TECHNICAL SPECIFICATION

ISO/TS 24597

First edition
2011-06-15

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)

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In other circumstances, particularly when there is an urgent market requirement for such documents, a technical committee may decide to publish other types of document:

— an ISO Publicly Available Specification (ISO/PAS) represents an agreement between technical experts in an ISO working group and is accepted for publication if it is approved by more than 50 % of the members of the parent committee casting a vote;

— an ISO Technical Specification (ISO/TS) represents an agreement between the members of a technical committee and is accepted for publication if it is approved by 2/3 of the members of the committee casting a vote.

An ISO/PAS or ISO/TS is reviewed after three years in order to decide whether it will be confirmed for a further three years, revised to become an International Standard, or withdrawn. If the ISO/PAS or ISO/TS is confirmed, it is reviewed again after a further three years, at which time it must either be transformed into an International Standard or be withdrawn.

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

Introduction

The International Organization for Standardization (ISO) draws attention to the fact it is claimed that compliance with this document may involve the use of patents concerning the evaluation method using the contrast-to-gradient (CG) method given in 6.4.

ISO takes no position concerning the evidence, validity and scope of this patent right.

The holder of this patent right has assured ISO that he/she is willing to negotiate licences under reasonable and non-discriminatory terms and conditions with applicants throughout the world. In this respect, the statement of the holder of this patent right is registered with ISO. Information may be obtained from:

Patent holder: Hitachi, Ltd.

Address: Marunouchi Center Bldg., 6-1, Marunouchi 1-chome, Chiyoda-ku, Tokyo, 100-8220, Japan.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights other than those identified above. ISO shall not be held responsible for identifying any or all such patent rights.

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 (2σ) of the Gaussian profile used to make a convoluted image

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 σ

3.7
contrast-to-noise ratio
CNR
ratio of $I_A - I_B$ to σ_n, where I_A and I_B are the image intensities for the object and the background and σ_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.

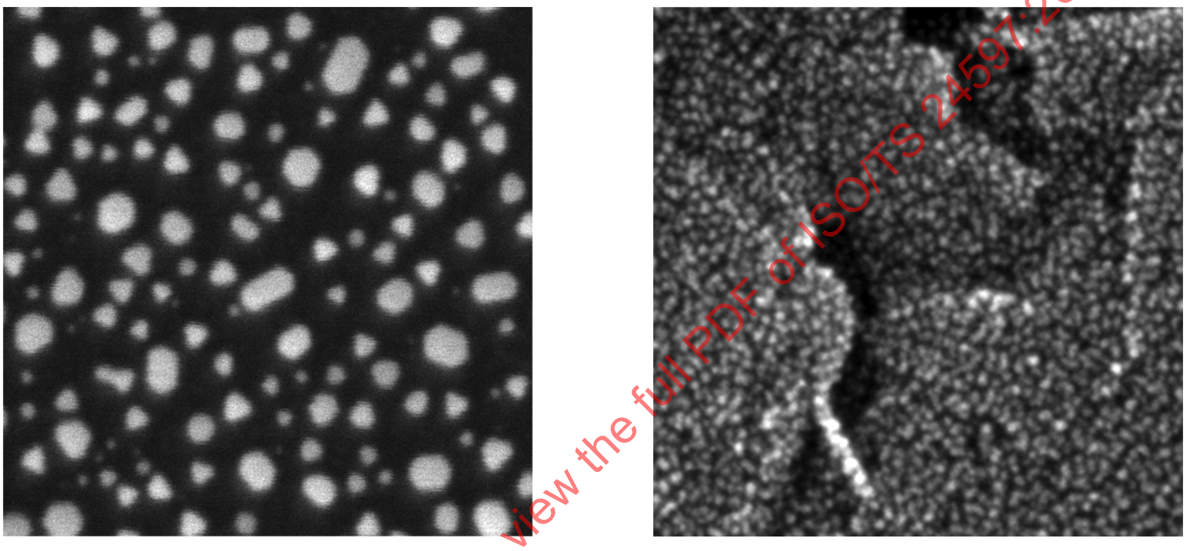
4.3 Specimen tilt

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_p (in nm) is determined from the following equation:

$$L_p = \frac{L_{FOV}}{N_p}$$

where

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

N_p is the number of pixels covering the horizontal width of the field of view.

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:

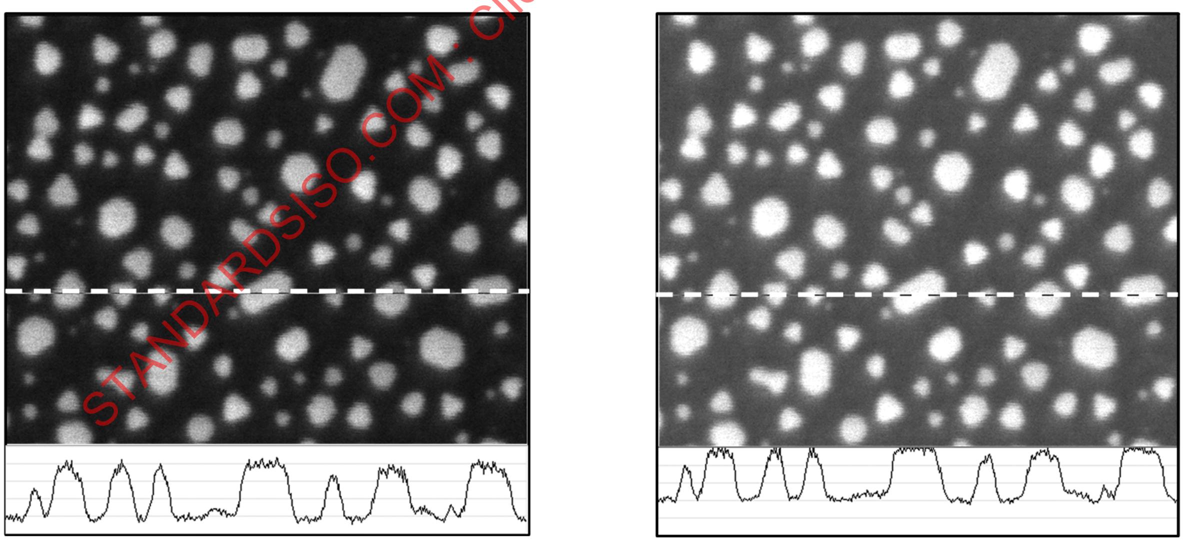
$$R_L = L_p \times R_{PX}$$

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.

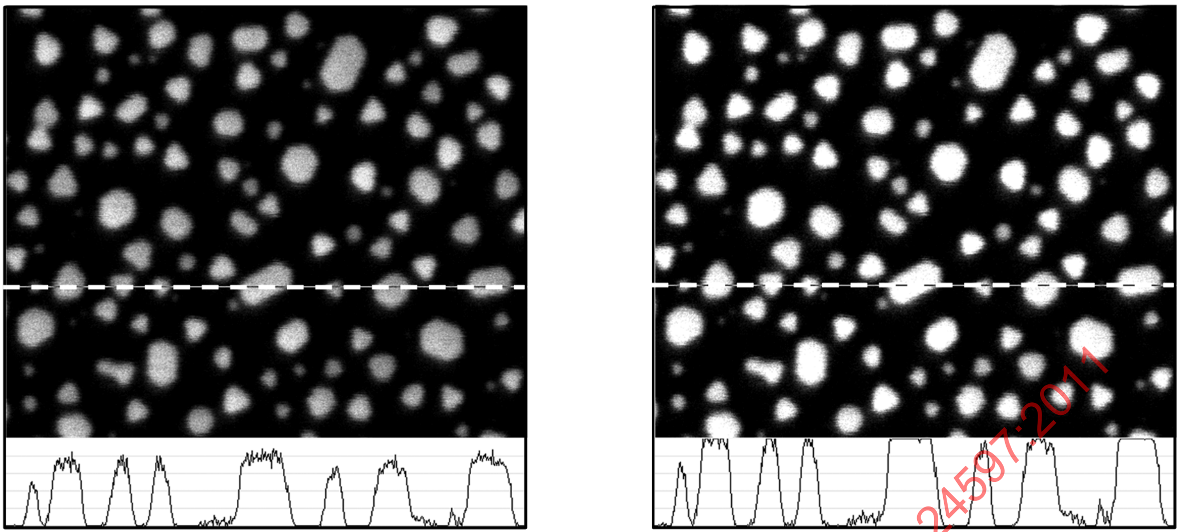
4.6 Brightness and contrast of the image

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*)



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_{image} to the standard deviation σ_{n} of the image noise (see Figure 3).

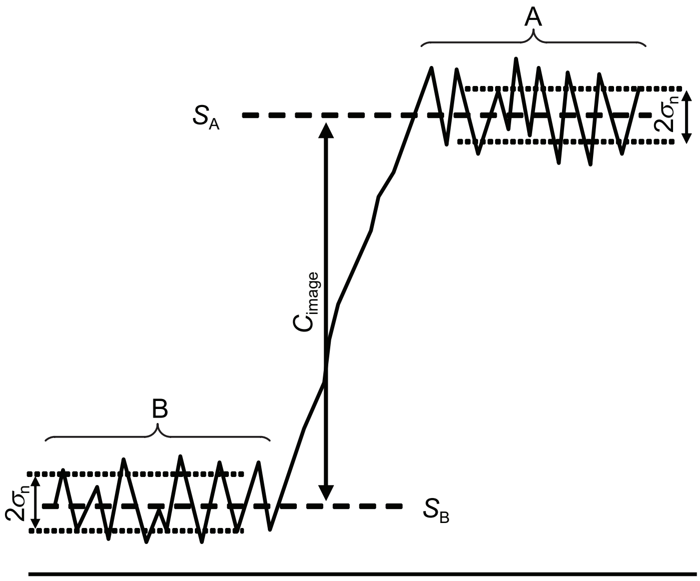
$$\mathrm{CNR} = C_{\mathrm{image}}/\sigma_n$$

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.

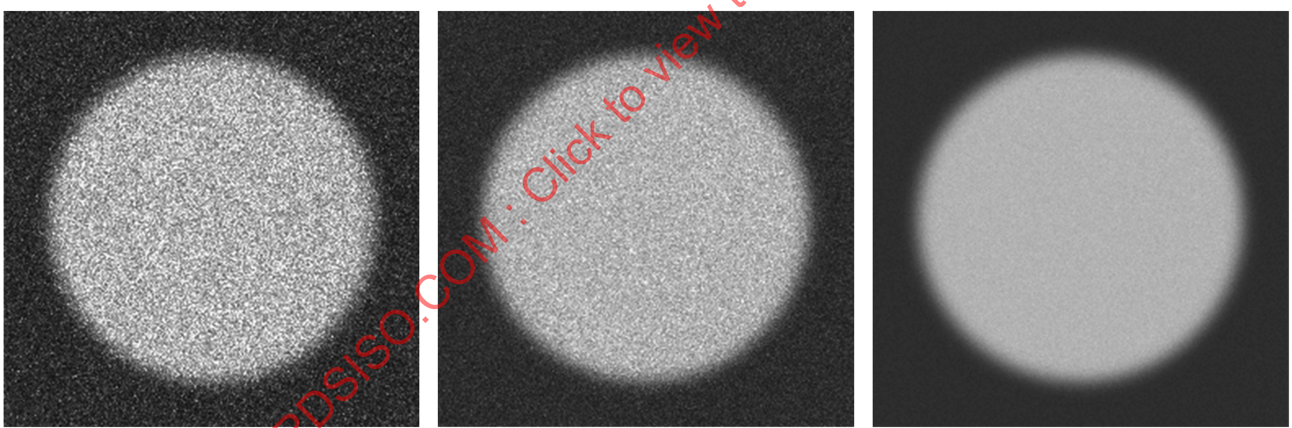


Key

A region A

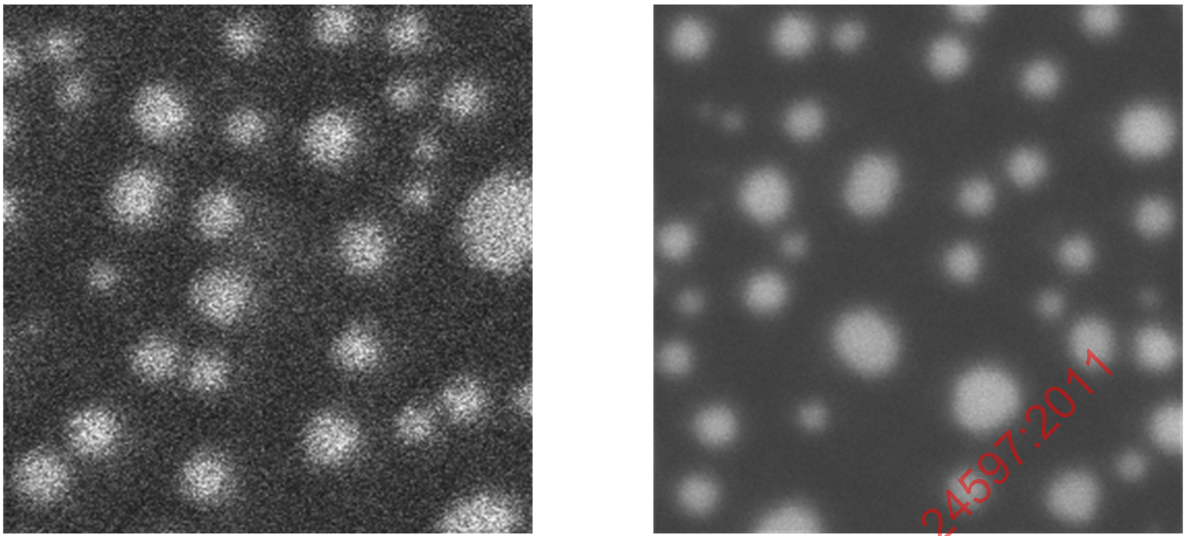
B region B

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



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 × 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.

