PHILIPS

Aberration retrieval for high-NA optical systems using the Extended Nijboer-Zernike theory

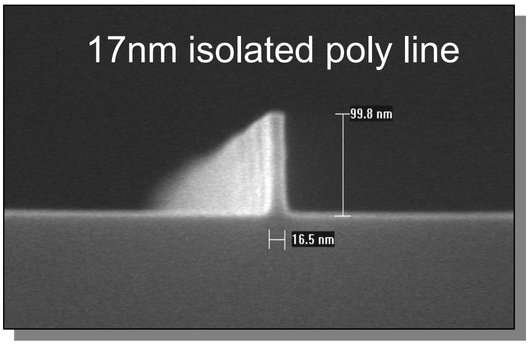
P. Dirksen[1], J. Braat[2,3], A. Janssen[3] and A. Leeuwestein[3]

1) Philips Research Leuven, Belgium
2) Technical University of Delft, Delft, The Netherlands
3) Philips Research Eindhoven, The Netherlands

Overview

- Introduction
- Review low-NA ENZ-Theory
  - Retrieval of aberrations and image blur parameters
- High-NA ENZ-Theory
- Validating high-NA formulas
- Experimental high-NA retrieval results

Introduction



17nm isolated poly line

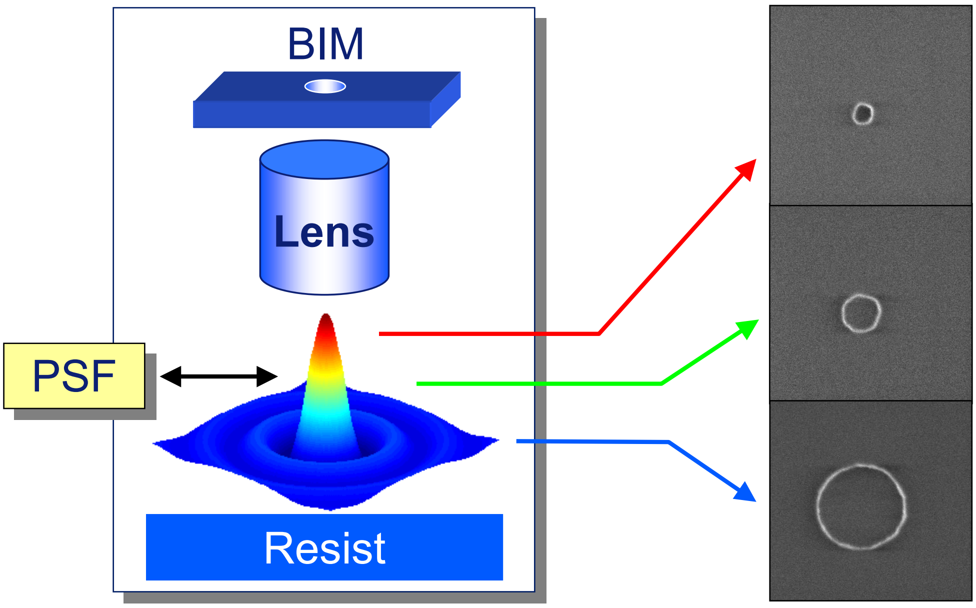
- Trend:
  - High resolution, tight CD budgets
  - Very high-NA optical system
  - Increasing impact of aberrations and image blur

Introduction: aberrations and blur

- Aberrations of the projection optics
  - e.g. spherical, coma and transmission errors
- Image blur:
  - In the horizontal plane: acid diffusion, stage noise,…
  - In the vertical plane: focus noise caused by chromatic aberrations combined with laser bandwidth,…
- This presentation discusses the pinhole experiment to retrieve aberrations and image blur parameters for *high-NA* optical systems

