



Visibility retrieval and spatial dark-field resolution in DP-XGI

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Abstract: There has been a rising interest in multi-scale imaging of materials and structures. However, conventional X-ray-based imaging methods are fundamentally limited by the discretization of the image, causing a direct coupling between pixel size and field of view. Through small-angle scattering, X-ray dark-field (DF) imaging is sensitive to the sub-pixel structure of the sample being imaged, overcoming this limitation. In grating-based dark-field imaging, the DF signal is operationally defined as the relative change in visibility of the interference pattern in each pixel, which is commonly probed via the process called phase stepping. We show through simulations that the real-space DF resolution in dual-phase X-ray grating interferometry (DP-XGI), for which the interference pattern is directly resolvable, is limited by the fringe period, being larger than the pixel size. We therefore propose a single-shot visibility retrieval algorithm for DP-XGI, which does not require precise phase stepping and is by design restricted to the real-space resolution given by the fringe period. The simulation demonstrates that minimal physical information is lost with a single shot. It is argued that phase-stepping in DP-XGI has only limited benefit compared to single-shot, while it comes at the cost of more complex measurement.

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1. Introduction

When irradiating a sample with a beam of X-rays, the internal structure of the sample is conventionally studied through the attenuation of the X-ray beam [1]. This is due to the fact that X-rays can penetrate matter, but are attenuated according to the Lambert-Beer law, revealing contrasts in electron density along different raypaths. In recent years, new modalities have been developed to extract additional information, including from X-ray small-angle scattering (SAS). The scattering angles at which statistically more photons are directed through SAS, yield clues about how the material is structured on a sub-micron scale. This is measured directly in the experimental method SAXS [2,3], which requires dedicated instrumentation, making high-resolution imaging difficult. X-ray Dark-field (DF) imaging is a technique which attempts to exploit how SAS in a sample modifies the image of a mask or an interference pattern. This allows for the attenuation image to be retrieved simultaneously with the SAS (and often also phase shift) image. As illustrated in Fig. 1, detector pixels where the same attenuation signal might be found, can have a different sub-pixel structure. The sub-pixel information which DF imaging is tuned to, is statistical in nature, relating to the autocorrelation function of the electron density evaluated at a probed correlation length [4]. This way, DF images can contain information originating from the nanoscale structure while keeping the whole sample in the FOV, which can be centimetre-scale. This enables multi-scale analysis, having applications in medical imaging [5–7] and material science [8,9].

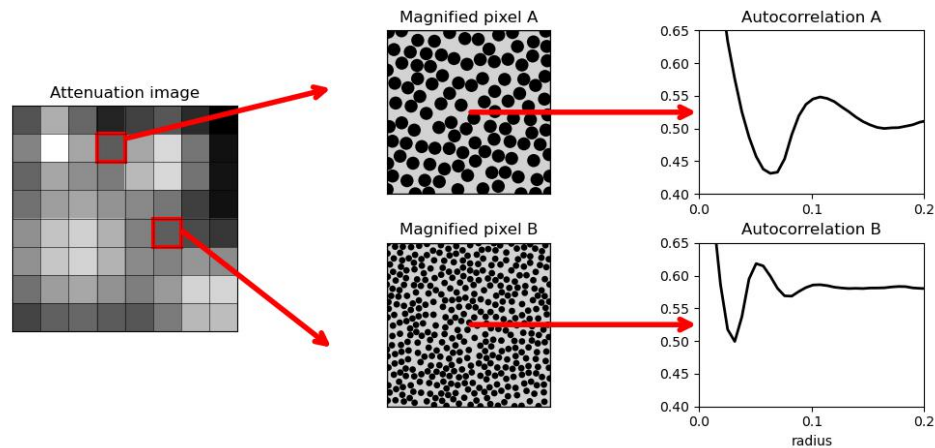


Fig. 1. Illustration of the sub-pixel structure information in DF. In an attenuation image, two pixels may have a similar grey value, despite their sub-pixel nanostructure being different. By scanning the correlation function, a model nanostructure's correlation function may be fitted to extract some parameters, e.g. the nanosphere diameter in this illustration. Fixed-geometry DF imaging setups only have one specific radius available to probe the autocorrelation function.

