Experimental Investigation of the Influencing Factors on the Structural Resolution for Dimensional Measurements with CT Systems

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Abstract
This paper presents an experimental investigation on the factors influencing the metrological structural resolution (MSR) of CT systems. The investigation consists of structured experiments involving several CT data acquisition and processing parameters. The method used to assess the metrological structural resolution is based on the amplitude transfer function (ATF). Because of the intrinsic relation between structural resolution and noise, the extracted surface RMS deviation was also evaluated. The results show how dependent the MSR is on the influencing factors and provides useful functional relations between data acquisition and processing parameters, the MSR and the surface deviations. They also help demonstrating the applicability of the ATF-based method to characterize the metrological structural resolution of CT systems.

Keywords: Computed tomography, dimensional metrology, metrological structural resolution, extracted surface, RMS deviation

1 Introduction
The proper selection and configuration of a computed tomography (CT) system requires practical knowledge of the factors influencing the metrological performance for each specific case of use. When the application involves the measurement of small geometries, the metrological structural resolution (MSR) [1] plays a major role in the accuracy of measurements. Unfortunately, the available knowledge on the factors that affect the MSR of CT systems is still scarce, mostly qualitative and fragmented. The main cause of this situation can be traced to the lack of an internationally accepted method for assessing the MSR of CT systems [2,3]. In the last years, several new procedures and reference objects have been proposed to improve this scenario [3-8] but, until now, there is still no consensus on a method for an international standard. Some of those works reported studies of the influence of specific factors [3-5,7,8], but the results are difficult to compare because, in most cases, they are method-dependent. Another important aspect that has been overlooked is the fundamental trade-off between structural resolution and noise in transmitting signals with CT systems [9]. Although the national guideline [1] establishes that the results of MSR tests should be reported together with those of probing tests (the probing error of form $F_p$ is particularly relevant in this case), this issue is seldom considered in research works on the MSR of CT systems.

This paper presents an investigation on the key factors influencing the MSR of CT systems. The main goal is to improve the quantitative knowledge on the cause-effect relations between data acquisition and processing parameters and the MSR. The method used to assess the MSR is the spatial frequency response analysis on sinusoidal surfaces, already introduced in [8] and described here with a few improvements. The study includes the analysis of extracted surface deviations to characterize the trade-off between structural resolution and noise.

2 Investigated Factors
The influencing factors investigated in this work have been classified in three main groups, (i) spatial sampling-related parameters, (ii) X-ray effects and techniques for their reduction, and (iii) data filtering. The following subsections define the factors in each group and provide information for their understanding.

2.1 Spatial sampling-related parameters
Voxel size
The voxel size ($V_x$) is one of the most employed parameter for comparison of CT data sets. As mentioned in [1], it is often used (even if incorrectly) as a measure of structural resolution. Reasons for such use include the availability and simple interpretation: in general terms, the smaller the voxel size, the better the structural resolution.

The voxel size of a cone beam CT system is given by (1):

$$V_x = \frac{Sp}{M} = \frac{(Bn \cdot Pp)}{(Dsd \cdot Dso)}$$

where $Pp$ is the detector pixel pitch, $Bn$ is the detector binning, $Sp$ is the effective pixel size, $Dsd$ is the source-to-detector distance, $Dso$ is the source-to-object distance and $M$ is the magnification. As (1) shows, a given voxel size value may result from several combinations of parameters. Most research works on MSR of CT system explored the influence of the voxel size (e.g. [3-5,7,8]), but the influence of the voxel size under different combinations of parameters has yet to be investigated.
**Focal spot blurring**

The blurring caused by the focal spot is another major contributor to the structural resolution of CT systems. The geometrical unsharpness \((U_g)\) is a widely used model to estimate the amount of blurring caused by the focal spot. The \(U_g\) depends on the focal spot size \((B_r)\) and on the magnification. The influence of \(U_g\) on the structural resolution depends not only on its own value, but also on its relation with the effective pixel size. This can be rearranged in the form of a dimensionless parameter here termed **relative geometrical unsharpness** \((U_{g,r})\) according to (2).

\[
U_{g,r} = \frac{U_g}{Sp} = \frac{B_r}{(M - 1)/Sp}
\]

The influence of the focal spot size associated with the magnification and the pixel size was explored using the X-ray projections of a dimensional CT system \([10]\). The influence of the focal spot blurring as function of the magnification and the focal spot size has yet to be investigated for the MSR of CT systems. A study using the \(U_{g,r}\) model will be presented in this work.