Introduction: pinhole experiment

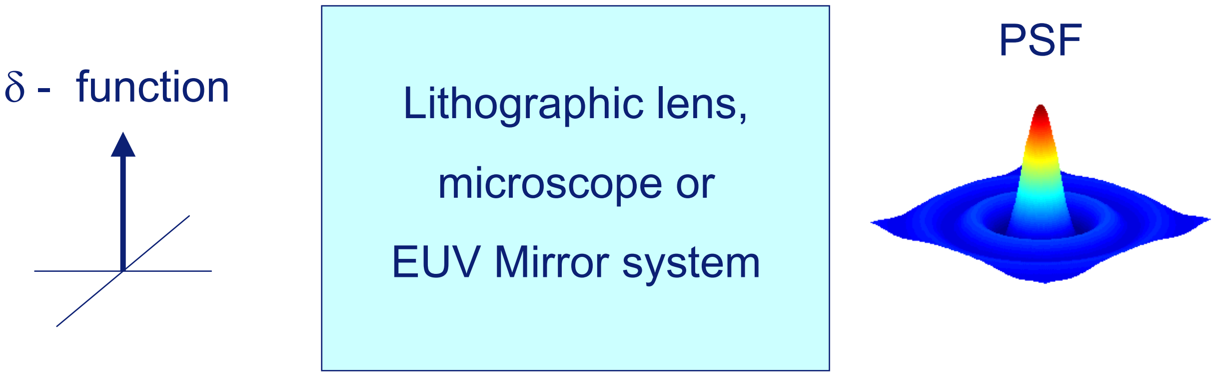
Reconstruct intensity PSF from top-down SEM images



Introduction: through-focus PSF

How to retrieve aberrations and image blur parameters from a through-focus intensity PSF for a high-NA system ?

