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Methodology and software tool for focal spot characterization of X-ray micro- and nano- focus tubes

Méthodes et outil logiciel de caractérisation de la tache focale des générateurs RX de type micro et nano foyer

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Abstract

This article presents a brief overview of a methodology, numerical algorithms and their implementation for the evaluation of the focal spot size and shape of X-ray sources with spot sizes inferior to 5 μm . The work has been carried out within the framework of the NanoXSpot project [1]. The main outcomes are proposals for revisions and new parts of EN 12543 standard, a new design and implementation of a gauge and a reference implementation of the algorithms on a stand alone software tool. Within this contribution, we focus on the software tool, through evaluations on simulated and experimental images as part of the validation procedure.

1. Introduction

X-ray Computed Tomography (XCT) systems are used in various industrial applications, for structural characterization, flaw inspection or dimensional conformity, both on samples or final products. In order to ensure a reliable and traceable inspection, the XCT system characterization and/or certification is essential. For applications where a very high spatial resolution is required, the focal spot size of the X-ray source is the main factor of image quality degradation. Therefore, the size and the shape of the focal spot need to be correctly evaluated and in order to obtain comparable results on different systems, the method needs to be standardized. The available standards cover a broad range, but only down to 5 μm . Within the framework of the NanoXSpot [1] consortium, several methods for focal spot size and shape characterization were proposed. In particular, new parts of EN 12543 standard were proposed with new methods covering an even broader range, down to 100 nm. CEA List contributed to the definition of the reference gauge through evaluations with the help of CIVA RT/CT simulation tool [2] and by implementing a stand alone software tool that includes the proposed methods in the new standards.

This work introduces the methodology and the selected algorithms for the new standards, with a focus on the

implemented software tool and on the validation process. A more detailed description of the numerical algorithms can be found in [3-5]. The article is structured as follows. The second section presents the general methodology and the selected algorithms. The third section describes the validation procedure and the sets of test cases which were used. Before concluding, the fourth section presents the results and a discussion on the performances and reliability of the algorithms and their implementation.

2. General methodology and evaluation algorithms

In X-ray imaging setups using a divergent or cone-beam setup, a non-ideal or macroscopic source will generate unsharpness on the radiographs and therefore the precision of the inspection or of dimensional measurements is negatively affected. The impact of this phenomenon is more significant for systems employing a high magnification ratio and aiming very high spatial resolution performance. An illustration of this effect is presented in Figure 1, with the red curve indicating the profile plot of an ideal rectangular signal.

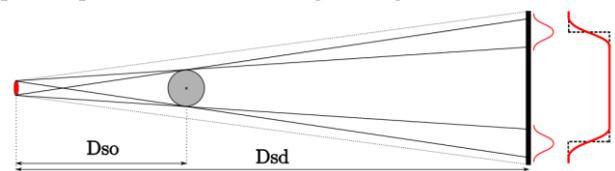


Figure 1: Illustration in 2D of the unsharpness effect of a non-ideal spot

In order to separate and to limit the image degradations through an optimal parametrization, the X-ray source and the detector need to be characterized independently. The focal spot size of an X-ray tube is generally measured by using reference gauges with special patterns that allow an evaluation through mathematical transformations. The simplest method uses an edge, which evolved to dual edge, line pair, line group patterns and also to star-shaped patterns. As alternatives, hole patterns are also employed with adapted algorithms. Traditionally edge and line pairs were used and the methods are well defined through several standards (e.g. EN 12543, ISO 19232, ASTM E

1165, or ASTM E 2002). As an example, Figure 2 presents the elements for a dual profile analysis on a hole type gauge.

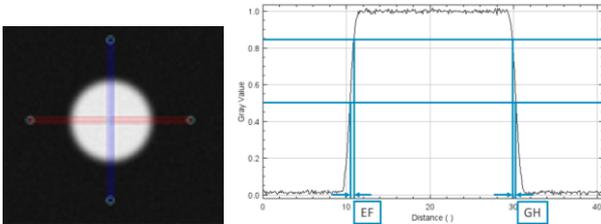


Figure 2: Illustration of a dual profile analysis method on a hole type pattern (radiographic image and profile plot)

Since the standards available in 2018 were limited to spot sizes larger than 5 μm , the NanoXSpot consortium proposed to extend the range down to 0.1 μm , with new and adapted algorithms and patterns. The initial evaluation of the consortium concluded that no existing gauges were well suited for this objective. A new design was therefore proposed as “NxS gauge”, which was manufactured in a small series for internal evaluation. The first version of the design includes four quadrants with line group, star shape and hole type patterns, as depicted in Figure 3.

