 2, \ldots, i_{\max} - 1 \text{ (and } j_{\max} - 1) \tag{C.10}$$

g) Determine the minimum principal radius $R_{\text{p,min}}(i, j)$ of the curvature at each pixel $(i, j)$ as follows:

$$R_{\text{p,min}}(i, j) = 1/K_{\max} \quad \text{for } i \text{ (and } j) = 1, 2, \ldots, i_{\max} - 1 \text{ (and } j_{\max} - 1) \tag{C.11}$$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Here, $K_{max}$ is the reciprocal of the maximum principal curvature. It is obtained from the quadratic equation below and is, in fact, the root with the larger absolute value of the equation.

$$K^2 - 2 \times C_1 \times K + C_0 = 0 \tag{C.12}$$

where

$$C_1 = \frac{(1+g_x^2)g_{yy} + (1+g_y^2)g_{xx} - 2g_x g_y g_{xy}}{2(1+g_x^2+g_y^2)^{3/2}} \tag{C.13}$$

$$C_0 = \frac{g_{xx}g_{yy} - g_{xy}^2}{(1+g_x^2+g_y^2)^2} \tag{C.14}$$

$$g_x = (\partial z/\partial x)_{x=0} = d(i,j) \quad \text{and} \quad g_y = (\partial z/\partial y)_{x=0} = e(i,j) \tag{C.15}$$

$$g_{xx} = (\partial^2 z/\partial x^2)_{x=0} = 2a(i,j), \quad g_{yy} = (\partial^2 z/\partial y^2)_{x=0} = 2b(i,j) \quad \text{and} \quad g_{xy} = (\partial^2 z/\partial x \partial y)_{x=0} = c(i,j) \tag{C.16}$$

h) Determine the weighted function $w_{i,j}$ and its fluctuation $\Delta w_{i,j}$ at each pixel $(i, j)$ from the following equations:

$$w_{i,j} = g(i, j; \theta) \quad \text{and } \Delta w_{i,j} = \Delta g(i,j) \quad \text{for } R_p(i, j; \theta) \leqslant 2R_{p,min}(i,j) \tag{C.17a}$$

$$w_{i,j} = 0 \quad \text{and } \Delta w_{i,j} = 0 \quad \text{for } R_p(i, j; \theta) > 2R_{p,min}(i,j) \tag{C.17b}$$

i) Calculate the contrast $C$ of the image using step d), but count only the pixels with $w_{i,j} > 0$. The $q$ value is similarly taken as 0,2 % of the total number of pixels, but only those with $w_{i,j} > 0$, for segment-image $s$.

j) Calculate the correction factor for the threshold contrast as follows:

$$f_{corr} = C/C_{temp} \tag{C.18}$$

k) Correct the values of $R_p(i, j; \theta)$ and $\Delta R_p(i, j; \theta)$ at each pixel $(i, j)$ by multiplying them by the correction factor $f_{corr}$, giving

$$f_{corr} \times R_p(i, j; \theta) \quad \text{and} \quad f_{corr} \times \Delta R_p(i, j; \theta) \quad \text{for } i \text{ (and } j) = 1, 2, \ldots, i_{max} - 1 \text{ (and } j_{max} - 1) \tag{C.19}$$

l) Determine the directional sharpness $R_k$ and the ratio of its fluctuation $\Delta R_k$ to $R_k$ at azimuth angle $\theta_k$ by the following equations:

$$R_k = \frac{\sum_{i=1}^{i_{max}-1}\sum_{j=1}^{j_{max}-1} w_{i,j}}{\sum_{i=1}^{i_{max}-1}\sum_{j=1}^{j_{max}-1}\left[w_{i,j}/R_p(i, j; \theta_k)\right]} \tag{C.20}$$

and

$$\frac{\Delta R_k}{R_k} = \frac{1}{\sum_{i=1}^{i_{max}-1}\sum_{j=1}^{j_{max}-1} w_{i,j}} \sqrt{\sum_{i=1}^{i_{max}-1}\sum_{j=1}^{j_{max}-1}\left[1 - \frac{2R_k}{R_p(i, j; \theta_k)}\right]^2 \left(\Delta w_{i,j}\right)^2} \tag{C.21}$$

where $(2k - 1)(\pi/k_{max}) \leqslant \theta_k < (2k + 1)(\pi/k_{max})$ and $k = 0, 1, \ldots, k_{max} - 1$ ($k_{max} = 16$).

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m) Compute the directionally averaged sharpness $R_r$ and the ratio of its fluctuation $\Delta R_r$ to $R_r$ for the (1/$r$)-size image as the root mean square of $R_k$:

$$R_r = [(R_0{}^2 + R_1{}^2 + \ldots + R_{15}{}^2)/16]^{1/2} \tag{C.22}$$

$$\frac{\Delta R_r}{R_r} = \left(\frac{1}{k_{\max}}\right)^{1/2} \sqrt{\sum_{k=1}^{k_{\max}-1} \left(\frac{R_k}{R_r}\right)^4 \left(\frac{\Delta R_k}{R_k}\right)^2} \tag{C.23}$$

### C.2.4 Calculation of the CG image sharpness

This subroutine calculates the CG image sharpness $R_{\mathrm{CG}}$ as follows.

a) Compute the corresponding values of $R$ and $\Delta R/R$ at $r = 1$ for $R_r$ and $\Delta R_r/R_r$ for all the (1/$r$)-size images from the following equations:

$$R = r \times R_r \tag{C.24}$$

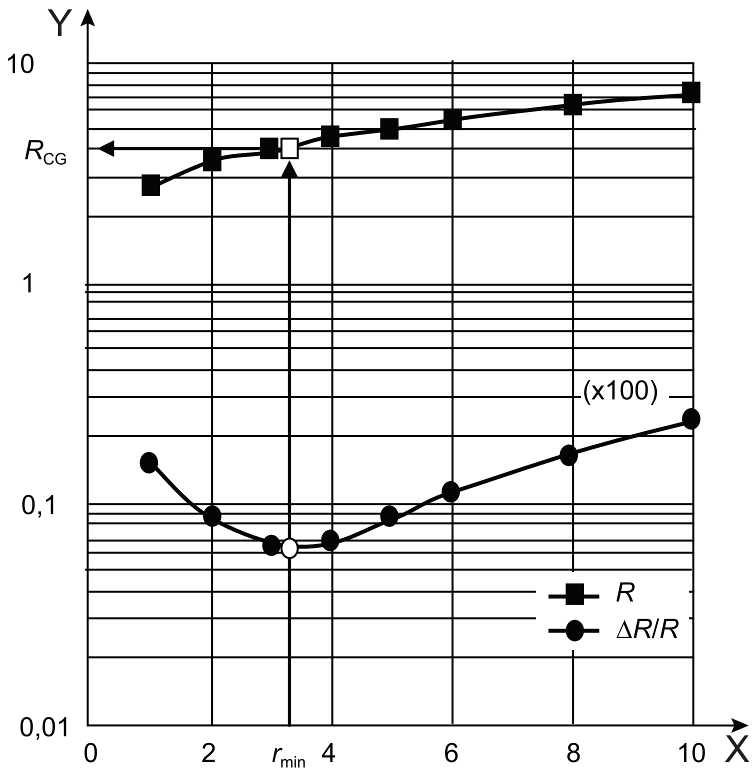
$$\Delta R/R = \Delta R_r/R_r \tag{C.25}$$

b) Plot a graph of $R$ and $\Delta R/R$ as a function of $r$, as shown in Figure C.6.

c) Find the reduction value $r_{\min}$ at which the ratio $\Delta R/R$ has the minimum value by interpolation.

When there is no minimum, take a point of inflection.

d) Determine the CG image sharpness $R_{\mathrm{CG}}$ corresponding to $r = r_{\min}$ from the curve of $R$ versus $r$ (see Figure C.6).




**Key**

X reduction factor $r$

Y $R$ and $\Delta R/R$

**Figure C.6 — Graph of $R$ and $\Delta R/R$ as a function of $r$**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## C.3 Generation of the standard images and calculation of their CG image sharpness $R_{CG}$

A flow chart of this subroutine is given in Figure C.7. The subroutine generates the standard images and calculates their CG image sharpness as follows:

a) Make the binary image with the levels $L_{low}$ and $L_{high}$ for the median-filtered image using the threshold intensity $z_{threshold,s\text{-}av}$, where

$$L_{low} = \text{Maximum}[50, \text{Int}(3{,}5\sigma_{n,max})] \quad (C.26)$$

$$L_{high} = \text{Minimum}[200, 255 - \text{Int}(3{,}5\sigma_{n,max})] \quad (C.27)$$

$$\sigma_{n,max} = 255/(2 \times 3{,}5 + \text{CNR}) \quad (C.28)$$

and

$$z_{threshold,s\text{-}av} = [\text{Av}(z_{max,av,s}) + \text{Av}(z_{min,av,s})]/2 \quad (C.29)$$

The values of $\text{Av}(z_{max,av,s})$ and $\text{Av}(z_{min,av,s})$ used here are determined in the same way as in the CNR evaluation process (see Annex A).

NOTE The factor of 3,5 lowers the frequencies of over- and under-saturation to about 0,2 % in the random-noise added pixel-intensity in the standard images.

b) Initialize the $i$th calculation loop described in steps c) to h) below, i.e. $i = 1$, and set the sharpness factor $2\sigma_i$ at $i = 1$ as $2\sigma_1 = \text{Int}(2\sigma)$, where $2\sigma_0 = A_{default}R_{CG} + B_{default}$, $A_{default} = 3{,}099\ 5$ and $B_{default} = -\ 0{,}775\ 0$. The $R_{CG}$ value used here is obtained in the same way as in Clause C.2.

c) Make the $i$th standard image with a sharpness factor $2\sigma_i$ and including the CNR, as follows:

   1) Make a convoluted image of the binary image with a Gaussian profile with standard deviation $\sigma_i$.

   2) Add Gaussian random noise with standard deviation $\sigma_n$ to the convoluted image, where $\sigma_n = (L_{high} - L_{low})/\text{CNR}$.

d) Calculate the $R_{CG}$ value for the $i$th standard image. The calculation process is identical to that given in Clause C.2.

e) If $i \geqslant 2$, go to the next step, f). Otherwise, go to step g).

f) Compare the $R_{CG}$ value with the values of $R_{CG,i-1}$ and $R_{CG,i}$. End the routine if either of the following inequalities is satisfied. Otherwise, proceed to step g).

$$R_{CG,i-1} < R_{CG} \leqslant R_{CG,i} \quad \text{or} \quad R_{CG,i-1} > R_{CG} \geqslant R_{CG,i} \quad (C.30)$$

g) Set the increment $\Delta\sigma$ as follows:

$$\Delta\sigma = 0{,}5 \text{ when } \sigma_i < 4 \quad (C.31a)$$

$$\Delta\sigma = 1 \quad \text{when } \sigma_i \geqslant 4 \quad (C.31b)$$

h) Proceed to the $i$th step, i.e. $i = i + 1$, and increase or decrease the $\sigma_i$ value by $\Delta\sigma$ as follows:

$$\sigma_i = \sigma_{i-1} + \Delta\sigma \quad \text{when } R_{CG,i} < R_{CG} \quad (C.32a)$$

$$\sigma_i = \sigma_{i-1} - \Delta\sigma \quad \text{when } R_{CG,i} \geqslant R_{CG} \quad (C.32b)$$

Then go back to step c).