**Number of projections**

The number of projections \((P)\) is also associated with the structural resolution of CT systems. For instance, an improvement on the modulation transfer function (MTF) of a cone beam CT system was observed by increasing the number of projections \([11]\). However, the influence of the number of projections on the MSR of CT systems has yet to be investigated.

**2.2 X-ray effects and techniques for their reduction**

The effects caused by X-ray/matter interactions and by the effectiveness of the techniques for their mitigation on the structural resolution of CT system is another significant research topic. The influence of the beam hardening (and correction algorithms) on the structural resolution of CT systems were investigated in \([12,13]\). Results obtained with the MTF calculated from the edge response function (ERF) pointed out that a better structural resolution is achieved in the presence of beam hardening \([12,13]\), while the opposite was observed with the MTF estimated from line pair gauges \([13]\). Moreover, an increase on the noise of the volumetric image was reported in \([12]\) with the use of beam hardening correction. It is expected that X-ray related effects also have influence on the MSR of CT systems. A study involving techniques to reduce radiation-related effects will be presented.

**2.3 Data filtering**

The purpose of data filtering is usually the removal of unwanted information (noise) added to the signal of interest. The trade-off involved in using data filtering is the loss of information originally contained in the signal, which, in the case of CT systems, leads to a loss in structural resolution. Data filtering on CT measuring systems for noise removal can be applied in many stages of the CT dimensional measuring chain e.g. (i) on the projections, (ii) during the reconstruction (as modifications of the high-pass ramp filter in Fourier-based algorithms), (iii) on the extracted surface (3D surface filters) and (iv) on the extracted integral features (profile or area filters). A study of the influence of data filtering on dimensional measurements with CT was reported in \([14]\). In spite the focus of the analysis was on the calibrated dimensional characteristics of the calotte cube, the results showed relevant changes in the radius of the semi-spherical elements, which were associated with the loss in structural resolution. This work will present a study involving different filtering routines implemented before the surface determination, with focus on the relative trade-off between MSR and surface deviations among different filter types.

**3 Materials and Methods**

**3.1 Equipment**

**Multi-wave standard for CT systems (CT-MWS)**

The multi-wave standard (MWS) used for the investigations was specifically designed for CT systems \([5]\). It is made of aluminium and has two reference surfaces (plane and cylinder) for the mathematical alignment. The CT-MWS and the amplitude spectrum from the calibration are shown in Figure 1. The uncertainty of the amplitude values used on this work \((U(Ap) = 0.1 \mu m)\) is only a first estimate. Indeed, the uncertainty of amplitude spectra of MWS is still an open issue \([15]\).

![Figure 1: The CT-MWS used for the experiments (left) and the amplitude spectrum from the calibration (right). The multi-wave content (signal) is represented in blue, the surface error content (noise) is represented in grey.](image-url)
CT measuring system

The CT system used for the experiments is installed in the laboratories of the CERTI Foundation. The room temperature is (20 ± 1)°C. The hardware characteristics of the CT measuring system used for the investigation are presented in Table 1.

| Data processing software | All the CT data processing operations performed to obtain the volumetric image (e.g. projections filtering, reconstruction, X-ray artefact correction) were performed with the CT system operating software [16]. The surface determination (segmentation), extraction of the circumferential lines and volumetric image filtering operations were performed with a CT data processing software [17]. The analysis of the extracted circumferential lines was performed with a dedicated application [18]. |

3.2 Assessment of the MSR

The method is based on the amplitude transfer function (ATF), which can be obtained by means of a frequency response analysis using calibrated sinusoidal surfaces as the input signal [8]. From the viewpoint of the analysis, the ATF obtained using this method is similar to MTF method based on line pair gauges (e.g. transmission of discrete spatial frequencies). However, because the input signal consists of a surface, the method covers the segmentation operation, allowing evaluating the complete CT dimensional measuring chain. In this sense, it is analogous to the instrument transfer function (ITF) as defined for surface topography measuring systems in [19]. It is worth mentioning the ATF method is based on the transmission of the surface content, not directly on the measurements of small geometries. A systematic description of the method follows. Specifics and comments are provided to support the analysis of the results and/or to describe improvements implemented since [8].

