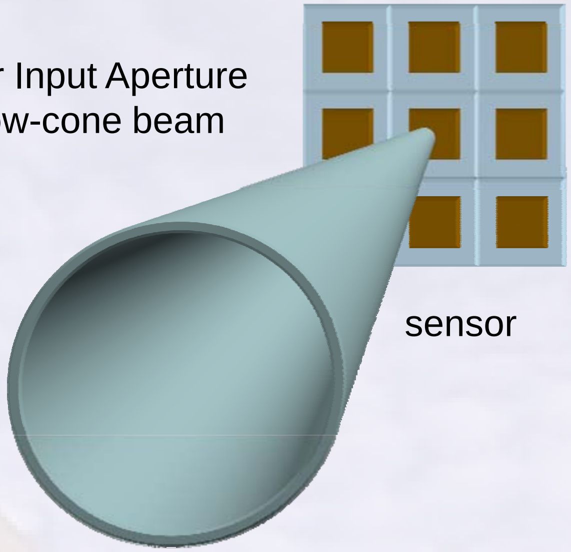
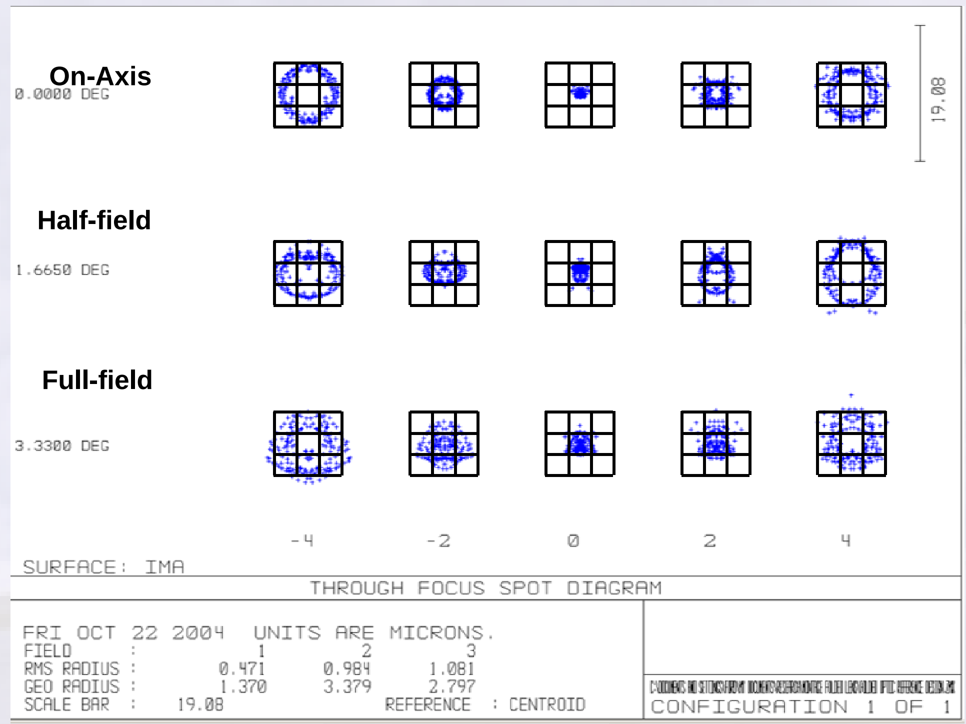
Depth of Focus / Depth of Field

Annular Input Aperture
→ hollow-cone beam



"Through-Focus" spot distributions for the 8-Refl. Lens



Depth of Focus (Geometrical)

$$\text{depth of focus} = \frac{D_{blur}}{\tan\left(\sin^{-1}\left(\frac{NA}{n}\right)\right)} \approx \frac{D_{blur} \cdot n}{NA}$$

