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Validation of a fast and traceable radiographic scale calibration of dimensional computed tomography

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Abstract

A fast and highly precise method of determining the geometrical scale factor of computed tomography (CT) measurements has been validated successfully by Bundesanstalt für Materialforschung und -prüfung (BAM), the Federal Institute of Metrology (METAS) and Physikalisch-Technische Bundesanstalt (PTB) within the scope of AdvanCT (Advanced Computed Tomography for dimensional and surface measurements in industry), a project funded in the European Metrology Programme for Innovation and Research (EMPIR). The method has been developed by PTB and requires only two radiographic images of a calibrated thin 2D standard (hole grid standard) from two opposite directions. The mean grid distance is determined from both radiographs. From this and with the help of the calibration result, the radiographic scale and therefore the voxel size is determined. The procedure takes only a few minutes and avoids a time-consuming CT scan. To validate the method, the voxel sizes determined via this method were compared with voxel sizes determined from CT scans of calibrated objects. Relative deviations between the voxel sizes in the range of 10^{-5} were achieved with minimal effort using cone-beam CT systems at moderate magnifications.

Keywords: industrial CT, voxel size, geometrical magnification, dimensional metrology

(Some figures may appear in colour only in the online journal)

1. Introduction

Traceable dimensional measurements using industrial computed tomography (CT) require traceable knowledge of the

radiographic scale (mm/pixel) which corresponds to the voxel size (mm/voxel) in the reconstructed volume in the case of an error-free reconstruction. This value is usually determined by means of a CT scan of a calibrated reference standard [1–3], a procedure which is very time-consuming and might be affected by 3D reconstruction artefacts. Therefore, in this work, we have developed a fast and accurate method of determining the scale factor (the radiography in reversal orientation technique, or RRT). The RRT requires only two radiographic images of a calibrated hole pattern in an Invar foil [4, 5], provided the rotary axis can be assumed to be precise

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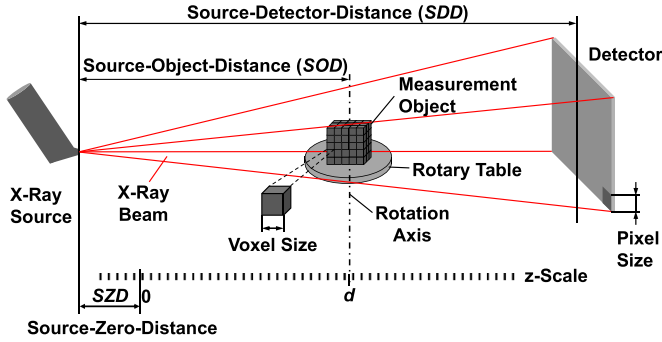


Figure 1. Geometry of the CT-system.

enough that its errors have no significant influence on the results of the methods described here. It allows the SI-traceable determination of the radiographic scale factor with a relative uncertainty of only a few 10^{-6} , and subsequently the absolute geometry determination of a CT system (i.e. the positions of the source, the object and the detector in respect to a physical zero-position usually realized by an index mark. Additionally, the tilt angles of the rotation axis, and its displacement $SOD-SZD$, see figure 1 and [4, 6], are measured down to the micron-range within only a few minutes. Nevertheless, for 3D objects systematic deviations might occur due to beam-hardening, source scatter etc, that must be corrected and considered in the uncertainty budget.

Within the scope of AdvanCT [7], the European Metrology Programme for Innovation and Research (EMPIR) project, this radiographic scale calibration method was validated on the CT systems of BAM, METAS and Physikalisch-Technische Bundesanstalt (PTB). These systems included different types of industrial CTs and the BAMline system at the BESSY II electron storage ring in Berlin, Germany, which is operated by HZB [8]. One idea of this project is to validate a standard and a method that could contribute to a future specification of uncertainty in industrial CT.

2. CT scale calibration method

The RRT uses the substitution principle: instead of the CT measurement object, a thin 2D geometrical standard is placed on the rotary table to allow the geometrical magnification M of the CT system to be determined. The basic concept of the method is to determine two magnification values M_1 and M_2 in two opposite rotary positions to eliminate the unknown displacement between the geometrical standard and the rotary axis that leads to different source to object distances SOD_1 and SOD_2 . The distance SOD of the rotary axis is the mean value of SOD_1 and SOD_2 . Therefore, the magnification M is the harmonic mean of the magnifications M_1 and M_2 :

$$M = \frac{SDD}{SOD} = \frac{SDD}{\frac{1}{2}(SOD_1 + SOD_2)} = \frac{1}{\frac{1}{2}\left(\frac{1}{M_1} + \frac{1}{M_2}\right)} = \frac{2M_1M_2}{M_1 + M_2}. \quad (1)$$

SDD is the source to detector distance.