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 2σ 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 2σ (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 $k = 1/\sqrt{2}$.

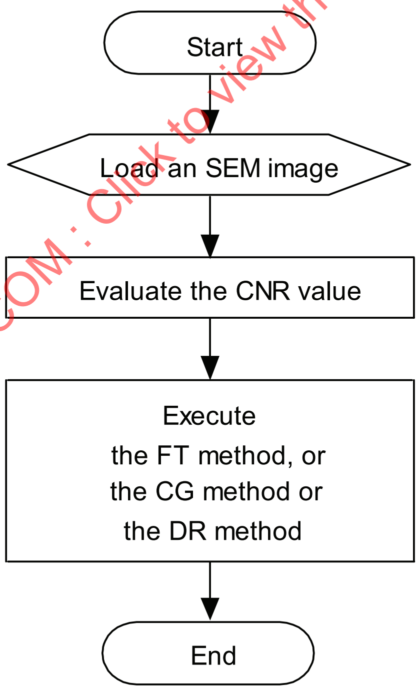


Figure 6 — General flow chart for the evaluation of an SEM image

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.

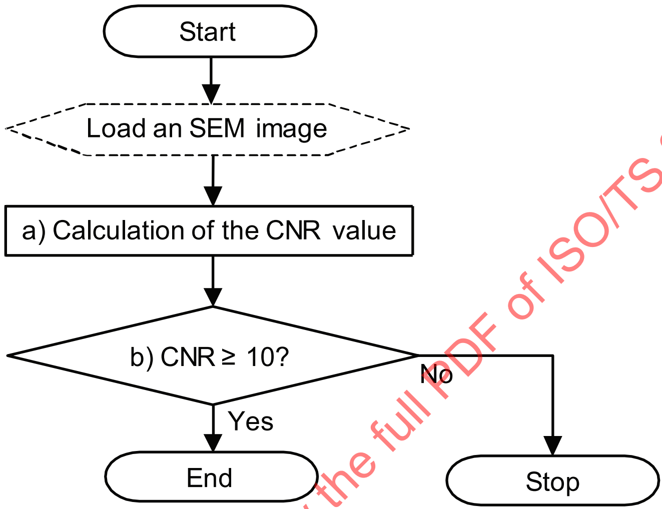


Figure 7 — Flow chart for the evaluation of the CNR

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 2σ (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_m is expressed as $I_m(i, j)$, 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.

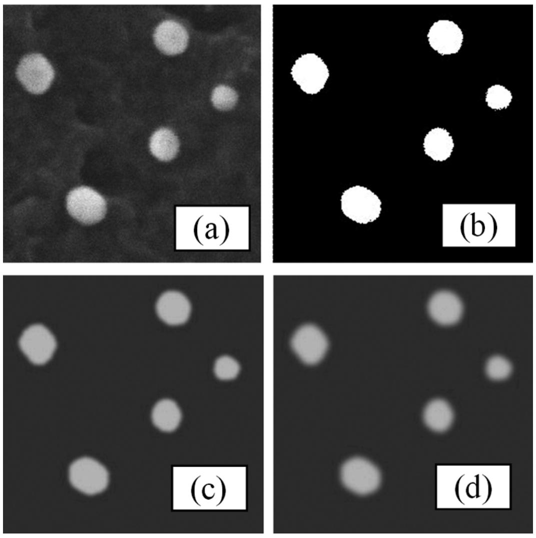
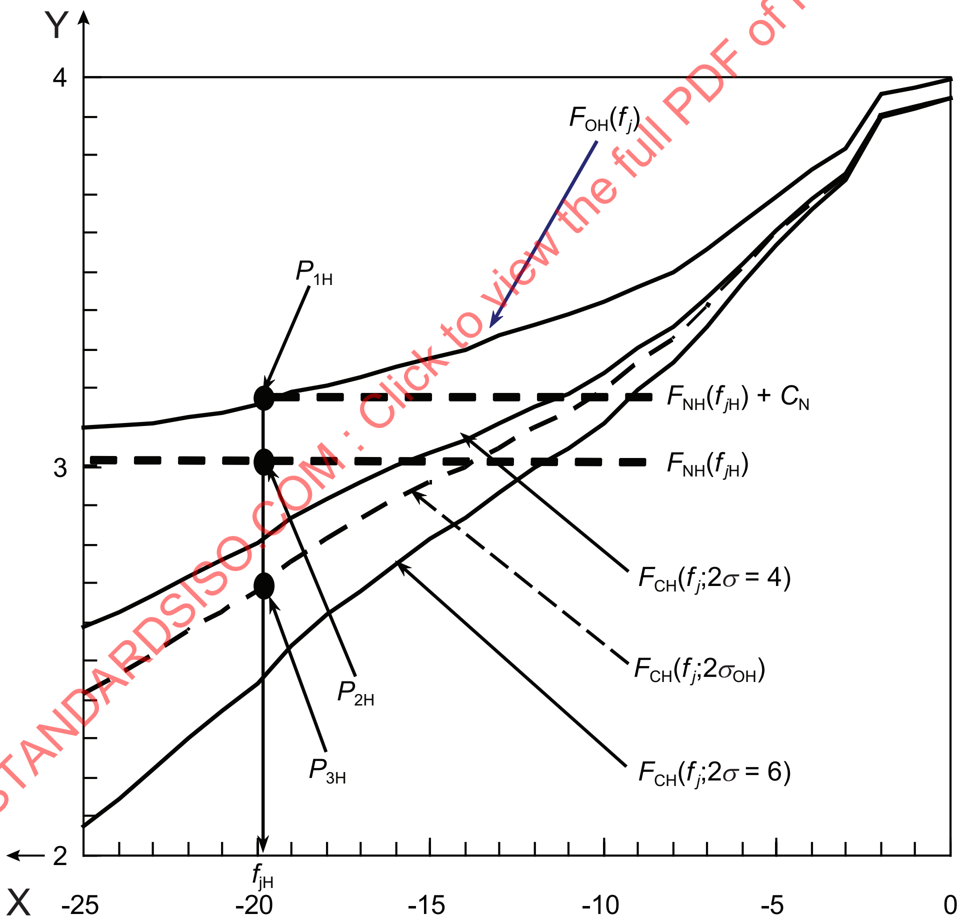


Figure 8 — (a) a selected SEM image $I_O(i, j)$ with image size $L = 256$, (b) the binarized image $I_B(i, j)$, (c) and (d) the convoluted images $I_C(i, j; 2\sigma)$ with $2\sigma = 4$ pixels and $I_C(i, j; 2\sigma)$ with $2\sigma = 6$ pixels, respectively



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

a) Generation of a convoluted image

1) Generate a filtered image $I_{OF}(i, j)$, processed by the 3×3 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 σ 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.

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 $R_{PX} = 2\sigma_C / \sqrt{2}$.

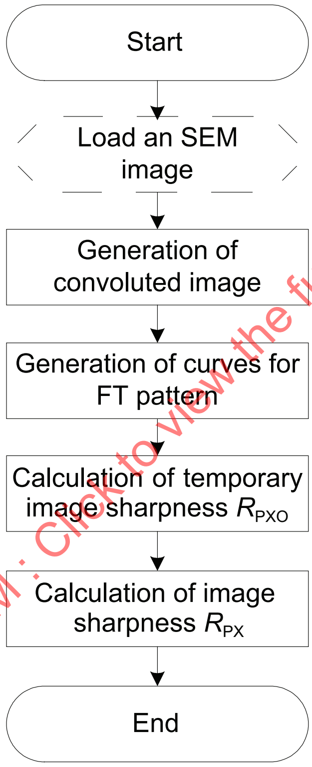
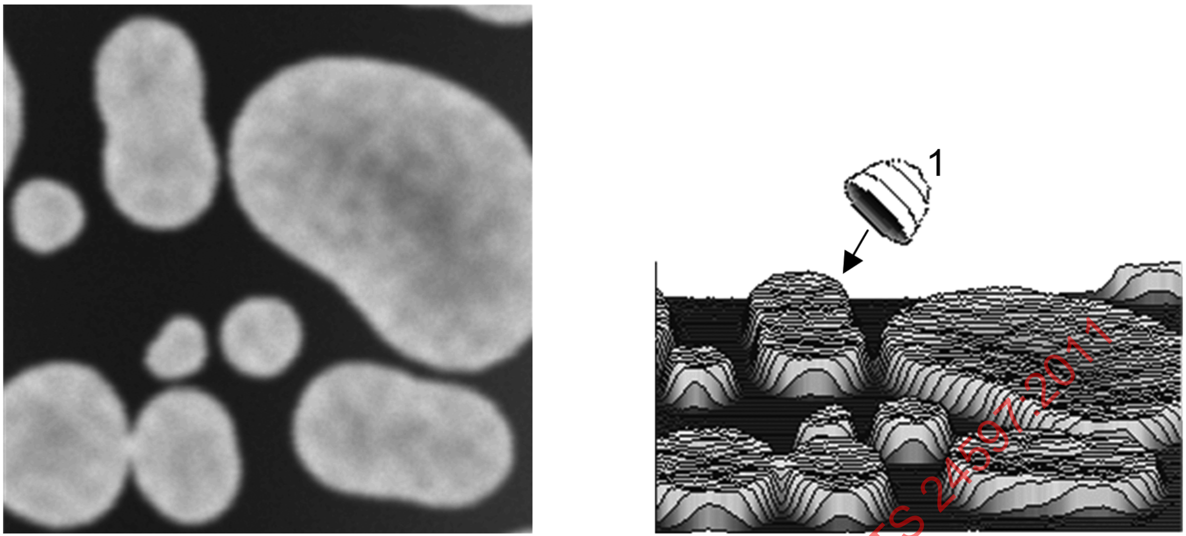


Figure 10 — Brief flow chart of processes in the FT method

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 3×3 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 2σ.



a) **Original SEM image**

b) **Depth image corresponding to the original image, showing a typical quadratic surface fitted to the 3 × 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 × 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_{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 ΔR is the fluctuation in R.

1) Local sharpness

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

$$R_p(i, j;\ \theta) = 2\Delta C/g(i, j;\ \theta)$$

where

ΔC is the threshold contrast;

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

The local gradient is found by fitting a quadratic surface over a 3 × 3 pixel area centred at each pixel (i, j). The fitting error Δg provides the fluctuation in R_p, i.e. ΔR_p.

2) Directional sharpness

The directional sharpness R_k, defined as the weighted harmonic mean of the local sharpness in the kth sector of azimuth angle θ in the image, is calculated. The values of $\Delta R_k/R_k$ are also calculated using $\Delta R_p/R_p$.

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_{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_{min} at which $\Delta R/R$ is a minimum is then found. The CG image sharpness R_{CG} is defined as R at $r = r_{min}$. 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_{CG}

Standard images are blurred images formed by convoluting a binary SEM image with Gaussian profiles having different known sharpness factors 2σ 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 2σ.

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

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

where

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

2σ is the sharpness factor, given by

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

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

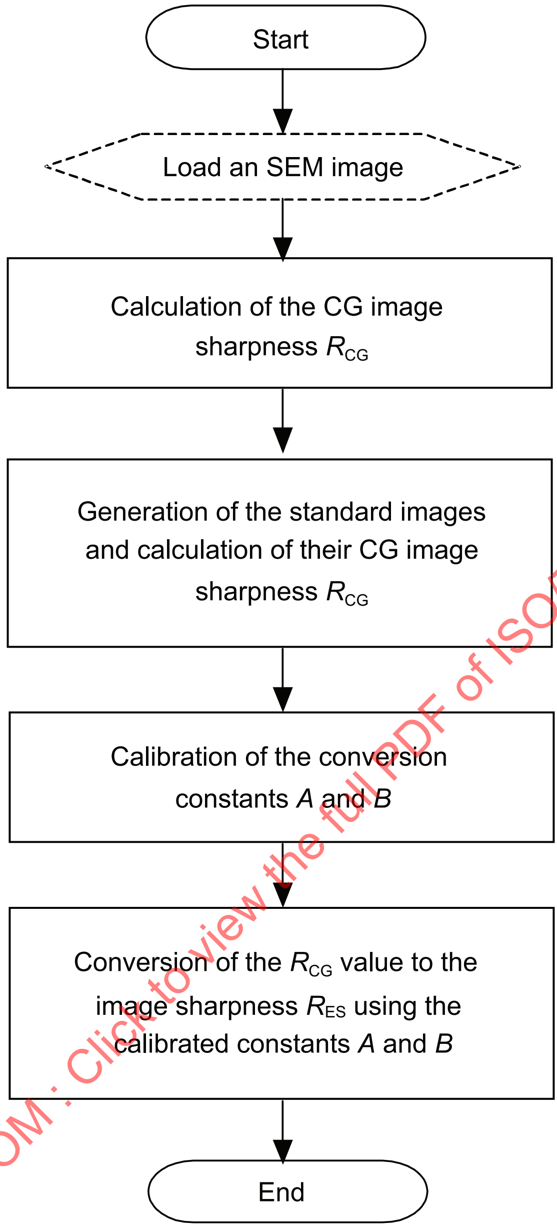
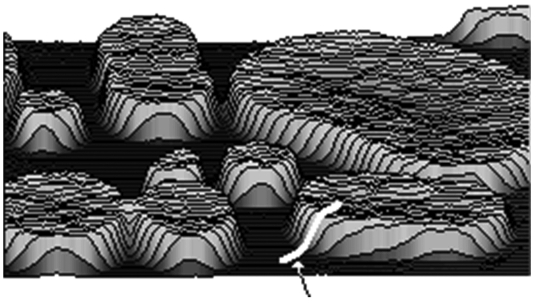


Figure 12 — Brief flow chart of the CG method

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 σ 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 σ.

