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## EVALUATION OF VOLUMETRIC CALIBRATION FOR DIMENSIONAL ACCURACY IN X-RAY AND NEUTRON COMPUTED TOMOGRAPHY

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**Abstract:** Tomographic imaging employs penetrating radiation to reconstruct three-dimensional representations of internal structures. Common radiation sources include X-rays and neutrons, with X-ray computed tomography (XCT) being the most widely utilized modality. Although XCT is extensively applied in industrial dimensional metrology, its measurement uncertainty is not yet fully characterized. Calibration phantoms—typically consisting of calibrated multi-sphere artifacts—serve a critical role in enhancing traceability and measurement accuracy. These phantoms facilitate volumetric calibration, wherein the reconstructed voxel volume is scaled linearly based on known reference distances between sphere centerpoints. This study investigates the influence of volumetric calibration on the dimensional accuracy of both XCT and neutron computed tomography (NCT) systems, employing a custom-designed phantom compatible with both modalities. Experimental evaluations were conducted using two XCT systems, one of which is metrology-grade, and an NCT system. The findings indicate that while volumetric calibration ensures metrological traceability, its effectiveness in reducing measurement error is dependent on the specific system configuration.

**Key words:** X-ray tomography, neutron tomography, calibration phantom, traceability, metrology.

### 1. INTRODUCTION

Computed tomography (CT) is a highly effective technique for volumetric imaging of various structures. Accurate and reliable volumetric measurement is essential in X-ray computed tomography (XCT) systems for both qualitative and quantitative analyses [1–3]. Neutron computed tomography (NCT), which utilizes neutron radiation to penetrate materials, offers unique advantages over XCT—particularly in imaging specimens composed of high atomic number (Z) elements that are relatively opaque to X-rays [4]. Although NCT typically provides lower spatial resolution compared to XCT, its potential for dimensional metrology remains underexplored. In contrast, XCT has been successfully integrated into metrological workflows using calibration standards and reference artifacts [5]. To date, comparable metrological frameworks have not been systematically developed or validated for NCT.

Geometric accuracy phantoms, with features like spherical beads, are vital for correcting geometric distortions and aligning imaging components [6]. Phantoms like the two-ball and wire phantom are integral to geometric calibration, enhancing operational efficiency [7] by enabling simultaneous object and phantom scanning. They ensure correct X-ray CT (XCT) system measurements by calibrating scaling factors, crucial for precision in applications like quality control [8]. Calibration phantoms adhere to traceable standards, allowing for consistent measurements across systems over time. Borosilicate beads phantoms, for instance, ensure scaling accuracy in micro-CT scanners [1].

The strategic use of calibration phantoms plays a vital role in minimizing systematic errors such as scaling factors and reprojection inaccuracies by providing a stable and metrologically traceable reference for CT systems. Two main types of calibration approaches can be

distinguished. The first is volumetric calibration [9], which involves scaling the reconstructed voxel volume to match a known reference dimension, thereby correcting global volumetric distortions. The second approach involves 2D image-based correction, where reference length adjustments are applied directly to the projection images before reconstruction [10, 11]. Each method has its advantages and limitations, and their effectiveness can depend on the CT system used and the nature of the measurement task.

The objective of this study is to evaluate the impact of volumetric calibration on the dimensional accuracy of both X-ray computed tomography (XCT) and neutron computed tomography (NCT) systems. This evaluation is conducted using a specially designed calibration phantom that is compatible with both imaging modalities. By applying a consistent calibration approach across XCT and NCT, the study aims to assess the potential for improving measurement traceability and reliability in NCT, drawing parallels with established practices in XCT-based dimensional metrology.

## 2. MATERIALS AND METHODS

### 2.1 Artifacts of the experiment

A calibration phantom and specimen were designed. The structure and the dimensions of the calibration phantom is shown in Fig. 1. The sphere in the centre of the calibration phantom is misaligned by 0.5 mm nominally, which results three different distances between the center points of the spheres. DST1 represents the distance between the first and second sphere-center, DST2 the first and the third and DST3 is the second and third. The diameters of the spheres are also measured by the CT systems.

The designed specimen is shown in Fig. 2. The specimen contains cylindrical features and a slot with perpendicular planes. The distances between the planes in the slot are represented as L1, ..., L6.

