MAMMO_QC imageJ plugin
Reference manual
version 1.0.0

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The software is updated to the the European guidelines and supplements [5, 6] as well as their recent updates [4] and to EUREF protocol version 1.03 (March 2018) "Protocol for the Quality Control of the Physical and Technical Aspects of Digital Breast Tomosynthesis Systems" [18].

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Contents

Glossary

AEC : Automatic Exposure Control. 9, 10, 15, 16, 20

AGD : Average Glandular Dose: the mean dose abdorbed by the breast (usually in mGy). 6

BTO : Breast Tomosynthesis Object. 22, 23

CR : Computed Radiography. 18

CT : Computed Tomography. 6

DAK : Detector air kerma, usually in µGy – see ESAK definition. 8–10, 15–21, 23–25

DBT : Digital Breast Tomosynthesis. 20, 21

DICOM : Digital Imaging and Comunication in Medicine: the standard for the communication and management of medical imaging information and related data. 6, 9, 11, 15, 19, 20, 24

DQE : Detective Quantum Efficiency. 11, 12, 19

DR : Digital Radiography. 18

ESAK : Entrance Surface Air Kerma: the air kerma at the entrace surface of the patient (usually in mGy). 6

FFDM : Full Field Digital Mammography. 3, 15

mAs : milliampere – second: the tube loading (tube current times exposure time product). 6, 8, 9, 15, 20

NNPS : Normalized Noise Power Spectrum. 11, 12, 18, 19

NPS : Noise Power Spectrum. 19, 24

PMMA : Polymethyl methacrylate. 10, 16, 20, 21 pMTF : pre–sampled Modulation Transfer Function. 10–12, 25, 26

PV : Pixel Value. 8, 16, 22

ROI : Region of Interest. 7–10, 15–25

SDNR : Signal Difference to Noise Ratio. 16, 21

SNR : Signal to noise ratio. 9, 10, 15, 18, 20, 22

2 Installation

2.1 System requirements

- java jre 8
- ImageJ installed (version 1.52a or later)

2.2 Plugins installation

If ImageJ is not installed in your computer, download it from http://imagej.nih.gov/ij/download.html and install it following the instructions. If you have already installed an older version of ImageJ (version 1.51 or older) in your computer, you need to upgrade it to the latest version (available online at http://imagej.nih.gov/ij/download.html).

If you do not have java installed in your computer you can choose to download ImageJ bundled with 64-bit Java 1.8.0_112 from the above url.

If you have already installed ImageJ (version 1.52a or later) in your computer, you just need to download the plugin, without the need of upgrading ImageJ.

After downloading the zip archive, un–zip it to a folder (e. g.. `C:\imageJ`).

Download the MAMMO_QC plugins zip file from http//dx.doi.org/10.17632/8jj7865wfn.1. Unzip the file inside yours imageJ "plugins" folder. Start ImageJ. You will see a "MAMMO_QC" menu under "Plugins".

3 Description of the individual plugins

MAMMO_QC is a series of plugins for the analysis of digital mammography and digital breast tomosynthesis images, mainly based on European Guidelines. All plugins request that the user follows precise instructions. Some plugins report the output in a RESULTS window from which the data can be copied or exported using the context menu that appears upon right–clicking the mouse. Some of the output plots can be printed, saved as image (e.g., `png`, `jpg`, `tiff`, etc.) and/or exported, saving the underlying data as comma–separated value (`csv`) file.

3.1 General Utilities

3.1.1 Sort By Acquisition Time

This plugin requests the user to select a folder and searches if there are DICOM images inside with a DICOM `"Acquisition Time"` tag (0008,0032); it renames the files related to these images with the value of this tag (hhmmss.frac.dcm) with hh, mm, ss equal to hour, minute and second, respectively, and frac equal to the decimal fraction.

3.1.2 Sort By Slice (CT format)

This plugin asks the user to select a folder and searches if there are DICOM images inside it with a DICOM tag `"Slice Location"` (0020,1041) and renames the files related to these images with the value of this tag.

3.2 General Tests

3.2.1 AGD from Header

This plugin extracts the nominal AGD (Average Glandular Dose) from the DICOM header and other relevant info (i. e., breast thickness, mAs and ESAK - i. e., Entrance Surface Air Kerma). It prompts the user to select a folder and search within if there are DICOM images with a DICOM `"Organ Dose"` tag (0040,0316). For each of these images the plugin reports in the `RESULTS` window:

- Thickness (mm): the contents of the DICOM `"Body Part Thickness"` tag (0018,11A0) — if valid — otherwise the image file name
- mAs: the tube loading (mA·s) from the DICOM header tags `"Exposure in uAs"` (0018.,1153) or `"Exposure"` (0018,1152)
- ESAK (mGy): the content of the DICOM tag `"Entrance Dose in mGy"` (0040,8302)
- AGD (mGy): the content of the DICOM `"Organ Dose"` tag (0040,0316): if valid its multiplied by 100 (because the DICOM standard requires it is expressed in dGy in the header)

3.2.2 Bad Pixel Map

This plugin reads the text files describing the bad pixel map (currently it works only for Hologic and Siemens systems) of a detector. It converts the file to an image in `png` format. The plugin asks whether to process the text file or directly compare two images related to maps acquired at different times.

- Process map file: the user should select the type of system in question (Siemens / Hologic) and, subsequently, the file to be analysed. The user should then indicate or confirm the number of rows and columns of the detector relative to the file under examination. The plugin produces a white background image where the bad pixels are indicated in black and surrounded by red ROIs; it also indicates the number of bad pixels obtained from the analysis of the map file. The user then has the ability to save the image a) with overprinted images (image not valid for subsequent comparisons) or b) with only the bad pixels; in the latter case the plugin asks if the user wants to proceed with the comparison to other images obtained from other bad pixel maps (see the following point 'Compare map images').

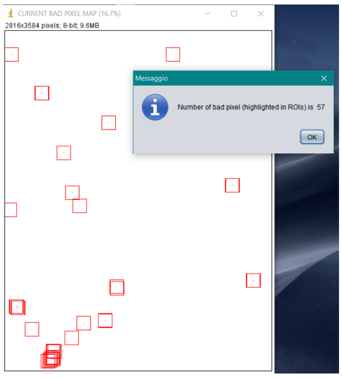


Figure 1: Example of map file converted from `txt` to `png` image.

- Compare map images: the plugin compares the previously saved images (without the ROIs) and creates a difference image between the two maps. The user should select the `png` image of the current map and then the respective previously saved map image. The plugin shows the output image on a black background and with the bad difference pixels, surrounded by a white ROI; the plugin also reports the number of bad pixel difference.

