Sensitivity analysis comparison of unobscured TMA: freeform vs. co-axial

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NASA Mirror Tech Days 2016 – Greenbelt, MD

Motivation for this comparison

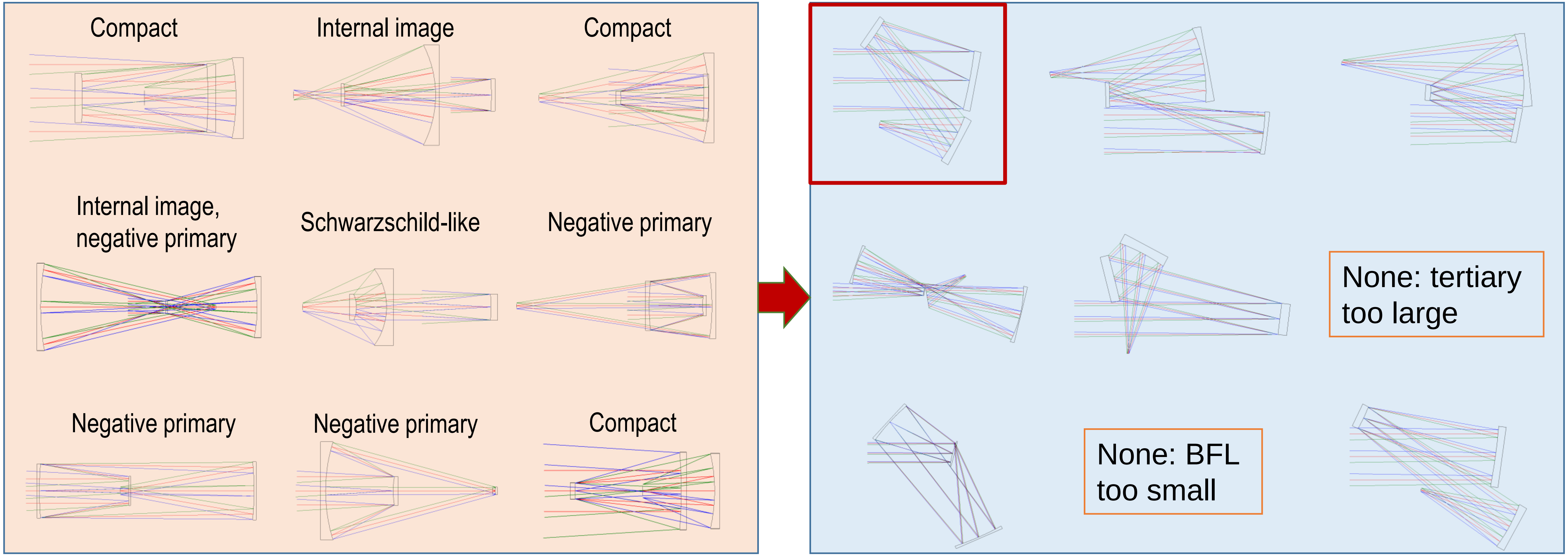
- Freeform allows for more freedom in geometry (volume, beam direction)
- Potential design tradeoff with alignment sensitivity
- What is the extent of this tradeoff?
    - We need a comparison with a traditional TMA
- Other direct TMA comparisons have been made
    - Thompson [EOSAM 2014, OptiFAB 2015] showed that a certain freeform geometry was at least not more sensitive than a slower TMA with faster mirrors
- We desire to compare sensitivity of a compact fully freeform geometry to an equivalent traditional co-axial TMA or a non-co-axial TMA but with off-axis aspheres
    - Same 1st order specifications
    - Similar volumes (to the extent possible)
    - Same FFOV
    - No intermediate image

Results from previous work

- *1-6° circular full FOV*
- *250 mm aperture*
- *F/3 (750 mm EFL)*
- *Broad spectral coverage (UV, Vis., NIR, FIR)*
- *Compact footprint*

Co-axial starting points
(co-axial single-conic equations)

Diffraction-limited
freeform designs



E. Schiesser *et al.* FiO 2016

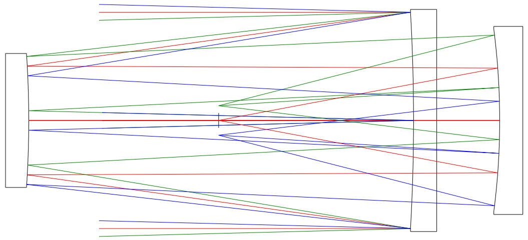
Compact freeform design

CENTER FOR FREEFORM OPTICS

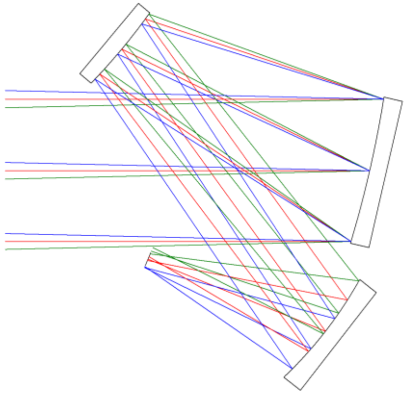
Design method:

- Starts from a 3rd order corrected co-axial TMA
- Mirrors are tilted to remove obscuration
- Freeform surface shapes and final geometry optimized to recover performance

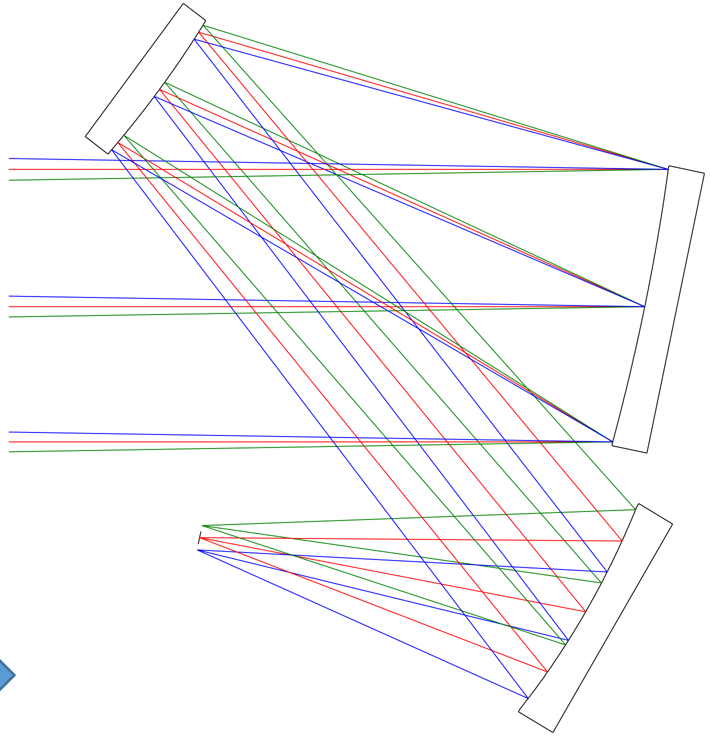
Co-axial TMA



Unobscured
(tilted surfaces)