Large NA & long focal lengths mean short depth of field

→ Fine for long range (i.e. surveillance) applications

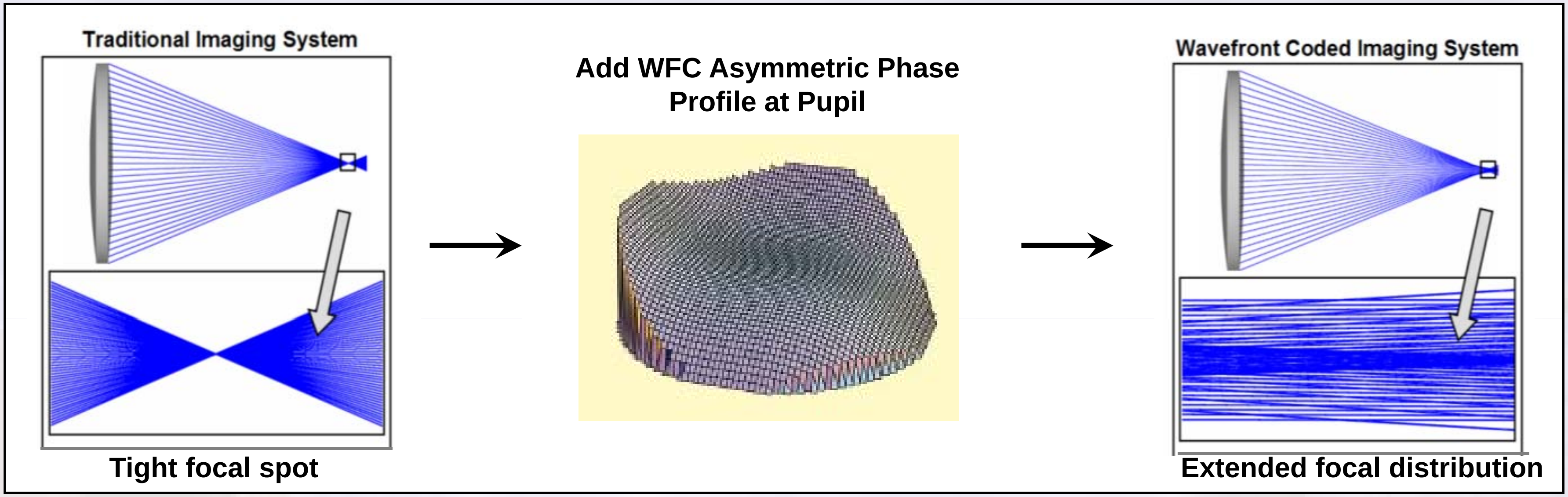
→ Not for nearby/deep object fields (i.e. cellphones)

