High-NA lens characterization by through-focus intensity measurement

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TOM 4

EOS Annual Meeting

October 16th 2006

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Introduction

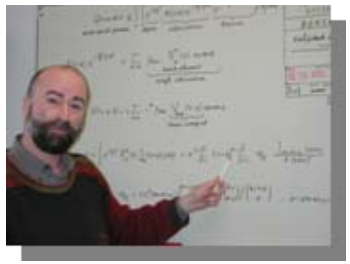
- New applications demand enhanced quality and exact specifications of (micro-) optical components.

- Various methods to obtain specs.
  - Impulse response based methods
  - Frequency based methods
  - Interferometric methods
  - **Inversion methods**

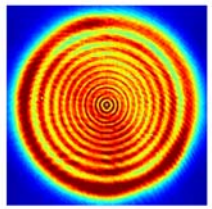
- We propose an inversion method based on the **Extended Nijboer-Zernike (ENZ)** theory of diffraction

ENZ-theory of diffraction

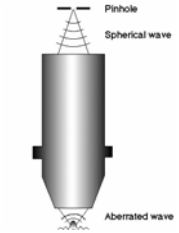
ENZ is born



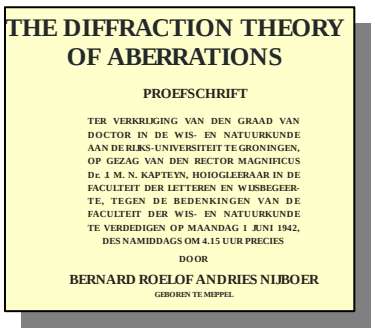
Arbitrary defocus, general retrieval



ENZ for lens metrology



1942 // **2000** **2002** **2004** **2006**


THE DIFFRACTION THEORY OF ABERRATIONS

PROEFSCHRIFT

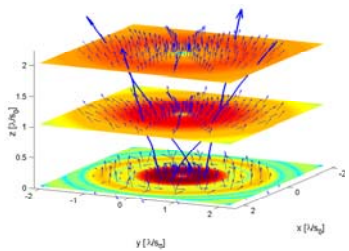
TER VERKRIJGING VAN DEN GRAAD VAN DOCTOR IN DE WIS- EN NATUURKUNDE AAN DE RIJKS-UNIVERSITEIT TE GRONINGEN, OP GEZAG VAN DEN RECTOR MAGNIFICUS Dr. J. M. N. KAPTEYN, HOOGLEERAAR IN DE FACULTEIT DER LETTEREN EN WIJSBEGEERTE, TEGEN DE BEDENKINGEN VAN DE FACULTEIT DER WIS- EN NATUURKUNDE TE VERDEDIGEN OP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

