Energy weighted x-ray dark-field imaging

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Abstract: The dark-field image obtained in grating-based x-ray phase-contrast imaging can provide information about the objects’ microstructures on a scale smaller than the pixel size even with low geometric magnification. In this publication we demonstrate that the dark-field image quality can be enhanced with an energy-resolving pixel detector. Energy-resolved x-ray dark-field images were acquired with a 16-energy-channel photon-counting pixel detector with a 1 mm thick CdTe sensor in a Talbot–Lau x-ray interferometer. A method for contrast-noise-ratio (CNR) enhancement is proposed and validated experimentally. In measurements, a CNR improvement by a factor of 1.14 was obtained. This is equivalent to a possible radiation dose reduction of 23%.

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References and links
gle scattering strength of the object caused by differences in the real part of the refractive index [5–7]. The dark-field image shows the distribution of ultra small an-

1. Introduction

In grating-based x-ray imaging with a Talbot-Lau interferometer, three images of the object can be obtained: the usual attenuation image, the differential phase image [1–3] and the dark-field image [4]. The differential phase image displays the distribution of gradient in the projected real part of the refractive index [5–7]. The dark-field image shows the distribution of ultra small an-


on a scale smaller than the pixel size \([4,8]\). The dark-field image is thus an image of the granularity or fibrousness of the sample. It was shown that biological, human and inanimate objects with different microstructural properties can produce contrasts in the dark-field image \([9–11]\). This information on the microstructure of the sample, not necessarily accessible with standard radiography, is of special interest for an eventual application in medical imaging \([12–16]\).

A Talbot-Lau interferometer is optimized to a certain photon energy named the design energy. Photons with this energy produce an interference fringe pattern with largest contrast. With integrating flat panel detectors, typically used in projective medical imaging modalities, the individual photon energies are not resolved. Photons with energies different to the design energy contribute with lower visibility to the measured phase-stepping curves, which are obtained by sequentially acquiring images with the imaging detector and translating the analyzer grating by a part of the fringe pattern period of the design energy. As the noise of the differential phase and the dark-field images depends on the fringe visibility, energy-bands besides the design energy lower the dose efficiency. Therefore the use of a polychromatic x-ray spectrum is followed by drawbacks in image quality. Because of the energy dependence of the refractive indices and of the setups performance, adequate energy-weighting of images acquired with a photon counting detector is expected to improve image quality. Energy-weighting methods for image quality improvement were proposed for conventional attenuation imaging for example by Cahn et al. \([17]\) or Giersch et al. \([18]\). In previous publications, Talbot-Lau interferometers were combined with energy-resolving x-ray detectors for phase-contrast imaging only. It was shown that artifacts can be removed \([19]\) and that the image quality can be improved by setting optimized energy thresholds \([20]\) or by appropriate energy-weighting \([21]\). Here, we evaluate the benefit of an energy-resolving detector in x-ray dark-field imaging. A method for contrast-to-noise ratio improvements in x-ray dark-field imaging is presented, using the energy-resolving Dosepix detector with a 1 mm thick CdTe sensor.

2. Materials and methods

The Dosepix-detector \([22]\) is a hybrid photon-counting pixel detector with a \(16 \times 16\) pixel matrix. The pixel pitch is \(220 \mu m\), resulting in an active area of about \(3.5 \times 3.5 \text{mm}^2\). In this experiment, the Dosepix was bump-bonded to a 1 mm thick CdTe sensor layer by the Freiburger Materialforschungszentrum (FMF). The sensor layer is biased for electron collection in the pixel electrodes. In the pixel cell, the current induced by the drifting charge carriers is amplified and shaped. The time of the preamplifier output pulse exceeding an analog threshold is a measure of the pulse height and therefore of the deposited energy. In the detector pixel, this time is obtained by counting the clock cycles of a 100 MHz clock. This so-called Time-over-Threshold (ToT) value is then compared to 16 individually set digital ToT-thresholds in the pixel cell. Each pixel is equipped with 15 counters that are incremented if a photon is detected whose ToT is between the lower and upper threshold of the corresponding energy channel. A 16th counter is incremented if the highest threshold is exceeded. The relation between ToT and deposited energy is not exactly linear and varies among the pixels \([23]\). This dependence of ToT on deposited energy was determined prior to the measurements by illumination with x-ray photons from fluorescence targets and radioactive \(\gamma\)-sources. The digital thresholds were set to values equivalent to energies from 15 keV to 60 keV in 3 keV steps. The measurements were carried out with a tungsten anode medical x-ray tube operated at 60 kVp. So the 16th energy-channel was excluded from analysis as it only records events corrupted by analog pile-up. Pile-up occurs if the analog signal caused by two photons overlap in time and are then classified as one event of higher energy. To reduce analog pile-up in the detector, the tube current was set to 1 mA. This provided a detection rate of about \(10^4\) counts per second and pixel, where a sufficient count-rate linearity is given \([24]\). For generation of the x-ray images, we used the central region
of the detector with $10 \times 10$ pixels, as the edges of the sensor suffer from increased noise. In Fig. 1 a picture of the CdTe Dosepix assembly is shown.