1. Scanning a calibrated MWS with the CT system and extracting a set of circumferential lines from the multi-wave surface

An example of a measurement of the CT-MWS using a CT measuring system (voxel size of 78.7 µm) is shown in Figure 2.

2. Obtaining the amplitude spectra of the extracted circumferential lines by means of a discrete Fourier transform (DFT)

The amplitude spectrum (Ap(ω)) of a circumferential line represented in polar coordinates (r(θ)) is obtained according to (3):

\[
Ap(\omega) = |DFT\{r(\theta)\}| \times \frac{1}{N/2}
\]

where ω are the spatial frequencies (in UPR) and N is the number of points of the extracted circumferential line.

3. Calculating the relative transmission values of the multi-wave content by performing a frequency response analysis

The relative transmission values Tr(sf) are calculated according to (4):

\[
Tr(sf) = \frac{\overline{Ap}_{CT}(sf)}{Ap_{cal}(sf)}
\]

where \(\overline{Ap}_{CT}(sf)\) are the averaged CT transmitted amplitude values (in mm), \(Ap_{cal}(sf)\) are the calibrated amplitude values (in mm) and sf are the spatial frequencies (in mm⁻¹). The use of averaged CT amplitude values is an improvement over [8], and significantly improved the signal to noise ratio of the CT amplitude spectrum.

4. Estimating the uncertainty of the relative transmission values

The standard uncertainties of the relative transmission values u(Tr(sf)) are calculated according to (5):

\[
u^2(Tr(sf)) = \left[\frac{1}{Ap_{cal}(sf)}u(\overline{Ap}_{CT}(sf))\right]^2 + \left[\frac{\overline{Ap}_{CT}(sf)}{Ap_{cal}(sf)}\right]^2 u(Ap_{cal}(sf))^2
\]
where \(u(\Delta p_{CT}(sf))\) are the standard uncertainties of the CT transmitted amplitude values (in mm) and the \(u(\Delta p_{cal}(sf))\) are the standard uncertainties of the calibrated amplitude values (in mm). Two sources of uncertainty associated with the CT transmitted amplitude values are being considered: the variation observed among extracted circumferential lines from the same measurement and the variation observed between the mean of repeated measurements. This model was not implemented in [8].

5. Determining the amplitude transfer function (ATF) by fitting an amplitude transmission model to the relative transmission values using a weighted nonlinear regression

Because the information provided by the multi-wave content is sparse on the spatial frequency domain, it becomes necessary to determine an amplitude transmission model to characterize the ATF. The frequency domain generalized Gaussian model was previously used to characterize the MTF of electro-optical devices [20]. The main advantage in using this model is that it allows determining an amplitude transmission model to characterize the ATF. The frequency domain generalized Gaussian model was

\[
\overline{Tr}(sf) = \exp[-k (sf/sfc)^n]
\]

where \(\overline{Tr}(sf)\) are the transmission model values, \(n\) is the order of the transmission model, \(sfc\) is the cut-off spatial frequency of the model (in mm-1) and \(k\) is the constant that determines the \(\overline{Tr}(sfc)\) value.

The order \((n)\) defines the shape (steepness) of the amplitude transmission model. For high values it approaches the transmission characteristic of an ideal (sharp cut) low-pass filter. Particular cases include \(n = 1\), for which the function becomes a pure exponential decay; and \(n = 2\), for which the function becomes a pure Gaussian model. Note that the term ‘order’ adopted here does not have the same meaning of the term ‘order’ of transfer functions obtained using e.g. the z-transform.