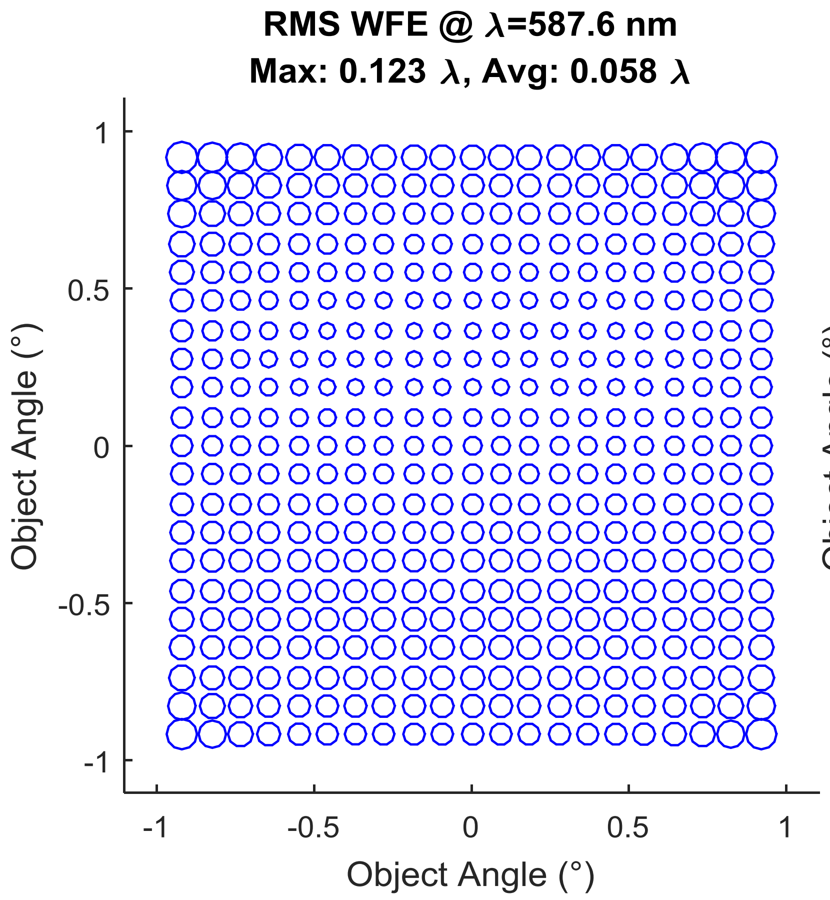


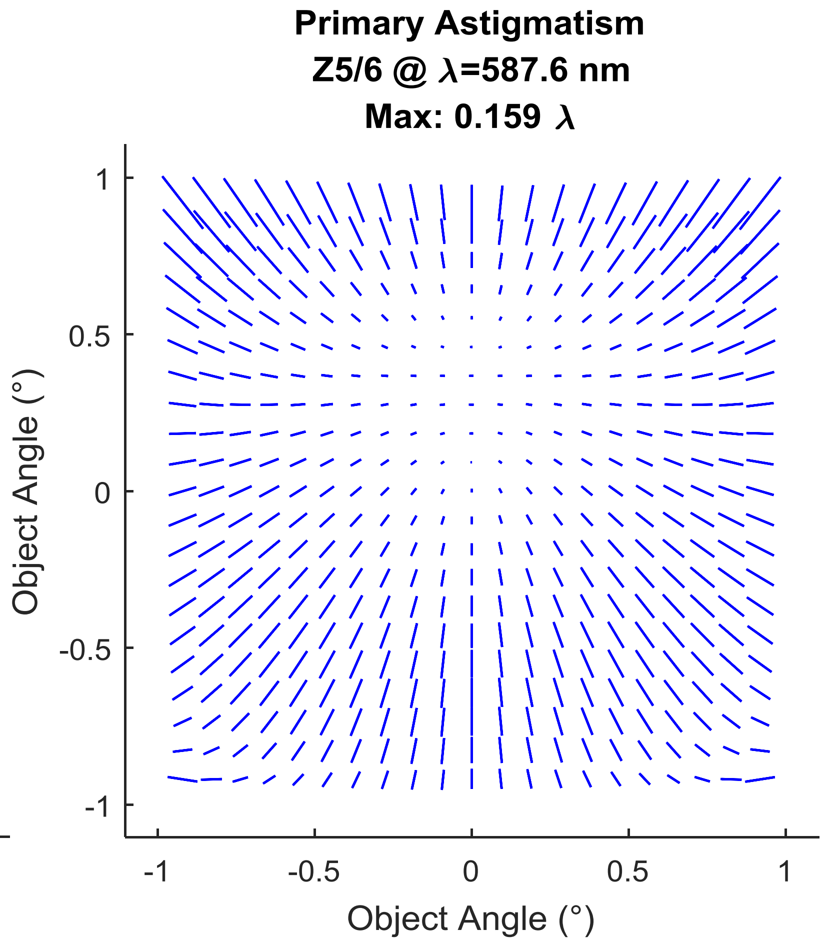
Freeform three-mirror imager

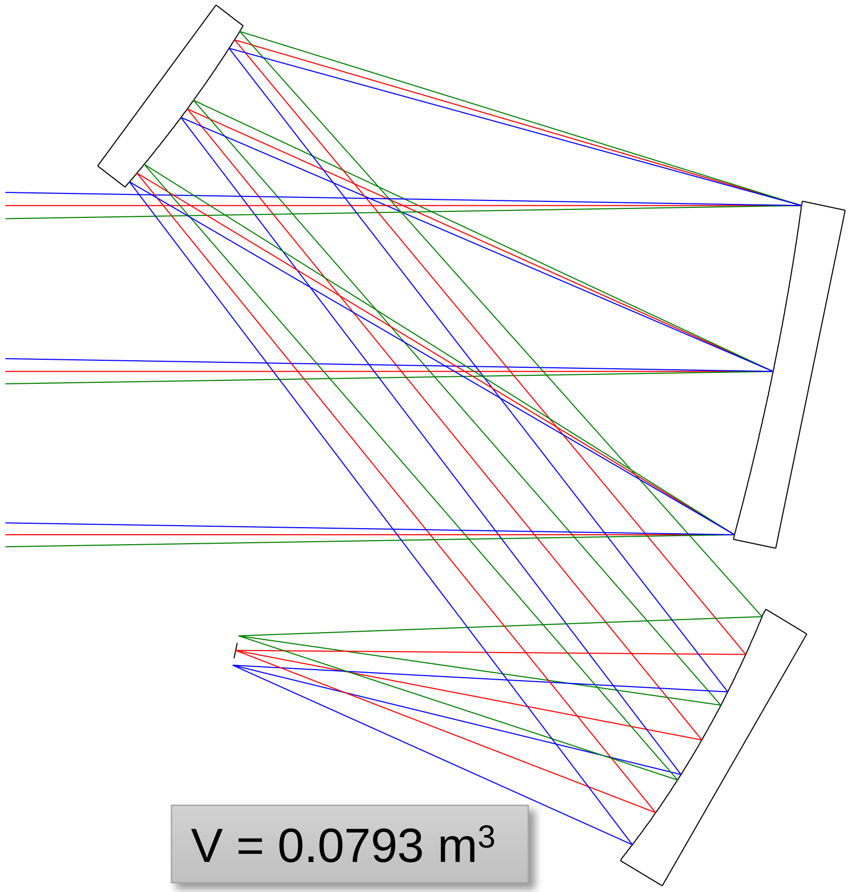


V = 0.0793 m^3
~ 79 L

Compact freeform design







Baseline TMA design

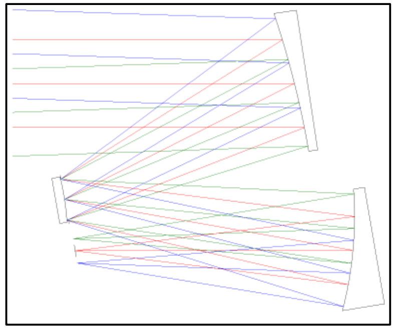
Design method:

- Starts from a "three-mirror compact" (TMC) A.K.A. "reflecting Cooke triplet" design [Egdall 1985]
    - CODE V "threemrc.seq" sample lens
- Scaled to relevant focal length (aperture reduced to match F/#)

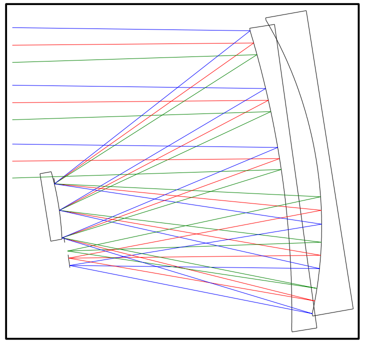
Design Optimized to

- Ensure diffraction limited performance
- Match FFOV of freeform design
- Match volume (to extent possible) of freeform for diffraction limited performance

