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Technique for Complex Averaging of Electron Holograms

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Electron holography has been used to characterize electrostatic and magnetic behaviour of specimens in transmission electron microscopy [1]. Although widely applied, it remains a challenge to obtain the signal-to-noise ratio required to achieve the high phase resolution needed for observations of small variations in local charge on a specimen. Holography often requires long acquisition times implying the need for stable laboratory conditions. One approach to improve phase resolution is to combine many individual holograms acquired with short individual acquisition times and average them [2]. Here we report on the practical aspects of registration, alignment, and averaging of hologram series.

The observed phase resolution scales with the electron counts and observed fringe visibility (or contrast),

$$\Delta\phi \simeq \frac{2}{NV^2} \qquad (1.)$$

where N is the electron count per reconstructed pixel and V is the visibility [3]. In general, increasing the electron count rate decreases the visibility and vice versa. For example, increasing the exposure time linearly improves counts but transients and drift of the apparatus decreases the observed visibility. Similarly, spreading the illumination increases the visibility by making the illumination more parallel, but decreases the electron flux and hence observed counts for a fixed exposure time.

If a series of holograms is recorded instead of a single long-exposure, it is possible to estimate the drift frame-to-frame and then align and sum the holograms. The cross-correlation must be done on the reconstructed amplitude or phase, or the correlation will be far stronger to the fringes than any feature of the object. This requires averaging of complex data, which is a non-trivial problem [2]. We have developed a method for summing via the phase offset-matching strategy and several alignment methods, implemented in MATLAB [4].

Results on experimental data suggest that the method reduces shot noise considerably compared to a single frame (Fig. 1). Noise in the phase for a subarea in vacuum was reduced from $2\pi/20$ (not shown) to $2\pi/500$ (Fig. 1d). Further characterization and refinement of the algorithm is best done with simulated data in order to test a variety of objects, alignment methods, and noise conditions (Fig. 2). For hologram simulation we calculate per-pixel Poisson shot noise and then filter by best fits of modulation and noise-transfer function [5]. Accurate cross-correlation alignment is often complicated by image artifacts introduced by the reconstruction process. Image artifacts are typically stationary such that the magnitude of the object drift is typically underestimated by a cross-correlation.

References

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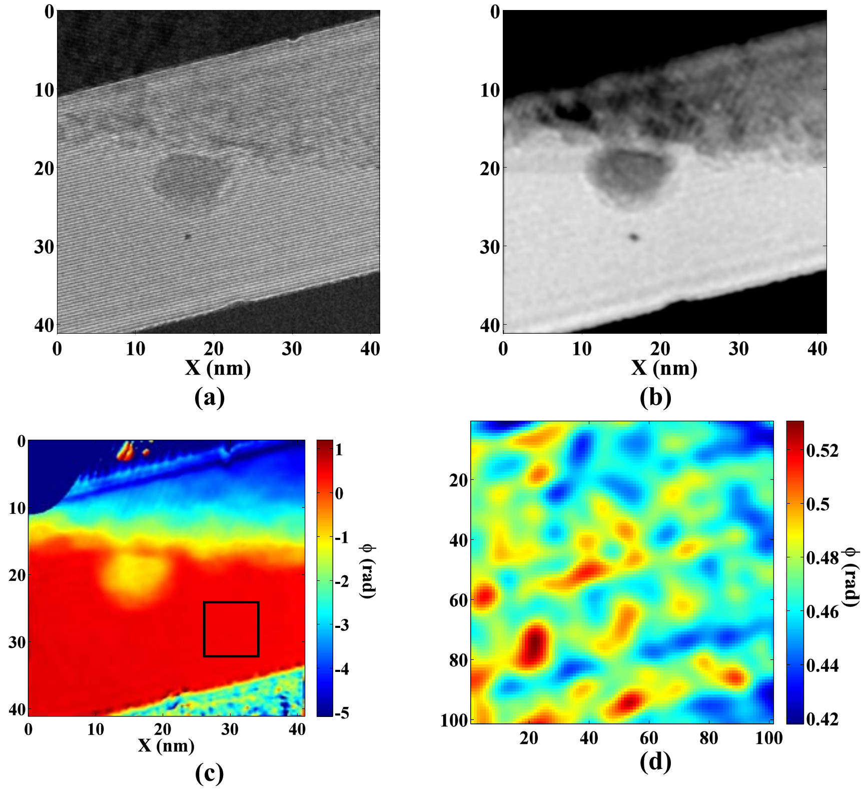
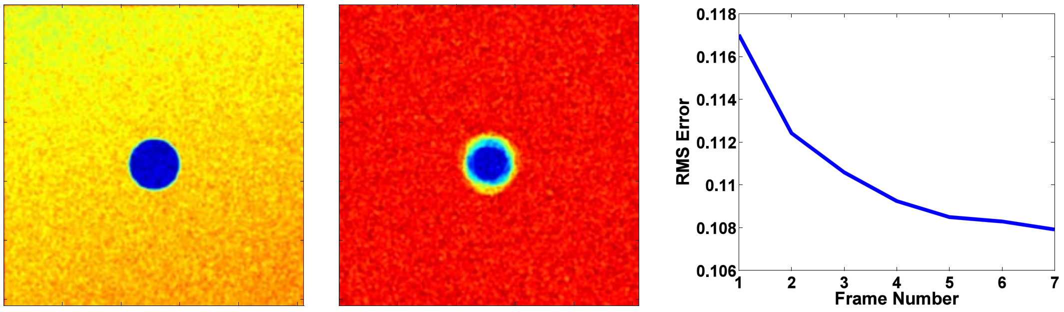


(a) (b) (c) (d)

Figure 1: (a) an example $1\ s$ exposure electron hologram of a PtRu nanoparticle on a carbon nanotube (top of frame). For the complex sum reconstruction, one hundred $1\ s$ holograms and ten $10\ s$ references were recorded. The (b) reconstructed amplitude and (c) unwrapped phase shift are shown. To find a value for the phase flatness in the vacuum, a 100 x 100 pixel region was extracted (black rectangle in (c), shown in (d) with adjusted contrast limits) and found to have a standard deviation of $2\pi/500$.



(a) (b) (c)

Figure 2: Reconstructed phase of a top-hat object that has been (a) aligned and registered and (b) summed without alignment. The RMS error for (a) compared to a phase object with no noise is shown (c) as a function of the number of frames used.