A comfortable procedure for correcting X-ray detector backlight

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Abstract. A novel approach is suggested to strongly suppress artifacts in radiography and computed tomography caused by the effect of diffuse background signals “backlighting” of 2D X-ray detectors. Depending on the detector geometry the mechanism may be different. Either based on the optical scattering of the fluorescent screen materials into the optical detection devices or Compton or X-ray fluorescence scattering by the detector components. Consequently, these erroneous intensity portions result in locally different violations of Lambert Beer’s law in single projections (radiographs) as a function of the detector area coverage and the magnitude of the attenuation. The absorption of multiple metal sheets is investigated by monochromatic synchrotron radiation, thus excluding beam hardening. The proposed correction procedure simply requires the individual subtraction of one and the same fraction of the primary and transmitted mean intensity, as a constant (non-local) scattering mechanism is assumed.

1. Introduction
Discrepancies regarding the validity of Lambert Beer’s law of attenuation often are not detected in qualitative radiology. Since the most practical radiographic applications apply polychromatic X-rays quantitative assessment is hampered and the perceptibility of material structure, flaws of interest etc. is sufficient. Comparison to tabulated data would require knowledge of the specific combination of the incident spectrum, the irradiated material composition and the detection system response that would enable a quantitative estimation of beam hardening. We observed those discrepancies performing synchrotron CT experiments. The attenuating mass turned out to be a non-conserved quantity for all angles of projection. But this is one of the very basic prerequisites for successful reconstructions. The only two variable parameters are the detector coverage and the actual penetration length of the specimen. Furthermore, the distortions of intensity can be caused by scattering effects (arising from refraction, diffraction and incoherent Compton scattering) or by improper pixel calibration [1]. We checked our experimental findings by simple experimental setups. We only changed the sample position while keeping all other parameters constant. The causing effect of intensity distortion can be traced back to a diffuse detector based background signal, which obviously causes the violation of the absorption law.

2. Preliminary experiments – variation of the detector coverage
In order to investigate the observed effect systematically we performed an attenuation experiment at a synchrotron source. A double multilayer monochromator (coating: 150 × W(1.2 nm)/Si(1.68 nm)) was
used to monochromatize the parallel synchrotron radiation to 10 keV (band width 2%). A 7 µm Y₃Al₅O₁₂:Ce (YAG) scintillator [2] converts the X-rays into visible fluorescence light. The visible light is collected by a microscope objective and detected by a Princeton Instruments CCD camera with a Nikon objective.

The lateral position of a stack of Al sheets (total thickness \(D = 270 \mu m\), \(\mu_{Al}(10 \text{ keV}) = 64.2 \text{ cm}^{-1}\) [3], i.e. \(\mu D = 1.74\)) was varied in steps of 50 µm (see figure 1 inserts). The resulting effective attenuation coefficients determined by the conventional Lambert-Beer’s law (after removal of dark current) exhibited a strong dependence on the detector coverage: they are derived the smaller the less detector area is shadowed by the sample. The largest observed relative difference amounts to 5.5 %. \(\mu\) is measured too low all over the shaded detector area and the deviation is most pronounced near the materials edge. The monochromatic set-up allows the comparison to tabulated values: We obtain nearly ideal congruence for the full detector coverage.

3. Variation of the penetrated thickness
We now choose tin foils of 12.5 µm thickness whose number \(N\) is successively increased from 1 to 8 in single images series. The experimental conditions were identical to section 2 except for the photon energy applied (15 keV) and the detector fluorescent screen (50 µm CdWO₄ on a YAG substrate).

The attenuation coefficient of tin (\(Z = 50, \rho = 7.3 \text{ g/cm}^3\)) at 15 keV is \(\mu_{Sn} = 340.5 \text{ cm}^{-1}\) [3]. This results in an attenuation of \(\exp(-0.425) = \exp(-\mu D)\) per single foil. By increasing the number \(N\) of foils a linear dependence \(N(\mu D)\) is expected. This is examined as an integral criterion derived from the mean values of sample and flat field measurements.

Moreover, a vertical background modulation arising from the primary beam monochromator is observed (see figure 2, radiographs \(I(x,y)\) and \(I_0(x,y)\), \(x\) and \(y\) designate the pixel coordinates of the CCD camera). Since sample and flat field measurements are performed immediately one after the
other temporal changes of the modulation can be excluded. The transmission images \(I(x,y) / I_0(x,y)\) are examined for remnants of these „multilayer stripes“ as a local criterion

3.1. Full detector coverage
Firstly, the tin foils were sized larger than the projection of the active detector area. The local and integral criterion is fulfilled in good approximation: stripe modulations and local detector irregularities are cancelled in the transmission image of a 7-fold foil stack (figure 2, top left). This is proved numerically considering the respective variances \(\sigma \) \(\sigma(I(x,y)) \sim 10 \%\) clearly exceeds the estimated \( 6 \%\) expected for a mean intensity of 300 counts, i.e. the background modulation rules the variance. In contrast the transmission image exhibits a variance of merely \(4.8 \%\). The linear dependence \(N(\mu D)\) is fulfilled as well (black dotted graph in figure 2). The mean value \((\mu D)_0\) is in very good approximation to the tabulated values \(0.430(2), \mu = 344 \text{ cm}^{-1}\) given above.