![Image of CdTe Dosepix assembly](image)

Fig. 1. Photography of the first CdTe Dosepix assembly during manufacture. The ASIC was not wire-bonded to the circuit board at this point.

A three grating Talbot–Lau type x-ray interferometer was set up in order to acquire dark-field images of a 2.7 cm thick Melamine sponge. Figure 2 shows a sketch of the experimental setup. The source grating $G_0$ divides the incoming x-ray field into multiple slit sources. The second grating $G_1$ is a $\pi$-shifting phase grating for a design energy $E_{\text{design}}$ of 40 keV. According to the Lau-effect, for each slit-source a Talbot self-image is produced. The analyzer grating ($G_2$) in front of the detector was placed in the third fractional Talbot order. The grating $G_0$ ($G_1$, $G_2$) was made of Au (Ni, Au), had a period of $p_0 = 6.97 \mu m$ ($p_1 = 3.57 \mu m$, $p_2 = 2.4 \mu m$), and had a height in beam direction of 120 $\mu m$ (14 $\mu m$, 80 $\mu m$). $G_1$ ($G_2$) is positioned 60.2 cm (80.9 cm) downstream from $G_0$. The object was placed in short distance upstream of $G_1$. By incremental movement of $G_2$ by 10 steps over two periods $p_2$ of $G_2$ the interference pattern was sampled. The acquisition time for each of the ten phase-steps was 3 s. For each pixel and energy channel,
Fig. 3. Spectral behavior of the visibility measured in the Talbot-Lau interferometer with a design energy of 40 keV. The visibility influences the image quality in phase-contrast and dark-field x-ray imaging. The errorbars are not visible due to the small statistical error of the measurement.

A phase-stepping curve was obtained. In the following, quantities obtained with the object are indicated with the superscript obj. A Fast-Fourier-Transform of the sinusoidal phase-stepping curve in an energy channel $i$ gives its amplitude $A_i^{\text{obj}}$ and average value $\bar{N}_i^{\text{obj}}$ measured in number of counts. The identical measurement- and analysis-protocol was then carried out again, but without the melamine sponge in the beam to correct for grating-inhomogeneities among the pixels. This reference measurement is referred to with the superscript ref. Thus images of the visibility $V_i^{\text{ref}} = A_i^{\text{ref}} / \bar{N}_i^{\text{ref}}$ without the sponge were obtained. For our setup, Fig. 3 shows the measured reference visibility of the phase stepping curves obtained in the energy bins. The data was averaged over all pixels and 100 repetitions of the measurements. Due to this high number of measurements the statistical error is not visible in the errorbars. It can be seen that the largest visibility is measured close to the nominal design energy of 40 keV. Towards higher energies the visibility decreases significantly. The plateau of the visibility observed at lower measured energies is due to charge-sharing among neighboring sensor pixels. Here the charge carriers generated by a photon are spread over the pixel-borders thus triggering several pixels. In these cases the reconstructed energy of the event is corrupted and events are registered wrongly with lower energy. Additionally, the production of fluorescence photons of Cd or Te after K-shell photoelectric effect and their detection in neighboring pixels leads to a distribution of the primary energy over several pixels. These effects distort the visibility information at low measured energies. The influence of analog pile-up becomes visible in the two highest energy bins, showing increasing visibility. The dark-field signal is commonly defined as the normalized visibility $D_i \equiv V_i^{\text{obj}} / V_i^{\text{ref}}$ [4] where $V_i^{\text{obj}}$ denotes the measured visibility with the object. Thus we also define the dark-field image $D_i$ in energy-channel $i$ as

$$D_i \equiv \frac{V_i^{\text{obj}}}{V_i^{\text{ref}}}, \quad (1)$$

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To investigate the influence of energy-weighting not only on the dark-field signal but also on the image contrast, a second dark-field image was acquired in air. Therefore two additional phase-stepping acquisitions were done without the sponge. From these, an air dark-field image \( D_{\text{air}} \approx 1 \) was calculated. Comparing the two images – one with \( D_{\text{sponge}} \) and one without the sponge \( D_{\text{air}} \) – the contrast was investigated.