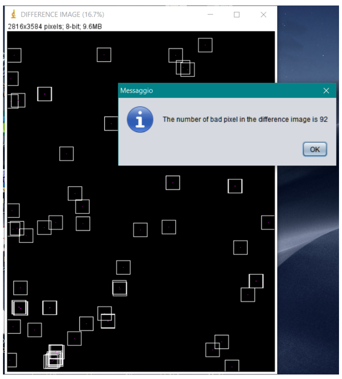


Figure 2: Example of a (fictious) `png` maps comparison: the white squares are multiple ROIs surrounding bad pixels (coloured magenta) that are in different positions in the two maps.

3.2.3 Response Function

The plugin evaluates the function that allows to convert pixel values into DAK values (mGy) — see [5, para. 2b.2.2.1.1], [18, para. 4.1.1] and [6, app. A7.4]. The user should select the images to be analysed and, for each of them, should indicate the value of DAK corresponding to the mAs used to form the image. The plugin creates a 5 mm x 5 mm ROI, centered laterally and placed 60 mm from the edge of the chest wall (reference ROI), and calculates the average pixel value (PV) of the ROI. The output in the `RESULTS` window is (for each image):

- DAK: The Detector Air Kerma corresponding to the mAs used to obtain the image
- the average pixel value of the reference ROI

The plugin shows the plot of PV vs DAK and attempts to fit the points with a linear or logarithmic function:

$$\begin{cases} y = & A \cdot x + B \\ y = & A \cdot \ln(x) + B \end{cases}$$

If neither the linear nor the logarihmic fit is succesuful (based on R^2) the plugin shows an alert to the user; otherwise the following output lines are placed on top of the plot:

- whether the best fit is linear or logarithmic
- R^2: the coefficient of determination of the fit
- the value of A (i. e., slope) and B (i. e., intercept) coefficient

3.2.4 Noise evaluation

The plugin allows evaluating the components of the noise and to characterize the noise as a function of the DAK [5, para. 2b.2.2.1.2] and [18, para. 4.1.2]. It asks the user to select the images to be opened and to insert, for each image, the value of DAK associated with them. The user can then indicate the coefficients of the response function A and B and select whether this function is linear or logarithmic:

$$\begin{cases} y = & A \cdot x + B \\ y = & A \cdot \ln(x) + B \end{cases}$$

The user can also choose not to linearise the image by clicking the button "No linearisation". The plugin, on each of the images, creates a reference 5 mm x 5 mm ROI (see Section 3.2.3) and converts the pixels within that ROI using the inverse of the selected answered function; the variance SD^2 of the linearised (converted) pixels within that ROI is calculated. The plugin performs a second order polynomial fit on the variance values thus obtained, to determine the coefficients of the equation

$$SD^2 = k_e^2 + k_q^2 \cdot p + k_s^2 \cdot p^2$$

- k_e^2: Coefficient of electronic noise
- k_q^2: Coefficient of quantum noise (Poisson distribution)
- k_s^2: Coefficient of structured noise
- p: mean value of the linearised pixels in the reference ROI or, equivalently, value of DAK relative to the image

As an output, the plugin shows the coefficients k_e^2, k_q^2 and k_s^2, the curve related to the fit and in the `RESULTS` window:

- DAK: The Detector Air Kerma corresponding to the mAs used to obtain the image
- SD^2: the variance of the pixels in the reference ROI

3.2.5 AEC — Long Term

This plugin allows evaluating the long-term stability of the automatic exposure control system — see [6, para. 2b.2.1.3.4] and [18, para. 2.3]. The user may select the image to be analysed and, insert the coefficients and type of the response function to convert the pixel values into DAK (see the sections 'Response Function' — Section 3.2.3 — and 'Noise evaluation' — Section 3.2.4). Then the SNR value is calculated (from a reference 5 mm x 5 mm ROI) according to the equation

$$SNR = \frac{PV}{SD}$$

- PV: mean value of the linearised pixels within the reference ROI
- SD: standard deviation of the linearised pixels within the reference ROI.

As an output, the plugin reports the value of the mAs extracted from the DICOM header and the value of SNR in the reference ROI.

3.2.6 AEC — Local Dense Area

With this plugin it is possible to evaluate the behavior of the automatic system of exposure in the presence of localized areas of greater density — see [6, para. 2b.2.1.3.6] and [18, para. 2.6]. The plugin prompts to select the images to be opened and to insert the coefficients A and B and the type of the conversion function (linear or logarithmic) to convert the pixel values into DAK values. The user can also choose not to linearise the images by clicking the button "No linearisation". Next, for each image,the user needs to insert the thickness in mm of the added PMMA. For each image, the plugin asks to draw and / or center an ROI that covers the area with the additional PMMA (giving the user the ability to vary the window level and width). Subsequently, for each image, the plugin creates a 5 mm x 5 mm ROI placed at the center of the ROI selected by the user and, using the inverse of the selected answered function, calculates the value of SNR whitin that ROI (see Section 3.2.5).

As an output, in the `RESULTS` window the plugin reports (for each image):

- PMMA (mm): the thickness in mm of the added PMMA
- SNR: the value of SNR in the ROI centered on the added PMMA

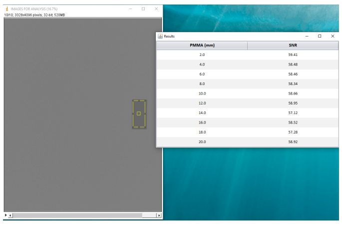


Figure 3: Example of the output for the AEC — Local Dense Area plugin, with the ROIs centered on the added PMMA.

3.2.7 MTF — Edge pMTF

The plugin calculates the pMTF curve — pre–sampled MTF vs mm^{-1} (or, equivalently, lp/mm) — from the image of a radiopaque edge — see [6, para. 2b.2.4.2] and [18, para. 4.4]. The user should select the image to be opened and insert the coefficients A and B and the type of the conversion function (linear or logarithmic) to convert the pixel values into DAK values. The user can also choose not to linearise the image by clicking the button "No linearisation". The plugin shows a 40 mm x 40 mm ROI and asks the user to move the ROI over the edge. The calculation algorithm is based on a previous work [13] (which in turn is based in the literature — see [2, 15, 17]):

- computation of the direction of the edge (horizontal / vertical)
- creation of pixel profiles converted in DAK along the whole ROI and in the direction computed previously (horizontal / vertical)
- search for the maximum pixel value of each profile and linear fit of the obtained values to determine the angle of inclination of the edge and the position of the line of interest
- definition of the array of profiles and projection of the pofiles along the horizontal (or vertical) line in order to concatenate all the projections.