The objective function for the regression is minimizing the sum of the squared residuals divided by the expanded uncertainties of the relative transmission values, \(U(\overline{Tr}(sf))\). This is also an improvement over [8], which reduces the influence of relative transmission values with higher uncertainties

6. Calculating the metrological structural resolution value

The metrological structural resolution is defined as the cut-off spatial wavelength (\(\lambda_c\) in mm), according to (7), for an amplitude transmission model value of 50%. This is the same definition adopted in [19]. The constant for this criterion is \(k = -\ln (0.5)\).

\[
MSR \equiv \lambda_c = 1/sfc
\]  

(7)

3.3 Quantification of the extracted surface noise

The parameter used to quantify the noise added to the surface model is the extracted surface RMS deviation parameter (Eq), which is calculated by taking the root-mean-square value of the task-specific error profile [21]. For MWS (well-defined spatial frequencies and mirror-like surface finishing, see Figure 1), the error profile \(r_E(\theta)\) can be obtained by suppressing the multi-wave content from the CT extracted circumferential lines \(r_{CT}(\theta)\) on the spatial frequency domain according to (8):

\[
r_E(\theta) = \text{DFT}^{-1} \{ H \ast \text{DFT} \{ r_{CT}(\theta) \} \}
\]  

(8)

where \(H\) is an array containing 0’s for elements corresponding to the spatial frequencies of the multi-wave content and 1’s for elements corresponding to all other spatial frequencies.

3.4 Experimental plan

To investigate the influence of the factors defined and discussed in §2, a set of experiments was designed. Each experiment was referenced on a base setup, around which the levels of the respective factors were varied. This was done to allow evaluating the relative influence of factors not only within experiments, but also among experiments. The data acquisition parameters of the base setup are presented in Table 2. The data processing parameters of the base setup are presented in Table 3. Parameters active by default (e.g. Shepp-Logan window and lateral displacement of the rotary table for reducing ring artefacts) were included on the base setup. The values of focal spot size are theoretical, not experimental.

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Table 2: Data acquisition parameters of the base setup. Values in bold are derived (not directly set) parameters.

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<th>Rec. filter</th>
<th>Scattering correction</th>
<th>BH correction</th>
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<td>Shepp-Logan</td>
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Table 3: Data processing parameters of the base setup.

**Experiment #1: Influence of the voxel size and focal spot blurring**

Two experiments were designed to study the influence of (i) the voxel size and (ii) the focal spot blurring. The setup parameters for the experiments are shown in Table 4. For all setups, the focal spot size was increased to 96 µm (by changing the current to
For setups using half the binning in relation to the base setup (Setups #1.1 to #1.10), the width of the region of interest and the number of projections were doubled.

### 3.6 Presentation of results

For all experiments, the results are presented in three mutually complementary plots. The scale of the plots was maintained identical for all experiments to allow a better comparison on the relative influence of the evaluated factors. The amplitude transfer function (ATF) plot shows the relative transmission values and the associated amplitude transmission model for each setup. The error bars on the ATF plot represent the expanded uncertainties of the relative transmission values \( U(T(r)) \), obtained after (5). The other two are the cut-off wavelength (\( \lambda_c \)) plot and the extracted surface deviations (\( E_q \)) plot. For the \( \lambda_c \) and \( E_q \) plots, the error bars represent the 95% confidence interval associated to the average value of three replicates. The combined analysis of the \( \lambda_c \) and \( E_q \) plots allows evaluating the trade-off between structural resolution and noise. For both plots, smaller values mean better metrological performance. In addition, for one of the experiments, a plot of the ATF order \( (n) \) values is also used.
4 Results and Discussion

4.1 Influence of spatial sampling-related parameters

Influence of the voxel size

The results of Experiment #1.1 to evaluate the influence of the voxel size as a combination of the magnification and the effective pixel size are shown in Figure 3. An analysis of the ATF plot shows, for equal voxel sizes, measurements performed with bigger pixel sizes and higher magnifications \((Bn \ 2)\) presenting a better amplitude transmission than those performed with smaller pixel sizes and lower magnifications \((Bn \ 1)\). This can be more clearly analysed on the \(\lambda c\) plot, which reveals a consistent difference in MSR among measurements performed with different magnifications/ pixel sizes. The same shift can be observed for the surface deviations in the \(Eq\) plot. This analysis demonstrate that the voxel size is not an independent influence factor for neither the metrological structural resolution nor the extracted surface deviations.