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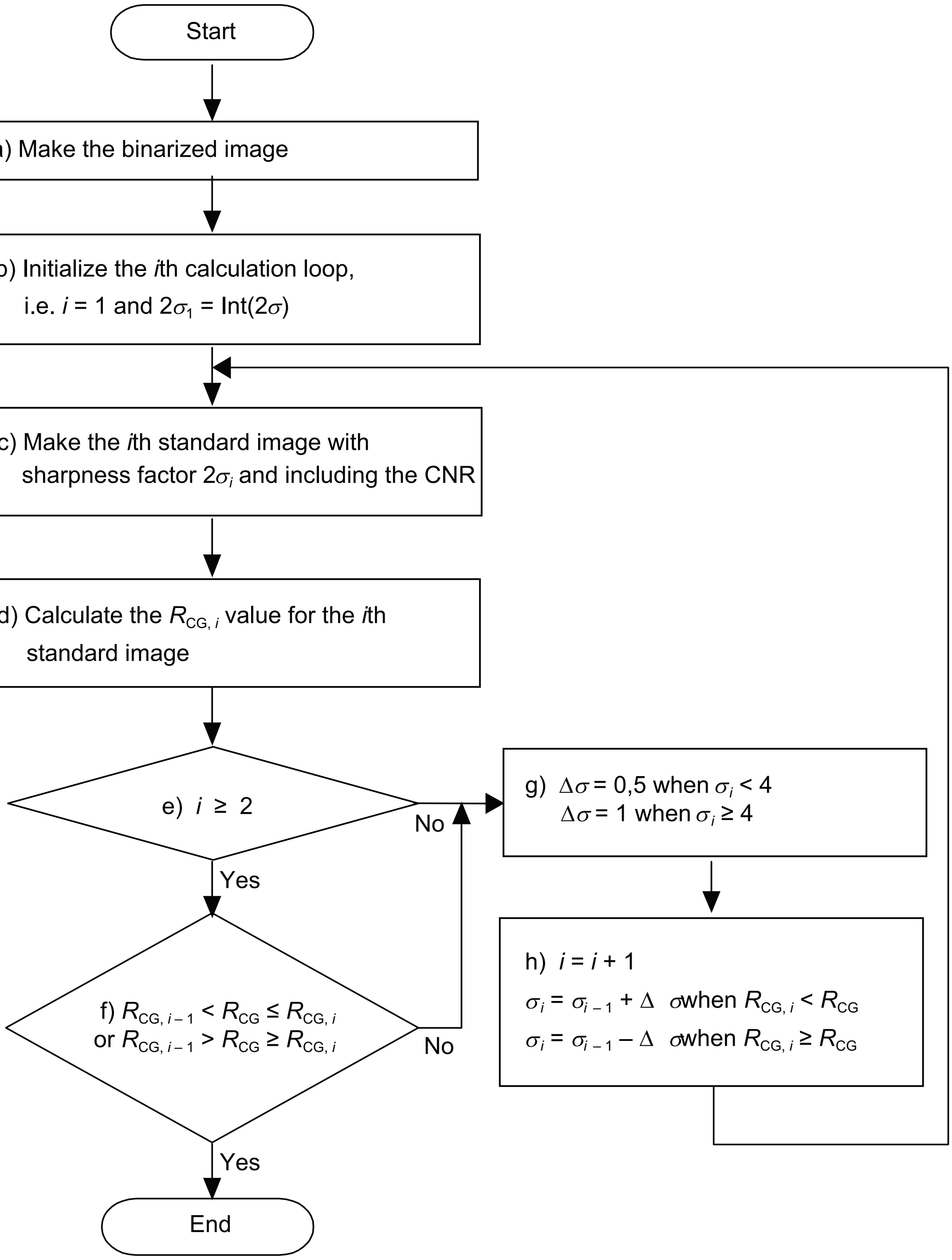


**Figure C.7 — Flow chart for the generation of the standard images and calculation of their CG sharpness $R_{CG}$**


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## C.4 Calibration of the conversion constants $A$ and $B$

This subroutine calibrates the conversion constants of $A$ and $B$ by solving the following simultaneous linear equations (which are shown in graphical form in Figure C.8), as follows:

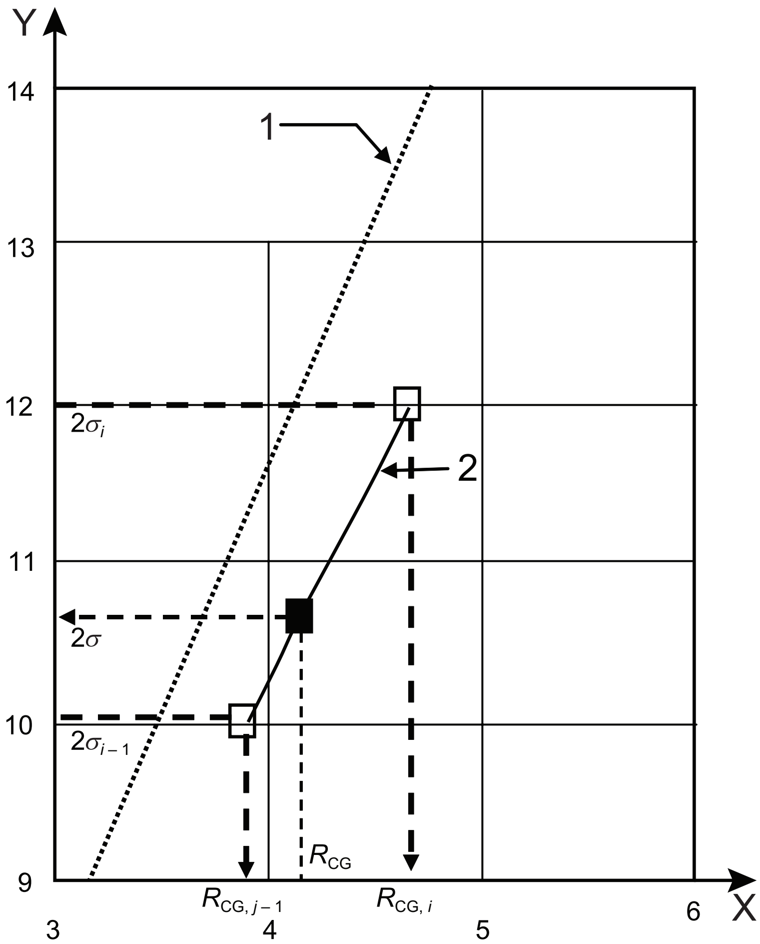
$$2\sigma_i = A_{\text{calib}} \times R_{\text{CG},i} + B_{\text{calib}} \quad \text{(C.33)}$$

$$2\sigma_{i-1} = A_{\text{calib}} \times R_{\text{CG},i-1} + B_{\text{calib}} \quad \text{(C.34)}$$

We then obtain the calibrated conversion constants:

$$A_{\text{calib}} = 2\Delta\sigma/(R_{\text{CG},i} - R_{\text{CG},i-1}) \quad \text{(C.35)}$$

$$B_{\text{calib}} = 2\sigma_i - A_{\text{calib}} \times R_{\text{CG},i} \quad \text{(C.36)}$$




**Key**

X $R_{\text{CG}}$ (pixels)

Y sharpness factor $2\sigma$ (pixels)

1 default line $2\sigma = 3{,}099\,5R_{\text{CG}} - 0{,}775\,0$

2 calibrated line $2\sigma = A_{\text{calib}} \times R_{\text{CG}} + B_{\text{calib}}$

**Figure C.8 — Sharpness factor $2\sigma$ plotted as a function of $R_{\text{CG}}$ for the calibration**

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## C.5 Conversion of the $R_{\mathrm{CG}}$ value to the image sharpness $R_{\mathrm{ES}}$

This subroutine converts the $R_{\mathrm{CG}}$ value to the image sharpness $R_{\mathrm{ES}}$ as follows:

$$R_{\mathrm{ES}} = k \times 2\sigma \tag{C.37}$$

where

$k = 1/\sqrt{2}$;

$2\sigma$ is the sharpness factor, given by

$$2\sigma = A_{\mathrm{calib}} \times R_{\mathrm{CG}} + B_{\mathrm{calib}} \tag{C.38}$$

$A_{\mathrm{calib}}$ and $B_{\mathrm{calib}}$ are the calibrated conversion constants. The evaluated $R_{\mathrm{ES}}$ values show small fluctuations due to random image-noise used in the generation of the standard images [see step c) 2) in Clause C.3]. Here, the image sharpness $R_{\mathrm{ES}}$ shows little noise-dependency and is evaluated with the CNR value as a given parameter.


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# Annex D
(normative)

# Details of the derivative (DR) method

## D.1 General

This annex provides details of the procedures of the derivative (DR) method.

There are four routines — Clause D.2, generation of a binary mask image $M(x, y)$; Clause D.3, generation of an edge position map $E(x, y)$; Clause D.4, extraction of the edge profiles $P_j(x, y)$ and model fitting; and Clause D.5, calculation of the image sharpness $R$.

## D.2 Generation of a binary mask image $M(x, y)$

a) Compute the gradients $G_x(x, y)$ and $G_y(x, y)$ of a selected SEM image $I_N(x, y)$, using Gaussian derivatives of scale parameter $s$ ($s = 2$ pixels), as follows:

$$G_x(x,y) = \sum_{q=0}^{m-1}\sum_{p=0}^{n-1} I_N(p,q) \times \frac{p-x}{2\pi s^4} \times \exp\left(-\frac{(x-p)^2+(y-q)^2}{2s^2}\right) \quad \text{(D.1a)}$$

$$G_y(x,y) = \sum_{q=0}^{m-1}\sum_{p=0}^{n-1} I_N(p,q) \times \frac{q-y}{2\pi s^4} \times \exp\left(-\frac{(x-p)^2+(y-q)^2}{2s^2}\right) \quad \text{(D.1b)}$$

NOTE 1 $n$ and $m$ are the $x$-size and $y$-size, respectively, of the image and these are typically 512. For the coordinates $(x, y)$ of the image, $x = 0, 1, \ldots, n - 1$ and $y = 0, 1, \ldots, m - 1$.

NOTE 2 An SEM image can have any type of real data, but the data values are usually 8-bit integers.

It is recommended that the fast Fourier transform and the inverse fast Fourier transform be used for the convolution calculation.

b) Compute the gradient magnitude $G_\mathrm{M}(x, y)$ from:

$$G_\mathrm{M}(x,y) = \sqrt{G_x(x,y)^2 + G_y(x,y)^2} \quad \text{(D.2)}$$

c) Compute a two-mean threshold image (binary image) $B(x, y)$ from $G_\mathrm{M}(x, y)$ by the following steps 1) to 5).

1) Generate a histogram $h(g)$ of $G_\mathrm{M}(x, y)$.

2) Determine the minimum value $g_\mathrm{min}$ and the maximum value $g_\mathrm{max}$ of $g$ in the histogram $h(g)$ that have non-zero values (see Figure D.1).

3) Set the initial value of $T_i$ to 128 for the iteration.


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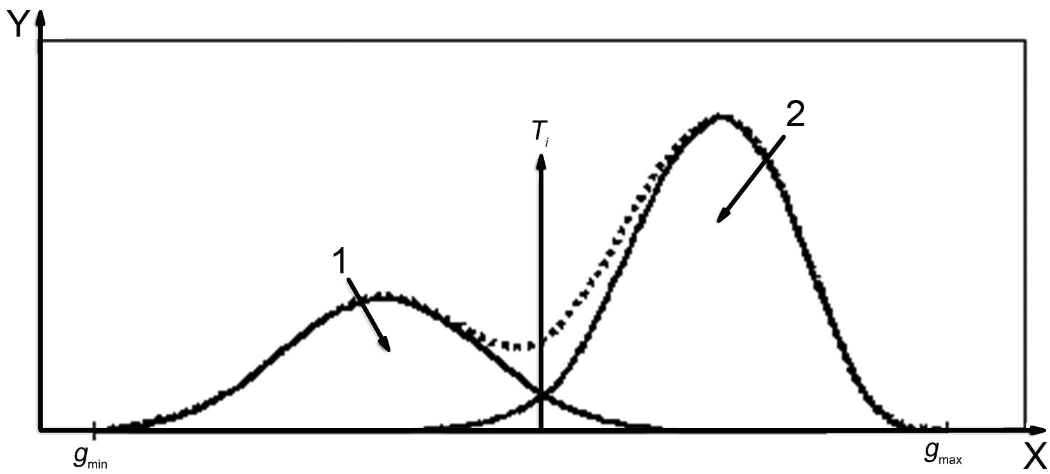
4) Then, repeat the following iteration until the value of $T_i$ is stable.

$$T_i = \frac{T_l + T_r}{2}$$

where

$$T_l = \frac{\sum_{g=g_{\text{min}}}^{T_i} g \times h(g)}{\sum_{g=g_{\text{min}}}^{T_i} h(g)} \quad \text{and} \quad T_r = \frac{\sum_{g=T_i}^{g_{\text{max}}} g \times h(g)}{\sum_{g=T_i}^{g_{\text{max}}} h(g)}$$

Select the value for judging the convergence of the iteration as 0,1 for practical purposes.




**Key**

X grey value

Y occurrence

1 background

2 object

**Figure D.1 — Example of a two-mean threshold**

5) Generate a two-mean threshold image (binary image) $B(x, y)$ by applying the threshold value $T_i$ to $G_M(x, y)$.

NOTE Binary images contain only the logical values 0 and 1.

Examples of input SEM images of the kinds generated in the procedures above are shown in Figure D.2.



