POLARISATION-ABERRATION RETRIEVAL FOR HIGH-NA SYSTEMS USING THE EXTENDED NIJBOER-ZERNIKE DIFFRACTION THEORY

Joseph J.M. Braat[1], Peter Dirksen[3], Augustus J.E.M. Janssen[2], Arthur S. van de Nes[1]

[1] Delft University of Technology, Delft, [2] Philips Research Laboratories, Eindhoven, The Netherlands; [3] Philips Research Laboratories, Leuven, Belgium.

ABSTRACT

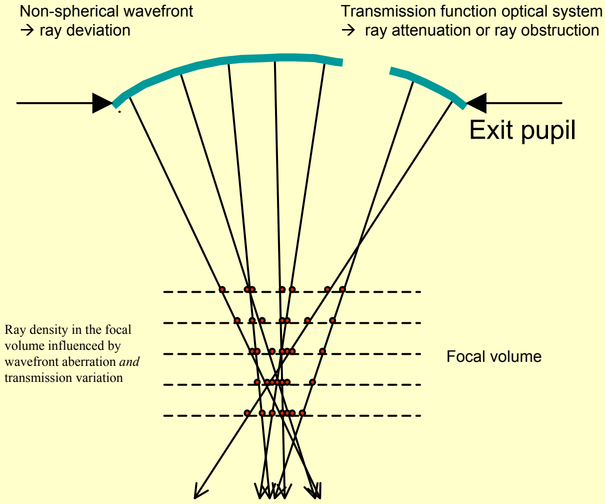
We have derived analytical expressions for the field components in the focal region of a high-numerical-aperture imaging system using the so-called Extended Nijboer-Zernike diffraction theory. It is shown that the transmission function, aberrations and polarisation properties of an imaging system with high numerical aperture can be derived from the through-focus intensity map via an inversion process based on this analysis.

Problem definition:

How to retrieve optical system properties (*amplitude*, *phase* and polarisation in the exit pupil) from *intensity* measurements through the *focal volume*?

1) Intuitive picture, based on ray optics:

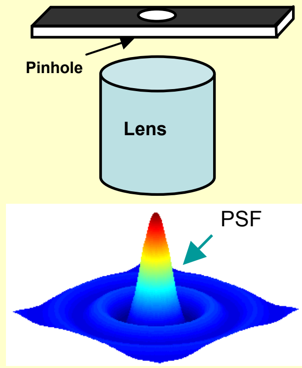
change in ray direction (wavefront aberration) and ray attenuation determine ray density (intensity) in focal volume !



2) More rigourous picture is based on scalar diffraction theory:

Huygens-Fresnel diffraction integral for light propagation from exit pupil → image plane.

In the presence of aberrations: theory of Nijboer-Zernike (1942)



Extension :

from source

to exit pupil

to focal volume :

Extended Nijboer-Zernike theory for through-focus point-spread function,

see: J. Opt. Soc. Am **A19**, 849-857 (2002)

Basic diffraction integral with defocus: $U(r,\varphi,f)=\frac{1}{\pi}\int_0^1 \rho\exp(if\rho^2)\int_0^{2\pi} A(\rho,\vartheta)\exp\{i\Phi(\rho,\vartheta)\}\exp\{i2\pi r\rho\cos(\vartheta-\varphi)\}\,d\vartheta\, d\rho$

Introduction of Zernike polynomial expansion representing amplitude *and* phase: $A(\rho,\vartheta)\exp\{i\Phi(\rho,\vartheta)\}=\sum_{n,m}\beta_n^m R_n^{|m|}\exp(im\vartheta)$

Bessel series solution: $U(r,\varphi,f)=2\sum_{n,m} i^m\beta_n^m V_n^{|m|}(r,f)\exp im\varphi$ with: $V_n^{|m|}(r,f)=\exp(if)\sum_{l=0}^{\infty}\left(\frac{-if}{\pi r}\right)^l\sum_{j=0}^{p}u_{lj}\frac{J_{|m|+2j+l+1}(2\pi r)}{2\pi r}$

3) Vector diffraction theory for high-NA focused beams (forward):

ENZ-theory for complex exit pupil function with due account of

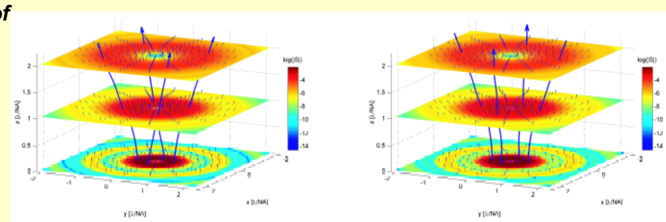
a) radiometric effect b) high-NA defocusing factor

c) polarisation state

Electric field density is: $w_E=\frac{\varepsilon_0}{4}n_r^2|E|^2=\frac{\varepsilon_0}{4}n_r^2\{E_1E_1^*+E_2E_2^*+E_3E_3^*\}$

with explicit analytic expressions available for electric field vector components in the focal volume.

See: J. Opt. Soc. Am. **A20**, 2281-2292 (2003)



Vectorial **forward** calculation using the Extended Nijboer-Zernike theory. Energy flow (arrows) and intensity distribution (colour-coded) in the focal region. Left-hand figure: circularly polarised; Right-hand figure: circularly polarised + orbital angular momentum. The lateral coordinates are in units *λ/NA*. The light propagates in the vertical direction; the *NA* of the focused beam is 0.85

4) Polarisation-aberration retrieval using ENZ-theory at high NA:

'backward' calculation from energy density in focal volume leads to complex lens function + polarisation effects (birefringence)

State of polarisation in the exit pupil depends on :

a) geometrical lens properties (NA, transmission, aberration),

b) birefringence ('scrambling' of polarisation state)

Description of state of polarisation via Jones matrix :

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

For a pure phase birefringence, the Jones matrix reduces to :

$$\begin{pmatrix}E_{x,j}\\E_{y,j}\end{pmatrix}=\begin{pmatrix}m_{11}&m_{12}\\-m_{12}^*&m_{11}^*\end{pmatrix}\begin{pmatrix}a_j\\b_j\end{pmatrix}$$ with $|m_{11}|^2+|m_{12}|^2=1$

Conclusion:

four 'inverse' operations are sufficient for retrieval of the 'polarisation-aberrations' of an optical imaging system

Detailed information about the ENZ-theory and its applications in optical aberration theory, lithography and lens metrology can be found at the website:

http://www.nijboerzernike.nl

TU Delft

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