

High-NA lens characterization by through-focus intensity measurement

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TOM 4

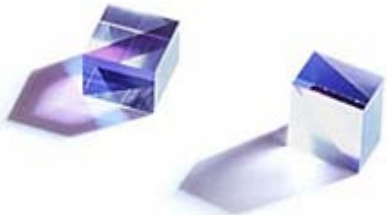
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Introduction

- New applications demand enhanced quality and exact specifications of (micro-) optical components.
- Various methods to obtain specs.
 - Impulse response based methods
 - Frequency based methods
 - Interferometric methods
 - **Inversion methods**



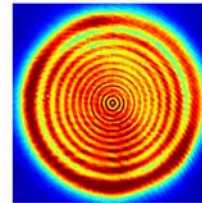
- We propose an inversion method based on the **Extended Nijboer-Zernike (ENZ)** theory of diffraction

ENZ-theory of diffraction

ENZ is born



Arbitrary defocus,
general retrieval



ENZ for lens
metrology



1942

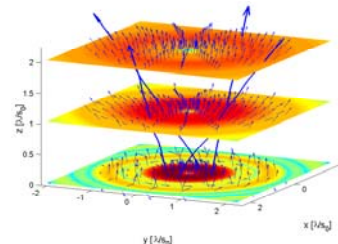
2000

2002

2004

2006

High-NA,
vector diffraction



chromatic errors
and vibrations

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
DE J. M. N. KAPTEIN, HOOGLEERAAR IN DE
FACULTEIT DER LETTEREN EN WISBEGER-
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

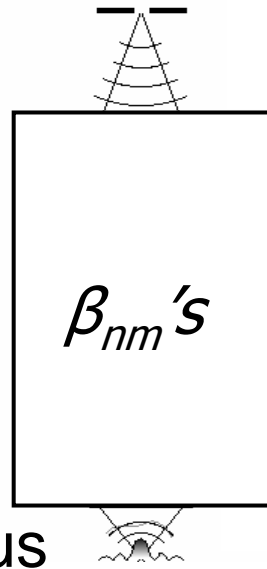
DOOR

BERNARD ROELOF ANDRIES NIJBOER
GEBORN TE MIPPEL

October 16th 2006

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ENZ-theory of diffraction

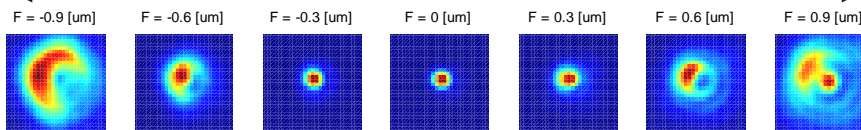


The Extended Nijboer-Zernike (ENZ) theory gives an analytical expression for the through-focus complex PSF:

$$U(r, f) = 2 \sum_{nm} \beta_{nm} V_{nm} \cos(m\theta),$$

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

β_{nm} : Zernike Coefficient



ENZ-theory of diffraction

Main features:

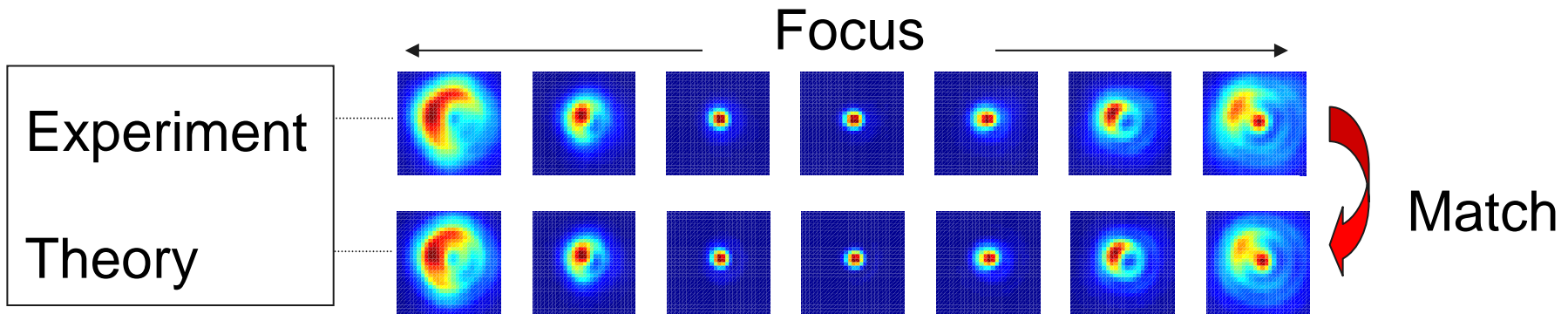
- Complete description of any optical system by a set of complex Zernike coefficients (β_{nm} 's)
- Analytic nature of the formalism opens the possibility of inverse calculations (getting β_{nm} 's from intensity data)