There are multiple experimental techniques to measure the DF signal. Speckle-based imaging is an approach which tracks the blurring of (often disc-shaped) images of attenuation masks to reconstruct the SAS [10–12]. Talbot-Lau interferometry (TLI) exploits the Talbot and moiré effects using gratings [13,14]. Circular diffractive optics combine properties of both, and can result in directional DF due to circular symmetry [15]. In each of these methods, a specific configuration of the setup geometry is sensitive to detecting a particular correlation length range. In the illustration Fig. 1, this implies selecting a specific radius in the autocorrelation plots, and measuring the DF at that autocorrelation length. To change the probed correlation length and scan a range of the autocorrelation function, these setups require the sample position to change, affecting the setup geometry. Particularly in lab-based cone-beam imaging, sample repositioning causes a change in the magnification, limiting the available FOV and changing the effective pixel size (pixel size divided by magnification). Dual-phase X-ray grating interferometry (DP-XGI), on the other hand, is a technique applicable to lab-based sources in which the correlation length can be scanned without changing the sample position, in fact by harnessing the cone-beam geometry [16]. This makes it possible, after taking spectral effects such as beam- and visibility hardening into account [17], and adjusting for the macroscopic scattering cross-section, to fit a model of the projected autocorrelation function to the retrieved DF as a function of the inter-grating distance on a pixel-wise basis. This yields the parameters of the modelled nanostructure in an image format, i.e. quantitative DF imaging [18]. For comparison, SAXS, by measuring scattered intensity as a function of scattering angle, achieves this averaged over the illuminated volume.

In DP-XGI, interference patterns of two phase gratings are recorded. SAS, caused by a sample in the beam, affects the interference patterns formed by the gratings with microscopic pitch (G_1 , G_2) by lowering their visibility predictably [19,20]. Due to the cone-beam geometry of the microfocus source (S), the Talbot pattern of the second grating (G_2), which is placed just behind G_1 , will have a slightly magnified period in the x -direction. The interplay between the two patterns with slightly mismatched period, causes moiré fringe patterns with a period p_{fr} at the X-ray detector (D) level, that can be large enough to be directly resolved [16]. These elements are shown in Fig. 2. By quantifying the position-dependent reduction of the fringe visibility caused

by a sample, compared to the reference pattern, the DF image can be retrieved on a cm-scale object.

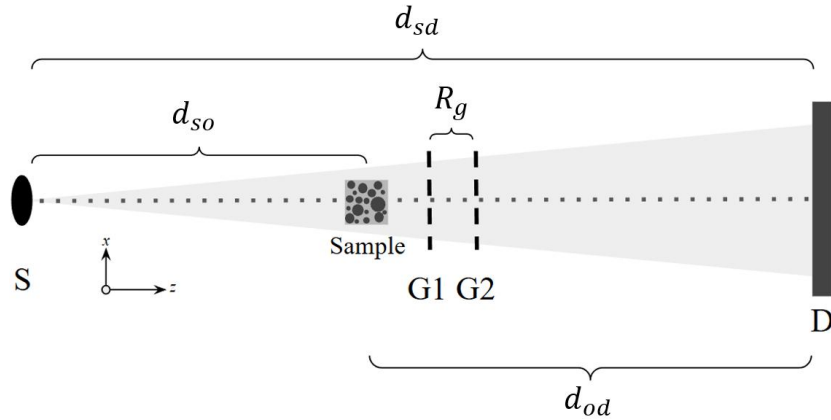


Fig. 2. Setup of DP-XGI. Geometrical distances needed in this work are indicated. Not to scale. The grating lamellae are parallel to the y -axis and perpendicular to the x -axis.

The distance between the two gratings (denoted R_g in this work) determines the period of the fringe pattern on the detector (p_{fr}), which is a factor defining the probed correlation length (ξ_l). This parameter is the argument of the real-space projected autocorrelation function of scattering centres in the sample, and thus connected to structural information on this scale. By changing R_g , access to this structural information in sub-micron range can be obtained [16,21].

By analysing a series of DF images from a scan of R_g and measuring the autocorrelation function, DP-XGI promises to yield quantitative information about a sample on a sub-micron scale, while maintaining a macroscopic field-of-view. The SAS information is the same type of information, as measured by a SAXS experiment [3], though so far less accurate and detailed. However, it can do so with simpler equipment, and in a full FOV on a pixel-wise basis, rather than in one average curve for the whole illuminated sample region. Development of quantitative DF imaging with DP-XGI has been the subject of recent research [18,22,23].