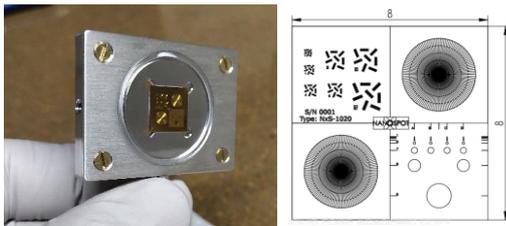


Figure 3: NxS gauge v1, photograph and drawing

The physical gauge is made of a layer of gold with a thickness of 8 μm deposited on a silicone substrate. The patterns start from 3 μm width for the line groups and 5 μm diameter for the holes.

Two main approaches were selected for the evaluation algorithms, a simple version referred as user method and a complex version referred as manufacturer method, for both line group and hole type patterns. The basics and the mathematical equations for the selected algorithms were described in previous publications [2-5].

3. Impact of manufacturing errors of gauges on the focal spot evaluation

Since one of the objectives were to extend the range of measurements down to nanometre scale, the gauges needed to include patterns with very small features, at the limits of the manufacturing machines in terms of precision. Even with advanced evaluation algorithms, geometrical imperfections on real gauges might have an important impact on the measurements which was unknown beforehand. For this purpose, a parametric study was carried out, using simulation tools. CEA and BAM

participated to this work by generating several sets of test images.

3.1. Modelling geometrical deviations on gauges

From a large number of potential dimensional deviations in a physical gauge, we selected a reduced but representative number of cases for the study. A combination of a higher number of parameters would have resulted in a number too large to be evaluated without a complete automatization of the process, which was outside the scope of the work. The selection was based on two primary criteria, the potential impact and the probability of appearance of the deviation. The selected choices have estimated high impact and also a high probability of appearance.

Several deviations from the ideal geometry were generated as separate CAD models and used by the simulation tools. The approach was to generate one CAD model with deviations close to the manufacturing limits, one with intermediate errors, and one with extreme errors (not likely to occur).

Figure 4 illustrates the first three geometries for the line group case. The relative deviations ranged from ~1% for the expected level, ~3% for a moderate level and more than 10% for the extreme cases.

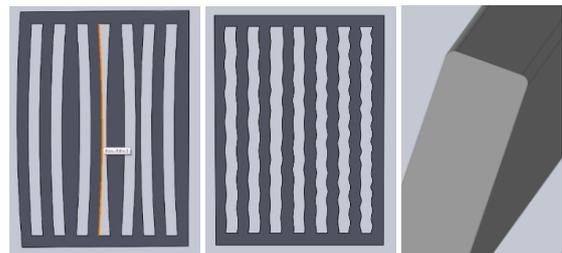


Figure 4: Geometrical deviations for line group patterns: line bending, line waviness and corner roundness

Figure 5 illustrates the first three effects for the hole type case. The relative deviations ranged from ~0.5% for the expected level, ~1% for a moderate level and more than 5% for the extreme cases.

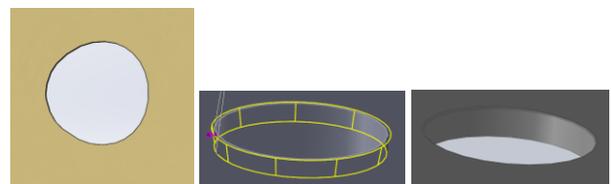


Figure 5: Geometrical deviations for hole type patterns: Circle roundness (example with 3 undulations per revolution, side wall angle and corner roundness

3.2. Results

The models with geometrical deviations were used on simulation configurations of two representative CT systems. The evaluations were done for four spot sizes 5.0

μm , $1.0 \mu\text{m}$, $0.5 \mu\text{m}$ and $0.1 \mu\text{m}$. Since the last configuration does not respect the recommendations in terms of sampling and magnification, the evaluation showed significant offsets. Figures 6 and 7 present the results for the three source sizes and for two different CT systems. The graphs display the relative error on the value computed with the evaluation algorithm with respect to the reference value, which corresponds to a perfect geometry.