The key: ENZ theory



δ - function

Lithographic lens,

microscope or

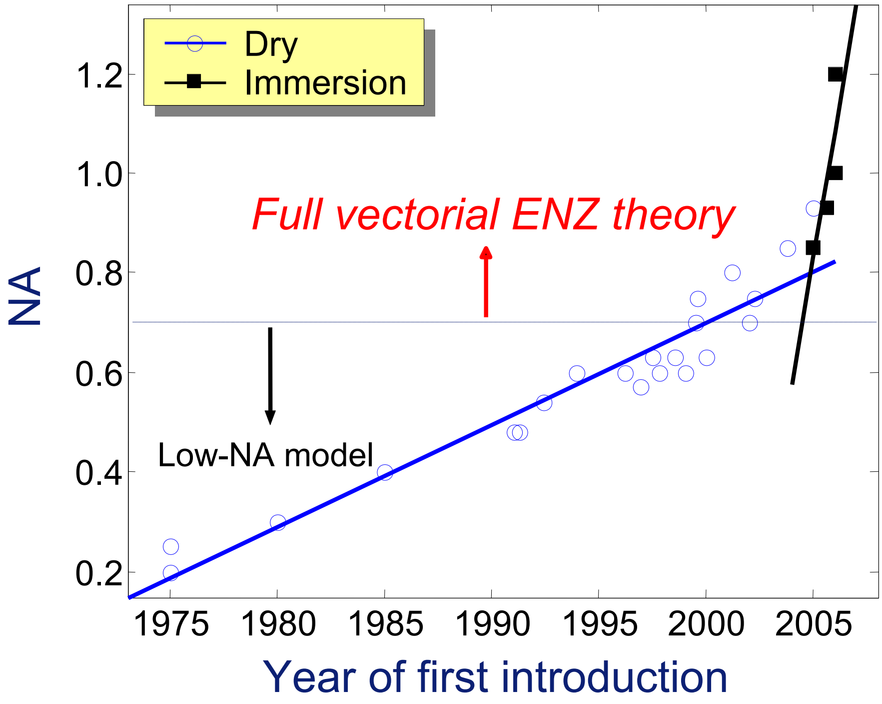
EUV Mirror system

PSF

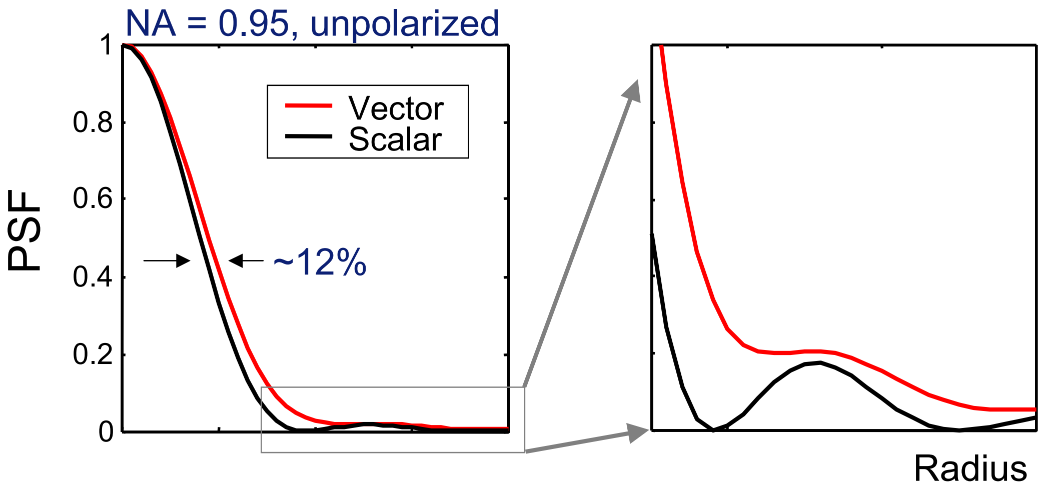
The high-NA Extended Nijboer-Zernike (ENZ) theory provides an analytical description of the PSF

The theory allows the retrieval of aberrations and image blur parameters from the measured intensity PSF

Introduction: evolution of NA



Introduction: scalar versus vector

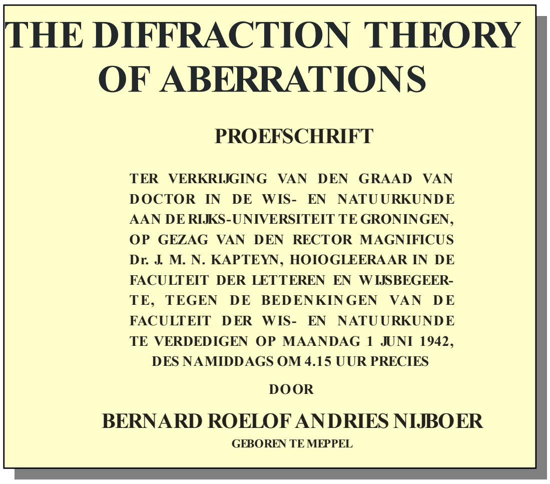


- For NA>0.70:
  - Low-NA retrieval provides reduced accuracy
  - Low-NA overestimates image blur parameters
- Vector model needed

Overview

- Introduction
- Review low-NA ENZ-Theory
  - Retrieval of aberrations and image blur parameters
- High-NA ENZ-Theory
- Validating high-NA formulas
- Experimental high-NA retrieval results

It started with the 1942 thesis of Nijboer…



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 WIJSBEGEERTE, 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

E-field = Airy + Zernike • aberrations

$$U(r,\varphi) \approx 2\frac{J_1(r)}{r} + 2\sum_{n,m} i^{m+1}\alpha_{nm}\frac{J_{n+1}(r)}{r}\cos(m\varphi)$$

- Best focus, small aberrations
- Defocus included for a few low order terms only

Low-NA Extended Nijboer-Zernike theory (2002)

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

- The basis for aberration retrieval
- $V_{nm}(r,f)$ have a convenient Bessel series representation with nice symmetry and orthogonality properties
- The old theories (Airy, Lommel and Nijboer-Zernike) arise as special cases

Low-NA aberration retrieval

$$I(r,\varphi,f) \approx I_{0,0}(r,f) + \sum_{n,m} \alpha_{\mathrm{n,m}} [\text{Aberration terms}]$$

- Best match between experimental intensity PSF *I(r,φ,f)* and theoretical expression
- α_{nm} are found by solving a system of linear equations
- *Details are given in this conference paper*

Additions to low-NA ENZ theory

In the period 2002-2004, various additions were made:

- Retrieval of phase and transmission errors
- Finite pinhole size is taken into account
- Image blur caused by stochastic variation of (x,y,z), retrieval of image blur parameters
- Large defocus
- Retrieval of large aberrations by iterative procedure

Overview

- Introduction
- Review low-NA ENZ-Theory
  - Retrieval of aberrations and image blur parameters
- High-NA ENZ-Theory
- Validating high-NA formulas
- Experimental high-NA retrieval results

From low-NA to high-NA ENZ *(2003)*

Scalar: $U(r,\varphi,f) = 2V_{00} + 2\sum_{nm} \alpha_{nm} i^{m+1} V_{nm} \cos(m\varphi)$