threemrc.seq

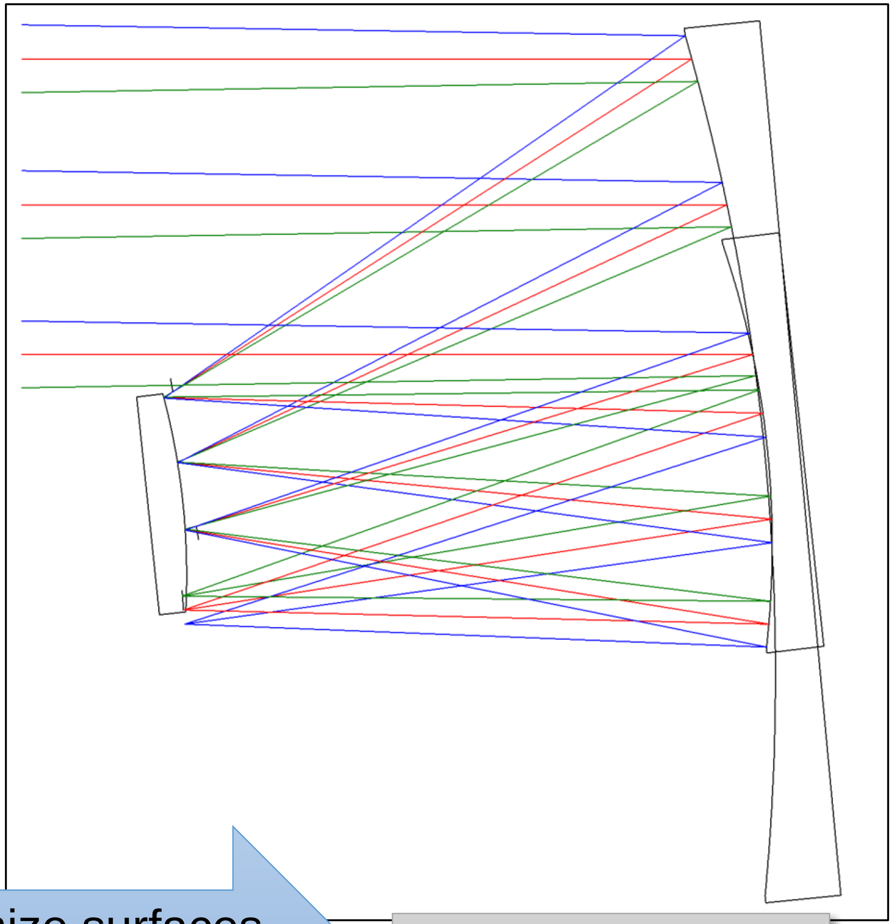


Scaled, match FFOV



V = 0.117 m^3

Baseline TMA optimized for compactness

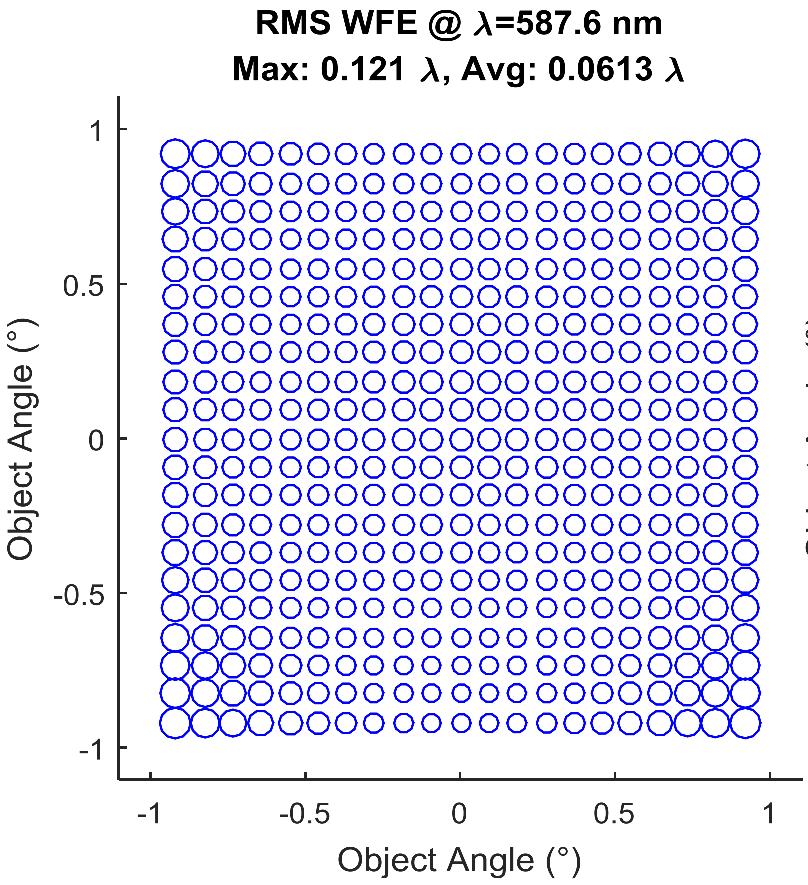


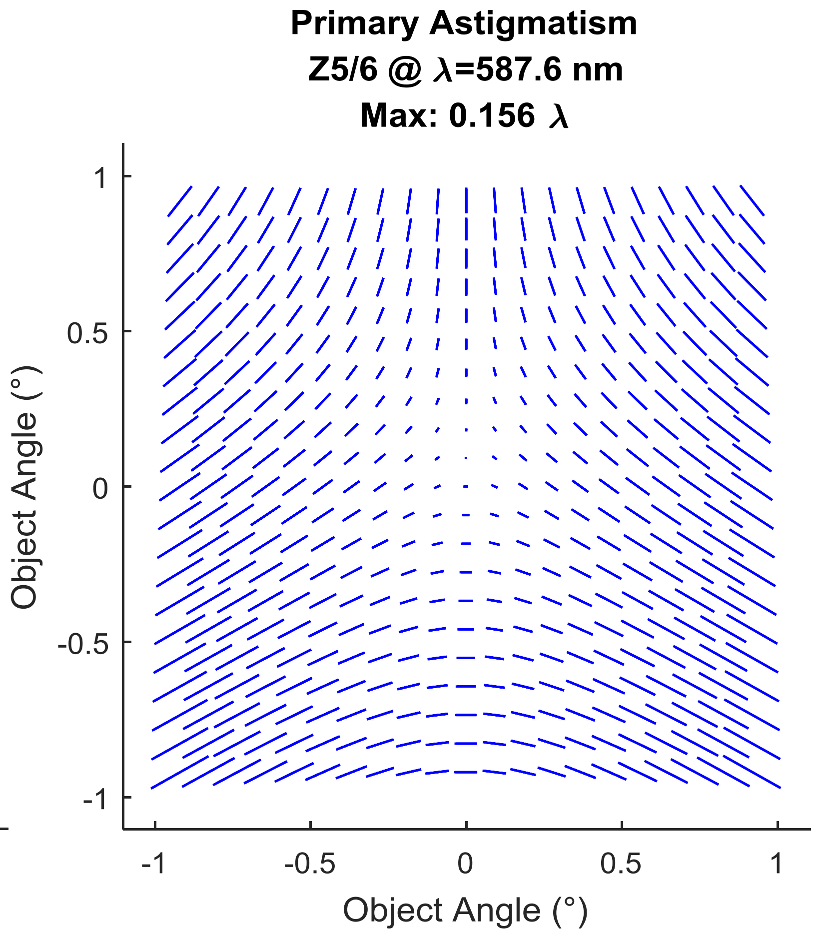