2.1. Procedure

For the RRT, a calibrated thin 2D standard with multiple redundant length embodiments (e.g. a hole grid) is placed near the rotary axis. This standard is visible in the x-ray projection and its rotational orientation can be easily aligned perpendicular to the x-ray beam with a deviation of less than $1/20$ degree (see section 2.3). In this way, the cosine scale error remains smaller than 0.4 ppm. Two radiographic images are recorded and evaluated—one image in this position and the other image in a position rotated by 180° . The geometrical magnification is defined as:

$$M_{1,2} = \frac{ImageSize_{1,2}}{ObjectSize} = \frac{PixelSize \times MGD_{rad\ 1,2}}{MGD_{opt}}, \quad (2)$$

where MGD_{opt} is the optical calibrated mean grid distance (MGD), i.e. the mean hole center-to-center distance in case of a hole grid, in mm/grid unit, and $MGD_{rad\ 1,2}$ are the radiographic measured MGDs in pixels/grid unit for both radiographies. The influence of a possibly existing vertical inclination of the 2D standard can be ignored if only the horizontal distances are evaluated. $PixelSize$ is given by the detector pitch. Using equations (1) and (2) yields

$$M = \frac{PixelSize \times MGD_{rad}}{MGD_{opt}} \quad (3)$$

with

$$MGD_{rad} = \frac{2 \times MGD_{rad\ 1} \times MGD_{rad\ 2}}{MGD_{rad\ 1} + MGD_{rad\ 2}}$$

and the scale calibration is given by the voxel size:

$$VoxelSize = \frac{PixelSize}{M} = \frac{MGD_{opt}}{MGD_{rad}}. \quad (4)$$

The pixel size of the detector is only an intermediate value not contained in the final result of the calibration. The image distortion of the detector must be corrected before applying this method, or can alternatively be taken from the distortion measured from the grid radiographies.

2.2. Reference standards

To implement the method, Invar foils with a thickness of $50\ \mu\text{m}$ and an etched grid pattern of 1591 circular holes (40×40 holes, less nine missing holes that serve as orientation marks) were realised. Invar is a nickel-iron alloy with a low coefficient of thermal expansion (CTE); a low CTE is necessary to guarantee stable and reproducible results. For the thin rolled foils used, this value was measured and found to be $<1 \times 10^{-6}\ \text{K}^{-1}$. The orientation marks allow the x-ray projection to be localised even if the projection does not show the entire grid.

Holders were designed whose principal components were a transparent PC back plate, a PET foil cover and a PEEK clamp. Special care was taken to ensure that the foils lay flat but could expand freely to minimise temperature effects.

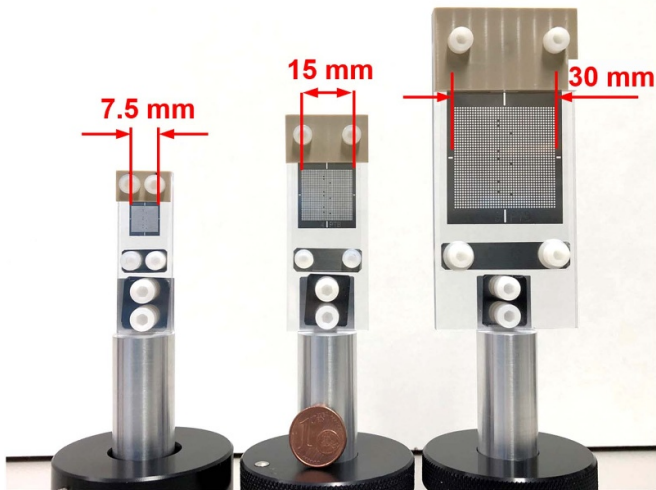


Figure 2. Example hole grid standards (size labels 5, 4, 3) whose etched Invar metal foil grids have 40×40 holes.

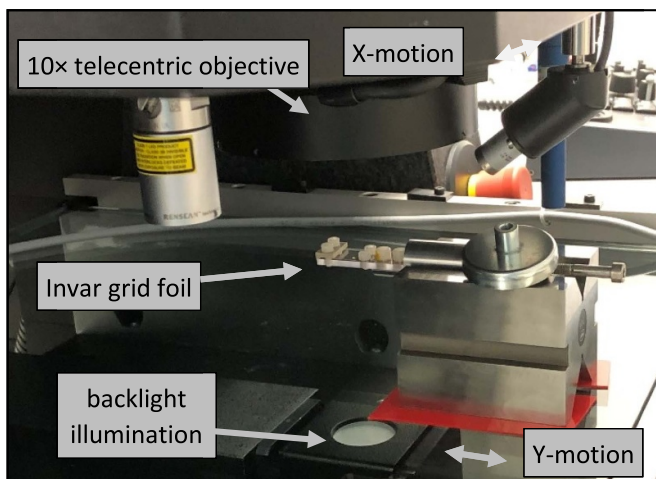


Figure 3. 2D standard measured on an optical CMM in backlight illumination configuration.