Wavefront Coding for Extended Depth of Field

UCSD Photonics

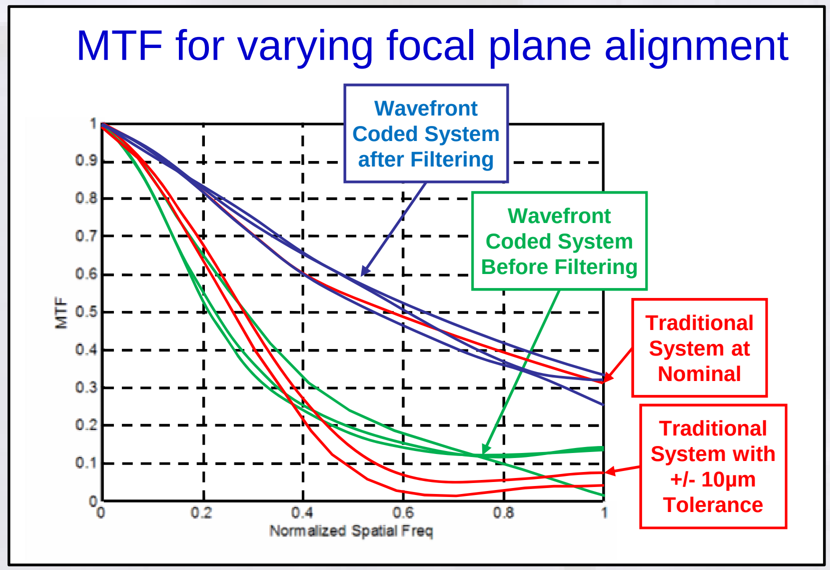
Collaboration with CDM Optics

WFC: Cathey & Dowski Applied Optics **41**, p.6080, 2002

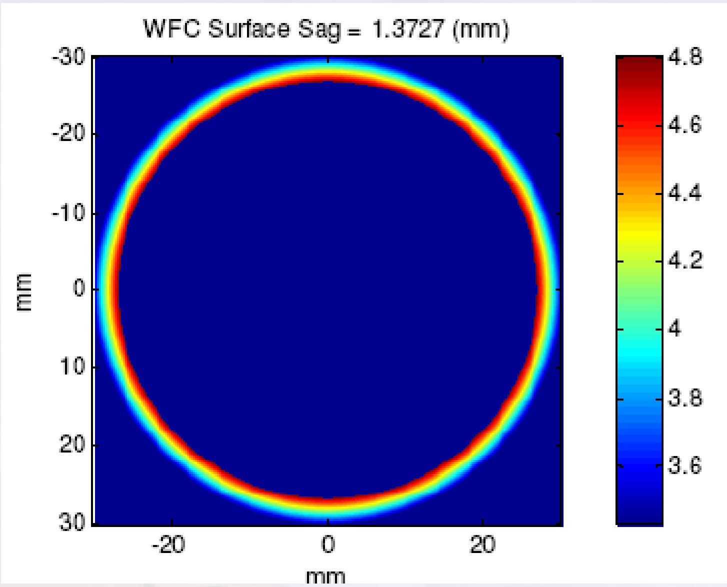


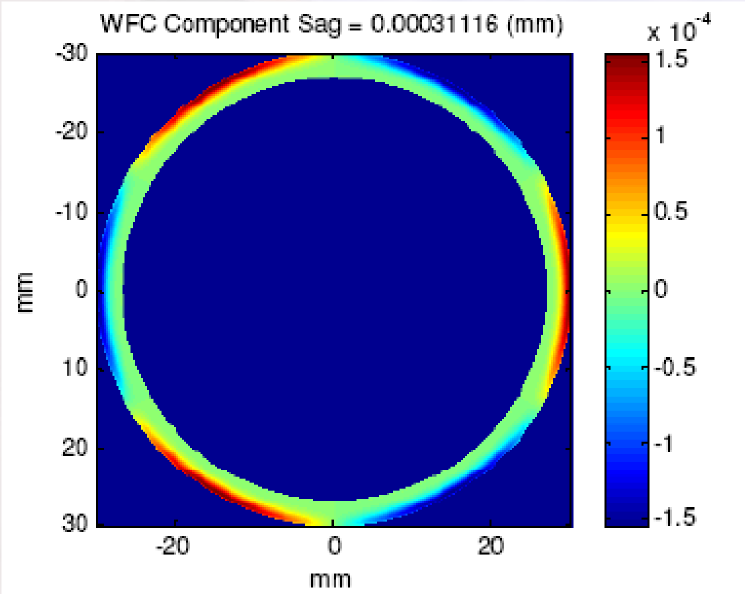
- Wavefront Coding with Post-processing
  - Rotationally Symmetric fabrication errors
  - Focal plane alignment
  - Temperature variations
  - Thickness tolerances

- Post-processing (remapping RGB planes)
  - Lateral color aberration
  - Field dependent coma



Wavefront Coded Design for the 8-Reflection Prototype

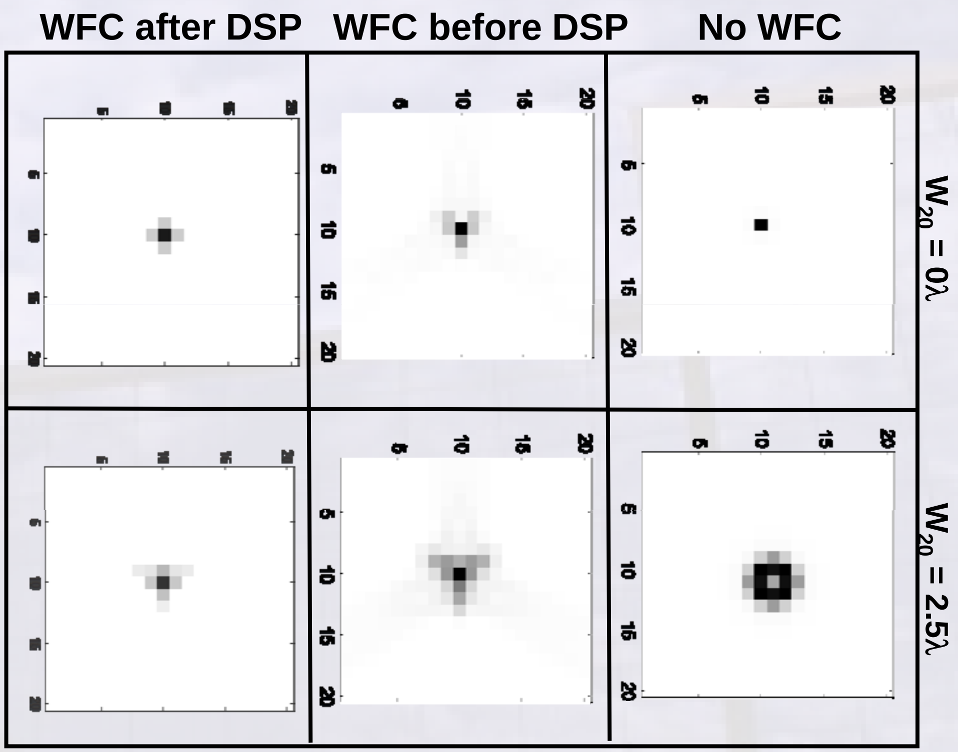




Wavefront Coded Surface Design: Joel Rutkowski, Inga Tamayo (CDM Optics)
Testing & Characterization: Eric Tremblay, Ron Stack (DFC)