The materials selected for both the calibration phantom and the specimen were specifically

chosen to be compatible with both X-ray and neutron computed tomography, thereby enabling direct comparative analysis across the two modalities [4]. The calibration spheres are of G10 grade, as specified in [x], while ZrO<sub>2</sub> stabilized with Y<sub>2</sub>O<sub>3</sub> was selected for its ability to provide high imaging contrast without causing excessive attenuation. Additionally, Ti6Al4V alloy was included in the experiment due to its favorable transmission characteristics for both X-rays and neutrons, which are essential for achieving high-quality tomographic imaging. Ti6Al4V also minimizes hydrogen-related neutron scattering, thereby improving measurement reliability, and its high strength-to-weight ratio contributes to mechanical stability. Importantly, both ZrO<sub>2</sub> and Ti6Al4V generate only short-lived activation products, allowing for safe handling following neutron exposure.

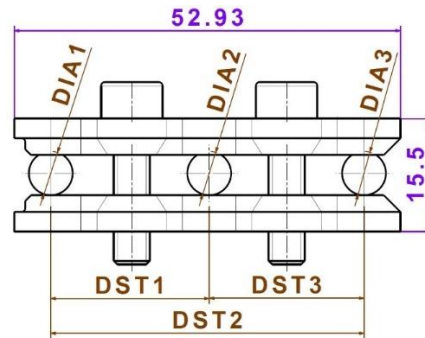


Fig. 1. dimensions of the calibration phantom

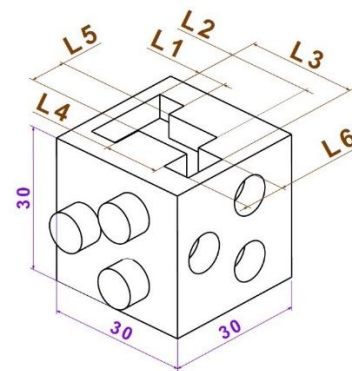


Fig. 2. dimensions of the specimen

### 2.2 XCT systems

The scans were conducted using two different XCT systems: GE Micromex (XCT1) and Waygate Technologies Vtomex M (XCT2). XCT1 features a compact 200 x 200 mm digital

detector positioned horizontally within the machine. This design, with a horizontal rotary axis, poses challenges due to potential deflection of the part-fixture. To minimize deflection, which can lead to blurred contours in the voxel volume, the fixture must be as rigid as possible. The X-ray tube is vertically aligned, and the machine's geometrical structure is not ideal for high-precision dimensional measurements. In contrast, XCT2 is a metrology-grade system with a horizontally oriented X-ray tube and a vertically aligned flat panel, along with a vertical rotary table axis. This configuration is well-suited for metrological tasks. The parameters of the scans are shown in Table 1.

Table 1

Scanning parameters of the XCT systems.

| XCT systems           | XCT1<br>Micromex | XCT2<br>Vtomex M |
|-----------------------|------------------|------------------|
| Voltage [kV]          | 180              | 170              |
| Current [ $\mu$ A]    | 50               | 290              |
| Physical filter       | 0.5 mm Sn        | 0.5 mm Cu        |
| Voxel size [ $\mu$ m] | 63.68            | 40               |
| No. of projections    | 1440             | 1800             |
| Exposure time [ms]    | 200              | 500              |
| No. of images         | 30               | 2                |
| Magnification         | 3.141            | 5                |
| FDD [mm]              | 641.37           | 807.24           |
| FOD [mm]              | 204.2            | 161.45           |

### 2.3 NCT system

The NCT experiment took place at the RAD station located within the horizontal channel No. 2 of the Budapest Research Reactor, where neutrons served as the radiation source. To ensure that only the desired energy range of neutrons was used, a sapphire filter measuring 150 mm in length was strategically placed between the sample and the neutron source. This filter was specifically designed to eliminate higher energy neutrons, such as epithermal and fast neutrons. Consequently, the filtered neutron beam that was generated had a thermal equivalent flux of  $3 \times 10^7$  neutrons/cm<sup>2</sup>s, with significantly reduced interference from higher energy neutrons.

For structural support, the phantom was wrapped in aluminium foil. The experiment involved capturing a total of 601 projection images as the sample underwent a 180-degree rotation. This was achieved using a scintillation screen made of <sup>6</sup>LiF/ZnS, which was 100 micrometers thick. Each image exposure lasted for 60 seconds. The images were collected using a sophisticated large area sCMOS camera, specifically the Andor Neo5.5 model, which was paired with a primary lens that had a fixed focal length of 105 mm.

