Correction of Multi-Angle Plasma FIB SEM Image Curtaining Artifacts by Fourier-based Linear Optimization Model

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Introduction

Focused Ion Beam Scanning Electron Microscopy (FIB SEM) is a block face serial section tomography technique capable of providing sophisticated 3D analysis of higher order topology such as tortuosity, connectivity, constrictivity, and bottleneck dimensions [1, 2]. Emerging Xe^+ Plasma FIB (PFIB) technology allows imaging of previously infeasible volumes. A rocking mill technique is used to mitigate "curtaining" artifacts caused by differences in phase density and milling rates, creating the straight-line artifact at two discrete angles [2] (see fig. 1). Previous works, such as those described in [3] & [4], correct only single-direction, often vertical, curtaining artifacts. Correcting these artifacts is crucial for further quantitative analysis, which often requires accurate segmentation.

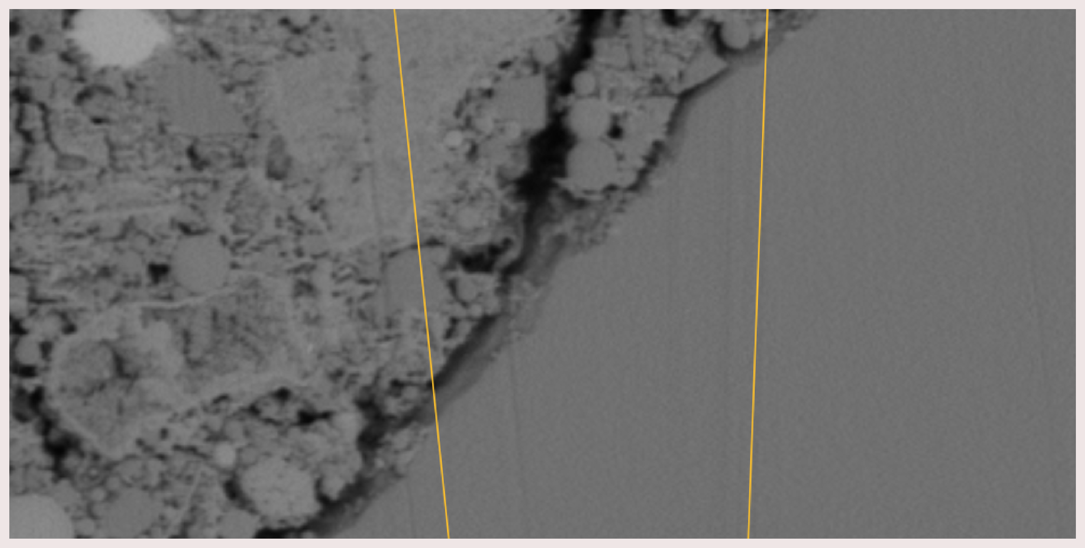

Figure 1: PFIB SEM with rocking mill introduces curtaining artifacts along two discrete angles, seen here in a concrete dataset with curtains in the approximately 7° and -1° directions.

Fourier Basis

In order to correct artifacts along a specific angle, we construct a Fourier basis as follows:

$$F(x,y) = a_0 + \sum_{i=1}^{N} a_i \cos\left(\frac{2\pi i}{N}(u_x x + u_y y)\right) + b_i \sin\left(\frac{2\pi i}{N}(u_x x + u_y y)\right)$$

