SAND2012-10657P

Exceptional service in the national interest

Sandia National Laboratories

Active Reflective Components for Adaptive Optical Zoom Systems

Matthew E. L. Jungwirth

Doctoral Defense

9 Nov 2012

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

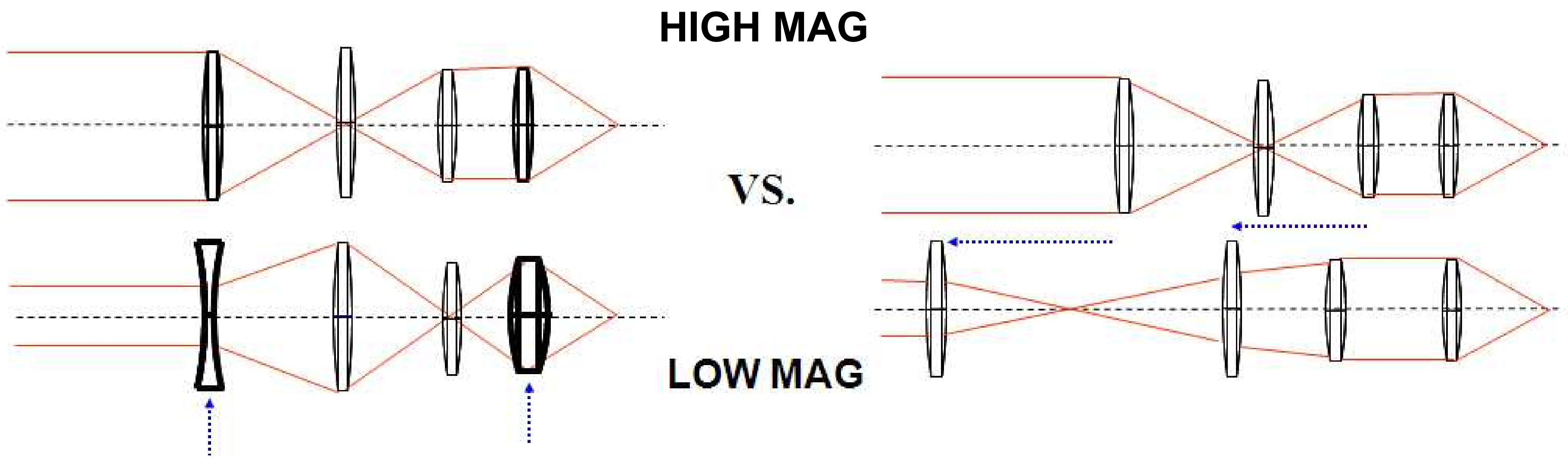
- Goal of research
- Overview of adaptive optical zoom
- Design theory of adaptive optical zoom
  - Derivation of theory
  - Tradespace analysis
  - Results in Zemax
- Active CFRP mirror
  - Design of active mirror system
  - Active mirror testbed to test mirror
  - Results
  - Improvements
- Summary

Goal of Research

- Derive optical design theory for adaptive optical zoom systems
  - Two-element, Cassegrain objective
  - Tradespace analysis to analyze millions of designs
  - Design large-aperture, two-state system
- Design, construct, and test a large-aperture active mirror
  - Change radius of curvature
  - Clear aperture is 160mm
  - Mirror fabricated of carbon fiber reinforced polymer (CFRP)
- Adaptive optical zoom system
  - Design system with theory/tradespace analysis
  - Utilize developed mirror in actual system
  - Applications are defense/aerospace

Adaptive optical zoom

- Traditionally move elements along optical axis for zoom
- Adaptive optical zoom (AOZ) uses variable focal length elements



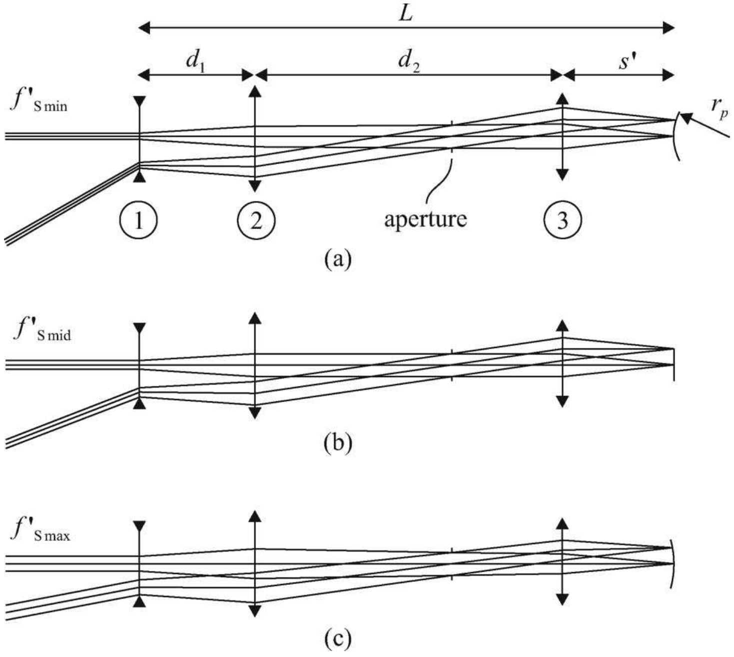
- Best option for zoom at large apertures

Existing AOZ Theories

- Gaussian reduce two-element polymer lens system (Opt.Exp. **18** (7), 2010)
- Minimize Petzval sum in first-order design

$$\frac{1}{\hat{r}_p} = \sum_N \hat{\phi}_i = \sum_N \frac{1}{\hat{f}_i}$$

App. Opt. **48**(21), 4097-4107 (2009).



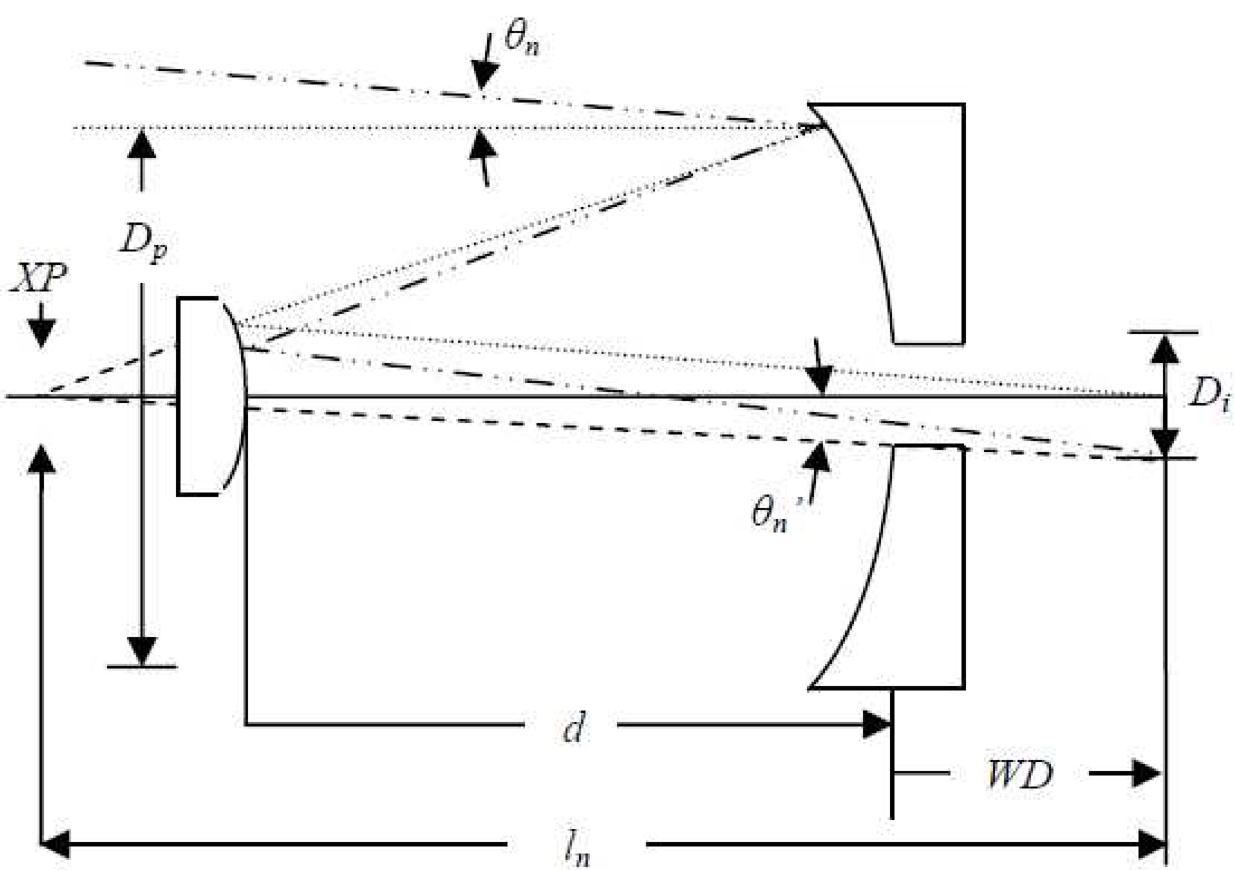
- Experimental system has 4 mirrors

Brief of Theory

- Design an AOZ Cassegrain objective
  - Primary and secondary are active elements
  - Classical Cassegrain topology
- Combination of existing theories
  - 3rd-order objective design
  - 3rd-order aberration simulation
- Tradespace analysis
  - Simulate hundreds of millions of designs
  - Down-select based on given criteria

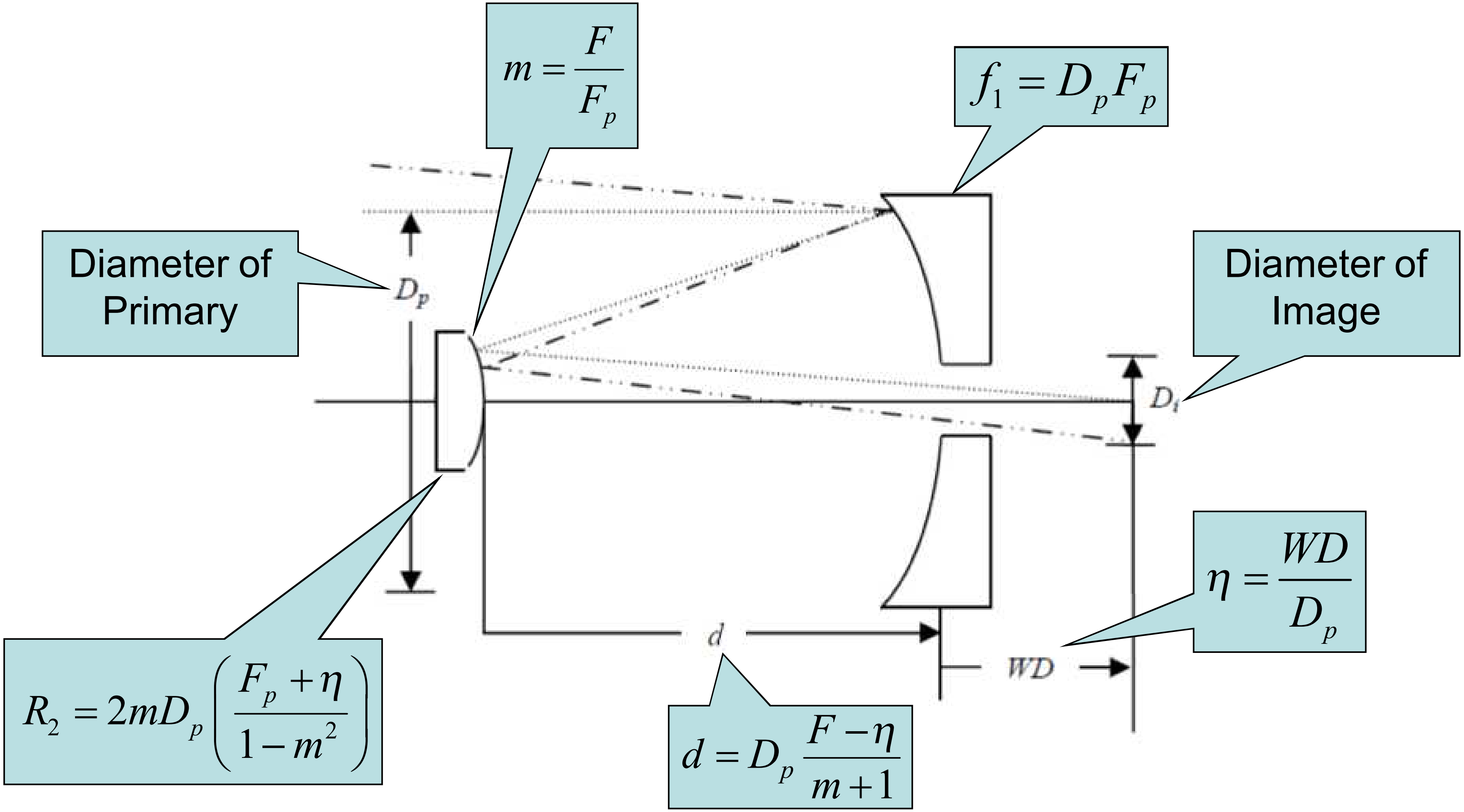
Cassegrain Telescope Design

- Two active element Cassegrain objective



App. Opt. **11**(12), 1972, pp.2817-2832.