Electric field vector for *X*-polarized illumination

$$\mathbf{E}^x(r,\phi,f) = -i\gamma s_0^2 \exp\left(\frac{-if}{u_0}\right) \sum_{n,m} i^m \beta^x_{nm} \exp(im\phi) \begin{pmatrix} V_{nm,0} + \frac{s_0^2}{2} V_{nm,2} \exp(2i\phi) + \frac{s_0^2}{2} V_{nm,-2} \exp(-2i\phi) \\ -\frac{is_0^2}{2} V_{nm,2} \exp(2i\phi) + \frac{is_0^2}{2} V_{nm,-2} \exp(-2i\phi) \\ -is_0 V_{nm,1} \exp(i\phi) + is_0 V_{nm,-1} \exp(-i\phi) \end{pmatrix}$$

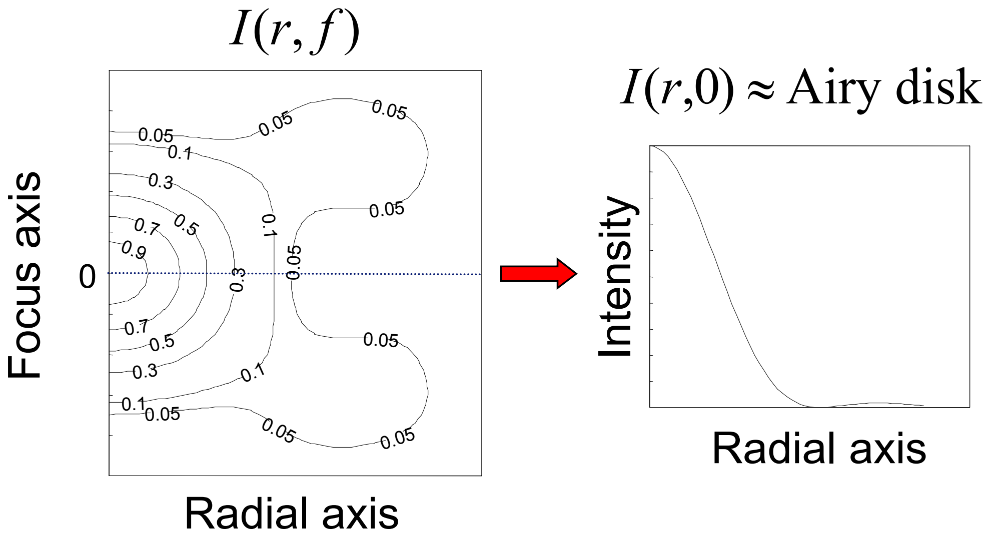
Polarization dependent aberrations

$V_{nm,j}$ is expressible in terms of the ‘old’-V_{nm} functions

A significant increase in complexity, however …

- This presentation: unpolarized illumination case
  - A simplification occurs and the retrieval scheme strongly resembles the low-NA scheme. The various additions can also be made for the high-NA case
  - Second simplification: analysis limited to the case of rotationally symmetrical terms
- *General, polarized case is presented elsewhere*

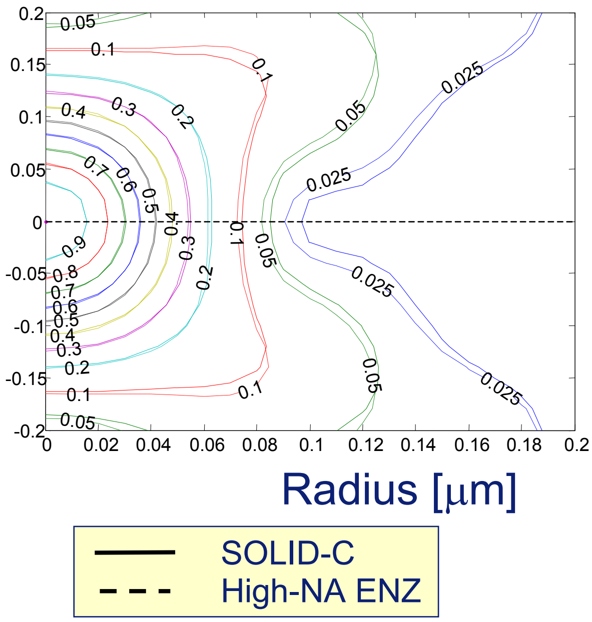
Display through-focus intensity PSF



Validation forward calculation

- First we validate the forward high-NA ENZ calculation by comparing the ENZ results to results obtained from a lithographic simulator (SOLID-C)

