Reducing the influence of environmental scattering in industrial computed tomography by system optimisation and correction algorithms

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Abstract
High energetic X-ray photons are scattered in both the object and the system’s components and cause artefacts in industrial computed tomography (CT). In this contribution, we investigate the influence of individual CT components on environmental scattering by experimentally verified Monte Carlo simulations. An assessment of different configurations indicates a potential reduction in environmental scattering by 81 ± 4 % due to system modifications. The contribution of environmental scattering to the transmission signal displays only a weak spatial variation. Thus, an analytical correction method is suggested, which is applied on the transmission images prior to reconstruction. This procedure requires a single input parameter and is applied on measurements of an industrial CT system operating a source with 450 kV maximum acceleration voltage. The suggested procedure increases the contrast of the central hole in an aluminium step cylinder with a diameter larger than 160 mm by more than a factor of 2.4 compared to non-corrected data.

Keywords: Modelling and Simulation, Image Processing, Computed Tomography, X-ray Scattering, Correction Algorithm, Monte Carlo Simulations, Cone-beam Computed Tomography

1. Introduction
X-ray computed tomography (CT) is a non-destructive method to inspect samples for defects and deviations in both internal and external structures. Typical applications include the failure analysis of industrial products [1,2], the investigation of structures in the sample [3,4] and dimensional metrology [5]. In conventional industrial CT, the object is rotated around a fixed axis in small angular steps and, in each orientation of the specimen, an X-ray transmission image is recorded [6]. A key assumption for the reconstruction of the tomographic cross-sections in classical CT is a linear propagation of the photons from generation to detection. Scattering processes invalidate this assumption and cause a deterioration of the imaging quality due to the detection of scattered photons. For energies exceeding 150 keV, the interaction cross-sections of (inelastic) scattering events dominate those of (photo-electric) absorption processes for most industrially relevant materials [7] highlighting the importance to consider the influence of scattered radiation for medium- and high energy CT applications. Discriminating scattered from non-scattered photons is very challenging in experiments. Therefore, Monte Carlo simulations with established packages such as GEANT4 [8-10] or EGS/Rosi [11] are performed, in which the propagation of the photons through the sample and the system is tracked and thereby the contribution of scattered photons to the detected signal can be quantified. For the CT-system considered in this contribution, a Monte Carlo model was implemented in the GEANT4 framework and experimentally verified [8, 10, 12]. In this contribution, the effect of different system configurations on the distribution of detected scattered radiation is examined with simulations. Based on the results of the simulation study, the system setup has been modified and the results of the experimental verification will be presented. Based on an elementary assessment of the spatial distribution of the scattered radiation, a correction procedure will be presented, which displays a significant improvement of the image quality on the examined test sets.
2. Materials and Methods

2.1 Monte Carlo modelling of X-ray photon propagation with GEANT4
The models for the X-ray propagation are implemented in the GEANT4 framework (version 4.9) as described in [8,12]. The components of the CT scanner are modelled as geometrical primitives employing bulk material properties. For electrons, the following physical processes are activated: ionization, bremsstrahlung and multiple scattering processes. In addition, for photons, models for Rayleigh and Compton scattering as well as for the photoelectric effect are included. The photons are generated at the source location with an energy spectrum adopted from an experimentally verified model of the source assuming 450 kV acceleration voltage and an external filtration of 1.0 mm tungsten [10]. The photons are emitted isotropically in a cone with an opening angle of 7.25° (half-angle). For all simulated photons, the total energy deposited in the scintillator (cesium-iodide with 2 mm thickness) mounted on an aluminium plate of 1 mm thickness is recorded. Furthermore, the total deposited energy from photons scattered in the mirror, in the detector or in the walls is recorded. If the photon is scattered in more than one of these components, the deposited energy is split equally between the interacting parts. In each simulation, the histories of \(8 \times 10^6\) or \(8 \times 10^7\) photons are analysed (the number of considered photons was increased whenever the statistics was insufficient). The error of the estimated photon numbers is calculated as the standard deviation of the results from 8 independent Monte Carlo runs with a length of one eighth of the total number of events.