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.

c) Extraction of the edge profiles $P_j(x, y)$ and fitting of an error function

1) The normalized gradient $G_N(x, y)$ is computed for all positions of $E(x, y)$, based on the normalization of $G_M(x, y)$.

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

3) The sub-pixel intensity values $P_j(x, y)$ at $P_{Si}(x, y)$ 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_{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_{DR} is calculated as $R_{DR} = \sqrt{2}s$.

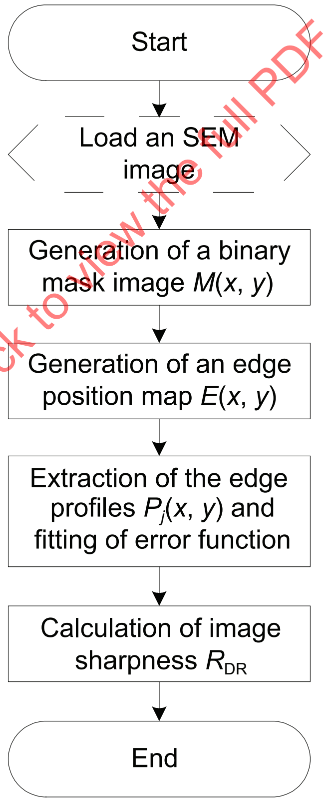


Figure 14 — Brief flow chart of the DR method

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.

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.

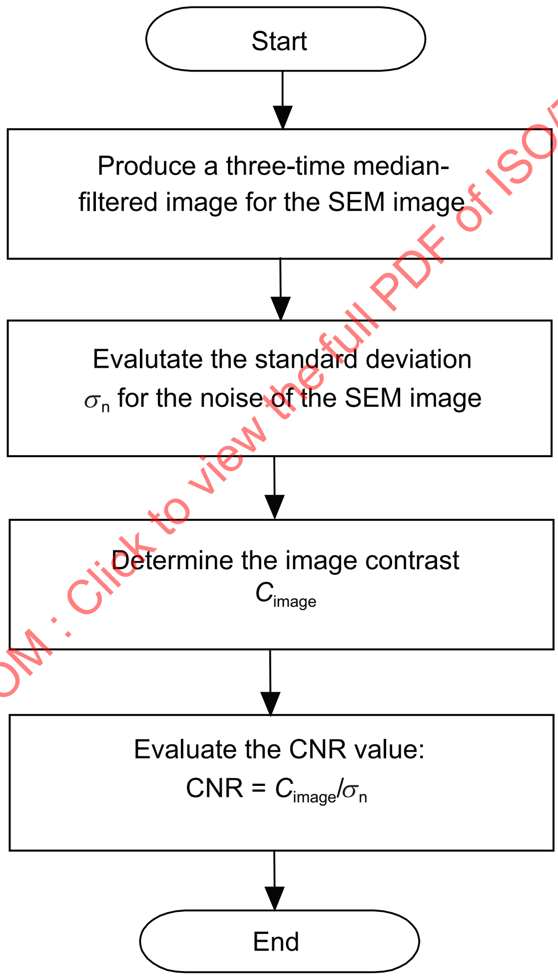


Figure A.1 — Flow chart of the CNR evaluation

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

NOTE 1 The principle of 3×3 median filtering is shown in Figure A.2. The median filtering is calculated by first sorting the intensities of the pixels in the 3×3 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}).

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).

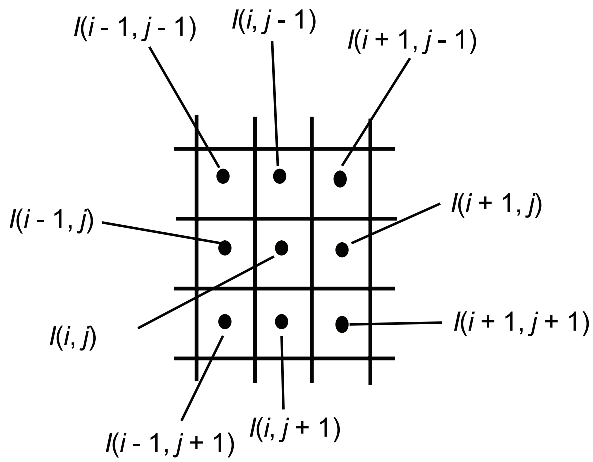


Figure A.2 — The principle of 3 × 3 median filtering: the figure shows the pixel (i, j) concerned and its neighbouring pixels in the 3 × 3 square

b) Evaluate the standard deviation σ_n of the image noise:

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

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).

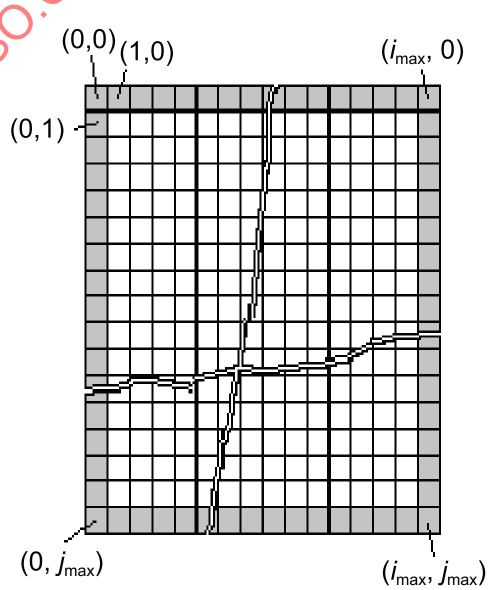


Figure A.3 — Intensities of a three-time median-filtered image

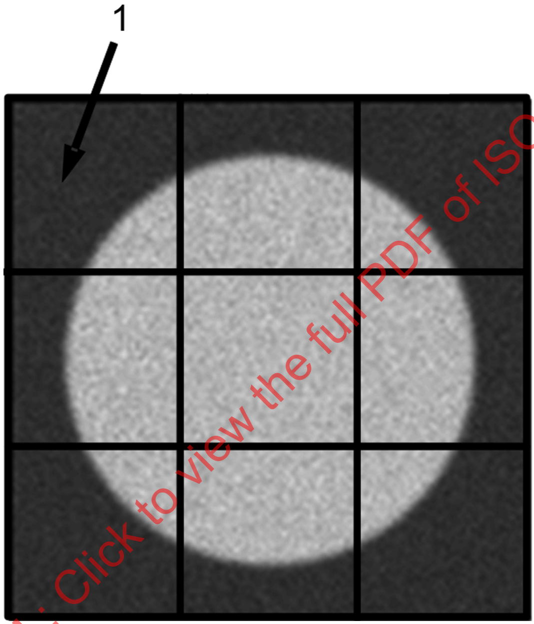
c) Determine the image contrast C_{image}.

1) Divide the three-time median-filtered SEM image into nine (or 3 × 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_{max} (or j_{max}) = 511 and from 1 to 84, 85 to 169 and 170 to 254 for the image of i_{max} (or j_{max}) = 255.

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

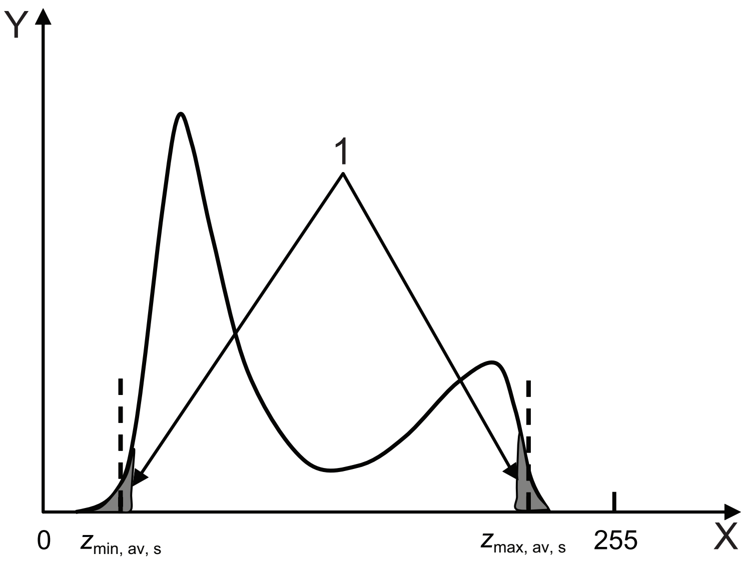
3) For each segment s, compute $z_{max,av,s}$ by arithmetically averaging the first to qth elements of the descending intensity sequence and compute $z_{min,av,s}$ by arithmetically averaging the first to qth elements of the ascending intensity sequence. Here, q is an integer that corresponds to 0,2 % 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



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 $z_{\mathrm{threshold},s\text{-av}}$ as follows:

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

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

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

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

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

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

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

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

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

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

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

3 × 3 median filtering:

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

where

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

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

The median-filtering function $M_{ED}(a_1, a_2, \ldots, a_N)$ 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 $F_{IN}(\ldots, \ldots)$ and carry out $M_{ED}[\ldots\ldots]$.

Annex B
(normative)

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.

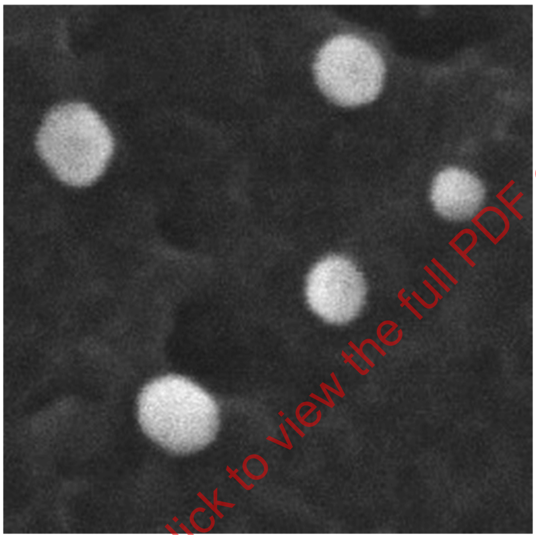


Figure B.1 — Example of an SEM image

B.2 Generation of convoluted images

a) Prepare a filtered image $I_{OF}(i, j)$, processed three times sequentially by the unweighted 3 × 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 $h_s[(S_1 + S_2)/2] < h_s(S_2) - 0{,}02$.

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:

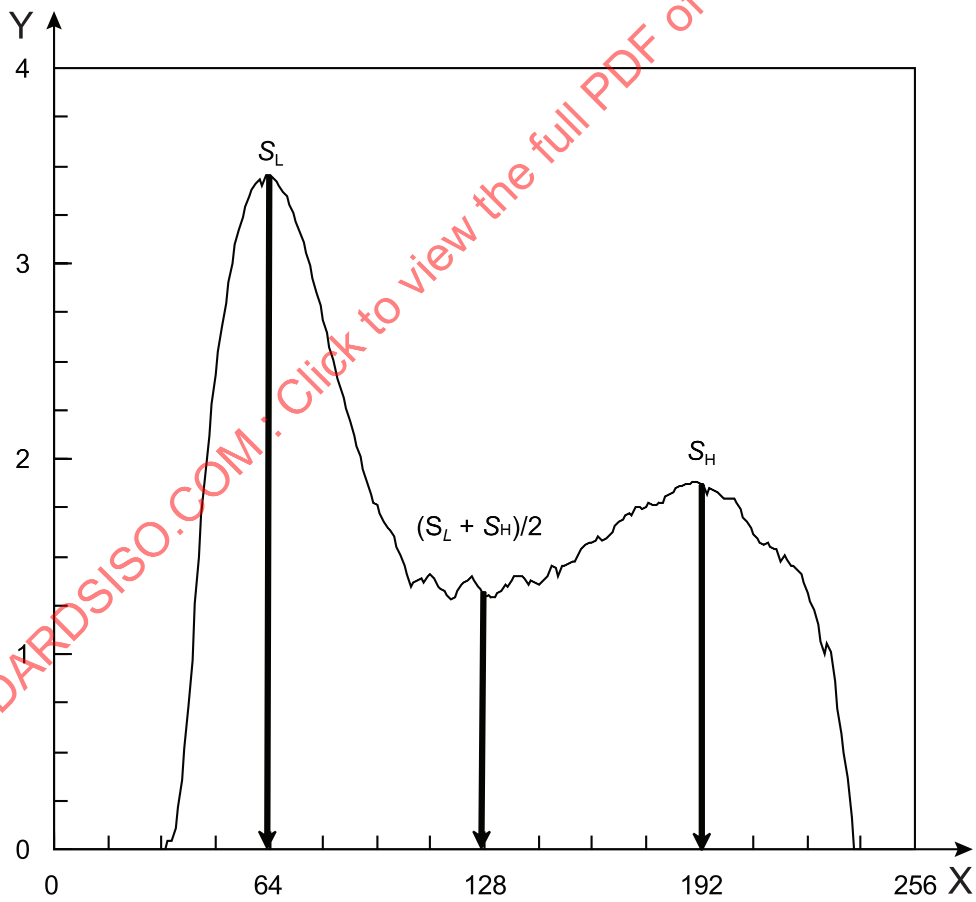
$$S_L = S_A + C_R\sqrt{S_A} \quad \text{and} \quad S_H = S_B - C_R\sqrt{S_B}$$

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

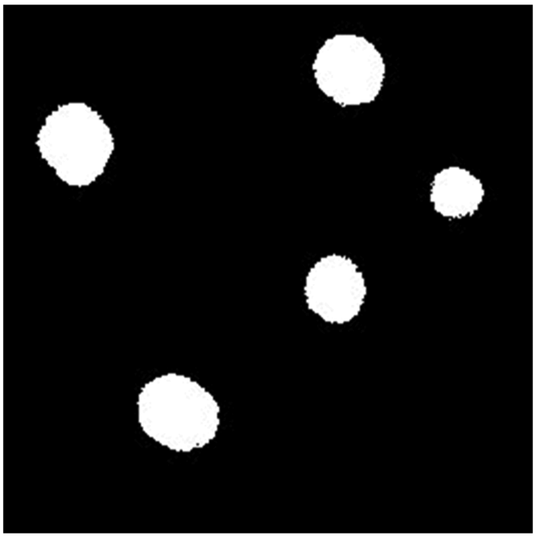


Figure B.3 — Example of a binarized image $I_B(i, j)$

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:

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

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 2σ, given by

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

where σ 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 $2\sigma(N) = 2^{Q+1} + 2^{Q-1} \cdot (N - 4Q)$.