- arrangement of the array to get the projections in order of increasing x, with x equal to the direction along which to calculate the pMTF curve
- resampling of the profile with a pitch of 1/10 pixel dimensions (extracted from the DICOM header) to get an Edge Spread Function - ESF (the composition of the profile along the edge will give the ESF)
- smoothing of the profile using a moving average with Gaussian weighting and a width of 3 points
- numerical differentiation of the ESF to obtain the LSF curve (Line Spread Function)
- elimination of the continuous component of the LSF curve (to de–trend a potential low-frequency pattern in the background: the plugin compute that component using the last parts of the tails)
- normalization of LSF to its maximum value
- application of a Hann filter with a window of 12.5 mm (in order to reduce the noise due to points outside the useful signal of the LSF curve)
- calculation of the Discrete Fourier Transform (DFT) and its modulus, to define the points of the MTF curve
- resampling of the MTF curve with a pitch of $0.25\,\mathrm{mm}^{-1}$ and normalization to 1 at zero spatial frequency ($0\,\mathrm{mm}^{-1}$)

The reported output consists of the values of pMTF_{50}, pMTF_{10} — spatial frequencies at which the pMTF curve reaches 50% and 10%, respectively — and the value of the pMTF curve at Nyquist frequency [1].The plugin also shows the graphs of the oversampled ESF curve, the ESF after smoothing, the LSF curve and the pMTF curve. Furthermore, the values of spatial frequencies and the corresponding values of the pMTF curve are shown in the `RESULT` window. The user can also choose between saving the pMTF curve in a `csv` (comma–separated value) file or to load a previously saved file and averaging the data before saving them again. The saved file can be used for a subsequent DQE computation (see Section 3.2.8).

3.2.8 DQE

The plugin computes the DQE (Detective Quantum Efficiency) using previously saved `csv` files of pMTF and NNPS data (see Section 3.2.7 and Section 3.3.7). It asks the user to select an SNR_{in}^2 value from various Mammographic beam qualities from IEC or European guidelines [3, 6], or by choosing a commercially available mammography or tomosynthesis system and selecting the X–ray beam quality by entering the tube voltage (kVp) and Anode/inherent Filter combination. In the latter case, the SNR_{in}^2 value is computed by applying a 2 mm Al additional filter (to simulate an average breast). The X-ray spectrum is updated in real–time reflecting the user's choices. The SNR_{in}^2 input values and spectra have been taken from the `booneweb` software available at the Siemens Healthcare website (https://health.siemens.com/booneweb/index.html). The pMTF and NNPS data are 'paired', discarding data if the pMTF and NNPS curves are not of the same length. The DQE values are calculated from

[1] half of the sampling rate , i.e., 1/2 of pixel pitch (taken from the DICOM header)

0.25 mm^{-1} onwards because potential low-frequency artefacts will lead to high NNPS value at zero frequency which gives an underestimate of DQE[9]. As an output, the plugin shows the pMTF, NNPS and DQE plots. The user can choose to export the DQE table as an Microsoft Excel file.

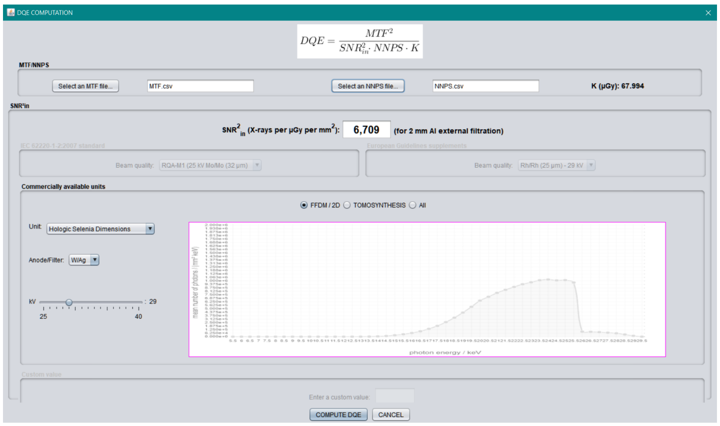


Figure 4: DQE plugin user interface.

3.2.9 CDMAM — Analyse CDMAM

This plugin allows to analyze the images (or the output of the CDCOM software[2]) related to images of CDMAM test tools[3] (CDMAM 3.4 and CDMAM 4). This type of analysis allows to determine the Threshold contrast visibility — see [6, para. 2b.2.4.1] and [5, para. 2b.2.4.1].

The user is asked to select the type of CDMAM test tool (3.4 or 4). Then, the user should select the type of input for the analysis[4]:

- single average matrix obtained from previous CDCOM analysis
- matrices obtained from CDCOM analysis on one or multiple images
- images to be processed by CDCOM[5]

The plugin prompts to select the files (or images) to be opened, then analyses them with the following steps:

- detection of discs using CDCOM
- combining the results of the CDCOM [20, 21]
- smooth of the detection matrix using the following (approximate) Gaussian kernel:
$$\begin{pmatrix} 0.25 & 0.50 & 0.25 \\ 0.50 & 1.00 & 0.50 \\ 0.25 & 0.50 & 0.25 \end{pmatrix}$$
- the plugin computes an effective attenuation coefficent μ of gold related to the exposure settings extracted from the DICOM header using a linear fit of the data in [12] (draft version).

[2] CDCOM is available from the EUREF website (www.euref.org)
[3] CDMAM, Artinis, Nijmegen, Netherlands (www.artinis.com)
[4] The CDCOM software, for every image, produces two files with the detection matrices of the center and the corner gold discs, respectively.
[5] the MAMMO_QC zip archive contains the CDCOM executable files for both 3.4 (CDCOM v. 1.6) and 4.0 (CDCOMV4 version 1.0) test tools

- fitting of the psychometric curve [19]:

$$p(d) = \frac{0.75}{1 + e^{-f(C - C_t)}} + 0.25$$

with C = logarithm of the signal contrast; $C = log(1 - e^{-\mu t})$
C_t = signal contrast at the threshold of 62.5%
f = fitting parameter
$p(d)$ = the probability of detection of an object of size d

- estimation of the threshold at 62.5% (C_t) for every diameter
- converting the resulting thresolds to human readout: turning fitted contrast threshold into gold thickness thresholds and correct them using a power–law correction factor as described in [20] for results obtained from CDMAM 4.0 images converting the resulting thresolds to human readout and using a linear correction on contrasts C [7, 8, 21] for images of the CDMAM 3.4 test tool[6]
- fitting the resulting predicted threshold gold thicknesses with a third–order polynomial function [20]:

$$T = a + \frac{b}{x} + \frac{c}{x^2} + \frac{d}{x^3}$$

T = threshold gold thickness (µm)
x = detail diameter (mm)
a, b, c and d = coefficients adjusted to achieve a least-squares fit; all are ≥ 0

to obtain the contrast-detail curve.

- computation of $IQFinv$:

$$IQFinv = \frac{1}{\sum_{i=1}^{N} x_i \cdot T_i} \cdot 100$$

where N is the number of different diameters analysed and x_i, T_i are the i–th diameter and its corresponding threshold, respectively.