The regression analysis on the \(\lambda c\) and \(Eq\) plots reveals an interesting linear relation between the magnification, the pixel size, the MSR and surface deviations. The relation between MSR and surface deviations is directly proportional, which means a synergistic improvement is obtained (no trade-offs) by increasing the magnification and reducing the pixel size. However, the relation between the derivatives are inversely proportional: the MSR increases quicker with increasing magnification for smaller pixels sizes \((Bn \ 1)\), while the surface deviations increase quicker for the bigger pixel sizes \((Bn \ 2)\).

![Figure 3. Experiment #1.1: the influence of the voxel size as a combination of the magnification and the effective pixel size. Setups with bigger pixel sizes and higher magnifications \((Bn \ 2)\) are represented by empty dots, dashed lines. Setups with smaller pixel sizes and lower magnifications \((Bn \ 1)\) are represented by filled dots, solid lines.](image)

Possible causes for this behaviour are: smaller object-detector distances for \(Bn \ 1\) setups, resulting in higher concentration of scattered radiation in the vicinity of the workpiece; non-proportional change in the MTF of the detector when changing the binning (e.g. the ratio between the scintillator blurring and the detector sampling blurring is higher for \(Bn \ 1\) setups); a combination of those, among others. The focal spot blurring and the number of projections (in spite the same criterion \(P = \pi W_{Bn/2}\) was used for all setups), if having a significant influence, are most likely favouring \(Bn \ 1\) setups than \(Bn \ 2\) setups.

Further observations regard the deviation of the relative transmission values from the amplitude transmission model for the lower spatial frequencies on the ATF plots. For the spatial frequency of 0.2 mm\(^{-1}\), the deviation is positive, and it seems to keep relatively constant values regardless of the voxel size. For the spatial frequency of 0.4 mm\(^{-1}\), the deviation is negative, and it increases in modulus for smaller magnifications. These deviations are not affecting the ATF parameters significantly because of the lower uncertainties for higher spatial frequencies and the characteristics of the transmission model (e.g. the transmission values approaches unity as the spatial frequency approaches zero). However, this behaviour must be further investigated.

Influence of the focal spot blurring

The results of Experiment #1.2 to investigate the influence of the focal spot blurring using the relative geometrical unsharpness model are shown in Figure 4. An analysis of the ATF plots shows that the amplitude transmission improves by increasing the magnification, but also that the improvement slows after the \(U_{g,r}\) assumes values above unity. By analysing the \(\lambda c\) plot, this observation becomes clearer, and an asymptotic behaviour for the MSR can be noted. For \(U_{g,r} < 1\), the absolute value of the derivative is high, meaning that increasing the magnification produces considerable improvements in the MSR. For \(U_{g,r} > 1\), only modest gains in MSR can be obtained by increasing the magnification. For \(U_{g,r} > 2\), the influence of the focal spot blurring starts overcoming the influence of the detector pixel sampling, and little improvements in MSR can be obtained by increasing the magnification. Similar asymptotic behaviours were observed in [10] with MTF tests performed on the projections.
On the other hand, an analysis of the $E_Q$ plot reveals a minimum around the unity value of $U_{g,r}$, and an increase of the surface deviations for $U_{g,r} > 1$. This implies a trade-off between MSR and surface deviations for $U_{g,r}$ values above unity, which can be quantified by comparing the derivatives of the $\lambda_c$ and $E_Q$ plots.

With this experiment (fixed focal spot size, varying magnification), it is not possible to infer whether the focal spot blurring have a significant influence for values of $U_{g,r}$ below unity or not. The opposite experiment (fixed magnification, varying focal spot size) should allow that. However, the performed experiment shows that using $U_{g,r}$ values above unity considerably degrades the surface quality and provides only modest improvements in structural resolution. It is also worth mentioning that $U_{g,r}$ is not an independent variable, and the influence of other related factors can be explored (e.g. different focal spot size as in [10], different pixel sizes, different radiation pre-filter, etc.) to better understand the influence of the focal spot blurring.