The conventional technique to perform signal retrieval, is by phase stepping (PS). This requires one of the gratings, conventionally G2, to be moved along the x -direction. The displacement must be precise and reproducible, while being a fraction (1/8 has been used in previous work) of the grating period. It will be shown in this work that while a signal is retrieved in each pixel, this does not mean that the spatial resolution of the DF image is primarily determined by the pixel size. It will be shown that neighbouring DF pixels are correlated and the actual spatial resolution in a DF image corresponds to the fringe period. Another technique is proposed, single-shot (SS) that is experimentally more simple due to not requiring this precise motorisation. However, it has a built-in resolution limitation of the retrieved images determined by the fringe period. Due to a similar spatial resolution limitation of the DF image in PS, we show that minimal physical information is lost by replacing phase stepping with SS for DF imaging.

2. Theory

2.1. Monochromatic DP-XGI patterns and relation to microstructure

Assuming the two phase gratings are parallel to the y -axis in the geometry indicated by Fig. 2, an idealised calculation leads to a model of the fringe pattern that depends on the inter-grating distance R_g and photon energy E [24]. To second order, the model intensity profile I_r of the interference patterns recorded on the detector plane when using a monochromatic beam, is given

by a weighted sum of periodic signals:

$$I_r(R_g, E, x, y) = a_{0,r}(E, x) \left(1 + V_{1,r}(E, R_g, x) \cos \frac{2\pi x}{p_{fr}(R_g)} + V_{2,r}(E, R_g, x) \cos \frac{4\pi x}{p_{fr}(R_g)} \right), \quad (1)$$

where $a_{0,r}$, $V_{1,r}$, and $V_{2,r}$ are conventionally called the reference visibility coefficients. The subscript r denotes that there is no sample present. In principle, higher order coefficients also could be included, but they do not significantly contribute in practice [25,26]. The x -axis is indicated in Fig. 2. The fundamental period of the fringe pattern p_{fr} on the detector plane depends on R_g , the source-to-detector distance d_{sd} and the period of the gratings p_g :

$$p_{fr}(R_g) = p_g \frac{d_{sd}}{R_g}. \quad (2)$$

The monochromatic fringe image when a sample is put in the beam, I_s , is parametrised with the T - and D_l -functions in the following expression:

$$\begin{aligned} I_s(R_g, E, x, y) &= T(E, x, y) a_{0,r}(E, x) \left(1 + D_1(R_g, E, x, y) V_{1,r}(E, R_g, x) \cos \frac{2\pi x}{p_{fr}(R_g)} \right. \\ &\quad \left. + D_2(R_g, E, x, y) V_{2,r}(E, R_g, x) \cos \frac{4\pi x}{p_{fr}(R_g)} \right), \\ &= a_{0,s}(E, x) \left(1 + V_{1,s}(E, R_g, x, y) \cos \frac{2\pi x}{p_{fr}(R_g)} \right. \\ &\quad \left. + V_{2,s}(E, R_g, x, y) \cos \frac{4\pi x}{p_{fr}(R_g)} \right). \end{aligned} \quad (3)$$

The T -signal is the transmission function, and D_l the visibility reduction function at l -th order, $l = 1, 2$. As seen in this expression, the intensity is lowered on a per-pixel basis by the transmission function T and the visibility at l -th order by the visibility reduction function at l -th order D_l . The transmission function is formulated as a path integral over the beam-path of the position-dependent material constant mass attenuation coefficient μ/ρ [27], and density ρ :

$$T(E) = \exp \left(- \int \mu/\rho(E, x, y, z) \rho(x, y, z) dl \right). \quad (4)$$

The visibility is lowered by SAS. The visibility reduction function D_l depends on R_g due to its dependence on the correlation length ξ_l , which in turn is a function of R_g :

$$\xi_l = l \frac{hc}{E} \frac{d_{so}}{d_{sd} p_g} R_g, \quad (5)$$

with h being Planck's constant, c the speed of light, and d_{so} the source-to-object distance. Similarly to intensity reduction, visibility reduction originates from interactions with the material described by an exponential coefficient, $\mu_{d,l}$ as [4]:

$$D_l(R_g, E) = \exp \left(- \int \mu_d(\xi_l, E, x, y, z) dz \right). \quad (6)$$

μ_d relates to the macroscopic scattering cross-section σ and real-space projected auto-correlation function $G(\xi_l)$ of scatterers, and is specifically defined as:

$$\mu_d(\xi_l, x, y, z) = \sigma (1 - G(\xi_l)), \quad (7)$$

wherein both σ and $G(\xi_l)$ are position- and energy-dependent, and G can have a directional dependency (direction of the y -axis) due to anisotropic scattering. Both T and D_l can be extracted from the monochromatic pattern by dividing respectively the retrieved coefficients a_0 and V_l before and after placing the sample in the beam (resp. subscript r for 'reference' and s for 'sample').

