Through-focus point-spread function evaluation for lens metrology using the Extended Nijboer-Zernike theory

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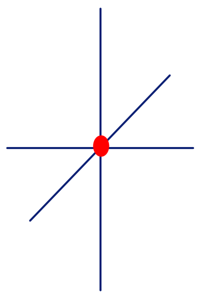
Overview

- Point Spread Function analysis and the Extended Nijboer-Zernike theory
- Retrieving aberrations
- Lithographic applications: retrieving aberrations, diffusion and focus noise parameters.
- Microscope analysis
- Extension to high-NA imaging: ‘polarisation aberrations’
- Summary and references / website

Point spread function

δ-function



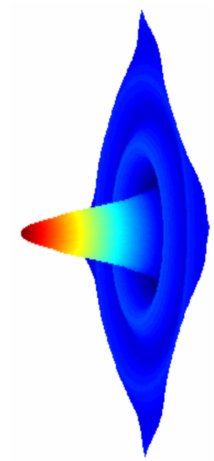
Lithographic lens,

reticle inspection tool,

microscope or

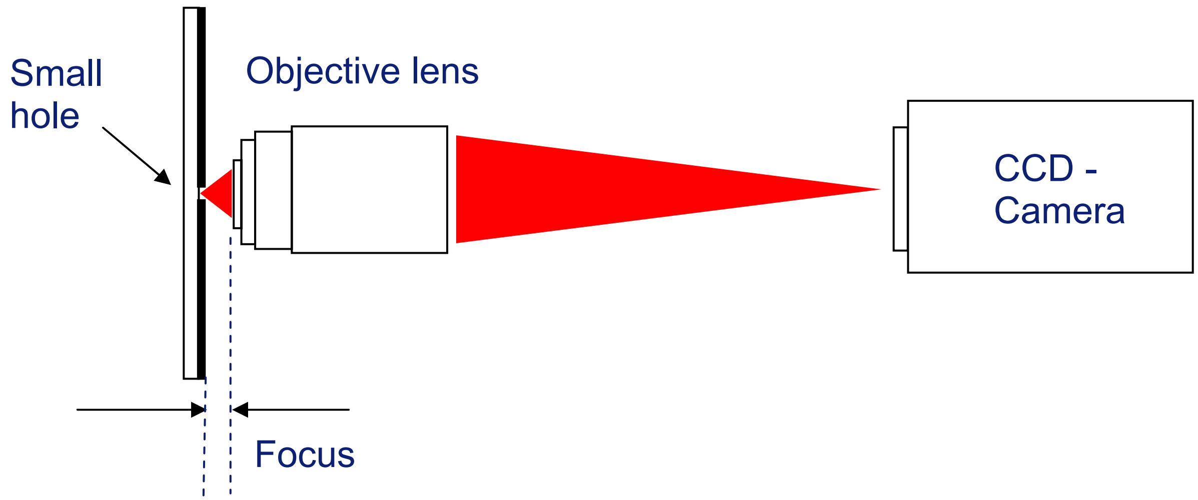
EUV mirror system.

PSF



The ENZ (Extended Nijboer-Zernike theory) provides an analytical description of the PSF and allows the retrieval of lens aberrations and process parameters from the measured PSF

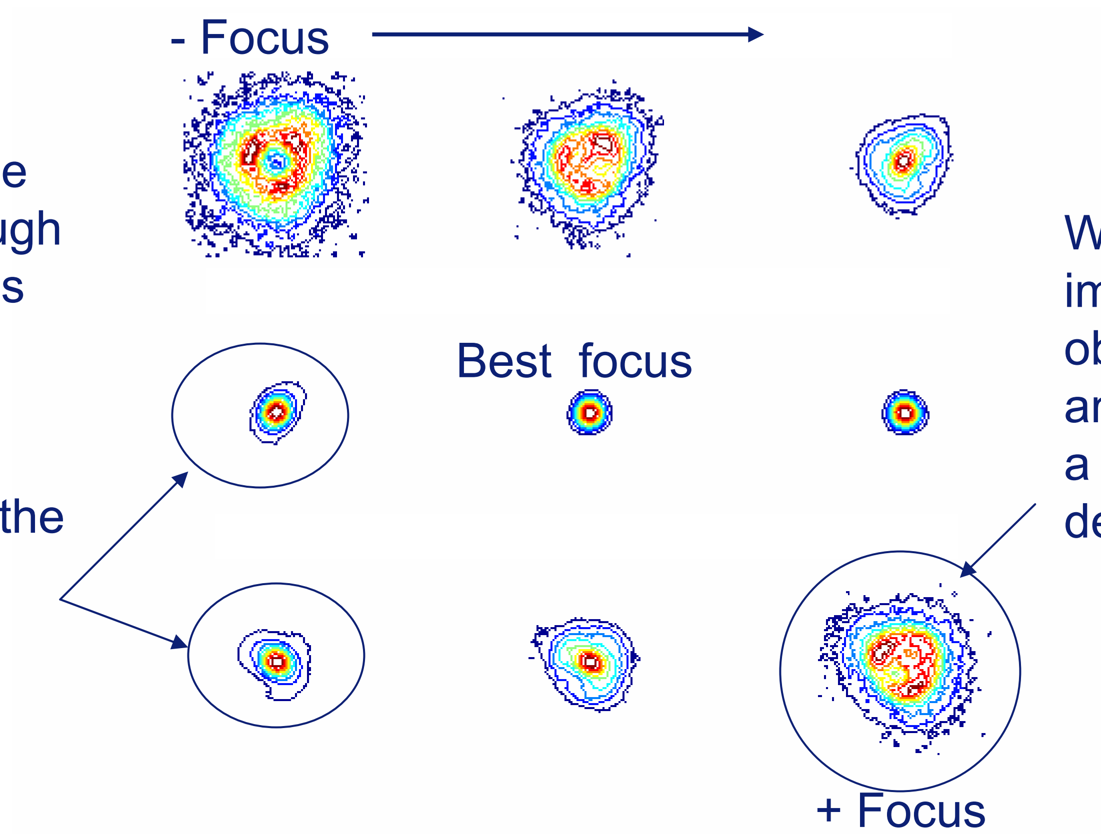
Basic scheme for microscope imaging



Record the through-focus intensity point-spread function

Experimental through-focus PSF

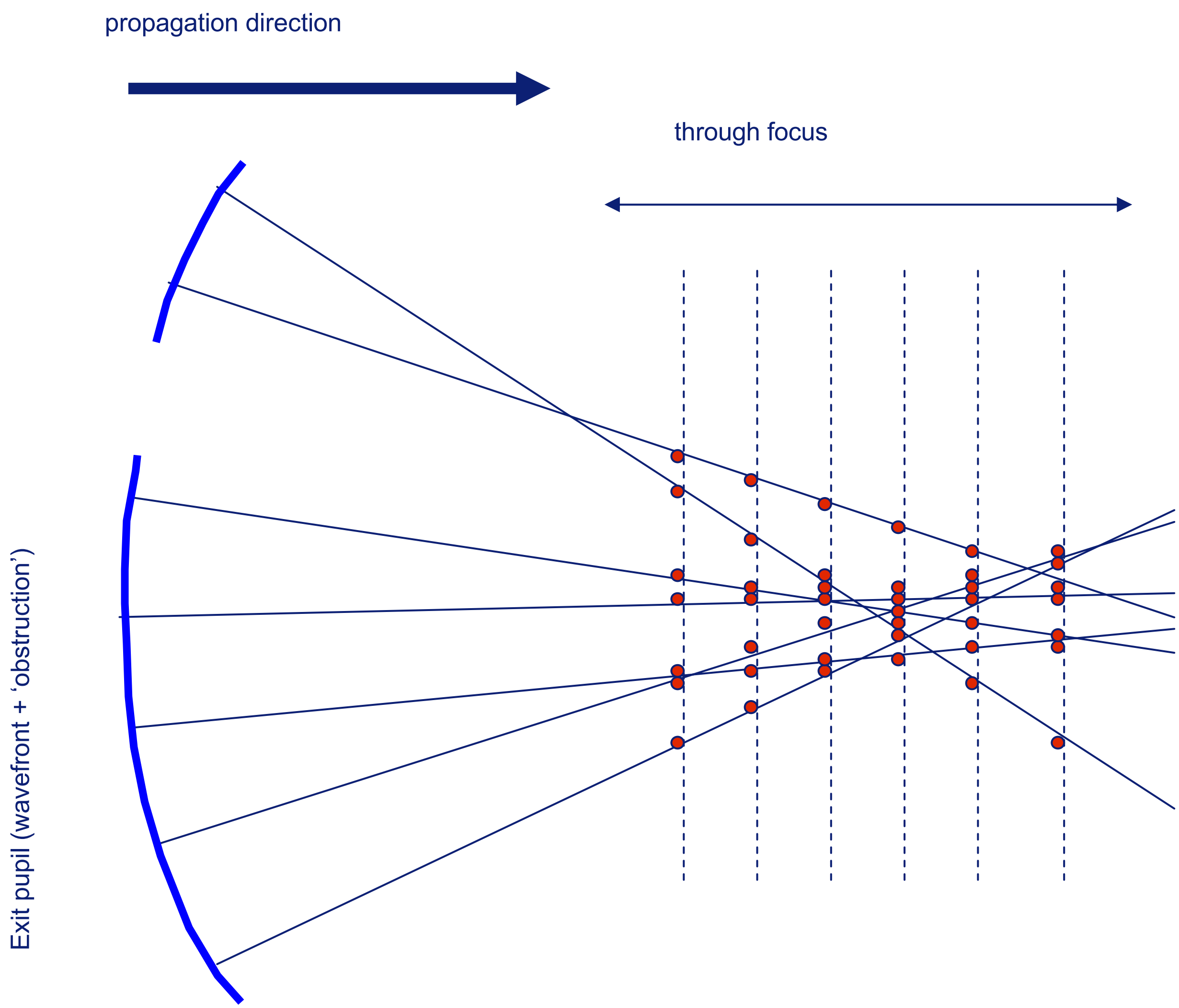
Elliptical shape that flips through focus indicates **astigmatism**. Note the ~45-degree orientation of the ellipse.



With a little bit of imagination one observes a small amount of **trefoil**: a ‘triangle’ like deformation

What aberration type, low order versus high order, how many *m*λ?

Intuitive picture of through-focus intensity



Diffraction theory of (through-focus) imaging

THE DIFFRACTION THEORY OF ABERRATIONS

PROEFSCHRIFT

TER VERKRIJGING VAN DEN GRAAD VAN DOCTOR IN DE WIS- EN NATUURKUNDE AAN DE RIJKS-UNIVERSITEIT TE GRONINGEN, OP GEZAG VAN DEN RECTOR MAGNIFICUS Dr. J. M. N. KAPTEYN, HOIOGLEERAAR IN DE FACULTEIT DER LETTEREN EN WIJSBEGEER-TE, TEGEN DE BEDENKINGEN VAN DE FACULTEIT DER WIS- EN NATUURKUNDE TE VERDEDIGEN OP MAANDAG 1 JUNI 1942, DES NAMIDDAGS OM 4.15 UUR PRECIES

DOOR

BERNARD ROELOF ANDRIES NIJBOER

GEBOREN TE MEPPEL

The old diffraction theories of

- Airy (in-focus, ideal,1835),
- Lommel (through-focus, ideal, 1885)
- Nijboer (‘in focus’, aberrated, 1942)

arise as special cases of the

Extended Nijboer-Zernike theory

(A. Janssen, 2002)

Features of the ENZ diffraction theory

- Complex pupil function allowed (amplitude *and* phase)
- Both transmission and aberration function are given by the (complex) coefficients of a Zernike expansion
- Large defocus allowed (up to ± 8 focal depths)
- Scalar version with pathlengths treatment for high NA
- Vectorial version developed for high NA

Applications:

- Linearised inversion scheme available for transmission and aberration function retrieval
- Iterative procedure developed for improved retrieval at larger aberrations and transmission defects