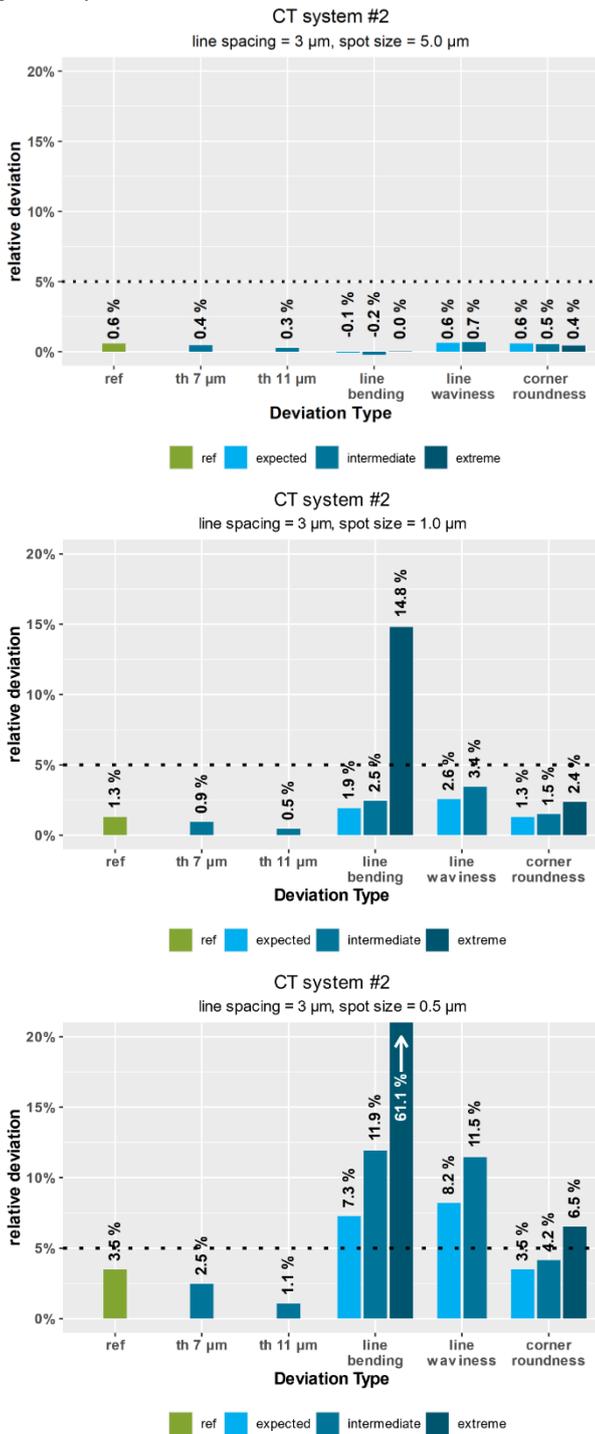


Figure 6: Evaluation results for line group patterns and three source sizes, CT system #2