The entire imaging process took 10 hours and covered a field of view measuring 100×100 mm<sup>2</sup>. The images produced a voxel size of 42.72  $\mu$ m. For processing the data, including the manipulation, reconstruction, and visualization of the 3D neutron datasets and tomographic images, a variety of software tools were employed. These included Fiji-ImageJ, Octopus 8.9, VGStudio MAX 3.2, and KipTool, each contributing to different aspects of the data handling and visualization process.

### 2.4 Geometrical measurements

The size of the voxels in the reconstructed volumetric pictures are depending on several parameters of the CT system and it needs to be precisely defined for metrological tasks.

The calibration phantom has calibrated values. The distances and the diameters are measured by a Zeiss Prismo coordinate measurement machine (CMM). The measurements were repeated five times and the mean of the measurement results were used as the reference values.

The calibration phantoms are scanned together with the specimen. The DST2 (Fig. x) is used for the volumetric calibration of the volumetric pictures, because it is the largest distance. The voxel volume is scaled so that the measurement error of the DST2 is near zero. The scaled voxel volume is then calibrated to DST2.

The measurements were not repeated; the CT systems (XCTs and NCT) scanned the calibration phantom together with the specimen only once. The measurements were made on the voxel volumes in two states: volumetric calibration applied or not applied.

The center of the spheres was determined by the fitted least squares ideal sphere against the point cloud extracted from the determined surface. The fitted spheres have centerpoints, which are used for the measurement of the distances (DST1-3, Fig. 1). The diameters of the fitted spheres were signed as DIA1-3.

The lengths of the slot (Fig. 2) is evaluated from the specimen. Planes are fitted with the least squares method to the point cloud of the specimen. The centre points of the planes are determined. The datum system is determined by the three planes of the cube. The primary datum is the plane with the wholes, secondary is the plane with the slot and the tertiary is the plane with the cylindrical shafts. The distances between the center points of the planes are evaluated regarding the datum system in VGStudio Max 3.5.1. software.

### 3. RESULTS AND DISCUSSION

#### 3.1 Measurement results of the calibration phantom

On the calibration phantom three different distances measurable between the center points of the spheres (DST1, DST2, and DST3, Fig. 1). The largest distance is the DST2 and this is why it was used for the volumetric calibration.

Measurement errors were determined by calculating the difference between the tomographically measured distances and the corresponding reference values, both with and without the application of volumetric calibration.

The results presented in Fig. 3 indicate that, for all CT systems, the measurement error of DST2 with volumetric calibration was nearly zero. However, in the cases of XCT1 and NCT, the volumetric images revealed not only linear scaling errors but also additional errors, which contributed to a higher overall measurement error. In the case of XCT2, which is metrology

grade CT system, the measurement error was not greater than 1  $\mu\text{m}$  after volumetric calibration.

The volumetric calibration led to a 0.05% decrease in the measurement error for DST2 in the case of XCT1. Conversely, it caused a 0.09% increase in measurement error for DST2 with XCT2, and a 0.12% increase in the case of NCT. The diameter of the spheres of the calibration phantom was also measured. The results are shown in Fig. 4. Before the volumetric calibration all CT system measured the diameters smaller, than the reference value.