Basic expressions

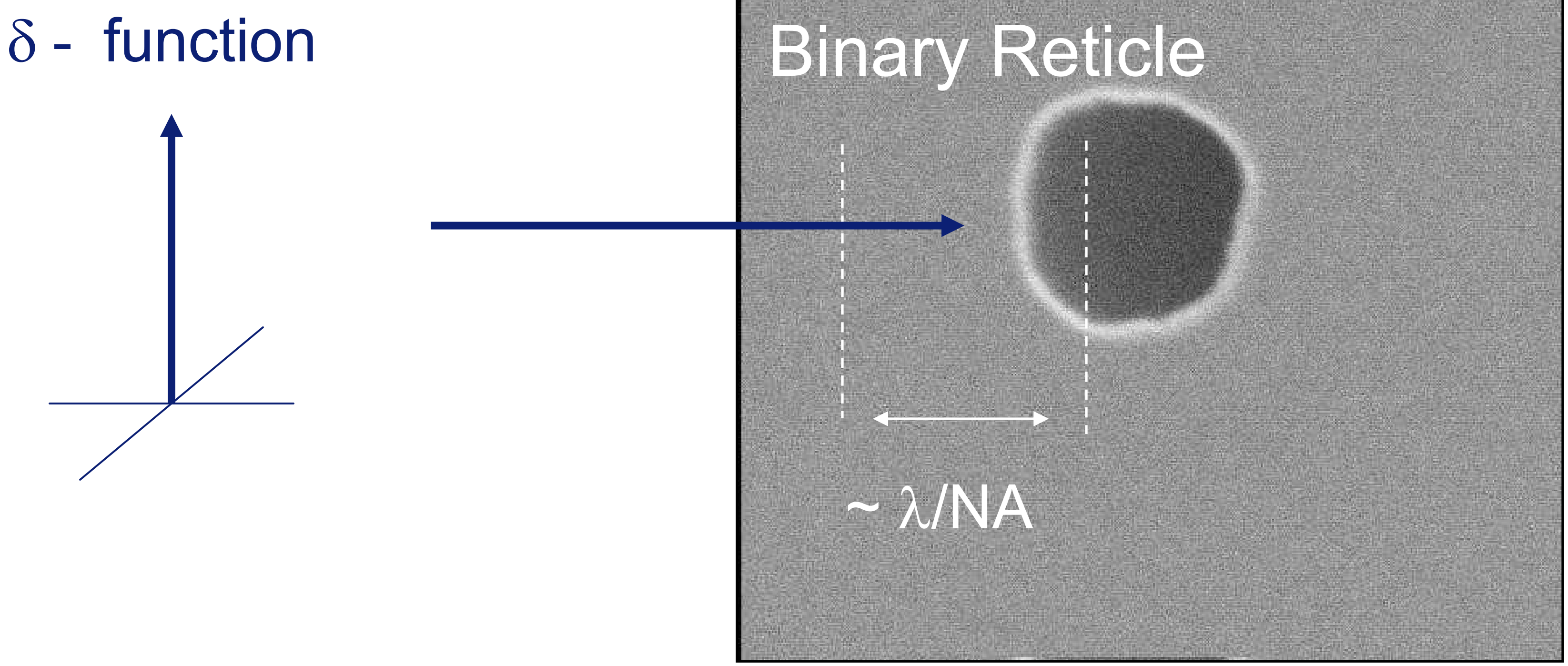
$$U(r,f,\vartheta) \approx 2V_{00}(r,f)+2\sum_{nm}\alpha_{nm}i^{m+1}V_{nm}(r,f)\cos(m\vartheta),$$

$$V_{nm}(r,f)=\exp(if)\sum_{l=1}^{\infty}(-2if)^{l-1}\sum_{j=0}^{p}v_{lj}\frac{J_{m+l+2j}(r)}{lr^{l}}$$

In practice: finite source diameter !

Numerical approach: integrate PSF over the finite hole diameter.

Finite source effect



Analytic approach: use complex focus parameter

$$f \to f + i.d \longleftarrow$$ *d* = diameter hole

Aberration retrieval

The lens aberrations are obtained from the through-focus point spread function.

$$\boxed{\underbrace{\text{Observed intensity}}_{\text{Measured}} = \sum \alpha_{nm} \ \underbrace{\text{basic-functions}\ (V_{nm})}_{\text{Calculated from theory}}}$$

Parameters to be retrieved

Aberration retrieval

$$U(r,\theta,f) \approx 2V_{00} + 2\sum_{nm} \alpha_{nm} i^{m+1} V_{nm} cos(m\theta),$$

$$I(r,\theta,f) \approx 4\left|V_{00}\right|^2 + 8\sum_{nm} \alpha_{nm} \operatorname{Re}\left\{ i^{m+1} V_{00}^* V_{nm} \right\} \cos(m\theta) + \ldots$$

Drops out !

$$\psi^m = m^{th} - \text{Fourier component of } I(r,\theta,f)$$

$$\psi^m = \sum_n \alpha_{nm} \psi_n^m \quad \text{with} \quad \psi_n^m = 4\operatorname{Re}\left\{ i^{m+1} V_{00}^* V_{nm} \right\}$$

'Fringes'

Take inner products:

$$(\psi^m, \psi_{n'}^m) = \sum_n \alpha_{nm} (\psi_n^m, \psi_{n'}^m) \longrightarrow$$ a linearised system of equations.

Aberration retrieval & noise

m^th^ - Fourier component ... basic intensity functions

$$\psi^{m} = \sum_{n} \underbrace{\alpha_{nm}}_{\text{Aberration parameter}} \psi_{n}^{m} \quad \text{with} \quad \psi_{n}^{m} = 4\,\mathrm{Re}\left\{ i^{m+1} V_{00}^{*} V_{nm} \right\}$$

Retrieval procedure:

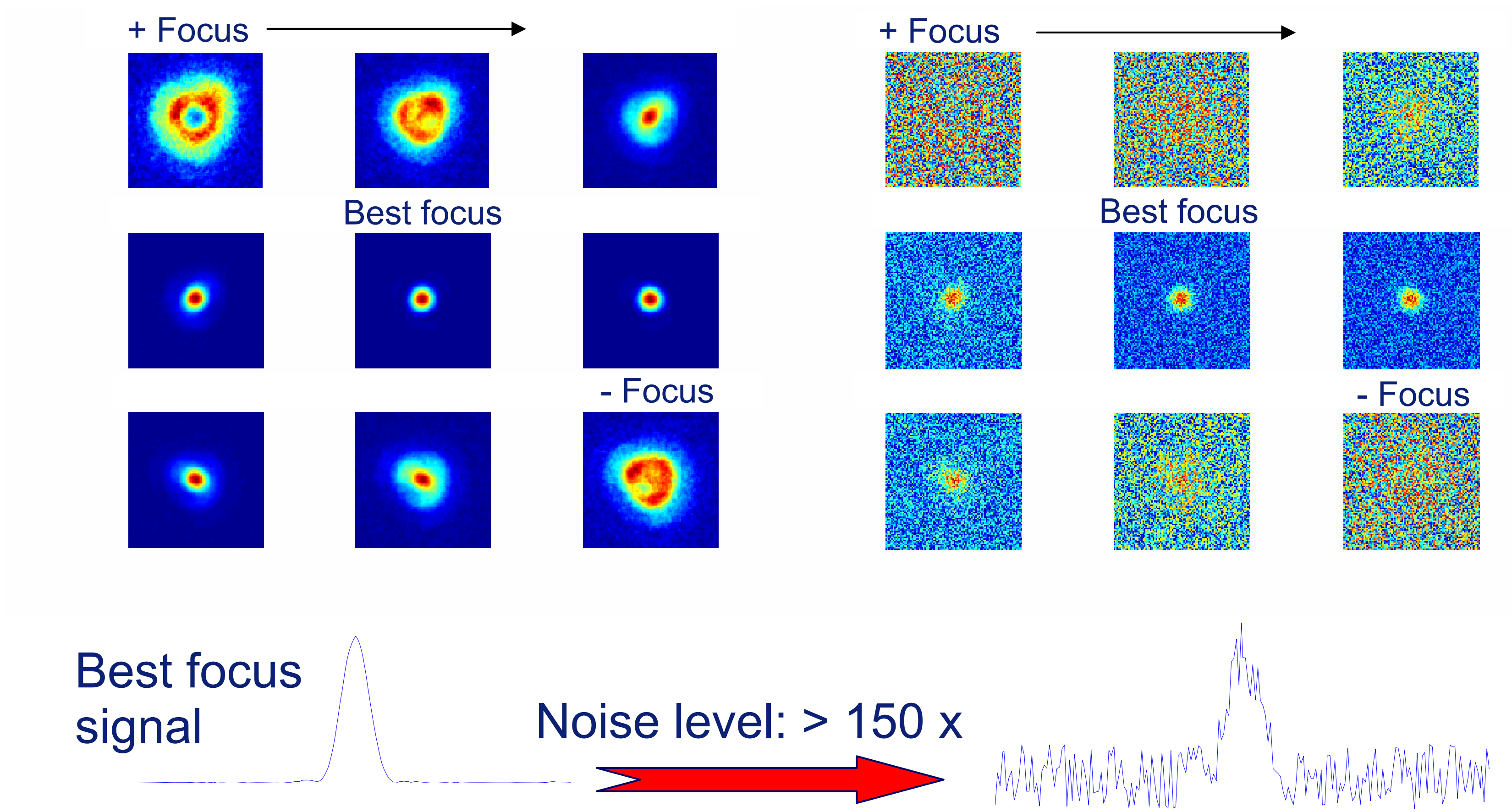
- match experimental frequency component (ψ^m) to specific through-focus signatures ($\psi^m{}_n$).

- only that part of the signal that matches the signature, contributes to parameter value:

• fairly noise insensitive

• !! be careful with DC-intensity offset

Example: impact noise

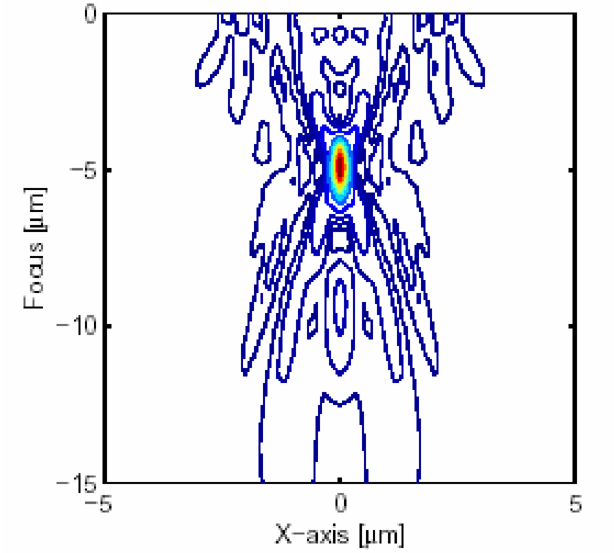


Small change in retrieved aberration coefficients: $\Delta Z \sim 10\ m\lambda$

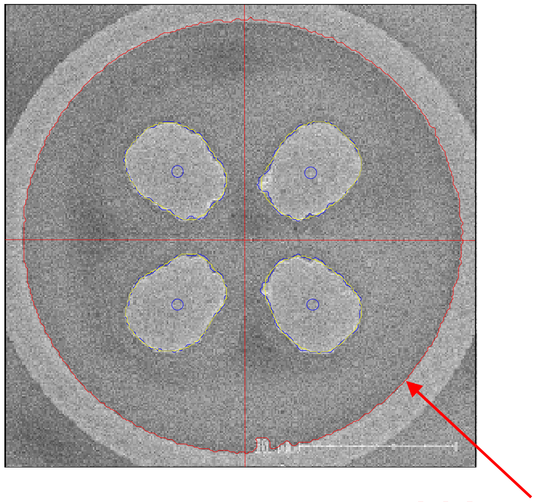
Generalizations ENZ theory

Various generalizations of the ENZ-theory exist, such as finite hole size, phase and transmission errors, large aberrations, large defocus.

ENZ - large defocus used to simulate the imaging properties of a Fresnel zone-lens for a DUV stepper (λ=0.248, NA =0.60)



Application: source metrology by moving to the far-field.
Example: quadruple source



NA - lens

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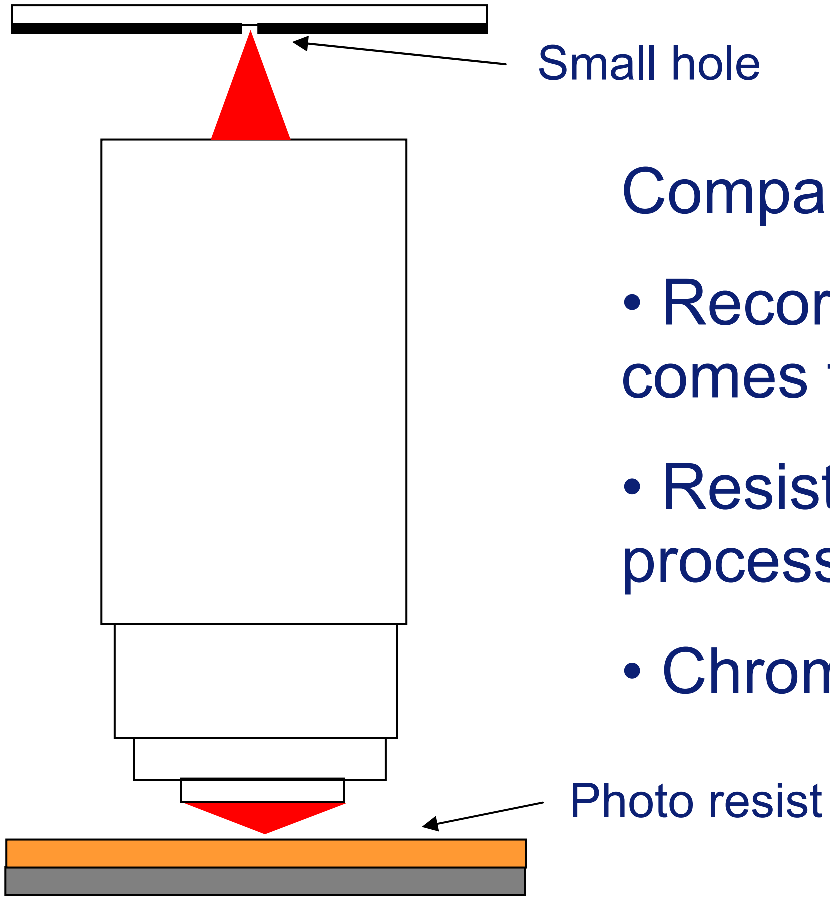
Basic imaging scheme for lithographic scanner