Validating forward calculation



Example: wet, NA=1.35, λ=193

Other cases (not shown):

- Finite pin hole size
- Aberrations
- Diffusion
- Focus noise

In all cases a good agreement with the simulator was found:

Max |error| < 1.5%

Retrieval at high NA

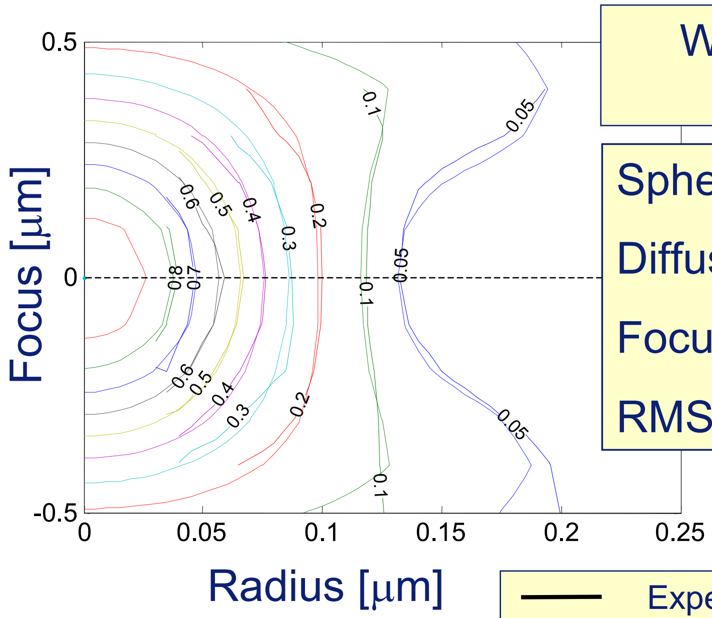
- The basic concept: the measured intensity PSF is matched to the intensity from the high NA ENZ-theory
- For an unpolarized system: a similar retrieval scheme as the low-NA case exists
- Solving a system of linear equations. The retrieval procedure estimates the aberrations as well as the image blur parameters (diffusion and focus noise)
- *Details are given in this conference paper*

Overview

- Introduction
- Review low-NA ENZ-Theory
  - Retrieval of aberrations and image blur parameters
- High-NA ENZ-Theory
- Validating high-NA formulas
- Experimental high-NA retrieval results

High-NA retrieval, immersion

Experimental data pinhole experiment



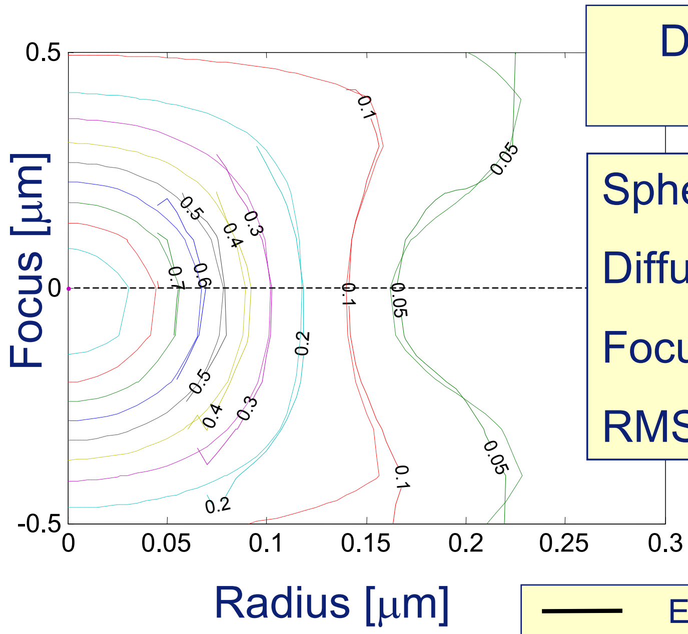
Wet, NA=0.85, λ=193,
Resist A

Spherical	< 10 mλ
Diffusion	= 16 nm
Focus noise	= 100 nm
RMS fit error	< 1.5 %

——— Experiment
- - - High-NA ENZ

High-NA retrieval, dry

Experimental data pinhole experiment



Dry, NA=0.75, λ=193,
Resist B

Spherical	< 10 mλ
Diffusion	= 20 nm
Focus noise	= 110 nm
RMS fit error	< 1.5 %

——— Experiment
- - - High-NA ENZ

Image blur and PEB time (1)