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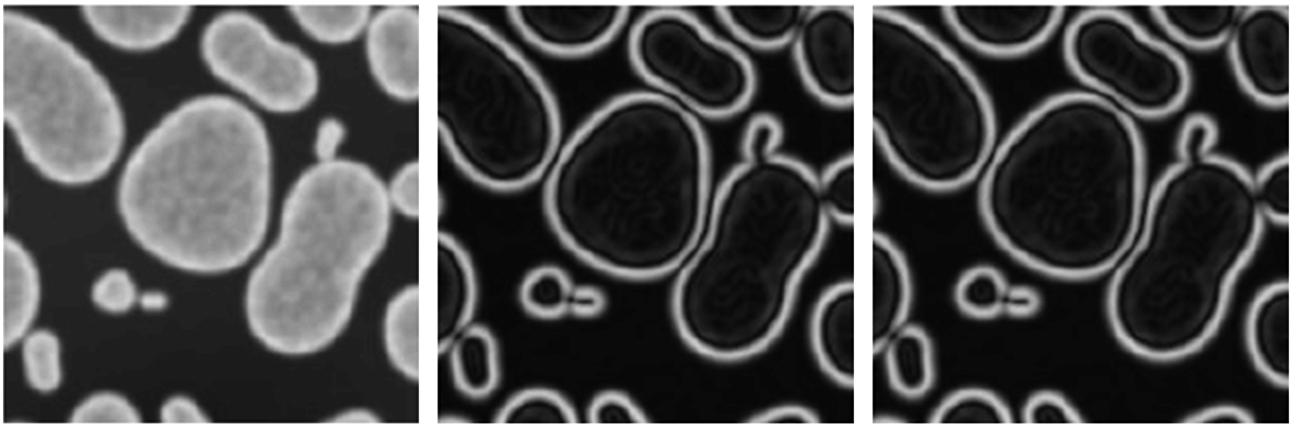

a) $I_N(x, y)$ b) $G_M(x, y)$ c) $B(x, y)$

**Figure D.2 — Examples of an input SEM image $I_N(x, y)$, a gradient magnitude image $G_M(x, y)$ and a two-mean threshold image (binary image) $B(x, y)$**
(all images are displayed linearly stretched over their dynamic range for better visualization)

d) Compute a binary mask image $M(x, y)$ from $B(x, y)$, using one-iteration binary closing [with structuring element $3 \times 3$ (city-block metric)], by the following steps:

1) binary dilation (see Clause D.8 for pseudo-codes);

2) binary erosion (see Clause D.8 for pseudo-codes).

e) Set all pixels in $M(x, y)$ that are closer than 30 pixels to the image border to zero. As regards the removal of boundary pixels, see Clause D.8 for the pseudo-codes.

f) Remove all objects in $M(x, y)$ that are smaller than 50 pixels by the following steps:

1) Label the objects (see Clause D.8 for pseudo-codes).

2) Count the number of pixels per object (see Clause D.8 for pseudo-codes).

3) Remove objects of less than 50 pixels (see Clause D.8 for pseudo-codes).

An example of an $M(x, y)$ image generated by the operations described in this clause is shown in Figure D.3.

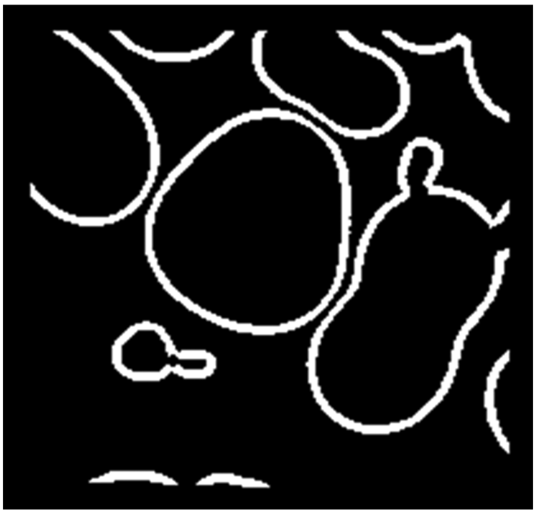

**Figure D.3 — Example of an $M(x, y)$ image as the outcome of the operations in Clause D.2**

--`,,```,,,,````-`-`,,`,,`,`,,`---



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## D.3 Generation of an edge position map $E(x, y)$

a) Compute an edge location image $P_L(x, y)$ as the sum of the image $L(x, y)$ and the second derivative in gradient direction SDGD$(x, y)$ of the image, as follows:

1) Compute $G_{xx}(x, y)$ and $G_{yy}(x, y)$ from the equations

$$G_{xx}(x, y) = \sum_{q=0}^{m-1} \sum_{p=0}^{n-1} I_N(p, q) \times \frac{(x-p)^2 - s^2}{2\pi s^6} \times \exp\left(-\frac{(x-p)^2 + (y-q)^2}{2s^2}\right) \quad \text{(D.3a)}$$

$$G_{yy}(x, y) = \sum_{q=0}^{m-1} \sum_{p=0}^{n-1} I_N(p, q) \times \frac{(y-q)^2 - s^2}{2\pi s^6} \times \exp\left(-\frac{(x-p)^2 + (y-q)^2}{2s^2}\right) \quad \text{(D.3b)}$$

It is recommended that the fast Fourier transform and the inverse fast Fourier transform be used for the convolution calculation.

2) Compute $L(x, y)$ as follows:

$$L(x, y) = \sqrt{G_{xx}(x, y)^2 + G_{yy}(x, y)^2} \quad \text{(D.4)}$$

3) Compute $G_{xy}(x, y)$ as follows:

$$G_{xy}(x, y) = \sum_{q=0}^{m-1} \sum_{p=0}^{n-1} I_N(p, q) \times \frac{(x-p)(y-q)}{2\pi s^6} \times \exp\left(-\frac{(x-p)^2 + (y-q)^2}{2s^2}\right) \quad \text{(D.5)}$$

It is recommended that the fast Fourier transform and the inverse fast Fourier transform be used for the convolution calculation.

4) Compute SDGD$(x, y)$ as follows:

$$\text{SDGD}(x, y) = \frac{G_{xx} G_x{}^2 + 2 G_{xy} G_x G_y + G_{yy} G_y{}^2}{G_x{}^2 + G_y{}^2} \quad \text{(D.6)}$$

NOTE For simplicity, the coordinates $(x, y)$ have been omitted from the right-hand side of Equation (D.6).

5) Compute $P_L(x, y)$ as follows:

$$P_L(x, y) = L(x, y) + \text{SDGD}(x, y)$$

b) Compute a two-mean threshold image (binary image) $M_1(x, y)$ from $T_1(x, y)$ as follows:

1) Compute

$$T_1(x, y) = T_0(x, y) \times M(x, y) \quad \text{(D.7)}$$

where

$$T_0(x, y) = \max[P_L(x, y)] - |P_L(x, y)|$$

NOTE The multiplication $T_0(x, y) \times M(x, y)$ is performed pixel by pixel.

2) Compute a two-mean threshold image (binary image) $M_1(x, y)$ as in Clause D.2, item c), for $T_1(x, y)$.


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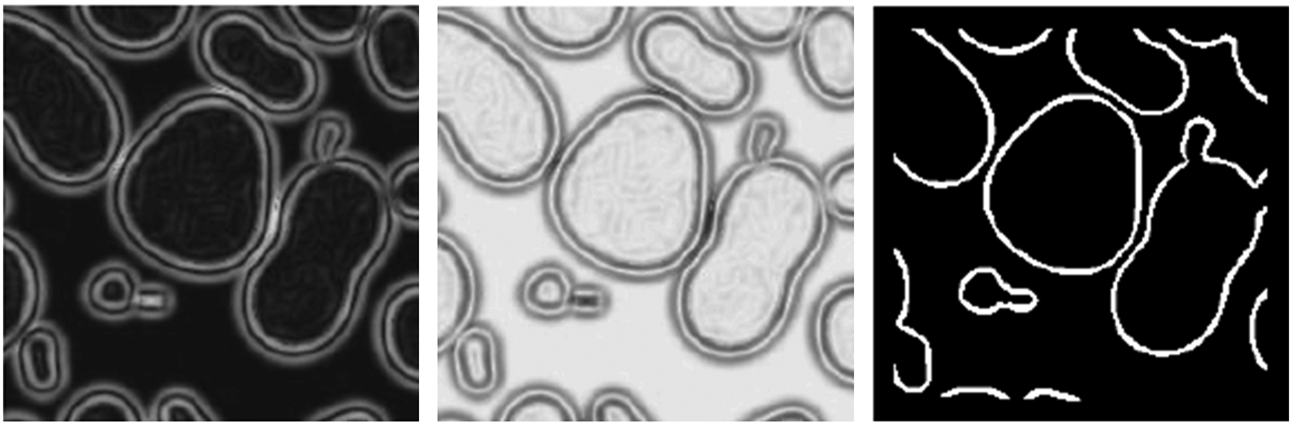
c) Compute an initial edge map $E_1(x, y)$ by the following steps:

1) Compute $M_2(x, y)$ as the one-iteration binary closing of $M_1(x, y)$ as in Clause D.2, item d).

2) Compute the binary skeleton of $M_2(x, y)$ and store it as $E_1(x, y)$. See Clause D.8 for the pseudo-codes for the binary skeleton.

d) Remove sufficient points from $E_1(x, y)$ such that the mutual distances between the remaining points are at least 10 pixels and store the result as $E(x, y)$. See Clause D.8 for the pseudo-codes for the points removed.

Figures D.4 and D.5 show examples.



**a)** $P_L(x, y)$ **b)** $T_0(x, y)$ **c)** $M_1(x, y)$

**Figure D.4 — Examples of $P_L(x, y)$, $T_0(x, y)$ and $M_1(x, y)$ images**
(all images are displayed linearly stretched over their dynamic range for better visualization)

**a)** $E_1(x, y)$ **b)** $E(x, y)$ **c) Directional line image**

**Figure D.5 — Examples of $E_1(x, y)$, $E(x, y)$ and a directional line image**
(the directional line image is shown for reference purposes)

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## D.4 Extraction of the edge profiles $P_j(x, y)$ and model fitting

a) Compute the normalized gradients $G_{\mathrm{N}x}(x, y)$ and $G_{\mathrm{N}y}(x, y)$ as follows:

$$G_{\mathrm{N}x} = G_x(x,y) / \sqrt{G_x(x,y)^2 + G_y(x,y)^2} \tag{D.8a}$$

$$G_{\mathrm{N}y} = G_y(x,y) / \sqrt{G_x(x,y)^2 + G_y(x,y)^2} \tag{D.8b}$$

b) Calculate all the edge profiles $P_j(\lambda)$ by repeating the following steps for all $j$ (= 1, 2, …, $N$) values.

$N$ is given by

$$N = \sum_{x=0}^{n-1} \sum_{y=0}^{m-1} E(x,y)$$

1) The coordinates of the sub-pixel position $(p_{jx}(\lambda), p_{jy}(\lambda))$ are given by

$$p_{jx}(\lambda) = x_j + \lambda \times G_{\mathrm{N}x}(x_j, y_j)$$

$$p_{jy}(\lambda) = y_j + \lambda \times G_{\mathrm{N}y}(x_j, y_j) \tag{D.9}$$

where $\lambda = -10, -9{,}5, -9, \ldots, 0, 0{,}5, \ldots, 9{,}5, 10$.

The number of sub-pixel positions is 41 for each edge profile.

NOTE The symbol $(x_j, y_j)$ denotes the coordinates of the edge map $E(x, y)$ having the $j$th value ($j$ = 1, 2, …, $N$).

2) Retrieve the edge profiles $P_j(\lambda)$ from $I_N(x, y)$ at 41 sub-pixel positions $(p_{jx}(\lambda), p_{jy}(\lambda))$, using the cubic interpolation method, as follows:

$$P_j(\lambda) = I_N(p_{jx}(\lambda), p_{jy}(\lambda)) = \sum_{n=0}^{3} \sum_{m=0}^{3} a_{nm} x^n y^m \tag{D.10}$$

NOTE The cubic-interpolated values at sub-pixel position $(p_{jx}(\lambda), p_{jy}(\lambda))$ are given by the pixel values at integer positions of $I_N(x, y)$ (see Clause D.7 for the coefficient values).

3) Compute

$m_0$ = median[$P_j(\lambda = 0)$] over all $j$ = 1, …, $N$

$m_r$ = median[$P_j(\lambda = -10)$] over all $j$ = 1, …, $N$

$m_l$ = median[$P_j(\lambda = +10)$] over all $j$ = 1, …, $N$

$d_y = (m_r + m_l)/2$

$m_d = m_0 - d_y/4$

$m_b = m_0 + d_y/4$



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Remove all edge profiles for which any of the following is true:

$P_j(\lambda) > m_d$ for $\lambda = -10, -9{,}5, \ldots, -7$

$P_j(\lambda) < m_b$ for $\lambda = 7, 7{,}5, \ldots, 10$

4) Determine the four coefficients $b$, $h$, $m$ and $\sigma_j$ such that the following fitting error $F_j$ is minimized:

$$F_j = \sum_{x=-20}^{20} \left[ f_j(x/2) - P_j(x/2) \right]^2 \tag{D.11}$$

where

$$f_j(x) = b + h \times \left[ \frac{1}{2} + \frac{1}{2} \mathrm{erf}\left( \frac{x-m}{\sigma_j \sqrt{2}} \right) \right]$$

NOTE The function erf($z$) denotes the error function and is defined as follows:

$$\mathrm{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z \exp(-t^2)\mathrm{d}t \approx 1 - \frac{1}{(1 + Az + Bz^2 + Cz^3 + Dz^4 + Ez^5 + Fz^6)^{16}}$$

where $A = 0{,}070\,523\,078\,4$, $B = 0{,}042\,282\,012\,3$, $C = 0{,}009\,270\,527\,2$, $D = 0{,}000\,152\,014\,3$, $E = 0{,}000\,276\,567\,2$ and $F = 0{,}000\,043\,063\,8$.