Figure 2 shows three assembled hole grid standards (HGSs). The edge lengths of the hole grids vary from 7.5 mm (left, size label No. 5) and 15 mm (middle, size label No. 4) to 30 mm (right, size label No. 3). The 1591 holes have a nominal MGD of 187.5 μm (left), 375 μm (middle) and 750 μm (right); each hole diameter is $2/3$ of these values. In addition to these standards, grids are available whose dimensions are 60 mm (size label No. 2) and 120 mm (size label No. 1).

The calibration of the MGD was carried out using an optical coordinate measuring machine (CMM) (Werth VideoCheck[®] HA) which is traced back via direct comparison to a calibrated Zerodur[®] scale. Figure 3 shows foil No. 5 mounted onto the CMM. In this example, the measurement time is approximately 4 h. All images were recorded through the PET foil cover, with four overlapping images taken of each hole.

The images and the position data logged from the CMM were evaluated using a contour evaluation software program based on the image acquisition (IMAQ) library of the LabVIEW[®] programming environment. The segments

Table 1. Mean grid distances determined for the 2D standards. Standard uncertainty of MGD_{opt} is ~ 2 nm (see [5]).

Label	5 PTB	4 PTB	3 PTB
Edge length of grid	7.5 mm	15 mm	30 mm
Nominal MGD	187.5 μm	375 μm	750 μm
MGD_{opt}	187.5129 μm	375.0193 μm	750.0190 μm

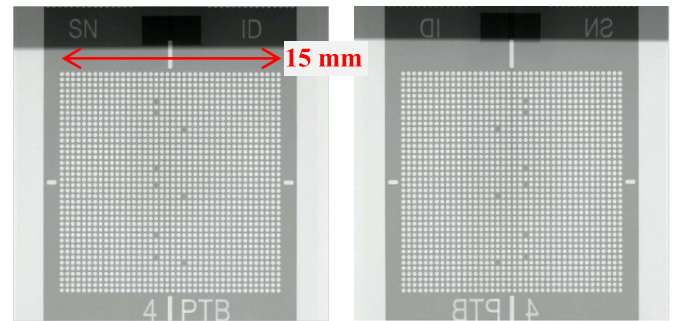


Figure 4. $2 \times 2k$ radiographic images of the metal foil grid. Front view (left) and back view (right).

recognised from the four images were stitched to fit a whole circle. Since the position of the images and the optical relevant pixel size are known by the CMM, it was possible to determine the centre point position of the circles [5]. Using a parametric model fit to all 1591 circle positions via a least-squares method allowed the MGD (in mm) of the holes to be calculated with high precision.

Table 1 lists and describes the used 2D standards and the $MGDs$ determined in comparison to the nominal values.

2.3. Evaluation of radiographic images (mean grid distance in pixels)

The determination of the scale is based on radiographic images and uses a radiographic front and back image, see figure 4. First, the film was adjusted using the rotation stage such a way that it could be seen from the side in the radiographic image, meaning that only a thin line was visible. The mean value of the rotational positions of both side views allowed a perpendicular alignment of the foil to the beam that was better than $1/20$ degree. Then, two radiographic images (front image, back image at 180° rotated position) were recorded.

At PTB, an interactive pattern recognition and grid model fitting software program written in LabVIEW[®] was used. Using this software program, the MGD and the axis position and orientation were determined. Because only the horizontal direction was used, it was not necessary to accurately adjust the inclination of the foil, for which no motorised adjustment is available. The reference pattern can be created synthetically or an image (snapshot) of a hole can be used. Figure 5 shows the magnified centre point deviation of the hole patterns from the fitted equidistant grid. A simple summation of the front/back deviations (even those that are small) eliminates the unevenness of the foil and small misalignments in good approximation. The residual deviations of ≈ 1.5 μm are the result of the production deviations of the foil; furthermore, the detector