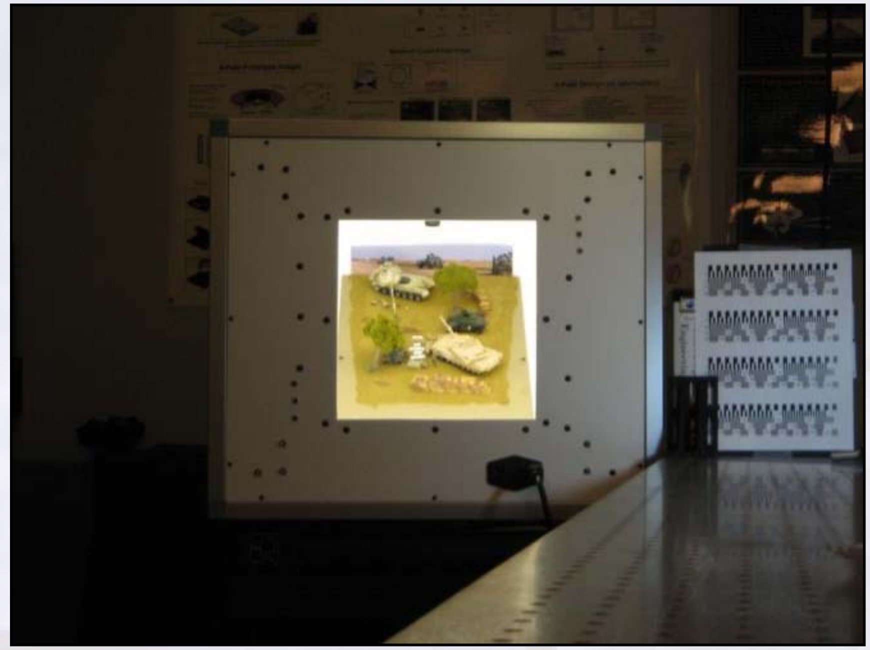
Modest tolerance specification

- WFC surface: 0.25 wave (at 546 nm)
- Flat surface: 0.25 wave (at 546 nm)



Simulated PSFs

Showdown Time: Live Phase 1 demo for DARPA



The Contenders
- **43mm Pentax SLR camera lens**
- **Symmetric 8-Reflection camera**
- **Wavefront Coded 8-Reflection camera**

The Contest
- **1000x700 pixels over 0.1 rad field of view**
- **Real-time image acquisition & processing**

E. J. Tremblay et al., Appl. Opt. **46**, 6751-6758 (2007).

Montage Phase 1 Demonstration

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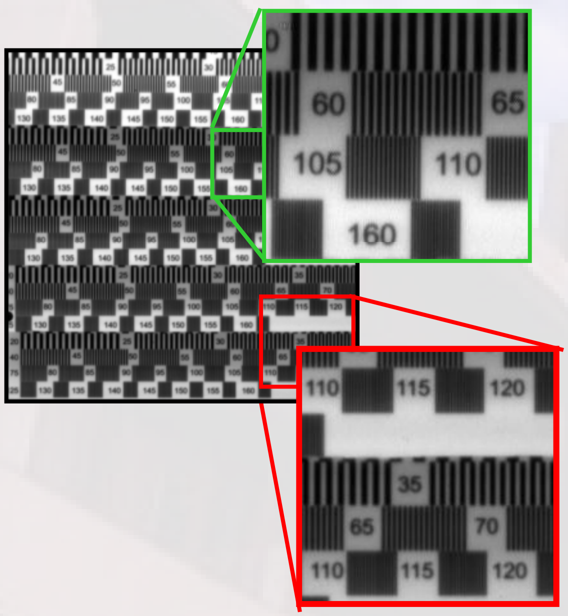
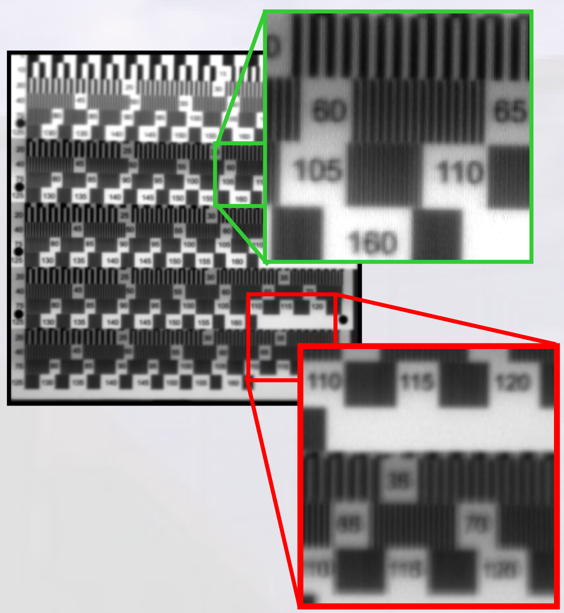
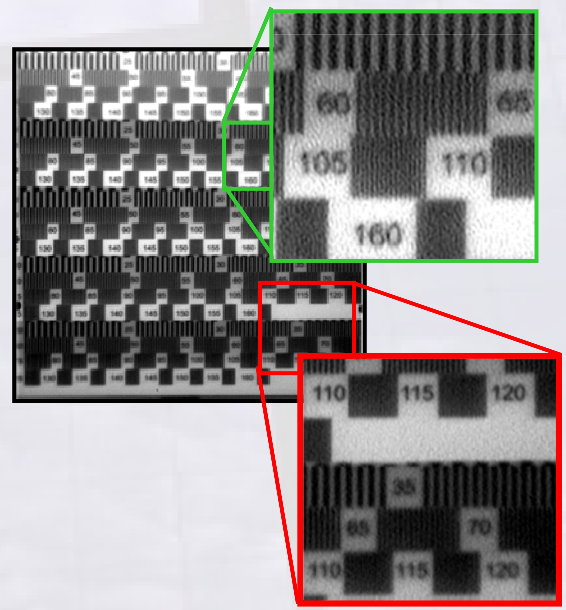
Conventional Pentax lens	8-Reflection Lens	Wavefront Coded 8-Refl. Lens