DOOR

BERNARD ROELOF ANDRIES NIJBOER

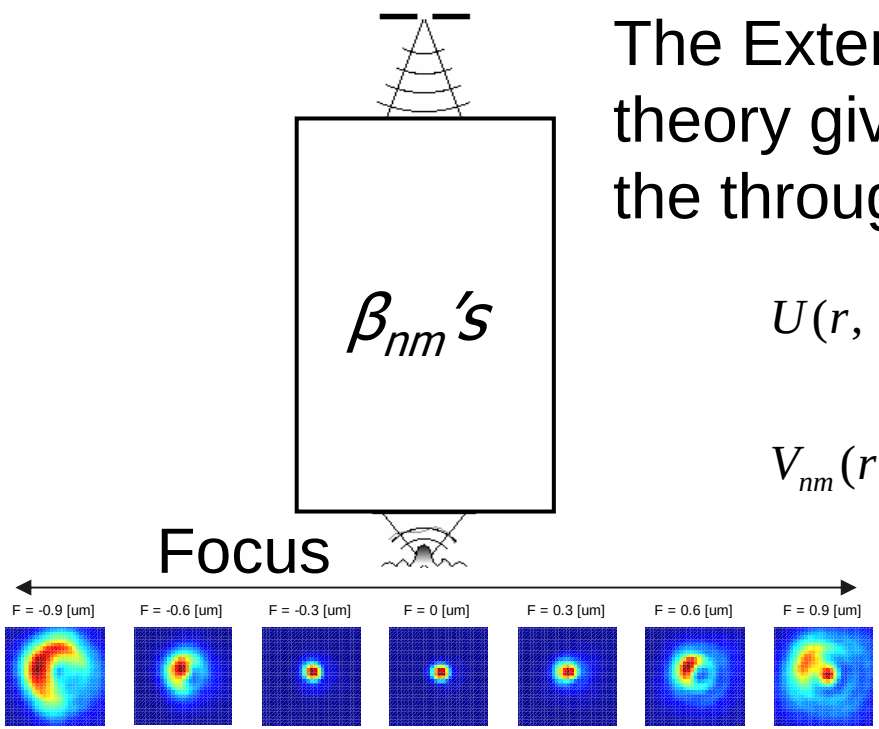
GEBOREN TE MEPPEL

High-NA, vector diffraction



chromatic errors and vibrations

ENZ-theory of diffraction



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

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

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

β_{nm} : Zernike Coefficient

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ENZ-theory of diffraction

Main features:

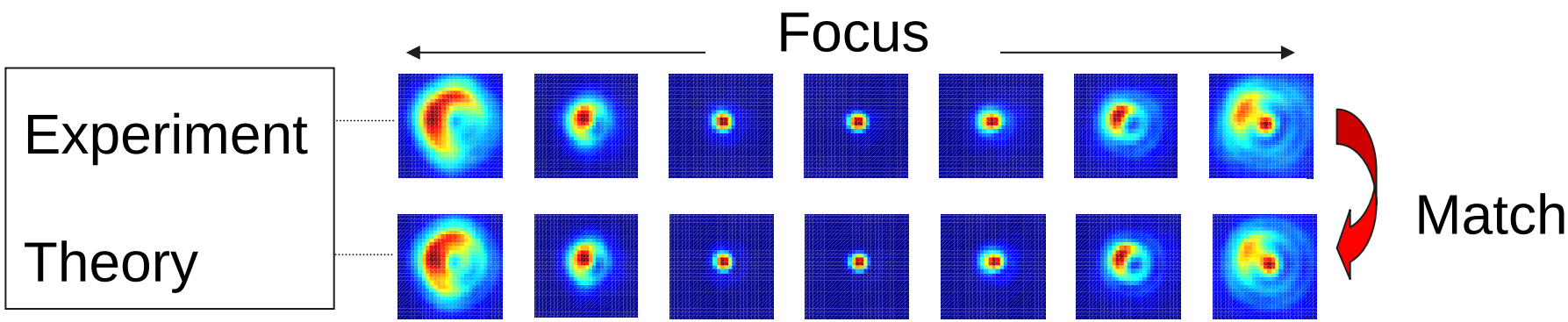
- Complete description of any optical system by a set of complex Zernike coefficients (β_{nm}'s)
- Analytic nature of the formalism opens the possibility of inverse calculations (getting β_{nm}'s from intensity data)

Lens characterization

Basic principles

Observed Intensity	= analytic expression
	≈ linearized analytic expression
	= ∑ β(m,n) x basic-functions

Match experiment to theory:



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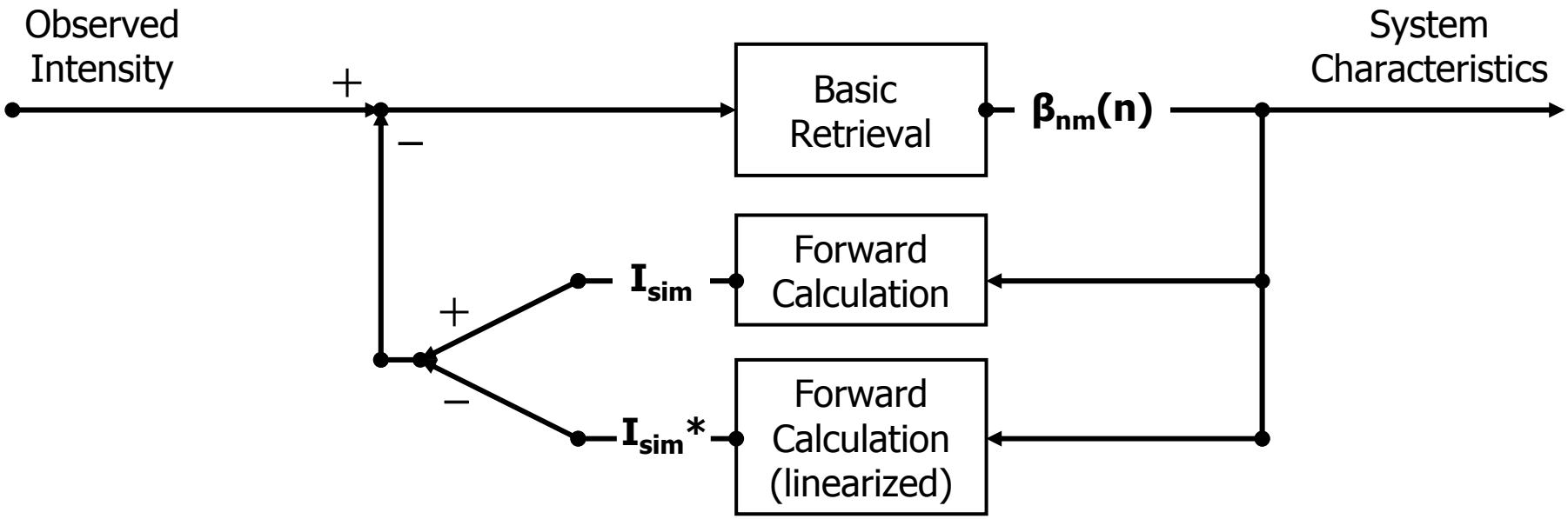
Lens characterization

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!

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

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

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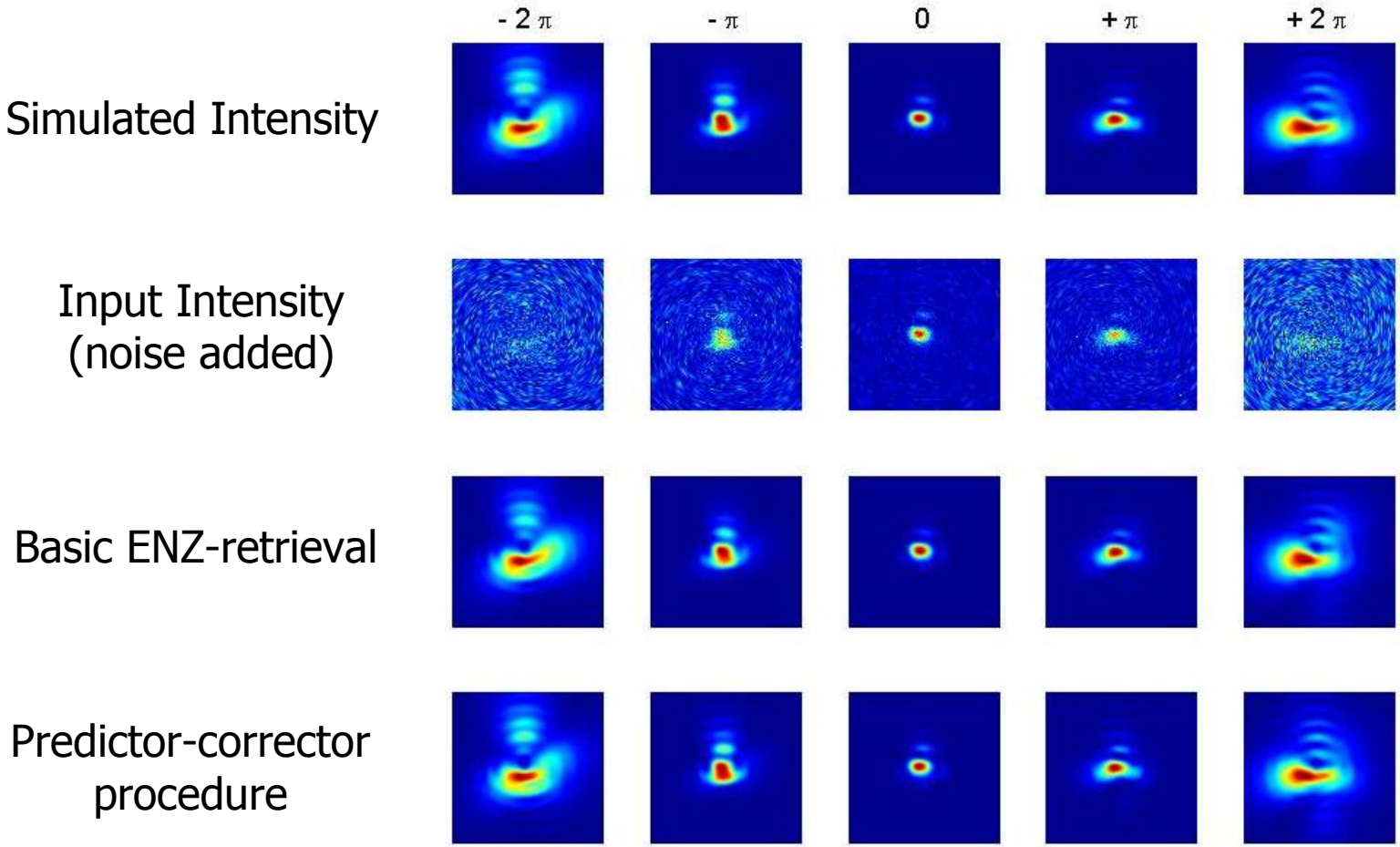
High-NA simulation results