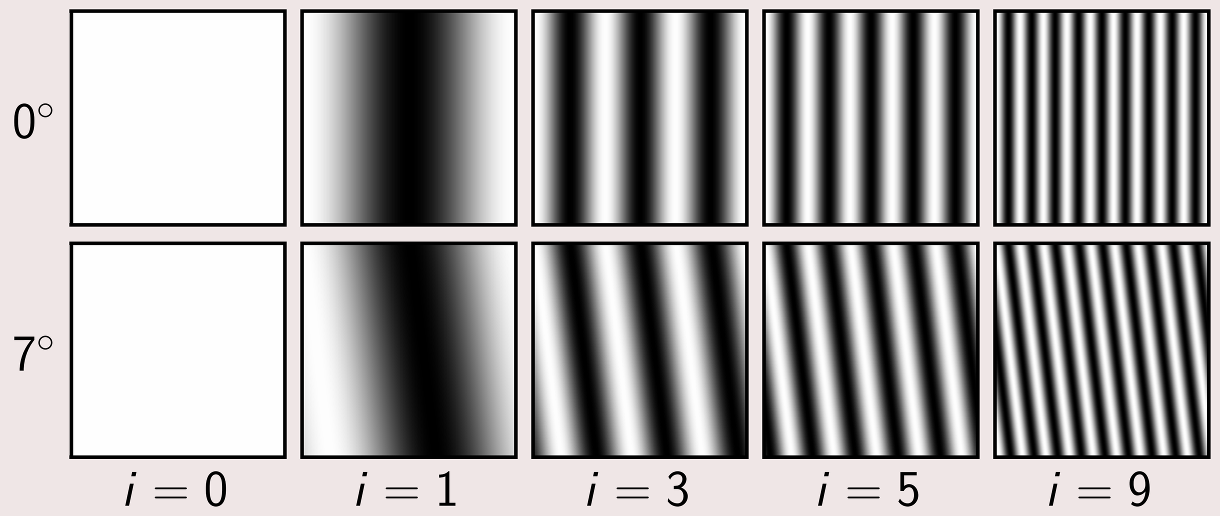

Figure 2: Visualization of Fourier basis used to correct curtains in specific directions without affecting other structures.

Linear Optimization Model

Multiplicatively construct a corrected image, J, from the original image I:

$$J(x,y) = I(x,y) \cdot F(x,y)$$

by solving for $a_0, b_1 \ldots a_N, b_N$:

$$\text{minimize} \quad \underbrace{\sum_{x,y\in box} |J(x+1,y) - J(x,y)|}_{A} + \underbrace{\lambda \sum_{x,y\in box} |1 - F(x,y)|}_{B}$$

$$\text{subject to} \quad |1 - F(x,y)| \le \begin{cases} \alpha, & \text{if } I(x,y) > a \\ \beta \le \alpha, & \text{if } I(x,y) \le a \end{cases}$$

- $\vec{u}$ defines a unit vector perpendicular to the curtain
- A penalizes the horizontal L1 difference norm (total variation) of the image
- B penalizes the overall change of the image
- λ controls the strength of the filter (higher = less change)
- α and β limit the amount of change depending on a given threshold, a, preserving dark voids
- multiple angles are corrected together in the same optimization problem

Results

Our optimization method effectively removes curtains along the two given angles, without introducing incorrect structure into the image or reducing the contrast of voids.