The complete experiment described above was repeated 100 times. Thus, 100 energy-resolved dark-field images of the sponge and 100 of air were acquired.

Furthermore, for each pixel and repetition, the sum of the measured spectrally resolved phase-stepping curves over all energy channels was calculated. This way, phase-stepping curves of an emulated single-threshold photon-counting detector were obtained. Next, dark-field images with and without the sponge were processed from the summed phase-stepping curves. These images are indicated with the subscript C (for counting) in the following.

We assign a weight \( w_i \) to the dark-field value measured in energy channel \( i \) and calculate a weighted average \( D_W \) of the dark-field signals \( D_i \) of the energy channels:

\[
D_W = \frac{1}{\sum w_i} \sum w_i \cdot D_i.  \tag{2}
\]

To incorporate the energy-dependence of the dark-field sensitivity on the one hand and that of the image noise on the other hand, we choose the ansatz

\[
w_i = \frac{(E_i/E_{\text{design}})^k}{\sigma^2(D_i)} \tag{3}
\]

with an a-priori unconstrained spectral index \( k \). \( \sigma^2(D_i) \) is the variance of the dark-field signal \( D_i \) expected from statistical fluctuations. According to [25–27] \( \sigma^2(D_i) \) can be calculated as

\[
\sigma^2(D_i) = \frac{(V_{i,\text{obj}})^2}{N_{i,\text{ref}}^2 (V_{i,\text{ref}})^2} \left( \frac{2}{(V_{i,\text{ref}})^2} + 1 + \frac{2}{T_i (V_{i,\text{obj}})^2} + \frac{1}{T_i} \right) \tag{4}
\]

with the transmission \( T_i \) of the object. \( T_i \equiv N_{i,\text{obj}} / N_{i,\text{ref}} \) is defined as the ratio between the number of detected photons of the object and the reference measurement in each energy channel \( i \). \( \sigma^2(D_i) \) is calculated from the measured visibilities and number of detected photons for each pixel, energy-channel and repetition separately. This choice for \( \sigma^2(D_i) \approx 1/w_i \) leads to the assignment of stronger weights to dark-field values of energy channels measuring smaller visibilities \( V_{i,\text{obj}} \) (stronger dark-field signal) because for given \( V_{i,\text{ref}}, N_{i,\text{ref}} \) and \( T_i \) the variance \( \sigma^2(D_i) \) decreases monotonously with decreasing \( V_{i,\text{obj}} \). The functional dependence of \( \sigma^2(D) \) on the photon energy depends on many parameters: charge-sharing among the pixels, the impinging spectrum, the transmission of the object as a function of energy, and the functional dependence of the reference visibility \( V_{i,\text{ref}} \) on photon energy which is governed by the interferometer setup (see Fig. 3).

Due to the energy dependence of the dark-field signal [8] we expect a larger scattering strength for low energy photons. To take this into account, the factor \( (E_i/E_{\text{design}})^k \) is included in \( w_i \). For \( k < 0 \) a stronger weight is assigned to lower energies which enhances the dark-field sensitivity.

### 3. Results

The energy-weighting was applied to the measurements with and without the sponge, for each pixel and for each repetition. For the 100 image pairs \( D_{\text{sponge}} \) and \( D_{\text{air}} \) the CNR was calculated.
This was carried out for the energy-weighted as well as for the photon-counting dark-field images. We use the CNR defined as [28, 29]

$$\text{CNR} = \frac{|D_{\text{pompe}} - D_{\text{air}}|}{\sqrt{s^2(D_{\text{pompe}}) + s^2(D_{\text{air}})}},$$  \hspace{1cm} (5)

where $D_{\text{pompe}}$ and $D_{\text{air}}$ denote the average value of the dark-field signals in the image ($10 \times 10$ pixels) for each pair of repetitions. $s^2(D_{\text{pompe}})$ and $s^2(D_{\text{air}})$ denote the ensemble variance of the signals among the $10 \times 10$ pixels in the corresponding measurement. The averaged contrast-to-noise ratio ($\langle \text{CNR} \rangle$) over the 100 repetition pairs was then calculated. Its uncertainty is given by $\Delta \langle \text{CNR} \rangle = s(\text{CNR})/\sqrt{100}$ where $s(\text{CNR})$ is the standard deviation of the distribution of the CNRs among the 100 repetition pairs.