2.2. Visibility retrieval & spatial resolution

In TLI, the standard way to retrieve visibility is through phase stepping (PS) [14], which has also been adopted for DP-XGI [16]. The procedure requires one of the gratings to be stepped along its period as indicated by Fig. 3. This causes the recorded fringe pattern to shift. The 2D pattern is recorded at several steps, such that a datacube with shape (n_x, n_y, n_{steps}) is retrieved from the measurement. For each of the $n_x \times n_y$ pixels, the third dimension is called the phase stepping curve (PSC), covering a full period. Visibility coefficients can be retrieved from Fourier decomposition of the PSC in each pixel [9,14,18,28]. As the period of the grating was $1\mu\text{m}$ in previous setups [16,26], the phase stepping motors must be precise down to nm-scale.

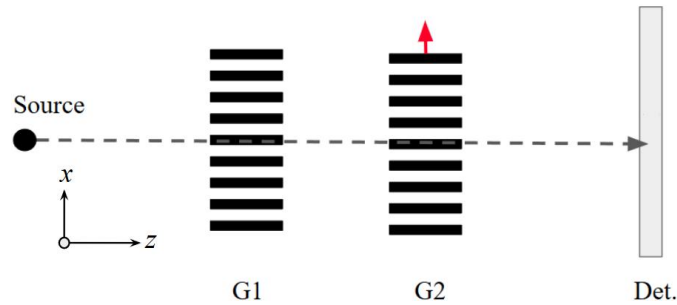


Fig. 3. Illustration of phase stepping. G2 is moved in the transverse direction along one period, causing the fringe pattern to shift along its period on the detector. Not to scale.

When a fringe pattern is created with a period large enough that it is directly resolvable, one can also retrieve the visibility coefficients per pattern period from an individual exposure, rather than per pixel from multiple phase steps. This is then called single-shot (SS) visibility retrieval. A similar approach has been used in TLI [28]. From a practical viewpoint, it is simpler to not have to perform phase stepping, as this requires an additional, high-precision motor and more measurement time. Uncertainty in the shift for the grating is a potential source of measurement error or artefacts. The trade-off for this reduced experimental difficulty, is the apparent and often assumed reduction in the DF image spatial resolution.

The term ‘resolution’ must be clarified in the context of DF imaging, by which we denote the variation of SAS behaviour over the field-of-view and not the size of the scattering features themselves. In DP-XGI, the system is tuned to a specific correlation length (corresponding to a real-space size range of these scattering features) by changing the inter-grating distance R_g . However, at the same time the fringe period p_f also changes. In SS, the resolution of the retrieval method is manifestly limited by this period. In PS, on the other hand, a PSC is analysed for each detector pixel. However, similar to a focal spot size effect in conventional imaging [29], the pixel size is only a limiting factor, and it is better to quantify the true resolution. In accordance with conventional methods, the ‘spatial resolution’ will be defined as the FWHM of the first derivative of the edge response in this work. The first derivative of the edge response is known as the point spread function, which is used to quantify the sharpness in conventional imaging. The research question this work addresses, is whether using SS instead of PS reduces the spatial DF resolution. The hypothesis is that in PS, there is still a spatial resolution limit of the DF image that is larger than the pixel size, and there is minimal loss in spatial resolution in the resulting DF images when using SS instead.

3. Materials & methods

3.1. Simulation

Based on earlier work, the wave propagation simulator by Tang et al. [18] will be extended to investigate a simulated sample.

One virtual sample is initially constructed as a box filled with SiO_2 monodisperse diluted nanospheres (MDNs), with a height of $25\ \mu\text{m}$ along the y -axis, width of $1000\ \mu\text{m}$ along the x -axis, and thickness of $500\ \mu\text{m}$ along the z -axis i.e. the optical axis (same reference frame as in Fig. 2 and 3). The MDN diameter is set to $500\ \text{nm}$, and the volume fraction is 5%. The spheres are suspended in vacuum. Two scenarios are simulated: one with a box completely filled with MDNs, and one with a half-filled box, as illustrated in Fig. 4 (b) and (c). In DF imaging, a transition is to be expected between maximal and zero signal in the half-filled case, due to the absence of nanostructure in the empty half. The retrieved signal difference between the full and the half-empty box can be compared to assess the spatial resolution. While the simulated interference patterns will have a different visibility depending on the structure of the sample, the visibility retrieval algorithms merely distinguish the visibility coefficients as defined in Eq. (1) and Eq. (3). MDNs are chosen to constitute the test sample due to their simplicity. This choice is assumed not to affect conclusions about the performance of the visibility retrieval algorithms, because the definition of visibility according to Eq. (1) is applied in the visibility retrieval regardless of the underlying structure. Depending on its projected autocorrelation function, only the R_g -dependent DF value associated with the pattern is expected to be different if a different test structure were used, provided it is accurately retrieved [4].