Impact Post Exposure Bake (PEB) time:

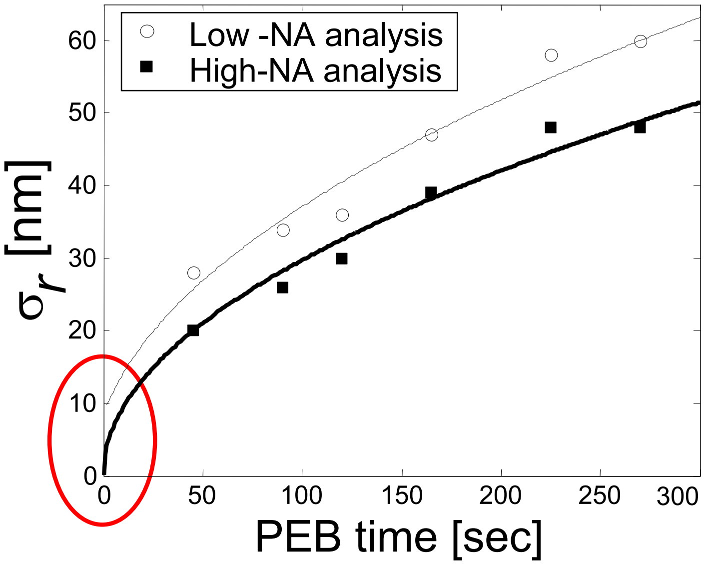
- A simple Fickian diffusion model predicts an increase in diffusion length with time:

$$\sigma_r = \sqrt{D \cdot t}$$

- Experiments shown on previous sheet repeated for various PEB times

Image blur and PEB time (2)

Resist B, Dry, NA=0.75, λ=193



$$\sigma_r = \sqrt{D \cdot t + \text{offset}}$$

10 nm offset found with low NA model: of the order of the diffusion length

$\Rightarrow$ **High-NA model required for accuracy**

Summary

- The *inverse problem* of retrieving aberrations and image blur parameters from the intensity PSF, is solved by using the high-NA ENZ approach
- High-NA model needed if NA > 0.70
- High-NA model was validated, good agreement between experiment, theory and numerical simulations
- Method also applies to immersion systems

Acknowledgement

- The authors wish to thank David Van Steenwinckel, Hans Kwinten and Mike Benndorf from Philips Research Leuven and David Laidler from IMEC for their valuable input and experimental support
- Philips Research Leuven makes use of the cleanroom facilities of IMEC

www.nijboerzernike.nl

Additional slides …

The key: match measured and theoretical Fourier components

Fourier analysis of the through-focus PSF: splits according to azimuthal order and suppresses noise.

$$\boxed{\psi^m = \frac{1}{2\pi}\int_0^{2\pi} \mathrm{I}(\mathrm{r},\varphi,\mathrm{f})\ \cos(m\varphi)d\varphi}$$