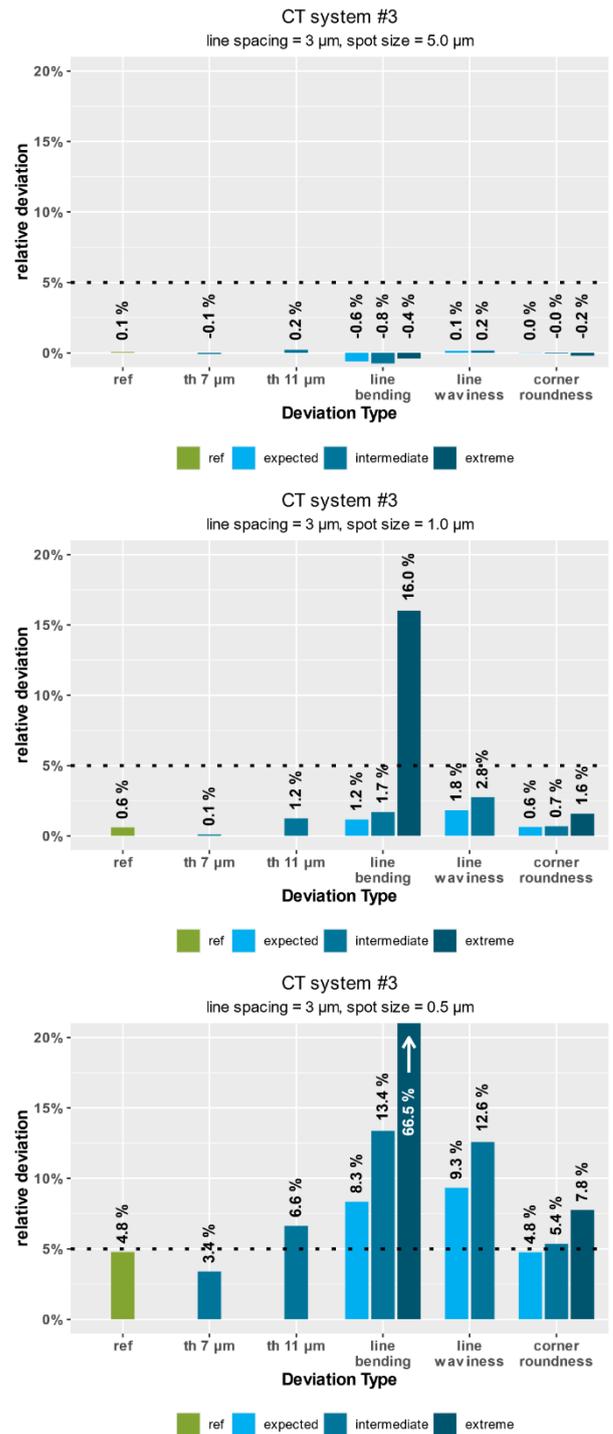


Figure 7: Evaluation results for line group patterns and three source sizes, CT system #3

A first conclusion was that for the cases of interest with deviations within expected limits, all the relative errors are inferior to 5%, except for the $0.5 \mu\text{m}$ source. The detector sampling and the magnification ratios were chosen to match experimental configurations and for spot sizes inferior to $0.6 \mu\text{m}$ these combinations were outside the recommended ranges for the evaluation algorithm.

Similarly to the line group patterns, figures 8 and 9 present the results for hole type patterns.