If $z > 10$, erf($z$) = 1, and if $z = 0$, erf($z$) = 0, for practical purposes.

The recommended initial values for the fit are as follows:

$b = \min[I_N(x, y)]$

$h = \max[I_N(x, y)]$

$m = 0$

$\sigma_j = 2$

See the latter half of Clause D.7 for fitted values of $\sigma_j$ by minimizing the fitting error given by Equation (D.11).

c) Store all fitted values of $\sigma_j$ ($j = 1, 2, \ldots, N$).

Figure D.6 shows an example.

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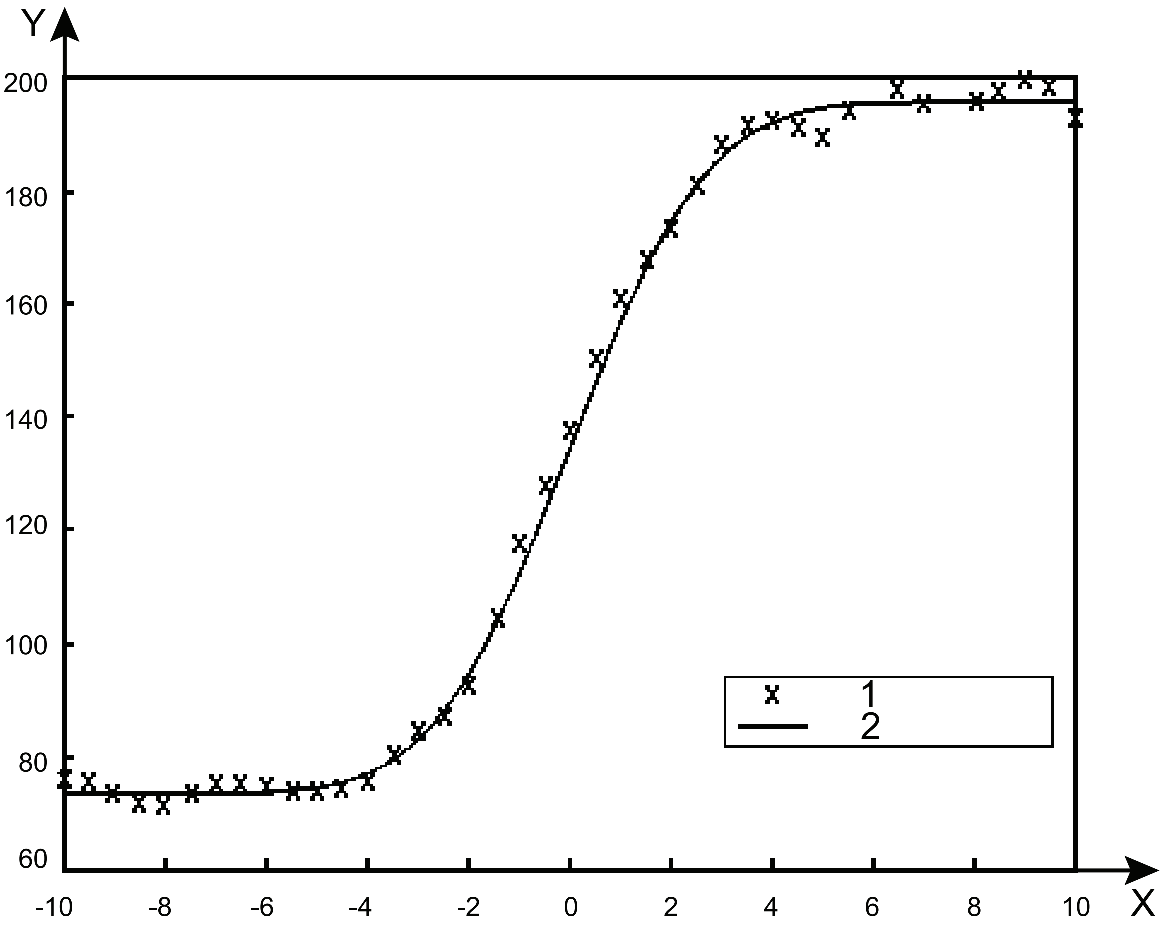


**Key**

X position perpendicular to the edge

Y intensity

1 edge intensities

2 error function fit

**Figure D.6 — Example of fitting the error function to the cubic-interpolated intensities of an SEM image**

## D.5 Calculation of image sharpness $R$

a) Calculate the average edge sharpness $\sigma$ from all the fitted edge sharpness parameters as follows:

$$\sigma = \frac{1}{N}\sum_{i=1}^{N}\sigma_i \tag{D.12}$$

NOTE See Clause D.9 for a reliability check of the value of $\sigma$ obtained.

b) Obtain the image sharpness as $R = \sqrt{2}\sigma$ .


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## D.6 Flow charts

Flow charts for the above procedures are given in Figures D.7 to D.11.

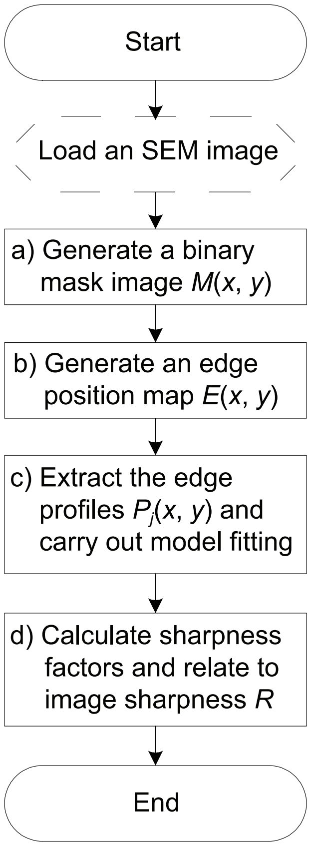


**Figure D.7 — Flow chart for the DR method**

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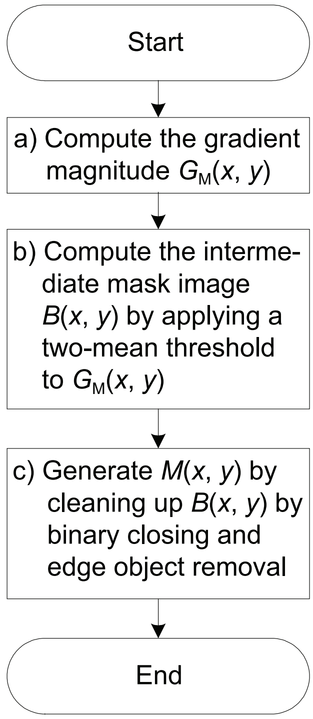


**Figure D.8 — Flow chart for the subroutine in Clause D.2 for the generation of a binary mask image $M(x, y)$**

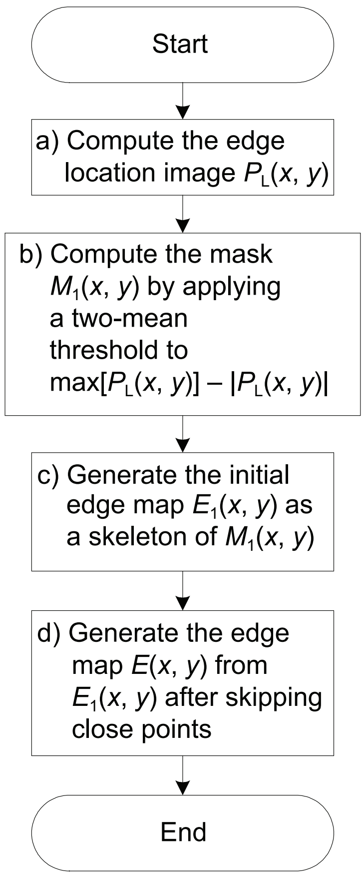


**Figure D.9 — Flow chart for the subroutine in Clause D.3 for the generation of an edge position map $E(x, y)$**


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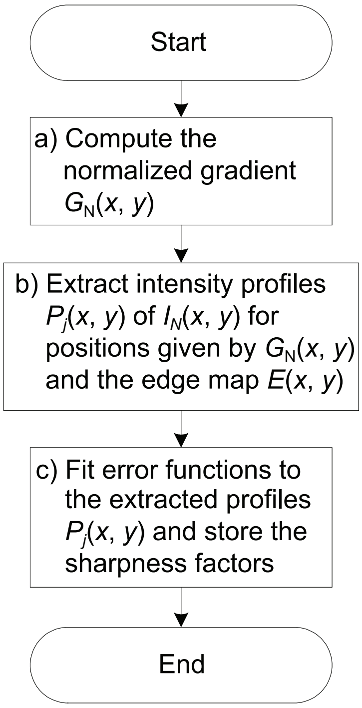


**Figure D.10 — Flow chart for the subroutine in Clause D.4 for the extraction of the edge profiles $P_j(x, y)$ and model fitting**

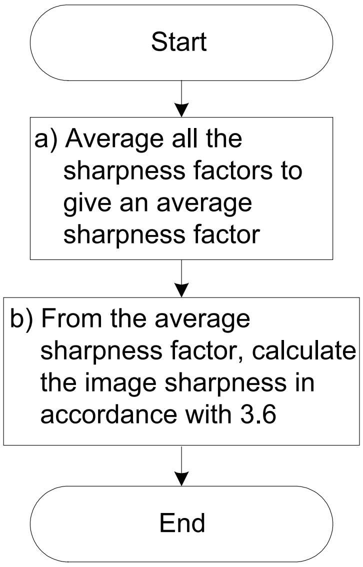


**Figure D.11 — Flow chart for the subroutine in Clause D.5 for the calculation of image sharpness**

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## D.7 Supplement 1

Cubic interpolation is given by

$$I_N(p_{jx}(\lambda), p_{jy}(\lambda)) = \sum_{n=0}^{3}\sum_{m=0}^{3} a_{nm} x^n y^m$$

For the above equation, the coefficients $a_{nm}$ are given by setting $xt$ equal to $p_{jx}(\lambda)$ and $yt$ equal to $p_{jy}(\lambda)$, as follows:

$$a_{00} = p_{00}$$

$$a_{01} = p_{y00}$$

$$a_{02} = -3p_{00} + 3p_{01} - 2p_{y00} - p_{y01}$$

$$a_{03} = 2p_{00} - 2p_{01} + p_{y00} + p_{y01}$$

$$a_{10} = p_{x00}$$

$$a_{11} = p_{xy00}$$

$$a_{12} = -3p_{x00} + 3p_{x01} - 2p_{xy00} - p_{xy01}$$

$$a_{13} = 2p_{x00} - 2p_{x01} + p_{xy00} + p_{xy01}$$

$$a_{20} = -3p_{00} + 3p_{10} - 2p_{x00} - p_{x10}$$

$$a_{21} = -2p_{xy00} - p_{xy10} - 3p_{y00} + 3p_{y10}$$

$$a_{22} = 9p_{00} - 9p_{01} - 9p_{10} + 9p_{11} + 6p_{x00} - 6p_{x01} + 3p_{x10} - 3p_{x11} + 4p_{xy00} + 2p_{xy01} + 2p_{xy10} + p_{xy11}$$
$$+ 6p_{y00} + 3p_{y01} - 6p_{y10} - 3p_{y11}$$

$$a_{23} = -6p_{00} + 6p_{01} + 6p_{10} - 6p_{11} - 4p_{x00} + 4p_{x01} - 2p_{x10} + 2p_{x11} - 2p_{xy00} - 2p_{xy01} - p_{xy10} - p_{xy11}$$
$$- 3p_{y00} - 3p_{y01} + 3p_{y10} + 3p_{y11}$$

$$a_{30} = 2p_{00} - 2p_{10} + p_{x00} + p_{x10}$$

$$a_{31} = p_{xy00} + p_{xy10} + 2p_{y00} - 2p_{y10}$$

$$a_{32} = -6p_{00} + 6p_{01} + 6p_{10} - 6p_{11} - 3p_{x00} + 3p_{x01} - 3p_{x10} + 3p_{x11} - 2p_{xy00} - p_{xy01} - 2p_{xy10} - p_{xy11}$$
$$- 4p_{y00} - 2p_{y01} + 4p_{y10} + 2p_{y11}$$

$$a_{33} = 4p_{00} - 4p_{01} - 4p_{10} + 4p_{11} + 2p_{x00} - 2p_{x01} + 2p_{x10} - 2p_{x11} + p_{xy00} + p_{xy01} + p_{xy10} + p_{xy11}$$
$$+ 2p_{y00} + 2p_{y01} - 2p_{y10} - 2p_{y11}$$