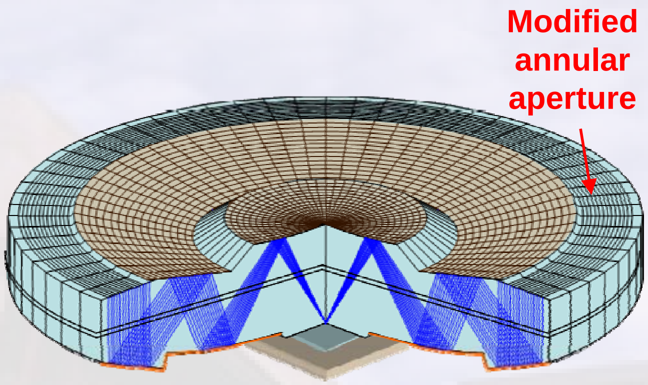
Pupil Phase Encoding & Post-Processing

Previously: Collaborated with CDM Optics to Wavefront Code the Eight-reflection camera

E.J Tremblay et.al., “Relaxing the alignment and fabrication tolerances of thin annular folded imaging systems using Wavefront Coding” *Appl. Opt.* ***46****, 6751 (2007)*

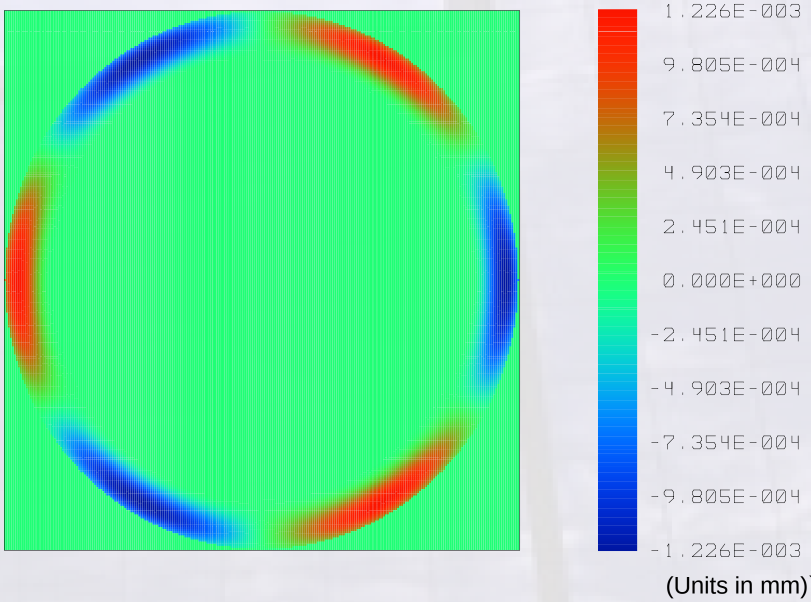
More recently: MDO Design of PPE and Post-Processing for the Four-Reflection camera:

E. J. Tremblay et. Al., "Ultrathin four-reflection imager" Appl. Opt. doc. ID 101823 (posted 4 November 2008, in press).



$$SAG(r,\theta) = \sum_{i=1}^{m} a_i r^i \cos(3\theta)$$

Phase encoded surface sag



The Four-Reflection design is optimized with a PPE surface for depth of field and tolerance enhancement. Resulting raw images are post-processed to produce the final images.