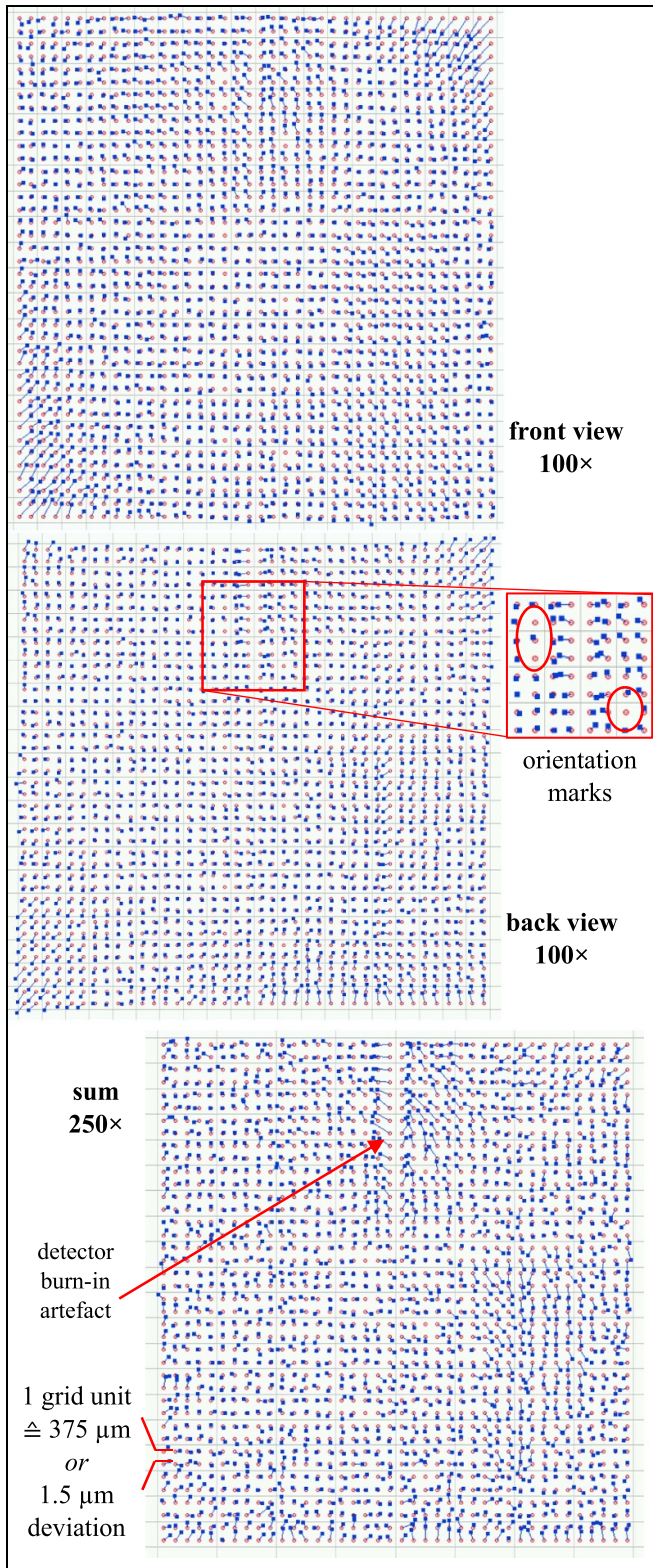


Figure 5. Pattern positions with deviations enlarged in such a way that the deviation becomes ~ 1 grid unit. The red circles are the model-fitted positions, while the blue lines/solid dots are the magnified deviation vectors.

distortion and (in the case shown) the *MGD* in pixels was calculated via the harmonic mean of the *MGD*s of the front and back images.

METAS has independently realised a LabVIEW-based software program which is based on gradient-based contour recognition. The grid positions and parameters obtained were in good agreement.

3. Validation

Numerous measurements were carried out to validate our method using three different sizes of 2D standards and different CT systems. The systems involved were the cone beam CT systems available at PTB and METAS, and the BAMline at the BESSY II (HSB) synchrotron source, which had a nearly parallel beam.

Our method was validated by comparing the scale determined via our method with the scale determined from CT scans of 3D reference objects, which are CMM-calibrated with low calibration uncertainty, and of the foil itself. Table 2 shows an overview of these measurements, which are described in more detail in the following sections.

3.1. Validation measurements carried out by PTB

3.1.1. Validation using a CT scan of the 2D standard. PTB used its Nikon MCT225 CT system for both validations described in this section. The first validation compared the RRT result with the CT evaluation of the HGS, which had been obtained via a complete high-quality scan (see figure 6). With an object such as this metal foil grid, the length to thickness ratio is unfavourable for a CT scan, as artefacts arise due to beam hardening and photon starvation. However, these artefacts are directed in plane; thus, they distort the centre positions to only a very small extent because the holes are fitted as cylinders that are constrained to the normal direction toward the foil plane.

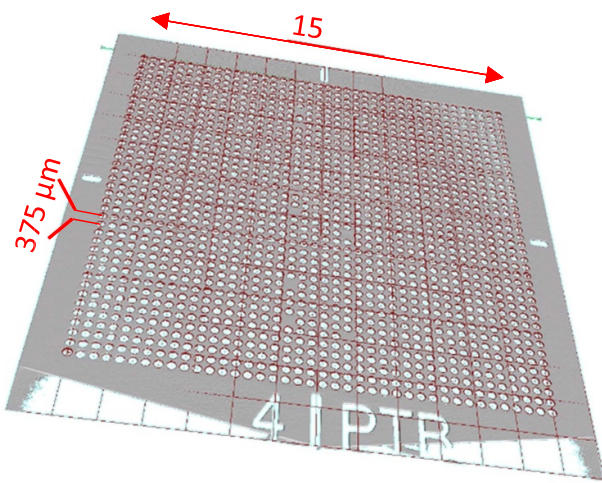
This validation is sensitive to irregular wobble errors of the rotary stage (position uncertainty of the axis regarding rotation) and to systematic deviations caused by the reconstruction and by the surface determination software program in combination with reconstruction artefacts; it is also sensitive to the uncertainty of the effective detection plane position [9]. It is insensitive to model-fit errors, as the Levenberg–Marquardt fit evaluation software program used for the validation was the same as that used to extract the *MGD* values.