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 2σ equal to $2\sigma(N)$ for the Nth step in a similar manner.

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

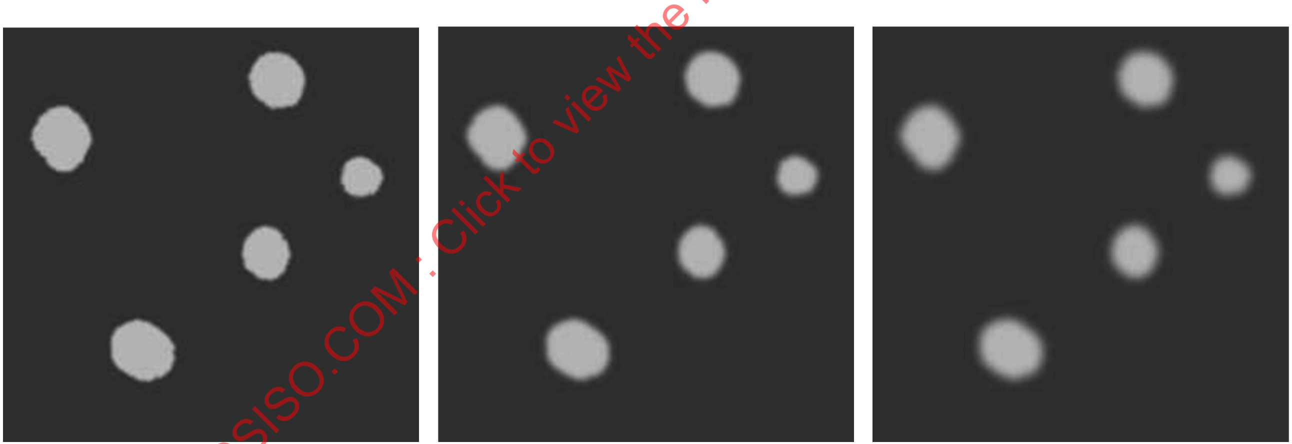
$$G_{BG}(f_i, f_j; 2\sigma) = G_B(f_i, f_j) \cdot G_G(f_i, f_j; 2\sigma)$$

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 $L = 256$

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

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

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

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

where

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

L is the image size.

e) Calculate a smoothed horizontal curve $F_{OH}(f_j)$ from $F_{OHA}(f_j)$ 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 $F_{OV}(f_i)$ from $F_{OVA}(f_i)$ in a similar manner.

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

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

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

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

h) Calculate a smoothed horizontal curve $F_{CHB}(f_j; 2\sigma)$ from $F_{CHA}(f_j; 2\sigma)$ 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 $F_{CVB}(f_i; 2\sigma)$ from $F_{CVA}(f_i; 2\sigma)$ in a similar manner.

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:

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

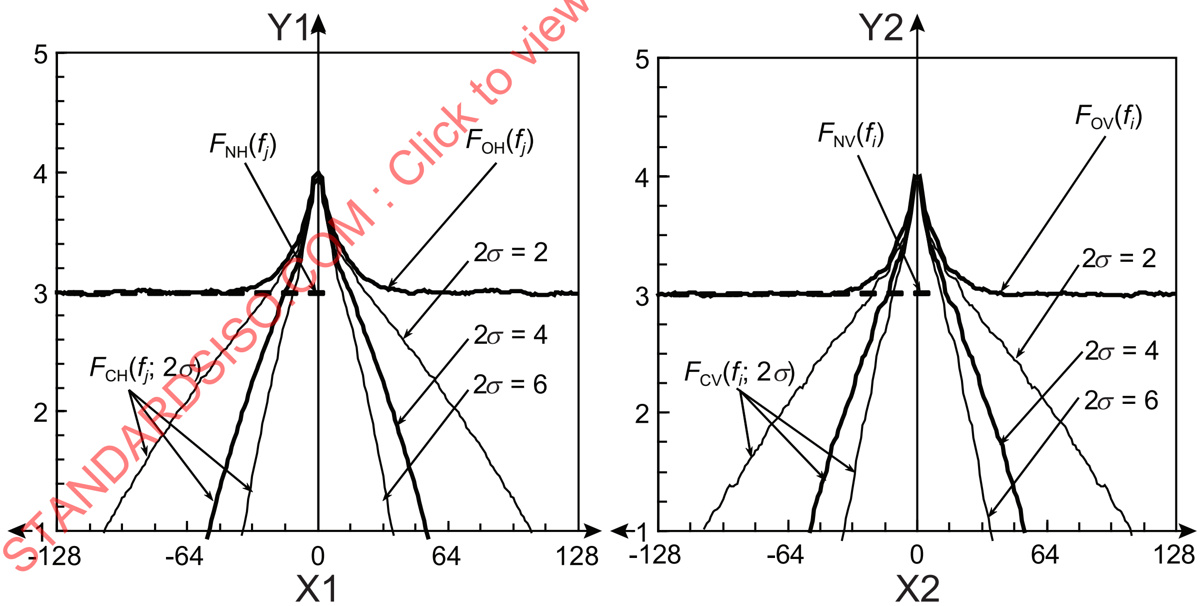
$$F_{NV}(f_i) = m_V \cdot f_i + b_V$$

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

d) Obtain the horizontal coordinate $f_j = f_{jH}$ as follows:

1) Set the parameters A and B as

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

where C_N is the contribution factor determined from the convoluted image in the Fourier space and is given by

$$C_N = \log_{10}(1 + a_N + \Delta a_N)$$

where

$a_N = 0{,}5$;

$\Delta a_N = -\,0{,}05$ (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 $f_j = f_{jC}$ for this change.

3) Calculate the horizontal coordinate f_{jH} as follows:

$$f_{jH} = \frac{F_{NH}(f_{jC}) + C_N - [F_{OH}(f_{jC} - 1) + m_H]}{F_{OH}(f_{jC}) - [F_{OH}(f_{jC} - 1) + m_H]} + (f_{jC} - 1) \text{ for } A - B > 10^{-4}$$

$$f_{jH} = f_{jC} \text{ for } A - B \leqslant 10^{-4}$$

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

$$P_{1H}\text{:} \quad (f_{jH},\, F_{NH}(f_{jH}) + C_N)$$

$$P_{2H}\text{:} \quad (f_{jH},\, F_{NH}(f_{jH}))$$

$$P_{3H}\text{:} \quad (f_{jH},\, F_{NH}(f_{jH}) + \log_{10} a_N)$$

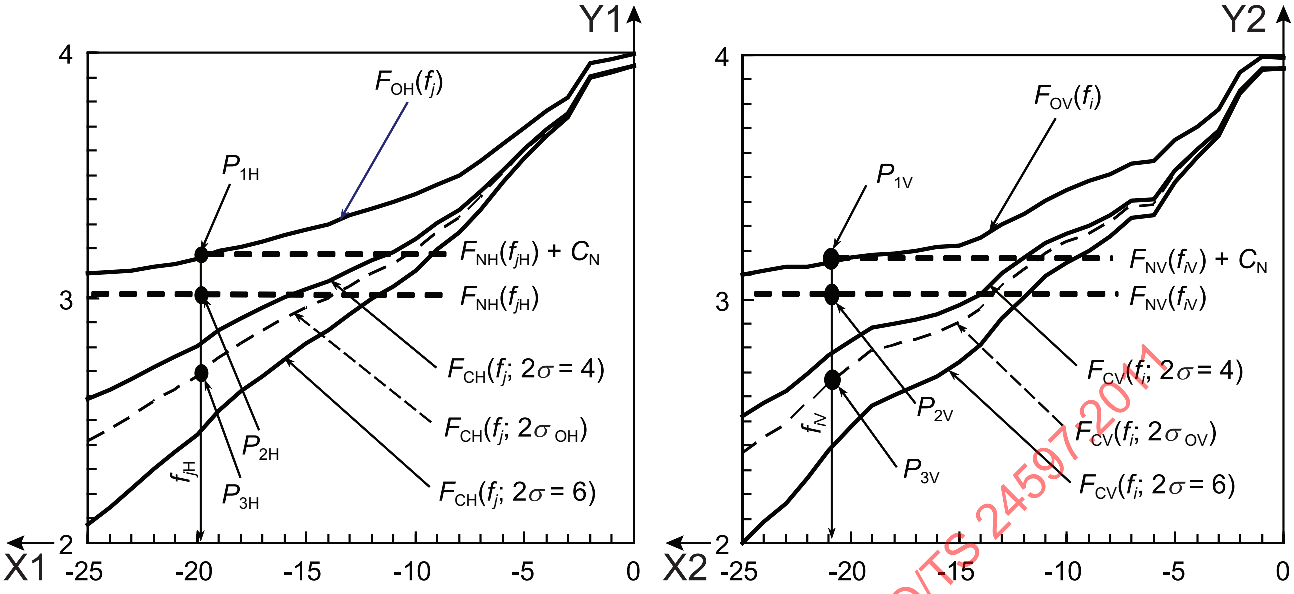
e) Obtain the vertical coordinate $f_i = f_{iV}$ using $f_i = f_{iC}$ in a similar manner.

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

$$P_{1V}\text{:} \quad (f_{iV},\, F_{NV}(f_{iV}) + C_N)$$

$$P_{2V}\text{:} \quad (f_{iV},\, F_{NV}(f_{iV}))$$

$$P_{3V}\text{:} \quad (f_{iV},\, F_{NV}(f_{iV}) + \log_{10} a_N)$$



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.

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

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

h) Calculate 2σ by linear interpolation as follows:

$$2\sigma_{OH} = \frac{[F_{NH}(f_{jH}) + \log_{10} a_N] - F_{CH}(f_{jH}; 2\sigma_{HU})}{F_{CH}(f_{jH}; 2\sigma_{HL}) - F_{CH}(f_{jH}; 2\sigma_{HU})}(2\sigma_{HL} - 2\sigma_{HU}) + 2\sigma_{HU}$$

$$2\sigma_{OV} = \frac{[F_{NV}(f_{iV}) + \log_{10} a_N] - F_{CV}(f_{iV}; 2\sigma_{VU})}{F_{CV}(f_{iV}; 2\sigma_{VL}) - F_{CV}(f_{iV}; 2\sigma_{VU})}(2\sigma_{VL} - 2\sigma_{VU}) + 2\sigma_{VU}$$

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

i) Obtain the sharpness factor $2\sigma_O$ as follows:

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

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

$$R_{PXO} = k \cdot 2\sigma_O$$

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

B.5 Calculation of image sharpness R_{PX}

a) Calculate the coefficient C_F by using the following formulae:

1) If $2\sigma_O < 3$ or $11 \leqslant 2\sigma_O$, then $C_F = 1$.