Existing Design Equations



→ **Distances are fixed, focal lengths vary**

Third-Order Design Theory

- Solving given equations for an adaptive system

$$R_{21} = \frac{2D_p f_{11} F_1 F_2 (f_{11} - f_{12})}{(f_{11} - D_p F_1)(f_{11} F_2 - f_{12} F_1)}$$

$$R_{22} = \frac{2D_p f_{12} F_1 F_2 (f_{12} - f_{11})}{(f_{12} - D_p F_2)(f_{12} F_1 - f_{11} F_2)}$$

$$d = \frac{f_{11} f_{12} (F_2 - F_1)}{f_{11} F_2 - f_{12} F_1}$$

$$WD = \frac{D_p f_{12} F_1 F_2 - f_{11}(f_{12} F_1 - f_{12} F_2 + D_p F_1 F_2)}{f_{12} F_1 - f_{11} F_2}$$

- Free parameters are $F_{\#}$ and f_1 (both states), D_p and D_l
- Parameter sweep establishes values

Zoom & Obscuration Ratios

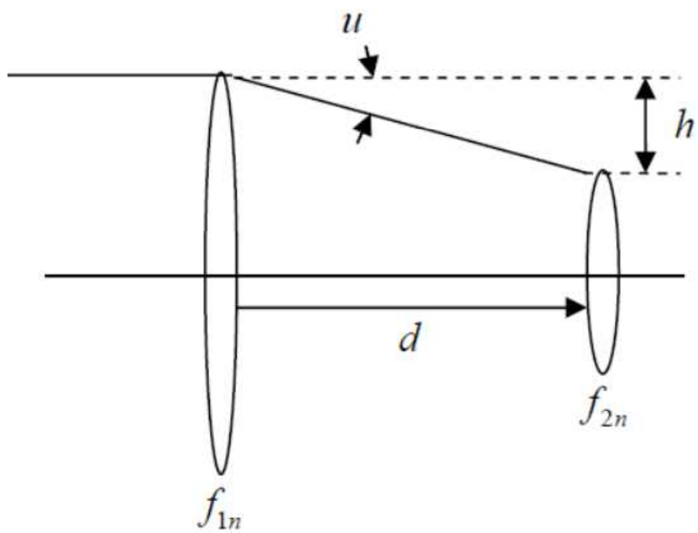
- Ratio of maximum to minimum system focal lengths

$$Z_R = \frac{f_{\max}}{f_{\min}}$$

- Ratio of secondary to primary diameters

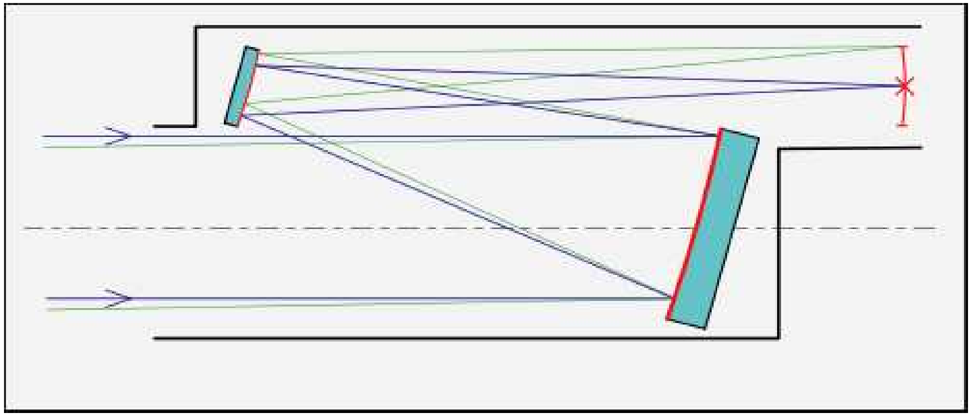
$$\varepsilon = \frac{D_s}{D_p}$$

$$\varepsilon = 1 + \frac{d}{f_{1n}}$$



Bilateral System Theory

- Paraxial aberration theory for bilateral systems
  - One plane of symmetry



Courtesy: ArtMechanic

- Result is Seidel aberration coefficients

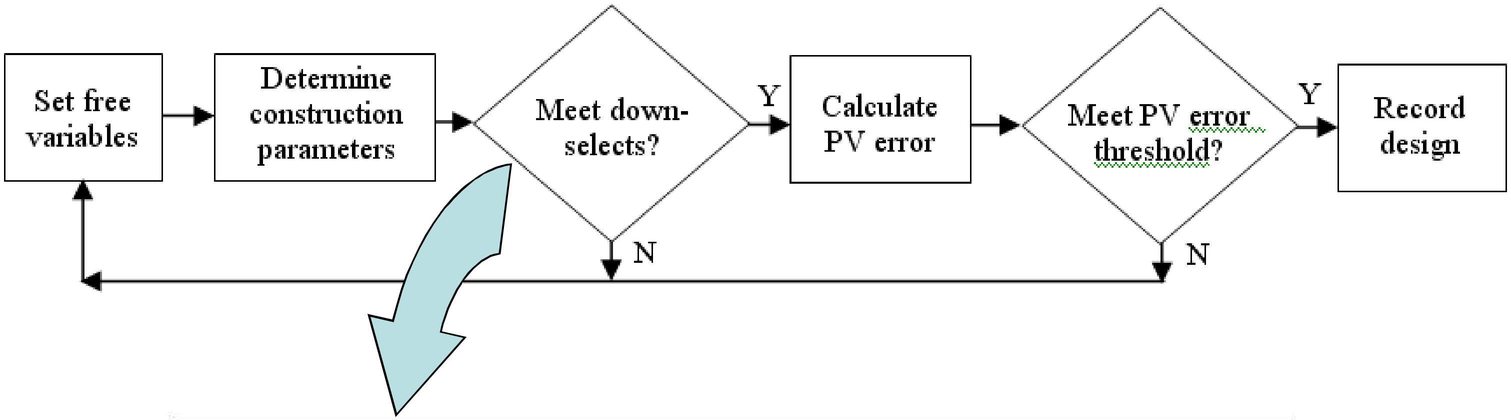
$$W(\vec{H},\vec{\rho}) = \sum_{k,m,n}^{\infty} W_{2k+n,2m+n,n} (\vec{H}\cdot\vec{H})^k (\vec{\rho}\cdot\vec{\rho})^m (\vec{H}\cdot\vec{\rho})^n$$

- Optimize further in Zemax/CodeV/etc

Opt. Eng. 33(6), 2045-2061 (1994).

Parameter Sweep Logic

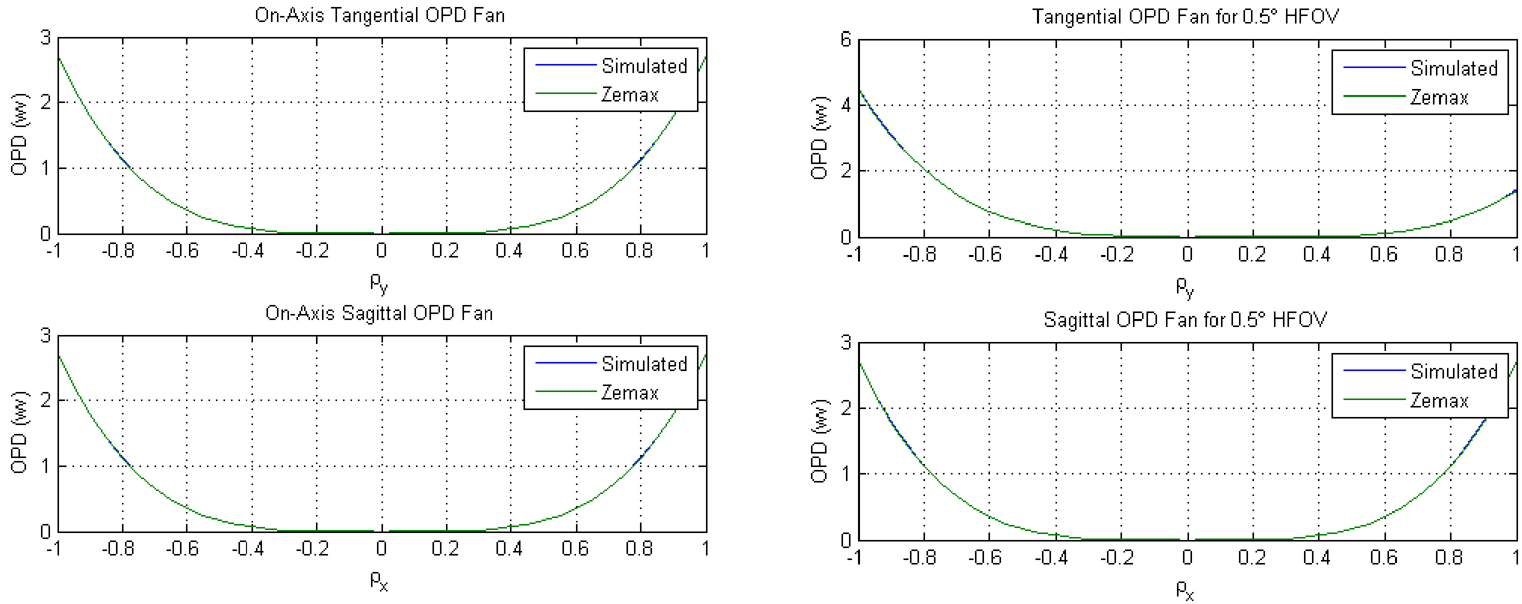
- Solve derived equations in Matlab code



Criterion	Description
$d > 0$	The distance d is defined to be positive.
$WD > 0$	The distance WD is defined to be positive.
$R_{21} \neq R_{22}$	The secondary ROC must change between states to achieve zoom.
$(d + WD) < T_L$	The system length must be less than the threshold.
$Z_R > T_{Z_R}$	The zoom ratio must be greater than the threshold.
$\varepsilon < T_\varepsilon$	The obscuration ratio must be less than the threshold.

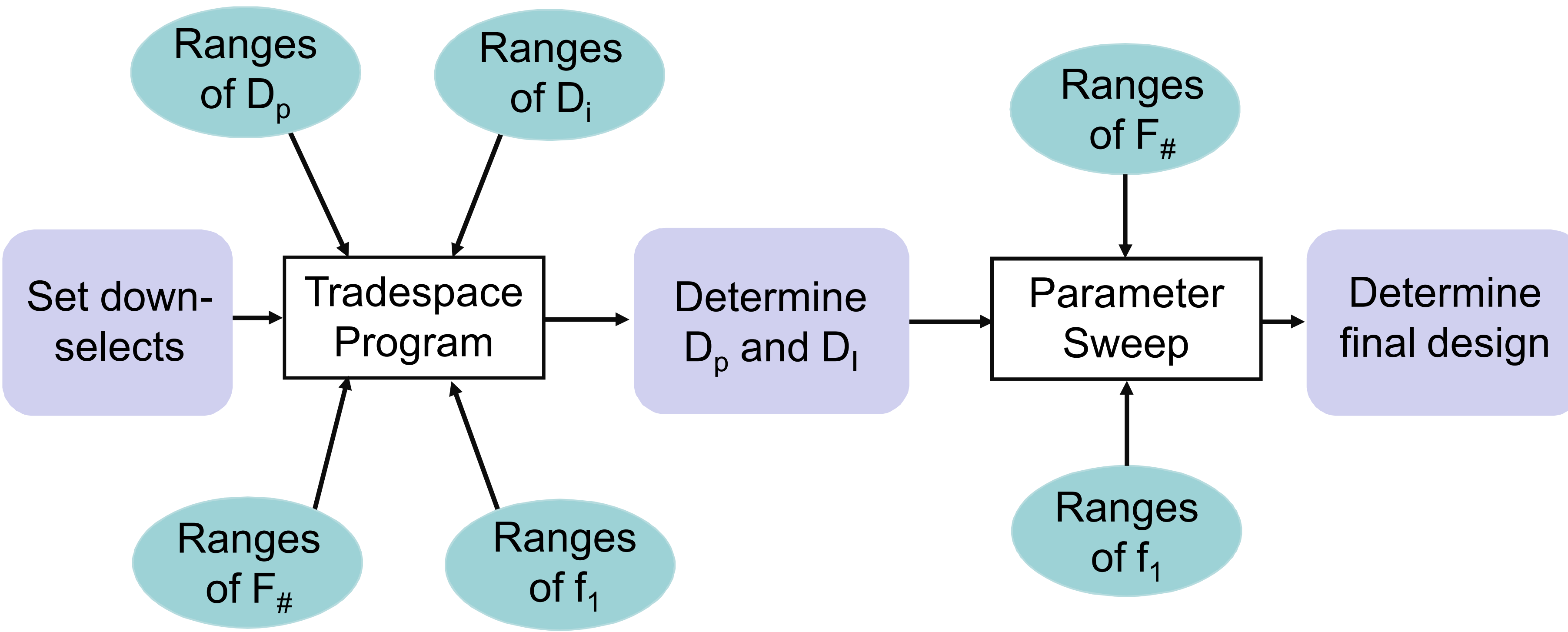
Verification of Code

- Simulate non-zooming Cassegrain



- Residual focus due to poor original design
- Defocus cannot be modeled with bilateral theory

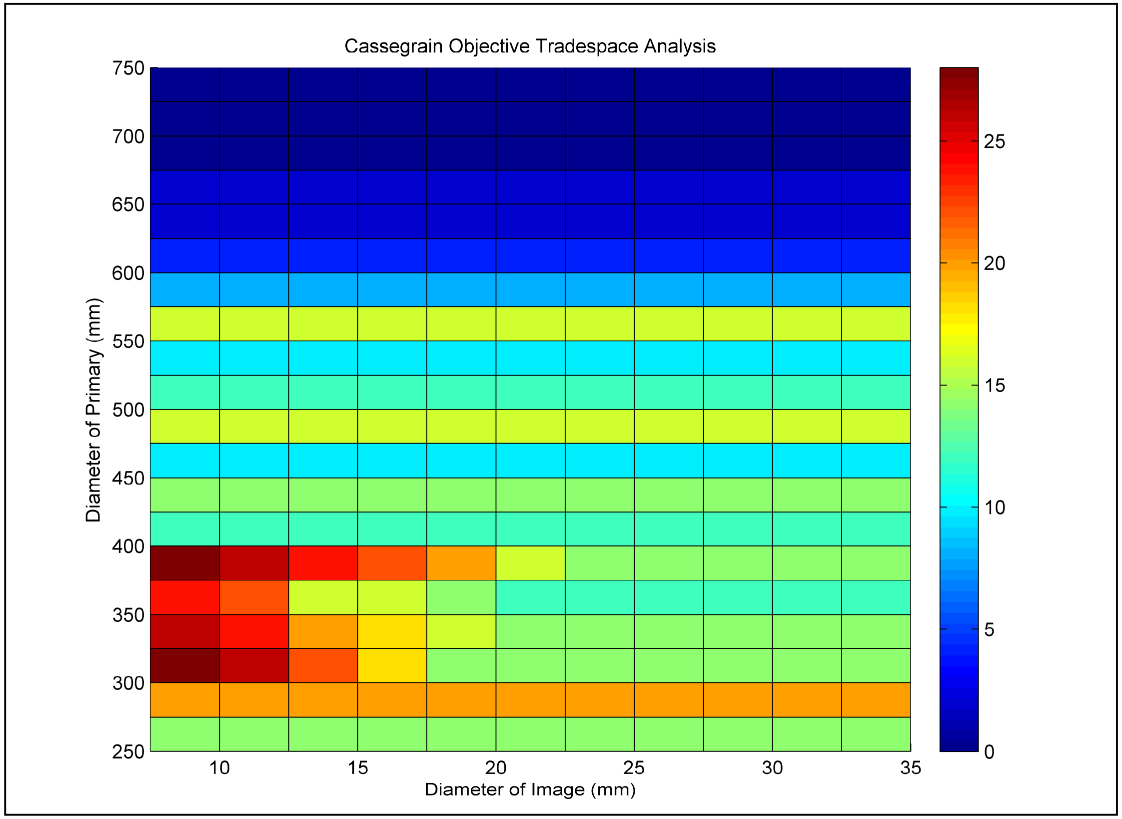
Tradespace Analysis



- Down-selects
  - Zr > 3, ε < 0.35, PV < 150wv, L < 3000mm

Set Primary & Image Diameters

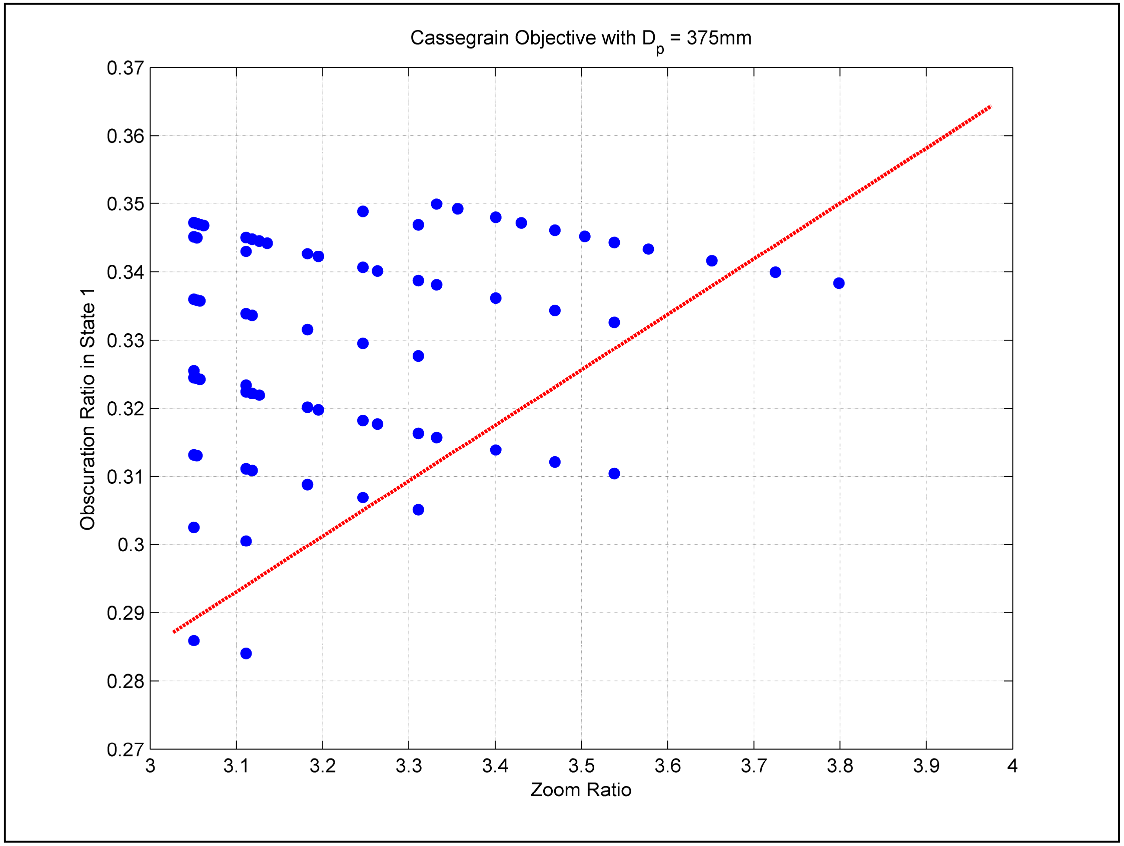
- Heat map of settings that resulted in many designs