Optimize surfaces, decrease volume

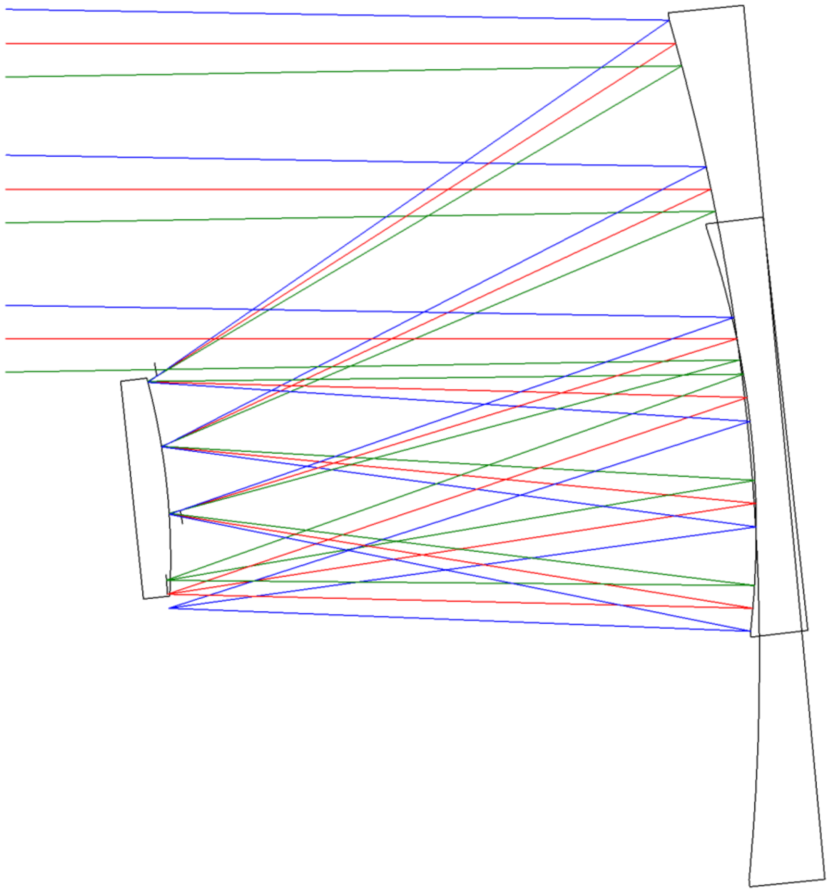
V = 0.097 m^3
97L (22% larger)

Egdall, Ira M. "Manufacture of a three-mirror wide-field optical system." *Optical Engineering* 24.2 (1985): 242285.

