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Benefits of simultaneous C_c- and C_s-correction

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The CEOS C_c- and C_s-corrector 'C-COR' for transmission electron microscopes consists of two multipole modules which are placed in between three transfer lens doublets to couple the objective, the multipole modules and the projective. Each multipole module comprises five major quadrupole stages. The mid-element provides the crossed electromagnetic quadrupole fields for the C_c-correction and octupole fields for the C_s-correction, respectively. The overall design aims for a spatial resolution of 0.05nm with an attainable field of view of several thousand equally-well resolved image points. The C-COR can be operated at accelerating voltages from 80 to 300kV.

Over the last years the benefit of C_s-correction has become obvious and commonly known. The key factor besides vanishing delocalization is the improvement of the point resolution limit down to the so called information limit (IL) by means of small tunable values for the third-order spherical aberration coefficient C_s. However, the different contributions to the IL and the methods for their individual measurement have rarely been fully discussed nor been established.
The contributions to the IL can be separated into two classes [1], namely 'image spread' (deflector noise, mechanical vibrations, lateral movement of the specimen) and 'focus spread' (energy spread, lens and high-tension instabilities, z-movement of the specimen). For today's electron microscopes the energy spread of the source in combination with the chromatic aberration coefficient of the objective lens determines the IL first of all. Hence the IL can be improved by monochromators or C_c-correction. The latter has the advantage to preserve the beam current of the electron source and to allow to image large energy windows almost into the same plane: By design the C-COR and the objective lens form an 'Apochromat' (three wavelengths are focused into one plane). At 200kV an energy window of 700eV is focused within 2.5nm [2]. This should enable many interesting experiments in energy filtered electron microscopy.

The benefit of C_s- and subsequent C_c-correction can be illustrated best within the framework of linear contrast transfer theory. Fig. 1 shows the contrast transfer function of an uncorrected microscope at 80kV (FEI Titan with ST pole piece) with a point resolution limit of 0.36nm, the chromatic damping envelope with C_s-correction by means of a CEOS hexapole corrector allowing for an IL of 0.16nm, and the damping envelope for the C-COR in the TEAM 1 microscope assuming a defocus spread of 0.48nm (rms, measured by tilt series) and an image spread of 29pm (rms, chosen to meet the experimental IL but neglecting the scattering amplitude) [2]. The experimental verification is given in Fig. 2 using the amorphous parts (carbon) of a cross-grating specimen, where a diffractogram at Scherzer focus for the uncorrected case is shown together with Young's fringe experiments for the C_s- and C_c/C_s-corrected case.
In the talk we will show that Young's fringes at parts of the cross-grating with gold clusters does not result in a measure for the information limit in total but for the image spread contributions only. This is due to the nonlinear terms for which the classical (linear) chromatic damping envelope does not hold true. As a consequence, the surprisingly good Young's fringe experiments shown with C_s-correction at 80kV on partly crystalline specimens are nonlinear artifacts. Significant linear contrast transfer at 80kV below 0.16nm down into the sub-Å region can only be obtained with C_c-correction.

References
[1] M. Haider et al., *Ultramicroscopy* 108 (2008) 167.
[2] M. Haider et al., *Microsc. Microanal.* (submitted).
[3] This research was partly founded by the Department of Energy within the TEAM project. The very good cooperation between all TEAM partners, FEI and the group of U. Kaiser, University Ulm, Germany is gratefully acknowledged.

