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Rapid Methods for Dynamic Autotuning

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Many of the key steps in analyzing an electron microscope image require accurate knowledge of the aberrations to be truly quantitative. Prior to the development of aberration-corrected instruments, it was usually possible to simplify the problem by treating the spherical aberration as constant and neglecting most non-round terms. However, this is insufficient when aberrations can be changed by orders of magnitude and more non-round aberrations need to be included. Dynamic measurement of aberration parameters is also important is for autotuning of the aberration corrector. Correctors consist of multiple layers, and each layer can consist of multiple elements, which may be rotatable and contain additional alignment coils. Thus an aberration corrector can add many extra controls (75 in a recent design [1]) to the column, each of which needs to be set accurately to obtain an 'aberration-free' image. Current software automates this procedure, at least partially, but another key problem is maintaining the corrected condition once it has been achieved. An important part of this problem is maintaining focus and therefore automatic rapid measurements of focus can be considered as a prototype for more complex algorithms.

Here we show how several different methods based on the electron Ronchigram [2] can be used to provide rapid focus measurements, all of which can be extended to higher-order aberrations. The Ronchigram is particularly interesting because it is a mix of real and reciprocal space information, containing 'the whole information' about the sample, which is the origin of the name "hologram". This mixture is due to rays at different angles going through the sample at different positions when aberrations are present (including defocus as an aberration). Here we exploit this property to measure aberrations and present focus measurement methods as an example. The key advantage of the Ronchigram is that we can measure many, possibly all, aberrations from one image or a very small set of images.

An established method is to move the sample by a known amount and to measure the resulting shifts, which depend on the local aberrations [3]. Thus this method requires a minimum of three Ronchigrams to measure all geometrical aberrations, and would require a focus change to extract information about chromatic terms. The Fourier transform of a Ronchigram has also been shown to provide convenient methods to measure aberrations [2, 4-6]. If the sample is a crystal, the Fourier transform will contain several "comets" [4]. These comets have a head and a tail with superposed interference fringes [4]. The shape of the tail is a particularly interesting problem and a solution has recently been given [7]. Here we consider only the position of the head of the comet. If the head of the comet is r_c pixels away from the center of an n pixel wide Fourier transform of a Ronchigram with c radians per pixel for a lattice spacing d then the defocus is given by $C_1 = r_c d/nc$. If the sample is amorphous, the Fourier transform will consist of a pattern of rings, very much like the contrast transfer function (CTF) of a traditional bright field TEM image (see Fig. 1). If the first zero is r_a pixels away from the center of the Fourier transform then the defocus is given by $C_1 = (r_a/nc)^2\lambda$. Note that this is the inverse of the usual result for a bright field CTF. The different dependence of the crystalline and amorphous diffractograms upon defocus highlights once again the curious mix of diffraction and real space information present in a Ronchigram. This result is of considerable interest when considering the transfer of information to the Ronchigram. It also suggests a route to simultaneously measure both temporal and spatial coherence as well as geometrical aberrations.

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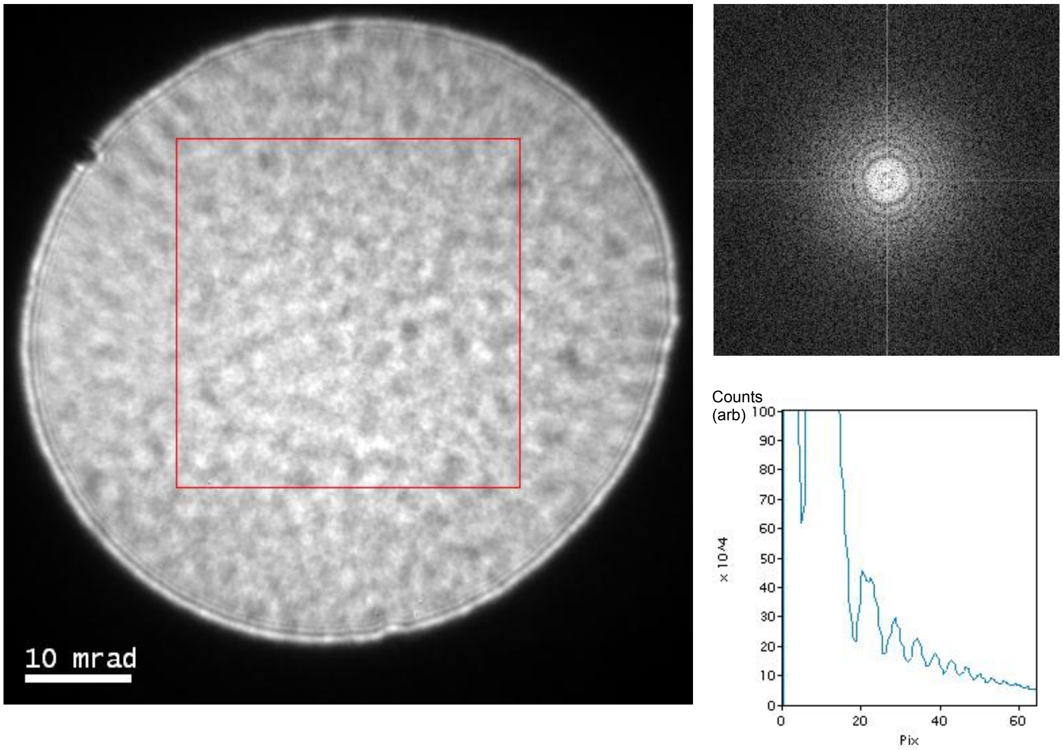

FIG. 1. (Left) Ronchigram of an amorphous carbon film at 100 kV. (Top right) Fourier transform of the patch indicated. (Bottom right) Rotationally averaged line profile from the Fourier transform. The magnitude of the measured defocus from r=18 pixels, n=256 pixels, c=0.126 mrad/pix, λ=3.7 pm is about 1143 nm.