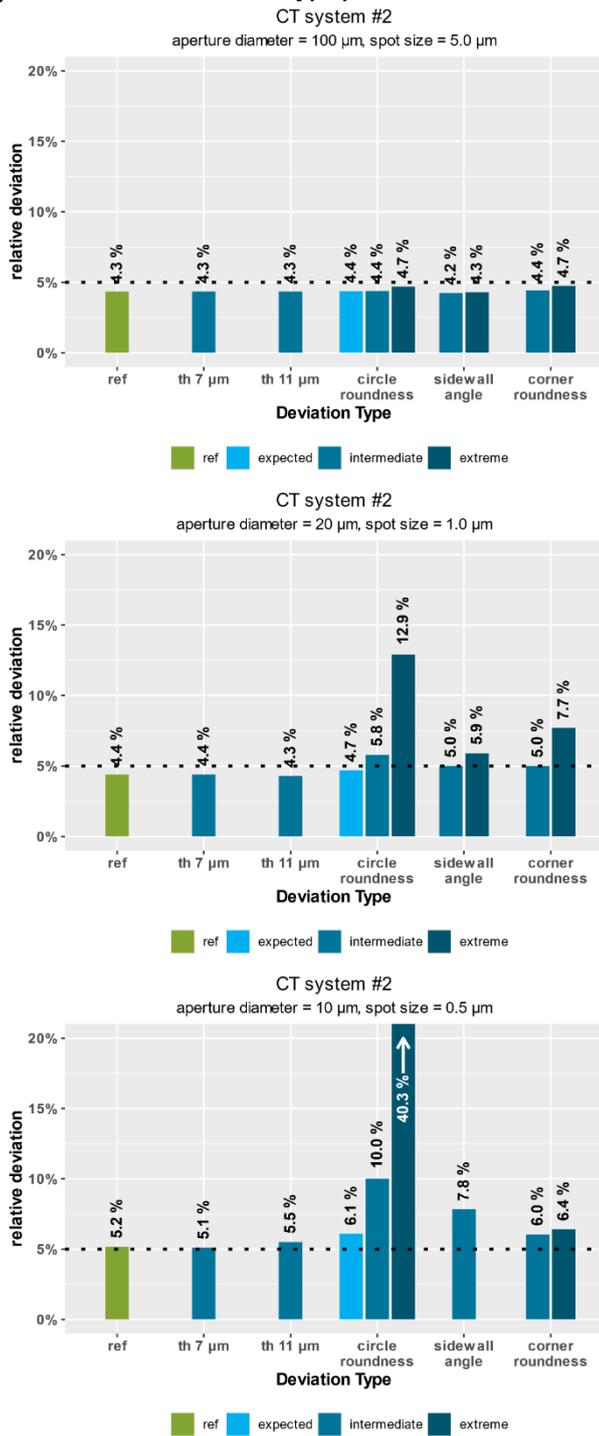


Figure 8: Evaluation results for hole type patterns and three source sizes, CT system #2

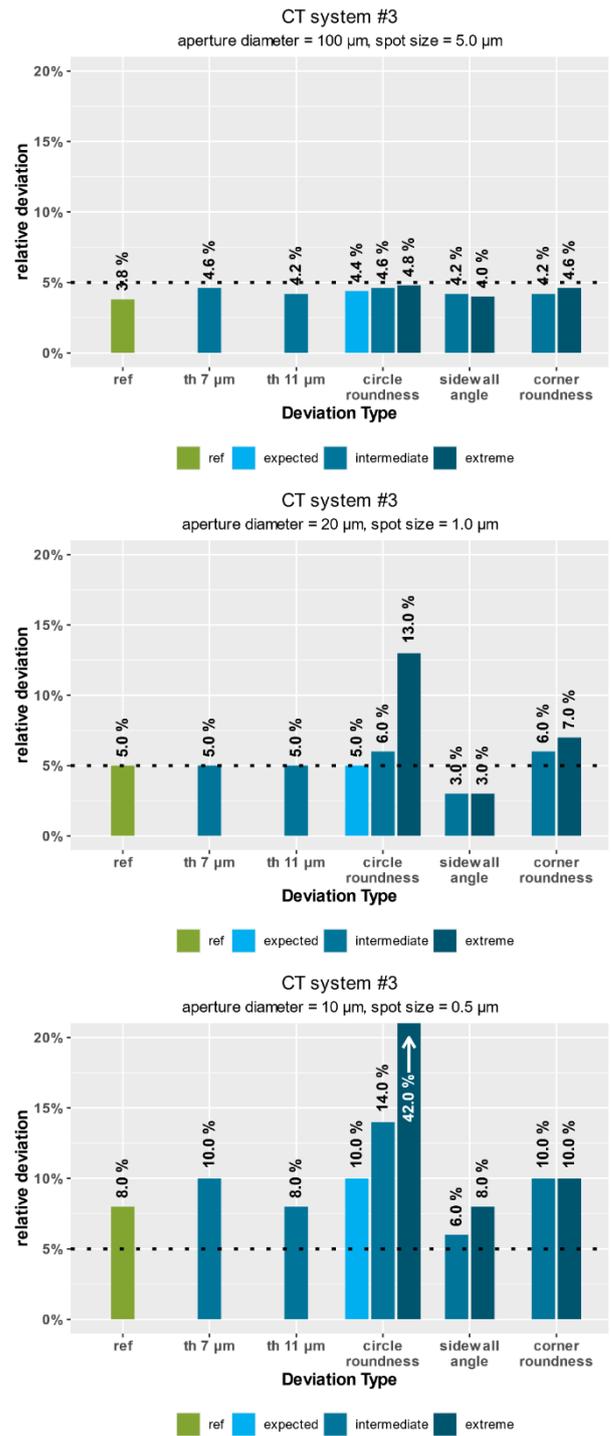


Figure 9: Evaluation results for hole type patterns and three source sizes, CT system #3

The results for this type of pattern are also sensible to the recommended ranges of sampling. In most of the cases except the smallest source size, the relative deviations are inferior to 5%.

4. Software tool, evaluation and validation

Based on the selected patterns and associated evaluation algorithms as agreed within NanoXSpot consortium, a reference implementation of the methods was prepared by CEA List, as a standalone software, available for public use.