Lens characterization

Basic principles

Observed Intensity = analytic expression
 \approx linearized analytic expression
 $= \sum \beta(m,n) \times \text{basic-functions}$

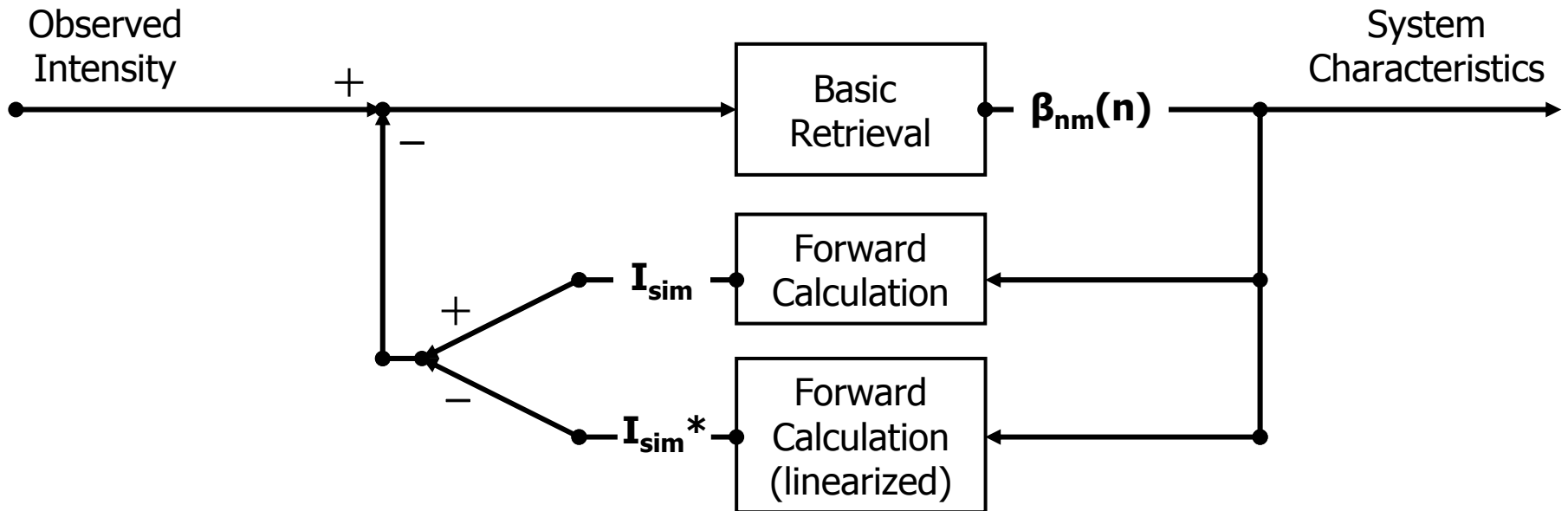
Match experiment to theory:



Lens characterization

Predictor-Corrector procedure

- Linearization-error is corrected applying a so-called Predictor-Corrector mechanism