The plugin reports the smoothed detection matrix, informs the user with the value of $IQFinv$ and shows a `RESULTS` table reporting, for every detail diameter:

- Disc diameter (mm)
- Automatic Threshold Thickness (µm): the (fitted) thickness at 62.5%
- Predicted Human Gold Thickness (µm): the converted thickness to human redout
- Fitted Threshold Gold Thickness (µm): the fitted thickness (T) using the third-order polynomial defined above

It also reports (see Fig. 5) a second summary table with the same columns as the first one but only for the following diameters: 0.10 mm, 0.25 mm, 0.50 mm, 1.00 mm (summary).

In the latter table, the fitted thresholds are compared against the acceptable and achievable thresholds provided by the European guidelines and the corresponding rows are highlighted with the following colors, based on the comparison:

[6] the choice of the corrections was made in order the final results to agree with Artinis software results (for CDMAM 4.0).

Result of the comparison	Color
Below the achievable threshold	green
Between the acceptable and the achievable thresholds	orange
Above the acceptable threshold	red

Table 1: Colors used for highlithing the summary table.

In the last two panels the plugin reports the plot of the fitted psychometric curves and the contrast–detail curve, with the human predicted thresholds (with 95% Confidence Interval[7]) as a function of detail diameter, the fitted third–polynomial curve and the European acceptable and achievable thresholds.

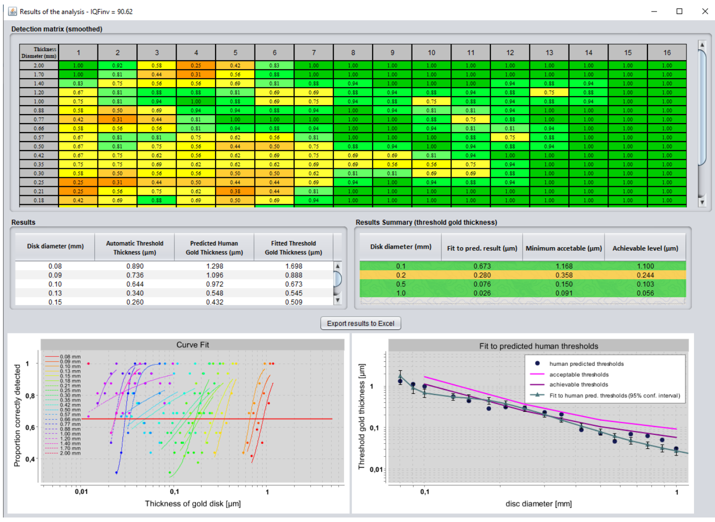
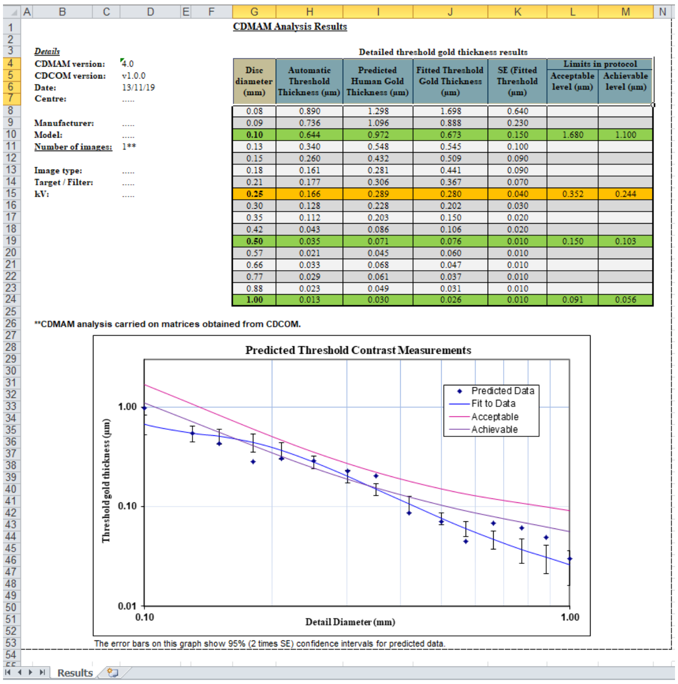


Figure 5: Output of the Analyse CDMAM plugin.

The user can click on a button to export the results in a Microsoft Excel file (see Fig. 6), well–formatted and potentially copied in other Microsoft Excel or Word files.

[7] computed from the SE (Standard Error of the mean as $2SE$), i.e., the quotient of the standard deviation of 32 previously analysed images and the square root of the number of used images



CDMAM Analysis Results

Details
CDMAM version: 4.0
CDCOM version: v1.0.0
Date: 13/11/19
Centre: .....
Manufacturer: .....
Model: .....
Number of images: 1**
Image type: .....
Target / Filter: .....
kV: .....

Detailed threshold gold thickness results

Disc diameter (mm)	Automatic Threshold Thickness (µm)	Predicted Human Gold Thickness (µm)	Fitted Threshold Gold Thickness (µm)	SE (Fitted Threshold (µm)	Limits in protocol: Acceptable level (µm)	Limits in protocol: Achievable level (µm)
0.08	0.890	1.298	1.698	0.640		
0.09	0.736	1.096	0.888	0.230		
0.10	0.644	0.972	0.673	0.150	1.680	1.100
0.13	0.340	0.548	0.545	0.100		
0.15	0.260	0.432	0.509	0.090		
0.18	0.161	0.281	0.441	0.090		
0.21	0.177	0.306	0.367	0.070		
0.25	0.166	0.289	0.280	0.040	0.352	0.244
0.30	0.128	0.228	0.202	0.030		
0.35	0.112	0.203	0.150	0.020		
0.42	0.043	0.086	0.106	0.020		
0.50	0.035	0.071	0.076	0.010	0.150	0.103
0.57	0.021	0.045	0.060	0.010		
0.66	0.033	0.068	0.047	0.010		
0.77	0.029	0.061	0.037	0.010		
0.88	0.023	0.049	0.031	0.010		
1.00	0.013	0.030	0.026	0.010	0.091	0.056

**CDMAM analysis carried on matrices obtained from CDCOM.

Figure 6: Automatically generated Excel report filled with the results of the CDMAM plugin.

3.3 FFDM

This section includes plugins for the evaluation of specific parameters for FFDM (Full Field Digital Mammography) systems, as described in [5, 6].