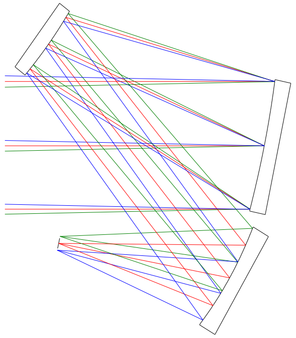
Compact TMA design

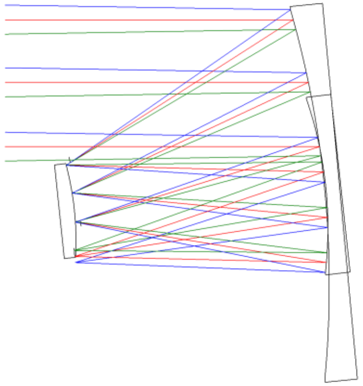






System comparison





	Compact Freeform	TMC
EPD (mm)	250	250
F/#	F/3	F/3
FFOV (degrees)	2.6°	2.6°
Volume (m^3)	0.0793	0.0965 (**22% larger**)
Max Mirror Diameter (mm)	256	300 (**18% larger**)
Surface shapes	Fringe Zernike Polynomials, centered on central field	12^{th} order Qcon aspheres
Field Bias	N/A	5.5°
Aperture Offset (mm)	N/A	222

Opto-mechanical design: current iteration

CeFO
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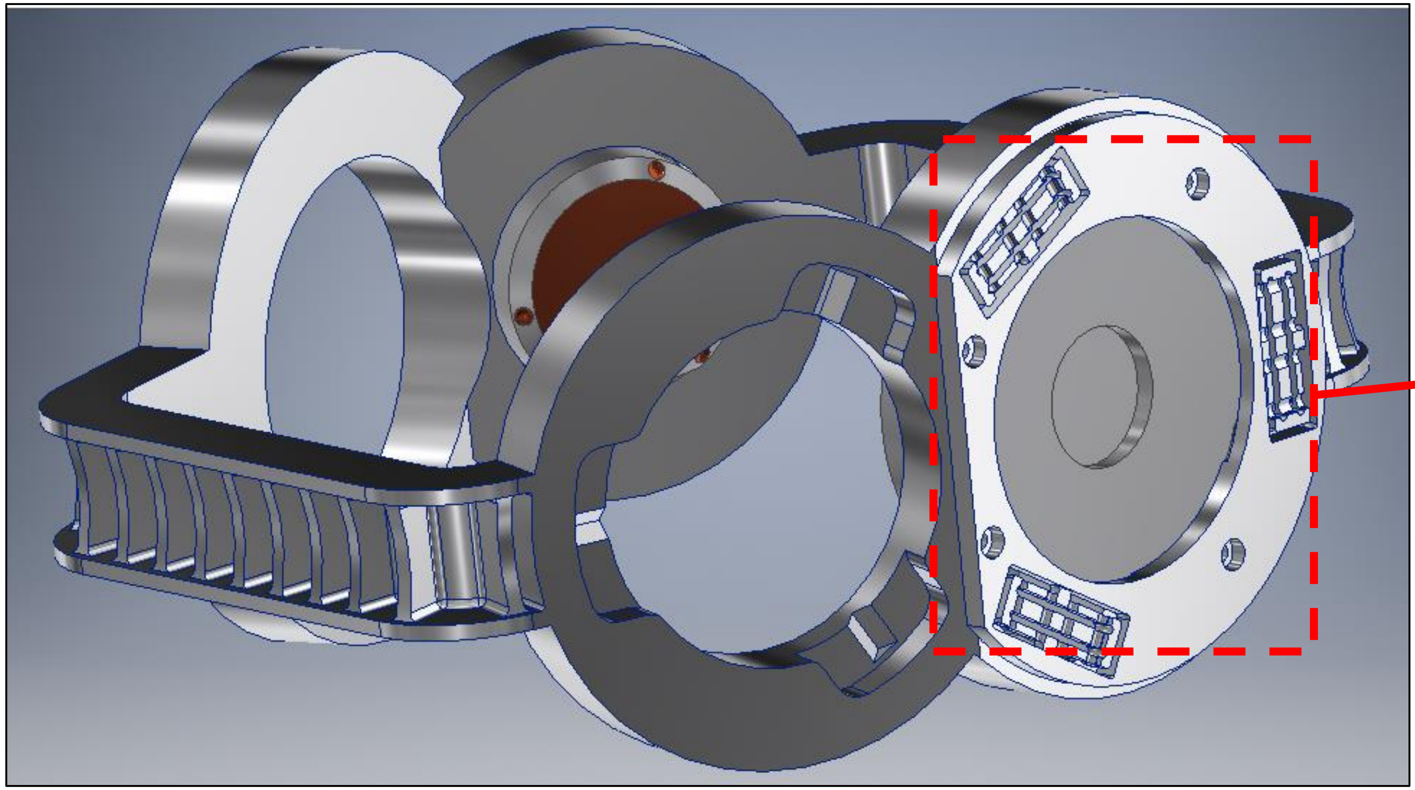
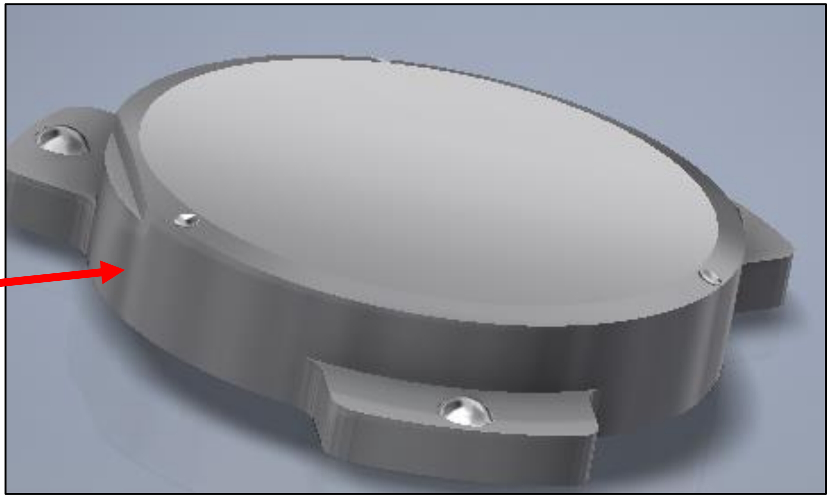