4.1. NxS Tool

The implemented software was simply named “NxS Tool” and it is available both on a dedicated webpage [6] and on an open access repository [7].

This tool takes as inputs one, two or a set of images acquired with a physical gauge including line group or hole patterns. For each pattern type, simple and complex methods are available. These algorithms are direct implementations of the methods proposed in the revisions and new proposed parts of the EN 12543 standard. Figure 10 presents the menu and the graphical user interface.

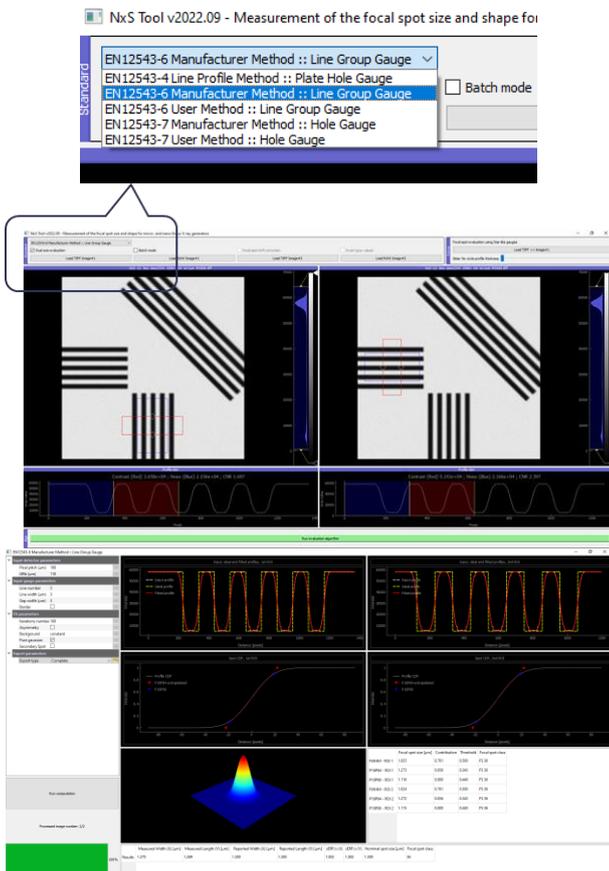


Figure 10: NxS Tool : selection menu, main interface and secondary window

For reasons concerning the ergonomics, a two-window workflow was chosen. In the main window one or two regions of interest are set which serve for extracting the necessary data for evaluation. The second window includes parameters linked to the acquisition, the gauge, of the evaluation algorithm and for the outputs.

The outputs are presented as proposed by the standard, with the nominal spot size and a focal spot class. A more

comprehensive description is provided in the user manual, available for download on the same sources as the software tool.

4.2. Evaluation and validation

The full validation process included three phases, the first two on simulated data and the third on experimental data. In a first phase, the robustness of the selected algorithms was tested on sets of images with varying noise levels, and with different sampling and magnification ratios. In the second phase additional images were included, with deviations of the position of the gauge (offset, orientation and tilt). The third phase was an intercomparison of experimental results on 8 selected CT systems. Since the focal spot sizes of experimental systems are only known from manufacturer specifications or other approaches, this phase served mainly as relative benchmarking and for testing on a variety of images produced by different devices. A fully known quantitative validation could only be done on simulated images. Within this work we focus on the evaluation on synthetic data.

The evaluations were done for several image datasets, with focal spots in the range 0.1 μm to 30 μm, for both types of patterns.

Figure 11 presents the results for the tested range of focal spot sizes, split in two parts, one up to 1 μm and the second up to 30 μm. The green bars represent the nominal value as a reference, and the error bar was set for a relative deviation of 5%.