The average CNR with the (non-weighted) photon-counting analysis resulted in

$$\langle \text{CNR}_C \rangle = 9.4 \pm 0.1.$$  \hspace{1cm} (6)

The contrast-to-noise ratio was calculated with the energy-weighting method for various spectral indices $k \in [-4, 2]$. Figure 4 shows the obtained, average CNR for the energy-weighting method as a function of the spectral index $k$. By fitting a parabola (red curve in Fig. 4) to the data points, a maximum of

$$\langle \text{CNR}_W \rangle = 10.7 \pm 0.1$$  \hspace{1cm} (7)

was found for a spectral weighting index of $k = -0.77$. This corresponds to a 13.8% higher CNR compared to the emulated single-threshold photon-counting detector.

The distribution of all dark-field values of 100 pixels in 100 repetitions with the object and without the object is shown in Fig. 5. The distribution for the air image $D_{\text{air}}$ is centered at
a dark-field value close to one. The values of $D_{\text{sponge}}$ are distributed around a dark-field of about 0.5. The widths of both distributions – with and without sponge – are reduced by the weighting-technique (red) compared to the photon-counting emulation (blue).

4. Discussion

In particular the width of the distribution measured in air is reduced by 22%, the width of the sponge’s distribution by 23%. This demonstrates, that energy weighting reduces statistical fluctuations of the signal. Additionally, the distance between the red peaks is increased. The optimal spectral weighting index of $k = -0.77$ gives stronger weight to the low energy bins. This exhibits a stronger signal (lower visibility) due to the energy dependence of the dark-field [8]. The preference of energy bins with smaller measured visibilities (stronger dark-field signal) by the energy weighting procedure manifests in the slight deviation of average value from 1.0 (see red peak on the right-hand side in Fig. 5). As was stated above, a stronger weight is given to energy channels measuring smaller visibilities $V_i^{\text{obj}}$ thus reducing the overall dark-field value calculated via Eq. (2). This optimization slightly shifts the distribution of the calculated $D_{\text{air}}$ towards stronger dark-field signals (smaller values). For the counting method, the distribution of $D_{\text{air}}$ is centered at 1.0 for the counting method which would be expected without energy weighting.

The distance of the peaks is increased by 3% from 0.437 to 0.451. This gain is small compared to the improvement in noise which manifests in reduced peak width. The optimal $k$ of $-0.77$ is not a very strong weight. In comparison, weighting factors proportional to $E^{-3}$ are found in attenuation imaging [17,18] and proportional to $E^{-2}$ for phase-contrast imaging [21]. Also in this measurement the index of $k = -0.77$ had to be determined iteratively. This was necessary as the expected energy-dependence of the dark-field signal is object dependent [8]. Moreover the obtained $k$-value can not be linked to a physical quantity as the measurements are corrupted by charge-sharing and analog pile-up. However, the sensitivity of the energy-weighted dark-field calculation is enhanced and the noise reduced. Both effects lead to the
improvement of the CNR. From this improvement the relative saving in radiation dose can be projected. With Eq. (4) the expected uncertainty of a dark-field measurement can be calculated by using the measured visibility, number of photons and transmission [25–27]. This value is equivalent to the variance calculated from an ensemble of pixels in a homogenous image region. So the expected noise of a dark-field image can be calculated using this formula. This means that the noise standard deviation \( s(D) \) of a dark-field image \( D \) is proportional to the expected Poisson noise, \( \sigma(D) \propto 1/\sqrt{N} \). Furthermore the \( \text{CNR}^2 \) (compare Eq. (5)) is proportional to the number of impinging photons \( N \) and therefore to the radiation dose. Under these conditions we can transfer the gain in CNR to a possible dose saving similarly to attenuation imaging [29]. From the CNR values obtained here it can be seen 23% of the dose could be saved with the proposed weighting method.

5. Conclusion

X-ray dark-field images were acquired using a Talbot-Lau grating interferometer combined with a multi energy-channel photon-counting detector. With the additional energy information, we were able to enhance the image quality by applying weighting factors to the images recorded in the energy channels. To evaluate the improvements, CNRs were calculated after performing the proposed method and additionally for an emulated single-threshold photon-counting detector. An increase in CNR by about 14% was observed. As the \( \text{CNR}^2 \) is linked to the radiation dose, the application of such an energy-sensitive detector is attractive especially for medical applications. The achieved CNR-improvement can be used to quantify the possible dose reduction. In this experiment, for an identical CNR, an energy-weighted dark-field image could have been acquired with only 77% of the radiation dose needed with a single-threshold detector. This shows the advantage of energy resolving photon-counting detectors in x-ray dark-field imaging.

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