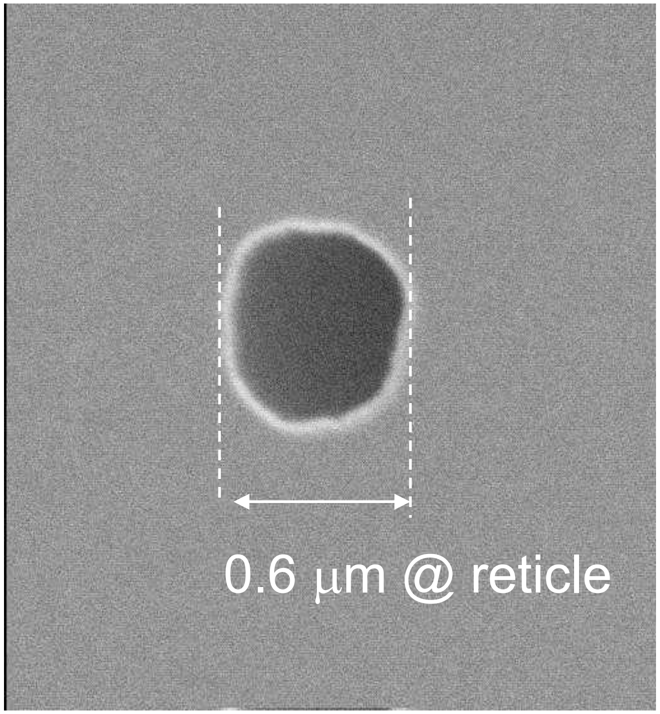


Compared to microscope with CCD:

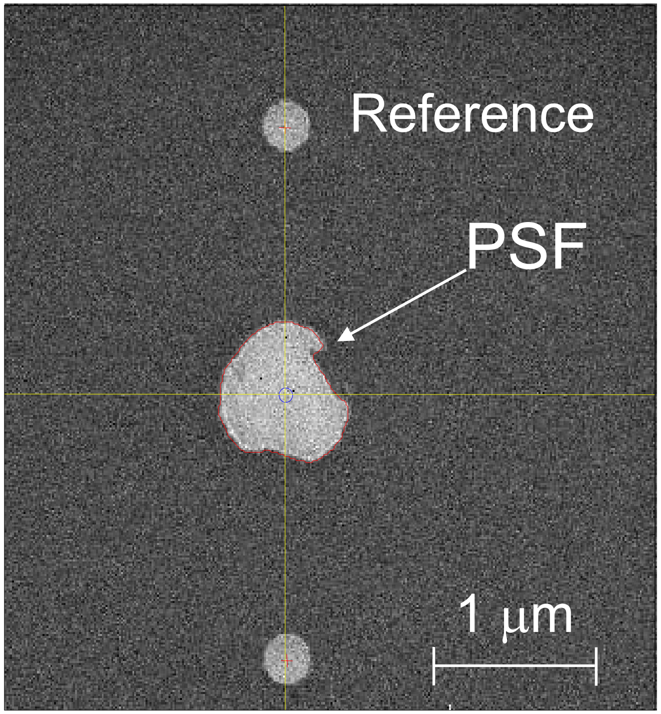
- Recording in *photo resist*: data comes from many SEM-images
- Resist baking and development process
- Chromatic aberrations

Record images in photo resist

Reticle

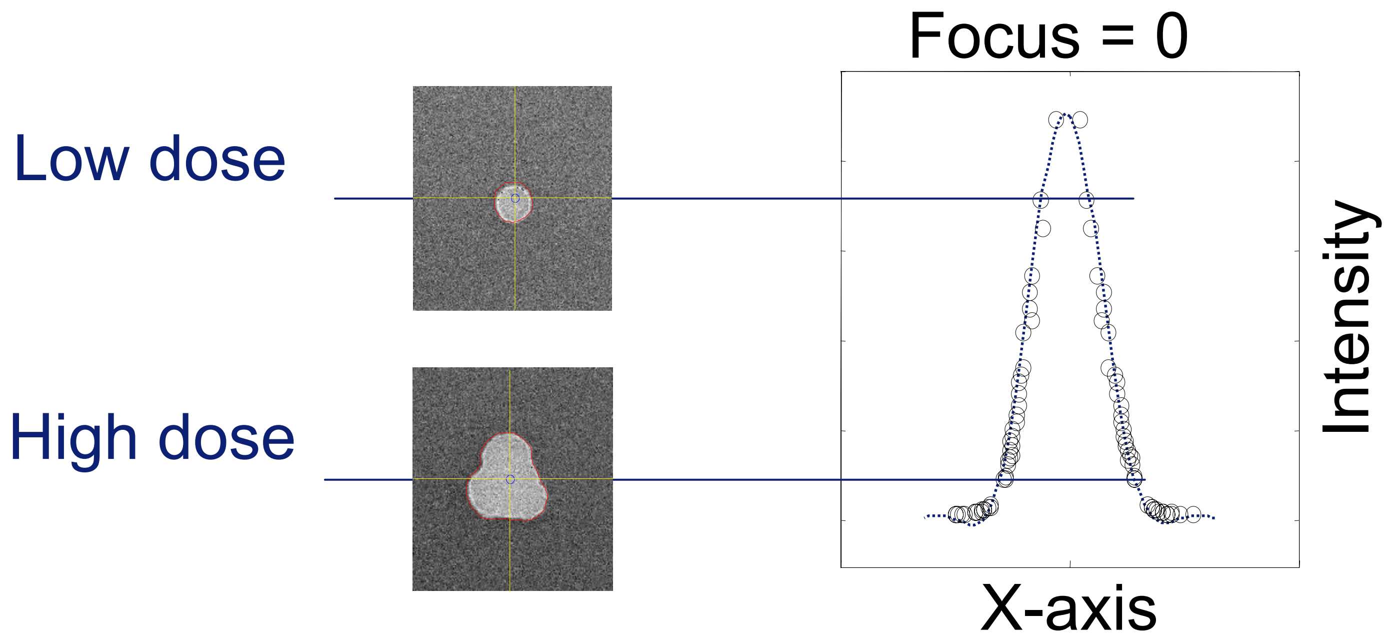


Wafer



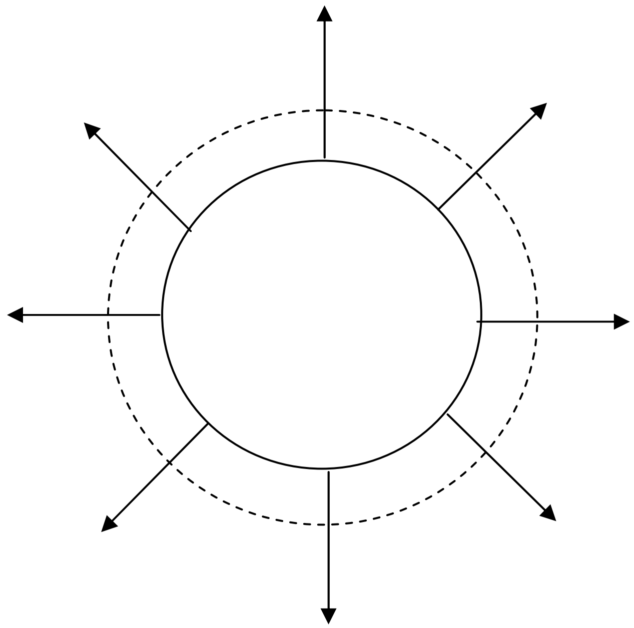
One exposure: single contour point-spread function

Contours to obtain intensity PSF



The through-focus PSF is constructed from a focus-exposure matrix

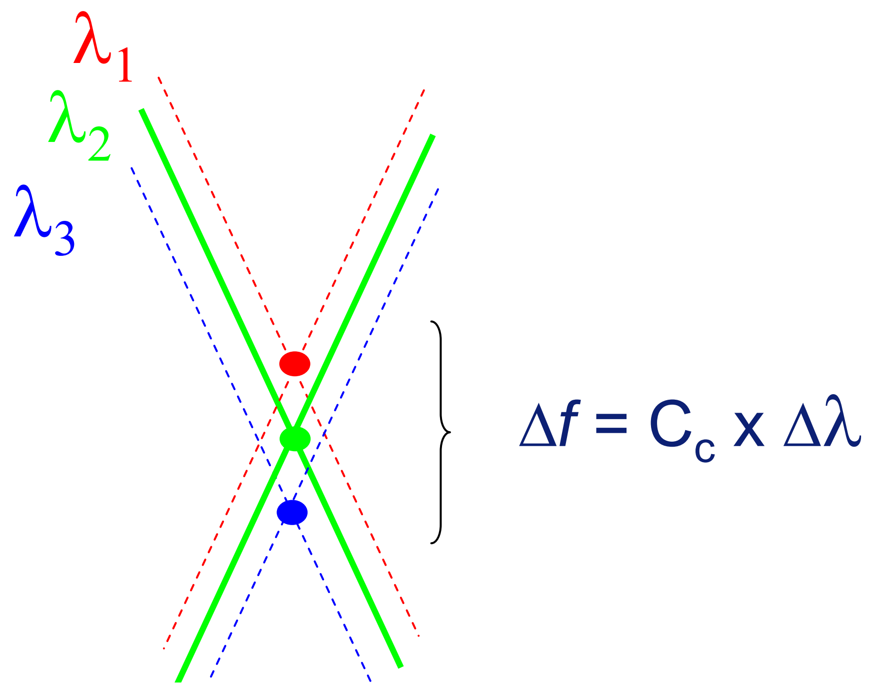
Diffusion



During the resist baking, a diffusion process takes place that increases the diameter of the PSF.

The ENZ theory can take the diffusion into account.

Chromatic aberrations



Chromatic aberrations and finite laser-bandwidth cause image blur along the focal axis: the observed DOF is *increased*.

The ENZ approach can take the focus noise into account.

More generalizations ENZ theory

- Retrieval of diffusion, chromatic aberrations,

$$I(r,f) \approx \sum_j Z_j[\text{Aerial image}] + \sigma_R^2[\text{Diffusion}] + \sigma_F^2[\text{Focus noise}],$$

$$\text{Aerial image} \quad : V_{n,m}V_{0,0}^{*}$$

$\leftarrow$ basic diffraction pattern

$$\text{Diffusion} \quad : -2\left|V_{0,0}\right|^2 + 4\left|V_{1,1}\right|^2 + \ldots$$

$$\text{Focus noise} \quad : -\frac{1}{6}\left|V_{0,0}\right|^2 + \frac{1}{3}\mathrm{Re}\left(V_{2,0}V_{0,0}^{*}\right) + \ldots$$

2 additional terms

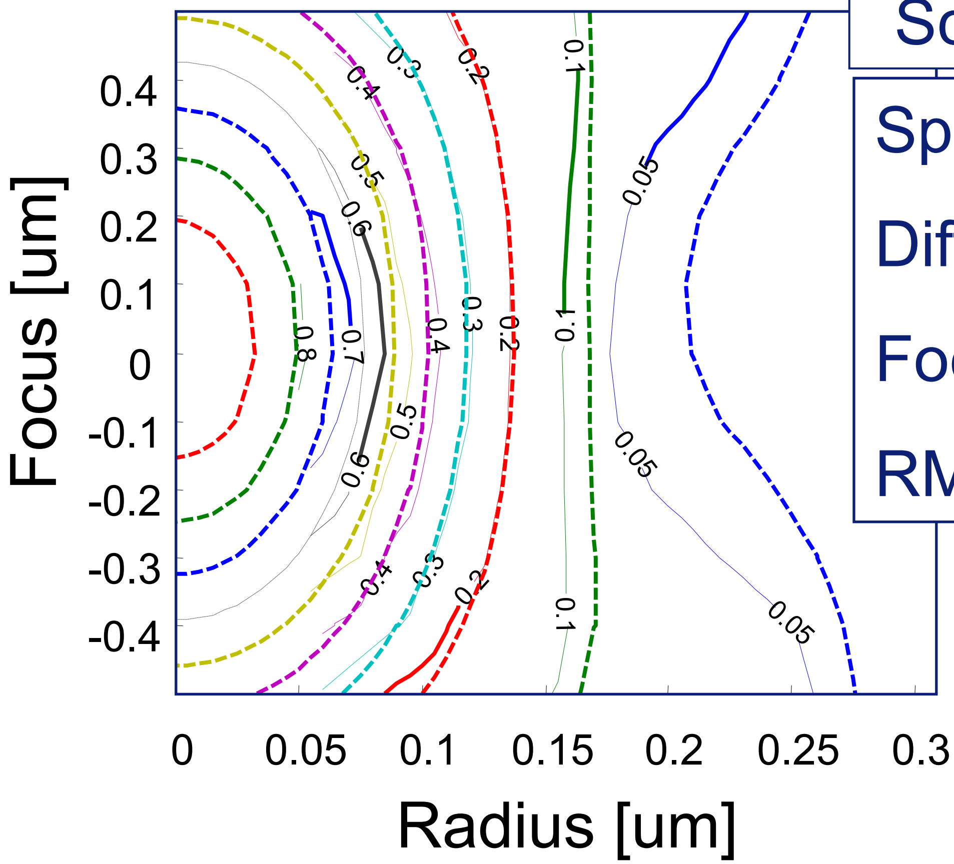
- Aerial image, diffusion and focus noise:

  basic intensity functions are known functions

  with specific ‘fingerprint’.