- Maximum at Dp = 375mm, Di = 7.5

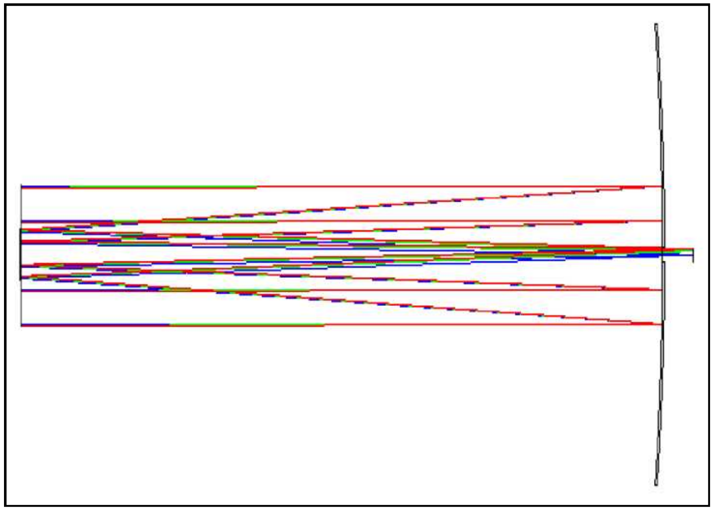
Set Design Parameters

- Single parameter sweep

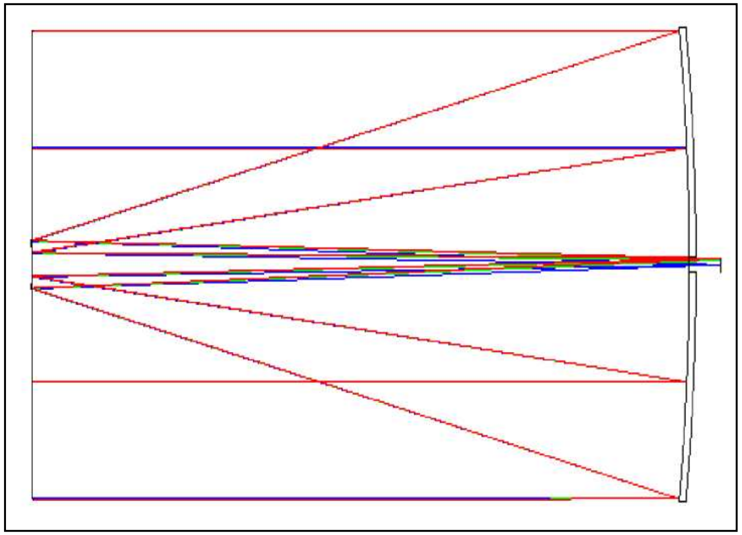


- Merit function is max. Z_R and min. ε

Design Results



Unzoomed State



Zoomed State

Design Prescription	
Parameter	Value
Z_R	**3.3**
ε	**0.34**
D_p (mm)	113.6, 375.0
F_n	19.7, 19.7
f_{1n} (mm)	1088.9, 803.4
κ_{1n}	-1.0, -1.0
f_{2n} (mm)	**-714.8, -91.8**
κ_{2n}	-8.37, -1.54
d (mm)	721.5
WD (mm)	3.4.4
$HFOV$ (degs)	0.13, 0.04
PV (waves)	**0.1, 0.07**

Theory Fidelity

- Goal was to decrease gulf between theory and design
- Most parameters agree well
- Largest difference is focal ratio in unzoomed state
  - Need down-select on focal ratio

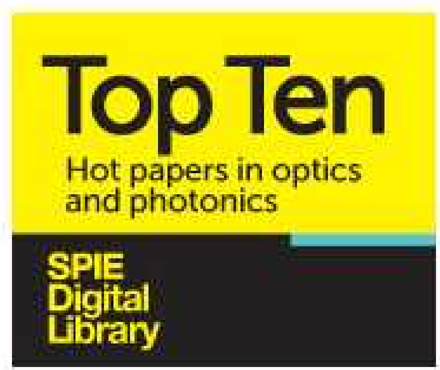
Parameter	Simulated Value	Final Value	Difference
Z_R	3.8	3.3	15.1%
ε	0.34	0.34	0.0%
F_n	**5.26, 20**	**19.7, 19.7**	**-73.3%, 1.5%**
f_{1n}	991.8mm, 720.4mm	1088.9mm, 803.4mm	-8.9%, -10.3%
R_{2n}	-1348.6mm, -141.9mm	-1429.6mm, -183.7mm	-5.6%, -22.7%
d	656.2mm	721.5mm	-9.1%
WD	**11.86mm**	**34.4mm**	**-65.5%**
HFOV	0.10°, 0.02°	0.13°, 0.04°	-23.1%, -50.0%

Journal Article

ARIZONA Sandia National Laboratories

- Worked published in *Opt. Eng.* **51**(8)
  - Invited paper at SPIE DSS 2012

- Currently most downloaded optics paper in SPIE's Digital Library



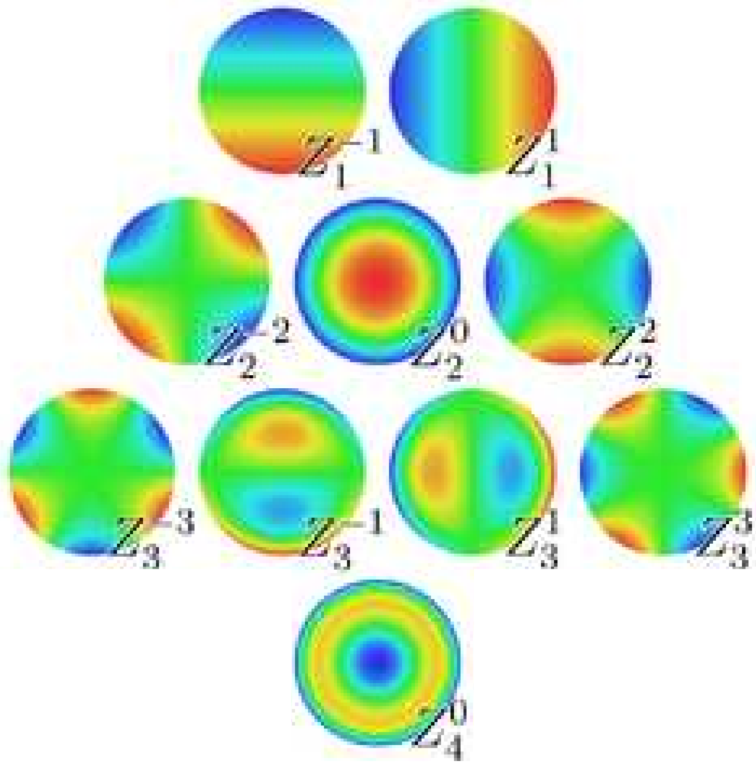
Optics

Optical Engineering | June 5, 2012

Theory and tradespace analysis of a reflective axial adaptive optical zoom system

Zernike Polynomials

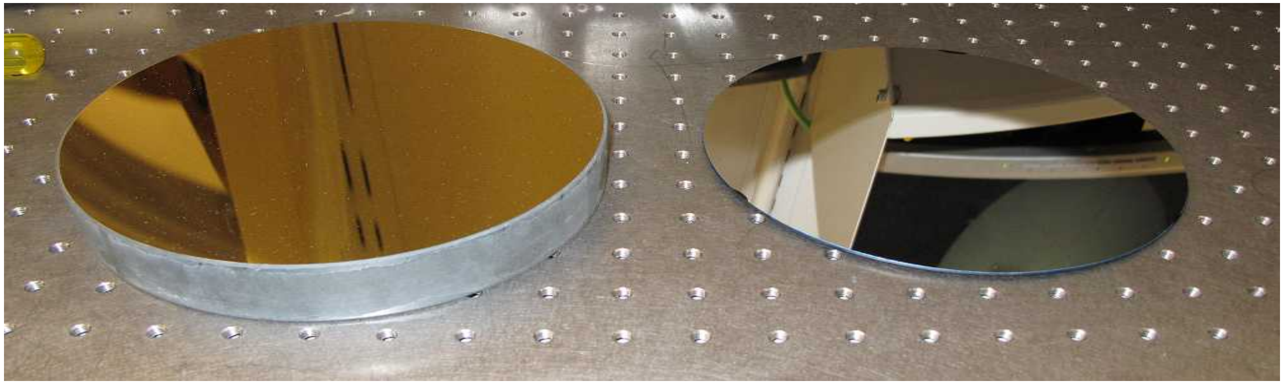
- Orthonormal basis set to describe aberrations



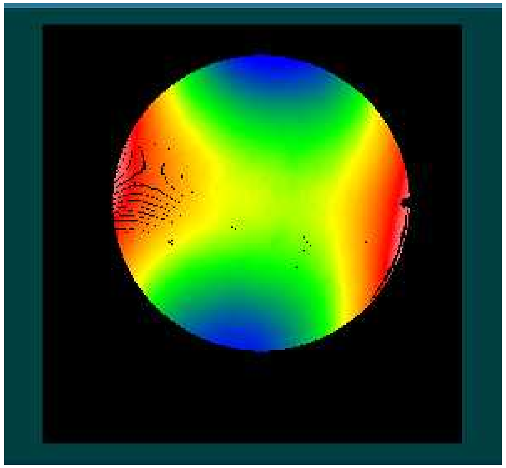
- Modal description of wavefront error (WFE)

Carbon Fiber Reinforced Polymer

- Mirror is carbon fiber reinforced polymer (CFRP)



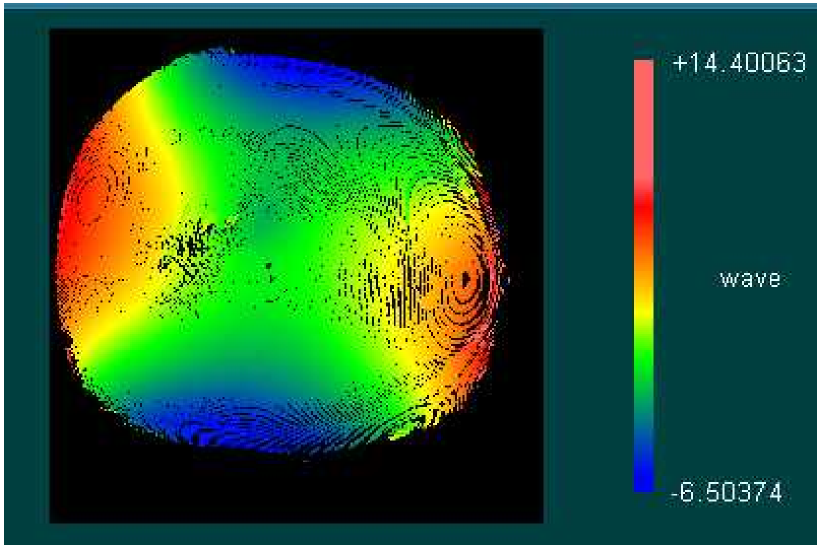
- Benefits
  - Very low CTE/hysteresis
  - Fabricated via replication
- Drawbacks
  - Not diffraction limited mirrors
  - Temporal degradation

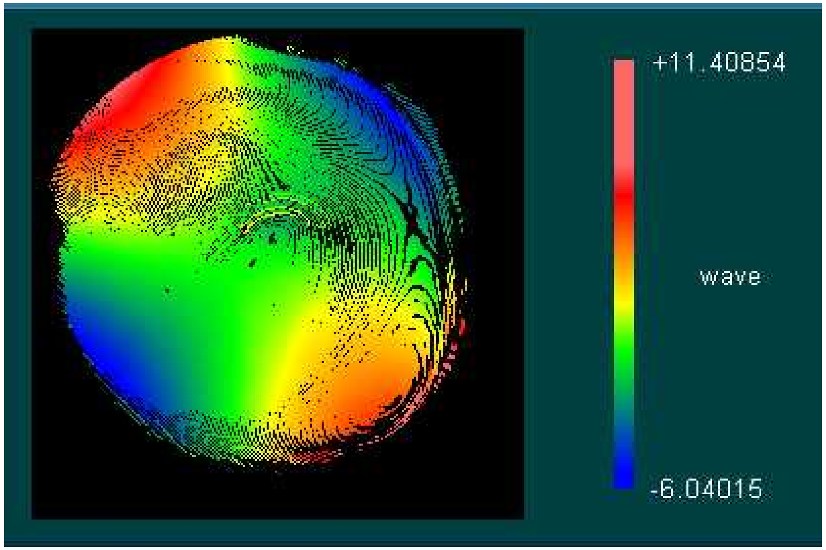


13.9wv PV, 2.58wv RMS

Cause of Astigmatism

- Large astigmatism in CFRP mirror
- Literature suggests main cause is gravitational sag