Figure 6 shows the evaluation of the CT reconstruction data. This evaluation generates the centre point positions of the holes. The 1591 cylinders fitted were constrained to the normal direction of the average plane. This position data was used to determine the CT data-based *MGD* (in voxels).

Table 3 summarises relevant *MGD* values for a series of experiments: the RRT was executed before and after the CT scan to estimate the drift of the geometrical magnification that was caused mainly by the x-ray source warming up. In addition, the RRT was repeated after one turn of the axis (with the bearing cage in the opposite direction) to estimate the axis' position uncertainty. Furthermore, the scale determination was repeated at different positions of the rotary table in an angular range of 720° . These rosette measurements showed a possible

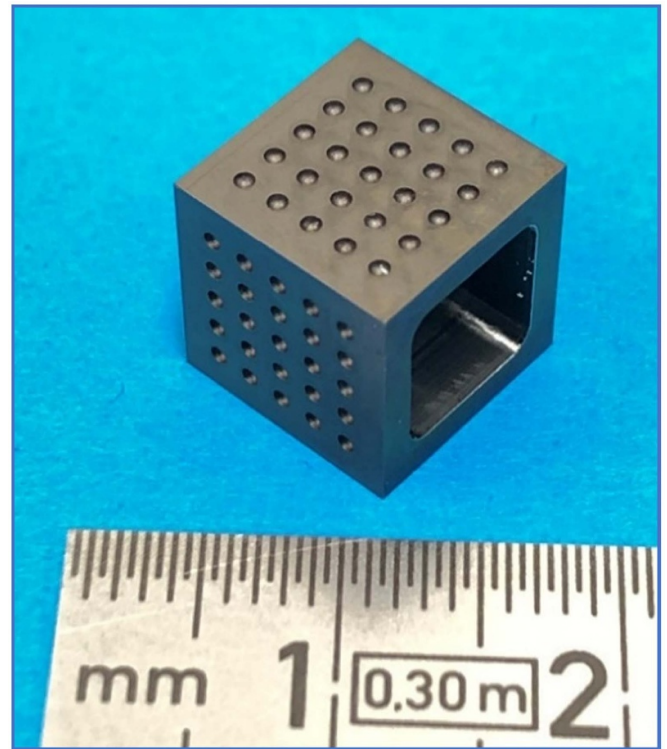
Table 2. Overview of selected validation measurements.

Institute	Measurement	Section	Grid	CT system
PTB	CT scan of the 2D standard	3.1.1	15 mm	Cone beam CT (Nikon MCT 225)
	Calotte cube as reference object	3.1.2		
BAM	CT scan of the 2D standard	3.2.1	7.5 mm	BAMline at BESSY II (Synchrotron)
	Sphere of a star styli as reference object	3.2.2		
METAS	MTCnano as reference object	3.3.1	7.5 mm	Home-built cone beam CT (METAS-CT)
	MSS Zerodur as reference object	3.3.2	30 mm	

**Figure 6.** CT data analysis of the hole grid standard with a 15 mm side length and 375 μm nominal MGD.**Table 3.** Mean grid distances in pixels (voxels for CT) determined for the direct RRT/CT comparison. The values in bold are used in the summary.

Experiment	MGD/pixel	Rel. deviation
RRT before	35.21097	-18×10^{-6}
RRT before + 1 turn	35.21196	$+10 \times 10^{-6}$
RRT average before	35.21147	-4×10^{-6}
CT	35.21160	Reference
RRT after	35.21109	-15×10^{-6}
RRT after + 1 turn	35.21202	$+12 \times 10^{-6}$
RRT average after	35.21156	-1×10^{-6}

radial run-out of $\lesssim \pm 1 \mu\text{m}$ for the rotary stage used. This yields a possible relative deviation of up to $\lesssim \pm 16 \times 10^{-6}$ at the given geometrical parameters and of half that value for an angular range of only 360° . Similar results were obtained with RRT measurements before and after the CT scan of the film (see table 3). The values with and without 1 turn differ by approx. 2.7×10^{-5} . At the given geometry parameters this yields to a change of the *SOD* of 1.6 μm.