Philips

Parameter extraction: best match

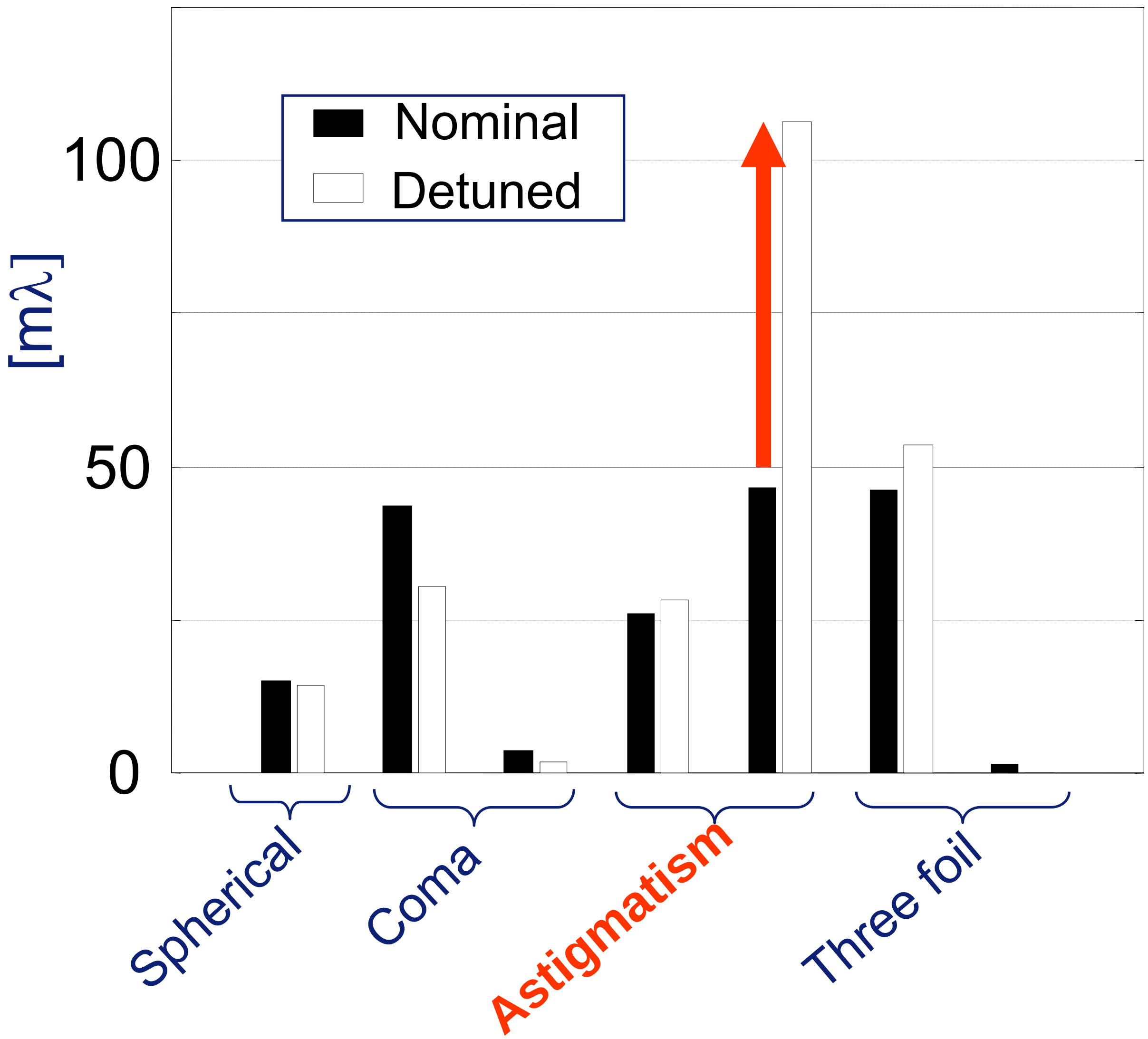


Scanner: NA=0.63, λ=193 nm

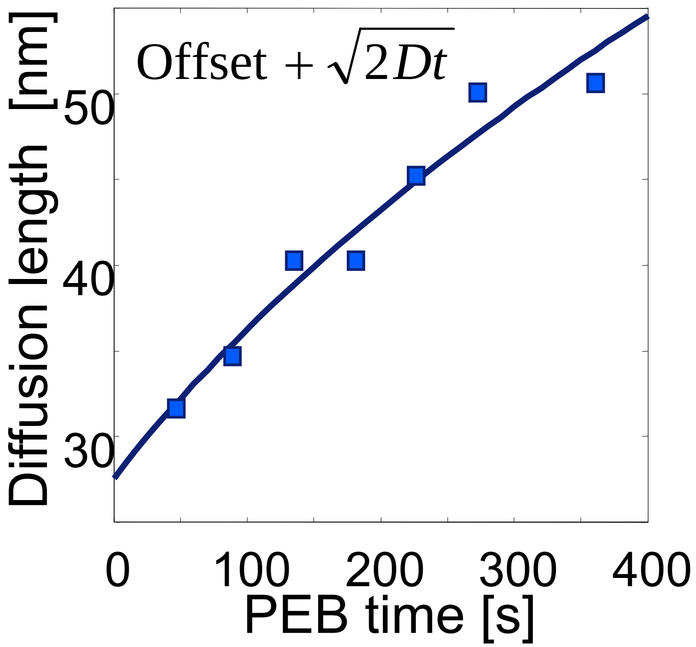
Spherical	= 34 mλ
Diffusion	= 31 nm
Focus noise	= 195 nm

RMS fit error 1.5 % typical

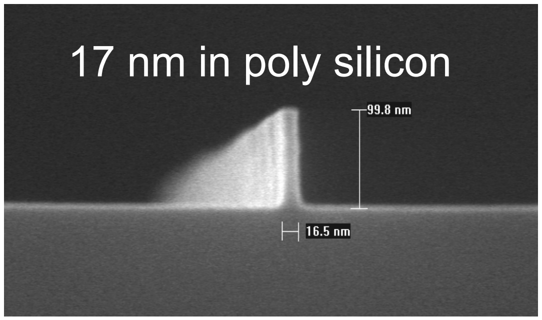
Aberrations



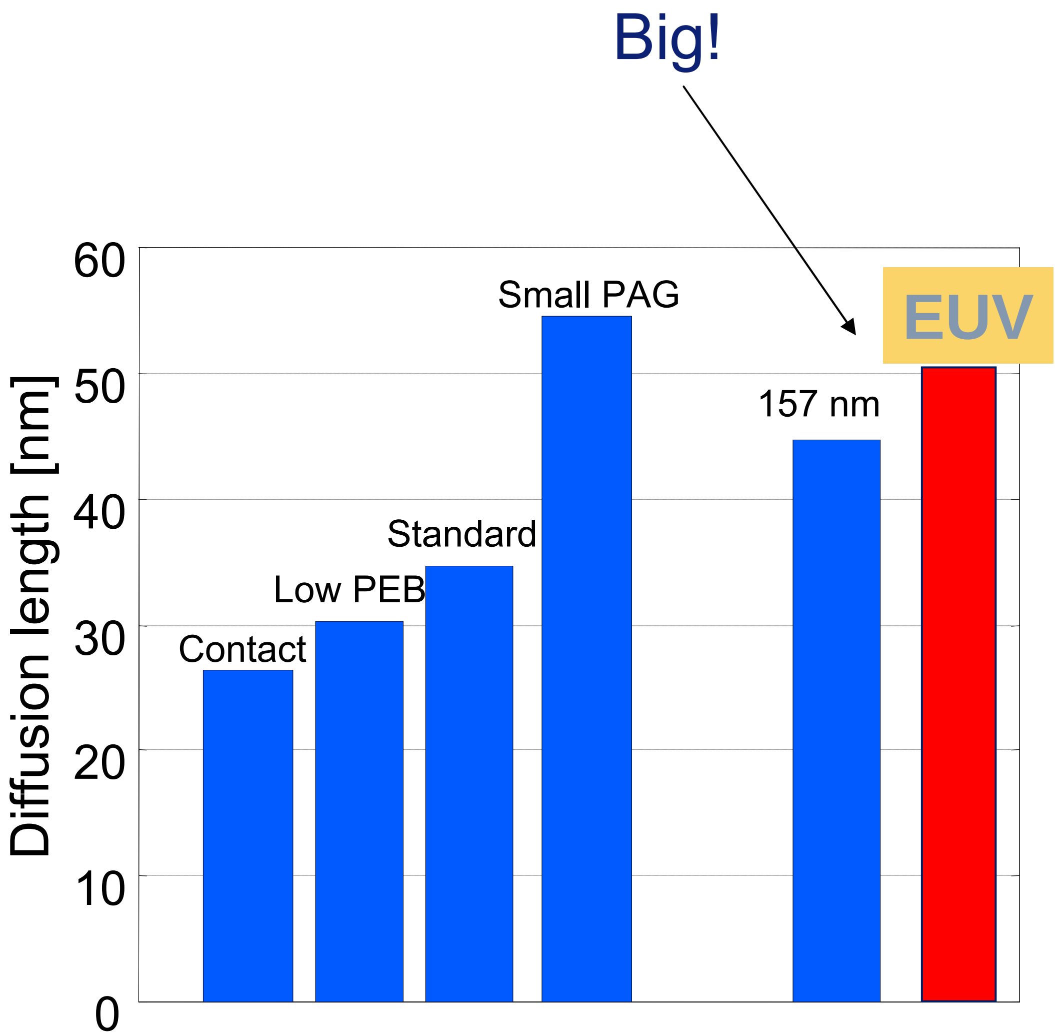
Diffusion



$\text{Offset} + \sqrt{2Dt}$
Diffusion length [nm]
30
40
50
0
100
200
300
400
PEB time [s]

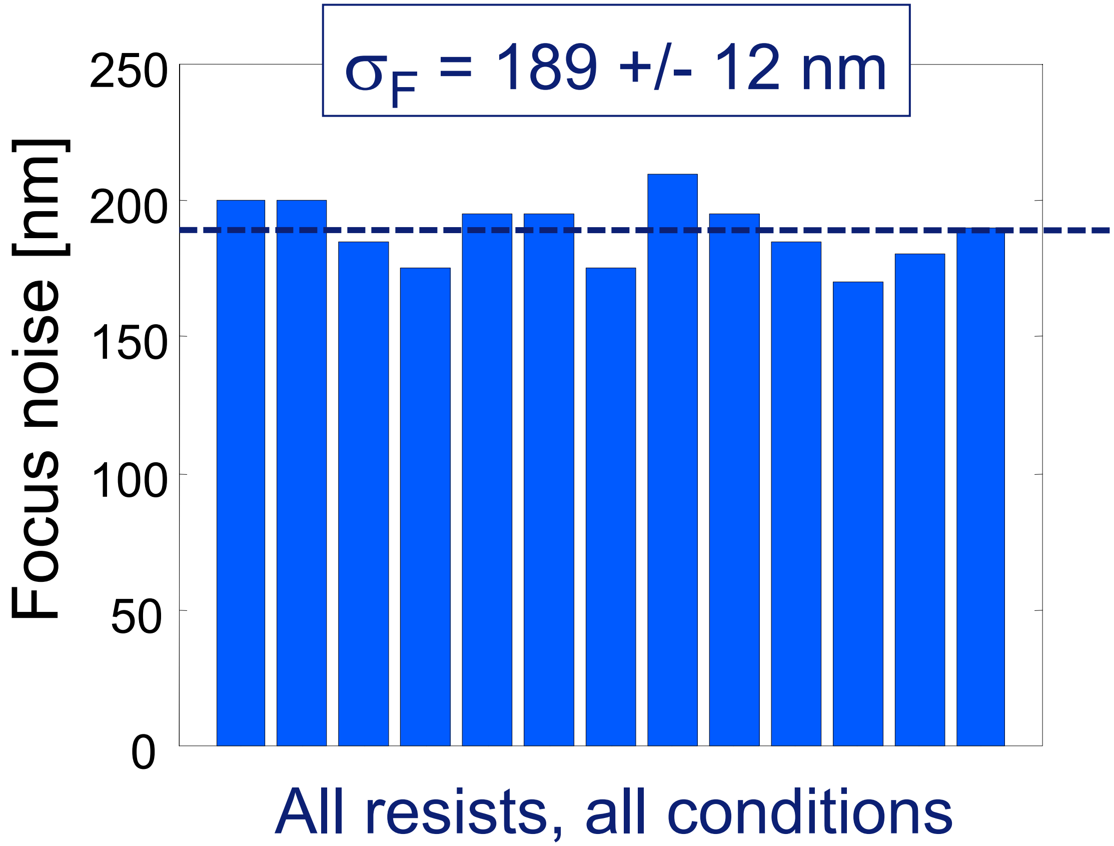


17 nm in poly silicon
99.8 nm
16.5 nm



Big!
EUV
Diffusion length [nm]
0
10
20
30
40
50
60
Contact
Low PEB
Standard
Small PAG
157 nm