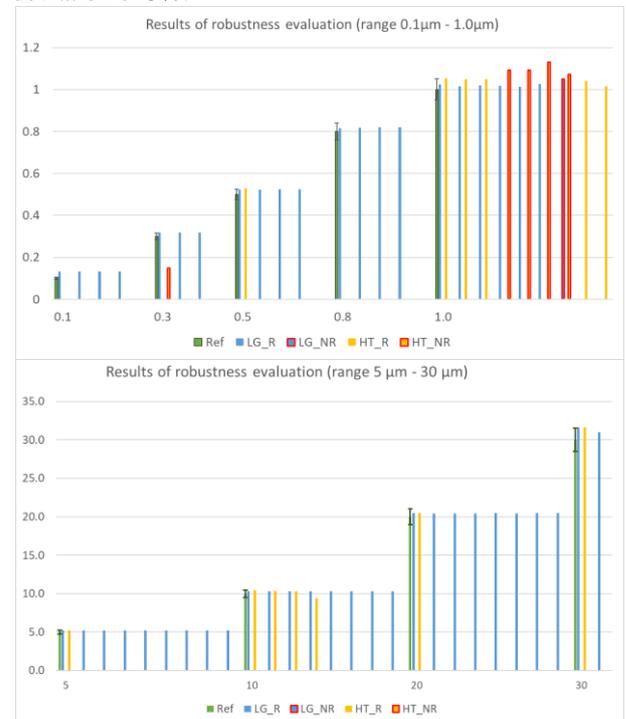


Figure 11: Results of the robustness study

The tests with line group patterns are indicated with the symbol LG and the hole type with HT. The cases outlined

with red (_NR) did not respect the sampling recommendations for the evaluation and were expected to produce larger deviations.

The results show a homogeneous behaviour of the evaluation algorithms. All the cases with parameters within the recommended range have values with relative errors within the limit of 5%. The cases with parameters set outside the recommended range have higher errors, up to more than 10% as relative difference.

In the second phase, more than 150 test cases were evaluated. The results are presented in Figure 12 with the same notations as previously.

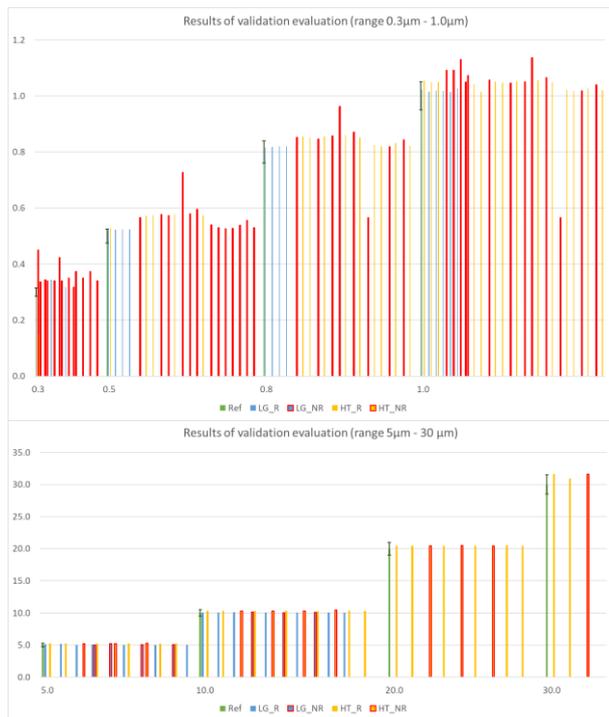


Figure 12: Results of the validation study on simulated data

The overall evaluation confirms a homogeneous behaviour of the algorithms over the tested focal spot ranges and for a variety of test cases. The majority of images generated with the recommended parameters have a relative deviation inferior to 5%. For the spot sizes 0.3 µm and 0.5 µm, some of the deviations are slightly higher than 5%. The chosen combination of gauge pattern and sampling parameters are close to the limits of the algorithms therefore higher deviations were to be expected. For the range 5 µm to 30 µm, the majority of values show less than 5% of relative error, including most of the ones with parameters outside the recommendations. The most representative and useful test cases were collected as reference data sets, which were made available for download on the same repositories as the software [6,7].

5. Conclusions

This paper presented contributions to a methodology and on the implementation of evaluation algorithms for measuring the focal spot size and shape of X-ray tubes. A new software tool was implemented and is distributed publicly as a reference implementation of the methods proposed in the new proposed parts of the standard EN 12543. The software tool was tested and evaluated on a large number of cases, generated with the help of simulation tools. This approach enabled a quantitative evaluation of the algorithms in order to meet the objective of a relative deviation inferior to 5%, which was confirmed during the validation process. The impact of geometrical deviation on physical gauges was also evaluated with the help of simulation tools, by deforming CAD models of the gauges. This study showed a good robustness of the evaluation methods and confirmed the choices of the algorithms and gauges with particular patterns.

Acknowledgements

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