**Figure 7.** Calotte cube [11] used for validation by PTB.

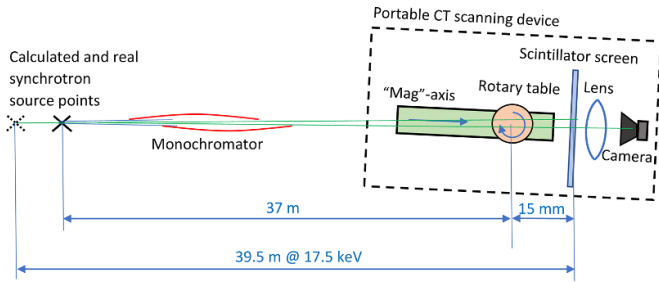
The cylinder fits of the CT surface point data were performed using a commercially available CT evaluation software program [10]. The RRT results determined before and after the CT (see table 3) deviate differently. This is thought to be caused by the lack of a warm-up period, as—in contrast—the following RRT measurements were recorded directly after the CT scan. The optical calibration gives a value of 375.0205 μm for the MGD and can be used to recalculate the voxel size in units of μm [5]. The relative uncertainty of the grid calibration is smaller (estimated as 5×10^{-6}). A larger contribution might be the indeterminacy of the effective source and the detector position; this indeterminacy is due to the x-ray spectrum changing via beam hardening [9].

3.1.2. Validation using a spherical calotte cube. For the second validation, a spherical calotte cube [11] was selected as a traceable reference object to determine the voxel size from a CT scan. The cube was made of titanium and hollowed out to improve its penetrability, see figure 7. The cube has a grid consisting of 5×5 spherical calottes (radius 0.4 mm) on three of its faces. The centre point distances of the calottes were calibrated by a tactile CMM in an accredited calibration laboratory with an expanded uncertainty ($k = 2$) of 1 μm. Due to its large number of calottes, this reference object is well suited for scale determination.

The optically calibrated 2D standard shown in the previous section, whose grid size is 15 mm, was used for this validation. Regarding radiographic images, it is important to take an additional white reference image without a sample between the source and the detector, especially after the CT scan. The

Table 4. Voxel sizes determined during validation with the calotte cube.

Experiment	Voxel size (μm)
RRT before CT scan	10.651781
RRT after CT scan	10.651969
RRT average before/after	10.651875
CT value of spherical calotte cube	10.651970

**Figure 8.** Sketch of the measurement setup of the BAMline.

white reference image is then subtracted from the image of the metal foil grid. Without a white reference image, burn-in effects may occur. These effects cause systematic errors which can degrade the accuracy of the scale determination in the range of up to about 1×10^{-4} , a value which has been estimated from experience. Table 4 summarises the voxel sizes determined.

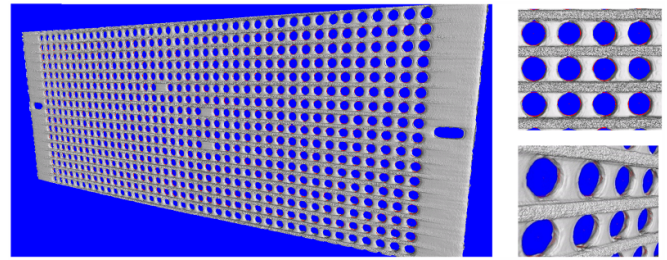
When the voxel sizes determined by evaluating the radiographic images are compared with the voxel size determined by evaluating the CT data of the calotte cube, a relative deviation of -8.9×10^{-6} is obtained. These results refer to the average of the evaluations of the 2D images recorded before and after the CT scan.

3.2. Validation measurements carried out by BAM

3.2.1. Validation using a CT scan of the 2D standard. The validation measurements carried out by BAM took place on the BAMline at the BESSY II synchrotron source [8]. Figure 8 shows the basic setup of the measurements.

First, RRT measurements were used to determine the distance SDD between the synchrotron source point and the detector. For this purpose, the voxel size was determined from radiographic images at several distances between object and detector ($ODD = 20, 40, 100$ mm). The SDD can then be determined from the offset and slope of the linear fit of this dependence. The SDD determined in this way for the energy 17.5 keV, 39.5 m, differs only slightly from the calculated SDD , which is 37 m.

The 180° rotation method described above, which is used to compensate for the inaccurate positioning (a few micrometres) of the foil grid with respect to the axis of rotation was not applied here because a nearly parallel beam was used (the nominal source to detector distance of the BAMline is approx. 37 m). Therefore, only one radiographic image was recorded. The images were taken with a $2\times$ magnifying objective.

**Figure 9.** CT data analysis of the hole grid standard (measurement on BAMline, iterative reconstruction).**Table 5.** Mean grid distances in pixels (voxels for CT) determined for the BAMline measurements.

Experiment	MGD/pixel
RRT, average value	84.19957
Evaluated CT value	84.18272

In the same way as at PTB, a high-quality scan of a 2D standard was also carried out on the BAMline. The CT scan of the grid was carried out at 30 keV with the same parameters as those used for the radiographic images. A sequence of 10 flat images was acquired at the beginning and after every 100 angular positions (projections) to compensate the radiation field change. To take the flat field images, the sample was moved out of the beam using the translation stage that had been oriented orthogonally to the beam.

