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Quantitative Assessment of Lower-Voltage TEM Performance Using 3D Fourier Transform of Through-Focus Series

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The spherical aberration corrector was a quantum leap in high-resolution transmission electron microscopy (TEM) [1]. It brought about a breakthrough in high-resolution lower-voltage TEM, and a variety of novel nanostructured materials have been explored utilizing its high spatial resolution, high image contrast and low knock-on damage [2,3]. The performance of an aberration-corrected TEM is determined by the information limit that is often evaluated using Young's fringe method, in which the diffractogram of a double-exposure image with a given image shift, is analyzed. It was already reported, however, that Young's fringe method shows unexpected high frequency information [4] due to the non-linear terms, which correspond to interference between diffracted waves. The presence of the non-linear terms is a major difficulty in the existing procedures for evaluating TEM performance as pointed out by a few researchers [5,6]. The three-dimensional (3D) Fourier transform (FT) of through-focus TEM images allows us to discriminate between the linear imaging terms and the non-linear imaging terms [7–9]. The linear imaging terms are observed on twin Ewald spheres in the 3D FT using an amorphous specimen. Here, we use the 3D FT of through-focus TEM images for the assessment of two TEM systems.

Two spherical-aberration-corrected microscopes were assessed and compared at a relatively lower acceleration voltage. One transmission electron microscope was a Titan^3 (FEI) equipped with a monochromator and a spherical aberration corrector for image forming (CEOS, CETCOR) operated at an acceleration voltage of 80 kV. The energy spread of the electron source was 0.1 eV under monochromated condition. The other microscope, the TripleC microscope, was equipped with a cold field-emission gun (CFEG) and the spherical aberration corrector developed for the TripleC project. This microscope was operated at 60 and 30 kV [10], and the energy spread was 0.3-0.4eV.

Figure 1 schematically shows the various 3D data processed in this study [9]. Acquired through-focus TEM images are stacked as a function of the defocus z, and a 3D data set I_{xyz} is formed (Fig. 1a). The 3D Fourier transform $\boldsymbol{I}_{uvw}$ (Fig. 1c) of through-focus images shows two paraboloids called Ewald spheres, attached at the origin. The information limit can be estimated as the observable range of the Ewald spheres. The 3D Fourier transform $\boldsymbol{I}_{uvw}$ may be obtained by an additional 1D Fourier transform along the z-axis from the 2D Fourier transform stack $\boldsymbol{I}_{uvz}$ (Fig. 1b) of each TEM image.

The signal of the Ewald spheres depends on various factors, such as atomic scattering factors, a specimen structure, a specimen thickness, the modulation transfer function of an imaging device, and other instrumental instabilities; therefore, the quantitative evaluation of diverse TEM systems is not straightforward. Here we apply the tilted incidence in the 3D Fourier transform method (Fig. 2) to normalize those factors. We achieve the quantitative evaluation of temporal partial coherence, in other words, we determine the spatial frequency at which information transfer decreases to $1/e^2$ (13.5%), as shown in Fig. 3. It was found that the energy spread of the electron source is the major limiting factor even in a monochromated microscope [11].

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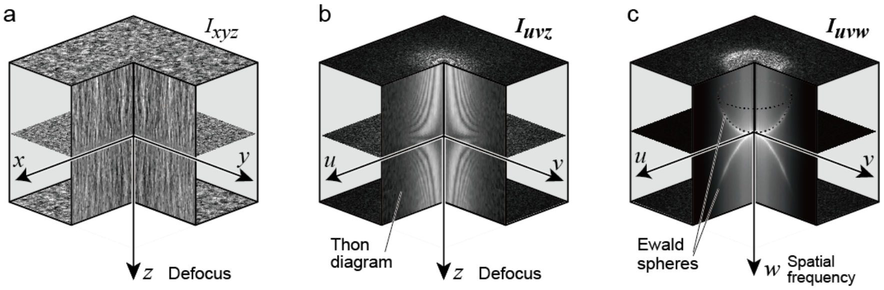


Figure 1. Schematics of (a) through-focus TEM images I_{xyz}, (b) stack of 2D Fourier transforms $\boldsymbol{I}_{uvz}$, and (c) 3D Fourier transform $\boldsymbol{I}_{uvw}$ of the through-focus images. Since $\boldsymbol{I}_{uvz}$ and $\boldsymbol{I}_{uvw}$ are complex, their moduli are shown in gray scale. The cross section $\boldsymbol{I}_{vz}$ is similar to the Thon diagram. Two Ewald spheres attached at the origin are observed in the 3D Fourier space $\boldsymbol{I}_{uvw}$.

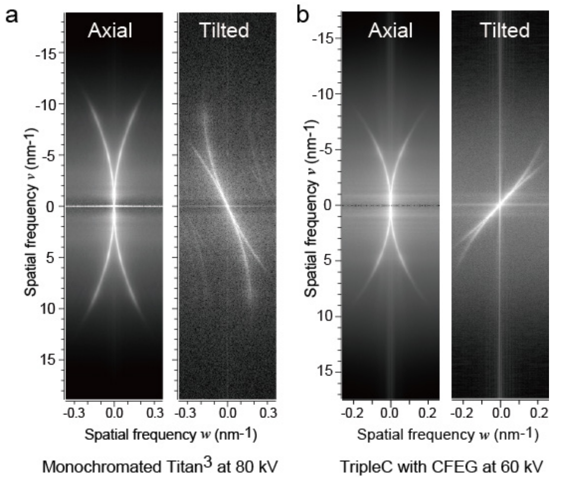
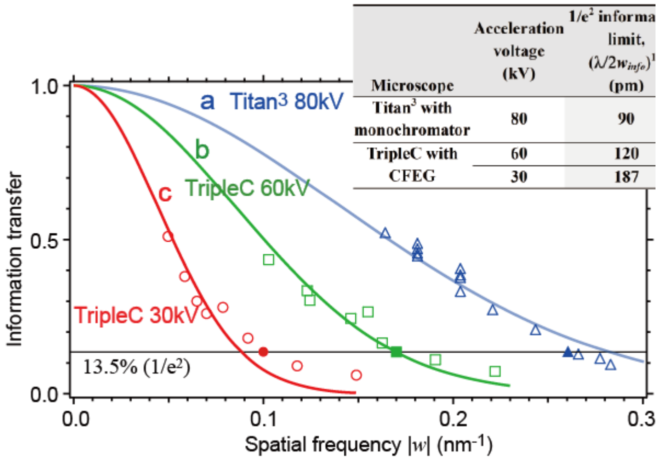


Figure 2. Cross sections of 3D Fourier transforms under on-axial and tilted incidence conditions. (a) Titan^3 (80kV) and (b) TripleC (60kV).



Microscope	Acceleration voltage (kV)	1/e^2 informa limit, $(\lambda/2w_{info})^1$ (pm)
Titan^3 with monochromator	80	90
TripleC with CFEG	60	120
	30	187

Figure 3. Information limit of (a) monochromated Titan^3 (80kV), TripleC at 60kV (b) and 30kV (c).