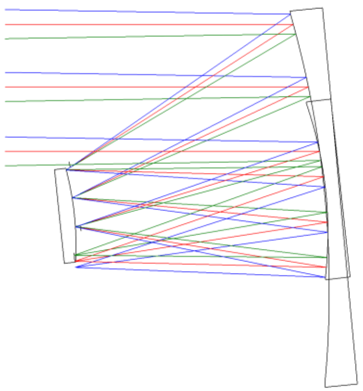
- Optics utilize kinematic mounts (3 Vee – 3 Sphere)
- Fiducials machined along chamfer just outside clear aperture
- All features machined during optic surface fabrication setup

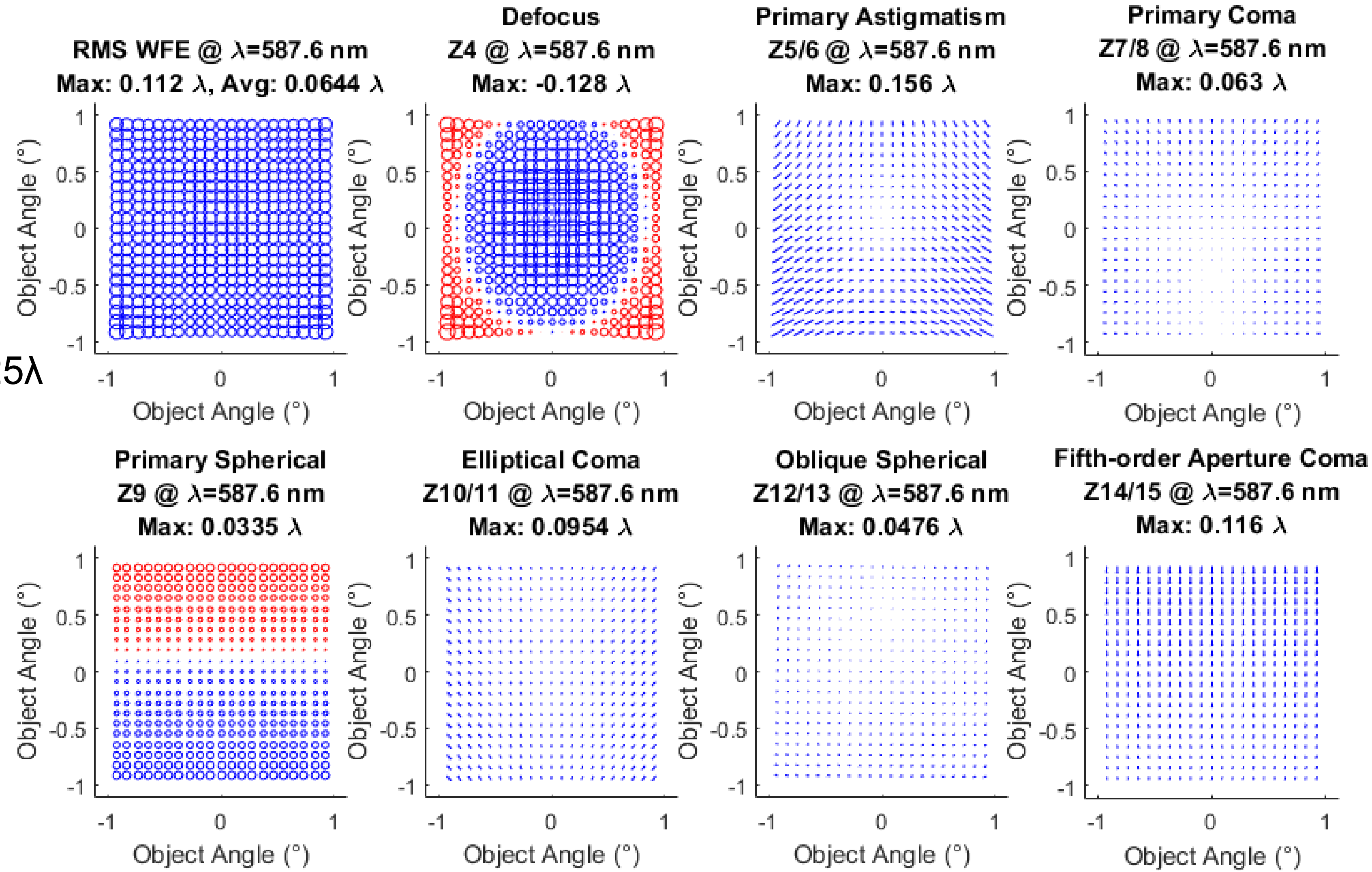
- Monolithic frame with optics mounted from outside
- Rectilinear flexures provide load on kinematic coupling
- 2 piece cap style enclosure (not pictured)