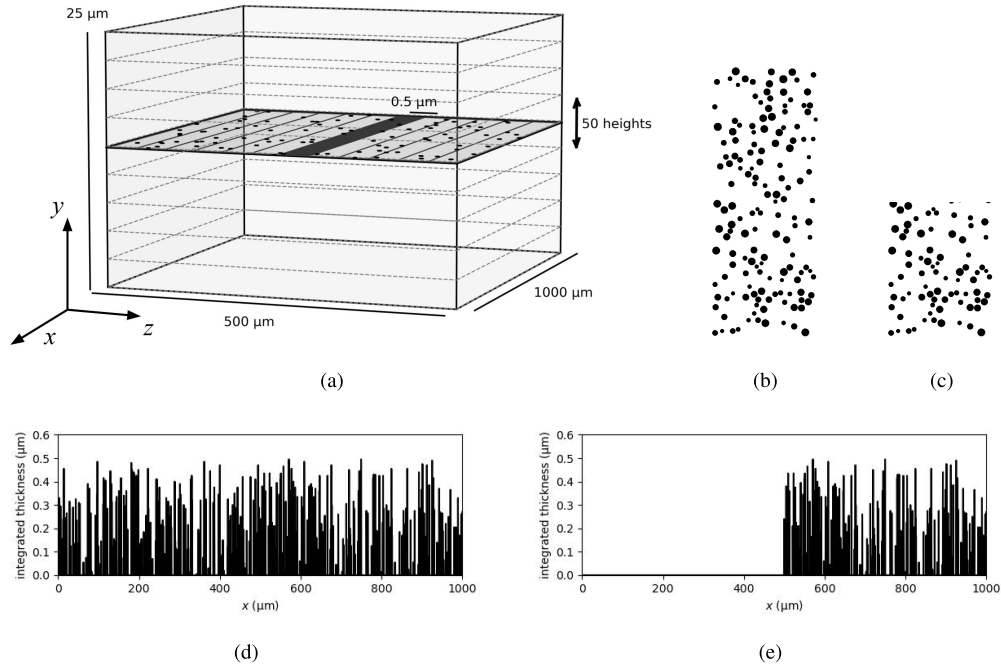


Fig. 4. Illustration of virtual sample preparation. (a) Indication of virtual sample dimensions and preparation of slices for multi-slice wave-propagation simulation. (b,c) Illustration of one horizontal plane (b) before and (c) after applying the mask. Black: SiO_2 . (d,e) Plot of integrated thickness for a randomly selected slice, unchanged in (d) and after masking (e).

The process to prepare the sample for wave propagation simulation in 2D, is clarified in Fig. 4. First, the box is sliced into 50 2D slices along the y -direction as in (a). They are not

fully independent due to the non-overlapping condition of the 3D MDN distribution. Then, along the z -direction, 1000 slices of thickness 500 nm are made. These slices are thin enough, such that the chance of multiple scattering within one slice would be close enough to zero, and the single-scattering approximation is valid within one slice. In each of these 1000 slices, the thickness of the MDNs is integrated along the z -axis (optical axis) into a 1D thickness profile parallel to the x -axis, an example of which is shown in (d) for the full sample. To make the half-filled box, a mask is applied that sets one half of all these profiles to zero, as in (e). These thickness profiles are used in the multi-slice wave propagation. In the simulation, both thickness profiles are periodically repeated along the x -axis to broaden the FOV, such that higher off-axis angles from the z -axis can also be studied.

The simulated settings for DP-XGI are tabulated in Table 1. The simulation is set to be monochromatic at 20 keV. The FOV of the simulation is taken such that the sample is imaged with the centre of the detector window off-axis from the beam by 0.65° , as this is where V_1 is maximal in the simulated setup [25]. In both simulation (where noise originates from the randomness of the MDN distribution) and experiment (where photon shot noise is also present, along with other sources of noise), a maximal V_1 is favoured to get good SNR [30].