**Influence of the number of projections**

The results of Experiment #2 to investigate the influence of the number of projections are presented in Figure 5. The ATF and $\lambda_c$ plots do not show any noticeable difference in the MSR obtained with different number of projections. The $E_Q$ plot, however, shows a decrease on the surface deviations with the increase of the number of projections. The trade-off, in this case, involves surface quality and measuring time. Further investigations can be made (e.g. placing the MWS more eccentrically in relation to the centre of rotation) to better understand the influence of the number of projections on the metrological structural resolution.

**4.2 Influence of X-ray effects and techniques for their reduction**

The results of Experiment #3 to investigate the influence of X-ray artefacts and combined techniques used for their reduction are shown in Figure 6. An analysis of the ATF plot shows a significant improvement on the amplitude transmission with the use of both pre-filter and correction routines. The analysis of the $\lambda_c$ plot confirms the improvements on the MSR obtained by using such techniques. This is in conflict with the results found in [12,13] for the MTF based on the ERF method, demonstrating the importance of including the surface determination on the assessment of the structural resolution for dimensional measurements.
With this respect, one remarkable observation is the drop of ATF steepness for setups more prone to the occurrence of X-ray artefacts. This behaviour can be better understood by observing the \( n \) plot (Figure 7), which shows ATF order values decreasing for the setups with lower pre-filter thicknesses and no correction routines. More striking is the increase in ATF order values by the same amount for all the pre-filter thicknesses when using correction, which further associates the ATF order values to the presence of radiation-related effects. In fact, if one would consider the amplitude transmission value of 15% as the cut-off criterion, the only varying parameter among (nearly all) setups would become the ATF order.

![Figure 6. Experiment #3: the influence of X-ray artefacts and combined techniques used for their mitigation. Setups without artefact correction are represented by filled dots, solid lines; setups with combined scattering and beam hardening correction (SBHC) are represented by empty dots, dashed lines.](image)

On the study performed using the X-ray projections [10] where e.g. no beam hardening artefacts were present, the Gaussian model fitted seamlessly the MTF data. The transmission models observed on the present work varied from below a pure exponential model (ATF order values of 0.7 for the setup without pre-filter or correction), to a nearly pure Gaussian model with the use of combined techniques (ATF order values of 1.9 for the setup with 1.0 mm of Cu pre-filter and SBHC).

![Figure 7. ATF order plot from Experiment #3.](image)

The analysis of the \( E_q \) plot showed an increase on the surface noise with the increase on the pre-filter thickness and with the use of correction routines. This implies a trade-off between MSR and surface deviations in using both the evaluated techniques. It is also interesting to observe a correlation on the surface deviation values and the ATF order values, for both the used of pre-filters and correction routines. Possible causes for the increase of noise in the case of pre-filters are the lower levels of X-ray energy (less signal) available after filtering and the scattering caused by the pre-filter itself. Regarding the correction routines, an increase on the volumetric image noise after using a linearization method for beam hardening correction was reported in [12]. Unfortunately, no specifics on the corrections routines used on this work were available for further discussions.

A final observation on the ATF plot regards the greater departure of the relative transmission values from the amplitude transmission model for the setup performed without pre-filter or corrections. This behaviour is likely to be related to non-linearities caused by the polychromatic nature of the X-ray spectrum, resulting in beam hardening (cupping, streaking) artefacts on the CT image, producing inter-modulation of the harmonics of the multi-wave content during the surface determination.

### 4.3 Influence of data filtering

The results of Experiments #4 to study the influence of data filtering on the projections, during the reconstructions and on the volumetric image on are shown in Figures 8, 9, 10 and 11, respectively. A general analysis of the results shows the expected reduction in surface noise levels at the expense of increased MSR values (except for one case, which will be discussed separately). A comparison among filters reveals different behaviours concerning transmission of the surface content and noise suppression. The median filter applied to the projections (Figure 8) showed a good reduction on the surface deviations, but a reasonably high increase in MSR. An interesting observation is that the filter also changed the ATF order value from 1.3 to 1.6 (plot not showed...
here). Unfortunately, the lack of information on the window size does not allow making quantitative comparisons with other filters. The filters applied during reconstruction (Figure 9) showed more moderated changes on both metrological characteristics, but still produced a significant trade-off between noise and structural resolution.