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

Table of Zernike coefficients

		$SNR = \infty$		$SNR = 10$	
Input coeff.		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

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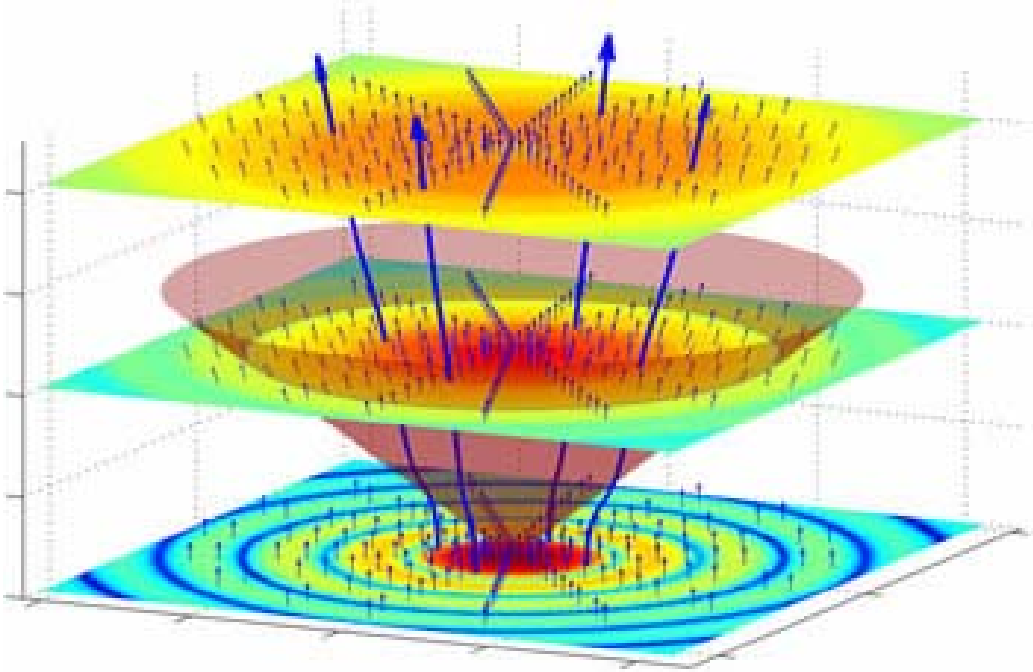
Closing remarks