Lens characterization

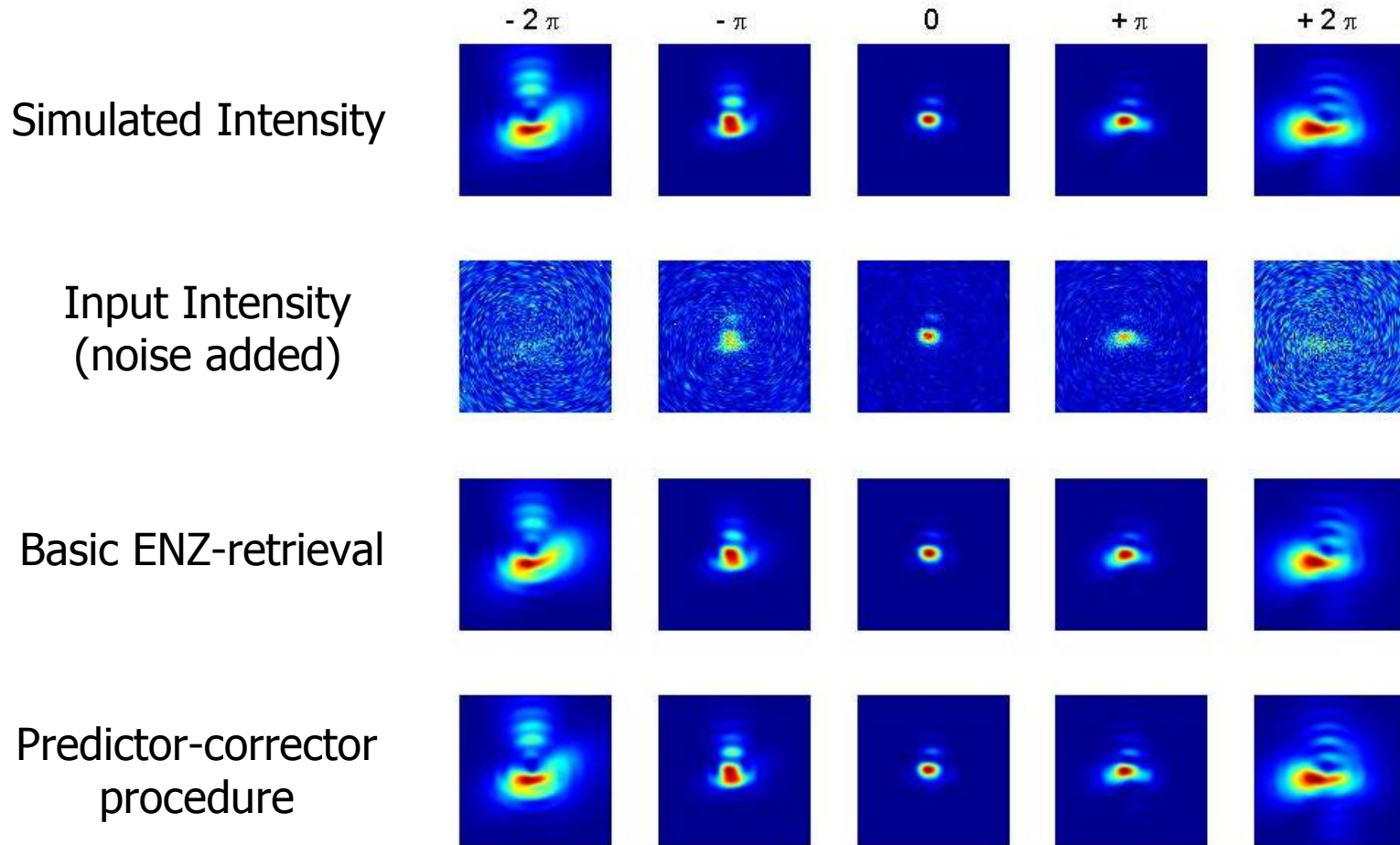
High-NA lenses

- vector diffraction theory
- polarization dependent, etc...
- Increased complexity, **BUT** outline remains the same!

$$E^x(r, \phi, f) = -i\gamma s_0^2 \exp\left[\frac{if}{\mu_0}\right] \sum_{n,m} i^m \beta_{nm}^x \exp[im\phi] \times \left(\begin{array}{l} V_{nm,0} + \frac{s_0^2}{2} V_{nm,2} \exp[2i\phi] + \frac{s_0^2}{2} V_{nm,-2} \exp[-2i\phi] \\ -\frac{s_0^2}{2} V_{nm,2} \exp[2i\phi] + \frac{s_0^2}{2} V_{nm,-2} \exp[-2i\phi] \\ -is_0 V_{nm,1} \exp[i\phi] - is_0 V_{nm,-1} \exp[-i\phi] \end{array} \right)$$

$$V_{nm,j} = \exp(g_j) \sum_{n,m} \alpha_{nm} \varepsilon_m \exp(if_j) \sum_{l=1}^{\infty} (-2if_j)^{l-1} \sum_{h=0}^p v_{lh} \frac{J_{|m|+l+2h}(2\pi r)}{l(2\pi r)^l}$$

High-NA simulation results



Ref: S. van Haver, J. Eur. Opt. Soc. -RP 1 (2006).