Figure 9 shows the reconstruction of the CT data. Significant out-of-plane artefacts can be seen in this measurement, which were reduced slightly by applying an iterative reconstruction using a commercial software program [10]. The model fitting of the dimensionless CT data resulted in a value of 84.18272 voxels for the MGD .

Table 5 summarises the MGD values. Comparing the evaluation of the radiographic images to the high-quality scan reveals a relative deviation in the range of about -2×10^{-4} . One reason for these large deviations compared to the PTB measurements is that no correction was made for the image distortion caused by the objective lens.

3.2.2. Validation using a calibrated sphere. The upper sphere of a ruby star stylus was used here as a traceable reference object, see figure 10. The nominal diameter of the sphere was 2 mm. The diameter of the sphere was calibrated by means of a modified form measuring instrument Mahr MFU8 at PTB with an expanded uncertainty ($k = 2$) of $0.1 \mu\text{m}$.

To achieve higher accuracy when determining the voxel size via RRT, two images were recorded at the 0° and 180° positions of the rotation stage. The results of the evaluation of the radiographic images are shown in table 6. The smallest foil, which had a 7.5 mm hole grid pattern, was used for this investigation. A subframe image of 12 holes was chosen as the width, which corresponds to 2.1 mm and can accommodate the sphere (diameter 2 mm) well. The results obtained before and

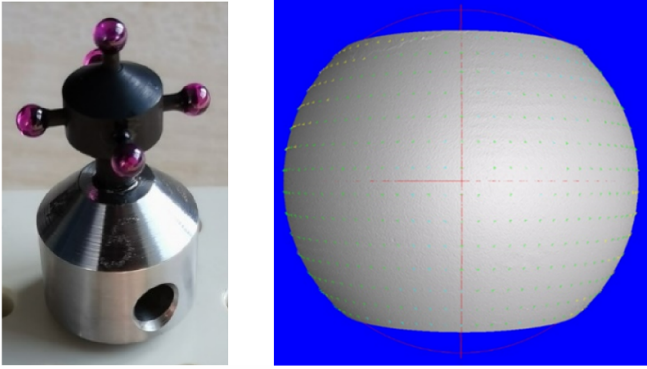


Figure 10. Star stylus used for validation (left). CT data analysis of the upper ruby sphere used as a reference object (right).

Table 6. Voxel sizes determined using the hole grid standard during validation with the ruby star stylus.

Experiment	Voxel size (μm)
RRT before CT scan	2.22862
RRT after CT scan	2.22864
RRT average before/after	2.22863
CT scan of ruby sphere	2.22828

after the CT scan are similar; for further considerations, the average was used.

During the evaluation of the reconstructed CT data of the sphere, spherical caps were symmetrically cut off at the top and bottom of the sphere to eliminate the influence of the assembly rod (see figure 10).

When the voxel sizes determined by evaluating the radiographic images are compared with those determined by evaluating the CT data of the sphere, a relative deviation of -1.5×10^{-4} is obtained. When this number is evaluated, it is important to consider that a diameter measurement is a bidirectional measurement (as it is the case with a tactile two-point measurement with opposite probing directions) in which the surface determination (among other factors) gives an offset value of a fraction of one voxel size additional to the above-mentioned image distortion effect; thus, larger deviations are to be expected. In contrast, errors in the surface determination have practically no effect on measured sphere centre distances.

3.3. Validation measurements carried out by METAS

3.3.1. Validation using a small calibrated multi-sphere standard. The measurements carried out by METAS took place using a transmission target and a 4k detector on the high-resolution metrology CT system developed in-house [12]. For the first validation, a 22-sphere standard (MTCnano; Zeiss METROTOM-Check nano) was used as a traceable reference object in combination with the smallest 2D standard, see figure 11. The multi-sphere standard was calibrated at METAS using their tactile micro-CMM [13].

Table 7 summarises the voxel sizes determined. The evaluation of the CT data of the MTCnano standard carried out by

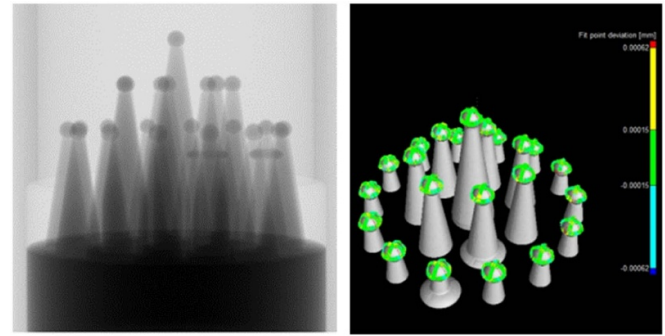


Figure 11. Radiograph of the MTCnano multi-sphere standard (left), reconstruction with tactile probing points mapped onto the surface (right).

Table 7. Voxel sizes determined during validation by METAS using the MTCnano-standard.