3.3.1 AEC — Short-term

This plugin allows to evaluate the short-term reproducibility of the automatic exposure control (AEC) system — see [6, para. 2b.2.1.3.3]. It prompts to select the images to be opened and to insert the coefficients A and B and the type of the conversion function (i. e., linear or logarithmic[8]) to convert the pixel values into DAK values. The user can also choose not to linearise the images by clicking the button "No linearisation". For each image, the plugin creates a reference 5 mm x 5 mm ROI (see Section 3.2.3) and converts the pixels within that ROI using the inverse of the selected answered function; the value of SNR is then calculated in this ROI (see Section 3.2.5). The output in the `RESULTS` window consists of (for each image):

- Image name: the name of the file related to the analysed image
- mean (linearised) PV: the mean value of the linearised (converted) pixels within the reference ROI
- (linearised) SNR: the value of SNR in the reference ROI
- Tube loading (mAs): the value of the tube current times exposure time product (extracted from the DICOM header) used to obtain the analysed image

[8] other function types would be available in future version of this software

3.3.2 AEC — SDNR

This plugin allows to evaluate the compensation, which is performed by the automatic exposure control (AEC) system, according to the thickness and composition of the breast — see [6, para. 2b.2.1.3.5]. The plugin requests the user to select the images to be opened and insert the coefficients A and B and the type of the conversion function (linear or logarithmic) to convert the pixel values into DAK values. The user can also choose not to linearise the images by clicking the button "No linearisation". For each image, the user should therefore enter the thickness in mm of the PMMA used. For each image, the plugin asks to draw and / or center an ROI that covers the area with the square of Aluminium (Al; leaving the possibility to the user to vary the window level and width). For each image, the plugin creates an ROI of 5 mm x 5 mm placed at the center of the ROI selected by the user and another 4 ROIs placed around the square of Al at 10 mm from the central ROI, in order to use them as a whole and minimize the non-uniformities due to the Heel effect (Fig. 7).

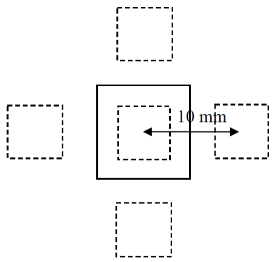


Figure 7: ROIs for the calculation of the SDNR value.

The plugin calculates the average value of the linearised (converted) pixels of background — $PV(background)$ — and the standard deviation of these pixels — $SD(background)$ — according to the following equations:

$$SD(background) = \frac{\sum_1^4 SD(ROI_n)}{4}$$
$$PV(background) = \frac{\sum_1^4 PV(ROI_n)}{4}$$

where ROI_n, with n ranging from 1 to 4, represents the 4 ROIs placed around the square of Al. In a similar way the mean pixel value — $(PV(signal))$ — and the standard deviation — $(SD(signal))$ — are calculated using the pixels of the central ROI located in the Al square.

The plugin then calculates the value of SDNR:

$$SDNR = \frac{PV(signal) - PV(background)}{\sqrt{\frac{SD(signal)^2 + SD(background)^2}{2}}}$$

The output, in the `RESULTS` window, is (for each image):

- PMMA (mm): the thickness in mm of the PMMA used for the image under investigation.
- SDNR: the corresponding SDNR value for the used PMMA thickness

3.3.3 Homogeneity

This plugin allows evaluating the homogeneity of the image — see [5, para. 2b.2.2.3.1].]. The user should select the image to be analysed and insert the coefficients A and B and the type of the conversion function (linear or logarithmic) to convert the pixel values into DAK values. The user can also choose not to linearise the image by clicking the button "No linearisation". The plugin then asks the user to create an ROI that covers the area of the image to be analysed (if the user does not select any ROI and presses "OK" the plugin analyses the whole image). The plugin converts all the pixels inside the ROI selected by the user and determines the average pixel value ($\overline{PV}_{global}$); The selected ROI is subdivided into several 1 cm x 1 cm ROIs and each of these is used to calculate the average pixel value (PV_{ROI}) and the SNR value (SNR_{ROI}); finally, the plugin calculates the average overall calculated SNR_{ROI} ($\overline{SNR}_{global}$). Afterwards, all the ROIs are checked and the plugin highlights the ROI over the tolerance according to the following criteria:

- ROI in GREEN: ROI for which PV_{ROI} differs from $\overline{PV}_{global}$ for more than 15%
- ROI in CYAN: ROI for which SNR_{ROI} differs from $\overline{SNR}_{global}$ for more than 15%
- ROI in RED: ROI for which both previous conditions are met

The plugin then asks if the image has been obtained from a CR system[9]. If so, the plugin makes a copy of the image (already converted into DAK) and asks again the user to draw an ROI for analysis. Then 5 ROIs are drawn: one central and 4 at the corners (one cm from the edge of the ROI designed by the user). The plugin repeats the analysis described above not covering the whole ROI defined by the user but using only the 5 ROIs for the calculations.

3.3.4 Artefact evaluation

This plugin allows evaluating the parameter 'Image receptor homogeneity' (creating a "Variance map" of the input image), in addition to the test described in the previous section — see [6, para. 2b.2.2.3.1]. The user should select the image to be analysed and insert the coefficients A and B and the type of the conversion function (linear or logarithmic) to convert the pixel values into DAK values. The user can also choose not to linearise the image by clicking the button "No linearisation". The plugin then asks the user to create an ROI that covers the area of the image to be analysed (if the user does not select any ROI and presses "OK" the plugin uses the whole image for analysis). The plugin converts all the pixels inside the ROI selected by the user. The selected ROI is divided into several 1 cm x 1 cm ROIs and, in each of these, the plugin creates smaller 2 mm x 2 mm ROIs to calculates the variance of each one:

$$Var(ROI_i) = \frac{\sum_{j=1}^{N}(PV_j - \mu_i)^2}{N-1}$$

where N is the number of pixels within each of the 2 mm x 2 mm ROIs, PV_j is the value of the j–th pixel within that ROI and μ_i represents the mean pixel value of the ROI. The mean of the variances obtained in the 2 mm x 2 mm ROI associated with the 1 cm x 1 cm ROI under examination is then determined. These ROIs are then compared to neighboring ROIs.

[9] if not, the plugin ends the analysis

The plugin asks if the image has been obtained from a DR or CR system, to determine the tolerance to be applied:

$$\begin{cases} 30\% & for\,DR\,[6, para.2b.2.2.3.1] \\ 10\% & for\,CR\,[5, para.2b.2.2.4] \end{cases}$$

The ROIs for which the average variance (calculated in the 2 mm x 2 mm sub–ROI) is greater than the tolerance with respect to the neighboring ROIs are shown on the image to allow the user to visually assess the presence of artefacts.