Table 1. Wave propagation simulation settings

Parameter	Simulation Value
source–G1 distance	500 mm
G1–detector distance	500 mm
sample–G1 distance	25 mm
p_g (grating period)	1 μm
p_d (detector pixel size)	5 μm
Number of phase steps	8
Photon energy	20 keV
Sample material	SiO ₂
Material density	2 g/cm ³
Realistic grating shape [18]	used

3.2. Single-shot algorithm

In DP-XGI, the interference fringes are directly resolvable. Thus, it is possible to obtain visibility from a single exposure, but this is only defined per period. Since the period changes during a measurement with variation in R_g , it is often necessary in this case to interpolate the result, such that the same image dimensions are retained. This could be done by fitting the form Eq. (1) to each period and then interpolating, but a more efficient approach exists via the Fourier space of the image [28]. The single-shot visibility retrieval algorithm used in this work is given below. Note that adding the zero padding in Fourier space is equivalent to a sinc interpolation in real-space, and is not capable of improving the FWHM in the signal.

1. Record a 2D image of the pattern $I(x, y)$, assuming grating bars perpendicular to y .
2. Transform the pattern into Fourier space: $\mathcal{F}[I(x, y)](\omega_x, \omega_y)$
3. Determine the fundamental harmonic $\Omega [\text{pix}]^{-1} = 1/p_f$ and the broadest possible spectral bandwidth $2\omega_w$. The half-bandwidth ω_w can at most be $\lfloor \Omega/2 \rfloor$ to avoid spectral overlap. The highest possible real-space resolution is achieved when $\omega_w = \lfloor \Omega/2 \rfloor$. If lower, blurring occurs in real-space.

4. Extract ROIs based on Ω and ω_w :

- DC region: a band around $\omega_x = 0$

$$DC = \mathcal{F}[I(x, y)]([-\omega_w, \omega_w], \omega_y) \quad (8)$$

- First-order (FO) region: a band around $\omega_x = \Omega$

$$FO = \mathcal{F}[I(x, y)]([\Omega - \omega_w, \Omega + \omega_w], \omega_y) \quad (9)$$

- Second-order region (SO): a band around $\omega_x = 2\Omega$

$$SO = \mathcal{F}[I(x)]([2\Omega - \omega_w, 2\Omega + \omega_w], \omega_y) \quad (10)$$

5. Zero-pad the ROIs to keep output size independent of p_{fr} .

6. Reconstruct visibility coefficients via inverse transform:

$$\begin{aligned} a_0(x, y) &= \mathcal{F}^{-1}[DC] \\ V_1(x, y) &= 2 \frac{\mathcal{F}^{-1}[FO]}{a_0(x, y)} \\ V_2(x, y) &= 2 \frac{\mathcal{F}^{-1}[SO]}{a_0(x, y)} \end{aligned} \quad (11)$$

The factor 2 in Eq. (11) arises from having to consider both the negative and positive frequency sideband contributions. Alternatively, due to symmetry, they can both be inverse transformed and then summed.

To compute DF, first-order visibility will be used, as this empirically has the dominant contribution to the pattern compared to higher orders:

$$\begin{aligned} A(x) &= -\ln\left(\frac{a_{0,s}(x)}{a_{0,r}(x)}\right), \\ DF(x) &= -\ln\left(\frac{V_{1,s}(x)}{V_{1,r}(x)}\right). \end{aligned} \quad (12)$$

As the simulated X-rays are monochromatic, these formulas are valid for T and D_1 according to Eq. (3), transformed with $-\ln(\cdot \cdot \cdot)$ according to convention.

If the sample morphology in the image contains spatial frequencies in the sideband around the first-order peak, the retrieved $V_{1,s}$ will be contaminated by this contribution, which causes artefacts in the DF image. Thus, this method is most reliable when sample features are larger than the fringe period in the x -direction. If this is not the case, more advanced processing steps may be necessary to isolate and remove the unwanted sideband contributions, to obtain a clean DF image.