Courtesy of Matt Davies' team at UNC Charlotte

TMC Sensitivity Analysis

TMC nominal performance

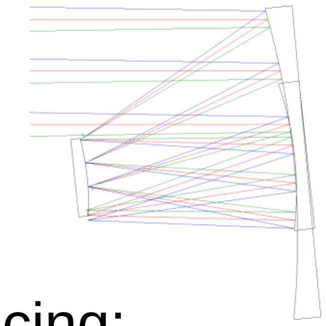




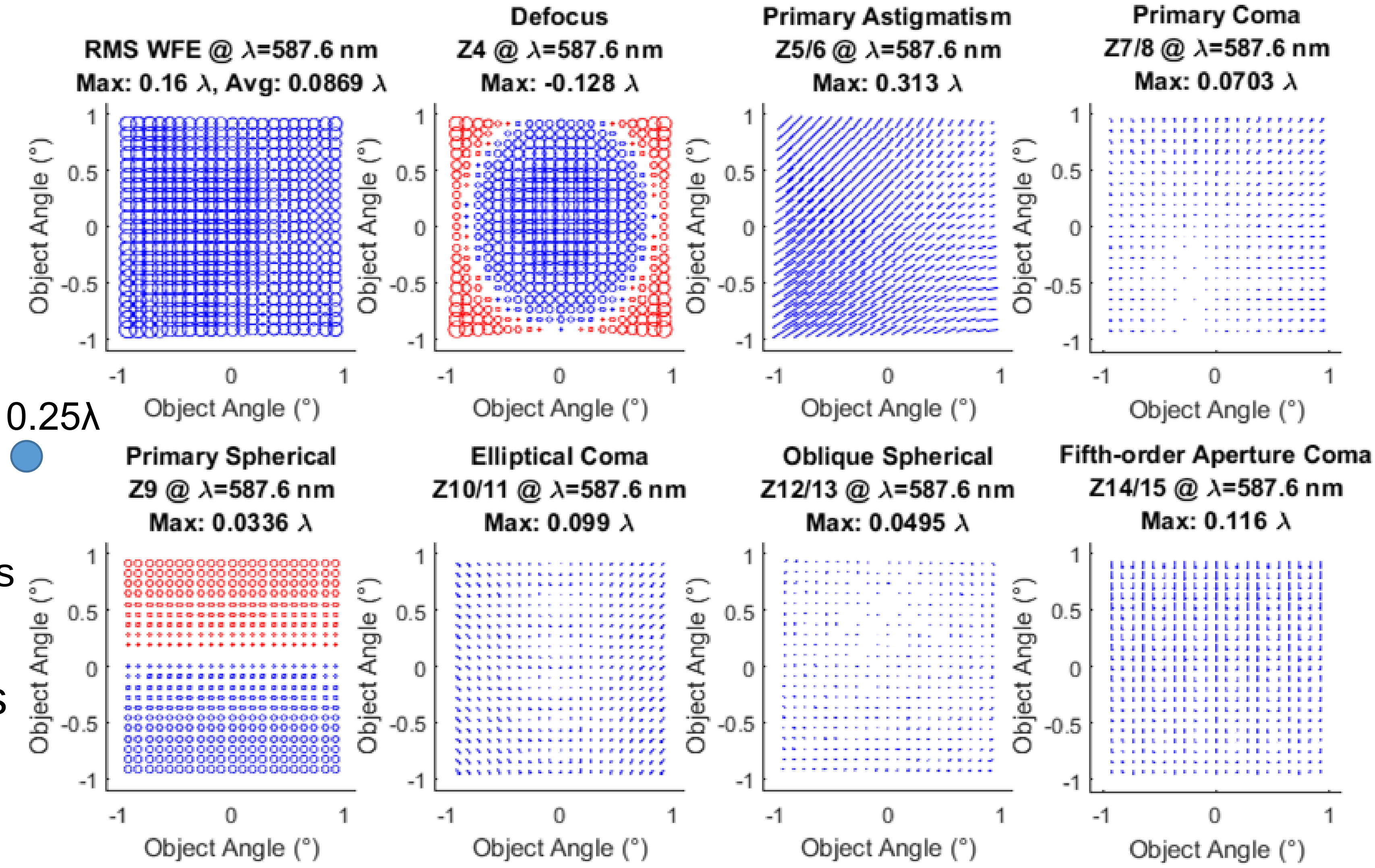
- Limited by field-conjugate astigmatism and field curvature

TMC with tip/tilt and X-Y decenter, refocus

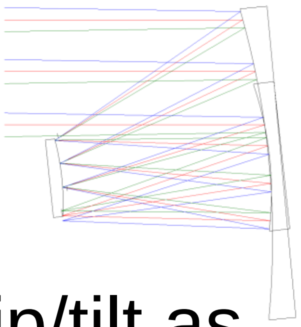
CeFO
CENTER FOR FREEFORM OPTICS



- Tip/tilts: 87 µrad
- Decenter/Despacing: 18 µm
- All mirrors perturbed to extreme values of tolerances
  - Image plane allowed to refocus
- Result: mostly field-constant astigmatism, coma node shifts
- Average RMS WFE over full field is not diff. lim.