2) If $3 \leqslant 2\sigma_O < 4{,}1$, then

$$C_F = b_0 + b_1/2\sigma_O$$

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

3) If $4{,}1 \leqslant 2\sigma_O < 11$, then

$$C_F = c_3(2\sigma_O)^3 + c_2(2\sigma_O)^2 + c_1(2\sigma_O) + c_0$$

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 $2\sigma_C$ as follows:

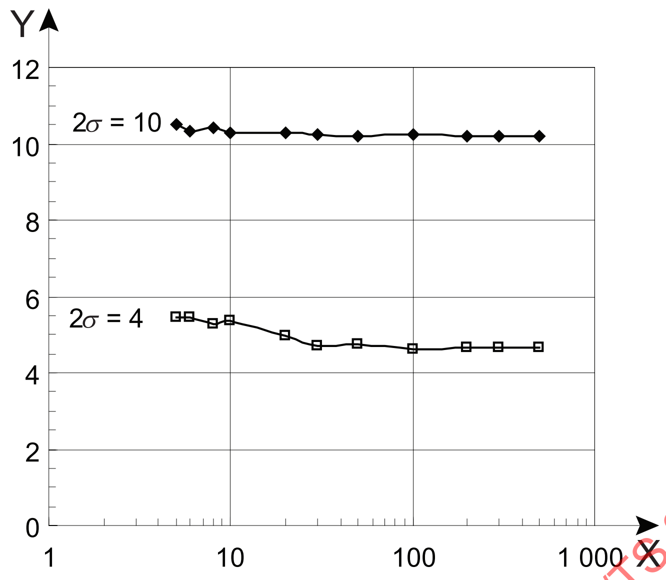
$$2\sigma_C = C_F \cdot 2\sigma_O$$

NOTE The coefficient C_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_{PX} as follows:

$$R_{PX} = k \cdot 2\sigma_C$$

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

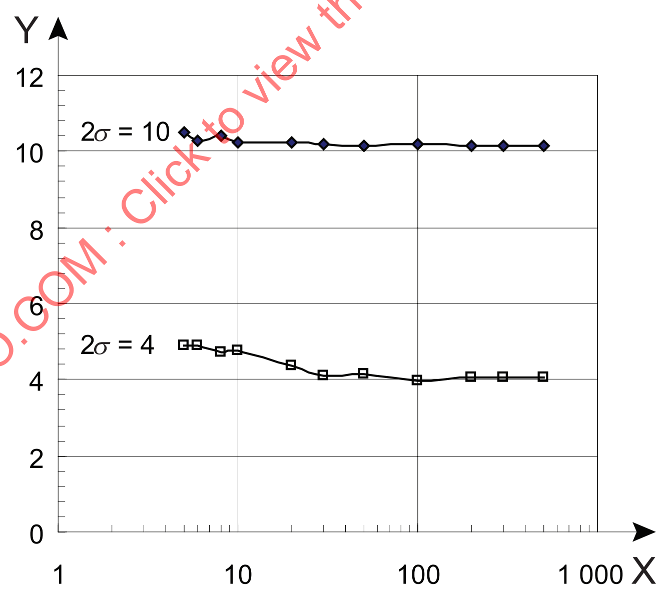


Key

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)

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:

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

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

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

c) Calculate the variance of r from:

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

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

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

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

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

$$b_{\text{OUT}} = \bar{F} - m_{\text{OUT}} \cdot \bar{r}$$

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

$$F - \bar{F} = m_{\text{OUT}} \cdot (r - \bar{r})$$

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

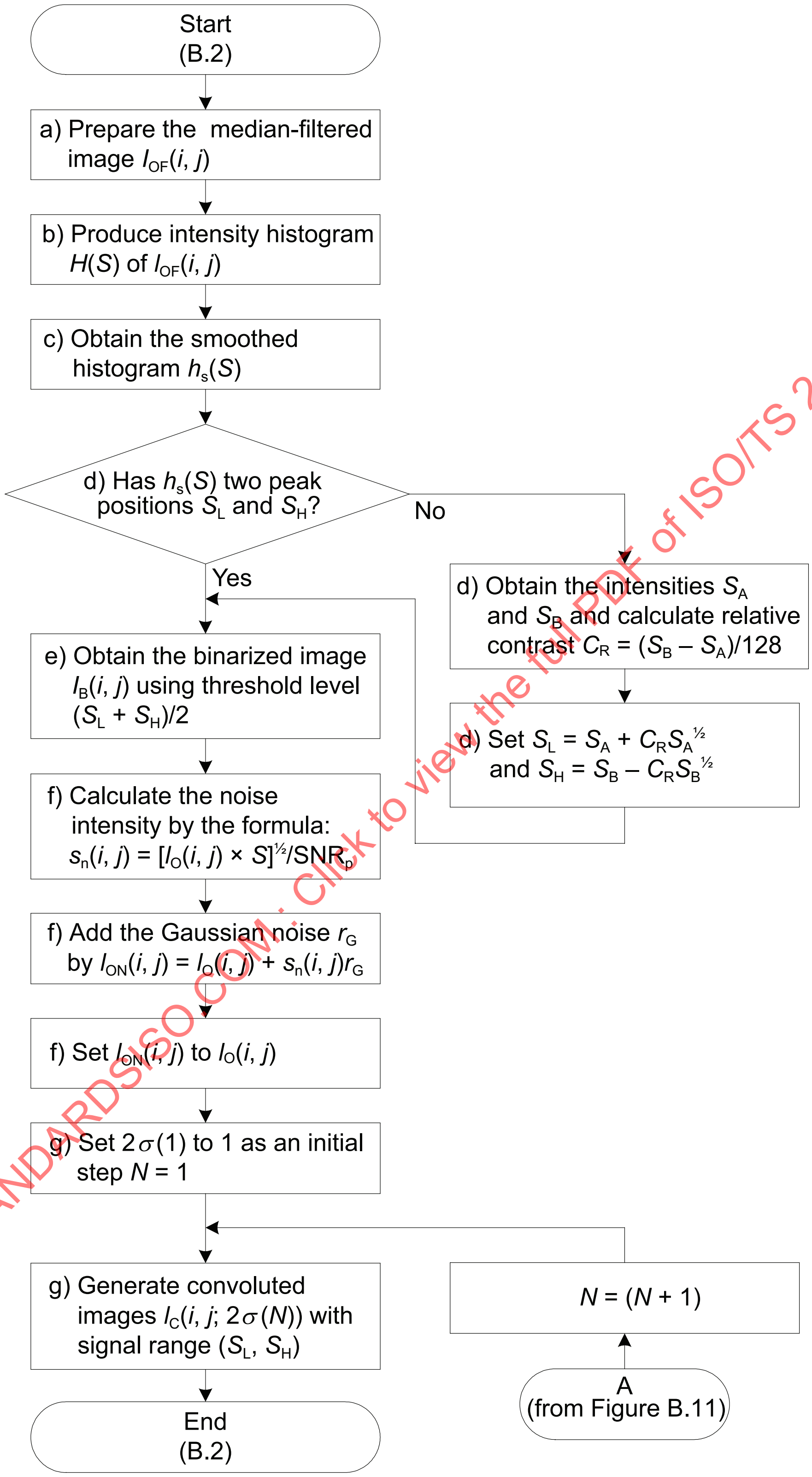


Figure B.9 — Flow chart for the procedure described in Clause B.2

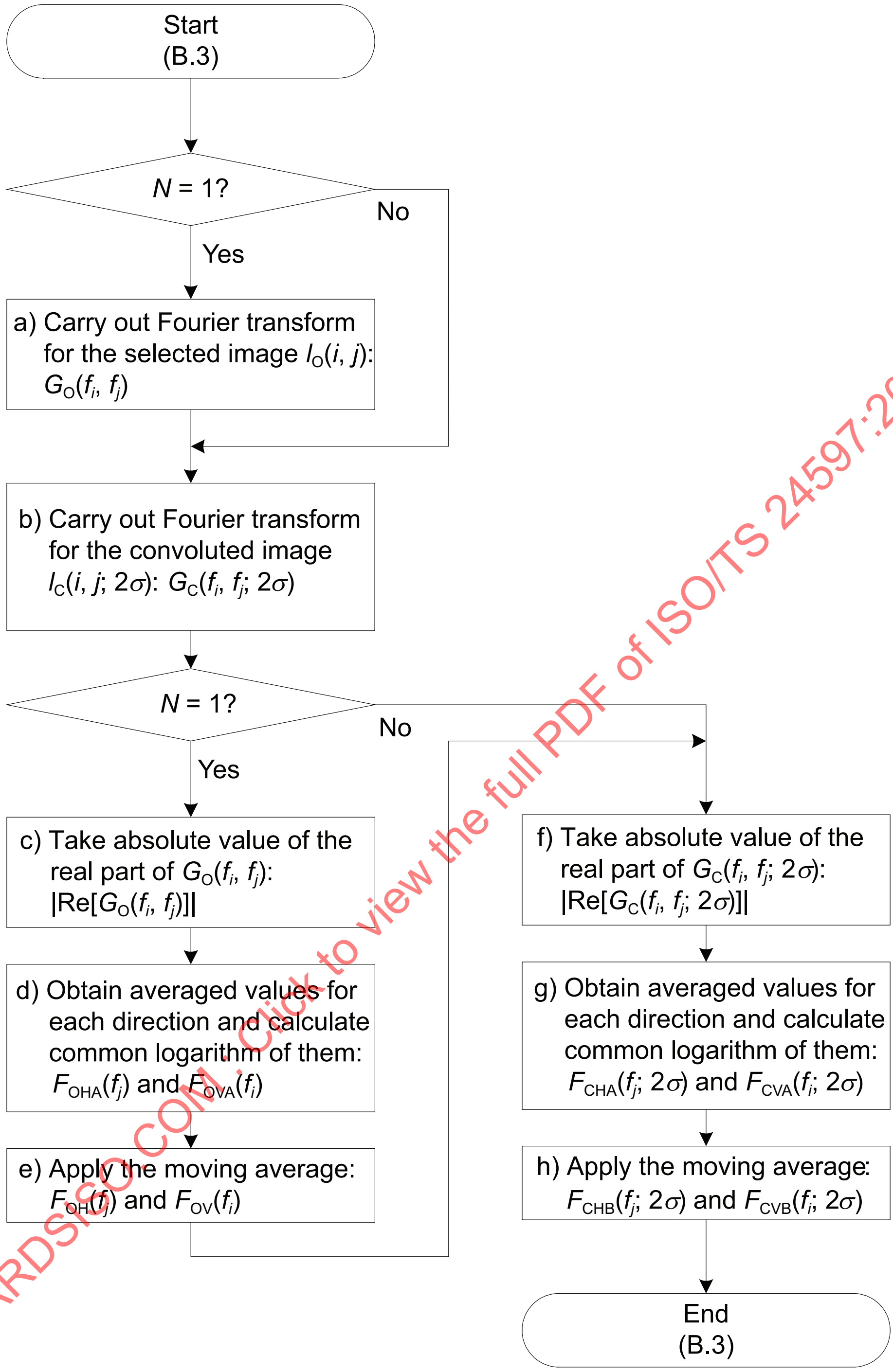


Figure B.10 — Flow chart for the procedure described in Clause B.3

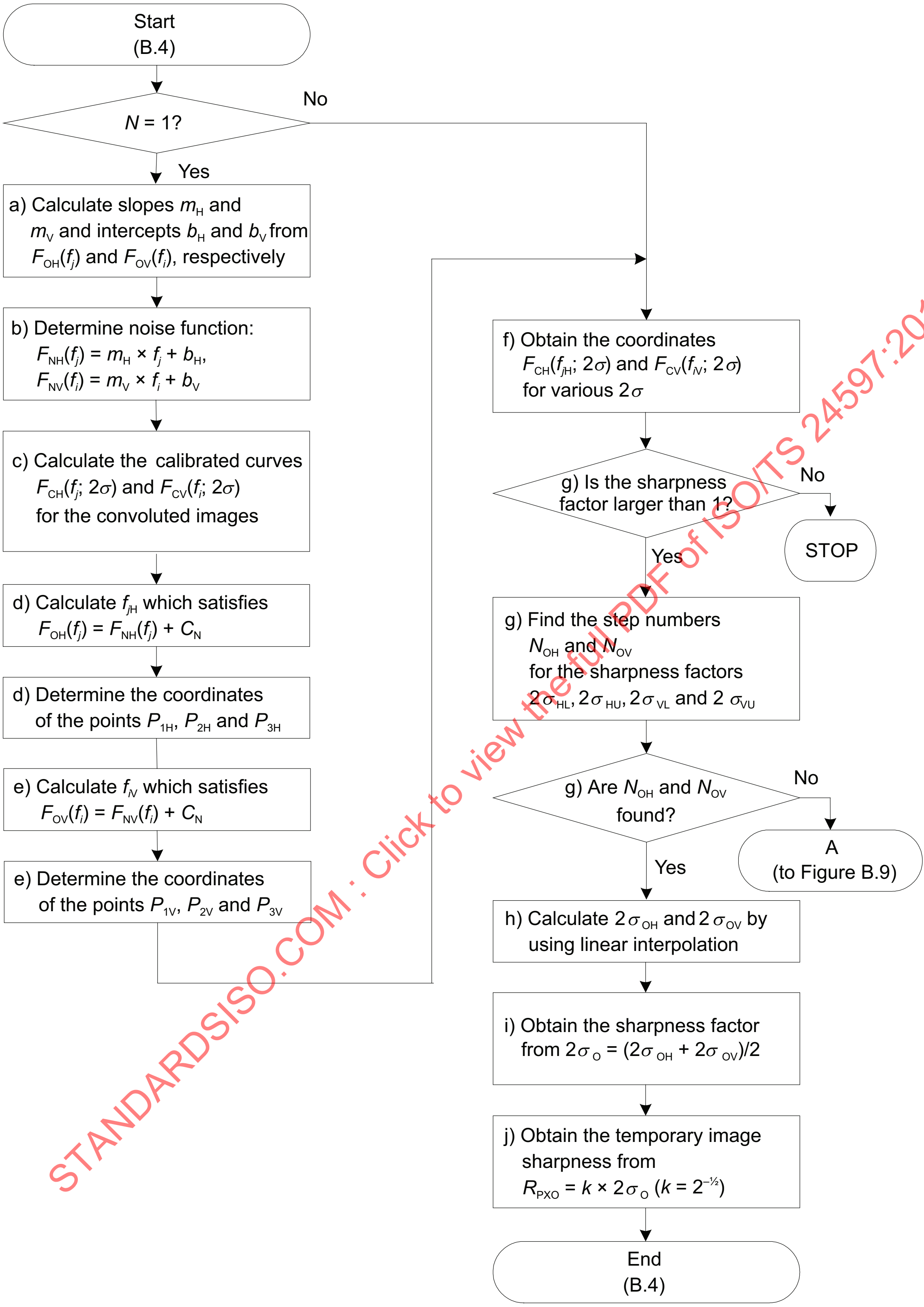


Figure B.11 — Flow chart for the procedure described in Clause B.4

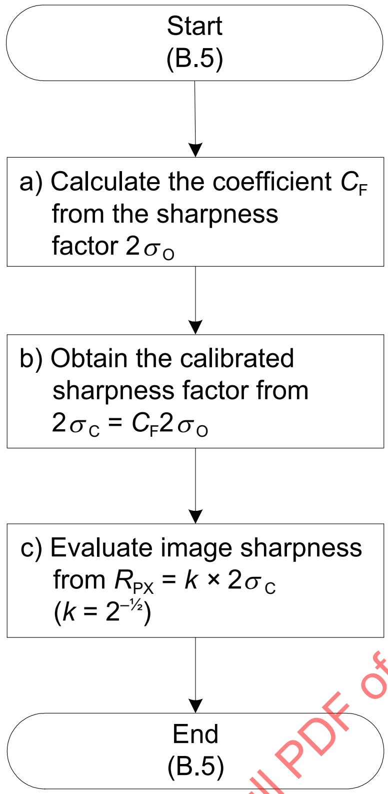


Figure B.12 — Flow chart for the procedure described in Clause B.5

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.