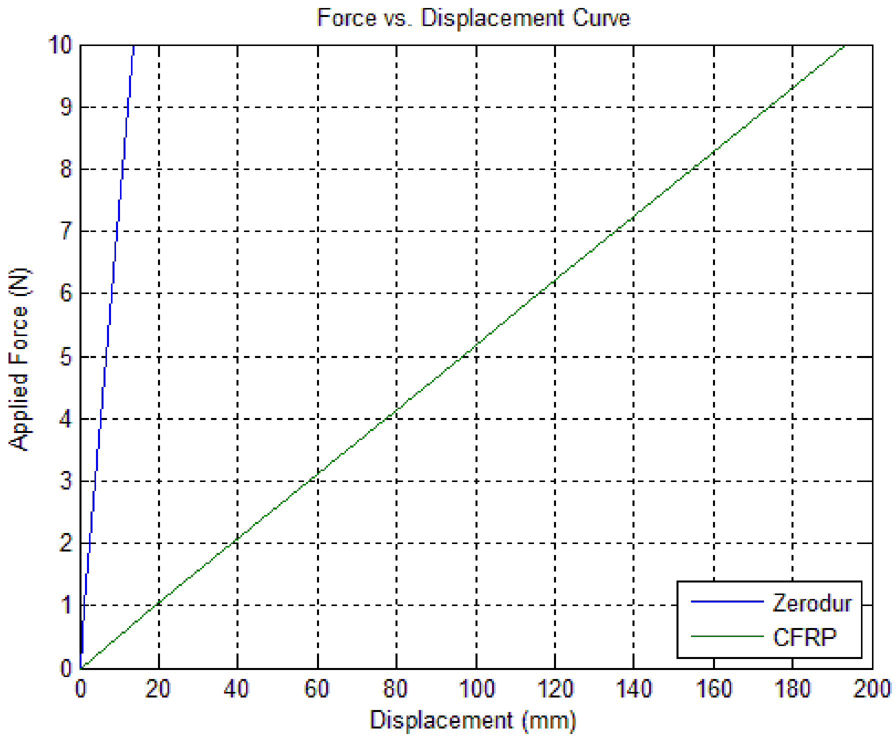




- Astigmatism tracks mirror rotation
- Thus, CFRP mirror itself is cause

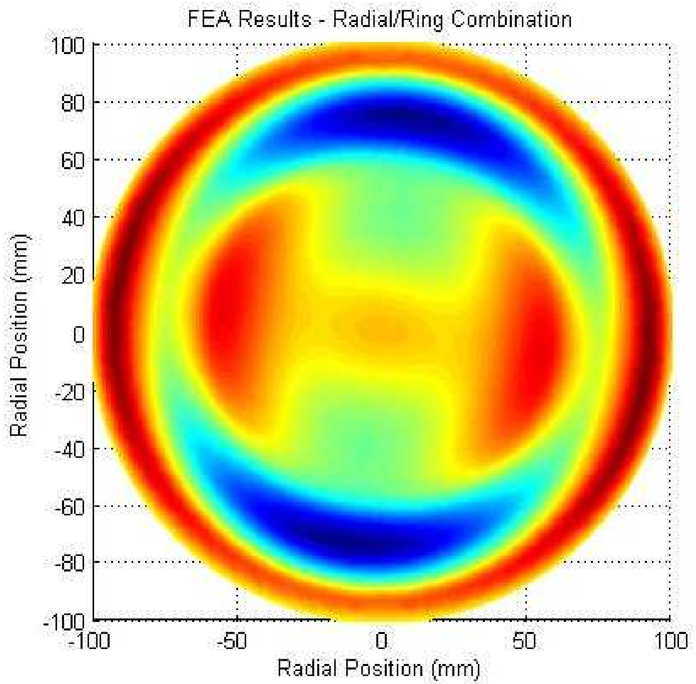
CFRP vs. Zerodur

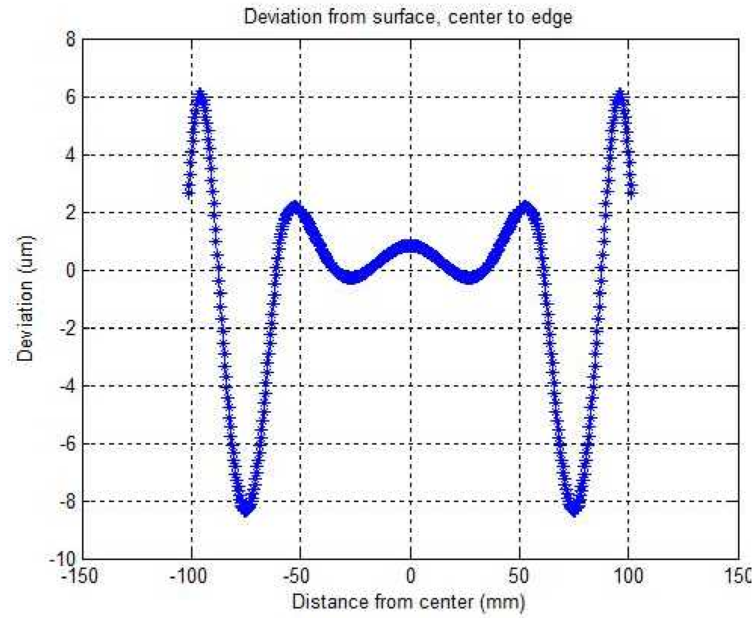
- CFRP much lower weight than Zerodur
- Robustness during actuation



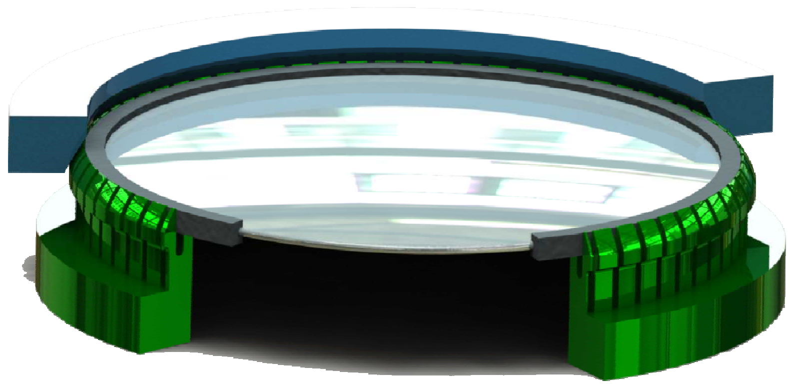
- Overall, great reduction in SWaP-C

FEM of Actuation Modalities



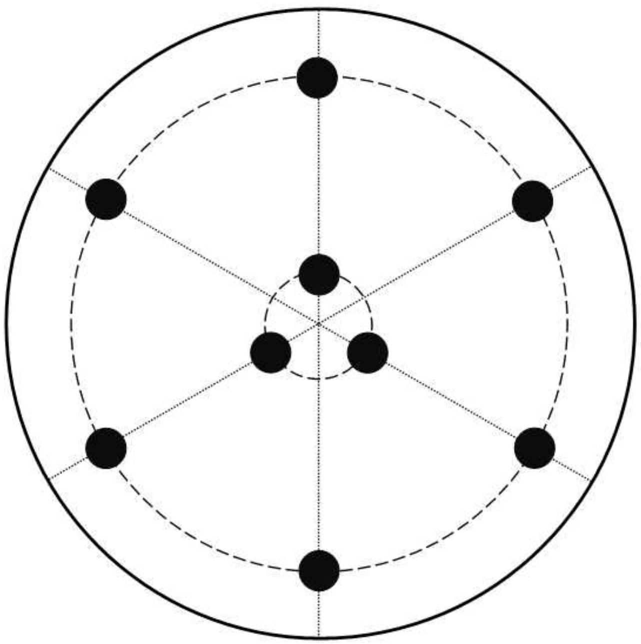


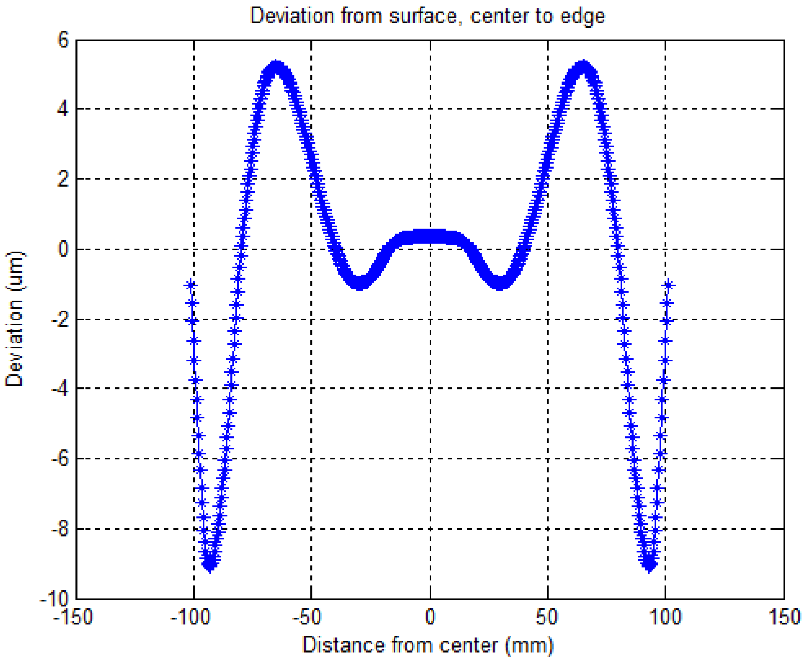
- Radial/Ring force
- ROC – 2m to 1.25m
- 24.6wv PV, 20kN total force



Actuation Modality

- Lower force, lower WFE
- Force perpendicular to stiffness gradient

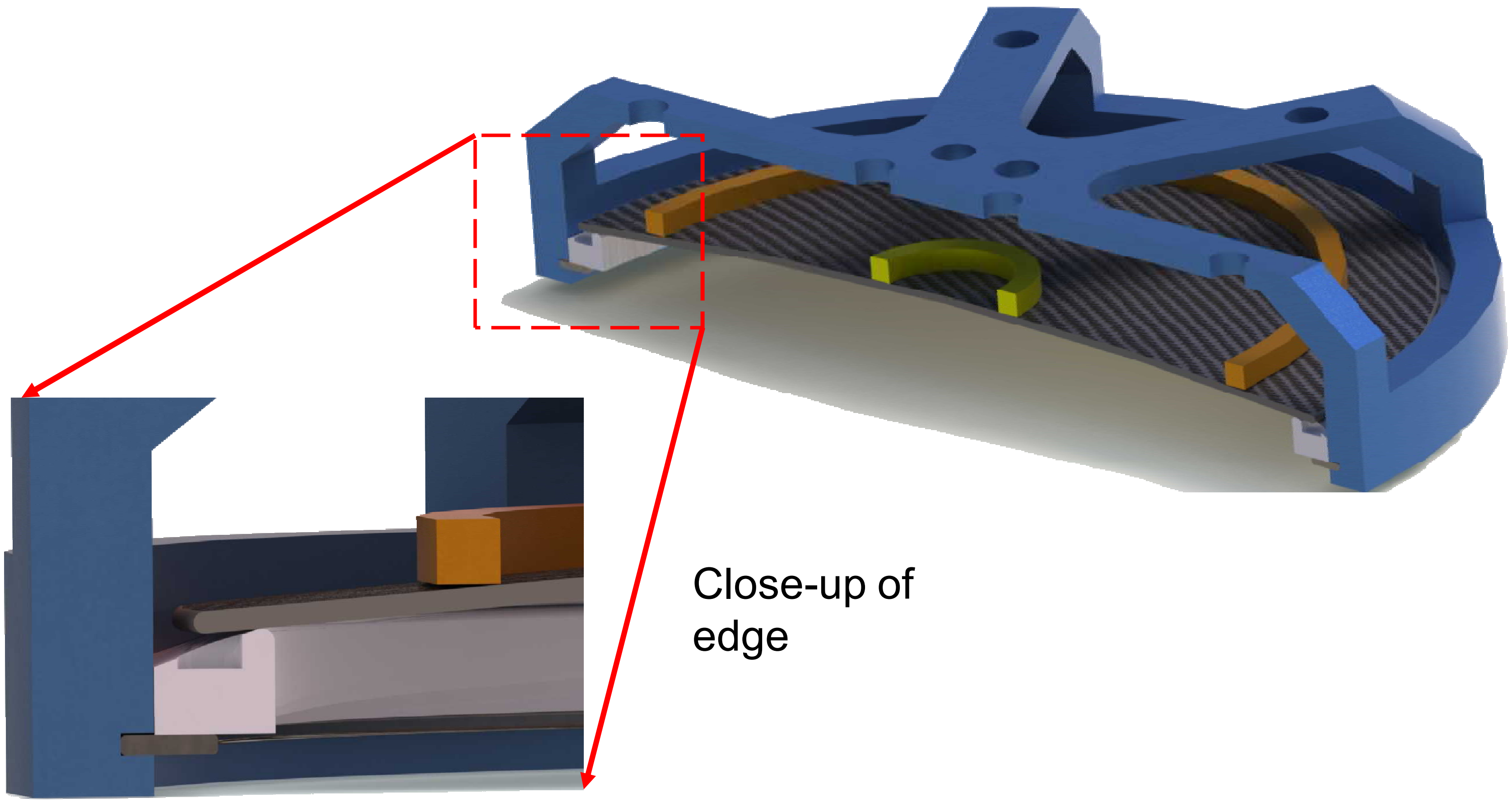




- Nine actuators (black dots) on two annular rings

Opto-Mechanical Apparatus

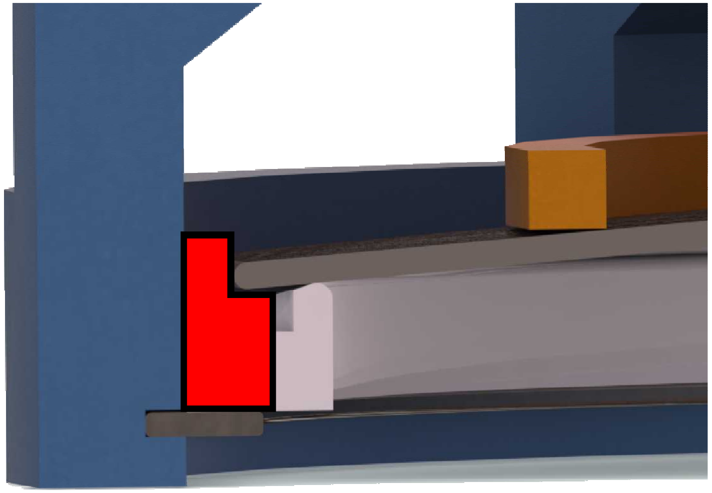
- CAD model of mount



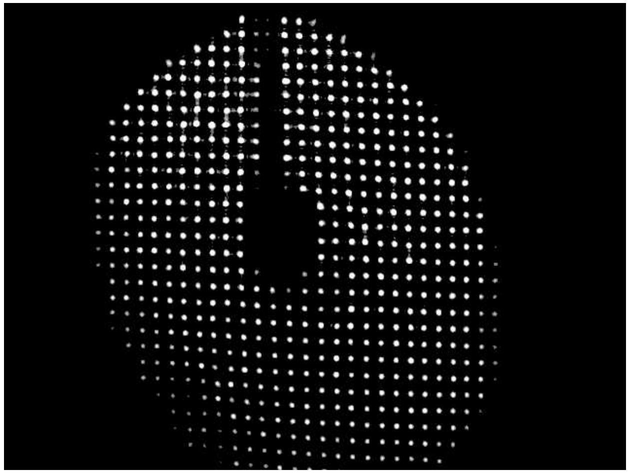
Close-up of edge

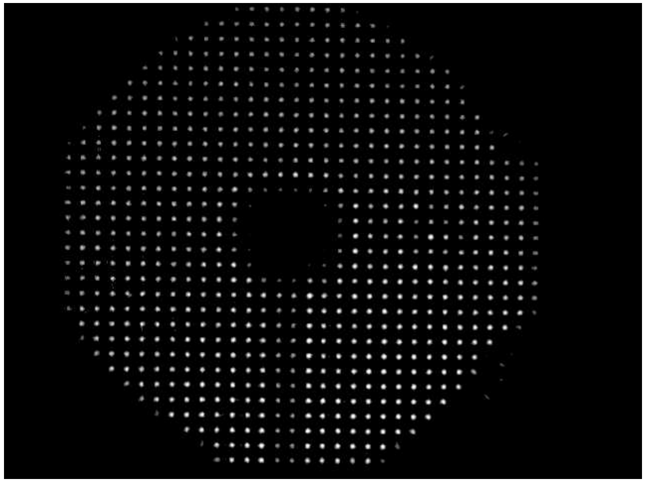
Edge Constrain

- Edge of mirror must be completely unconstrained
- Notice difference in Hartmanngrams