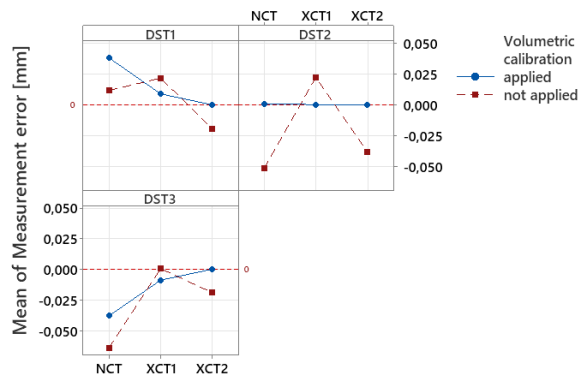


Fig. 3. results of the distance measurements

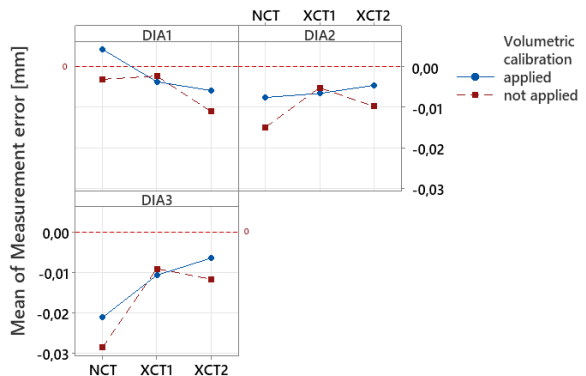


Fig. 4. results of the diameter measurement

#### 3.2 Measurement results of the specimen

The results of the lengths, grouped by the volumetric calibration and measurement machine, are presented in separate diagrams (Fig. 5). These results indicate that, for the NCT, the measurement error shifted positively due to volumetric calibration. In contrast, the measurement error for XCT1 decreased across all lengths as a result of volumetric calibration. For XCT2, the measurement errors were close to

the zero line for lengths L1, L3, and L5. However, for lengths L2, L4, and L6, the measurement errors increased with volumetric calibration.

The measurement error in length measurements is directly affected by the precise amount of change in DST2 resulting from the volumetric calibration. Waring et. al. in [1] concluded that the scaling error of the scanners are reduced below 0.1%. In our experiment, the relative measurement error in % for DST1, DST2 and DST3 is lower than 0.1 %. The volumetric calibration was effective only in the case of the distances and by the XCT2, which is a metrology grade CT system. By the lengths (L1-6) the measurement error was not decreased effectively by the volumetric calibration with the DST2.

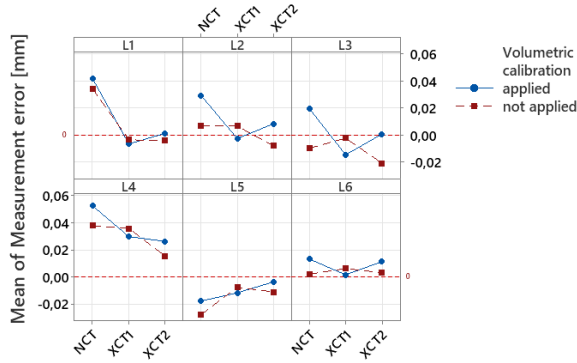


Fig. 5. results of the specimen

### 3.2 Comparison

Table 2 presents the differences in measurement errors (ME) observed with and without volumetric calibration across three machines (XCT1, XCT2, and NCT) for various features of calibration phantom and the specimen (DST1–DST3 and L1–L6).

XCT1 consistently shows negative deviations, indicating that applying volumetric calibration reduces the measured values. In contrast, XCT2 and NCT display positive deviations. The relative change due to volumetric calibration is consistent across all length features, with the highest being 0.12% on the NCT.

This demonstrates that while volumetric calibration ensures metrological traceability, it does not necessarily improve the measurement accuracy.

Table 2

Differences in measurement errors.

| Measurement machine | Feature | ME <sub>applied</sub> - ME <sub>not applied</sub> [mm] | %      |
|---------------------|---------|--------------------------------------------------------|--------|
| XCT1                | DST1    | -0,0128                                                | -0,06% |
| XCT1                | DST2    | -0,0221                                                | -0,05% |
| XCT1                | DST3    | -0,0093                                                | -0,04% |
| XCT2                | DST1    | 0,0194                                                 | 0,09%  |
| XCT2                | DST2    | 0,0386                                                 | 0,09%  |
| XCT2                | DST3    | 0,0191                                                 | 0,09%  |
| NCT                 | DST1    | 0,0266                                                 | 0,12%  |
| NCT                 | DST2    | 0,0525                                                 | 0,12%  |
| NCT                 | DST3    | 0,0259                                                 | 0,12%  |
| XCT1                | L1      | -0,0031                                                | -0,05% |
| XCT1                | L2      | -0,0092                                                | -0,05% |
| XCT1                | L3      | -0,0123                                                | -0,05% |
| XCT1                | L4      | -0,0060                                                | -0,05% |
| XCT1                | L5      | -0,0041                                                | -0,05% |
| XCT1                | L6      | -0,0046                                                | -0,05% |
| NCT                 | L1      | 0,0075                                                 | 0,12%  |
| NCT                 | L2      | 0,0221                                                 | 0,12%  |
| NCT                 | L3      | 0,0293                                                 | 0,12%  |
| NCT                 | L4      | 0,0145                                                 | 0,12%  |
| NCT                 | L5      | 0,0099                                                 | 0,12%  |
| NCT                 | L6      | 0,0111                                                 | 0,12%  |
| XCT2                | L1      | 0,0054                                                 | 0,09%  |
| XCT2                | L2      | 0,0161                                                 | 0,09%  |
| XCT2                | L3      | 0,0215                                                 | 0,09%  |
| XCT2                | L4      | 0,0107                                                 | 0,09%  |
| XCT2                | L5      | 0,0073                                                 | 0,09%  |
| XCT2                | L6      | 0,0081                                                 | 0,09%  |