Chromatic aberrations



Correlates to laser bandwidth and chromatic aberrations projection lens

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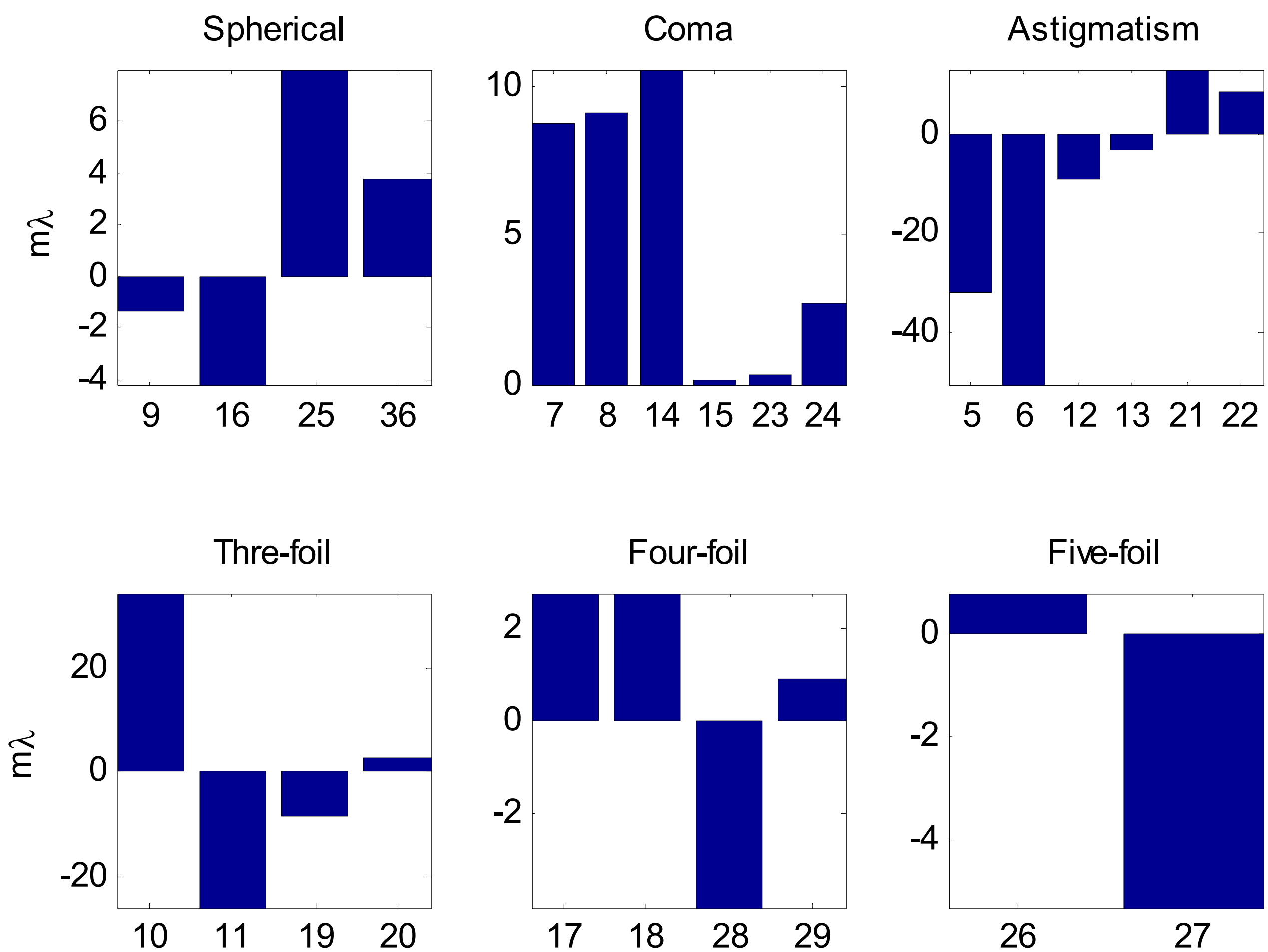
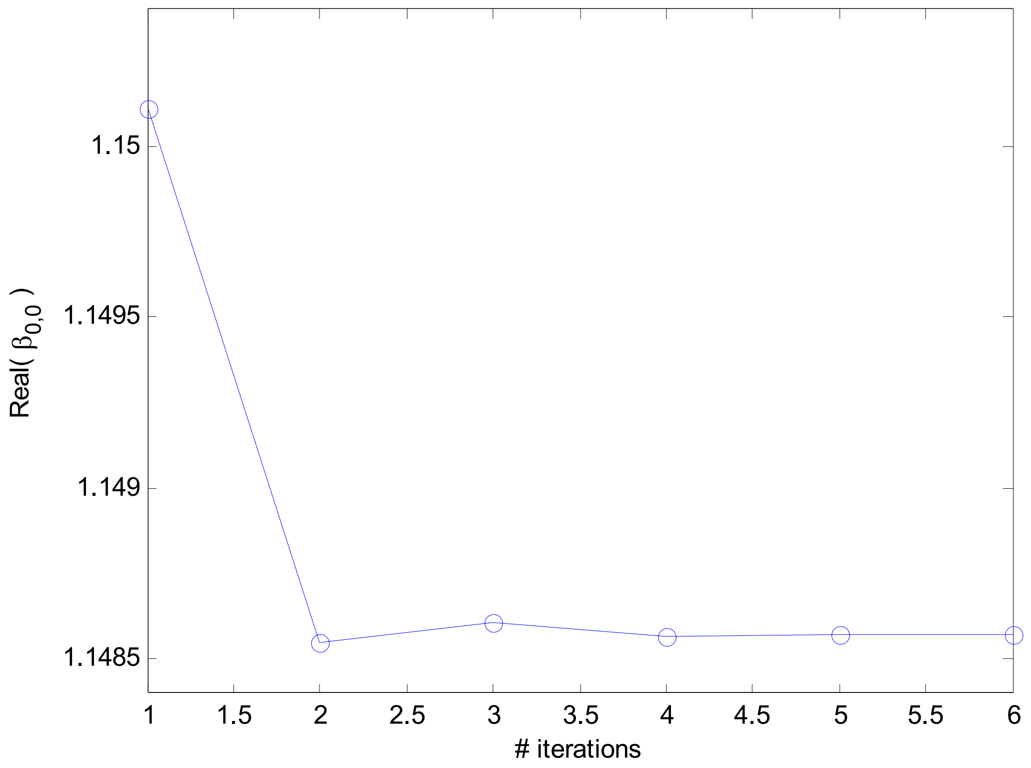
Experimental data microscope objective

- wavelength λ =0.248 μm
- NA=0.20
- number of focal planes: 31, with 1 μm increments
- low NA-model used, detection on the long-conjugate side with CCD (no diffusion or focal blurring)
- corrector-predictor method (5 iterations is sufficient)

Zernike coefficients (fringe convention)