Method of obtaining voxel size	Voxel size (μm)
2D standard before CT scan	2.055372
2D standard after CT scan	2.055303
2D standard average before/after	2.055338
Evaluation reference object (MTCnano)	2.055590
	relative uncertainty: 3.2×10^{-5}

METAS yielded a voxel size of $2.055590 \mu\text{m}$ with an expanded relative measurement uncertainty ($k = 2$) of the scale determination of 3.2×10^{-5} .

Because of differences in the voxel sizes before and after the CT scan, a drift compensation of the 2D images was carried out based on METAS' optical x-ray tube tracking system [14]. This compensation created agreement between the voxel sizes determined before and after the CT scan of about 3.4×10^{-5} , corresponding to an offset of $0.7 \mu\text{m}$ in the source position. Comparing the voxel sizes evaluated from the drift compensated average of the 2D standard images and from CT scan of the MTCnano yielded a relative deviation of -1.2×10^{-4} .

3.3.2. Validation using a calibrated 17-sphere standard. In another validation measurement carried out by METAS, the METAS-MSS-Zerodur 17-sphere standard, which matches the largest 2D standard in size (30 mm grid length), was used as a traceable reference object, see figure 12. The multi-sphere standard was also calibrated at METAS using its tactile micro-CMM [13].

The voxel sizes determined are listed in table 8. The evaluation of the CT data of the MSS-Zerodur standard yields a voxel size of $8.460078 \mu\text{m}$ with an expanded relative measurement uncertainty ($k = 2$) of the scale determination of 1.1×10^{-5} . As before, a drift compensation was carried out based on METAS' optical x-ray tube tracking system [14]. Comparing the voxel sizes evaluated from the drift compensated average of the 2D standard images and from the CT scan of the MSS-Zerodur yielded a relative deviation of -3.1×10^{-5} .

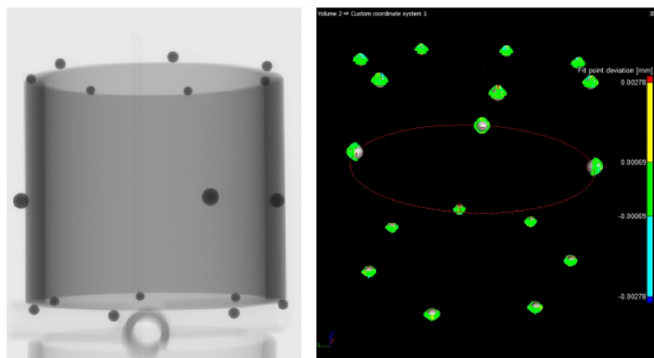


Figure 12. Radiograph of the MSS-Zerodur multi-sphere standard (left), reconstruction with tactile probing points mapped on to the surface (right).

Table 8. Voxel sizes determined during validation by METAS using the MSS-Zerodur standard.

Method of obtaining voxel size	Voxel size (μm)
2D standard before CT scan	8.459827
2D standard after CT scan	8.459811
2D standard average before/after	8.459819
Evaluation reference object (METAS-MSS-Zerodur)	8.460078 relative uncertainty: 1.1×10^{-5}

Table 9. Overview of the relative deviations of the validation measurements.

Institute	Measurement	Section	Grid	Relative deviation
PTB	CT scan of the 2D standard	3.1.1	15 mm	-4×10^{-6}
	Calotte cube as reference object	3.1.2		-8.9×10^{-6}
BAM	CT scan of the 2D standard	3.2.1	7.5 mm	-2.0×10^{-4}
	Sphere of a star styli as reference object	3.2.2		-1.5×10^{-4}
METAS	MTCnano as reference object	3.3.1	7.5 mm	-1.2×10^{-4}
	MSS-Zerodur as reference object	3.3.2	30 mm	-3.1×10^{-5}

4. Summary and conclusions

Table 9 summarises the resulting relative deviations between the evaluations of the radiographic images of the grid compared to the CT data analysis of the reference objects.

Moderate magnification (15 mm and 30 mm grid) allowed relative deviations in the range of 10^{-5} to be achieved easily, with the exception of BESSY, where additional distortions occurred due to the camera system. The method and the 2D standards are therefore well suited for determining, checking and correcting the voxel sizes quickly and reliably. The achievable accuracy of the method is—up to now—limited, for

example, by the spectrum-dependent penetration depth in the detector [6], which results in an object-dependent magnification. Additional measurements at METAS showed that, especially at very high geometrical magnifications (e.g. $100\times$), the influence of form errors of the holes (conicity, roundness) and of spectral effects in the target of the x-ray source can increase and must be investigated further.

The results show that with the described method the radiographic scale and thus the voxel size can be determined easily and quickly with high accuracy. It is therefore suitable for broad industrial use in determining the radiographic scale in order to ensure or increase the accuracy of CT measurements. The grid foil artefact and the method could be used, in future, as a part of the traceability chain in industrial CT with impact on the specification of uncertainty.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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