Rubber Gasket

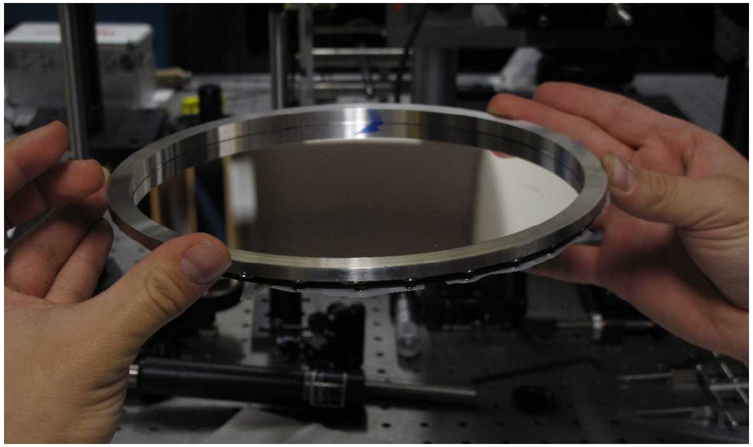




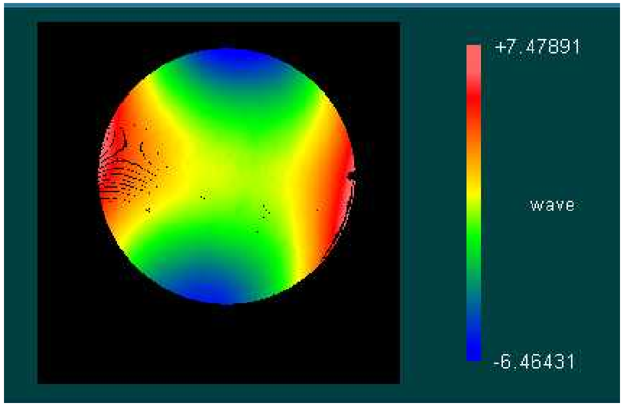
'Plunger'

‘Plunger’ Mirror Mount

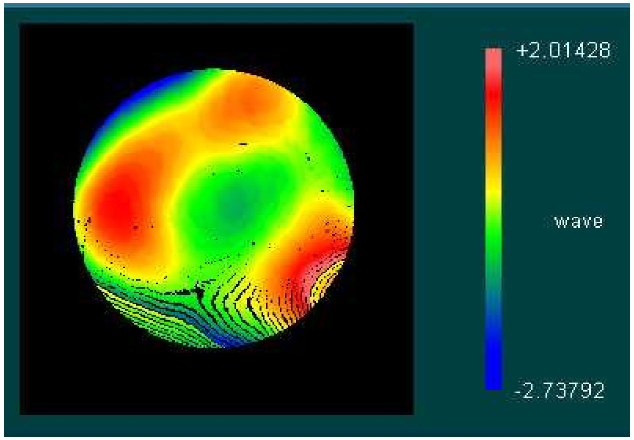
- Plunger provides clean boundary condition
- Magnets hold mirror in place
- Reduces WFE PV by 66%



Mirror held by magnets



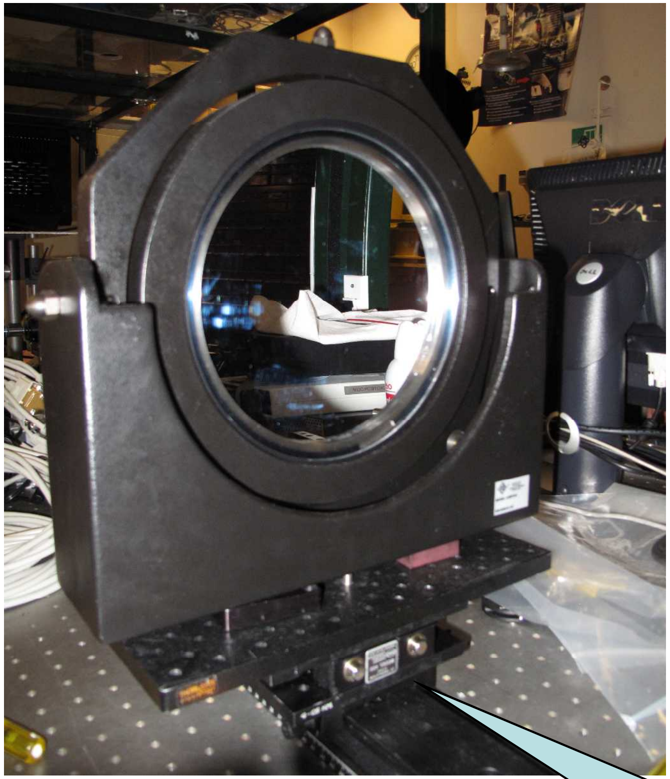
13.9wv PV, 2.58wv RMS



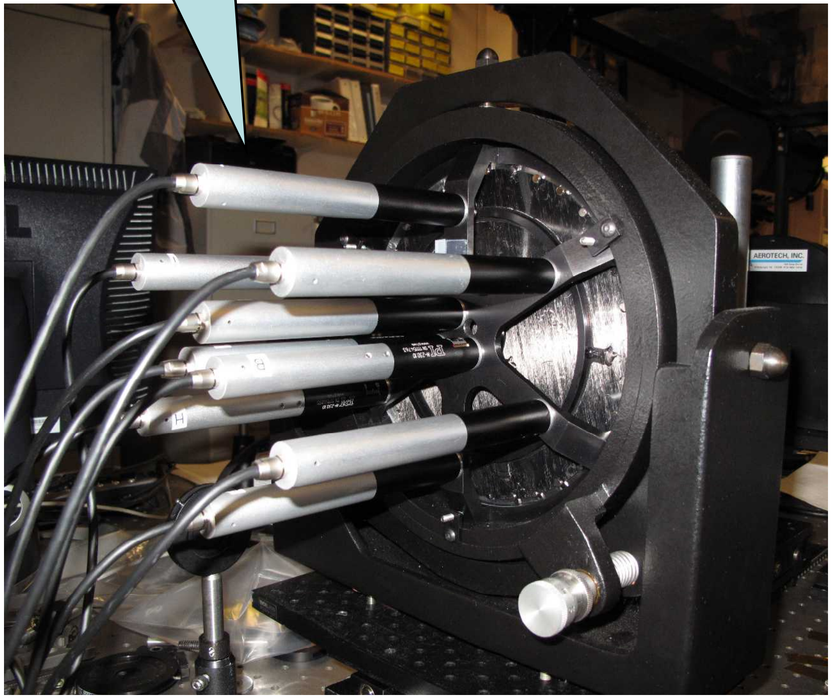
4.87wv PV, 0.79wv RMS

Final Apparatus

Physik Instrumente M230.10



Front

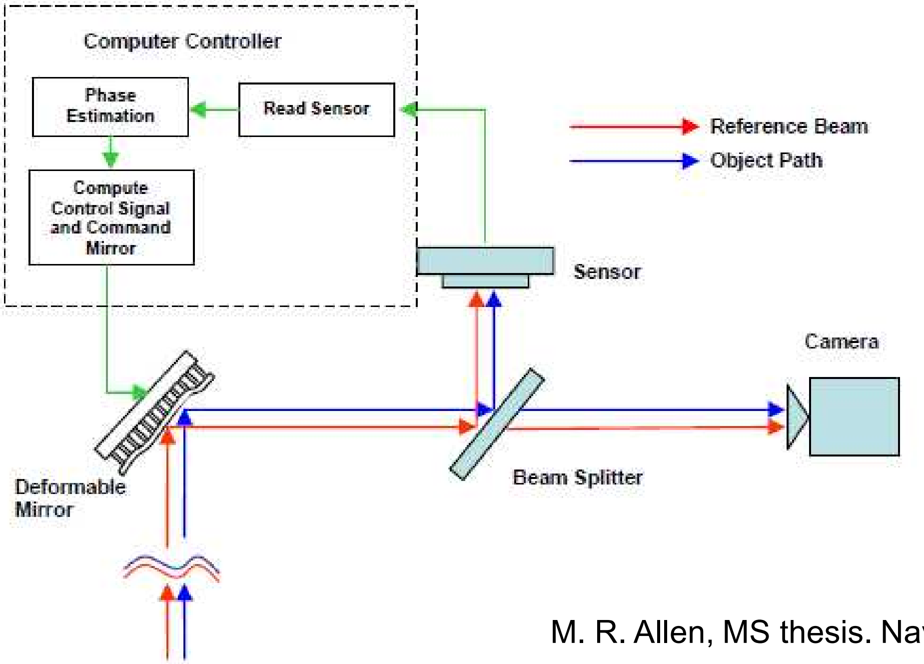


Back

Apparatus on rail

Adaptive Optics

- Active mirror tested with AO testbed
- Basic AO layout below

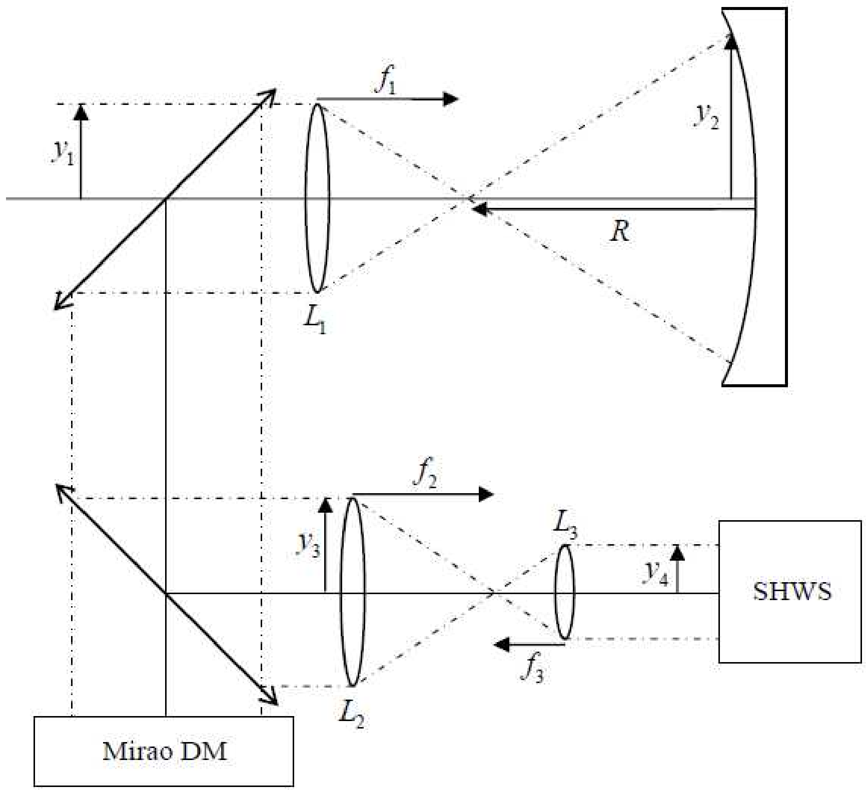


M. R. Allen, MS thesis. Naval Postgraduate School, 2007.

- Modal reconstruction of wavefront with Zernike coefficients

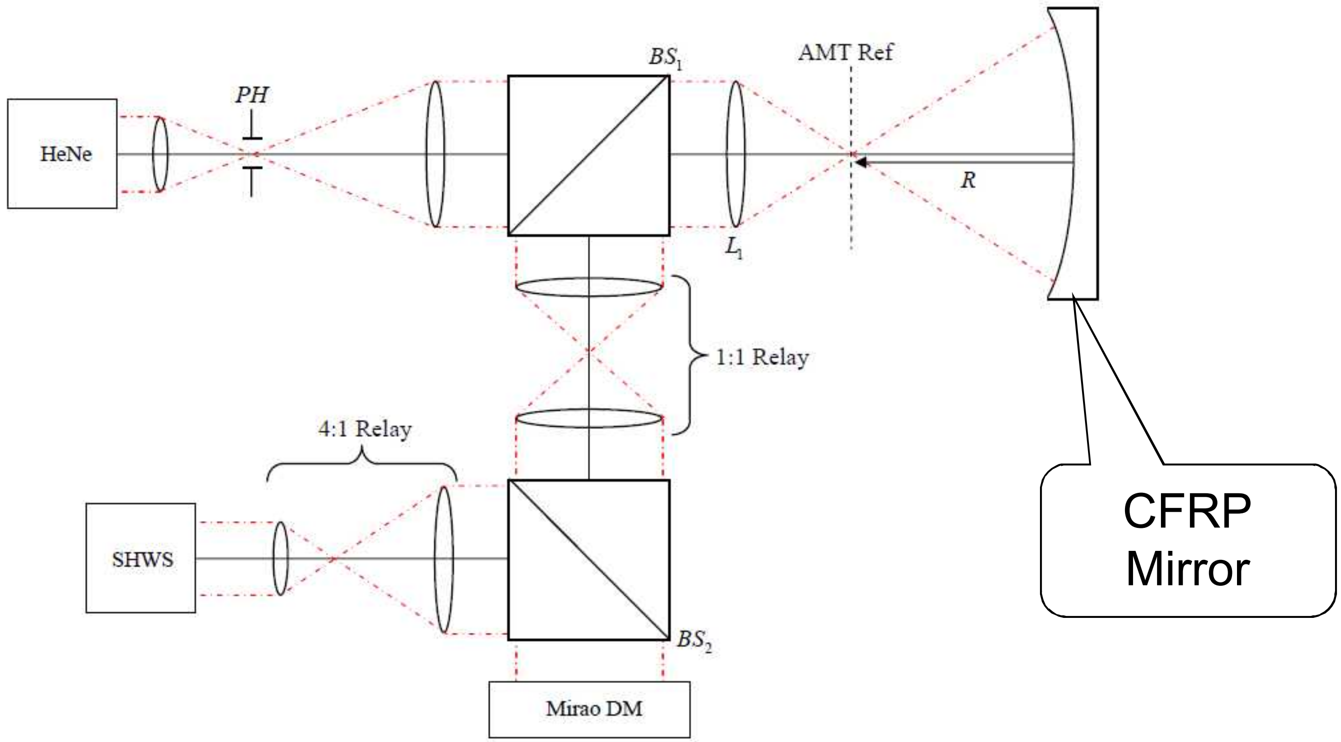
Active Mirror Testbed

- Design criteria:
  - Minimize # optics
  - Test with spherical beam
  - Use COTS components
  - Correct beam diameters
  - Correct conjugation
- Extra optics eliminated with beam sizing