Table of Zernike coefficients

Input coeff.	SNR = ∞		SNR = 10		
	Lin. retr.	Pr.-Corr.	Lin. retr.	Pr.-Corr.	
β_0^0	1.0	1.1294	1.0000	1.1291	1.0004
β_1^{-1}	0.0	0.1002	0.0000	0.0934	0.0050
	+i0.5	+i0.4278	+i0.5000	+i0.4277	+i0.4933
β_1^1	0.0	0.0997	0.0000	0.0973	-0.0124
	+i0.5	+i0.4576	+i0.5000	+i0.4598	+i0.5068
β_3^{-1}	0.5	0.4545	0.5000	0.4401	0.4688
	+i0.0	+i0.0028	+i0.0000	+i0.0144	+i0.0099
β_3^1	-0.5	-0.4330	-0.5000	-0.4339	-0.5041
	+i0.0	-i0.0008	+i0.0000	-i0.0174	-i0.0385
β_2^0	0.0	0.0382	0.0000	0.0220	-0.0264
	+i0.0	+i0.0000	+i0.0000	-i0.0176	-i0.0270
β_2^{-2}	0.0	0.1138	0.0000	0.1276	0.0112
	+i0.5	+i0.5813	+i0.5000	+i0.5306	+i0.4327
β_2^2	0.0	0.1113	0.0000	0.1122	0.0060
	+i0.5	+i0.3039	+i0.5000	+i0.3095	+i0.5137
β_3^{-3}	-0.5	-0.3269	-0.5000	-0.3821	-0.5468
	+i0.0	-i0.0843	+i0.0000	-i0.0641	+i0.0253
β_3^3	0.5	0.5534	0.5000	0.5631	0.5139
	+i0.0	+i0.0869	+i0.0000	+i0.0535	-i0.0296

Input

Basic retrieval

Predictor-Corrector

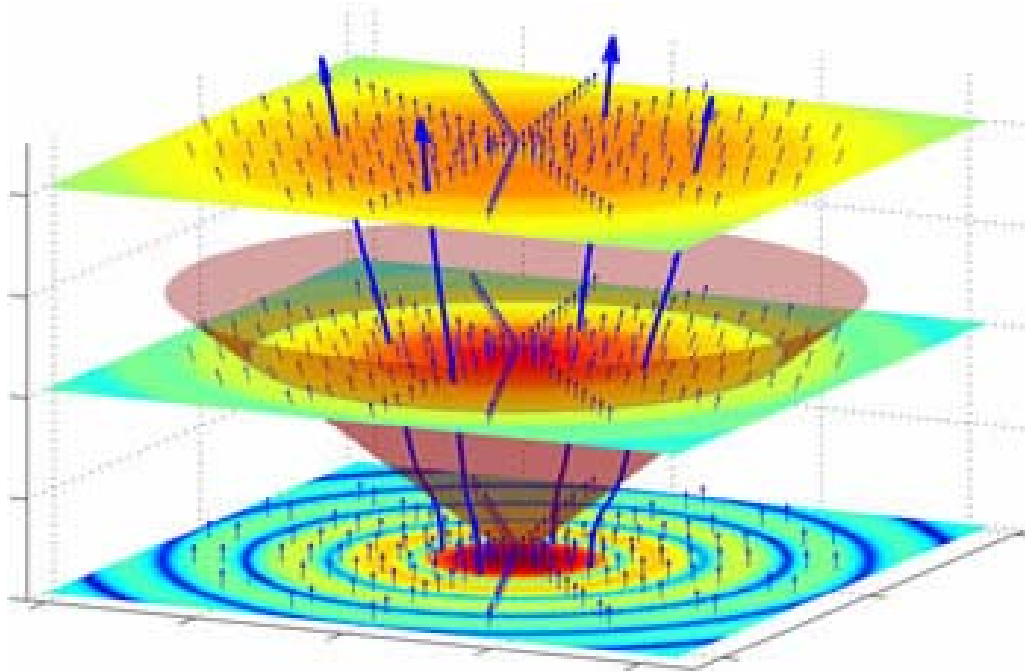
Ref:

S. van Haver, J. Eur. Opt. Soc. -RP 1 (2006).

Closing remarks

- We have proposed a new inversion method to determine High-NA lens characteristics
- Method is based on matching intensity data with linearized Extended Nijboer-Zernike (ENZ) theory
- The linearization error can be corrected using the described Predictor-Corrector mechanism

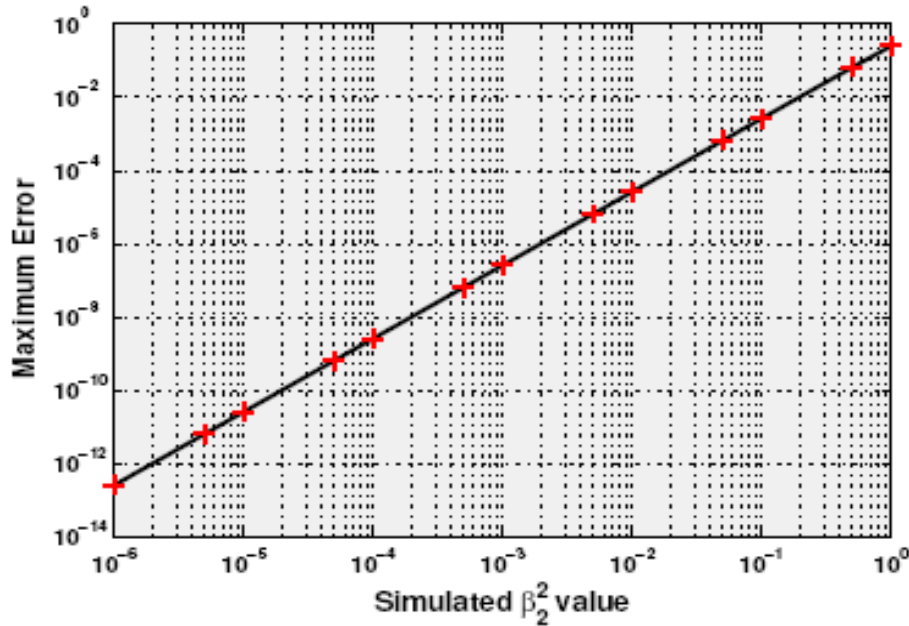
Questions?



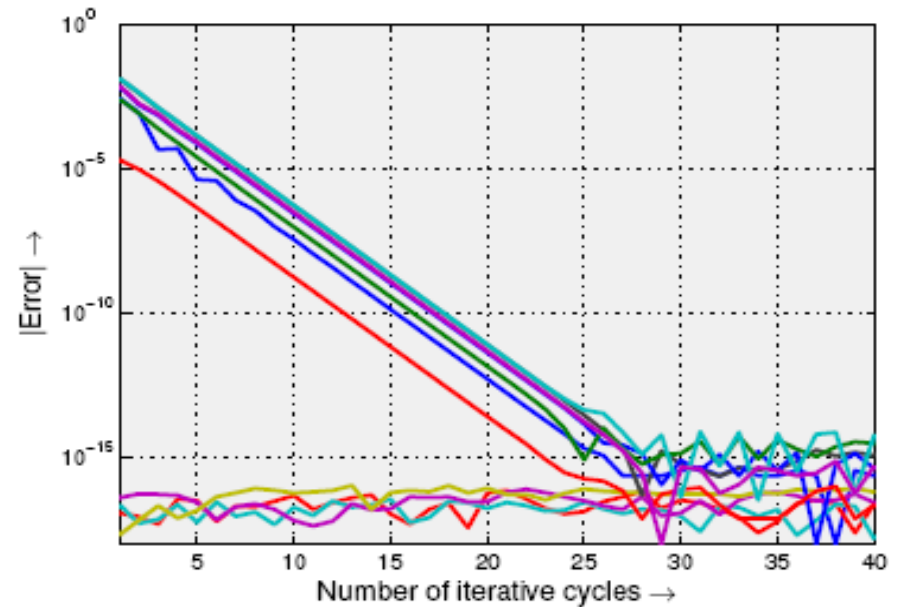
[Http://www.nijboerzernike.nl](http://www.nijboerzernike.nl)

Error in retrieved Zernike's

Error for a single Zernike



Error versus iteration cycle



Ref: S. van Haver, J. Eur. Opt. Soc. -RP 1 (2006).