2.2 Assessment of influence from different system configurations
Two different scintillator supports are considered (a more encompassing set of different configurations is considered in [12]). The different geometries are visualized in Fig. 3. The major differences between the two designs are the liner composition (iron-lead sandwich for the non-optimised setup, carbon fibre reinforced polymers, CFRP, with a thickness of 0.55 mm for the optimised setup) and the geometry (49 x 51 x 32 cm\(^3\) in the initial setup to 58 x 51 x 51 cm\(^3\) in the optimised setup). In the experimental setup, the scintillation light is recorded via a 45° mirror in a CCD camera at the bottom of the detector box. For this mirror two configurations are evaluated: glass matrix with 2.8 mm thickness or a polycarbonate plate (1.5 mm thick). To reduce the effect of backscattering from the walls the unlined walls are compared with a configuration where the walls are lined with a sandwich of tin (1 mm thick) and lead (2 mm thick) or a massive layer of lead (50 mm wall thickness). As test object, an aluminium parallelepiped with 70 x 70 x 190 mm\(^3\) is simulated at a distance of 1107 mm from the source (source-detector distance is set to 1500 mm).

2.3 Spatial variability of environmental scattering contribution
To assess the spatial variability of the energy deposited in the scintillator due to environmental scattering a total of \(2 \times 10^9\) photon histories are analysed. The sensitive area of the scintillator is split into areas of 0.96 x 0.96 mm\(^2\) (corresponding to a binning factor of four in the experiment) and the deposited energy in the corresponding volume is calculated. To reduce the effect of noise, a Gaussian image filter with a standard deviation of 5 pixels is applied to the “simulated transmission” image.

2.4 Experimental verification of reduced scattering by system redesign
The effect of the instrument redesign is evaluated with a CT scanner (described in detail in [12]) operating an X-ray source with 450 kV maximum acceleration voltage manufactured by Comet (Model MXR-451HP/11/Y). The source spectrum is filtered with a liner of tungsten (alloy HPM1750) with 0.5 mm thickness. The beam is shaped by an additional lead collimator to a vertical aperture of 4 mm for the evaluation of the instrumental redesign or to an angular
aperture of 8.87° x 6.09° (horizontal x vertical) for the assessment of the software correction. In the detector, the scintillation light generated in a Thallium-doped Cesium Iodide scintillator with 2 mm thickness is imaged by a CCD camera (Alta U32 from Apogee Imaging Systems) via a 45° mirror. Both detector setups are shown in Fig. 1. The non-optimised scintillator support is built from liners of lead and steel and described in detail in [8]. The optimised scintillator support is built from liners of CFRP (details given in [12]). For the experimental evaluation of the impact of the system modification, an aluminium step cylinder with levels of outer diameter 40, 60, 80, 100, 120, 160, 200, and 220 mm and a total height of 160 mm in steps of 20 mm is recorded. Along the symmetry axis of the cylinder a hole with 20 mm diameter has been drilled. The sample is positioned at 1107 mm from the source with a source-detector distance of 1500 mm. For the tomographic measurements with the slit collimator, an acceleration voltage of 450 kV and a tube current of 2.9 mA is set (reduced to 2.5 mA during flat field acquisition) to record a total of 720 projections with a total integration time of 8.0 s. The tomograms are reconstructed with the software of the system’s supplier based on the Feldkamp-Davis-Kress algorithm [14]. The measurements with a large angular opening are performed with a tube current of 3.3 mA (reduced to 3.0 mA during flat field acquisition) and an integration time of 4.0 s.

2.5 Correction algorithm for remaining environmental scattering

The observed low spatial variability of the contribution from environmental scattering (cf. Fig. 4) justifies the two assumptions that the contribution $I_{env}$ of environmental scattering to the image signal is isotropic and that it is independent of the local signal strength $I_{sig}$ in the presence of the sample or $I_{flat}$ in the absence of the object. Therefore, the measured transmission signal is

$$\bar{T} = \frac{I_{sig} + I_{env}}{I_{flat} + I_{env}}$$

Defining the environmental transmission as $T_{env} = I_{env}/I_{flat}$ and the actual transmission $T_{sig} = I_{sig}/I_{flat}$, we obtain for the actual transmission

$$T_{sig} = \bar{T} \left( 1 + T_{env} \right) - T_{env}$$

This correction formula is applied on the transmission images prior to reconstruction. As the reconstruction of the system’s supplier did not permit the reconstruction of modified data, an in-house implementation of the Feldkamp-Davis-Kress algorithm was employed for the evaluation of the effect of the correction formula. The parameter $T_{env}$ may be determined in a binary search process [13]. Evaluations on a broad set of test data indicate that it may be estimated from the projection images, given the projection images do not display an excessive spatial variation [13].