m=0: Spherical + aberration-free

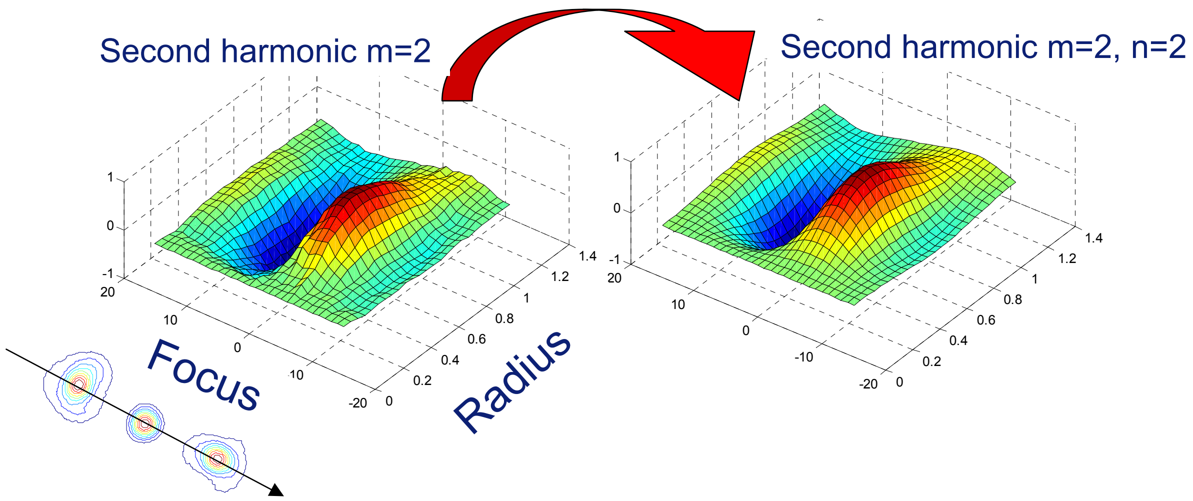
m=1: Coma

m=2; Astigmatism

Etc …

Retrieval example: astigmatism

$$\boxed{\text{Match experimental}\quad \psi^{m=2}(r,f)\quad \text{to}\quad \text{theoretical}\quad \psi^{m=2}_{n=2}(r,f)}$$


Weighting factor = Zernike coefficient

Second harmonic m=2

Second harmonic m=2, n=2

Some details on aberration retrieval

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

$$\mathrm{I}(\mathrm{r},\varphi,\mathrm{f}) \approx 4\left|\mathrm{V}_{00}\right|^2 + 8\sum_{nm}\alpha_{nm}\,\mathrm{Re}\left\{i^{m+1}V_{00}^{*}V_{nm}\right\}Cos(m\varphi) + \ldots$$

Drops out !

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

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

Take inner products:

$$(\psi^m,\psi_{n'}^m) = \sum_{\mathrm{n}} \alpha_{\mathrm{nm}}(\psi_n^m,\psi_{n'}^m) \longrightarrow$$

a linear system of equations.

Aberration retrieval & noise

m^{th} - Fourier component

basic intensity functions

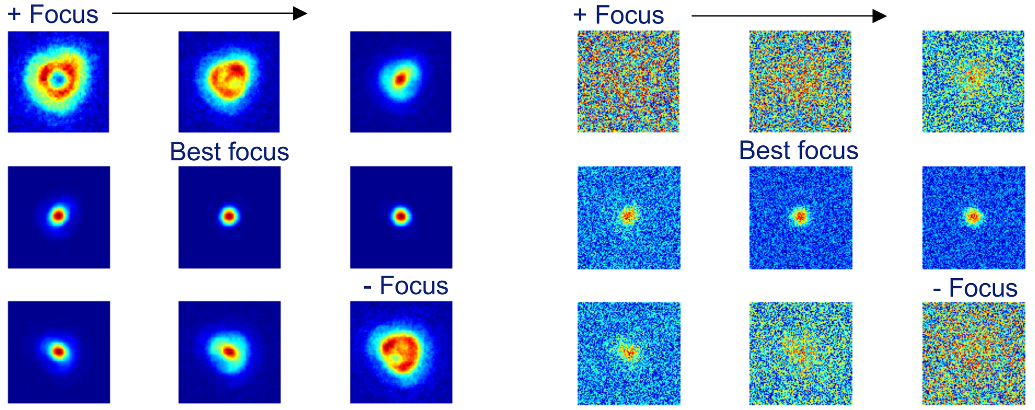
$$\psi^m = \sum_n \alpha_{nm}\psi_n^m \quad \text{with} \quad \psi_n^m = 4\,\mathrm{Re}\left\{i^{m+1}V_{00}^{*}V_{nm}\right\}$$

Aberration parameter

Match experimental frequency component (ψ^m) to specific through-focus signatures (ψ^m_n). The ψ^m_n are (close to being) orthogonal.

- Aberration retrieval is *noise insensitive*
- Be careful with DC-intensity offset

Example: impact noise



Small change in retrieved aberration coefficients: ΔZ~ 10 mλ

Validating image blur formulas