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where

$p_{00} = I_N(\text{floor}(xt),\text{floor}(yt))$

$p_{01} = I_N(\text{floor}(xt),\text{ceil}(yt))$

$p_{10} = I_N(\text{ceil}(xt),\text{floor}(yt))$

$p_{11} = I_N(\text{ceil}(xt),\text{ceil}(yt))$

$p_{x00} = G_x(\text{floor}(xt),\text{floor}(yt))$

$p_{x01} = G_x(\text{floor}(xt),\text{ceil}(yt))$

$p_{x10} = G_x(\text{ceil}(xt),\text{floor}(yt))$

$p_{x11} = G_x(\text{ceil}(xt),\text{ceil}(yt))$

$p_{y00} = G_y(\text{floor}(xt),\text{floor}(yt))$

$p_{y01} = G_y(\text{floor}(xt),\text{ceil}(yt))$

$p_{y10} = G_y(\text{ceil}(xt),\text{floor}(yt))$

$p_{y11} = G_y(\text{ceil}(xt),\text{ceil}(yt))$

$p_{xy00} = G_{xy}(\text{floor}(xt),\text{floor}(yt))$

$p_{xy01} = G_{xy}(\text{floor}(xt),\text{ceil}(yt))$

$p_{xy10} = G_{xy}(\text{ceil}(xt),\text{floor}(yt))$

$p_{xy11} = G_{xy}(\text{ceil}(xt),\text{ceil}(yt))$

NOTE ceil(...) means the least integer greater than a particular fractional value (i.e. rounding up) and floor(...) means the greatest integer less than a particular fractional value (i.e. discarding the fraction after the decimal point).

```
// Computing sigma[p] (p = 1, 2, ..., N) by minimizing the fitting error given by Equation (D.11)

FOR p = 1, 2, ..., N

  // N = number of data sets obtained

  // sqrt_2 = square root of 2

  // sqrt_pi = square root of 3,14159265358979323846

  // initial values

  b = params[0] = min(IN(x,y))

  h = params[1] = max(IN(x,y))

  m = params[2] = 0

  sigma[p] = params[3] = 2
```



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```
alpha = 1/(params[3]*sqrt_2)
// Computing the initial chisq
Set chisq = 0
FOR i = 0, 1, ..., 40
  // x[0] = –20, x[1] = –19, ...., x[40] = 20
  erf_app = erf(alpha*(x[i]/2 - m))
  model = b + h*(0,5 + 0,5*erf_app)
  deviation = P(x[i]/2) – model
  chisq += deviation*deviation
END FOR
FOR iter = 0, 1, ..., 99
  Set grad[i] = 0 for i = 0, 1, ..., 3
  Set Hessian[i][j] = 0 for i, j = 0, 1, ..., 3
  FOR i = 0, 1, 2, ..., 40
    // x[0] = –20, x[1] = –19, ...., x[40] = 20
    erf_app = erf(alpha*(x[i]/2 – m))
    model = b + h*(0,5 + 0,5*erf_app)
    deviation = P(x[i]/2) – model
    Gauss = exp(-(x[i]/2 – m)*(x[i]/2 – m)*alpha*alpha)
    d[0] = 1
    d[1] = 0,5 + 0,5*erf_app
    d[2] = –(h/sqrt_pi)*alpha*Gauss
    d[3] = (h/sqrt_pi)*(x[i]/2 – m)*Gauss
    grad[0] += –2*d[0]*deviation
    grad[1] += –2*d[1]*deviation
    grad[2] += –2*d[2]*deviation
    grad[3] += –2*d[3]*deviation
    FOR j, k = 0, 1, ..., 3
      Hessian[j][k] += d[j]*d[k]
    END FOR
```


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```
END FOR
Set lamda = 0,001
Set diff_chisq = –chisq
FOR iter_line = 0, 1, ..., 49
  FOR k = 0, 1, ..., 3
    Hessian[k][k] *= (1 + lamda)
  END FOR
  //Cholesky decomposition of the Hessian
  Set cholesky[j][k] = 0 for j, k = 0, 1, ..., 3
  FOR k = 0, 1, ..., 3
    Set sum = 0
    FOR n = 0, 1, ..., k-1
      sum += cholesky[n][k]*cholesky[n][k]
    END FOR
    // sqrt_d = square root of d
    d = Hessian[k][k] – sum
    cholesky[k][k] = sqrt_d
    FOR l = k+1, k+2, ..., 3
      Set sum2 = 0
      FOR n = 0, 1, ..., k-2
        sum2 += cholesky[n][l]*cholesky[n][k]
      END FOR
      cholesky[k][l] = (Hessian[k][l] – sum2)/(cholesky[k][k] + 1,0e-7)
    END FOR
  END FOR
  // Solving for the update vector
  // Forward substitution - intermediary solution
  Set sol1[0] = 0
      sol1[1] = 0
      sol1[2] = 0
```



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```
     sol1[3] = 0
FOR k = 0, 1, ..., 3
  Set sum = 0
  FOR n = 0, 1, ..., k-2
    sum += cholesky[n][k]*sol1[n]
  END FOR
  sol1[k] = (–0,5*grad[k] – sum)/(cholesky[k][k] + 1,0e-7)
END FOR
// Backward substitution - the actual update vector
Set update[0] = 0
     update[1] = 0
     update[2] = 0
     update[3] = 0
FOR k = 3, 2, ..., 0
  Set sum = 0
  FOR n = k+1, k+2, ..., 3
    sum += cholesky[k][n]*update[n]
  END FOR
  update[k] = (sol1[k] – sum)/(cholesky[k][k] + 1,0e-7)
END FOR
b_n = b + update[0]
h_n = h + update[1]
m_n = m + update[2]
alpha_n = alpha + update[3];
Set chisq_n = 0
FOR i = 0, 1, ..., 40
  erf_app = erf(alpha_n*(x[i]/2 – m_n));
  model = b_n + h_n*(0,5 + 0,5*erf_app)
  chisq_n += (P(x[i]/2) – mode)*(P(x[i]/2) – model)
END FOR
```


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```
      IF chisq_n < chisq
        b = b_n
        h = h_n
        m = m_n
        alpha = alpha_n
        lamda = lamda*0,1
        diff_chisq = chisq – chisq_n
        chisq = chisq_n
        break
      ELSE
        lamda = lamda*10,0
      END IF
    END FOR// end of loop for iter_line
    // Stopping criterion
    IF (diff_chisq > 0) and (diff_chisq < 0,01)
      break
    END IF
  END FOR// end of loop for iter
  sigma[p] = 1/(alpha*sqrt_2)
END FOR// end of loop (p = 1, 2, ..., N)
```

## D.8 Supplement 2

```
// binary dilation
Set M0[x][y] = 0 for x = 0, 1, …, n–1 and y = 0, 1, …, m–1.
FOR over pixel locations of x = 1, 2, ..., n–2 and y = 1, 2, ..., m–2
    IF B[x][y] == true OR B[x–1][y] == true OR B[x+1][y] == true OR B[x][y–1] == true OR B[x][y+1] == true
        M0[x][y] = true
    END IF
END FOR
```

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```
// binary erosion
Set M[x][y] = M0[x][y] for x = 0, 1, …, n–1 and y = 0, 1, …, m–1.
FOR over pixel locations of x = 1, 2, ..., n–2 and y = 1, 2, ..., m–2
    IF M0[x–1][y] == false OR M0[x+1][y] == false OR M0[x][y–1] == false OR M0[x][y+1] == false
        M[x][y] = false
    END IF
END FOR


// removing boundary pixels
FOR over pixel locations of x = 0, 1, …, n–1 and y = 0, 1, …, m–1
        IF x < 30 OR x > n–30 OR y < 30 OR y > m–30
            M[x][y] = 0
        END IF
END FOR

// labelling of objects
Set array C[i] = i (i = 0, 1, ..., nm), LA(x,y) = M(x,y), and NewLabel = 0, as initial values.
FOR over pixel locations of x = 1, 2, ..., n–2 and y = 1, 2, ..., m–2.
        IF LA(x,y) == true
            lp = LA(x–1,y)
            lq = LA(x,y–1)
            IF lp == false AND lq == false, increment NewLabel by 1, and then set lx = NewLabel.
            ELSE IF lp ≠ false, AND lq ≠ false,
                IF C[lp] ≠ C[lq],
                    FOR ALL k=0, 1,… NewLabel
                            IF C[k] == C[lp], set C[k] = C[lq].
                    END FOR
                END IF
                Set lx = lq.
            ELSE IF lp = false AND lq ≠ false, set lx = lq.
            ELSE IF lp ≠ false AND lq = false, set lx = lp.
            END IF
            Set LA[x,y] = lx.
        END IF
END FOR
FOR over pixel locations of x = 0, 1, …, n–1 and y = 0, 1, …, m–1.
        IF LA(x,y) ≠ false, set LA(x,y) = C[LA(x,y)].
END FOR
Set NO = NewLabel.
```


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```
// counting the number of pixels per object
Set array OS[0] = OS[1] = ........ = OS[NO+1] = 0.
FOR over pixel locations of x = 0, 1, …, n–1 and y = 0, 1, …, m–1
    increment OS[LA[x][y]] by 1.
END FOR

// removing objects with less than 50 pixels
FOR over pixel positions of x = 0, 1, …, n–1 and y = 0, 1, …, m–1
    IF OS[LA[x][y]] < 50
        LA[x][y] = 0
    END IF
END FOR

// binary skeleton
Perform the following routine until no more skeleton pixels.
E1[x][y] = M2[x][y] for x = 0, 1, …, n–1 and y = 0, 1, …, m–1.
FOR over pixel locations of x = 1, 2, ..., n–2 and y = 1, 2, ..., m–2
    IF M2[x–1][y] == false OR M2[x+1][y] == false
            OR M2[x][y–1] == false OR M2[x][y+1] == false
        // condition 1) do not remove single pixels and condition 3) do not break the connectivity
        IF three or four of the above conditions are true
            CONTINUE
        END IF
        // condition 2) do not break the connectivity
        IF two of the above conditions are true
            IF M2[x–1][y] == false AND M2[x+1][y] == false
              CONTINUE
            END IF
            IF M2[x][y–1] == false AND M2[x][y+1] == false
              CONTINUE
            END IF
        END IF
        E1[x][y] = false
    END IF
END FOR
```