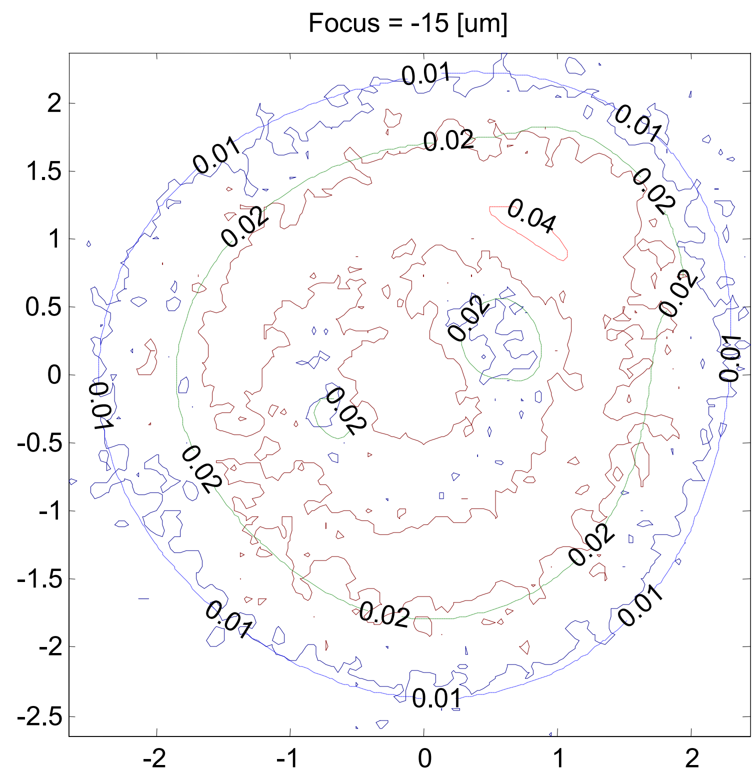


Corrector-Predictor convergence

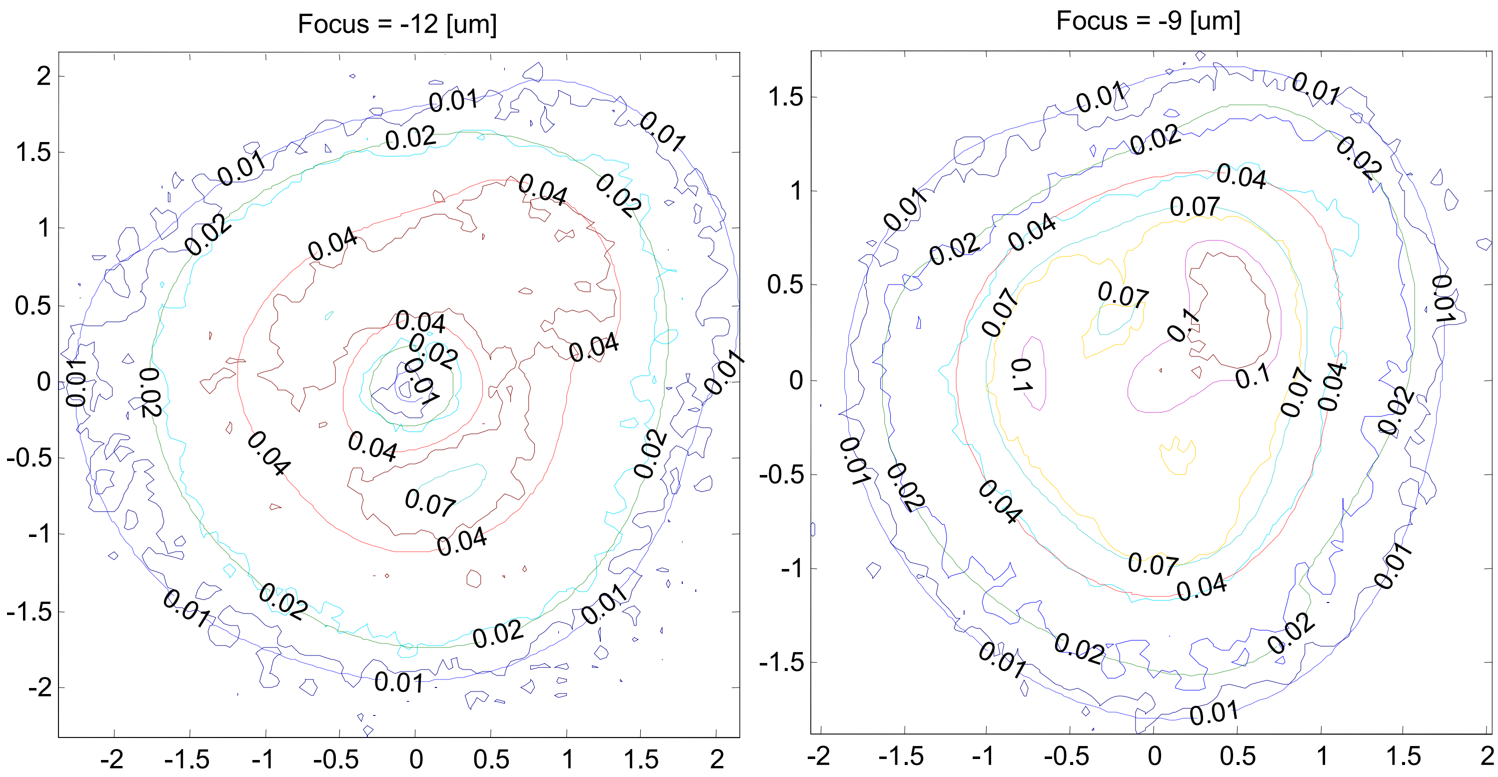


Microscope data, NA=0.20, λ=0.248 nm, pinhole diameter = 0.80 μm

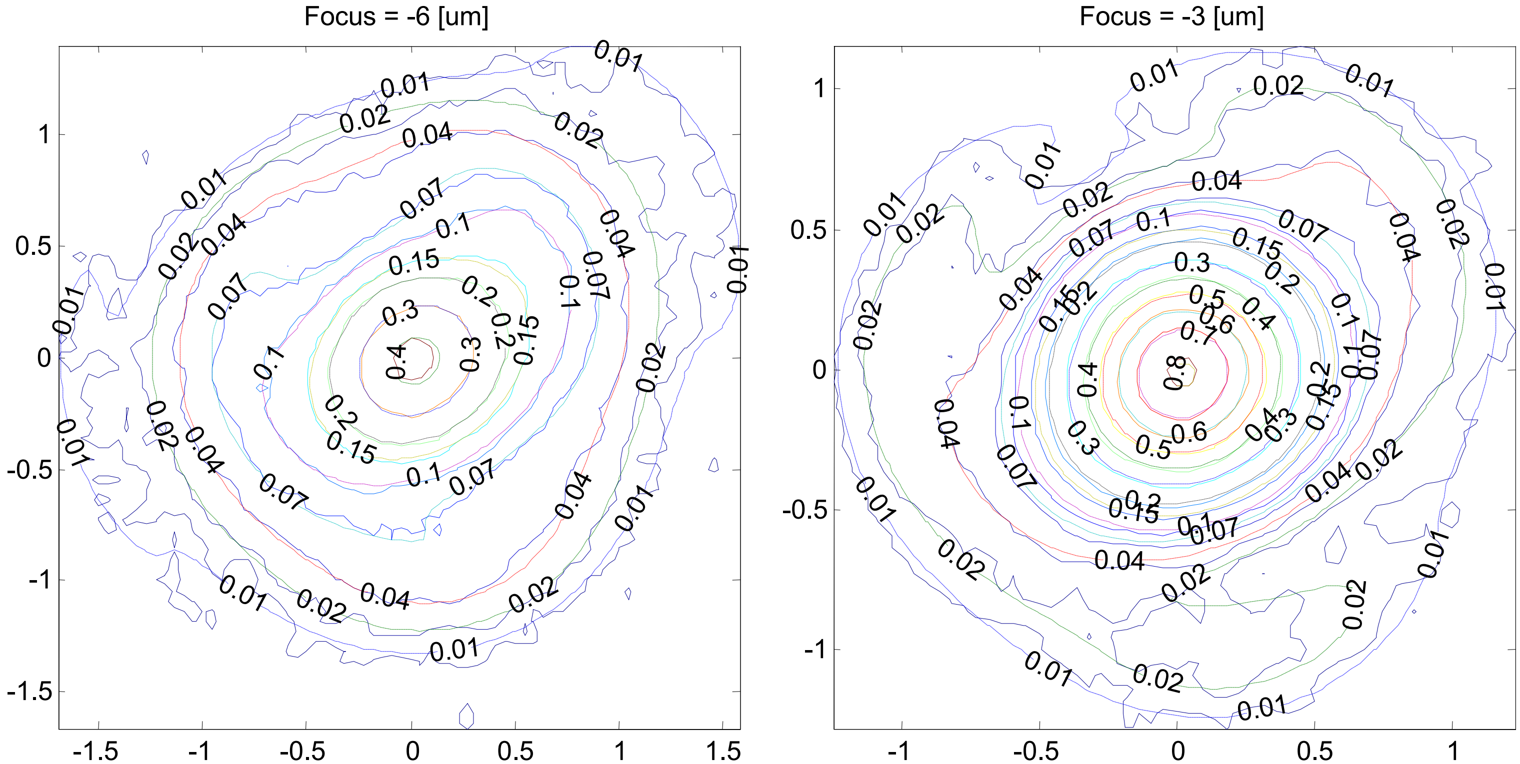
The following sheets show a through-focus series of the PSF for the low-NA microscope and a fit to the data to demonstrate the capabilities of the predictor-corrector method. The results after 5 iterations are shown (more than sufficient).



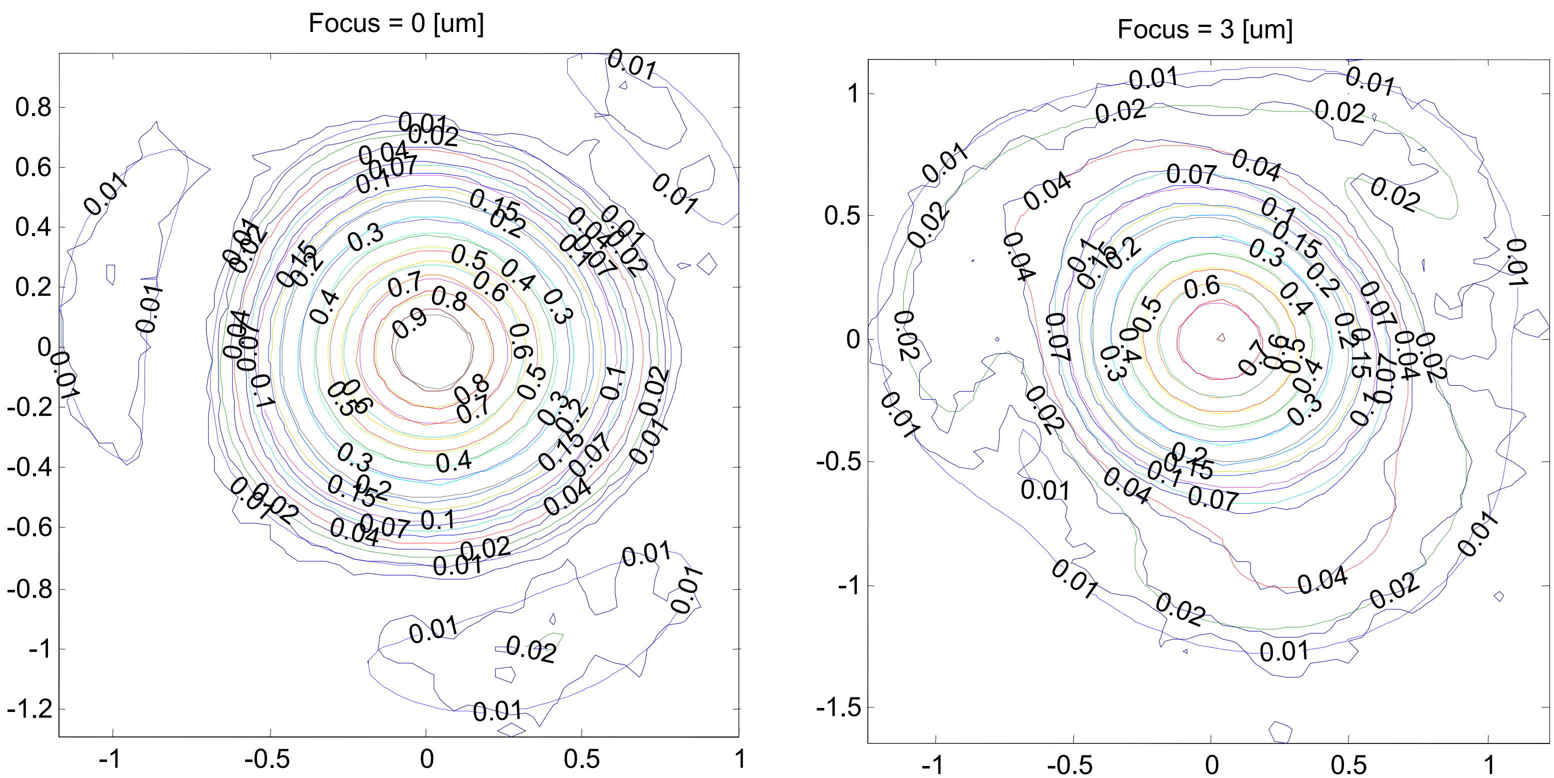
The focus values range from –15 microns … + 15 microns in steps of 1 micron (11 out of 31 pictures shown). Solid lines: raw experimental data, dashed lines fit using predictor-corrector.



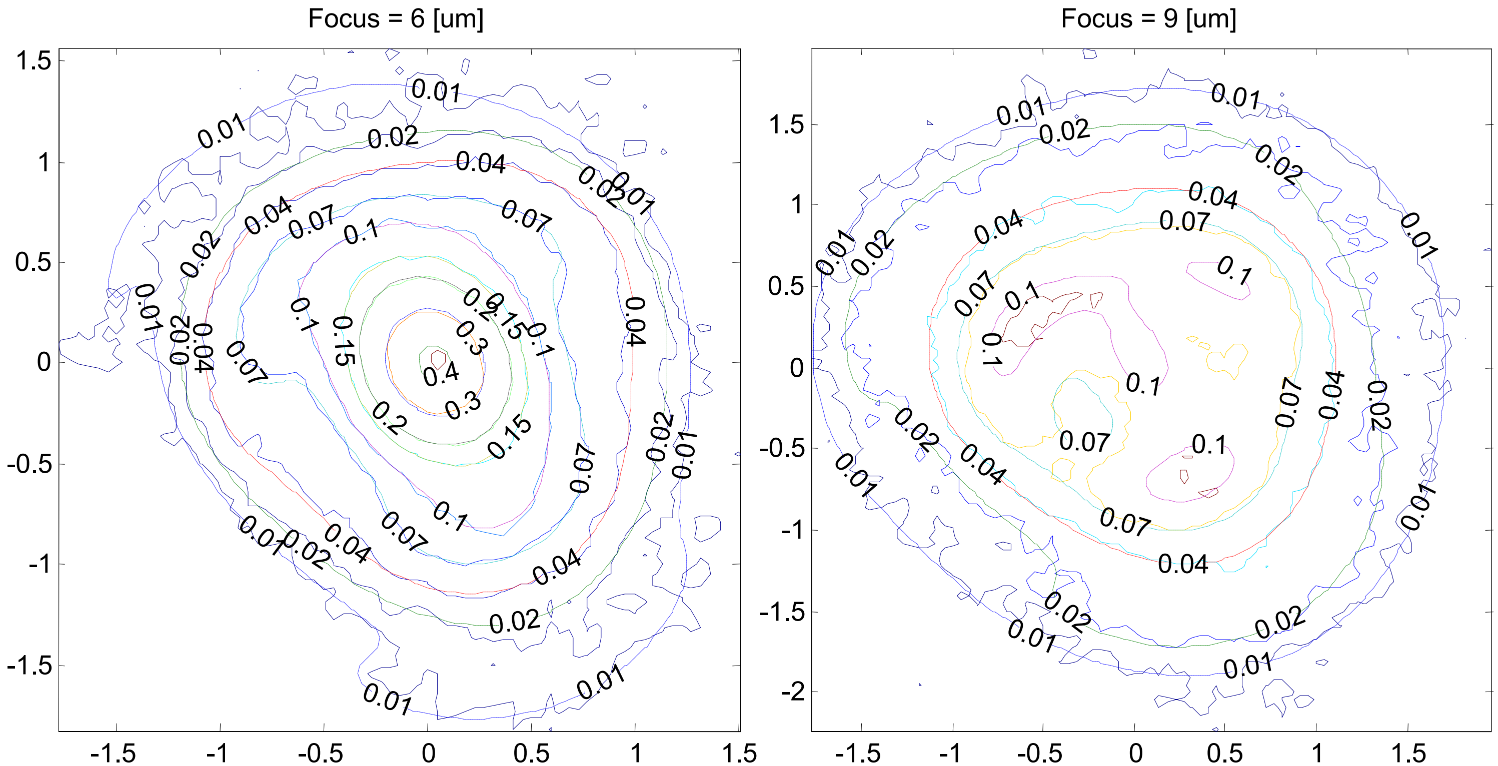
Solid lines: raw experimental data, dashed lines fit using predictor-corrector