3.3.5 Interplate sensitivity variations

This plugins allows evaluating the Inter plate sensitivity variations for CR systems – see [5, para. 2b.2.2.4]. The user should select the images to be analysed, insert the coefficients A and B and the type of the conversion function (linear or logarithmic) to convert the pixel values into DAK values, and enter the identification code (Plate ID) related to every image. The user can also choose not to linearise the image by clicking the button "No linearisation". The plugin computes the SNR in the reference 5 mm x 5 mm ROI (see Section 3.2.3). The output, in the `RESULTS` window, is (for each image):

- PLATE ID: the identification code of the CR plate used to obtain the image under investigation.
- SNR: the corresponding SNR value in the reference ROI

3.3.6 Uncorrected defective elements

With this plugin it is possible to evaluate the presence of uncorrected defective pixels (for DR systems). The user should select the image to be analysed and draw an ROI on the area of the image to be analyzed (if the user does not select any ROI and presses "OK" the plugin uses the whole image for analysis). The selected ROI is divided into several 1 cm x 1 cm ROIs and, in each of these ROIs, the plugin calculates the average pixel value. If the algorithm identifies that the pixel under investigation deviates by more than 20% from the average value, it highlights it with a red ROI and changes its color to magenta. Finally, the plugin reports the number of uncorrected defective elements found.

3.3.7 NNPS

The plugin calculates the normalized noise power spectrum (NNPS) from one or more uniform (flat field) images – see [6, app A7.5] and [5, para. 2b.2.4.2]. The user needs to select the image(s) to be analysed and insert the coefficients A and B and the type of the conversion function (linear or logarithmic) to convert the pixel values into DAK values. The user can also choose not to linearise the image by clicking the button "No linearisation". The plugin then creates, for each of the images, a 10 cm x 10 cm ROI to convert the pixels of that ROI into air kerma values using the inverse of the specified conversion function. The average pixel value for the normalization of the noise power spectrum ($mean_{global}$) is calculated for the converted ROI. The calculation algorithm (derived from European guidelines) used on each image is based on what has been specified in [6, app A7.5] and consists of the following steps:

- creation of a second order polynomial 2D fit, based on the source code of Dwight Urban Bartholomew [1], which in turn is based on its Polynomial Surface Fit plugin.
- subtracting the fit from the central 10 cm x 10 cm ROI
- division of the central ROI into half–overlapping 256x256 pixel M ROIs and, for each of them, division of each of the pixel values by the $mean_{global}$ global average
- calculation of the two dimensional (2D) Fourier Transform using the source code of the `FFTJ and DeconvolutionJ` plugin by Nick Linnenbrügger [10]
- calculation of the 2D NPS matrix using the formula:

$$NPS(u,v) = \frac{\Delta x \Delta y}{M \cdot 256 \cdot 256} \sum_{m=1}^{N} \left| \sum_{i=1}^{256} \sum_{j=1}^{256} I(x_i, y_j) e^{-2\pi i (u_n x_i + v_k y_j)} \right|^2 (\mathrm{mm}^2)$$

  where M is the number of 256x256 ROIs within the central 10 cm x 10 cm ROI[10]; Δx and Δy are equal to the pixel size in the x e y directions (extracted from the DICOM header); u e v are the spatial frequencies in the horizontal (n frequencies) and vertical (k frequencies) directions; $I(x, y)$ represents the value of the linearised (converted) pixel and decreased by the corresponding value of the second–order polynomial 2D fit.
- The radial average is calculated from the 2D matrix of the noise power spectrum
- The 1D NNPS spectra are calculated along the axes u and v, using the frequency axes $u = 0$ and $v = 0$ and 7 rows & columns above and 7 rows & columns below each of the axes (the axes are included according to [6, app A7.5]).
- Re–bin of the axial and radial 1D spectra, using 0.25 mm^{-1} as resampling frequency.

The plugin displays the graphs of the horizontal, vertical & radial 1D NNPS and the plot of the 2D planar NNPS; in addition, the 2D NNPS is shown as a 3D surface in a separate window, using the `3D Interactive Surface Plot` available in `ImageJ`. The plugin also shows the values of NNPS along x and y at 0.5 mm^{-1} and 2.0 mm^{-1}; finally, the plugin shows the K value equal to the linearised averaged DAK value (µGy) of the central 10 cm x 10 cm ROI used for the normalization (useful for a subsequent DQE computation).

The axial and radial plots can be saved as `csv` files and used for DQE calculation

[10] in case of multiple input images, M is calculated as the total number of 256x256 ROIs of all images

3.4 DBT

Note: some of the plugins dedicated to DBT (Digital Breast Tomosynthesis) systems are present in three versions:

- one for single images of type 'MG' (mammography) or 'CT' (computed tomography)
- one per multi-frame 'BTO' file (Breast Tomosynthesis Object)
- one for images obtained from 'Secondary Capture' images of Hologic systems unpacked with Hologic proprietary software. This version takes into account the variable pixel size with the height from the breast supporting surface[11].

3.4.1 AEC — Short-term

This plugin allows to evaluate the short-term reproducibility of the automatic exposure control (AEC) system, evaluated on 5 images related to the first projection of 5 repeated acquisitions of the standard phantom — see [18, para. 2.2]. The user should select the images and insert the coefficients A and B and the type of the response function (linear or logarithmic) to convert the pixel values into DAK values. The user can also choose not to linearise the image by clicking the button "No linearisation". The plugin, for each image, creates a reference 5 mm x 5 mm ROI (see Section 3.2.3) and converts the pixels within that ROI using the inverse of the selected answered response function; the value of SNR is then calculated in this ROI (see Section 3.2.5). The output in the RESULTS window consists of (for each image):

- Image name: the name of the file related to the analyzed image
- (linearised) SNR: the value of SNR in the reference ROI
- Tube loading (mAs): the value of the tube current times exposure time product (extracted from the DICOM header) used to obtain the analysed image

3.4.2 AEC — SDNR Tomo

This plugin allows evaluating the compensation, which is performed by the automatic exposure control (AEC) system, according to the thickness and composition of the breast — see [18, para. 2.4]. The plugin requests the user to select the images to be opened and insert the coefficients A and B and the type of the conversion function (linear or logarithmic) to convert the pixel values into DAK values. The user can also choose not to linearise the image by clicking the button "No linearisation". Next, for each image the user should insert the thickness. (in mm) of the used PMMA. Next, the plugin asks, for each image, to draw and / or center an ROI that covers the area with the square of Al (leaving the possibility to the user to vary the window level and width). On each image, the plugin creates a 5 mm x 5 mm ROI placed at the center of the ROI selected by the user and another 2 ROIs placed next to the square of Al to 10 mm from the central ROI and in an orthogonal direction to that of the X-ray tube (Fig. 8). The plugin calculates the average value of the linearised (converted) pixels of background — ($PV(background)$)

[11] The reconstructed planes have pixel dimensions slightly varying, depending on the distance from the breast support[14], so to achieve the same ROI dimensions, the number of pixels along x and y in the images have to varying according to that.