![Figure 8. Experiment #4.1: the influence of filtering on the projections.](image1)

Regarding the filters with fixed window applied to the volumetric image (Figure 10), several observations can be made. For the linear Gaussian, it can be noted that the changes on the metrological characteristics caused using the filter even with the minor kernel size ($3^3$) are relatively high (e.g. stronger than changes caused by the Hann window applied to the reconstruction filter). However, an analysis of the $\lambda_c$ plot shows that the derivative decreases with the kernel size. An increase on the ATF order values (from 1.3 for the base setup to 1.6 for the $7^3$ kernel) were also noted for the linear Gaussian filter (plot not showed here). For the median filter, the changes caused with the smaller window ($3^3$) are relatively small (e.g. comparable to the use of the cosine window during the reconstruction, with a slightly better trade-off, though). On the other hand, the $\lambda_c$ plot shows that the derivative of the median filter increases with the window size. An interesting observation concerns the influence of the non-linear behaviour of the median filter applied to the volumetric image on the transmission of the surface content, producing unusual departures of the relative transmission values from the amplitude transmission model for the $7^3$ window.

Finally, the adaptive Gaussian filter applied to the volumetric image (Figure 11) shows more moderated increases in MSR for the selected filter parameters. For setups with edge threshold values of 0.3, the ATF curves and the MSR values are comparable to those observed using the reconstruction filters. The surface deviations, however, are quite higher than those observed with the reconstruction filters. The results for setups with edge threshold values of 0.2 are quite unexpected after a filtering operation. Besides increasing the MSR values (losing surface content transmission capability), the filter increased the extracted surface deviation values. In this particular case, the use of filtering completely lost its purpose.

A general observation concerns the difficulty in predicting the impact that filtering operations applied before the surface determination will produce on the extracted surface. For instance, as it was pointed out in [14], applying non edge-preserving filters on the projections violates the CT projection geometry and leads to distortions on the geometry of the extracted surface. The responses shown here are specifically related to the characteristics of the MWS, and although a quantitative comparison was possible for the presented results, it is not expected that they can be generalized to other geometries (especially if non-linear...
image artefacts are present on the volumetric image). Therefore, filters and their parameters have to be carefully chosen according to particularities and requirements of each measuring task.

Figure 10. Experiment #4.3.1: the influence of filtering on the volumetric image using fixed window size filters. Setups with median filters are represented by empty dots, dashed lines; setups with linear Gaussian filters are represented by filled dots, solid lines.

Figure 11. Experiment #4.3.2: the influence of filtering on the volumetric image using the adaptive Gaussian filter. Setups with edge threshold values of 0.2 are represented by empty dots, dashed lines; setups with edge threshold values of 0.3 are represented by filled dots, solid lines.

5 Concluding Remarks

This work presented an investigation of the influencing factors on the metrological structural resolution of CT systems. The investigations was performed using the amplitude transfer function (ATF) method, and included an analysis of the trade-offs between metrological structural resolution and extracted surface deviations.

In general, the results demonstrate that the metrological structural resolution is highly dependent on the data acquisition parameters and processing algorithms. Because of the radiation-related effects, the MSR is also dependent on the material and geometry of the workpiece (or material measure). One of the consequences concerns the definition of specifications and performance tests for the MSR. In order to define e.g. acceptance and reverification tests that allow comparing CT system with basis on manufacturer's specifications (e.g. for the selection of CT systems), it is important that the nominal measuring conditions for performing the tests are also standardized. If the corrections routines for radiation-related effects are included in the dimensional measuring chain, different materials for the measuring standard may also be required.

The dependence of the MSR and surface deviations on the influence factors also calls attention to the complexity in configuring the CT system for measuring small geometries. With this respect, the structured experiments allowed obtaining functional relations that can be employed as a first guidance (and further explored) by CT metrologists in defining measurement procedures. The most remarkable findings are summarized in the next lines.