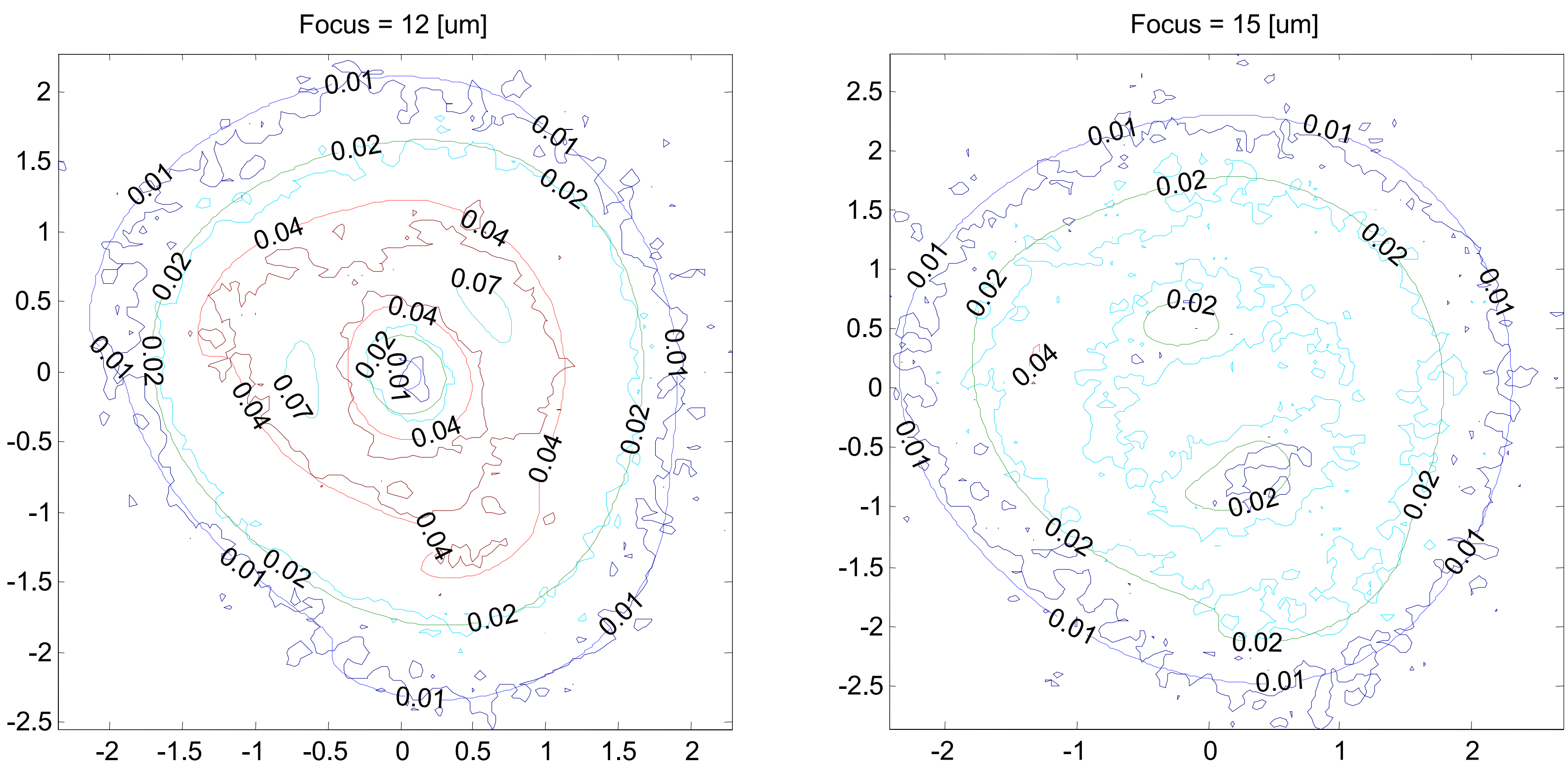
Solid lines: raw experimental data, dashed lines fit using predictor-corrector



Solid lines: raw experimental data, dashed lines fit using predictor-corrector

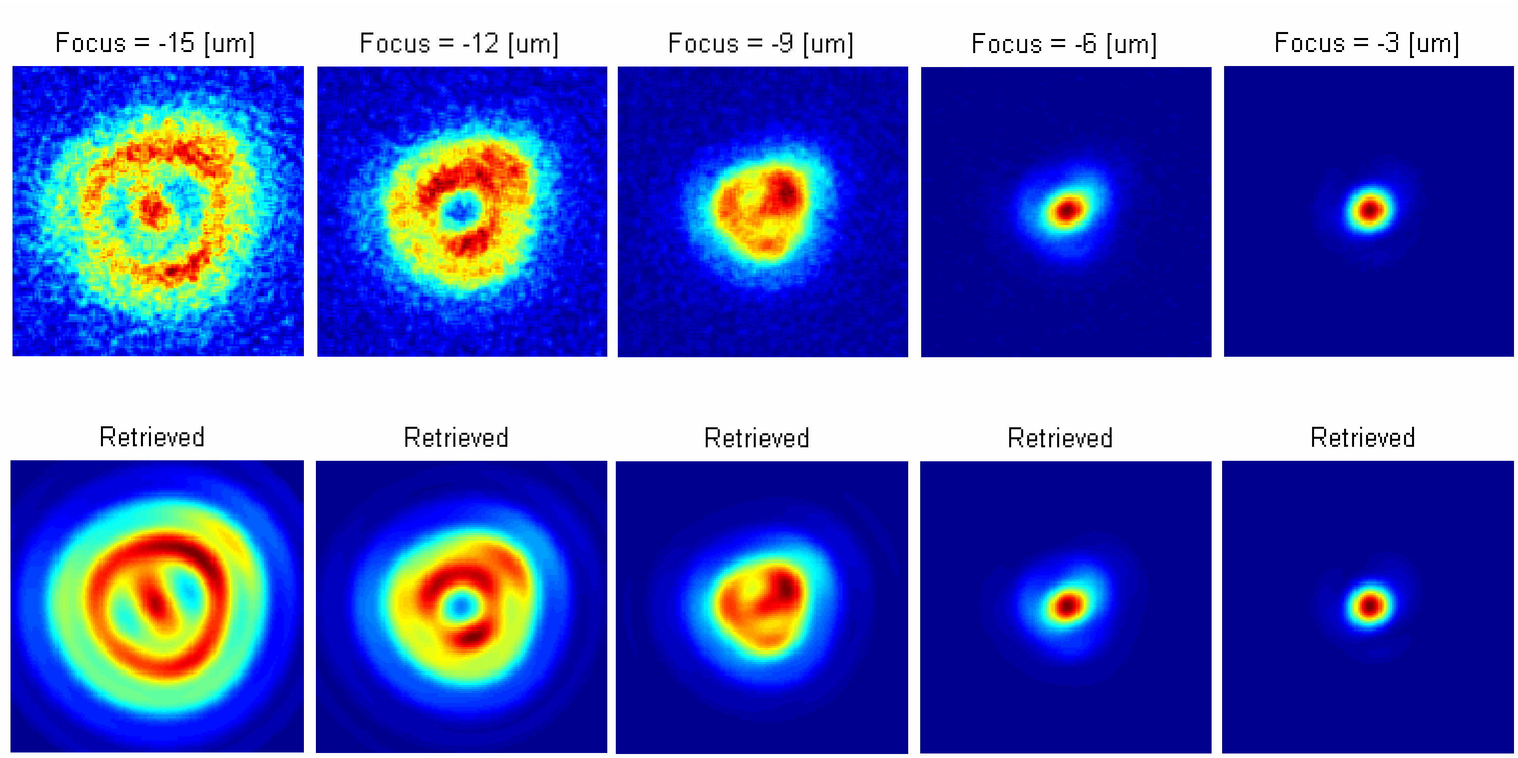


Solid lines: raw experimental data, dashed lines fit using predictor-corrector

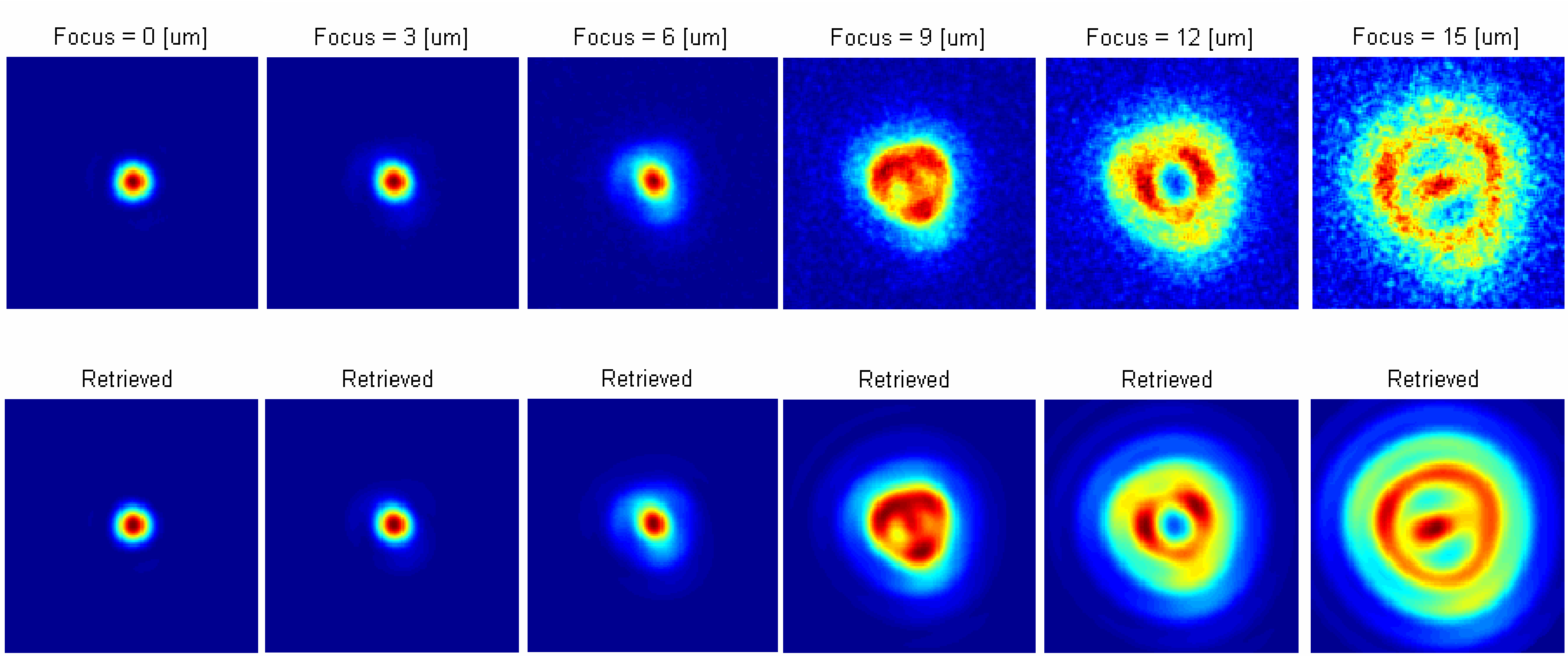


Solid lines: raw experimental data, dashed lines fit using predictor-corrector

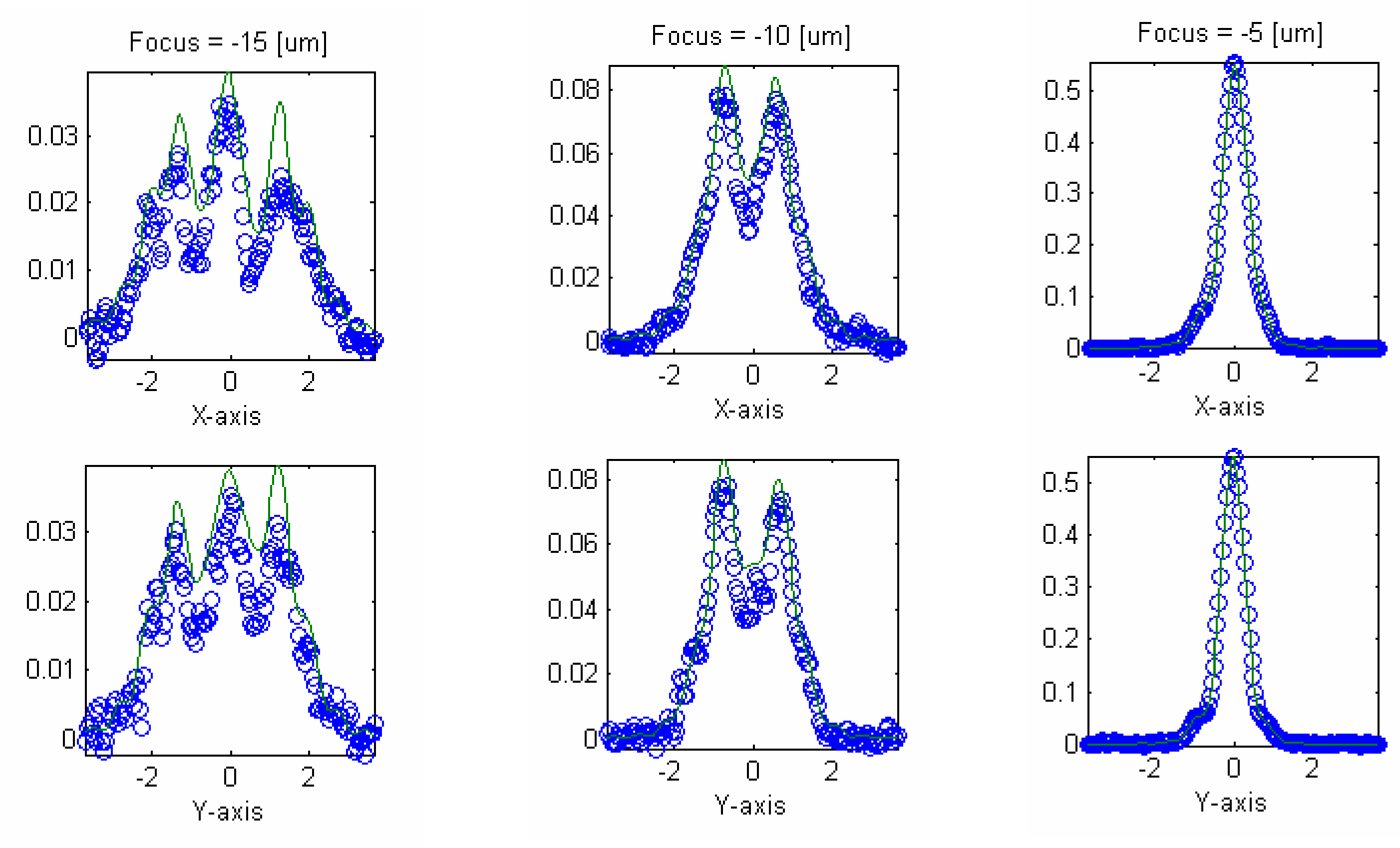
Color pictures (1)