MDO Optimization Process

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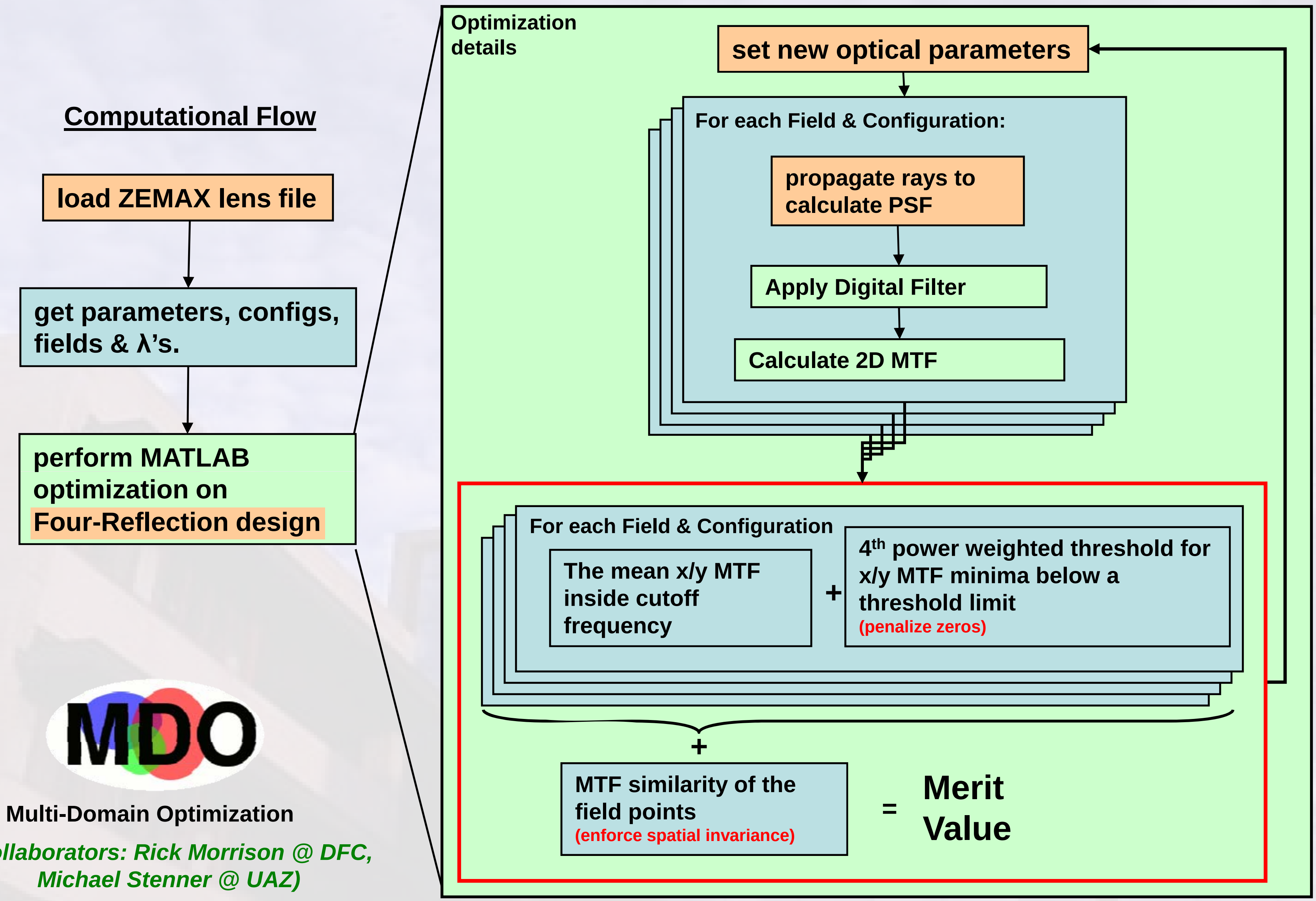
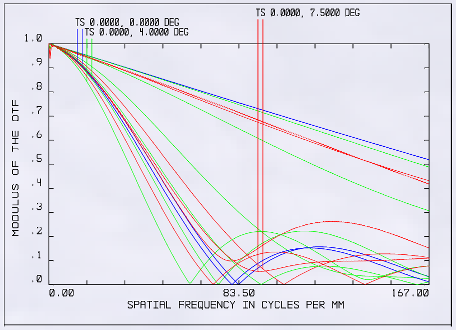


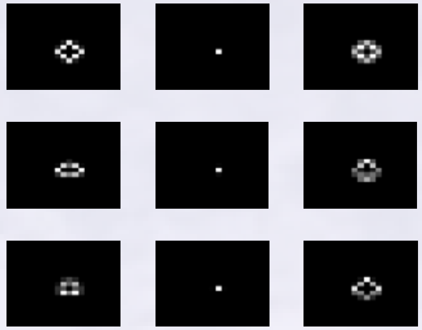
Multi-Domain Optimization

(Collaborators: Rick Morrison @ DFC, Michael Stenner @ UAZ)