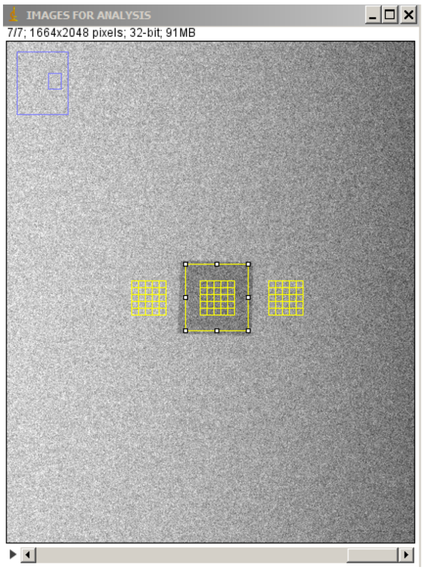


Figure 8: ROI for the calculation of the value of SDNR – DBT first projections.

— and the standard deviation of these pixels — ($SD(background)$) — according to the following equations:

$$SD(background) = \frac{\sum_1^2 SD(ROI_n)}{2}$$
$$PV(background) = \frac{\sum_1^2 PV(ROI_n)}{2}$$

where ROI_n, with n ranging from 1 to 2, represents the 2 ROIs placed around the square of Al. In a similar way the mean pixel value — ($PV(signal)$) — and the standard deviation — ($SD(signal)$) — are calculated using the pixels of the central ROI located in the Al square. The values of the variables of the previous equations are calculated from 1 mm x 1 mm ROIs — see Fig. 8 — and then averaged. The plugin then calculates the value of SDNR:

$$SDNR = \frac{PV(signal) - PV(background)}{SD(background)}$$

The output, in the `RESULTS` window, is (for each image):

- PMMA (mm): the thickness in mm of the PMMA used for the analyzed image
- SDNR: the corresponding SDNR value for the used PMMA thickness.

3.4.3 Homogeneity — UNIF

This plugin allows evaluating the homogeneity of the reconstructed images — see [18, para. 5.6] — working on images like '`MG`' or '`CT`'. The user should select the images of the reconstructed planes to be analyzed and insert the coefficients A and B and the type of the conversion function (linear or logarithmic) to convert the pixel values into DAK values.

The user can also choose not to linearise the image by clicking the button "No linearisation". The plugin then asks the user to create an ROI that covers the area of the images to be analyzed (if the user does not select any ROI and presses "OK" the plugin uses the whole image for analysis). The plugin, for each image, converts all the selected pixels inside the ROI selected by the user and determines the linearized average pixel value ($\overline{PV}_{global}$); The selected ROI is subdivided into several 1 cm x 1 cm ROIs and each of them is used to calculate the average pixel value (PV_{ROI}) and the SNR value (SNR_{ROI}); finally, the plugin calculates the average of all calculated SNR_{ROI} ($\overline{SNR}_{global}$). Then, for each image, all the ROIs are examined and the plugin highlights the ROIs beyond the tolerance according to the following criteria:

- ROI in GREEN: ROI for which PV_{ROI} differs from $\overline{PV}_{global}$ for more than 15%
- ROI in CYAN: ROI for which SNR_{ROI} differs from $\overline{SNR}_{global}$ for more than 15%
- ROI in RED: ROI for which both previous conditions are met.

The plugin reports in the `RESULTS` window, for each slice:

- Slice #: slice number (starting from the breast support plane) relative to the image under examination
- Max var. in PV (%): maximum variation in the linearised PV value for the slice analysed
- Max var. in SNR (%): maximum variation in the SNR value for the slice analysed

The plugin also reports the maximum percentage variation in PV on all the analyzed slices, as well as the relative variation in SNR. Finally, the plugin asks whether to display a series of plots:

- plot of the number of ROIs with variation in PV beyond tolerance vs. slice number (slice location)
- plot of the percentage change value (in PV_{ROI}) vs. slice number (slice location)
- plot of the number of ROIs with variation in SNR beyond tolerance vs. slice number (slice location)
- plot of the percentage change value (in SNR_{ROI}) vs. slice number (slice location).

3.4.4 Homogeneity — UNIF Hologic secondary capture

The plugin prompts to select the folder in which the unpacked files are located, then proceeds as in the previous Section 3.4.3, but by drawing the ROIs taking into account the variable pixel size of Hologic systems[12] (the system uses a reconstruction method which generates a variable pixel size in the reconstructed planes (smaller with increasing plane height)).

3.4.5 Homogeneity — UNIF BTO

The plugin asks to select the file 'BTO' with the images of the reconstructed planes, then it works as in Section 3.4.3

[12] see Footnote 11

3.4.6 Homogeneity — Artefact

This plugin allows evaluating a possible presence of artefacts in the reconstructed images,using a variance map — see [18, para. 5.6] — working on images like 'MG' or 'CT'. The user should select the images of the reconstructed planes to be analyzed and insert the coefficients A and B and the type of the conversion function (linear or logarithmic) to convert the pixel values into DAK values. The user can also choose not to linearise the image by clicking the button "No linearisation". The plugin then asks the user to create an ROI that covers the area of the images to be analyzed (if the user does not select any ROI and presses "OK" the plugin uses the whole image for analysis). The plugin, for each image, converts all the pixels inside the selected ROI and determines the linearised average pixel value (($\overline{PV}_{global}$)); The selected ROI is divided into several 2 mm x 2 mm ROIs and each of them is used to calculated the variance (Var_{ROI}); the ROIs are then checked by comparing the variance of each ROI with that of the neighboring ROIs and the plugin highlights the ROIs with variations in the variance of more than 30%. The plugin reports in the `RESULTS` window, for each slice:

- slices with possible artefacts: number of the slice (starting from the breast support plane) relative to the image in which it is possible that artefacts are present in the highlighted ROI.

3.4.7 Homogeneity — Artefacts Hologic secondary capture

The plugin prompts the user to select the folder where the unpacked files are located, then proceeds as above (Section 3.4.6); however by drawing the ROI to take into account the variable pixel size[13].

3.4.8 Homogeneity — Artefacts BTO

The plugin asks the user to select the file 'BTO' with the images of the reconstructed planes, then it works as in Section 3.4.6.

3.4.9 Uncorrected defective elements (TOMO)

The plugin allows evaluating the presence of uncorrected defective elements — see [18, para. 4.3]. The user should select the folder containing the images of the projections related to the exposures and after this create an ROI on the area of the image to be analyzed (if the user does not select any ROI and presses "OK" the plugin uses the whole image for analysis). For each of the images, the selected ROI is divided into 5 mm x 5 mm smaller ROIs. Within each ROI the linearised average pixel value is evaluated and examined if there are pixels that deviate more than 20% from this value. The plugin compares the analysis result on all images and, if there are pixels beyond this tolerance:

- pixels beyond tolerance but in different coordinates on images: the plugin shows a warning message.
- pixels beyond the tolerance placed at the same coordinates on all the projections of all the exposures: the plugin creates a new image with the uncorrected pixels surrounded by ROIs; moreover, in the `RESULTS` window, for each uncorrected faulty element, the corresponding row and column (i. e., element position) are reported.