Figure 1: CT-setup prior (left) and after redesign (right). Essential elements of the modified setup are a new scintillator support with larger dimensions from carbon fibre reinforced polymer, a foil mirror (not visible) and the bimetallic liners on the concrete walls.
3. Results and Discussion

3.1 Influence of scintillator support geometry and material

The fraction of energy scattered in the environment is displayed for different system configurations in Fig. 2. An exchange of the scintillator support built from steel-lead liners with a larger scintillator support from carbon fibre reinforced polymers permits a substantial reduction of the amount of backscattered radiation. As the beam stopping power of the support is lost upon the exchange, the backscattering of the walls increases substantially. The contribution of the mirror on the other hand is largely constant because the fraction of transmitted primary radiation is unchanged upon the exchange. Evaluating the position where the photons are scattered (cf. Fig. 3) indicates that most photons are scattered in the parts of the support in the primary beam. Exchanging the material of the support liners with lighter materials reduces the radiation scattered in the scintillator support only marginally, but a larger amount of radiation is scattered back by the walls [12]. Increasing the dimensions of the box permits a substantial reduction of the scattering. Therefore, in the new setup the dimensions of the box are increased and the liners are exchanged by CFRP.

Figure 2: Fraction of scattered radiation detected in scintillator for different configurations. Starting point is the initial, non-optimised setup as depicted in Fig. 1 (left). An exchange of the scintillator support yields a significant reduction of the scattered radiation, whereas the contribution of the walls increases due to the loss of the strong beam stopping power of the scintillator support. The contribution of scattered radiation may be further reduced by exchanging the mirror and lining of the walls.

Figure 3: Number of photons depositing energy in the scintillator and scattered in individual parts of the detector. (left) Non-optimized detector design with steel-lead liners (right) Detector designed for reduced environmental scattering. Key features of the new detector are the increased geometric dimensions as well as the replacement of dense materials in the primary beam by thin liners of carbon fibre reinforced polymers (CFRP).
3.2 Optimisation of mirror support and wall lining
Lining the walls with thick layers of lead (50 mm thickness) reduces the backscattering from the walls less effectively than a bimetallic liner of 1 mm tin and 2 mm lead. This bimetallic liner material outperforms all other combinations examined elsewhere [12] for the given setup, source energy and filtration. Please note here that for different applications another combination might be more effective.

Besides the scintillator support and the walls, the mirror causes substantial backscattering. In simulations, an substitution of the glass support of the mirror (thickness 2.8 mm) with a polycarbonate liner of 1.5 mm thickness reduces the back scattering contribution by 70 %. The reflective layer (thickness 20 µm) has only a marginal influence [12]. In the experiment, the mirror with the glass support was exchanged with a mirror based on a reflective foil. Compared to the initial setup, the contribution of radiation scattered in the environment is reduced by 81 ± 4 % if both the scintillator support and the mirror matrix are exchanged and the walls are lined with the bimetallic layers.

Besides the total contribution of scattered radiation to the deposited energy in the scintillator, the spatial distribution is investigated (cf. Fig. 4). Remarkably, the distribution of environmentally scattered radiation displays only a small spatial variation. The increase of the strength at a higher vertical position may be explained by the shorter distance of these scintillator parts to the mirror.