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```
// removing points
Set i = 0.
FOR over pixel locations of for x = 0, 1, …, n–1 and y = 0, 1, …, m–1
    IF E1[x][y] is true
        px[i] = x
        py[i] = y
        increment i by 1
    END IF
END FOR
Check the distance between any two points being 10 or larger, during the following loop.
FOR j = 0 to i – 1
    IF mod (j, 10) is true
        E[px[j]][py[j]] = true
    ELSE IF
        E[px[j]][py[j]] = false
    END IF
END FOR
```

## D.9 Supplement 3

The average edge sharpness $\sigma$, as given by Equation (D.12), is as follows:

$$\sigma = \frac{1}{N}\sum_{i=1}^{N}\sigma_i$$

First, check the distribution shape of $\sigma_j$ ($j = 1, 2, \ldots, N$).

NOTE If the distribution shape is far from Gaussian, the average edge sharpness $\sigma$ obtained is less reliable (see Figure D.12).

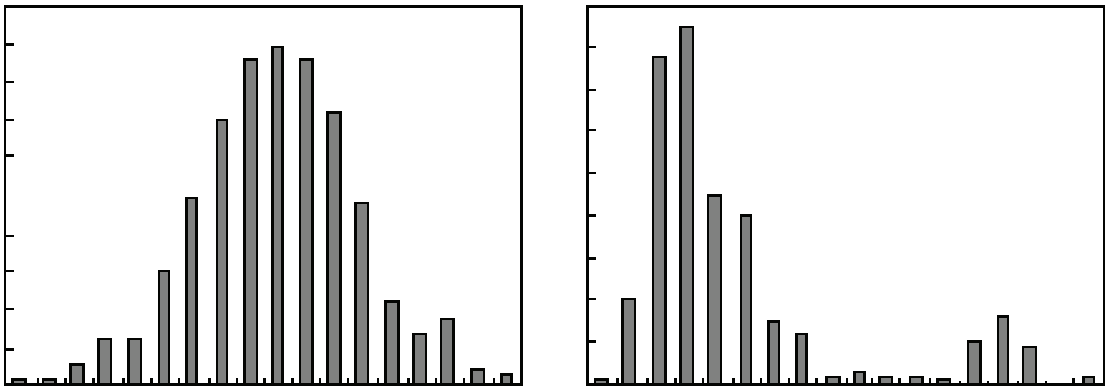

**Figure D.12 — Examples of the distribution of $\sigma_j$**



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Then, check the reliability of the average edge sharpness $\sigma$ as follows:

a) Compute the variance from

$$V^2 = \frac{\sum_{i=1}^{N}(\sigma - \sigma_i)^2}{N}$$

b) Compute the factor $F_R$ for the confidence limit from

$$F_R = \frac{t_\alpha \times \sqrt{V^2}}{\sqrt{N-1}}$$

using a value for $t_\alpha$ interpolated from those given in Table D.1.

**Table D.1**
(90 % reliability)

| $N$ | $t_\alpha$ |
|---|---|
| 10 | 1,812 |
| 20 | 1,725 |
| 30 | 1,697 |
| 40 | 1,684 |
| 60 | 1,671 |
| 120 | 1,658 |
| Infinity | 1,645 |

NOTE The mean value of the edge sharpness lies within the interval ($\sigma - F_R$, $\sigma + F_R$) with 90 % reliability. Here, the average edge sharpness $\sigma$ (the standard deviation of the Gaussian profile) is the sample mean. For example, if $\sigma = 3$ and $F_R = 1$, the "true $\sigma$" lies in the interval given by 2 < "true $\sigma$" < 4 with a reliability of 90 %.

c) If $F_R > 1$, the $\sigma$ value obtained is not considered to be reliable enough.

## D.10 Supplement 4

The Fourier transform (FT) of the Gaussian distribution function is given by

$$\mathrm{FT}[\exp(-ax^2)] = \frac{1}{\sqrt{2a}} \exp\left(-\frac{{\omega_x}^2}{4a}\right) \quad \text{for } a > 0$$

and the FT of the differentiated function is given by

$$\mathrm{FT}\left[\frac{\mathrm{d}^n f(x)}{\mathrm{d}x^n}\right] = \left(-\sqrt{-1}\right)^n \times {\omega_x}^n \times F(\omega_x)$$

where

$F(\omega_x) = \mathrm{FT}[f(x)]$;

$\omega_x$ is the angular frequency ($2\pi \times$ frequency) corresponding to $x$.

These equations can be used for the convolution calculation.

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# Annex E
(informative)

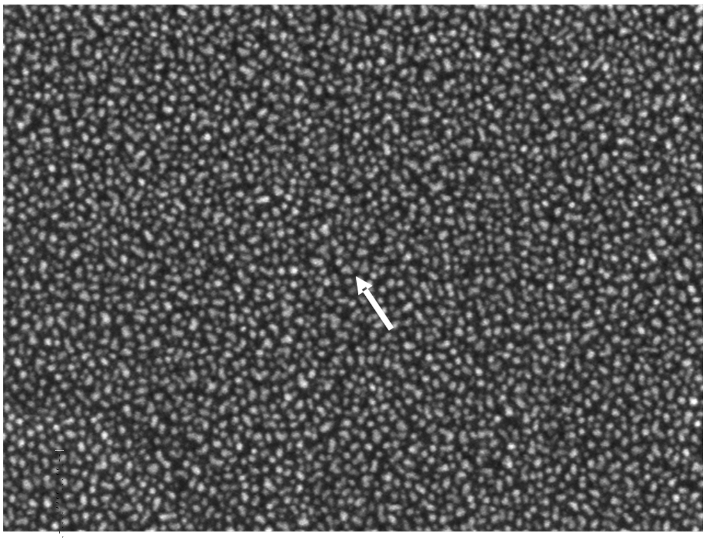
# Background to evaluation of image sharpness

## E.1 General

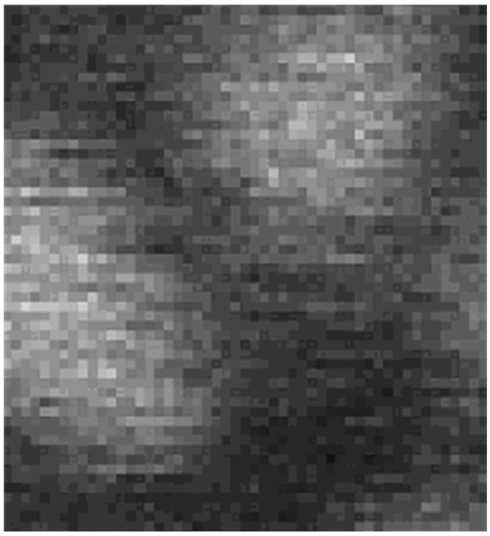
This annex provides the background to the evaluation of image sharpness and the theoretical background to the definition of image sharpness used in this Technical Specification.

## E.2 Conventional method of evaluating image sharpness

The sharpness of an SEM image is defined as the minimum distance between two neighbouring particles that can just be resolved. Therefore the sharpness depends on the contrast and the noise of the image, i.e. the contrast-to-noise ratio. A typical method of evaluating image sharpness in SEM is a gap measurement method. In this method, the image sharpness is evaluated by measuring the gap between two neighbouring particles in the SEM image as shown in Figure E.1 a). Figure E.1 b) shows the digitally magnified image at the gap indicated by the arrow in Figure E.1 a).



a) SEM image for evaluating image sharpness



b) Digitally magnified image at the gap

**Figure E.1 — SEM image and a magnified image of the gap area**

As shown in Figure E.1 b), it is difficult to determine clearly the gap boundaries due to image noise. Therefore the result of the evaluation of the image sharpness by the conventional gap method can vary due to human error since the width of the gap between neighbouring particles in an SEM image is measured by the human eye based on the sharpness at the local edges of these particles. In order to avoid errors, it is preferable to use appropriate image-processing techniques to evaluate image sharpness so that everybody obtains the same result.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## E.3 Concept of image sharpness as defined in this Technical Specification

So far, several computer algorithms, such as the Fourier transform (FT) method, contrast-to-gradient (CG) method and derivative (DR) method, have been developed for evaluating image sharpness in SEM (see Annexes B to D). The Fourier transform (FT) method has been developed based on a classical FT method by adding a new algorithm to separate the noise component from the image component in an SEM image. On the other hand, the contrast-to-gradient (CG) method and derivative (DR) method have been developed in order to evaluate the image sharpness using a concept similar to that of the conventional method utilizing information on the sharpness at local edges. However, none of the algorithms has been authorized as the standard one for international use. This Technical Specification will standardize the computer algorithms for evaluating the image sharpness based on the newly improved conventional method (FT method) and the newly developed CG and DR methods, so that one can determine the image sharpness from an SEM image without human intervention. The measurement does vary with the method used because each method uses a different procedure for taking the image noise into account. However, the differences in the results obtained for the image sharpness can be kept at an acceptable level by using images with a contrast-to-noise ratio of 10 or better (see Annex F). It must be noted that, although the actual beam profiles in SEM have a variety of shapes, the images used for evaluation in this Technical Specification are those produced by the convolution of a binary image with a Gaussian profile of sharpness factor $2\sigma$, where $\sigma$ is the standard deviation of the Gaussian distribution. The concept utilized throughout this document is first to determine the sharpness factor ($2\sigma$) from the convoluted image and then to calculate the image sharpness from the formula $2\sigma/\sqrt{2}$. In order to evaluate the image sharpness by using this Technical Specification, it is necessary to use a suitable specimen to obtain the SEM image.

## E.4 Comparison of the definition of image sharpness in this Technical Specification with conventionally used definitions

Rayleigh's criterion is usually applied to the definition of image sharpness for point objects. According to Rayleigh's criterion, the sharpness is defined as the distance ($R_d$) between two point objects when the concave trough in the overlapped profile is 74 % of the maximum, as shown in Figure E.2. The distance $R_d$ is given by