[13] see Footnote 11

3.4.10 NPS x–y plane

The plugin calculates the noise power spectrum (NPS) from a uniform (i. e., flat field) image, relative to the slice placed at 20 mm from the breast support surface — see [18, app II.1]. The user should select the image of type 'MG', 'CT' or 'BTO' and insert the coefficients A and B and the type of the conversion function (linear or logarithmic) to convert the pixel values into DAK values. The user can also choose not to linearise the image by clicking the button "No linearisation". In the case of a 'BTO' image, the 20 mm slice is selected. The plugin then creates a 5 cm x 5 cm ROI and converts the pixels of that ROI into DAK values using the inverse of the specified conversion function. The user is then asked to enter the value of α_z (effective aperture[14] size in z domain — see [16]). The calculation algorithm is based on what has been specified in[18, app II.1] and consists of the following steps[15]:

- creation of a second order polynomial 2D fit, based on the source code of Dwight Urban Bartholomew [1], which in turn is based on its `Polynomial Surface Fit` plugin.
- subtracting the fit from the central 5 cm x 5 cm ROI
- division of the central ROI into half–overlapping 256x256 pixel M ROIs
- calculation of the two dimensional (2D) Fourier Transform using the source code of the `FFTJ and DeconvolutionJ` plugin by Nick Linnenbrügger [10]
- calculation of the 2D NPS matrix using the formula:

$$NPS(u,v) = \frac{\alpha_z \Delta x \Delta y}{M \cdot 256 \cdot 256} \sum_{m=1}^{N} \left| \sum_{i=1}^{256} \sum_{j=1}^{256} I(x_i, y_j) e^{-2\pi i (u_n x_i + v_k y_j)} \right|^2 (mm^2)$$

  where M equals to the number of 256x256 pixels ROIs within the central ROI; α_z equals to the value of the aperture along z, Δx and Δy are equal to the pixel size in the x e y directions (extracted from the DICOM header); u e v are the spatial frequencies in the horizontal (n frequencies) and vertical (k frequencies) directions; $I(x, y)$ represents the value of the linearised (converted) pixel and decreased by the corresponding value of the second–order polynomial 2D fit
- The 1D NPS spectra are calculated along the axes u and v, using the frequency axes $u = 0$ and $v = 0$ and 7 rows & columns above and 7 rows & columns below each of the axes (the axes are included – see Section 3.3.7)
- Re–bin of the axial and radial 1D spectra, using 0.25 mm^{-1} as resampling frequency.

The plugin shows as output the graphs of the noise spectrum along the 2 axes; in addition, the 2D spectrum (planar and 3D visualisation) is shown in separate windows. The plugin also reports the values of NPS along x and y at 0.5 mm^{-1} and 2.0 mm^{-1}.

[14] in case of uncorrelated noise along z, the value to be used is equal to the thickness of the slice

[15] the noise spectrum in the case of images related to reconstructed slices, is already proportional to the incident air kerma [11] and, therefore, it is not necessary to be normalized to the mean value of the central ROI.

3.4.11 pMTF x–y plane

The plugin calculates the pMTF curve — pre–sampled MTF vs mm^{-1} (or, equivalently, lp/mm) — from the image of a radiopaque wire — see [18, para. 5.3]. The user should select the image of type 'MG', 'CT' or 'BTO' to be opened[16]. The plugin shows a 15 mm x 15 mm ROI and asks the user to move it over the wire. The plugin shows then another 15 mm x 15 mm ROI, placed next to the first one, and asks the user to verify that it is placed (or repositioned by the user) over the background (not over the wire). If the image is of the 'BTO' type, the user should select the slice (frame) corresponding to the height from the breast support at which the wire is in focus. The calculation algorithm is based on a previous work [13] (which in turn is based on literature —. see [2, 15, 17]) and [14] and consists of the following steps:

- computation of the direction of the wire (horizontal / vertical)
- creation of a second-order polynomial 2D fit and subtraction of the fit from the ROI placed over the wire
- creation of pixel profiles along the whole ROI and in the direction computed previously (horizontal / vertical)
- search for the maximum pixel value of each profile and linear fit of the obtained values to determine the angle of inclination of the wire and the position of the line of interest
- definition of the array of profiles and projection of the profiles along the horizontal (or vertical) line in order to concatenate all the projections.
- arrangement of the array to get the projections in order of increasing x, with x equal to the direction along which to calculate the pMTF curve
- resampling of the profile with a pitch of 1/15 pixel dimensions (extracted from the DICOM header) (Line Spread Function – LSF)
- smoothing the LSF with a simple 3 bin median filter
- elimination of the continuous component of the LSF curve (to de–trend a potential low-frequncy pattern in the background: the plugin computes that component using the last parts of the tails)
- application of a Hann filter with a window width equals to 80% of the total window in order to reduce the noise due to points outside the useful signal of the LSF curve
- normalization of LSF at the maximum point
- calculation of the Discrete Fourier Transform (DFT) and its modulus, to define the points of the pMTF curve
- resampling of the MTF curve with a sampling interval of 0.25 mm^{-1}
- normalization of the pMTF curve to it maximum

[16] The calculation algorithm takes into account the linear system theory metrics and, working in the region of a very thin wire, does not require the linearization (conversion into DAK values) of the pixels.

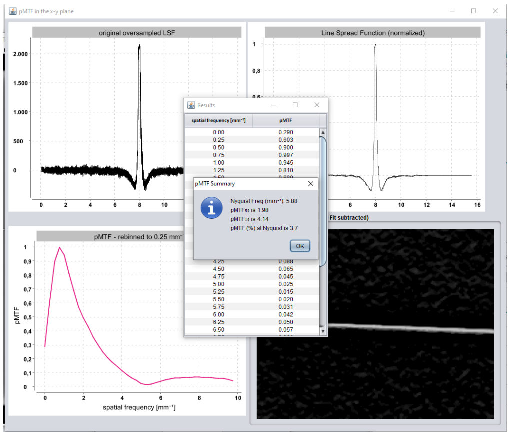


Figure 9: Example of the output for the MTF x–y plane plugin.

The reported output consists of the values of MTF_{50}, MTF_{10} – spatial frequencies at which the pMTF curve reaches 50% and 10%, respectively – and the value of the pMTF curve at the Nyquist frequency[17]. The plugin also shows (see Fig.9) the graphs of the oversampled LSF curve and the MTF curve. Furthermore, the values of lp/mm and the corresponding values of the pMTF curve are shown in the MTF window.

[17] see Section 3.2.7.

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