Active Mirror Testbed

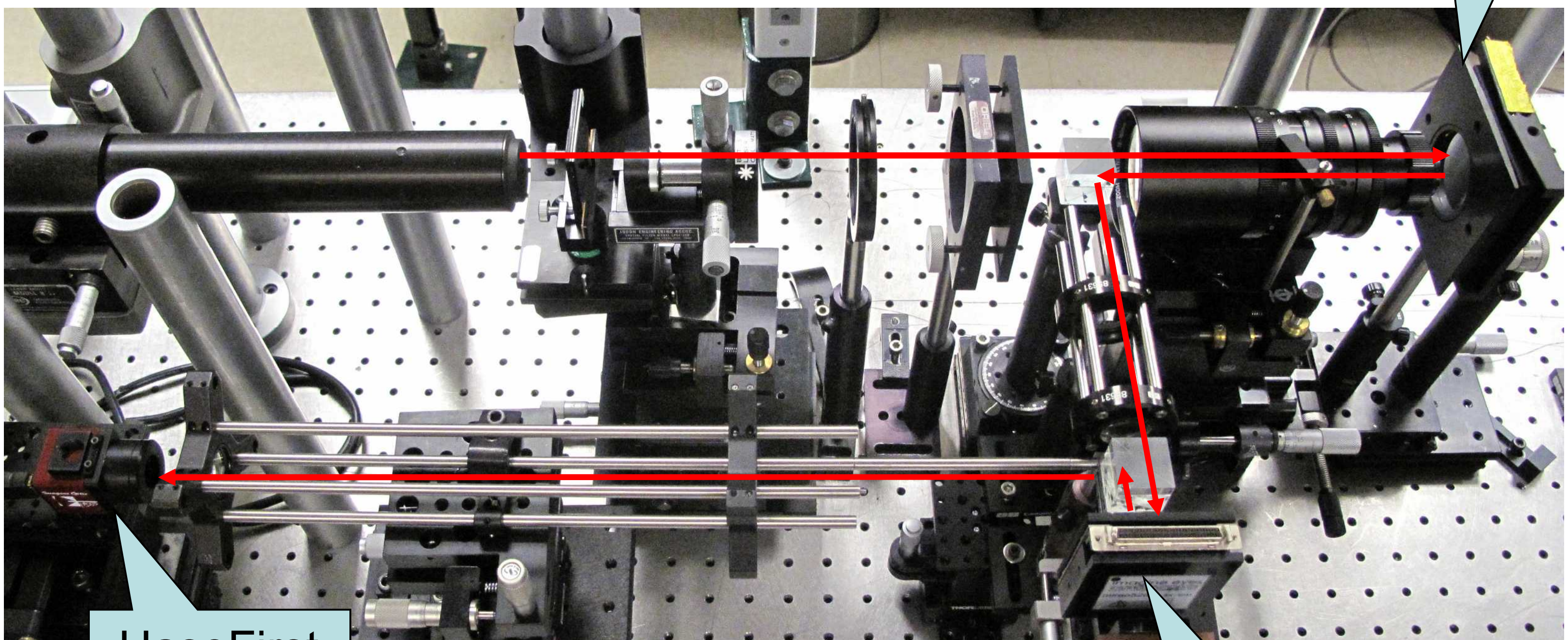
- Two deformable mirrors – CFRP mirror and COTS mirror
- Shack-Hartmann wavefront sensor measures beam



- Error of system is 0.53wv PV

AMT Picture

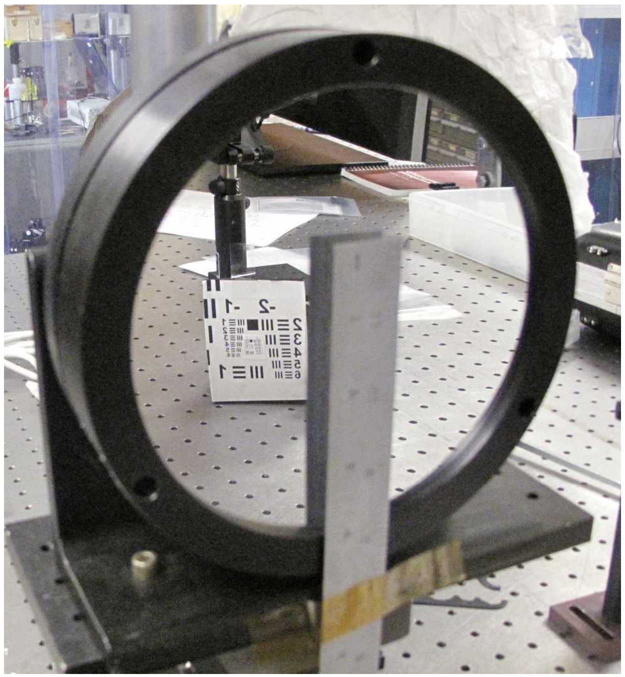
- Red line shows beam path

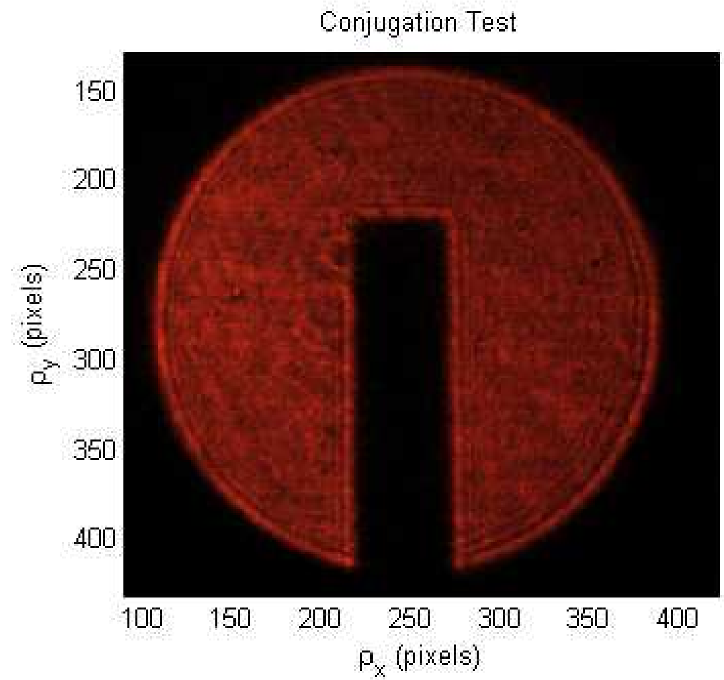


- CFRP mirror off to right

Verification of Conjugation

- CFRP/mirao/SHWS must be conjugated for proper wavefront sensing/correction

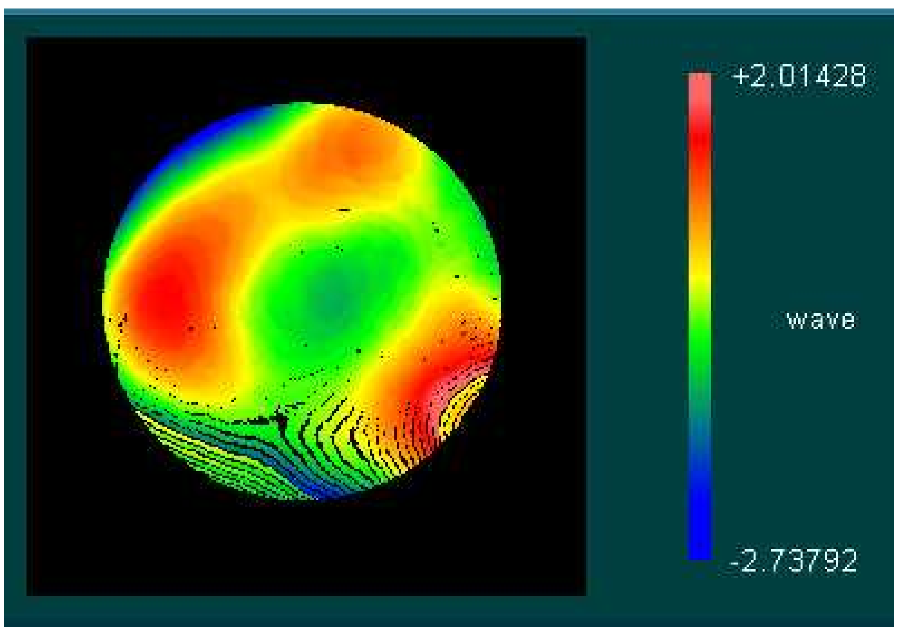




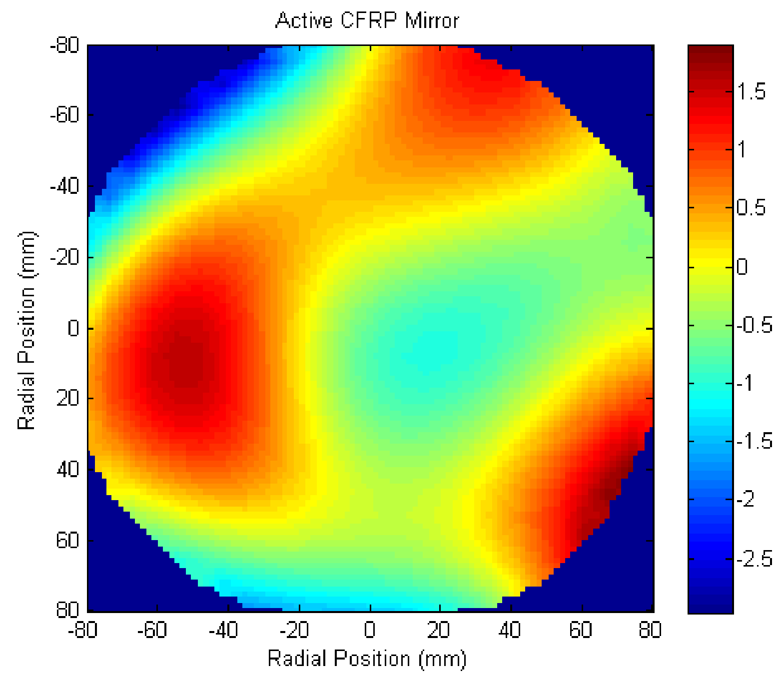
- Ruler in front of mirror demonstrates conjugation

Verification with Zygo

- Wavefront error (WFE) of CFRP mirror below
- WFE agreement with Zygo Verifire is +2.5%
  - High functional form correlation



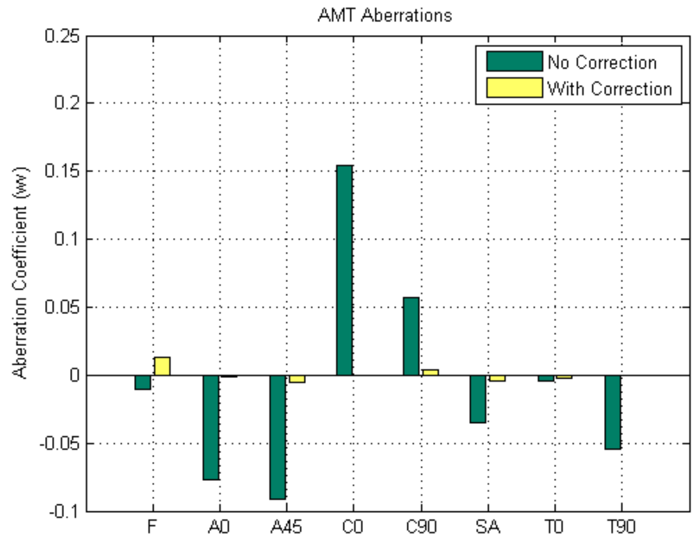
4.75wv PV, 0.73wv RMS

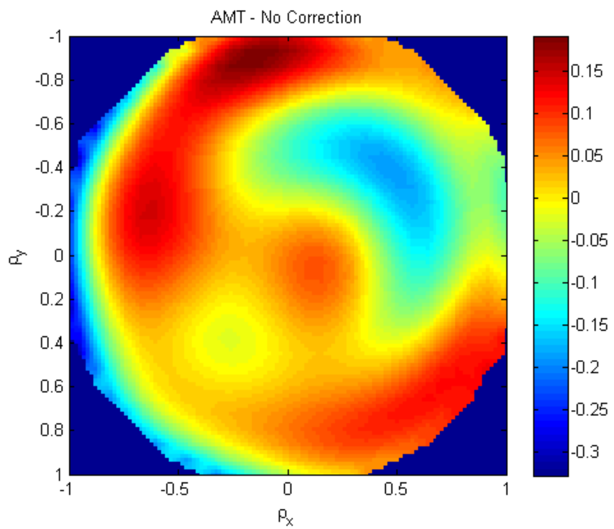


4.87wv PV, 0.79wv RMS

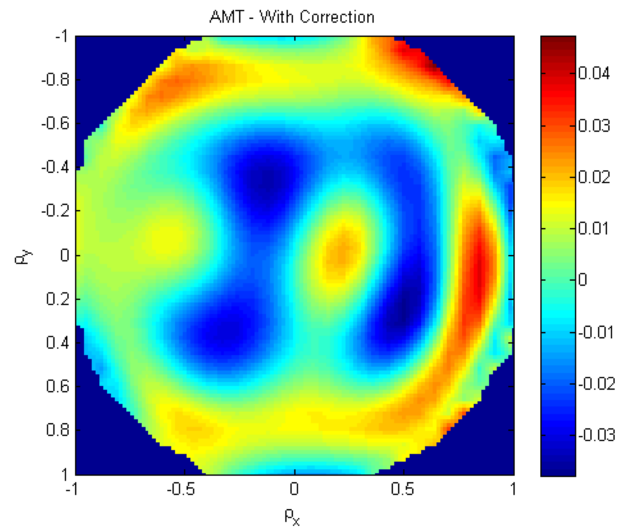
System Reference

- Internal reference is plane wave
- Created system reference to remove AMT errors