- 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

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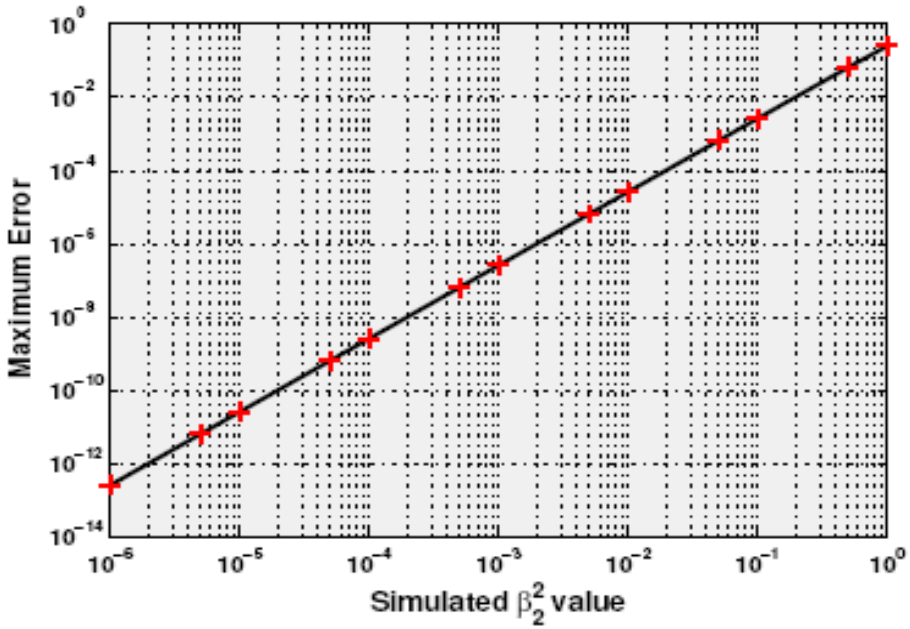
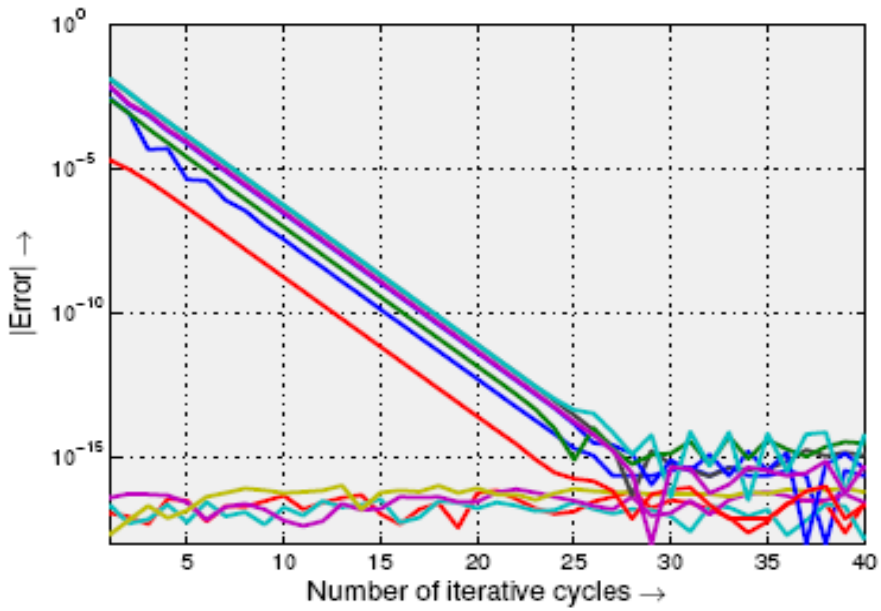
Error in retrieved Zernike's

Error for a single Zernike



Error versus iteration cycle



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