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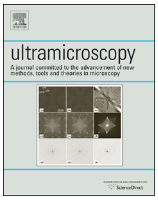

Full length article

Correcting nonlinear drift distortion of scanning probe and scanning transmission electron microscopies from image pairs with orthogonal scan directions

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ABSTRACT

Unwanted motion of the probe with respect to the sample is a ubiquitous problem in scanning probe and scanning transmission electron microscopies, causing both linear and nonlinear artifacts in experimental images. We have designed a procedure to correct these artifacts by using orthogonal scan pairs to align each measurement line-by-line along the slow scan direction, by fitting contrast variation along the lines. We demonstrate the accuracy of our algorithm on both synthetic and experimental data and provide an implementation of our method.

1. Introduction

Scanning probe microscopy (SPM) is a very powerful experimental tool due in part to the small probe size and corresponding high spatial resolution of contemporary physical and focused radiation probes. SPM experiments, such as scanning transmission electron microscopy (STEM), require that the probe be moved across the sample surface in order to form an image. This procedure can introduce artifacts in the measurement due to the time delay between measurements and the accumulation of error in the probe position, for example from drift of the sample [1–8]. Examples of these artifacts include linear distortions such as shear, expansion or contraction applied to the whole image, random “jitter” of each scanline's origin position with respect to the intended position on the sample, and jump discontinuities due to large sample jumps. Virtually all scanning probe experiments contain image distortions, and these distortions are often large compared to atomic-scale features.

Previous studies by other groups have attempted to measure and correct SPM distortions. Berkels et al. recorded and aligned series of STEM image exposures to improve peak precision [3], and have also devised a method for nonlinear registration of images series [5]. Jones and Nellist corrected both linear and some nonlinear distortions in single STEM images by assuming prior knowledge of atomic features [4]. Sang and LeBeau have developed the “REV-STEM” method, where linear drift coefficients are measured and corrected by a series of STEM images recorded in different scan directions [6]. Schnedler et al. introduced an algorithm that uses SPM measurements of a standard calibration sample to measure and correct the nonlinear image distortions [9]. In STEM experiments, many samples will be modified or damaged by excessive electron dose [10,11] and therefore using as few measurements as possible to correct drift distortions is desirable. To that end, we have created a general case algorithm which requires no *a priori* assumptions about image features and requires only two images as an input, minimizing acquisition time and electron dose needed for correction of drift artifacts.

In this paper, we first show how nonlinear drift can affect scanning probe images. We then develop an algorithm to correct all linear and nonlinear drift distortions in scanning probe images by correcting the scanline origin positions from two or more SPM images. We generate corrected images by using kernel density estimation to resample the images, and develop a Fourier weighting scheme to further reduce error. We test this algorithm on data, and both simple and complex experimental datasets. We evaluate the algorithm by measuring deviations of atomic sites in corrected images from the best-fit lattice positions, and by measuring complex lattice strain fields before and after correction.

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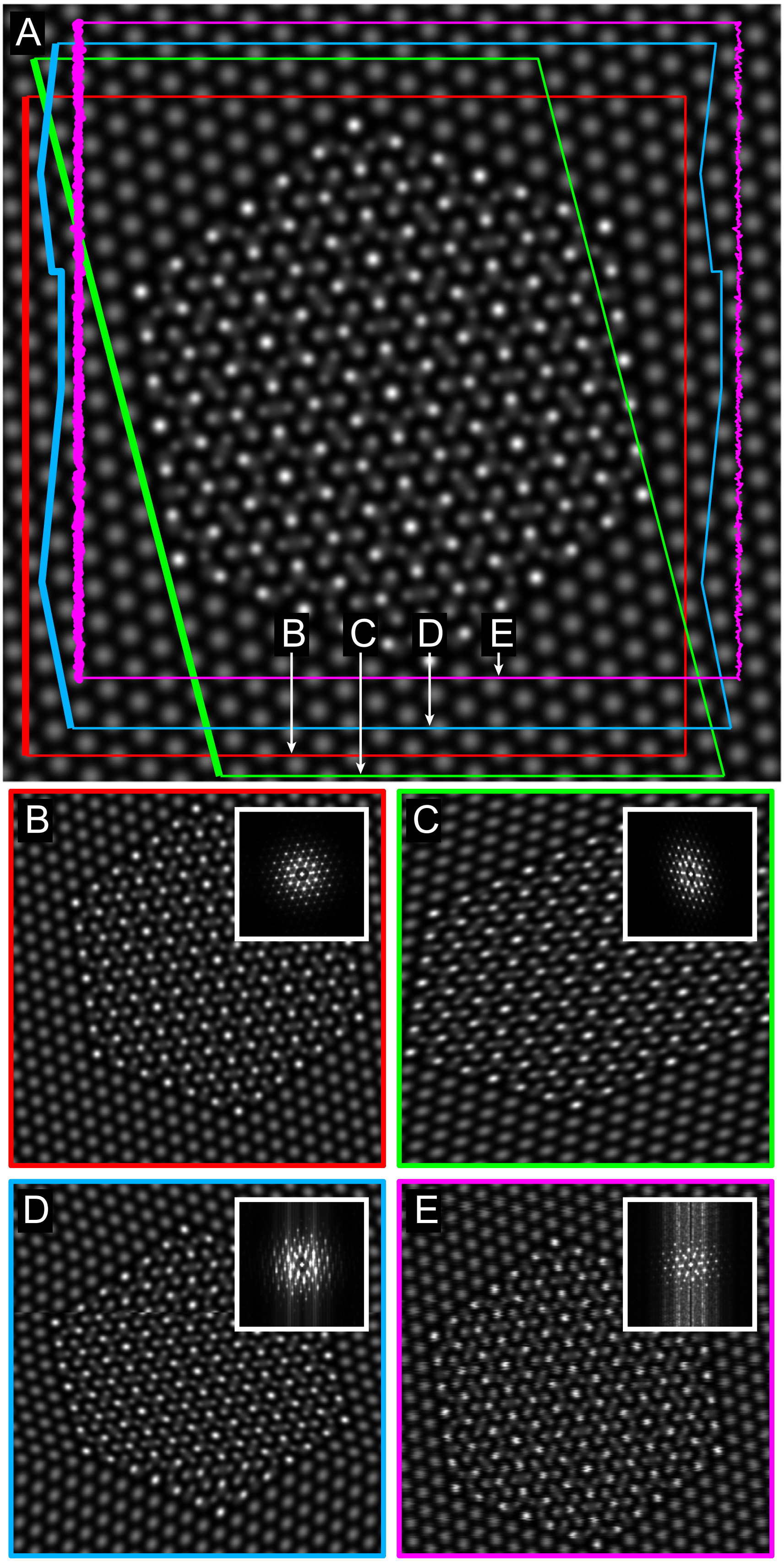

Fig. 1. (A) Synthetic dataset with examples of scanning probe microscopy images recorded with and without error in the probe positions, depicted by the colored outline where the scanline origins are represented by a thicker line. The cases considered are (B) perfect sampling, (C) linear drift distortion, (D) nonlinear drift distortions and a jump discontinuity, and (E) random noise added to the scanline origins. The square root of the Fourier transform amplitude is the inset into each image. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)