4. Results & discussion

In Fig. 5(a) and (b), two typical simulation results are shown at different inter-grating distances. Only a part of the simulated FOV in an interval around 0.65° off-axis is shown. The black curves represent PS results, the blue curves are obtained with SS. The two limiting cases are indicated with grey dotted lines: the signal without scattering object (i.e. $DF = 0$) and the nominal DF signal induced by the simulated scatterer, calculated by the PS result without the mask which causes the edge. For all PS-DF results, pixel binning is applied due to statistical noise in the DF

signal. For this, 4 pixels along the x -axis are binned together in all results. Since there are no photon statistics, it is assumed this noise originates in the random statistics of the sample itself. A low DF SNR resulting in the need for pixel binning, has also been observed experimentally [18]. The difference in maximal DF value between (a) and (b) is accounted for by the change in ξ_1 . It can be seen that for all techniques, the transition between high DF and low DF is faster at smaller p_{fr} , despite nothing else but R_g having been changed between the two simulation instances. Moreover, the length of the transition range roughly equal to p_{fr} , as is indicated by the secondary x -axis on top of the plot. For the SS results, two curves are plotted. The full line is the SS reconstruction using only the first phase step. This result is somewhat inaccurate due to noise. This originates from the spatially random MDN distribution, as no Poisson noise was added to the simulation. Noise manifests necessarily at lower frequency than the pixel size for this method, making it difficult to filter out with, for example, pixel binning. The dotted line represents the average of the SS DF result of the first three phase steps (3SS). Individually, these do not yield identical results. However, by averaging the DF signals, there is interference between the slow oscillations caused by noise on each signal, on average improving the result. In principle, all phase steps could be used to get the best possible result for a fair comparison to PS. This is illustrated in Fig. 5(d), in which the blue curves represent the SS result for each phase step, and the red curve is the average of them all, 8SS. It can be seen that the SS result is somewhat inconsistent between phase steps. The average, however, matches the PS result closely. It must be noted that this does not mean that both datasets require the same measurement complexity. Although the 8SS dataset experimentally still requires 8 different measurements, hence a translation stage for the grating, the accuracy of this stage is not as strict as for PS.

It is empirically found that a logistic function provides a decent fit to the edge response for PS. The logistic fit used here is defined as:

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}}. \quad (13)$$

The FWHM of the derivative of the logistic function, which is shown in Fig. 5(c), is inversely proportional to k . Similar to the point spread function (PSF), this can be used to estimate the real-space DF resolution. This estimated spatial resolution is plotted for a range of inter-grating distances in Fig. 5(c). In the same plot, p_{fr} is drawn. Comparing the two, p_{fr} and the estimated resolution from the FWHM of the PSF are similar.

5. Conclusion

In simulation, we see that the pattern period is the dominant factor limiting the spatial DF resolution. The inherent real-space resolution limit in SS due to the Fourier ROI selection, depends on the fringe period p_{fr} and can be expressed, with the sample magnification $m_s = d_{so}/d_{sd}$ and pixel size p_d , as

$$\Delta[\mu\text{m}] = \frac{p_{fr}[\mu\text{m}]}{m_s} = \frac{p_{fr}[\text{pix}]p_d[\mu\text{m}]}{m_s}. \quad (14)$$

The quality of the DF image can be maximally improved with multiple exposures whereby the relative y -positions of the gratings are perturbed. This reduces low-frequency noise originating from the microstructure statistics, but based on Fig. 5, does not result in an increased spatial resolution. In this case, the complete result is no longer considered single-shot, but rather an averaged image of multiple images that were each retrieved using the single-shot method. Importantly, the accuracy of the grating movement is less stringent than in PS.

When the phase stepping technique is used, the spatial DF resolution in the x -direction is found also to be limited by the fringe period according to Eq. (14). Only when Δ is smaller than the macroscopic feature size, are these features clearly resolvable. SS can therefore provide the same physical information, without requiring a precise phase stepping motor. SS with one exposure