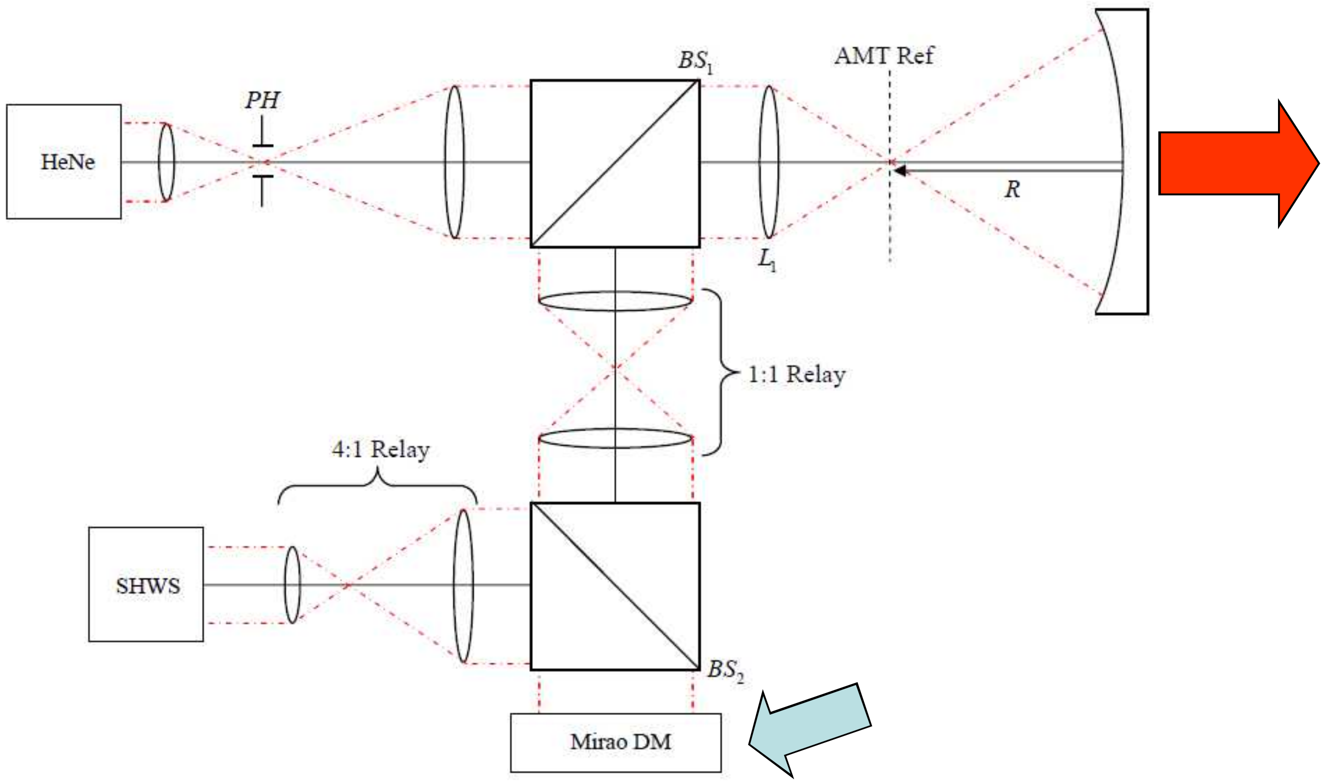
0.55wv PV, 0.09wv RMS



0.08wv PV, 0.01wv RMS

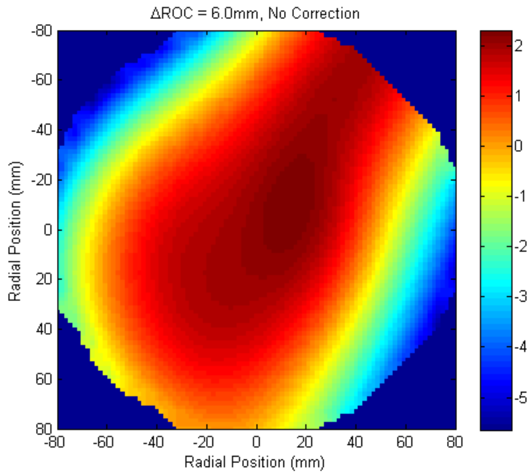
Increasing ROC

- CFRP mirror physically moved

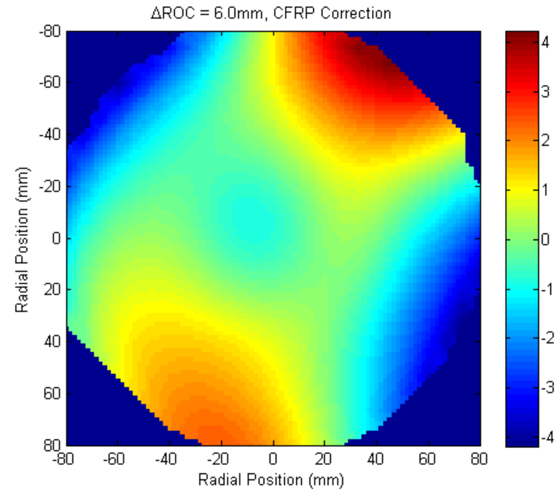


- Correct focus with CFRP mirror, mirao others

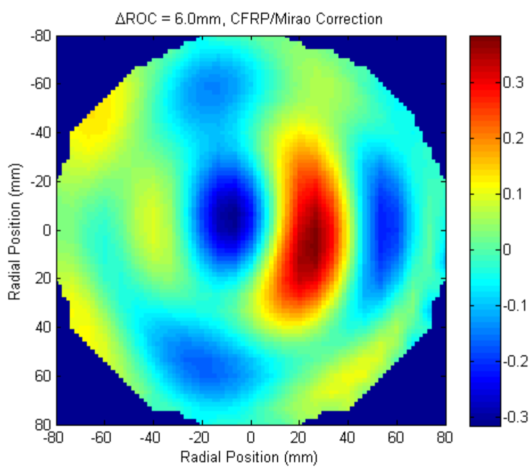
Results for ΔROC = 6mm (0.3%)



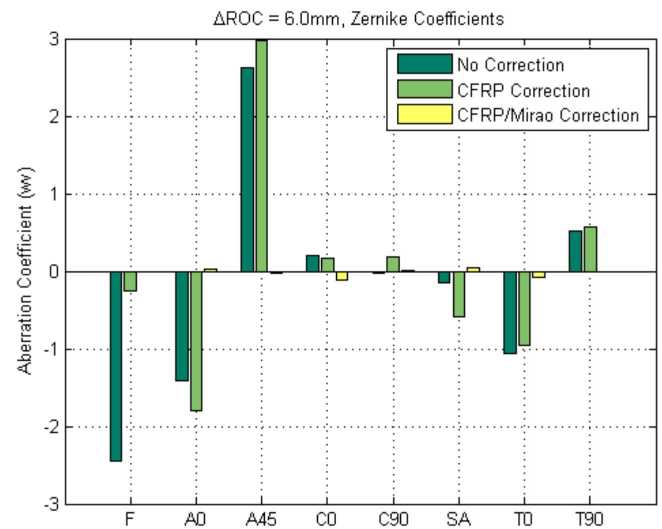
7.95wv PV, 1.875wv RMS



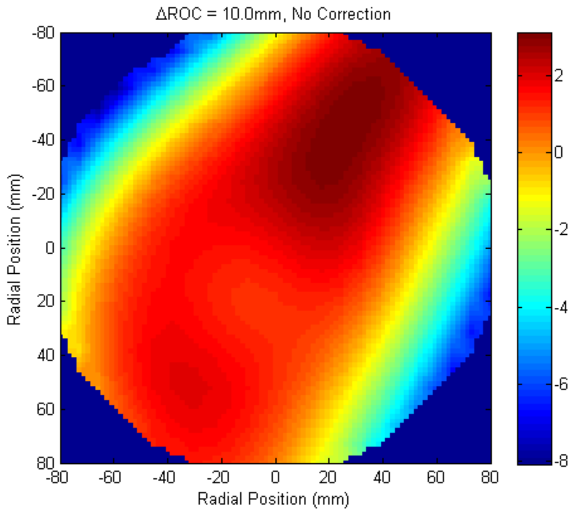
8.41wv PV, 1.501wv RMS



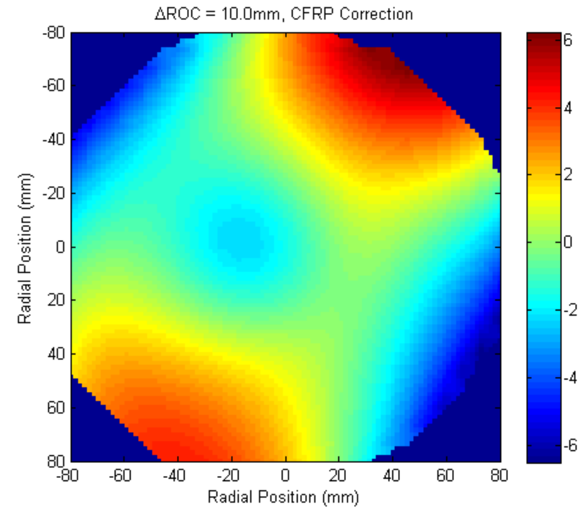
0.70wv PV, 0.111wv RMS



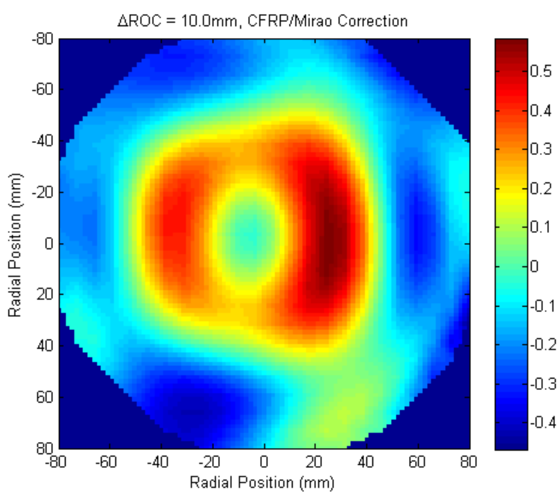
Results for ΔROC = 10mm (0.5%)



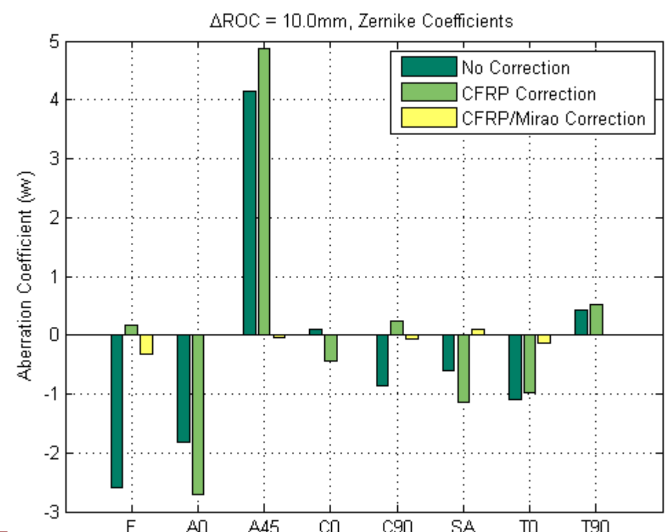
11.19wv PV, 2.38wv RMS



12.71wv PV, 2.32wv RMS

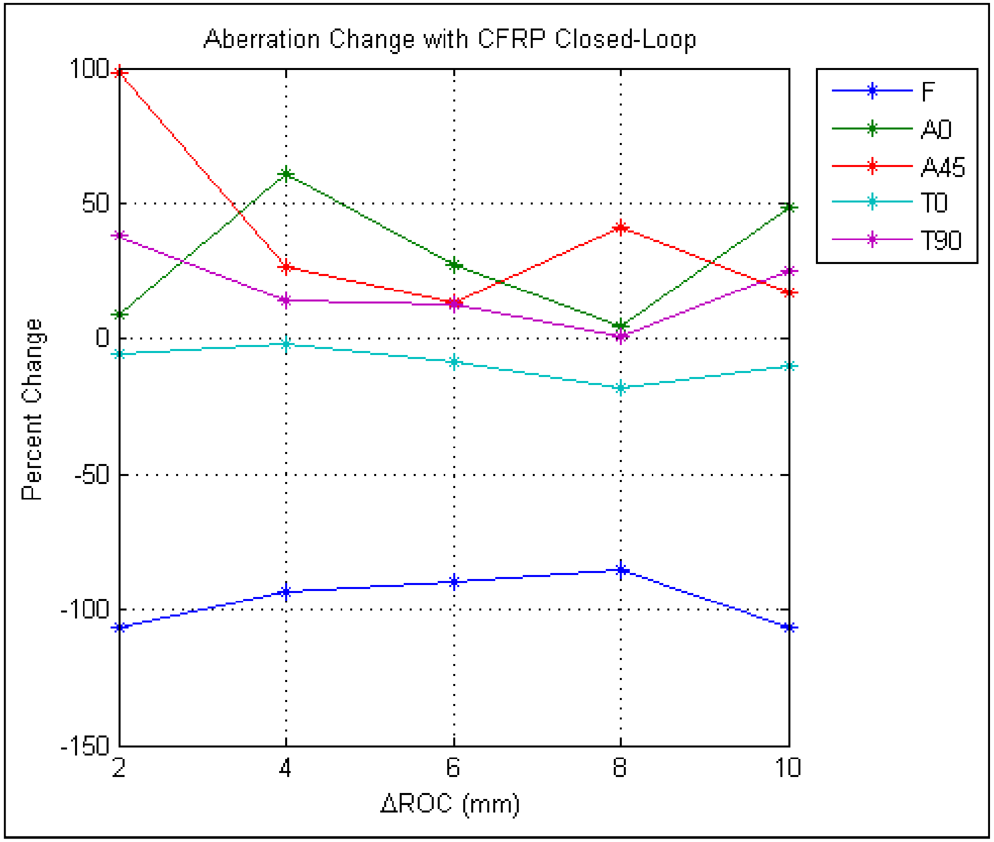


1.05wv PV, 0.23wv RMS



Error Correction

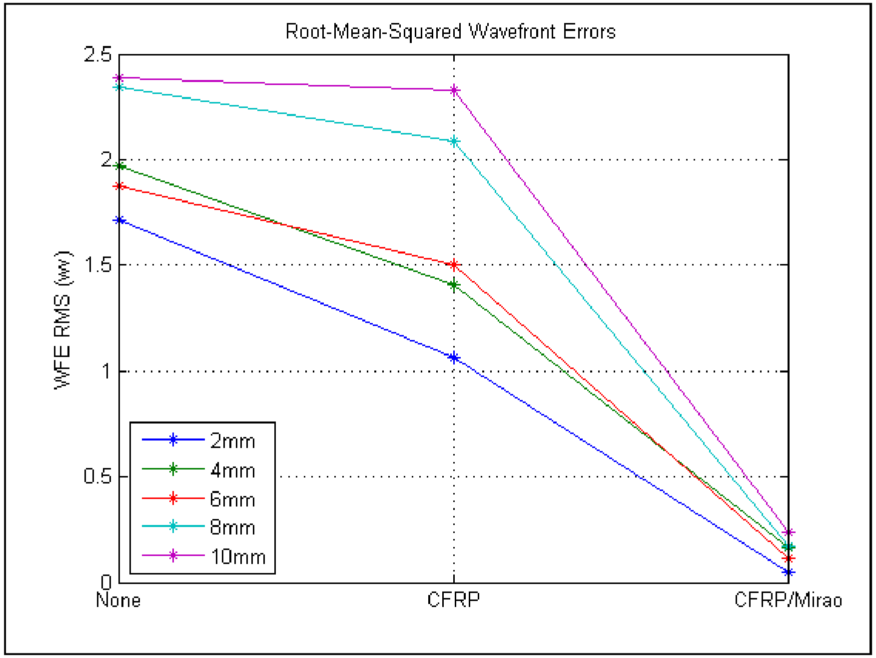
- CFRP mirror decreases focus, increases astigmatism