$$R_d = 0{,}61\lambda/\alpha$$

where

$\lambda$ is the wavelength;

$\alpha$ is a numerical aperture (NA).

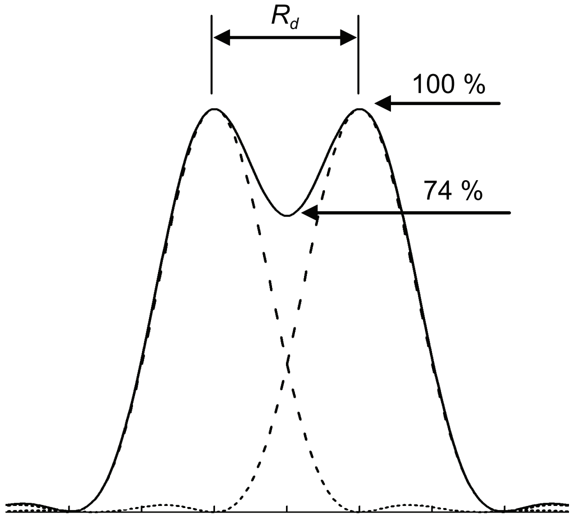


**Figure E.2 — Two overlapping profiles (Airy patterns) meeting Rayleigh's criterion**

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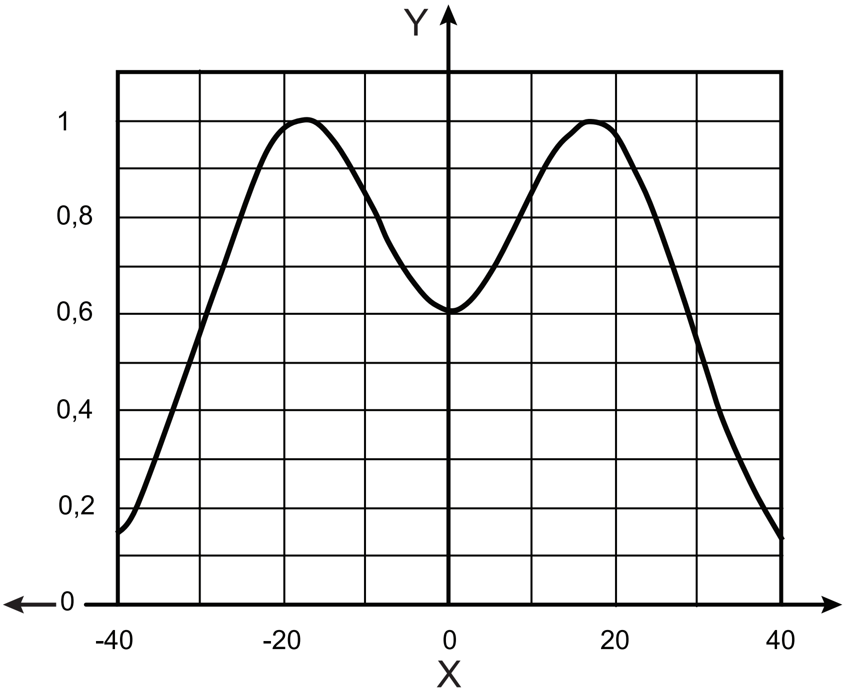
On the other hand, it is impossible to evaluate the sharpness of SEM images of point objects since all objects in SEM images have finite sizes. Figure E.3 shows a) a binary image of two circular objects each having a diameter of 20 pixels and with a separation of 14 pixels and b) its convoluted image with a sharpness factor ($2\sigma$) of 20 pixels. The separation of 14 pixels in Figure E.3 a) corresponds to $2\sigma/\sqrt{2}$ (the sharpness criterion used in this Technical Specification) when the sharpness factor ($2\sigma$) is 20 pixels. Figure E.4 shows a line profile of the convoluted image b) in Figure E.3. The depth of the trough between the two particles is 60 % of the maximum, corresponding to an equivalent or better contrast when compared to the conventional criterion proposed by Rayleigh (see Figure E.2). Thus, defining the image sharpness as $2\sigma/\sqrt{2}$ is practical compared to the conventional criterion.

NOTE The image sharpness defined in this Technical Specification is half of the value used by Rayleigh's criterion ($4\sigma/\sqrt{2}$).


**a) Binary pattern** **b) Blurred image**

**Figure E.3 — Binary pattern, a), and blurred image, b), produced by a Gaussian profile with a sharpness factor ($2\sigma$) of 20 pixels (the binary pattern is made up of two neighbouring circles of diameter 20 pixels separated by a distance of 14 pixels)**




**Key**

X line profile position (pixels)

Y signal intensity (arbitrary units)

**Figure E.4 — Line profile of blurred image**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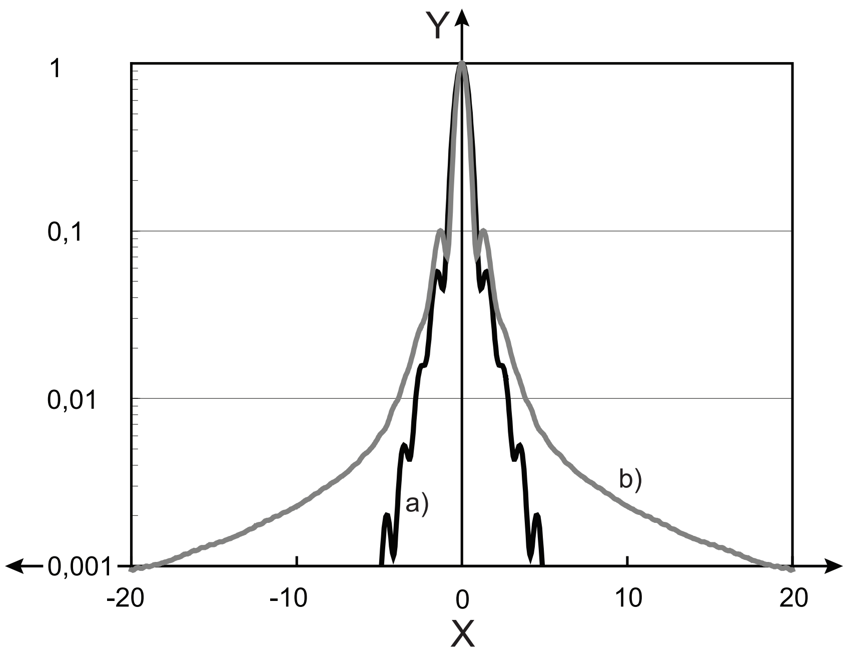
## E.5 Difficulty of determining the probe size from SEM images

The profile of a primary beam in SEM is usually regarded as a Gaussian distribution, and the beam size is often defined as the FWHM (full width at half maximum). However, in actuality, the beam profile in SEM has a variety of shapes, depending on the extent of electron diffraction and lens aberrations. Figure E.5 shows the beam profiles calculated under different beam conditions when a) electron diffraction is dominant in the optical system and b) lens aberrations are dominant in the optical system. Beam profile a) in Figure E.5 can be roughly approximated as a Gaussian distribution. However, profile b) in Figure E.5 differs significantly from a Gaussian distribution due to the wide spread produced by the lens aberrations. Because beam profiles a) and b) shown in Figure E.5 have the same FWHM values, the beam sizes, when simply defined as the FWHM, are the same for both profiles. Figure E.6 shows the SEM images obtained under the conditions represented by profiles a) and b) in Figure E.5. As shown in Figure E.6, the quality of SEM image a) is very different from that of image b), even though the FWHM values of the beams are same. Usually no-one knows the actual beam profiles when evaluating the image sharpness. The contrast of SEM images is affected by the interaction between a specimen and primary electrons. It is impossible to determine the beam profile (or beam size) simply from the SEM image. This is the reason why this Technical Specification does not apply to the measurement of beam (probe) size in SEM.




**Key**

X beam profile position (nm)

Y relative intensity (arbitrary units)

**Figure E.5 — Beam profiles calculated under different beam conditions: a) mainly electron diffraction and b) mainly lens aberrations**



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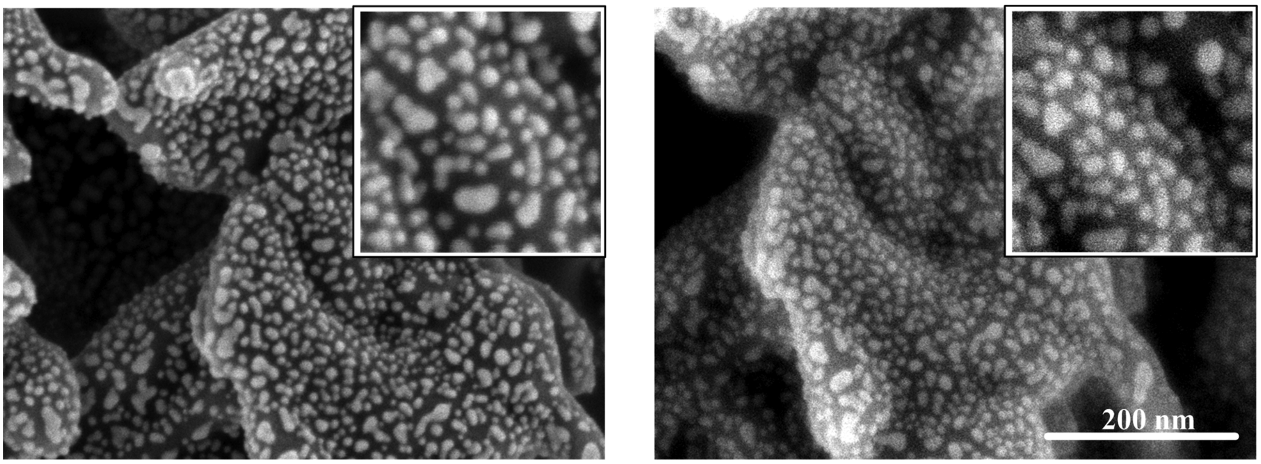


a) Image influenced mainly by diffraction

b) Image influenced mainly by lens aberrations

**Figure E.6 — SEM images obtained under different beam conditions**


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# Annex F
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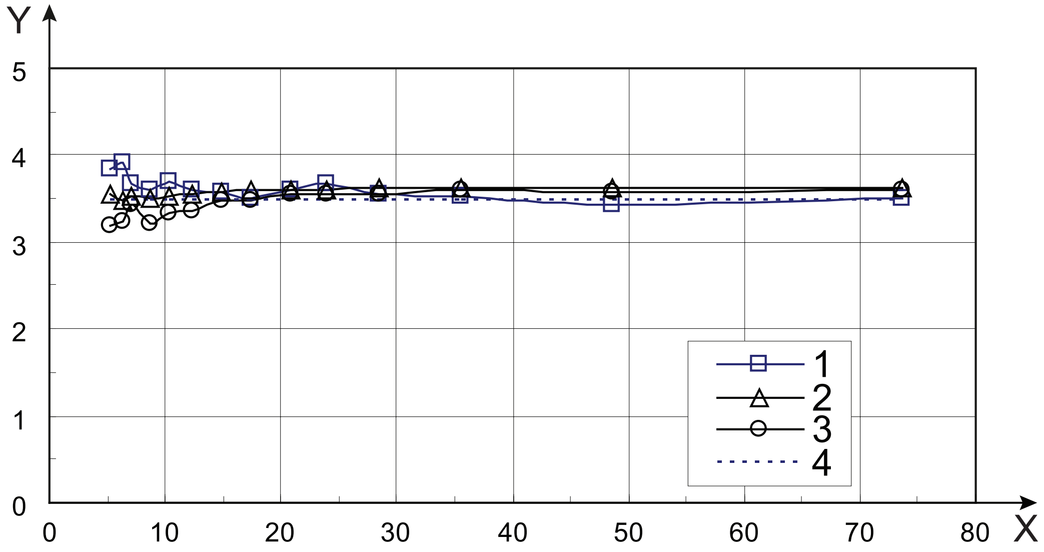
# Characteristics and suitability of the various evaluation methods

## F.1 Dependency of image sharpness on image noise

The image sharpness usually depends on the contrast-to-noise ratio (CNR) of the SEM image. Figure F.1 shows the dependency of the evaluated value of the sharpness on the CNR value for the FT, CG and DR methods. The CNR value should be 10 or larger for evaluations.




**Key**

X CNR

Y evaluated image sharpness $R$

1 FT method

2 CG method

3 DR method

4 theoretical

**Figure F.1 — Example of the dependency of the image sharpness on the CNR value for a simulated image with a sharpness ( $\sqrt{2}\sigma$ ) of 3,472 pixels**

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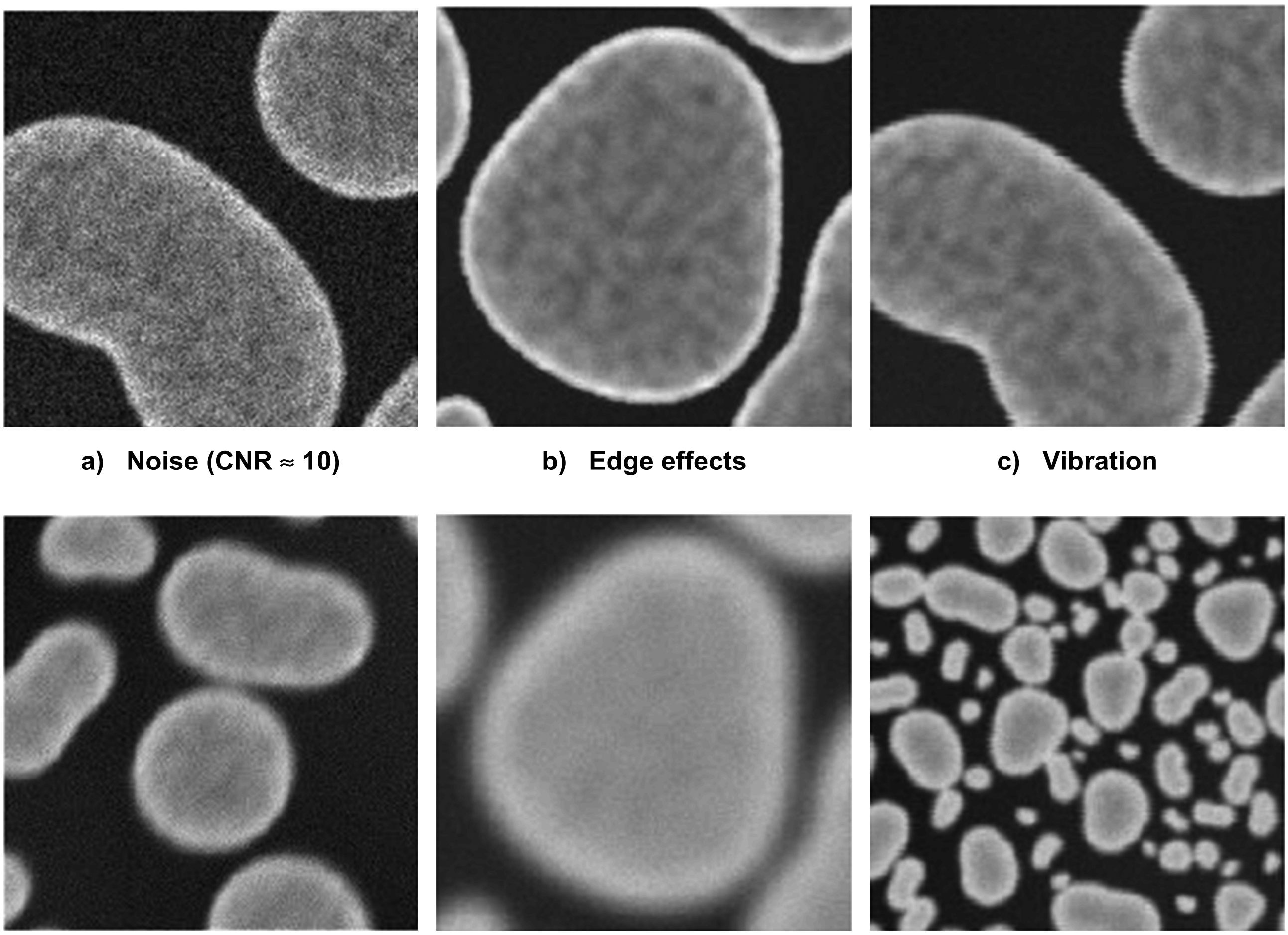
## F.2 Parameters influencing images for use in the FT, CG and DR methods

The image sharpness is influenced by noise, edge effects, vibration, astigmatism, poor focus and the density of the particles. Table F.1 shows the maximum limits of these parameters for the evaluation methods. Figure F.2 shows examples of SEM images significantly influenced by each of the parameters.

**Table F.1 — Maximum limits**

| Size of effect | | | | |
|---|---|---|---|---|
| **Very small** | **Small** | **Medium** | **Large** | **Very large** |
| Noise | | | | |
| Edge effects | | | | |
| Vibration | | | | |
| Astigmatism | | | | |
| Out of focus | | | | |
| Density of particles | | | | |



a) **Noise (CNR ≈ 10)**  b) **Edge effects**  c) **Vibration**

d) **Astigmatism**  e) **Poor focus**  f) **Density of particles**

NOTE 1 The particle edges in these images (except the out-of-focus image) have been sharpened for easier viewing.

NOTE 2 The images should be made up of particles. Images made up of line-and-space patterns are unacceptable.

**Figure F.2 — Examples of SEM images for use in the FT, CG and DR methods**
[only parts (210 × 210 pixels) of the images are shown]



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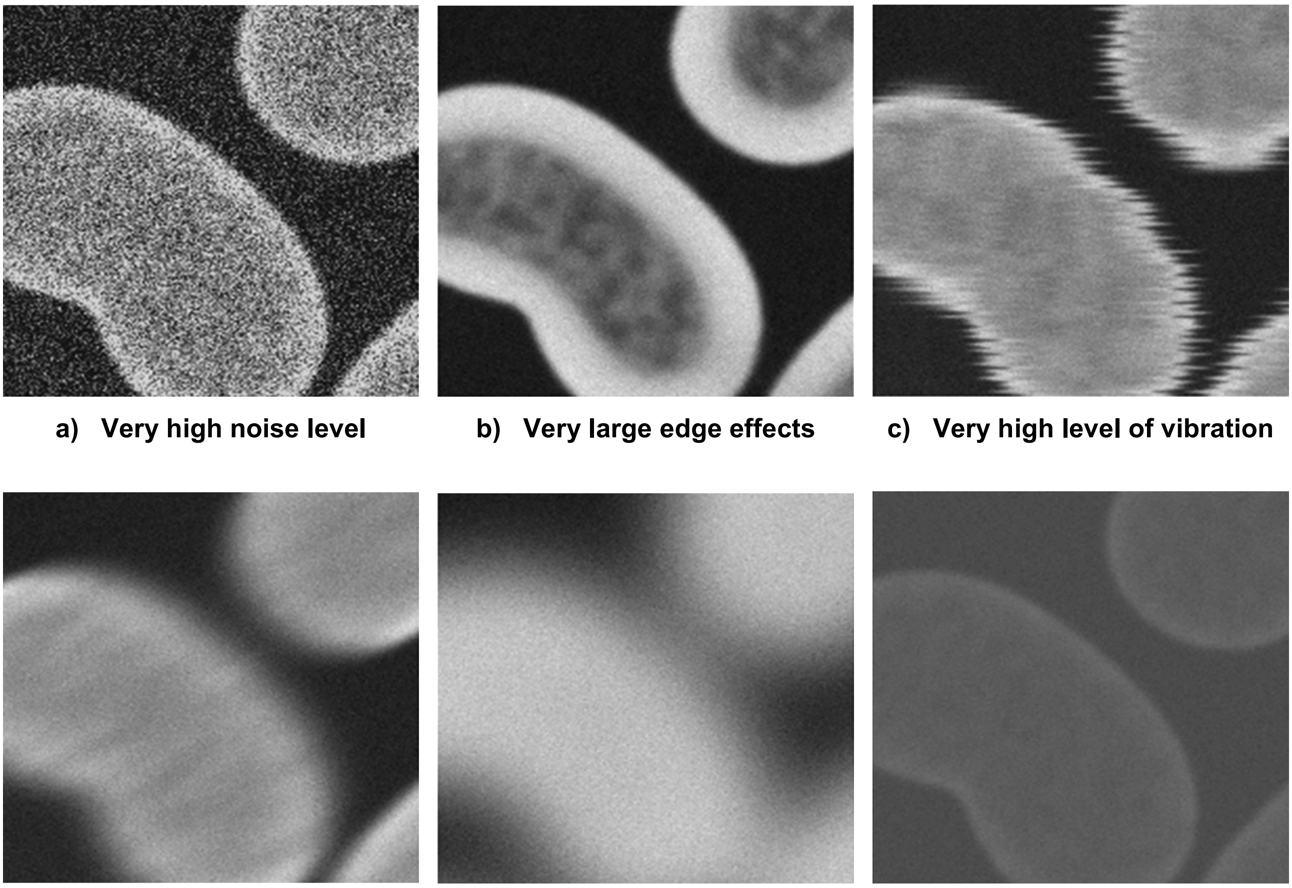
## F.3 Suitability of the FT, CG, DR and CNR methods

Table F.2 shows the suitability of the FT, CG, DR and CNR methods as judged by the effect of the various parameters which influence the SEM image. Figure F.3 shows examples of images with a very high noise level, very large edge effects, a very high level of vibration, very large astigmatism, very poor focus or very low contrast, corresponding to the items in Table F.1.

**Table F.2 — Suitability of the FT, CG, DR and CNR methods**

| Evaluation method | Very high noise level | Very large edge effects | Very high level of vibration | Very large astigmatism | Very out of focus | Very high particle density | Very low contrast |