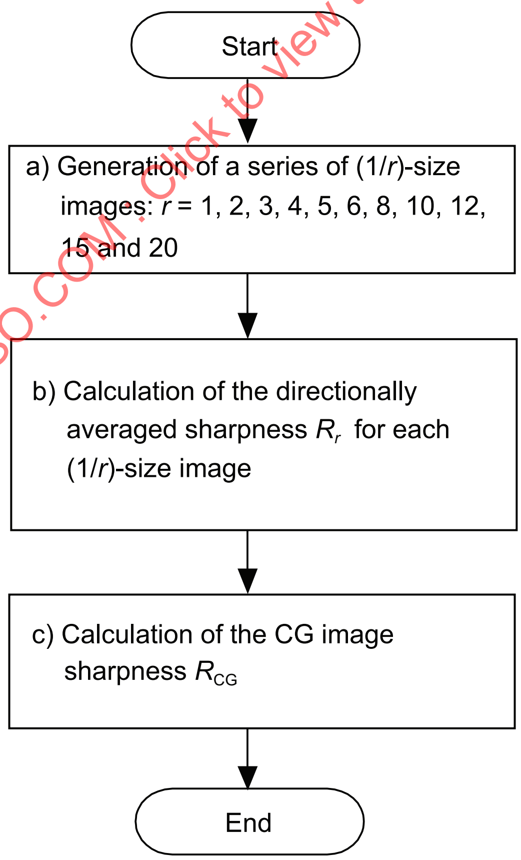


Figure C.1 — Flow chart for calculation of the CG image sharpness

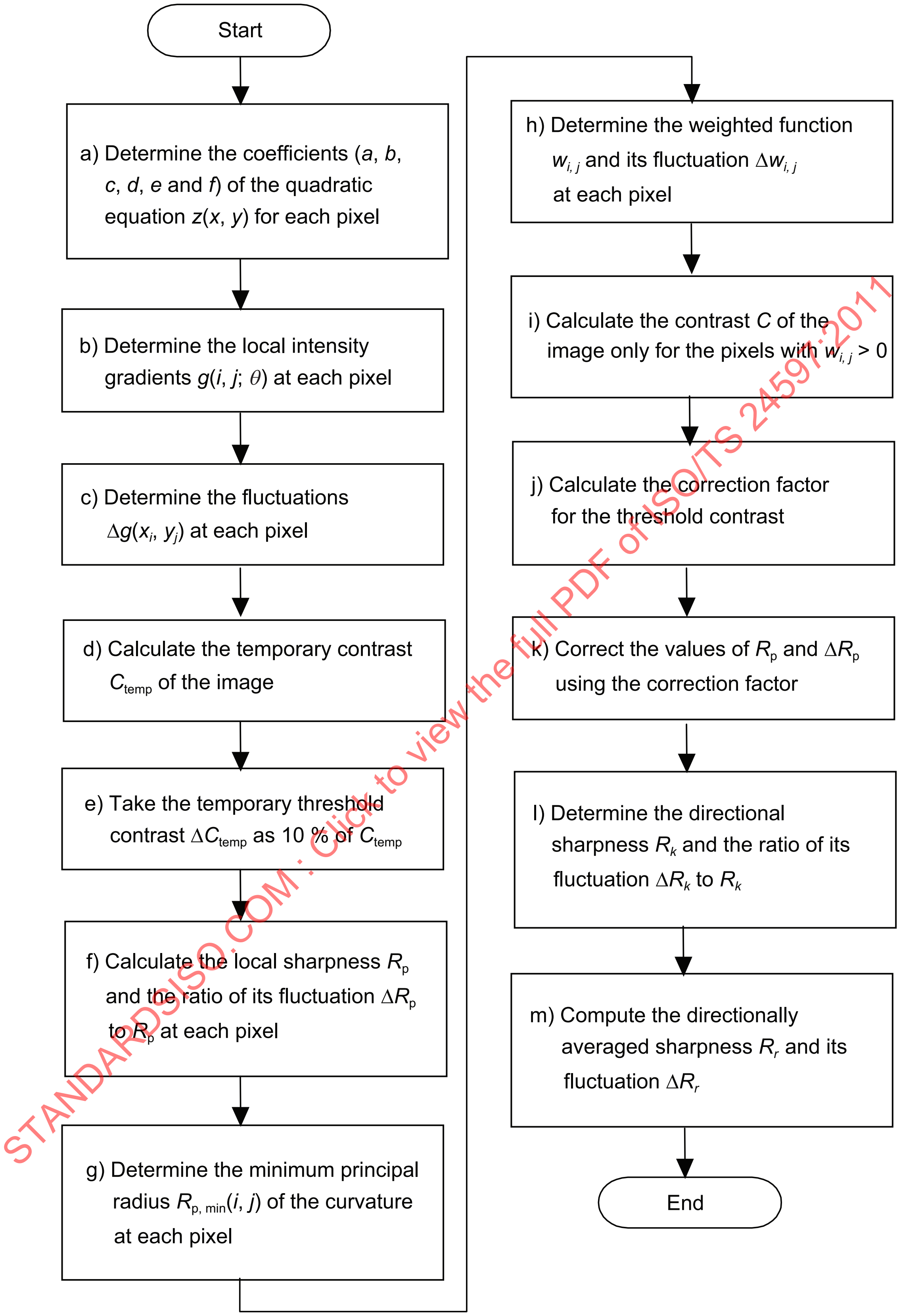


Figure C.2 — Flow chart for subroutine b)
(calculation of the directionally averaged sharpness) in Figure C.1

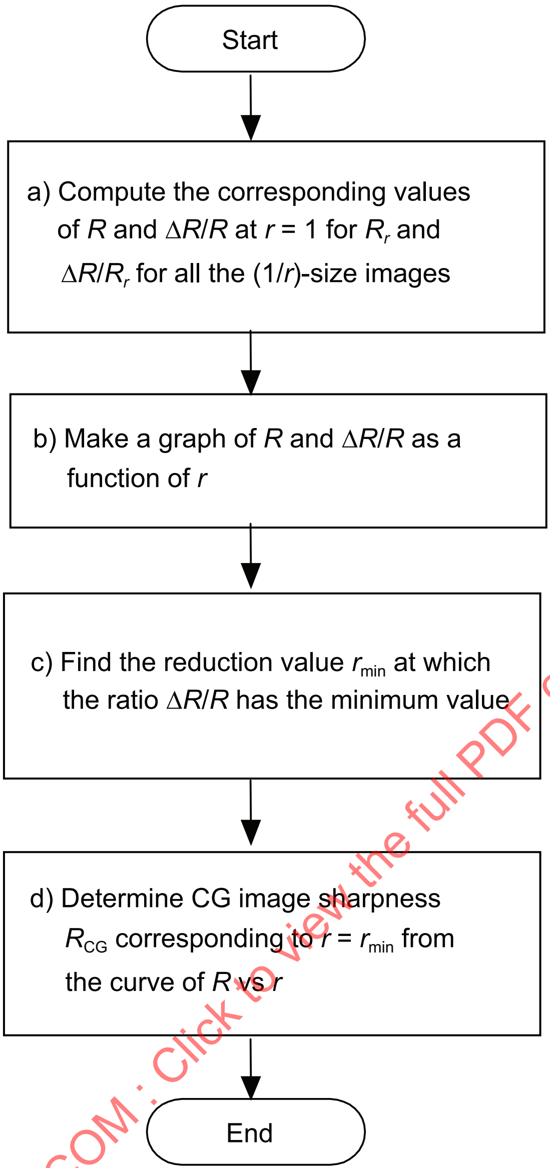


Figure C.3 — Flow chart for subroutine c) (calculation of the CG image sharpness) in Figure C.1

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).

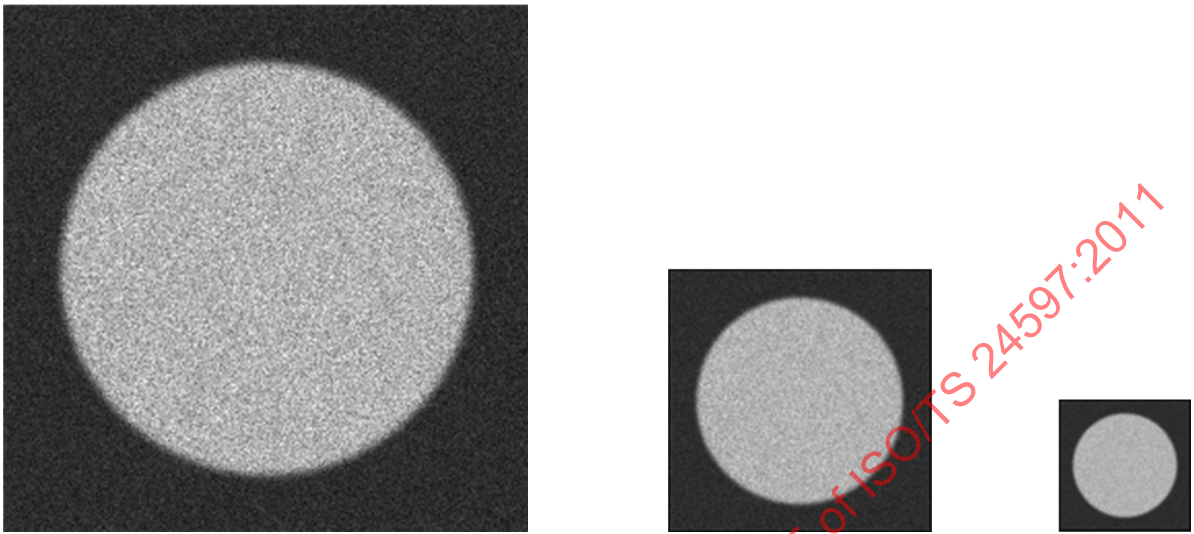
Generate the (1/r)-size images, obtaining the pixel intensity $I_r(i, j)$ by averaging the pixel intensities $I(p, q)$ in the original image as follows:

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

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}).

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:

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

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

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

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

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

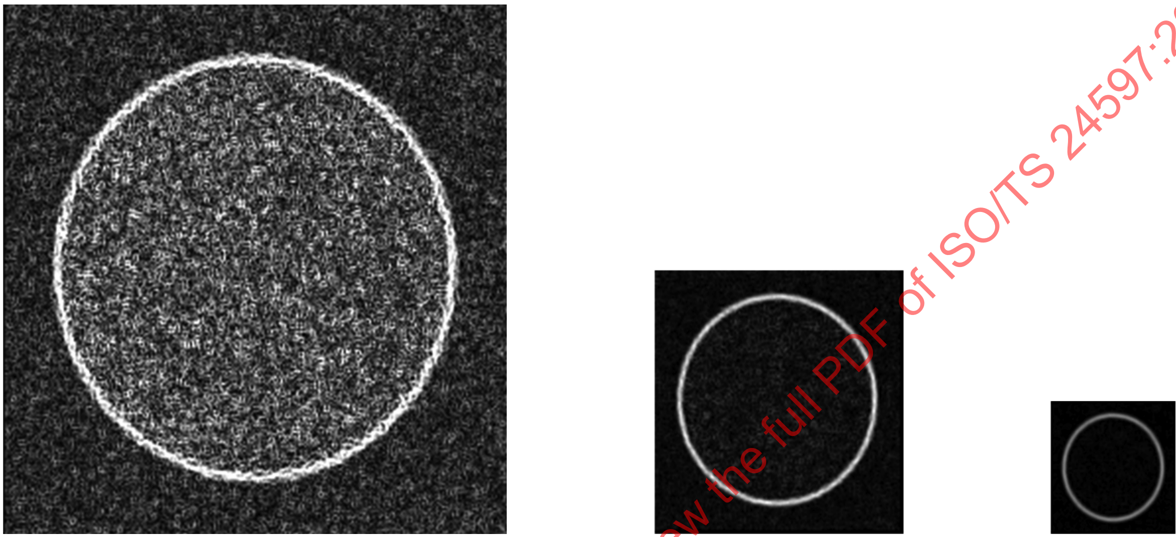
b) For each pixel, determine the local intensity gradients $g(i, j;\ \theta)$ by calculating the first partial-differential coefficients $\partial z/\partial x$ and $\partial z/\partial y$.

