Noise limit on practical electron ptychography

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Abstract. Ptychography is a wavelength-limited phase retrieval method that promises to provide sub-0.5Å resolution in the electron microscope, even if the lens employed (which is required only to form an illumination spot) can itself only achieve rather modest resolution. The fidelity of a practical specimen reconstruction using ptychography hinges on various experimental factors, the major one of which is the source brightness. Achieving a high degree of coherence of an electron beam requires source demagnification which reduces the electron counts reaching the detector for a given exposure time. Specimen drift, damage and contamination also limits the practical exposure time. In this paper we investigate the effect of the counting statistics required for a good quality ptychographic reconstruction.

1. Introduction

Ptychography can reconstruct the transmission function of a complex object (both phase and amplitude) from the diffraction patterns collected in the Fraunhofer diffraction pattern or the back focal plane of a microscope [1]. A requirement of the technique is that the system used to acquire the diffraction data must be set up to be in the most coherent configuration. To achieve this configuration in a field emission gun electron microscope, we change the potentials presented to the first focusing anode and make the aperture size of the probe-forming lens as small as possible. In doing so, we reduce the total effective number of electrons impinging on the sample. The resulting diffraction patterns are therefore noisier; however the visibility of interference effects in the diffraction pattern is increased.

To improve the signal-to-noise ratio we can increase our exposure time; however, the longer it takes to complete the experiment the more problems we have with sample drift, which introduces an uncertainty in our probe positions required for our reconstructions. An increase in the number counts per unit area on the specimen for a given illumination size will mean a reduction in the spatial coherence. A deeper insight into the counting statistics is necessary to make informed decisions about the compromises that are inevitable (i.e. counting statistics, electron probe dwell time and area of illumination on the sample). In this paper we shall investigate through numerical simulation the relationship between counting statistics and the quality of theoretical ptychographical reconstructions. In particular we assume that the total number of counts throughout the entire experiment for a given field of view is conserved; A field of view (spanned by a grid of 5x5 probe positions using a 90 nm probe defocus, and by a 16x16 grid using a 45 nm defocus) was recovered using the same electron
counts for both calculations). A common area of illumination is present for two adjacent probe positions (a fundamental requirement for the expression of ptychographic phase in the diffraction patterns [2]), this region is referred to as the ‘overlap region’ and in the case of our simulations this is equivalent to 87% of a probe diameter.

2. Effect of count statistics on reconstruction

It is not obvious whether the total count in the ptychographical data set determines the achievable resolution or the counts in a single diffraction pattern. To investigate this, we employ the setup shown in figure 1.

![Figure 1](image1.png)

Figure 1. Experimental setup. The recovered object resides at either of the defoci planes for different experiments.

In order to recover a given field of view, a largely defocused probe with a long exposure time or a smaller probe with short exposure time can be used. We put the total counts in the entire diffraction data sets to the same value; hence the data set for a small probe would have fewer counts per diffraction pattern but contain more diffraction patterns as indicated in figure 2.

![Figure 2](image2.png)

Figure 2. Ptychographic data set from probes of different defoci values

Employing a smaller probe with short exposure time per diffraction pattern reduces the effect of sample drift per diffraction pattern. The effective specimen drift should be mostly manifested in probe positions deviations from expected values which can in principle be accounted for during reconstruction [3]. This is not the case for larger probes with long exposure time as the effects of drift blurs out the spatial frequency information in each diffraction pattern thus reducing the maximum achievable resolution. Figure 3 and figure 4 show the probes used in the ptychographic reconstruction.
To account for the effects of an amorphous support, multislice calculations with a model of amorphous carbon was used [4]. Test features, analogous to small gold particles, but with varying periodicities, were placed upon this amorphous background. The smallest periodicities represent atomic planes separated by 0.06 nm. Currently, the resolution of ptychography is limited by drift, probe position uncertainties and noise. All calculations were undertaken with a 200 kV accelerating voltage. The maximum scattering angle captured by the detector (which had 512x512 pixels) was 64 mrad.

By modelling Poisson statistics for the recorded diffraction patterns, it was discovered that a count of about 10 electrons per detector pixel resulted in a reliable ptychographic reconstruction. Therefore achieving a resolution of say 0.1nm would require at least 10 counts per pixel in the corresponding...
spatial frequencies. Put simply, a strongly scattering specimen is easier to recover than a weak scattering specimen. The average dark field counts of the diffracted beams using a 90 nm probe data set was set to about 10 electrons per detector pixel. This corresponds to a count of 1 electron per detector pixel in the 45 nm probe data set using the same sampling condition.

The total counts/power required to reproduce the aforementioned count statistic is ~$10^7$ electrons. Experimentally, a highly coherent configuration with a beam current of 10pA produces a count of ~$10^5$ electrons for an exposure time of 1 minute (as measured on a JOEL 2010F). Figure 5 and figure 6 show the amplitude and phase of the complex exit-wave from the test specimen as it would appear under a plane wave illumination.

Figure 7 and figure 8 show the recovered phases from the two data sets. These results suggest that the counting statistic required for a good ptychographic reconstruction is easily achievable in a field emission gun electron microscope.

3. Conclusions
In this paper we showed that it was better to use a large defocused probe to generate a ptychographic diffraction data set as the counting statistic required for a reliable reconstruction is attainable in most modern electron microscopes.

The theoretical simulations presented here show that indeed it is possible to achieve a reasonable reconstruction when the number of counts in the dark-field is low (10 counts). This gives us confidence that we shall be able to carry out experiments with shorter exposure times, and thereby reduce the detrimental effects of drift and contamination encountered when carrying out ptychographical-type experiments in the transmission electron microscope.

4. References
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