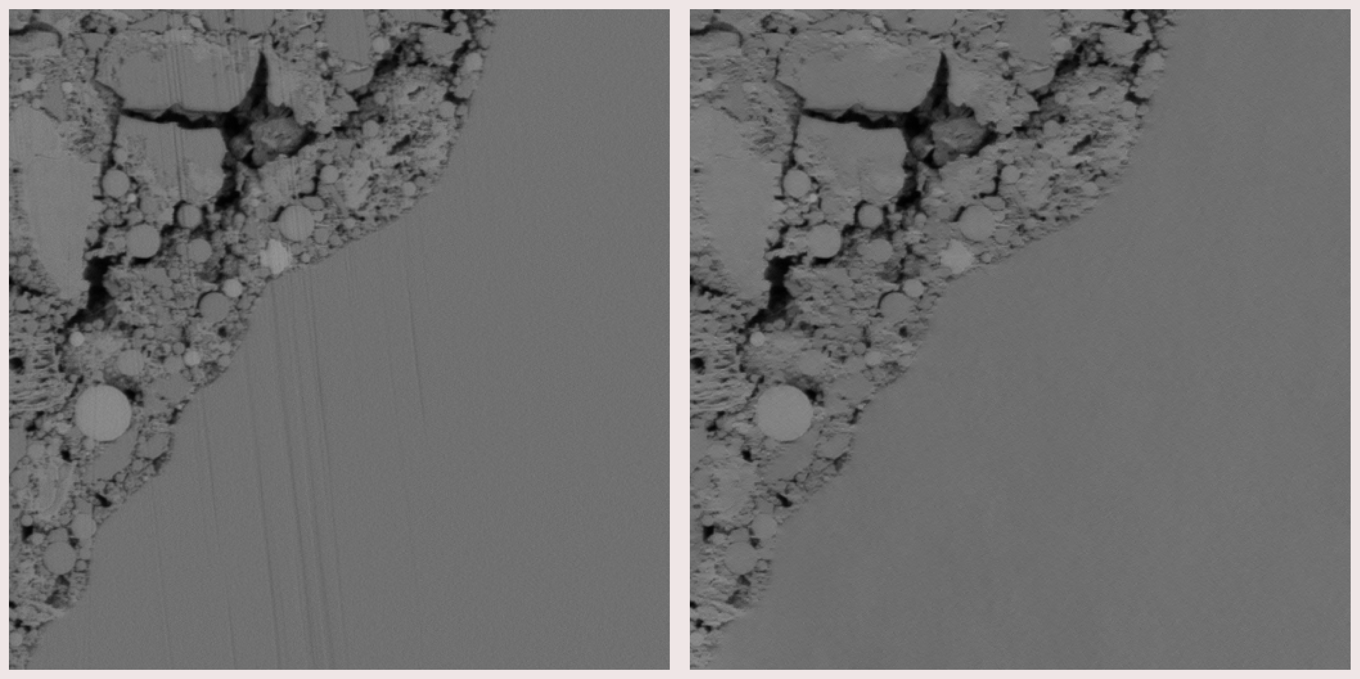

Figure 3: Curtains along -1° (approximated by 0° in calculations) and 7° angles are effectively removed from homogenous and non-homogenous areas of the concrete PFIB image (left: original image, right: corrected image).

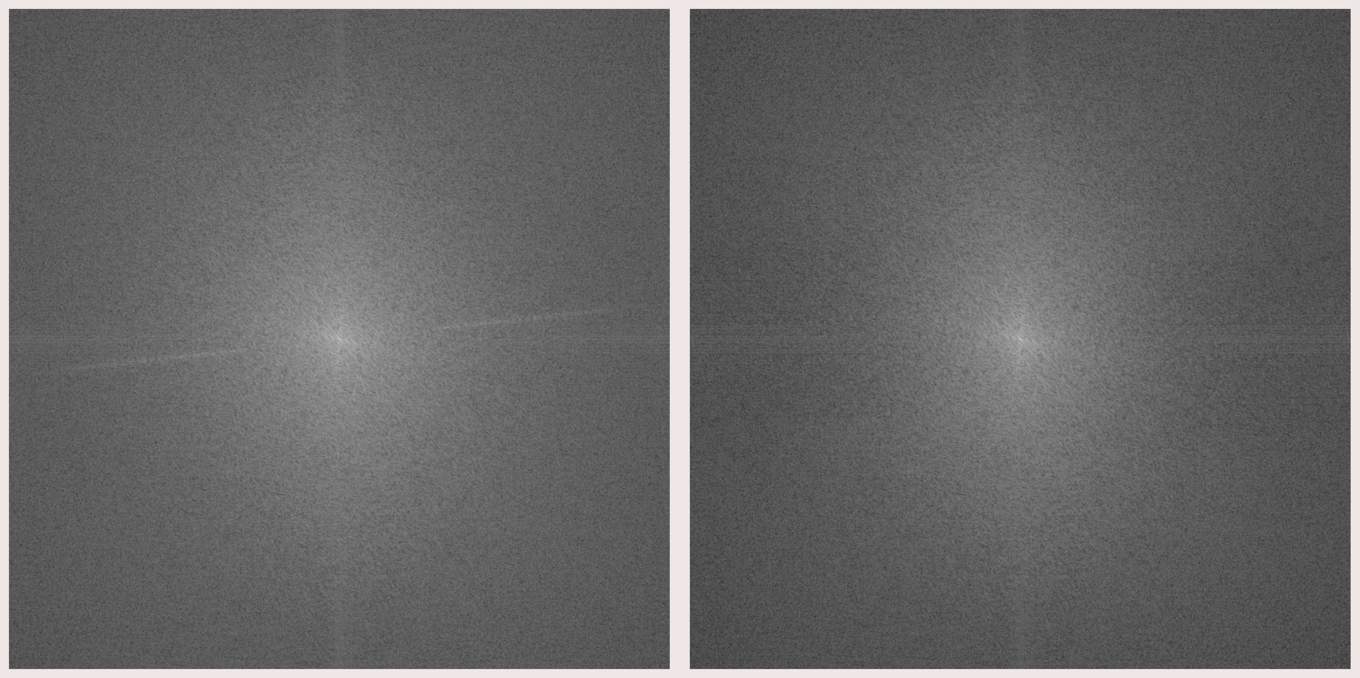

Figure 4: Log FFT of images in figure 3 show the absence of bright frequencies corresponding to curtaining directions.

Conclusions & Future Work

Our method effectively corrects multi-angle curtaining, without greatly modifying the image histogram or reducing the contrast of voids. Compared to other methods, our method does not introduce new, incorrect structure into the image. Ongoing work aims to improve the computational efficiency of the algorithm, taking advantage of its "embarrassingly parallel" nature. Future work includes exploring the benefit of a comprehensive model of curtaining which leverages rich knowledge about their physical properties. Simultaneous secondary electron images can provide better contrast for the curtains, which may prove useful in improving their detection and correction.

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CCEM Canadian Centre for Electron Microscopy