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

The angular information on the gradients is given by

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

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:

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

d) Determine the temporary contrast C_{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_{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 ΔC_{temp} as

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

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:

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

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

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

$$R_{\text{p,min}}(i, j) = 1/K_{\text{max}} \quad \text{for } i \text{ (and } j) = 1, 2, \ldots, i_{\text{max}} - 1 \text{ (and } j_{\text{max}} - 1) \qquad \text{(C.11)}$$

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 ΔR_k to R_k at azimuth angle θ_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 $k = 0, 1, \ldots, k_{max} - 1$ ($k_{max} = 16$).

m) Compute the directionally averaged sharpness R_r and the ratio of its fluctuation ΔR_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_{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:

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

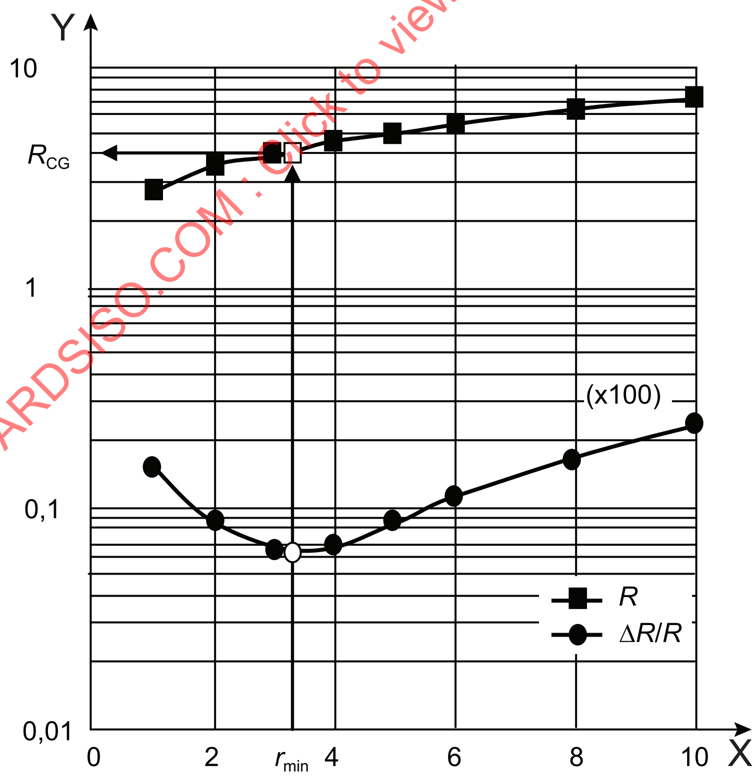
$$\Delta R/R = \Delta R_r/R_r \tag{C.25}$$

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_{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

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 ith 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 ith 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 σ_i.

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

d) Calculate the R_{CG} value for the ith 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 ith step, i.e. $i = i + 1$, and increase or decrease the σ_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).

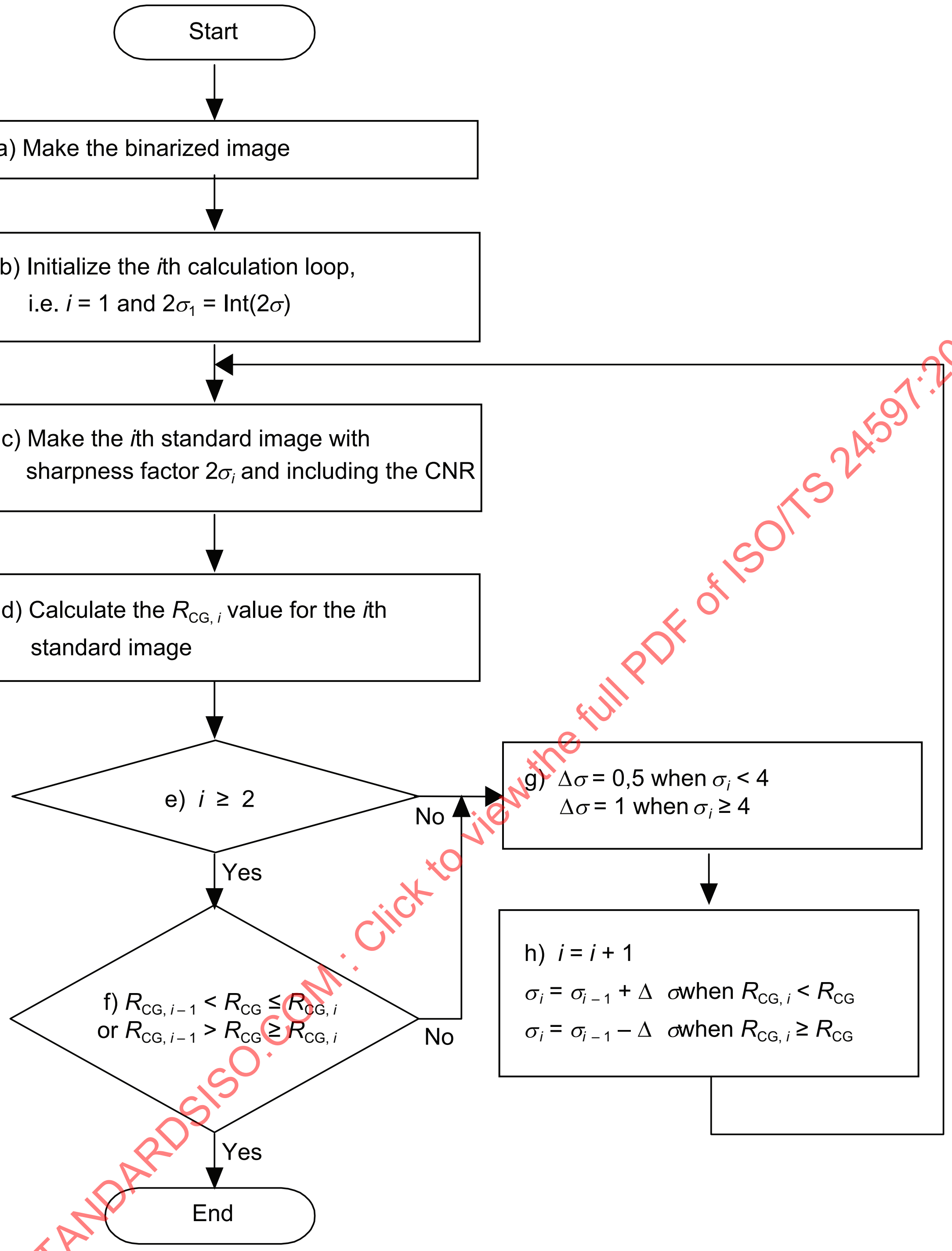


Figure C.7 — Flow chart for the generation of the standard images and calculation of their CG sharpness R_{CG}

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:

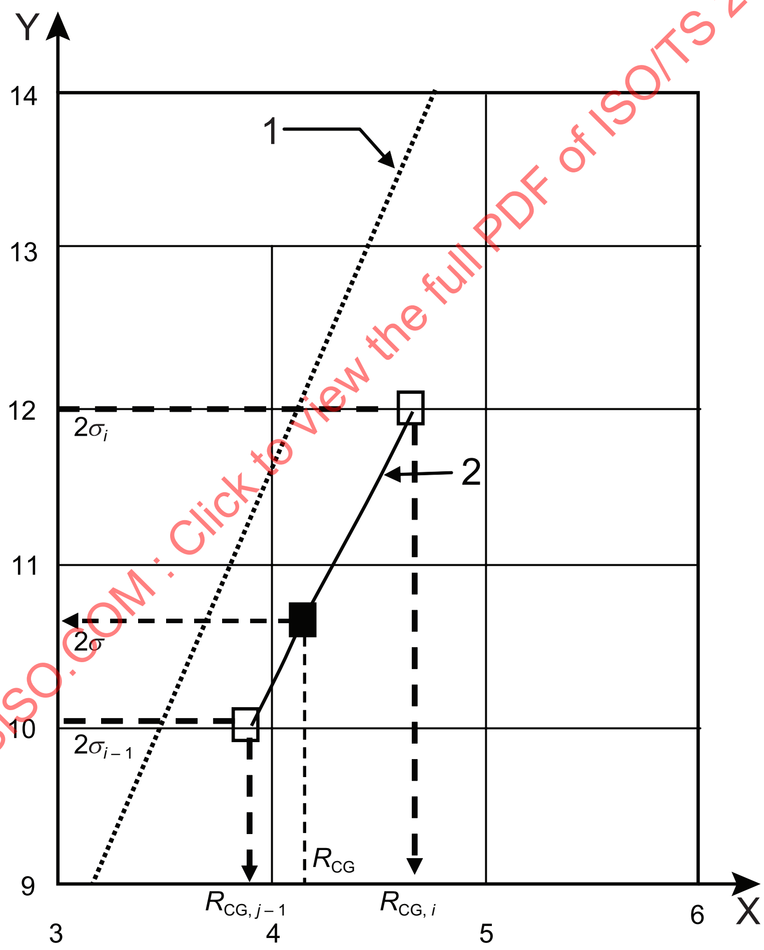
$$2\sigma_i = A_{\text{calib}} \times R_{\text{CG},i} + B_{\text{calib}} \tag{C.33}$$

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

We then obtain the calibrated conversion constants:

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

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



Key

X R_{CG} (pixels)

Y sharpness factor 2σ (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 2σ plotted as a function of R_{CG} for the calibration

C.5 Conversion of the R_{CG} value to the image sharpness R_{ES}

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

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

where

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

2σ is the sharpness factor, given by

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

A_{calib} and B_{calib} are the calibrated conversion constants. The evaluated R_{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_{ES} shows little noise-dependency and is evaluated with the CNR value as a given parameter.

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 $G_M(x, y)$ from:

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

c) Compute a two-mean threshold image (binary image) $B(x, y)$ from $G_M(x, y)$ by the following steps 1) to 5).

1) Generate a histogram $h(g)$ of $G_M(x, y)$.

2) Determine the minimum value g_{min} and the maximum value g_{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.

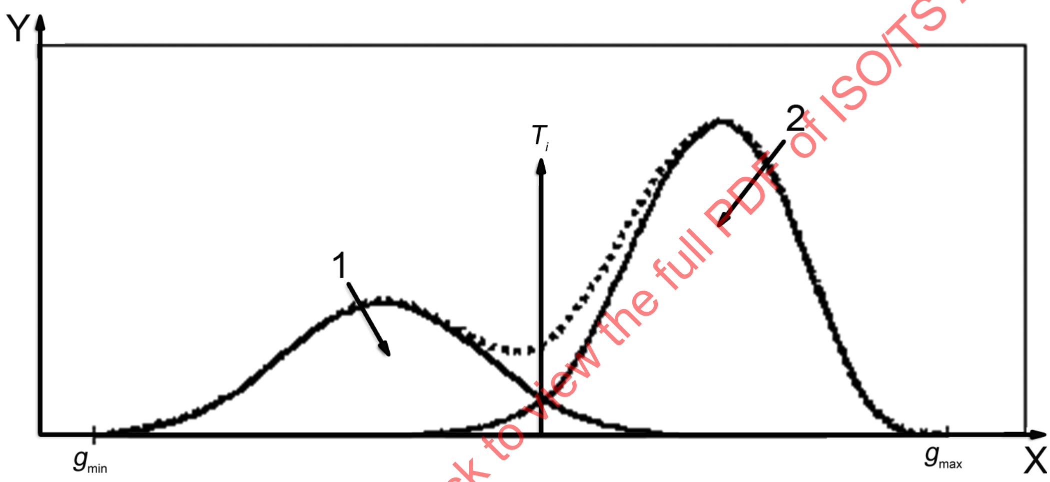
4) Then, repeat the following iteration until the value of T_i is stable.

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

where

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

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



Key

X grey value

Y occurrence

1 background

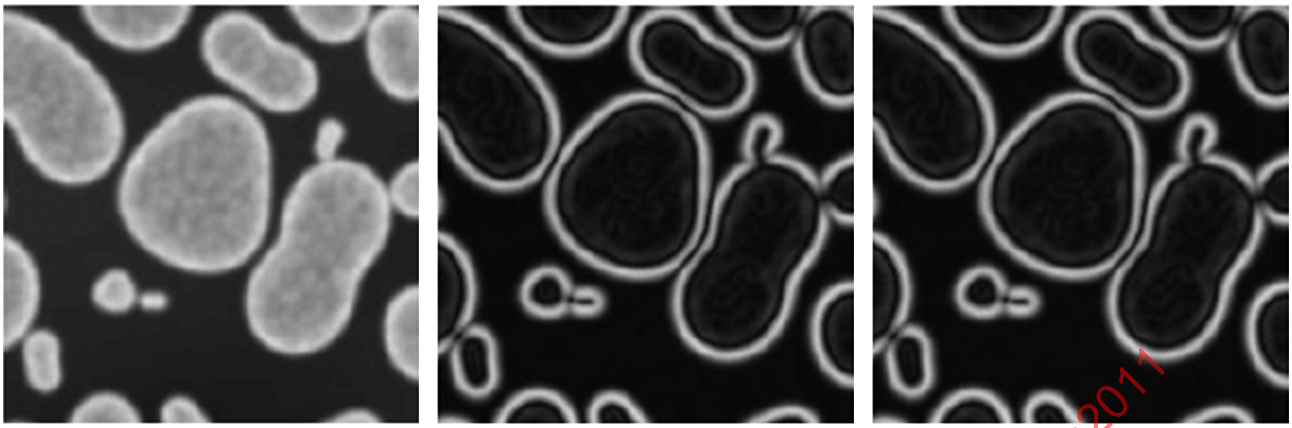
2 object

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.