|---|---|---|---|---|---|---|---|
| FT | G | NGNB | B | B | NGNB | NGNB | G |
| CG | B | NGNB | NGNB | G | G | G | G |
| DR | G | G | B | B | NGNB | NGNB | B |
| CNR | G | G | B | G | G | G | G |

G: good;
B: bad;
NGNB: neither good nor bad.



a) Very high noise level    b) Very large edge effects    c) Very high level of vibration

d) Very large astigmatism    e) Very out of focus    f) Very low contrast

**Figure F.3 — Examples of images with a very high noise level, very large edge effects, a very high level of vibration, very large astigmatism, very poor focus or very low contrast**
[only parts (200 × 200 pixels) of the images are shown]

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## F.4 Minimum value of image sharpness

The image sharpness $R$ should be greater than or equal to 2,0 pixels. If $R < 2,0$ pixels, re-acquire an SEM image with a smaller pixel size (or at a higher image magnification) and carry out the evaluation again.


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# Annex G
(informative)

# Method of preparing test specimens for evaluating image sharpness

## G.1 General

This annex provides basic techniques on how to prepare test specimens prior to imaging and evaluation of the image sharpness.

## G.2 Au particles deposited on a carbon substrate using vacuum deposition

Au particles on a carbon substrate are used to evaluate the SEM image sharpness. The combination of Au particles and a carbon substrate is essential to maximize the visibility of the grain edges for evaluation of the image sharpness. Au particles of various sizes are widely used. Vacuum deposition is one of the most popular techniques for preparing thin metallic films on solid substrates.

A polished carbon substrate or an HOPG (highly oriented pyrolytic graphite) substrate is often treated by ion beam bombardment or plasma etching to ensure the homogeneous distribution of the Au particles deposited by evaporation. Figure G.1 is an SEM image of Au particles deposited on an HOPG substrate using vacuum evaporation. The substrate was treated by plasma etching for 5 min before Au deposition.

## G.3 Nanometer-scale Au particles deposited on an HOPG substrate using a sputter coater

Another sample preparation technique which is proposed for evaluating image sharpness in the high-magnification range is the use of nanometer-scale Au particles deposited on an HOPG substrate using a conventional sputter coater to give an average thickness of about 1 nm. The grain sizes of the Au particles can be easily controlled by varying the sputtering time. Before SEM observation, mild baking of the sample at about 180 °C in a dry vacuum is effective in reducing the deposition of beam-induced contamination. The granularity and homogeneous distribution of the Au particles on HOPG have been demonstrated at a magnification of ×800k. The average grain size is 3,2 nm and the standard deviation is 1,3 nm when Au particles are coated on HOPG to an average thickness about 0,7 nm. An example of an SEM image of nanometer-scale Au particles on an HOPG substrate is shown in Figure G.2.

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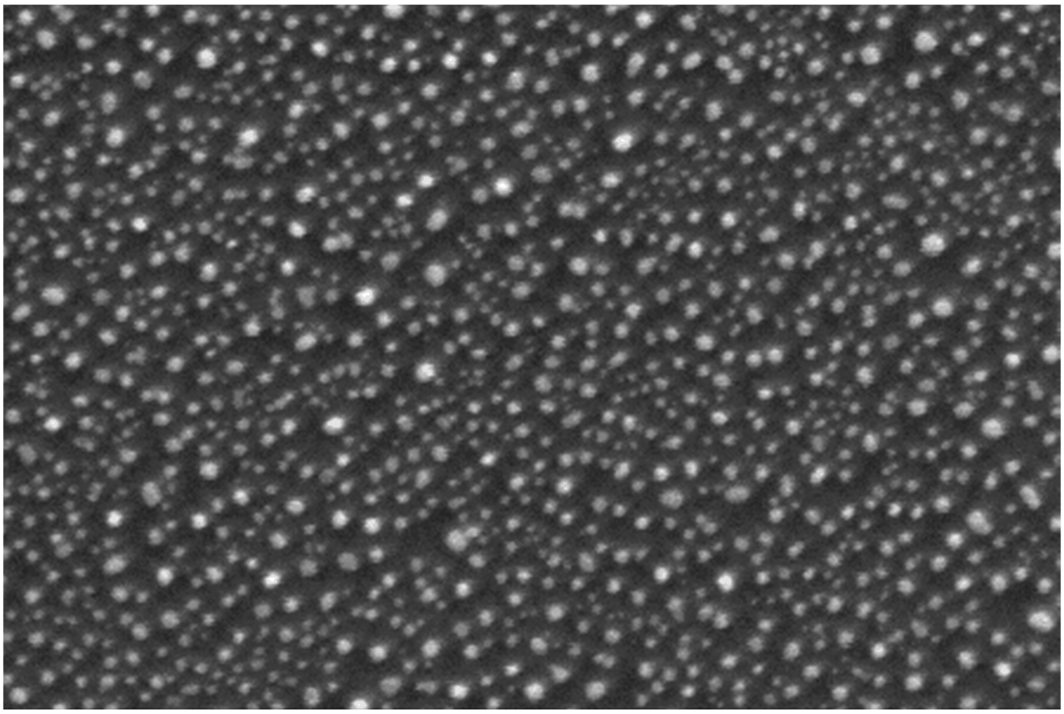

**Figure G.1 — SEM image of Au particles deposited on an HOPG substrate using vacuum deposition**
(the substrate was treated by plasma etching before deposition)

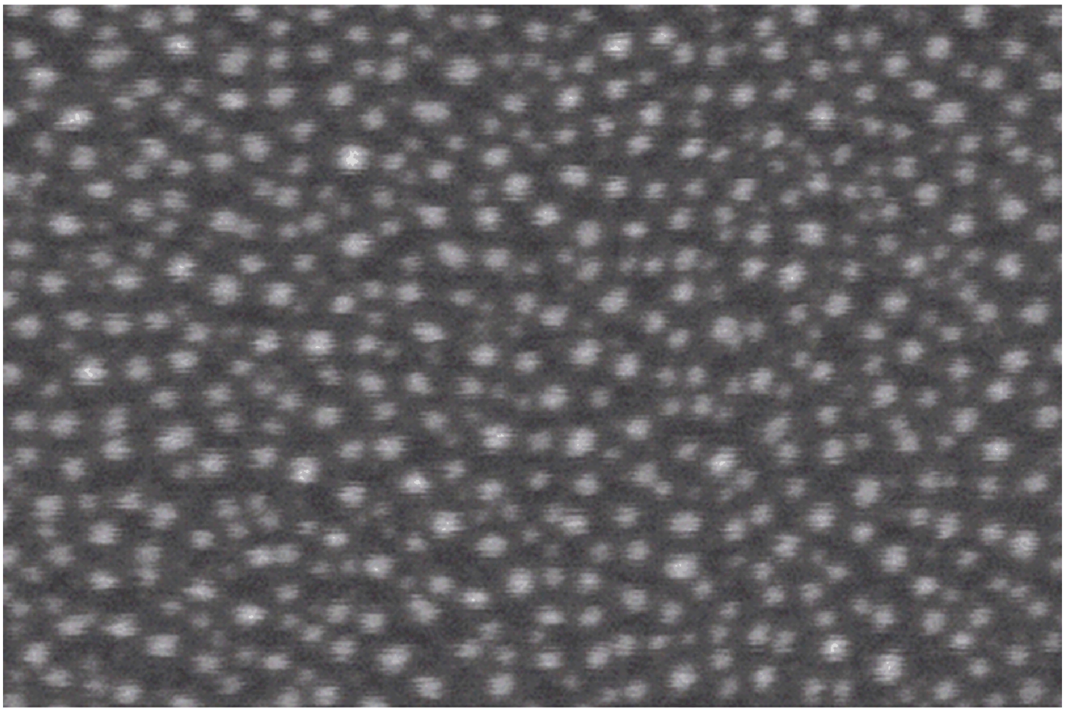

**Figure G.2 — SEM image of nanometer-scale Au particles on an HOPG substrate**
(the Au particles were deposited by sputter coater)


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# Annex H
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# Example of test report

## H.1 Test report for evaluation of image sharpness

An example of a test report is shown on the following page.

The test report shown consists of two tables. Table 1 is for information on the original image file. Table 2 is for information on the evaluation method and the results for the image evaluated.

The evaluation image selected from an original image should be kept.

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# Test report on image sharpness

| Institution identifier | Client identifier | |
|---|---|---|
| Name of laboratory: ................................ | Name of client: ...................................... | Date: ..................................................... |
| Address of laboratory: ............................ | Address of laboratory: ............................ | Reference material: ................................ |
| Number of test report: ............................ | | |
| Authority and operator identifier | Instrument model identifier | ISO reference: ISO/TS 24597 |
| Name and signature of authorizing person: | Name of manufacturer: .......................... | |
| ............................................................... | Model: .................................................... | |
| ............................................................... | Serial number: ...................................... | |
| Name of operator: .................................. | | |

**Table 1: Information on original image**

| Original image file name | Image size (pixels) | Acceln. voltage (kV) | Working distance (mm) | Image magnification | $L_{\text{image}}$ (mm) | $N_{\text{p}}$ (pixels) | $L_{\text{scale}}$ (nm) | $N_{\text{scale}}$ (pixels) | $L_{\text{p}}$ (nm) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| Image size: 640×480, 1280×960, 2560×1920, etc. | | | | | $L_{\text{image}}$: Horizontal width of original image<br>$N_{\text{p}}$: Number of pixels covering horizontal width of original image<br>$L_{\text{scale}}$: Length of scale marker on original image<br>$N_{\text{scale}}$: Number of pixels in scale marker<br>$L_{\text{p}}$: Pixel size<br>(see 4.5.2 and 4.5.3) | | | | | |

**Table 2: Evaluation results**

| No. | Evaluated image file name | Binarized file name | Selected image size (pixels) | | Evaluation method | | | $R_{\text{PX}}$ (pixels) | $R_{\text{L}}$ (pixels) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 512×512 | Other | FT | CG | DR | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |

| | | |
|---|---|---|
| Evaluated image file name: | Image selected from the original image | |
| Binarized file name: | Binarized image of selected image (if necessary) | |
| Image size (pixels): | 512×512 or other (specify the number of pixels) | |
| Evaluation method: | FT, CG or DR | |
| $R_{\text{PX}}$: | Image sharpness (pixels) | $R_{\text{PX}} = 2\sigma/\sqrt{2}$ |
| $R_{\text{L}}$: | Image sharpness (nm) | $R_{\text{L}} = L_{\text{p}} \times R_{\text{PX}}$ |



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## Attached images

| Original image file name: | Evaluated image file name: |
|---|---|
| Photo | Photo |

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