Simulated Results of Optimization



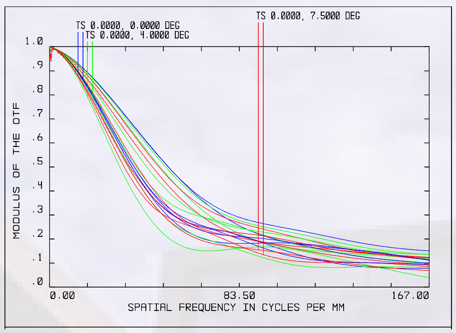
- 10 µm | In Focus | + 10 µm



0 deg
4 deg
7.5 deg

Initial unmodified Four-Reflection design

Optimization of phase encoded surface



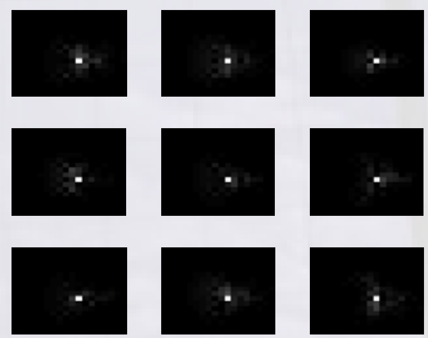
- 10 µm | In Focus | + 10 µm

0 deg
4 deg
7.5 deg

PPE Results (unfiltered)

Inverse filter

- 10 µm | In Focus | + 10 µm

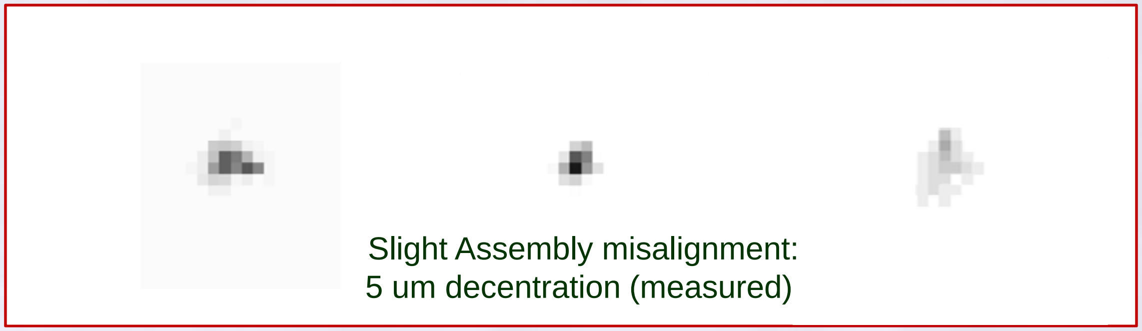


0 deg
4 deg
7.5 deg

Filtered results

PPE Four-Reflection Measured PSFs

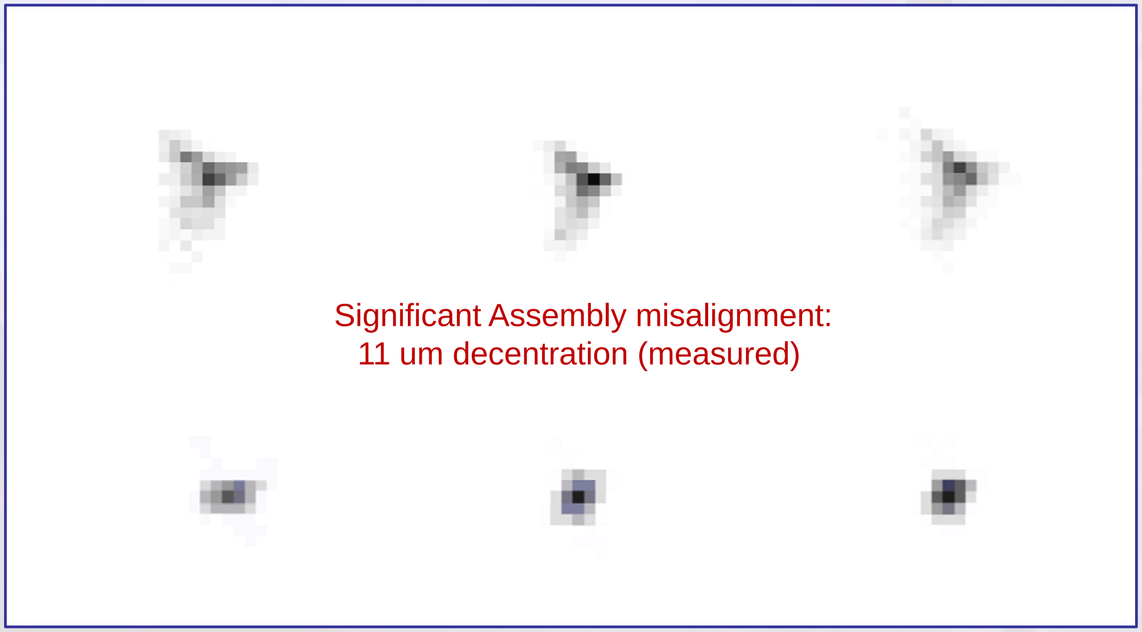
Axial Unmodified PSFs
(Exposure: 0.8 msec)