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 × 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.

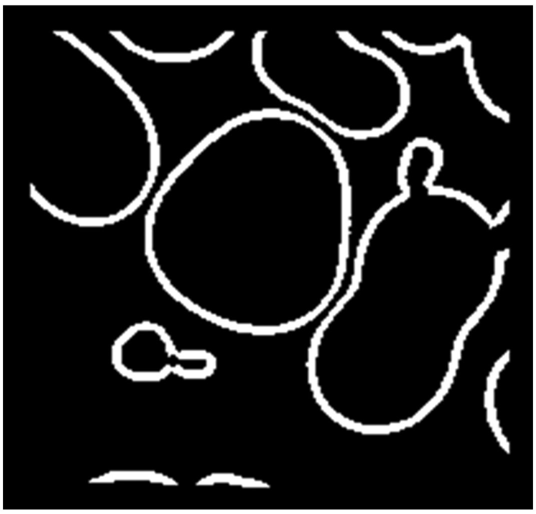


Figure D.3 — Example of an $M(x, y)$ image as the outcome of the operations in Clause D.2

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:

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

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 $T_1(x, y)$.

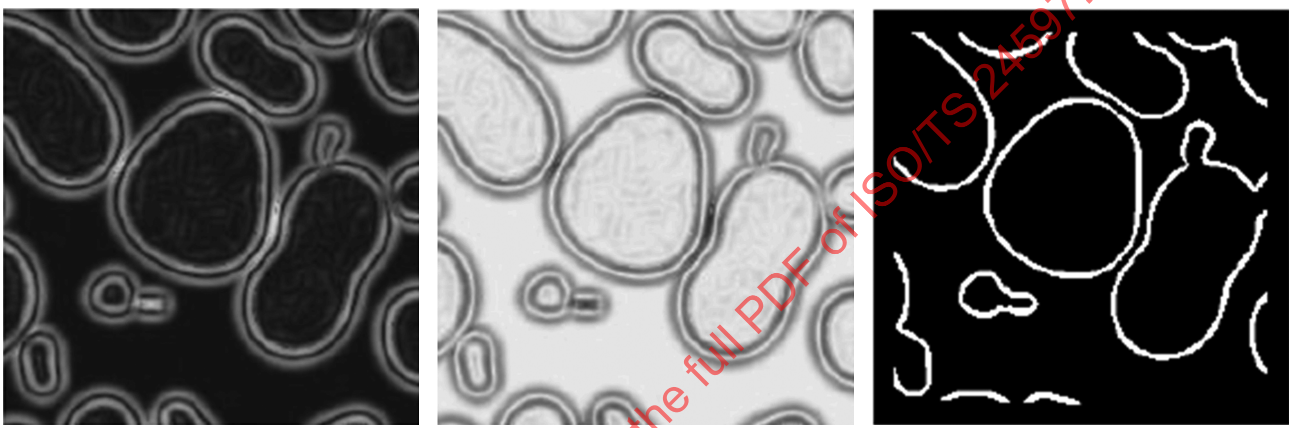
c) Compute an initial edge map $E_1(x, y)$ by the following steps:

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)

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

a) Compute the normalized gradients $G_{Nx}(x, y)$ and $G_{Ny}(x, y)$ as follows:

$$G_{Nx} = G_x(x,y) / \sqrt{G_x(x,y)^2 + G_y(x,y)^2} \quad \text{(D.8a)}$$

$$G_{Ny} = G_y(x,y) / \sqrt{G_x(x,y)^2 + G_y(x,y)^2} \quad \text{(D.8b)}$$

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

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

$$p_{jy}(\lambda) = y_j + \lambda \times G_{Ny}(x_j, y_j) \quad \text{(D.9)}$$

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 jth 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:

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

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

$d_y = (m_r + m_l)/2$

$m_d = m_0 - d_y/4$

$m_b = m_0 + d_y/4$

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 σ_j such that the following fitting error F_j is minimized:

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

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:

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

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

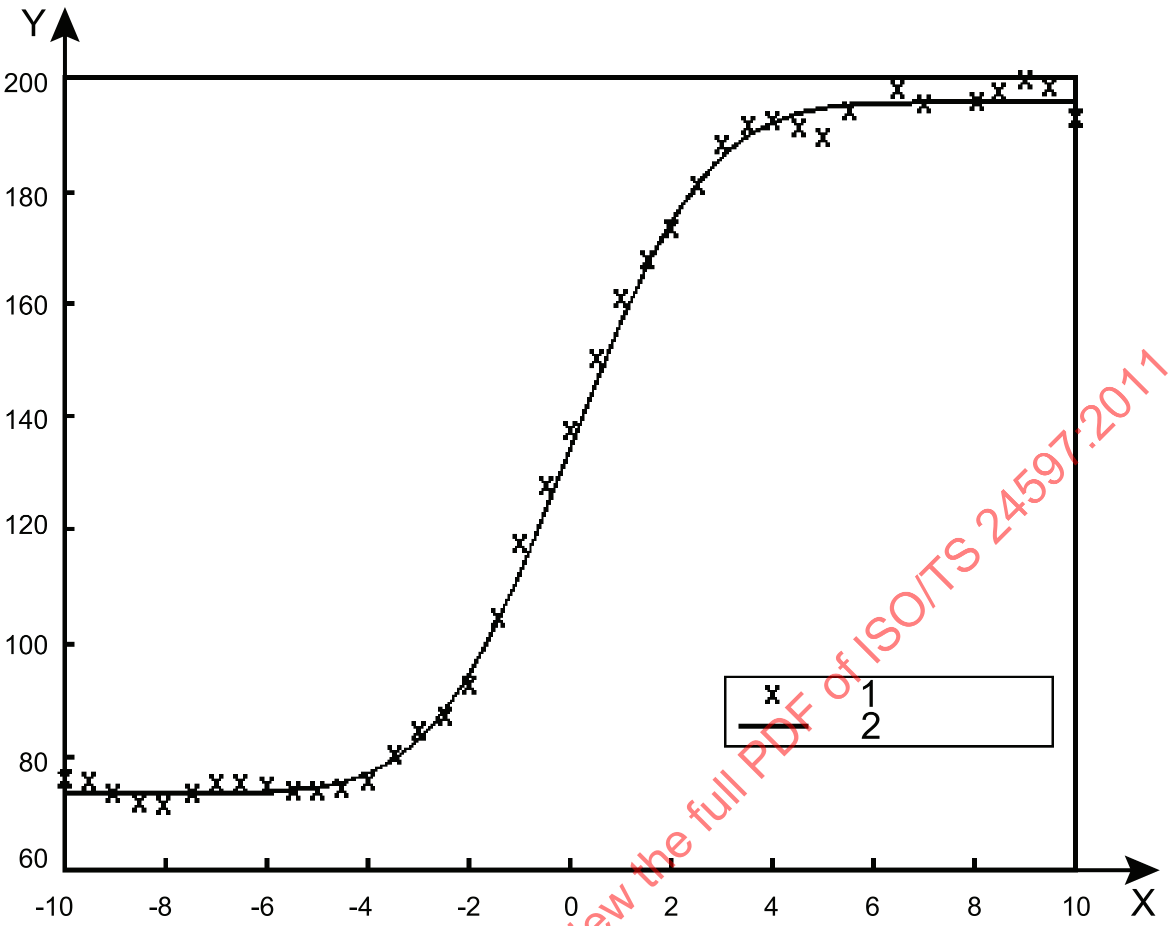
$m = 0$

$\sigma_j = 2$

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

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

Figure D.6 shows an example.



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 σ 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 σ obtained.

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

D.6 Flow charts

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

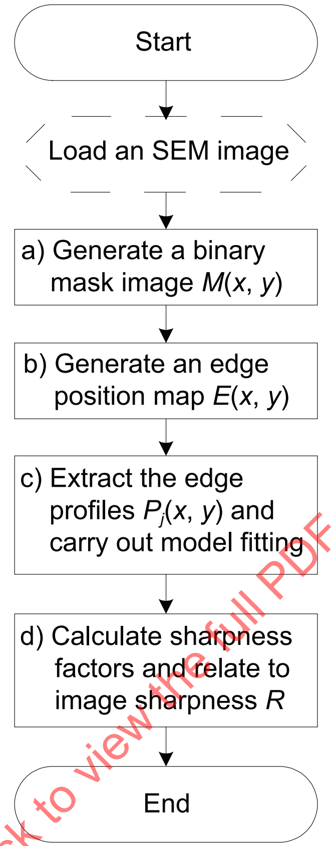


Figure D.7 — Flow chart for the DR method

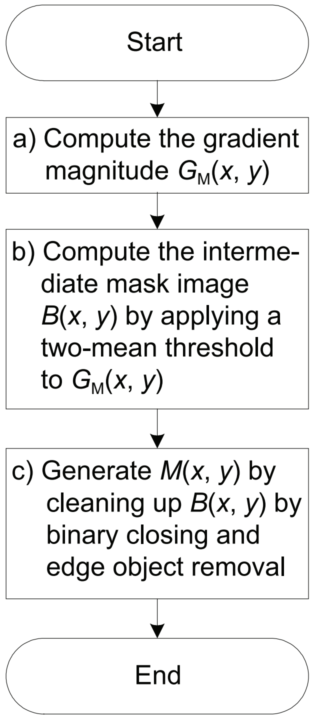


Figure D.8 — Flow chart for the subroutine in Clause D.2 for the generation of a binary mask image $M(x, y)$

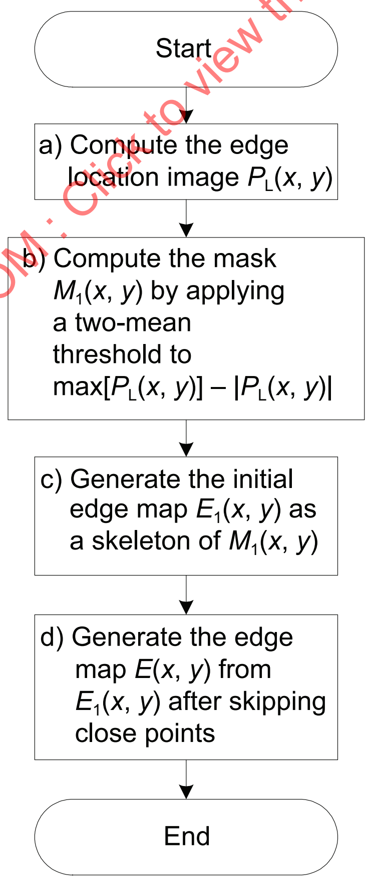


Figure D.9 — Flow chart for the subroutine in Clause D.3 for the generation of an edge position map $E(x, y)$

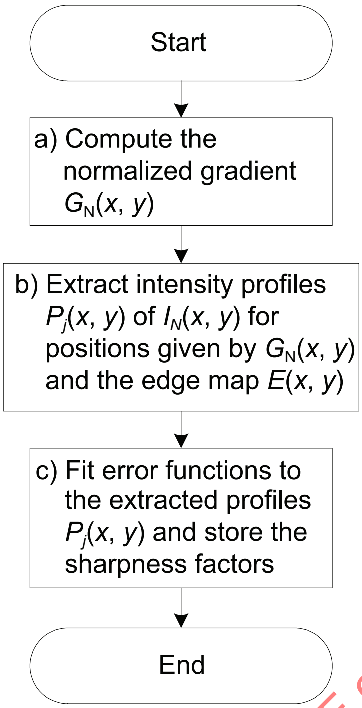


Figure D.10 — Flow chart for the subroutine in Clause D.4 for the extraction of the edge profiles $P_j(x, y)$ and model fitting

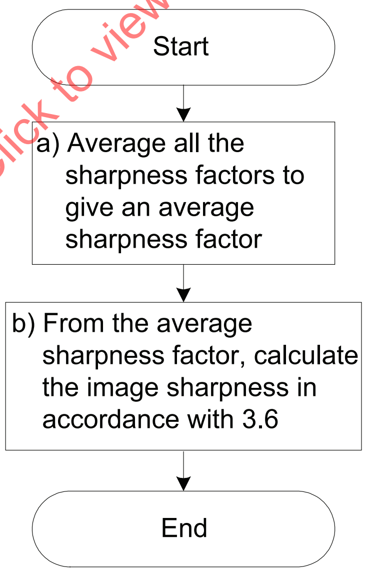


Figure D.11 — Flow chart for the subroutine in Clause D.5 for the calculation of image sharpness

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:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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
```



```
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
```



```
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
```

```
      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
```

```
        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
```

```
// 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.
```

```
// 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
```