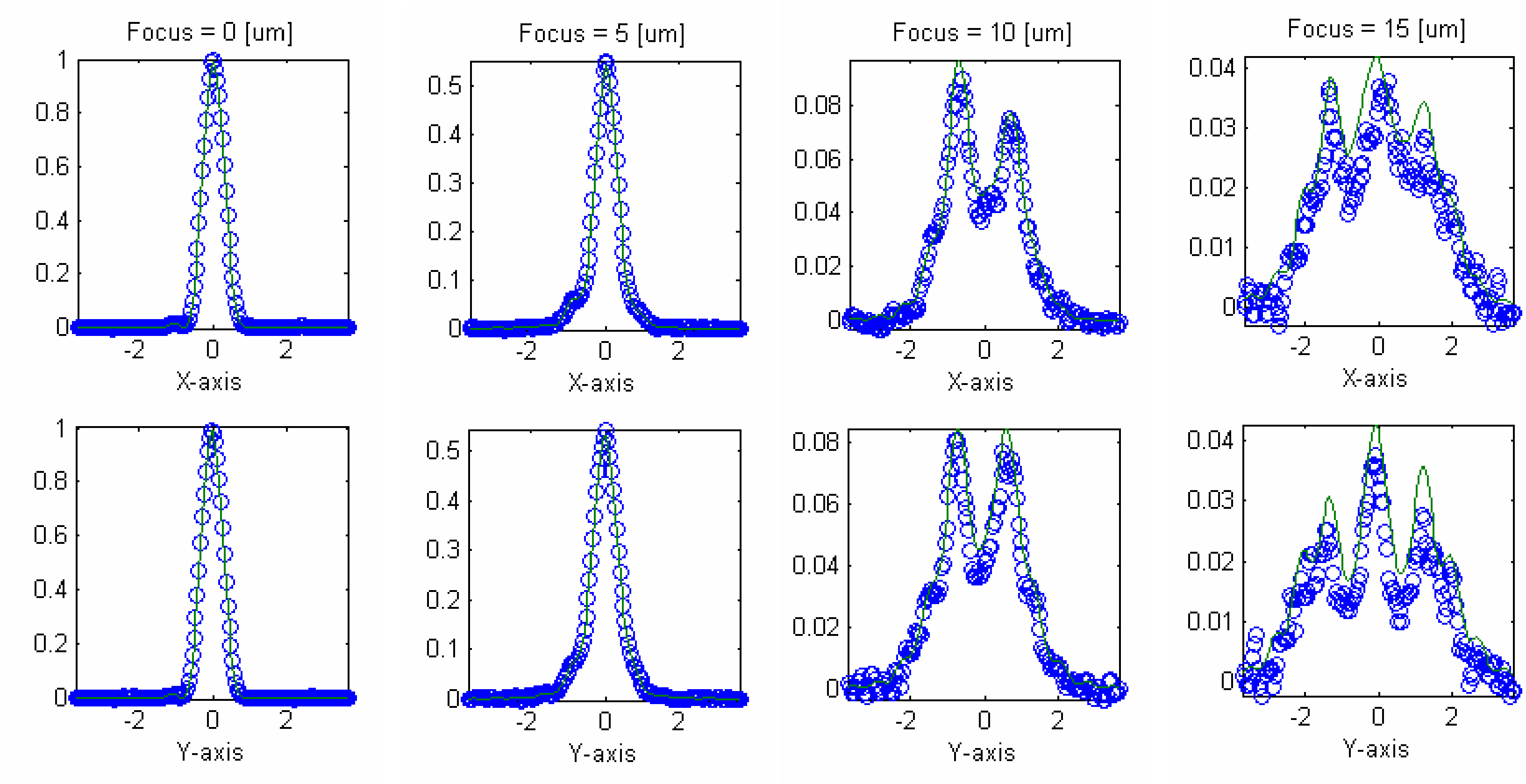
Color pictures (2)



Cross sections (1)



Cross sections (2)



Summary microscope data

A good data fit is obtained for all 31 focus values (11 pictures shown).

Some numbers on the quality of the experimental data fit (for all focus values, all (X,Y) points):

Maximum absolute error	2.2 %
Standard deviation (1σ)	0.36 %
Mean error	0.23 %

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Retrieval at high-NA (vector diffraction)

Vector components of EM-field in the focal region are needed

$$\vec{E}^{x}(r,\varphi;f) = -i\gamma\, s_0^2 \exp\left(\frac{-if}{1-\sqrt{1-s_0^2}}\right)\sum_{n,m} i^m \beta_n^{m,x} \exp(im\varphi)\times$$

$$\begin{pmatrix} V_{n,0}^m + \dfrac{s_0^2}{2}V_{n,2}^m \exp(2i\varphi) + \dfrac{s_0^2}{2}V_{n,-2}^m \exp(-2i\varphi) \\ -\dfrac{is_0^2}{2}V_{n,2}^m \exp(2i\varphi) + \dfrac{is_0^2}{2}V_{n,-2}^m \exp(-2i\varphi) \\ -is_0 V_{n,1}^m \exp(i\varphi) + is_0 V_{n,-1}^m \exp(-i\varphi) \end{pmatrix}$$

A comparable expression holds for the $y-$polarization component (entrance pupil).

Each aberration term creates its own $V_{n,k}^m \exp(ik\varphi)$ with $k = 0, \pm 1, \pm 2.$

General illumination mode (coherent) in entrance pupil:

$$\vec{E}_0 = a\vec{e}_x + b\vec{e}_y \qquad \text{(uniform illumination)}$$

High-NA vector diffraction

Exposure of resist or integrated detector current are proportional to the EM energy density, that itself is proportional to $\left|\vec{E}\right|^2$.

$$\left|\vec{E}\right|^2 = \left|a\,\vec{E}^x + b\,\vec{E}^y\right|^2 = \left(a\vec{E}_x^x + b\vec{E}_x^y\right)\left(a\vec{E}_x^x + b\vec{E}_x^y\right)^* + \left(a\vec{E}_y^x + b\vec{E}_y^y\right)\left(a\vec{E}_y^x + b\vec{E}_y^y\right)^* + \left(a\vec{E}_z^x + b\vec{E}_z^y\right)\left(a\vec{E}_z^x + b\vec{E}_z^y\right)^*.$$

Some special cases for incident polarization (normalized):

$a = 1, b = 0:$ linearly polarized light, $E_{inc} = a\vec{e}_x$

$a = 0, b = +i:$ left-handed circularly polarized light, etc.

Retrieval at high-NA

State of polarization in the exit pupil depends on:

a) lens properties (NA), accounted for in forward-calculation scheme

b) birefringence ('scrambling' of polarization state)

Ad b):

$$\begin{pmatrix} E_{x,j} \\ E_{y,j} \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} a_j \\ b_j \end{pmatrix}$$

Special case (only phase retardation, no differential absorption):

$$\begin{pmatrix} E_{x,j} \\ E_{y,j} \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ -m_{12}^* & m_{11}^* \end{pmatrix} \begin{pmatrix} a_j \\ b_j \end{pmatrix}$$

Retrieval at high-NA

With the property $|m_{11}|^2 + |m_{12}|^2 = 1,$ we have to retrieve three independent quantities for a complete characterization of the birefringent properties of the optical system.

Including the 'isotropic' geometrical properties of the lens (wavefront aberration and transmission function), four (4) retrieval steps are needed for a full reconstruction of the lens function!

Mathematics for the vector diffraction case are rather intricate but basically follow the same retrieval scheme as for the scalar case.

Final result:

a) geometrical aberration and transmission function

b) variation of birefringence over exit pupil

c) varying azimuth of polarization eigenstates over exit pupil

J.J.M. Braat, P. Dirksen, A.J.E.M. Janssen, S. Van Haver, A.S. van de Nes, “Extended Nijboer-Zernike approach to aberration and birefringence retrieval in a high-numerical-aperture optical system,” to be published in J. Opt. Soc. Am. A, December 2005.

Summary

♦ We have introduced a semi-analytic method to accurately calculate the intensity distribution in the focal volume; the complex Zernike coefficients represent the systems defects

♦ The method can be extended to high-NA systems using a vector diffraction model

♦ The *inverse problem, 'getting the Zernike coefficients',* is solved by using a linearised version of the Extended Nijboer-Zernike intensity. An iterative procedure improves the accuracy. Practical limit: Strehl intensity > 0.30

♦ Focus blur and chromatic lens effects are incorporated

Summary (continued)

♦ The inverse vector diffraction method is capable of retrieving the ‘polarisation aberrations’. Although leading to a rather intricate system of equations, the first retrieval operations with ‘synthetic’ data were successful ! So far, high-NA retrieval using experimental data has been limited to illumination with unpolarized light (NA=0.85, λ=193nm).

Further research

♦ High-NA (*n>1)* experimental retrieval for lithography

♦ ENZ forward calculation for reticle optimisation in lithography

References

1. A. J. E. M. Janssen, ''Extended Nijboer–Zernike approach for the computation of optical point-spread functions,'' J. Opt. Soc. Am. A **19**, 849–857 (2002).
2. J. J. M. Braat, P. Dirksen, and A. J. E. M. Janssen, ''Assessment of an extended Nijboer-Zernike approach for the computation of optical point-spread functions,'' *J. Opt. Soc. Am. A* **19**, 858, 2002
3. P. Dirksen, J. J. M. Braat, A. J. E. M. Janssen, and C. Juffermans, ''Aberration retrieval using the extended Nijboer–Zernike approach,'' J. Microlithogr. Microfabr. Microsyst. **2**, 61–68 (2003).
4. J. J. M. Braat, P. Dirksen, A. J. E. M. Janssen, A. van der Nes, "Extended Nijboer–Zernike representation of the vector field in the focal region of an aberrated high-aperture optical system", J. Opt. Soc. Am. A, Vol. 20, No. 12/December 2003
5. P. Dirksen, J . J. M. Braat, A . J. E. M. Janssen, A. Leeuwestein, H. Kwinten, D. Van Steenwinckel, "Determination of resist parameters using the extended Nijboer-Zernike theory", Proceedings of the SPIE, Vol. 5377, 2004
6. A. J. E. M. Janssen, J. J. M. Braat, P. Dirksen, "On the computation of the Nijboer-Zernike aberration integrals at arbitrary defocus", J. of Optics. A: Pure and Applied Optics
7. M. Dissel, P. Dirksen, C. Juffermans and H. Kwinten, "Monitoring the optical system of a Scanner", Interface 2003.
8. D. Van Steenwinckel, J. H. Lammers, "Enhanced Processing: Sub-50nm features with 0.8 micron DOF using a binary reticle", Proc. SPIE Vol. 5039, 2003, 225
9. D. Van Steenwinckel, M. Shimizu, J. H. Lammers, "Impact of Photoresist Formulation on DOF and Resolution Improvements, in Advances in Imaging Materials and Processes", Eds. H. Ito, P. R. Varanasi, M. M. Khojasteh, and R. Chen, Society of Plastics Engineers, 2003, p. 149-158.
10. B. Tollkühn, A. Erdmann, J. Lammers, C. Nölscher, A. Semmler, "Do we need complex resist models for predictive simulation of lithographic process performance?", Proceedings of the SPIE Vol. 5376, 2004, p. 983

References

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