![Figure 4: Vertical profile through simulated transmission image of an aluminium parallelepiped with 19 cm depth. Compared is the total transmission signal with the contribution of signal arising from detected photons scattered in the environment. The environmental scattering displays only a marginal spatial dependence, which may be attributed to the fact that at a higher vertical position the mirror is substantially closer to the scintillator than at a lower position.](image)

3.3 Experimental validation
In Fig. 5, a cross-sectional cut through the step with a diameter of 160 mm is compared for both setups. The grey level profile of the optimised measurement indicates an improved contrast and displays less noise compared to the analogous profile from the measurement of the non-optimised setup. Quantitatively, the contrast $C$ is calculated here as $C = (A_{Al} - A_{Hole})/A_{Hole}$ with $A_{Al}$ the average grey value in the profile of Fig. 5.c) for positions with an absolute value between 15 mm and 25 mm and $A_{Hole}$ the average grey value for positions with an absolute value below 5 mm from the centre of the hole. For the non-optimised setup, this yields a contrast value of $C = 1.4 \pm 0.3$ and, for the optimised setup, a value of $C = 1.9 \pm 0.3$ is determined, which corresponds to an increase of 36 %. This improvement of the contrast is in agreement with the reduction of environmental scattering predicted in-silico [12].
3.4 Effect of algorithmic scatter correction on image contrast

Although the instrumental redesign reduces environmental scattering substantially, the tomographic slices through the larger steps still display cupping artefacts (cf. Fig. 6 (left)). Applying the correction formula derived in section 2.5 with an optimised value of the scattering contribution $T_{env}$ corrects most of the cupping artefacts (cf. Fig. 6 (right)). The largest two steps display a high level of noise in the image grey values, which arises from the strong influence of noise on the logarithm of the transmission value (input for the reconstruction process) [13]. A common quality criterion for the reconstruction image is how much the grey values in the hole recover the grey value of air. As a figure of merit, the contrast $D = (A_{Al} - A_{Hole})/A_{Al}$ with $A_{Al}$ and $A_{Hole}$ defined as in section 3.3 is considered (the attenuation of air is assumed to be 0) and the values displayed in Table 1 are obtained. All contrast values for the corrected measurements outperform the corresponding values of the non-corrected measurement. For the steps with more than 160 mm diameter, the contrast increases by more than a factor of 2.4. A drawback of the correction procedure is that the noise in the grey level profiles increases (manifest by the increased standard deviation of the contrast values). An analysis of the influencing factors on the optimum value of the scattering contribution $T_{env}$ indicates that for a large class of objects the parameter $T_{env}$ may be estimated from the projection data [13].
Table 1: Step height values extracted for the aluminium step cylinder prior and after correction (cf. Fig. 6).

<table>
<thead>
<tr>
<th>Contrast</th>
<th>Level</th>
<th>Non-corrected</th>
<th>Corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40</td>
<td>0.93 ± 0.07</td>
<td>0.95 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.923 ± 0.007</td>
<td>0.967 ± 0.006</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>0.845 ± 0.008</td>
<td>0.953 ± 0.006</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.73 ± 0.01</td>
<td>0.922 ± 0.009</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>0.59 ± 0.01</td>
<td>0.90 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>0.30 ± 0.02</td>
<td>0.72 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.13 ± 0.03</td>
<td>0.42 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>0.09 ± 0.04</td>
<td>0.28 ± 0.12</td>
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</table>

4. Conclusion
Medium and high energy X-ray computed tomography may suffer from artefacts caused by radiation scattered in the object and the environment. In this paper, the contribution of the system components to environmental scattering is investigated and a simple correction procedure for the contribution of (environmental) scattering is evaluated.

Optimising the system components for low environmental scatter permits a reduction of environmental scattering by more than 80%. Key element for this reduction is to remove as much as possible elements from the primary beam, build the exposed elements by light materials permitting low wall thicknesses (such as carbon fibre reinforced polymers) and by lining the wall with bimetallic liners reducing the backscatter (in our study a combination of 1 mm tin and 2 mm lead outperformed the other combinations). For the optimised setup, the contribution of the environmental scattering for the investigated object is mostly spatially isotropic. To correct these scattering contributions, a simple procedure based on the assumption of a constant background is presented, which is applied on the projection images prior reconstruction. An evaluation of different test samples indicates that the estimation of the background strength has a strong influence on the effect of the correction. This observation explains why the substantial reduction of the environmental scattering by the system redesign yields a mediocre numerical improvement of the contrast. But for a substantial improvement of the image quality, the combined action of system redesign and correction algorithm is required.
References