3.6 m Object Distance	**3.9 m Object Distance**	**4.2 m Object Distance**

Axial PPE unprocessed PSFs
(Exposure: 3.3 msec)

Axial PPE processed PSFs



PPE vs. Unmodified: Image Comparison

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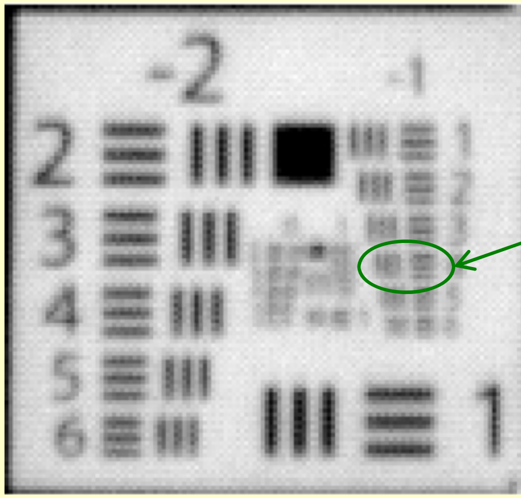
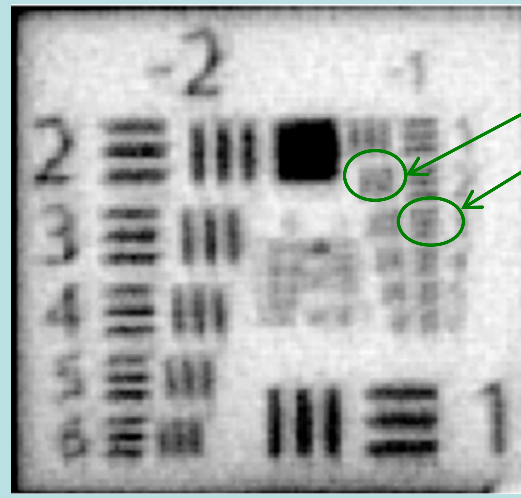
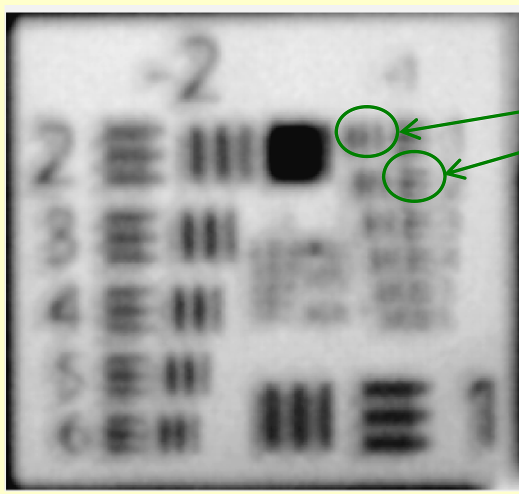
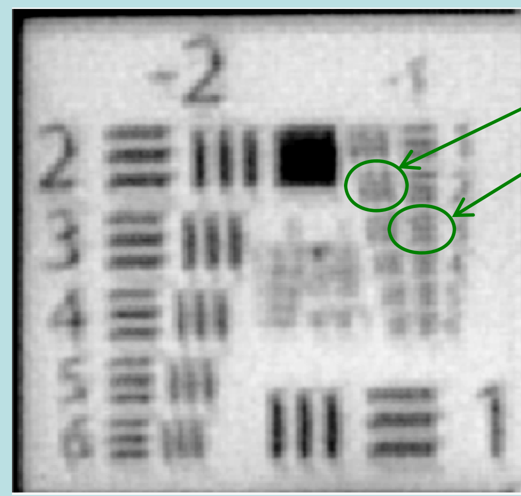
	Unmodified Four-Reflection Camera		PPE Four-Reflection Camera (processed)	
3.9 m (Best Focus)		.707 lp/mm		.56 lp/mm (H) .63 lp/mm (V)
3.6 m (3.5 waves defocus @ 550 nm)		.50 lp/mm (H) .56 lp/mm (V)		.56 lp/mm (H) .63 lp/mm (V)