Image reconstruction using a configurable detector in STXM

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Abstract. The use of a fast-readout CCD x-ray detector in a scanning transmission x-ray microscope (STXM) allows a range of simultaneous imaging modes to be realised. The CCD records the full 2-D distribution of x-rays transmitted by the sample for every pixel in the raster scan that generates the STXM image, potentially generating large volumes of data. The data in each CCD frame can then be processed in a variety of ways to produce useful image signals, including both absorption and phase contrast. Since the detector effectively records a convergent-beam micro-diffraction pattern for every position in the STXM raster other processing algorithms can be used to provide additional information to the user.

1. Introduction
The use of a segmented detector for the transmitted x-ray detector in the scanning transmission x-ray microscope (STXM) is increasing, as it allows a range of different forms of image contrast to be made available simultaneously, and more effectively exploits the information available about the sample structure. There are two main approaches: the first makes use of a large 2-D array of detector elements to record a full 2-D intensity distribution for every pixel in the raster scan of the STXM [1–3], while the other uses a few custom-designed detector segments, usually in the form of circular arcs and quadrants [4, 5]. Both types of detector allow the conventional incoherent brightfield image to be formed by summing the signals from all the detector elements, and both also provide information about the redistribution of the x-ray transmitted x-ray signal across the detector plane as a result of the x-ray interaction with the sample. It is this redistribution of the intensity that allows phase contrast image signals to be produced, usually in the form of differential phase contrast, when an antisymmetric detector response function is used.

The use of customised segmentation means that only a few image signals need to be recorded for each pixel in the image scan, and the detector can be optimised for fast and efficient data collection. The disadvantages are that the choice of detector configuration is fixed at the hardware design stage, and that the detector has a well-defined central axis that must be aligned carefully with optical axis of the STXM to ensure that signal differences across the detector plane arise only from the sample interaction, and not from beam misalignment. On the other hand, the use of a pixellated 2-D array detector, as shown schematically in Figure 1, means that a great variety of detector configurations can be chosen in software after the image data are acquired, so that different imaging modes can be considered retrospectively. The disadvantage in this case is that a much larger volume of raw data is acquired in the first instance, and 2-D
array detectors tend to have somewhat longer readout times. In practice an array of $128^2$ pixels allows quite fine control over the detector configuration, and a charge-coupled device (CCD) array of this size can be read out in only a few milliseconds [2].

In this paper we describe experiments made using the fast-readout CCD that is now in standard use as the transmitted x-ray detector on the Twinmic STXM on beamline 1.1L [6] at the Elettra synchrotron.

2. Imaging with the Twinmic STXM
In the STXM the transmitted x-ray detector can be assumed to lie in the far-field (Fourier transform plane) relative to the specimen plane, and the response of a configurable detector is described by the function $R(k)$, where $k$ is a spatial frequency vector. The image signal when the x-ray probe $\psi(r, r_o)$ is centred at position $r_o$ on the object is then

$$s(r_o) = \int |\psi(k, r_o)|^2 R(k) \, dk$$

and the choice of imaging mode is determined by $R(k)$. Setting $R(k) = 1$ gives the incoherent brightfield image, while $R(k) = k$ yields a first-moment detector response that produces differential phase contrast, with the image signal linearly related to the phase gradient of the object transmittance [7].

![Figure 1. Schematic representation of an STXM fitted with a pixellated detector, that can record a 2-D image of the transmitted x-ray signal.](image)

![Figure 2. Images of 1 µm diameter polystyrene spheres taken at a photon energy $\sim 653$eV. The scale bar is 2 µm. The contrast in the brightfield and integrated phase images has been stretched to fill the available grey levels.](image)
It is possible to reconstruct the object phase $\phi(x, y)$ by integrating the phase gradient signals; one approach that seems particularly quick and effective, even in the presence of image noise, is a Fourier method [8, 9]. With this method, the first-moment signals shown in Figure 2 are used to create a complex array

$$g(x, y) = a \left( \frac{\partial \phi}{\partial x} + i \frac{\partial \phi}{\partial y} \right) \implies \Phi(k_x, k_y) = \frac{G(k_x, k_y)}{2\pi i a (k_x + i k_y)}$$

where $\Phi(k_x, k_y)$ and $G(k_x, k_y)$ are the Fourier transforms of $\phi(x, y)$ and $g(x, y)$ respectively, and $a$ is a constant. The object phase can be found by an inverse transform of $\Phi(k_x, k_y)$. An example of this phase integration for images of 1 $\mu$m diameter polystyrene spheres is shown in Figure 2.

3. Discussion

The phase integration shown here is a very rapid process (typically less than 1 s) that can be applied directly to the image data from the STXM scan. However, there are some implicit assumptions: first, that the moment signals represent only a phase gradient, not a mixture of amplitude and phase information, and second, that the size of the focused x-ray probe is much smaller than any features of interest in the object field. In practice, for high resolution imaging it may often be necessary to correct for these effects.

For this reason, more sophisticated reconstruction algorithms are of considerable interest, and hybrids of conventional STXM and coherent diffraction imaging methods look particularly attractive. Ptychographic methods [10, 11] offer the ability to image extended objects and retrieve the complex amplitude transmitted by the object at a resolution that is not limited by the size of the x-ray probe, but they still require a good estimate of the form of the probe to ensure rapid convergence. The recent demonstration of scanning x-ray diffraction microscopy [3] looks even more promising, since the reconstruction algorithm can provide not only a complex reconstruction at high resolution, but also a measure of the illuminating probe itself.

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