- In spite being a rather simplistic model (e.g. it does not consider the shape of the focal spot size nor the size of the workpiece), the relative geometrical unsharpness showed to be useful in defining an optimal relation involving the focal spot size, the magnification and the effective pixel size. Increasing magnification until unitary $U_{g,r}$ values of are obtained...
provided a synergistic improvement between MSR and surface deviations. For values above unity, a trade-off between MSR and surface deviations was observed.

- Because the voxel size is not an independent influence factor, different combinations of associated parameters (e.g. magnification and effective pixel size) can be explored together with the $U_{g,r}$ model to improve the metrological characteristics of interest. If the voxel size is used as basis for comparing results obtained with different CT systems, reporting the parameters that defined it is recommended to avoid ambiguity.

- The number of projections did not alter the MSR significantly, even for relatively few projections. On the other hand, using fewer projections increased the surface deviations.

- The use of techniques to reduce radiation-related effects showed to be effective in improving the MSR by increasing the steepness of the ATF. The higher ATF values were achieved by the combined use of pre-filters and correction routines. However, there is a trade-off involved: the surface deviations increases with the use of both types of techniques.

- In general, the use of data filtering produced a trade-off between MSR and surface deviations. However, significantly different behaviours were observed for the evaluated filters. In particular, the adaptive Gaussian filter (in spite being an edge-preserving filter) showed an unusual behaviour, degrading both the MSR and the surface quality for specific setups. The selection of parameters for image filters should be made with care for surface-based applications.

It is important to note that the presented results are constrained to (i) the method, (ii) the procedure and (iii) the equipment used for the experiments. Regarding the method, the ATF quantifies the capability of the CT system in transmitting surface content, providing a more general (not geometry-specific) assessment of the MSR. Therefore, the results obtained with the ATF method are (probably) not directly comparable to the measurements of specific geometries. While some degree of correlation between the MSR and the dimensional values obtained from specific geometries is expected, quantitative studies on this issue must still be performed. Second, the specificities of the experimental design must also be taken into account. In particular, the overall design as a fractional factorial experiment did not allow taking into account many possible relevant interactions between the investigated influencing factors (e.g. using high $U_{g,r}$ values for data acquisition without pre-filtering, filtering in the presence of strong image artefacts, etc). Finally, specific hardware and software characteristics of the equipment (e.g. X-ray tube and detector models, artefact correction routines, etc.) may have a major influence on specific behaviours observed on the results. Therefore, care must be taken in using the conclusions obtained with the presented results for specific applications.

Regarding the application of the ATF-based method for assessing the MSR, more considerations can be done. In general, the method demonstrated sensitivity to analyse the capability of the CT system in transmitting surface content, with reduced sensitivity to noise and none to scale errors (characteristic of the method). That makes it adequate to evaluate the trade-off between transmission of surface information and generation of unwanted surface information (noise). The ATF order parameter ($n$) showed to be useful in quantifying the radiation-related effects present on the volumetric image, making the method suitable for evaluating the effectiveness of artefact reduction techniques (pre-filters, correction routines). More studies on this subject must be performed (e.g. what kind of artefact mainly affects the ATF order). Another particular behaviour observed was the significant departure of the relative transmission values from the transmission model for the lower spatial frequencies (or the whole spectrum on specific situations). This may be related with a non-linear transmission of the multi-wave content, which would be producing inter-modulation of the harmonics. However, because of the relatively high noise levels, it becomes difficult to observe the spurious frequencies that would appear on the amplitude spectrum as a result of the inter-modulation. This behaviour must be further investigated.

In conclusion, this work also help demonstrating the applicability of the ATF-based method to characterize the metrological structural resolution of CT systems. The researchers are still working on the method. Further developments include defining a procedure for estimating the uncertainty of the MWS, defining an uncertainty model for the ATF parameters and improving the design of the CT-MWS. Furthermore, studies to understand the systematic behaviours observed on the CT amplitude transmission values of specific spatial frequencies (or the whole spectrum on specific situations) and on the ATF order values are being performed.

References