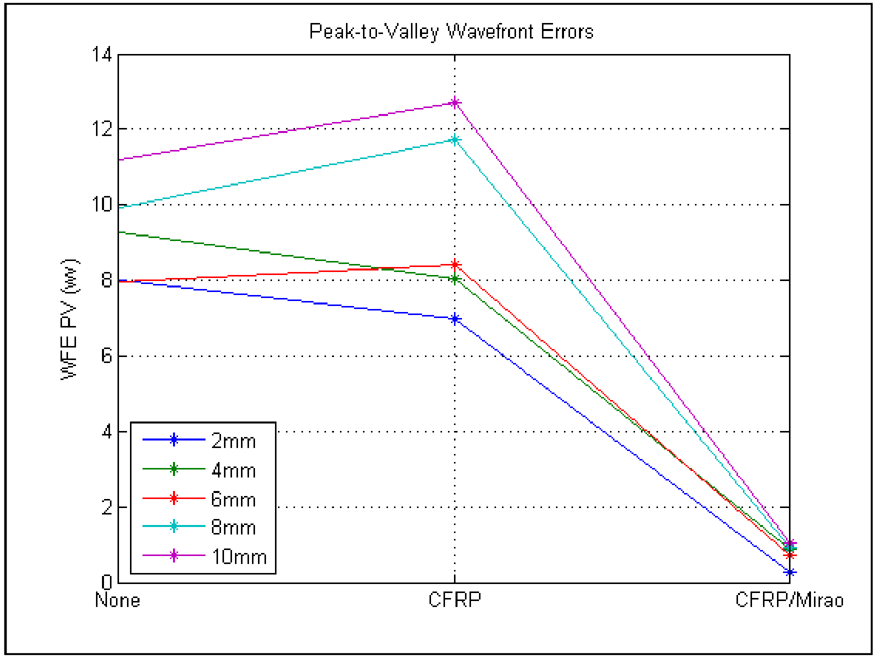


- CFRP mirror is good low, low-order corrector

Error Correction

- RMS decreases at each corrective step



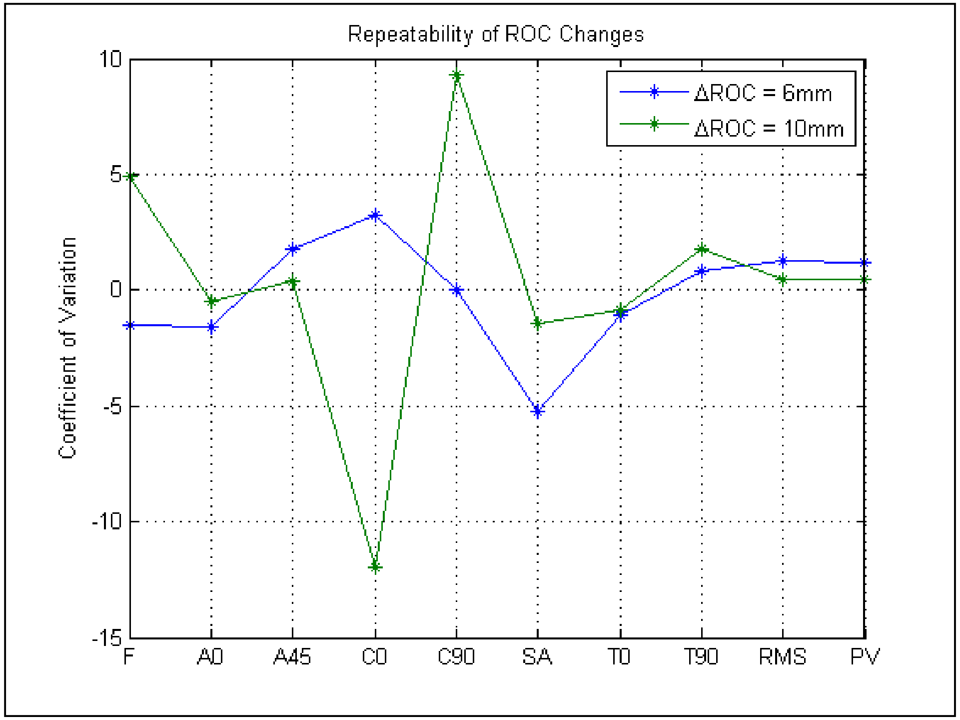


- PV increase due to astigmatism increase

ΔROC Repeatability

- Jump between states of ΔROC = 6mm and 10mm
- Track repeatability of low-order aberrations

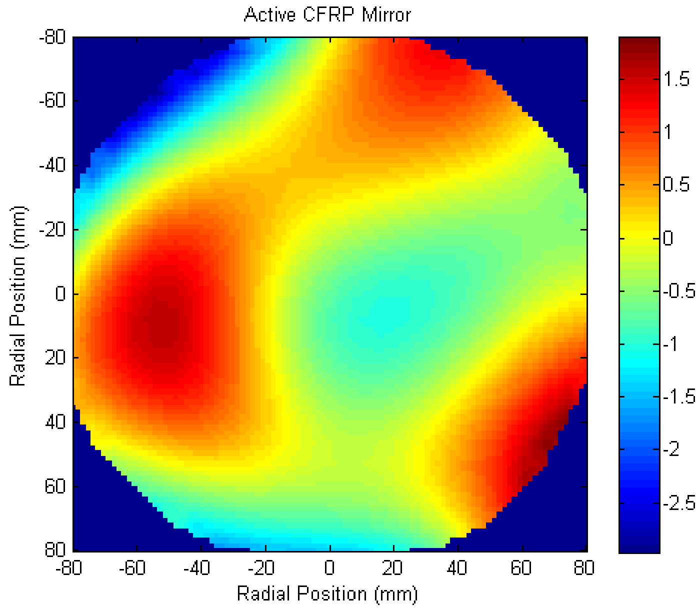
$$CV = \frac{\mu}{\sigma}$$



- Repeatability of ROC changes is quite high

System Improvements

- Apparatus improvements
  - Diamond turn plunger to further clean-up boundary condition
  - Increase outer actuators to 8 for astigmatism control
  - Push correction with CFRP mirror to other low-order aberrations
- CFRP mirror itself
  - WFE is far too high
  - Improved fabrication techniques
  - Tailor properties



4.87wv PV, 0.79wv RMS

Summary

- Novel AOZ optical design theory
  - Two-element Cassegrain objective
  - Tradespace analysis tested 260million designs
  - 3.3X, 375mm system
- Principle of active CFRP mirror demonstrated
  - ROC increased by 10mm (0.5%)
  - Focus controlled by mirror in closed-loop
  - Other low-order aberrations controlled by COTS DM
  - Aberrations measured by custom testbed
- AOZ system
  - ROC increase needs to be much larger
  - 5% very doable

Questions?

- http://spinsucks.com/social-media/social-media-questions/

HFOV Derivation

- Given equations from Wetherell & Rimmer

$$l_n = -\frac{m_n F_n (f_{1n} + D_p \eta)}{m_n F_n + \eta}$$

$$\theta_n' = \theta_n \frac{m_n F_n + \eta}{m_n (f_{1n} / D_p + \eta)}$$

- Trigonometry gives HFOV

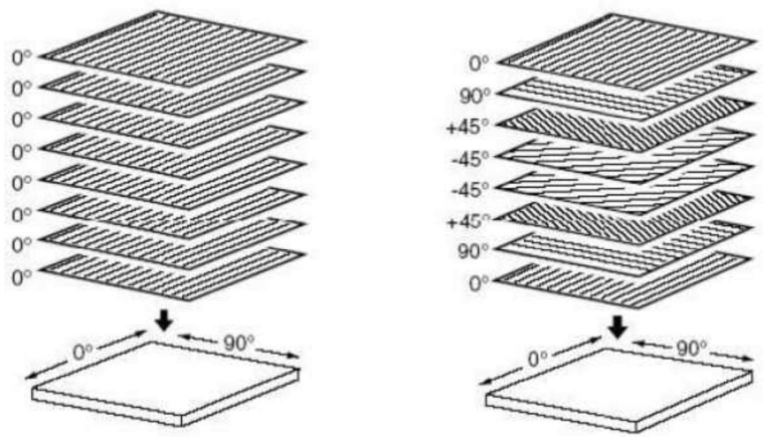
$$\tan \theta_n ' = \frac{D_i / 2}{l_n}$$

$$\boxed{\theta_n = \frac{m_n (f_{1n} / D_p + \eta)}{m_n F_n + \eta} \tan^{-1}\left(\frac{D_i}{2 l_n}\right)}$$

CFRP Mirror Fabrication

- Mirror fabricated via replication

- Varying fiber angles affects material properties



Modality Choice

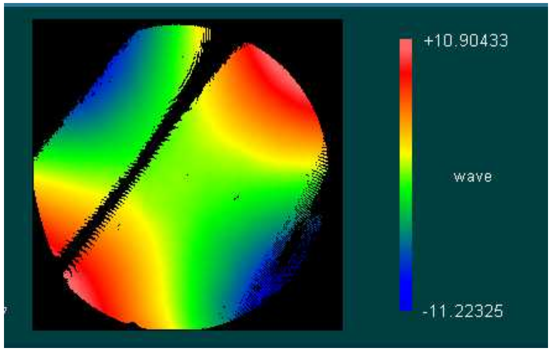
- Comparison of 5 different modalities

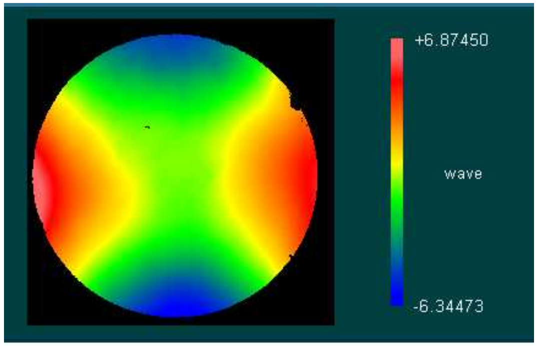
Modality	WFE (wv)	Total Force (N)	Ease of Control	Fine Control
Point-Load	493.2	462	High	Low
Radial Force	116.6	12891	High	Low
Radial/Ring	24.6	20577	Medium	Medium
Constant Pressure	166.1	1011	High	Medium
Annular Ring	22.0	358	Medium	High

- WFE is most important
- Total required force is second to reduce SWaP

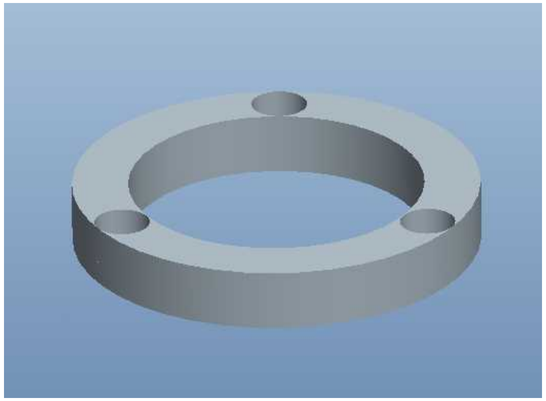
Inner Ring

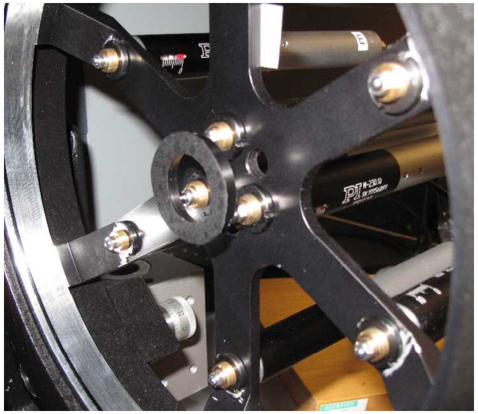
- Weight of rings increases astigmatism





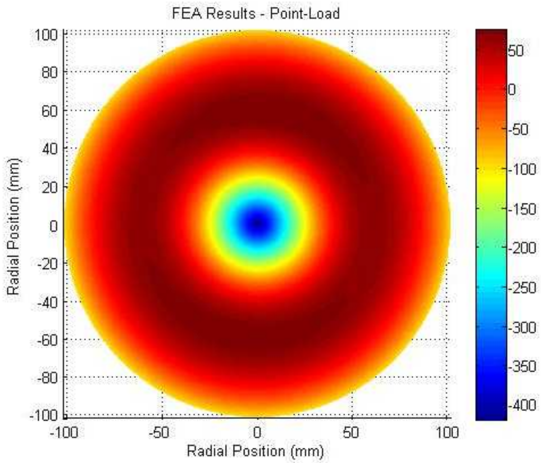
- Inner ring attached to actuators via magnets





Actuator Influence

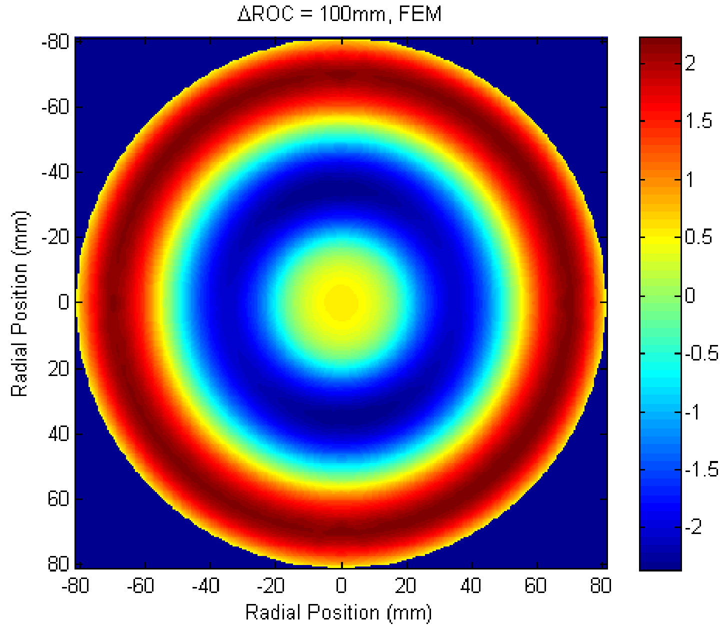
- FEM predicts large actuator influence function

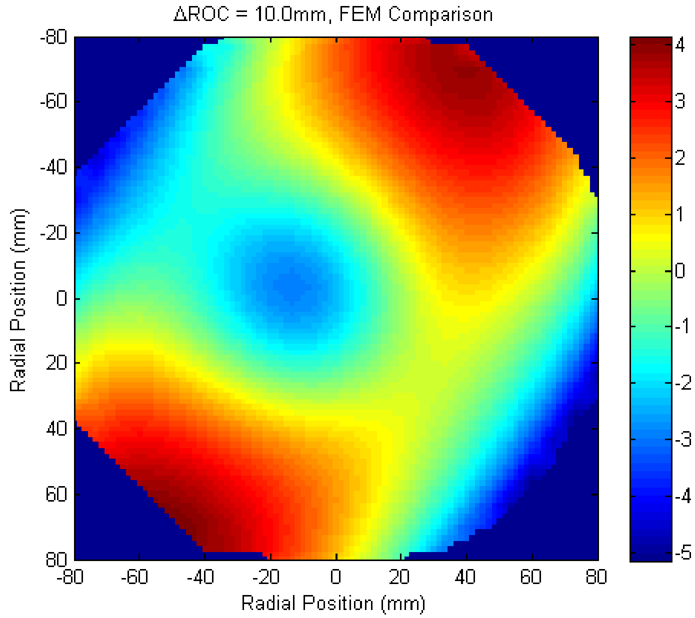


- Placed neoprene layer between ring/mirror

Comparison to FEM

- FEM assumes perfect spherical surface initially
- Initial WFE subtracted from final





- Low correlation between theory and experiment