Introduction: The term ‘electron holography’ is typically synonymous with ‘off-axis electron holography’ performed by interfering different parts of a coherent electron wave function using an electrostatic biprism. In addition to being a much simpler experiment, it has been shown that inline holography can be just as quantitative [1], can achieve much better signal/noise properties for the same dose [2], and measure holographic information also in cases where off-axis holography cannot be applied [3]. However, in order to overcome the twin image problem in inline holography [4] inline holograms (images) at more than just a single plane of defocus should be recorded. There exist numerous algorithms to reconstruct the electron wave function from such focal series, each making its own approximation. While most iterative algorithms may reconstruct high-frequency details very nicely, they usually require computationally prohibitive numbers of iterations (e.g. several $10^5$) to reconstruct low-frequency details. Deterministic phase retrieval algorithms usually make linear approximations and have other shortcomings, e.g. no mechanism to self-consistently verify the initial alignment of the experimental images, or, in the case of the transport-of-intensity equation (TIE), the amplification of low-frequency noise for small defocus changes and missing high-frequency detail at larger defocus changes (see Fig. 2).

The FRIH approach: In this contribution I will introduce a novel approach to inline electron holography which aims at reconstructing as large as possible a bandwidth of spatial frequencies. Based on the an iterative reconstruction algorithm consistent with a flux-preserving approximation to the imaging process in the microscope [6] the following improvements have been made:

1. Non-linear sampling of defocus values (see, for example, Fig. 1). The same small defocus step necessary to capture high-frequency phase information is impractical at the large defocus values necessary to recover low-frequency information.
2. Reconstructing a wave function that is larger than the experimental images (padding). It has been shown by Ophus et al that not imposing periodic boundary conditions enhances the reconstruction of low-frequency information [5].
3. Adjusting both phase and amplitude and not only the amplitude of the wave function at each iteration.
4. Incremental inclusion of images in the iterative algorithm. Looking at Fig. 1 it becomes obvious that images with largely different defocus cannot easily be aligned. However, starting the reconstruction with only slightly defocused images (e.g. $\Delta f = -200$ nm, 0, and $+200$ nm) and then aligning the next larger defocus values necessary to recover low-frequency information.

Results: Fig. 3 shows the comparison of amplitudes and phases reconstructed by different iterative approaches, demonstrating that the FRIH approach is able to reconstruct both high and low frequency details in the phase very accurately. Application of this approach to experimental bright-field (potential mapping) and dark-field (for strain mapping) inline holography has already delivered excellent results and will be presented as well.

References

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Figure 1. Simulated 7-member focal series. $E_0 = 200$ kV, $\alpha=0.05$ mrad, $C_s=1.0$ mm, dose in each image: $34.2 \text{ e}^-/\text{Å}^2$ (total dose $240 \text{ e}^-/\text{Å}^2$, 1 count per electron, contrast adjusted to intensity range).

Figure 2. Original (a) and TIE-reconstructed phase from 3-membered focal series with defocus values b) $-0.2\mu$m, 0, and $0.2\mu$m, c) $-1.6\mu$m, 0, $1.6\mu$m, and d) $-5.4\mu$m, 0, $5.4\mu$m. In order to make the total dose the same as in Fig. 1 the dose in each of the simulated images has been $80 \text{ e}^-/\text{Å}^2$ (total dose $240 \text{ e}^-/\text{Å}^2$).

Figure 3: Comparison of different reconstruction algorithm: Amplitude (top) and phase (bottom) for a) the flux-preserving reconstruction algorithm (FRPA), b) FRPA including padding the images with 25% of the image size at each edge, c) full-resolution inline holography (FRIH) reconstruction algorithm, and d) the original wave function. The same number of iterations was applied for all 3 algorithm variants (6 iterations with 3 images + 6 iterations with 5 images + 6 iterations with 7 images + 20 final iterations with all 7 images).