### 4. CONCLUSION

This study demonstrates that volumetric calibration significantly influences the dimensional measurement results of both X-ray and neutron computed tomography systems. While it effectively ensures metrological traceability—especially for distance measurements such as DST2—its impact on improving overall accuracy is machine-dependent. XCT2, a metrology-grade system, benefited the most, achieving sub-micron accuracy post-calibration, whereas XCT1 showed consistent error reduction and NCT exhibited a uniform positive shift in errors.

These findings underscore the critical role of calibration phantoms in advancing measurement

accuracy and emphasize that volumetric calibration is most effective when paired with high-quality, metrology-grade systems. The study expands the current understanding of calibration practices for both XCT and NCT, paving the way for future research aimed at enhancing traceability, reliability, and precision in industrial and scientific CT applications.

## 5. REFERENCES

- [1] Waring, C. S., Bax, J. S., Samarabandu, A., Holdsworth, D. W., Fenster, A., & Lacefield, J. C. (2012). Traceable micro-CT scaling accuracy phantom for applications requiring exact measurement of distances or volumes. *Medical Physics*, 39(10), 6022-6027.
- [2] Dao, A., & Drégelyi-Kiss, Á. (2020, June). Determination of GD&T Features Varying the Setting Parameters of X-Ray Computed Tomography by Response Surface Method. In *Materials Science Forum* (Vol. 994, pp. 280-287). Trans Tech Publications Ltd.
- [3] Marczis, A., Odrobina, M., & Drégelyi-Kiss, Á. (2024). Computed tomography as distortion mitigation method for selective laser sintering mass production. *The International Journal of Advanced Manufacturing Technology*, 133(9), 4845-4864.
- [4] Marczis, A., Kis, Z., & Drégelyi-Kiss, Á. (2023, October). On the Material Selection of Gauge for the Comparison of X-Ray and Neutron Tomography. In *The International Symposium for Production Research* (pp. 275-285). Cham: Springer Nature Switzerland.
- [5] Drégelyi-Kiss, Á. (2019, May). Towards Traceable Dimensional Measurements by Micro Computed Tomography. In *International Conference on Measurement and Quality Control-Cyber Physical Issue* (pp. 247-254). Cham: Springer International Publishing.
- [6] Duan, X., Cai, J., Ling, Q., Huang, Y., Qi, H., Chen, Y., ... & Xu, Y. (2021). Knowledge-based self-calibration method of calibration phantom by and for accurate robot-based CT imaging systems. *Knowledge-Based Systems*, 229, 107343.
- [7] Xiao, K., Han, Y., Xi, X., Bu, H., Li, L., Yan, B., ... & Liu, J. (2017, October). An optimized acquisition approach exploiting geometrical calibration in x-ray cone-beam computed tomography. In *AOPC 2017: Optical Sensing and Imaging Technology and Applications* (Vol. 10462, pp. 1266-1270). SPIE.
- [8] Oksuz, I., Bisbee, M., Cherepy, N., Hall, J., Townsend, A., Tringe, J., & Cao, L. (2022). Demonstration of fast neutron tomography for complex objects at sub-mm resolution. *Journal of Radioanalytical and Nuclear Chemistry*, 331(12), 5095-5100.
- [9] Su, S., Dai, N., Cheng, X., Zhou, X., Wang, L., & Villarraga-Gómez, H. (2020). A study on factors influencing the accuracy evaluation of dimensional X-ray computed tomography with multi-sphere standards. *International Journal of Precision Engineering and Manufacturing*, 21, 649-661.
- [10] Hardner, M., Liebold, F., Wagner, F., & Maas, H. G. (2024). Investigations into the geometric calibration and systematic effects of a micro-CT system. *Sensors*, 24(16), 5139.
- [11] Zemek, M., Blažek, P., Šrámek, J., Šalplachta, J., Zikmund, T., Klapetek, P., ... & Kaiser, J. (2020, February). Voxel size calibration for high-resolution CT. In *10th Conference on Industrial Computed Tomography (iCT)* (p. 8).

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