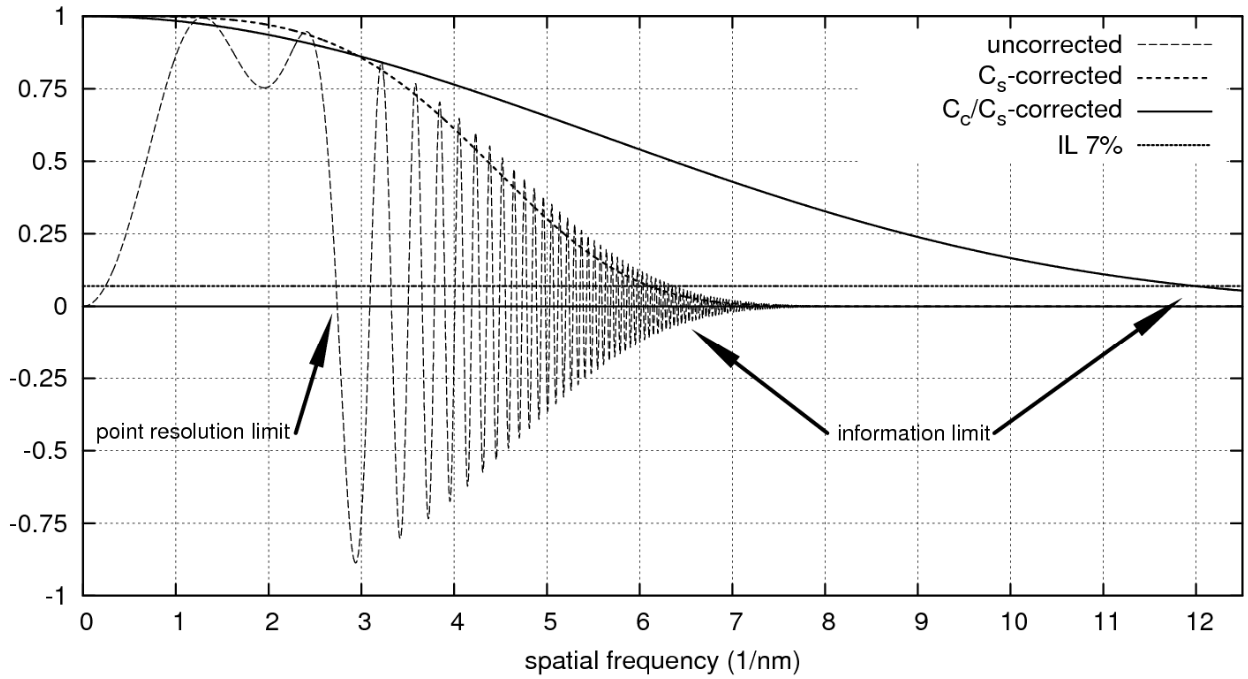

FIG. 1. Contrast transfer at 80kV. Uncorrected: Scherzer focus, C_s=1.4mm, C_c=1.38mm and dE=0.7eV; C_s-corrected: damping envelope, C_c=1.51mm. C_c/C_s-corrected: damping envelope with focus spread (0.48nm, rms) and image spread (29pm, rms).

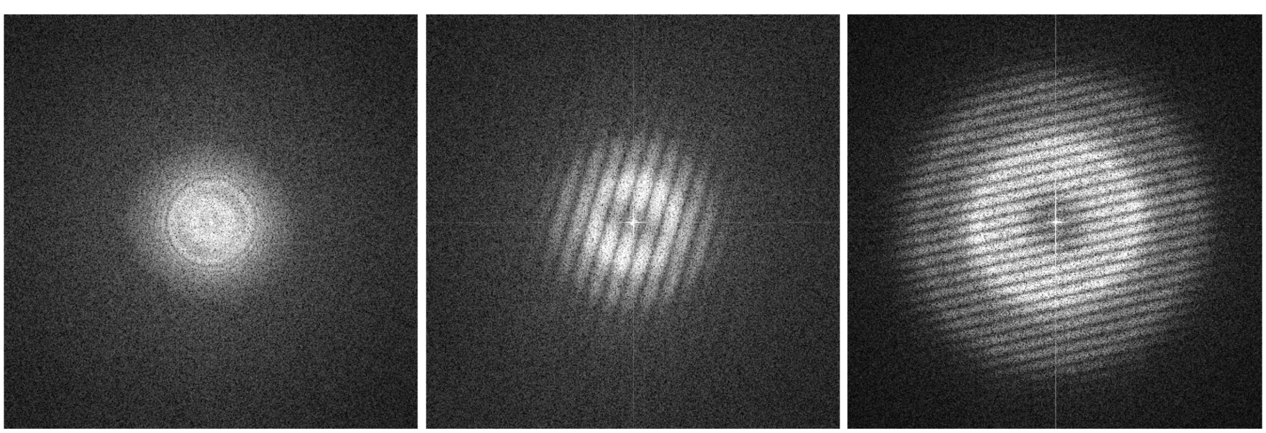

FIG. 2. Diffractograms of amorphous carbon parts on a standard cross-grating taken at 80kV. Left: uncorrected – point resolution limit of 0.36nm, middle: C_s-corrected – C_c-dominated information limit of 0.16nm, right: C_c- and C_s-corrected – image spread dominated information limit of 0.09nm. The Nyquist frequency is 12.5nm (equivalent to 0.08nm) for all images.

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