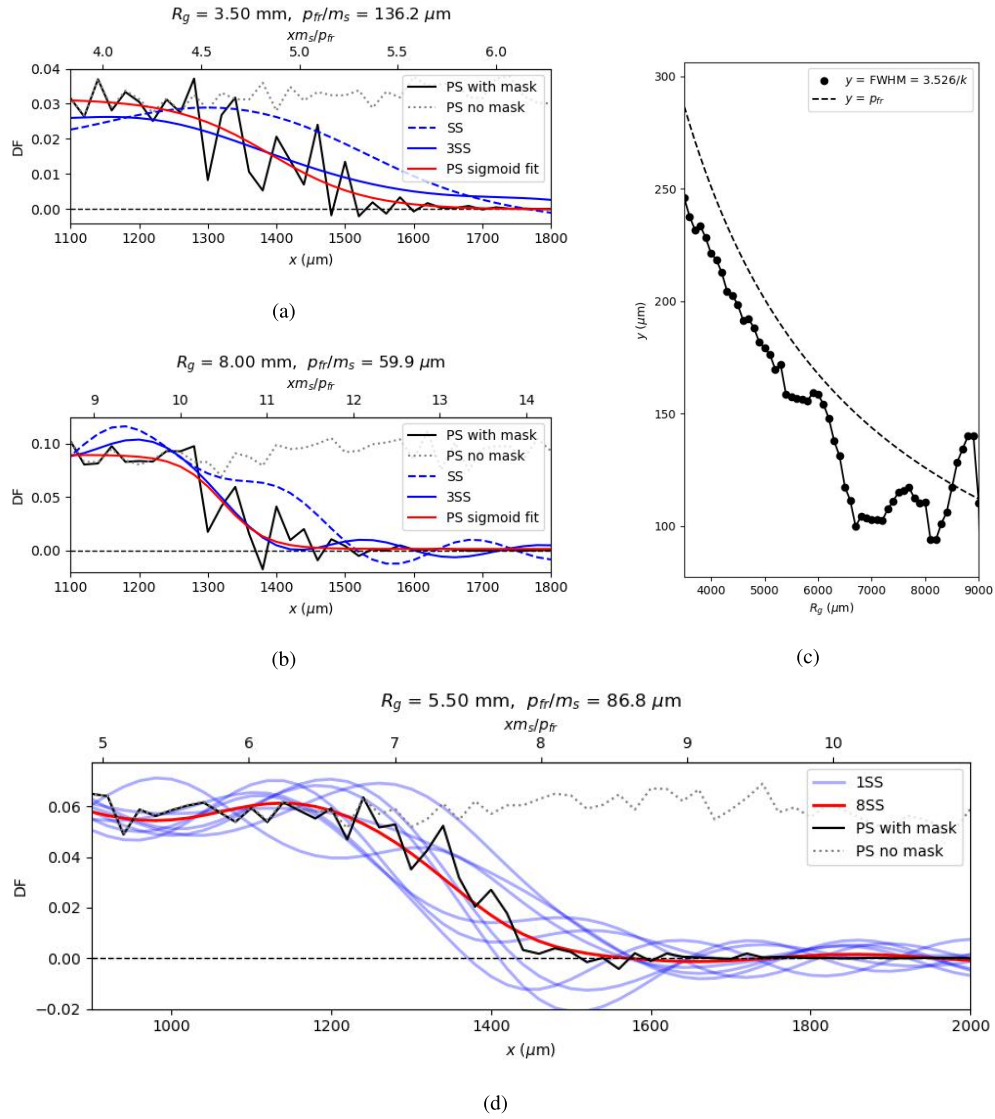


Fig. 5. (a) and (b): DF reconstructed by simulated PS in the black curve, both with edge (solid line) and continuous (dotted line), along with a logistic function fit (red line) and in blue the SS (full line) and 2SS (dashed line) reconstructions, both imaging the edge. At respectively 3.5 and 8 mm inter-grating distance. The bottom x axis represents physical distance on the detector plane; the top axis is the bottom axis transformed to represent a number of demagnified (at the level of sample) fringe periods, with magnification factor $m_s \approx 2.11$. (c) Comparison between retrieved spatial resolution from simulation for a range of inter-grating distances between 3.5 and 9 mm, and the corresponding analytical fringe period according to Eq. (2). Retrieved spatial resolution is based on the fitting Eq. (13) to the edge profile, by taking the FWHM of its derivative, which is $\approx 3.526/k$. (d) Similar graph as in (a) and (b), here with SS reconstructions for all 8 phase steps (blue), and their average (red) at $R_g = 5.5$ mm. Whereas pixel binning (4 pix) reduces the high-frequency noise in PS, it has no impact on the slow variations in SS.

can lead to artifacts that manifest as a wavy, low-frequency noise. This effect can be mitigated by moving the grating reproducibly as if phase stepping, to make multiple SS DF images and average them, causing the oscillation-like component to be cancelled.

The simulation represents an ideal case, assuming a monochromatic point source, nanospheres suspended in vacuum with a sharp edge, and no Poisson statistics for photon detection. It is assumed that the studied resolution limitation still applies in more complex samples, for partially coherent and polychromatic sources, and with Poisson statistics of the detector, since it is shown to be a fundamental limitation for the ideal case. Extension to source spots and a broadband spectrum does not affect the pattern's period.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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