3.2. Partial detector coverage
Secondly, the tin foils were cut into sheets that covered approximately half of the detector area. Figure 2 bottom illustrates that the application of the conventional Lambert-Beer’s law yields insufficient results assessing the local and integral criterion. The transmission image detail (extracted from the covered area) clearly reveals remaining multilayer modulations. The plot of \(\mu D\) versus \(N\) from the same area is not linear. In particular the difference between the measured \((\mu D)\) and the true \((\mu D)_0\) increases as a function of the absorber thickness, i.e. the intensity is measured too large. Figure 3 compares cumulative cross sections of sample and flat field measurement. While the intensity attenuated by the sample is measured too large the magnified detail of the graphs indicates the reverse effect outside the sample’s projected area: the flat field intensity is measured app. \(3.5 \%\) larger.

4. First-order approximation: diffuse detector background - an integral approach
The partial levelling of local intensities (i.e. overweighting small and underweighting large intensity) in one and the same sample measurement immediately suggests a partial re-distribution of the locally generated fluorescent intensity to the environment. This phenomenon is named “diffuse detector background“ or “backlight“. In a first-order approximation it is assumed to be homogeneous, i.e. the re-distribution of a fraction of local intensity on the entire fluorescent screen. This fraction \(\alpha\) is assumed to be independent of excitation site and intensity and refers to sample and flat field measurement in the same way. Consequently, both are corrected additively by one and the same fraction \(\alpha\) of their individual mean values. The modified intensities permit the definition of a modified Lambert-Beer’s law:

\[
(\mu \cdot D)(x,y) = \ln \left( \frac{I_{\text{corr}}(x,y)}{I(x,y)} \right) = \ln \left( \frac{I_0(x,y) - \alpha \cdot I_0}{I(x,y) - \alpha \cdot I_0} \right), \tag{1}
\]

As demonstrated by figure 4 the appropriate selection of parameter \(\alpha\) in equation (1) satisfies the required absorption criteria for the local as well as for the integral criteria. The “multilayer modulations“ on the uncorrected transmission image \((\alpha = 0, \text{ red box})\) disappear on the modified image \((\alpha = 0.105, \text{ blue box})\). Moreover, the application of a constant \(\alpha\) to the uncorrected (red) plot of \((\mu D)\) versus \(N\) reveals the linear (blue) plot, which coincides with the plot of the full detector coverage (see black dotted line in figure 2). The only required fit condition for finding the optimal \(\alpha\) is the linearity requirement \(\text{min}(\text{var}((\mu D)/N))\) which provides the lowest curvature of the plot. The procedure reveals as well the correct attenuation coefficient \(\mu = 346 \text{ cm}^{-1}\) without any further assumptions.

The present approach includes the correct validity of the conventional attenuation law in case of full detector coverage as the local intensity modification by the diffuse background contribution is everywhere the same and thus not apparent in the quotient image. Therefore equation 1 can be applied with any \(\alpha < 1\) and \(\alpha = 0\) has a physical meaning.

The discussed procedure of integral background correction does not include local variations which may be observed in detail by figure 3, which reveals a reduced difference of \(I_{\text{flat}} - I_{\text{meas}}\) further off the
sample edge. In relation to the integral intensity deviations the minor variations of the local response are considered to be negligible. Beyond the proposed integral treatment of intensity data an alternative procedure would employ the deconvolution of raw radiographs by a suitable point spread function (PSF). Long tailed PSF were used e.g. for the correction of X-ray cone beam projections [4]. However, we discarded this approach in order to avoid numerical instabilities and the additional incorrect intensity indications as reported e.g. by Krejčí et al. [5].

Figure 3. Cumulative horizontal cross-section of the 7-fold sample stack (black) and flat field image (red): outside the sample holds $I_{\text{meas}} < I_{\text{flat}}$ (ca. 3.5 %, see inset).

Figure 4. Results of the suggested integral correction of the "backlight". For $\alpha = 0.105$ the modulations are cancelled. The (modified) Lambert-Beer’s law is valid (blue line).

5. Conclusions
The effect of diffuse X-ray detector based background intensity (backlight) is characterized by a diffusive rearrangement of the recorded intensity. It distorts the measured attenuation coefficient up to some 10% (see figure 2). It can be corrected numerically - at least for homogeneous samples. It decreases with increasing detector coverage, and increases monotonously with the sample absorption. The presented findings permit the quite general advices for all types of X-ray detectors:
- place an aperture behind the fluorescence screen (in order to reduce the detected scattering),
- adapt the primary beam cross section to the sample cross area (reduces the image dynamics),
- alternatively: measure the entire irradiated area (in order to enable numerical correction),
- perform a standard measurement by a well-known reference sample (partial detector coverage).

Although the discussed measurements have been performed by a selected detector system the presented integral correction procedure is largely independent from the detector type. Solely the amount of deficiencies will differ among various systems.

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