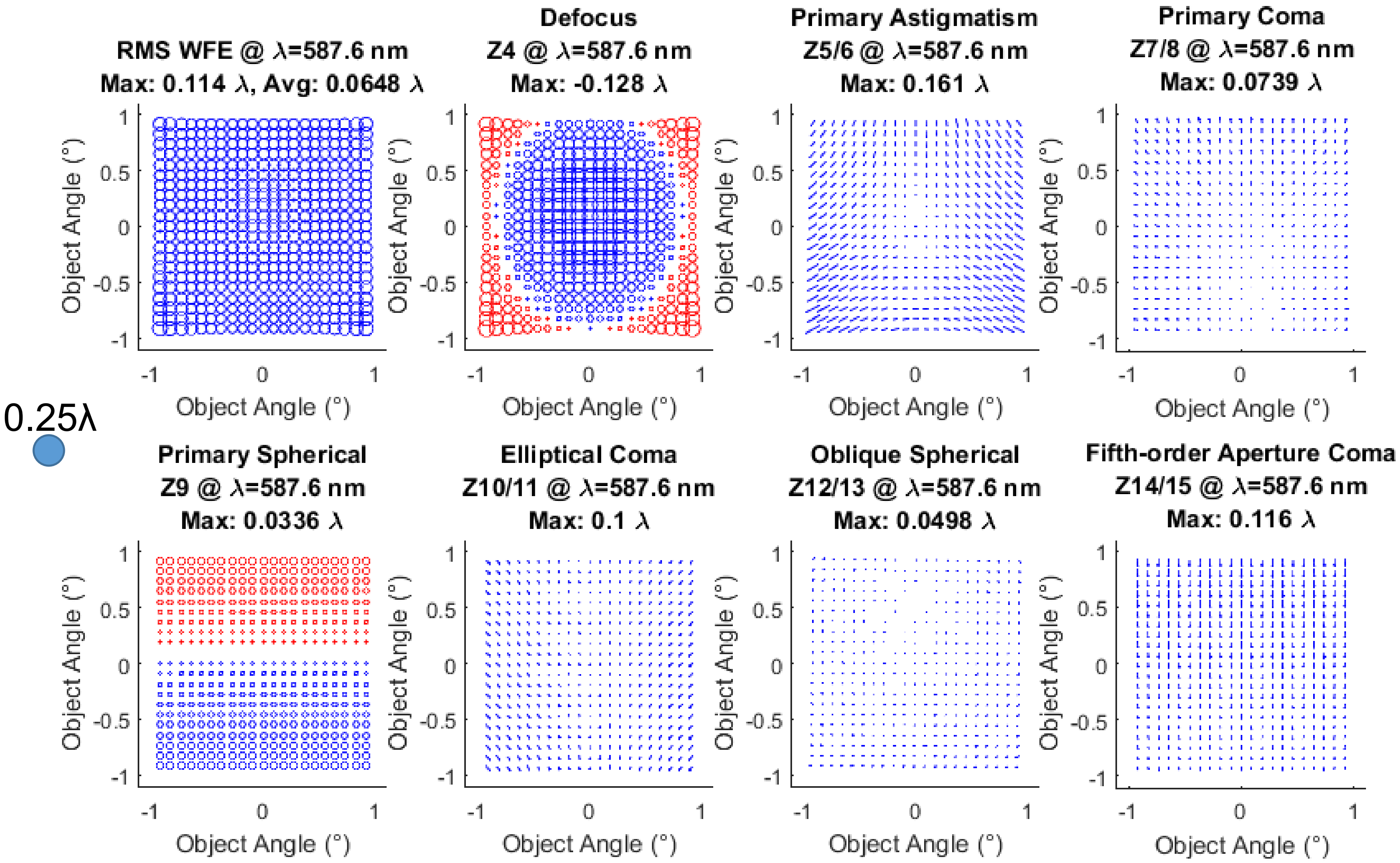


TMC after refocus and M3 tip/tilt compensators



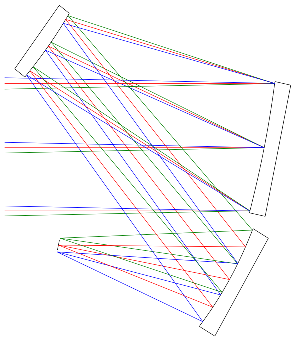
- Added M3 tip/tilt as compensator
- Average RMS WFE recovers to within 0.0004 of nominal
- Coma node remains shifted

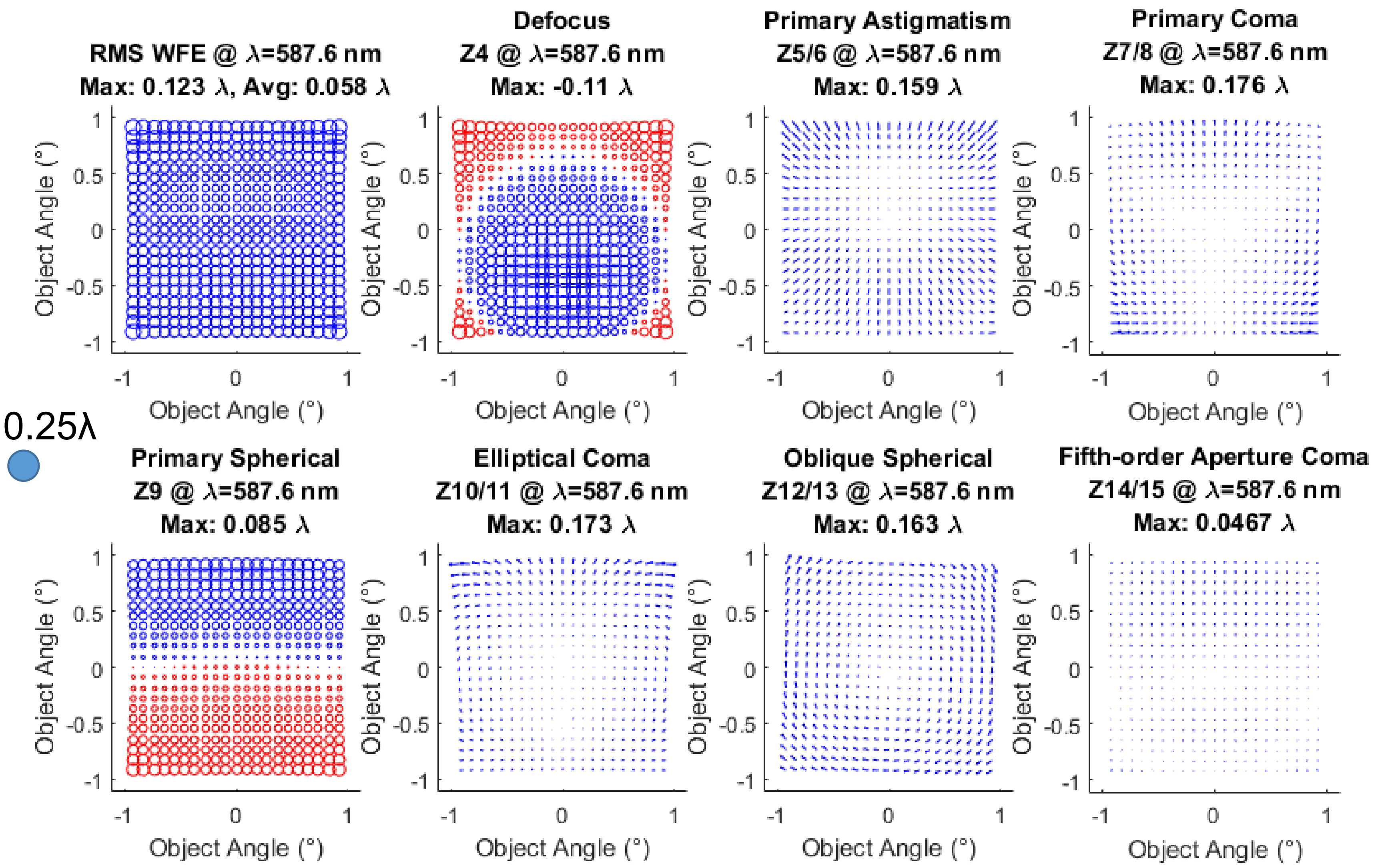
M3 compensation:
X-Axis: 0.0058°
Y-Axis: 0.0088°



Freeform Sensitivity Analysis

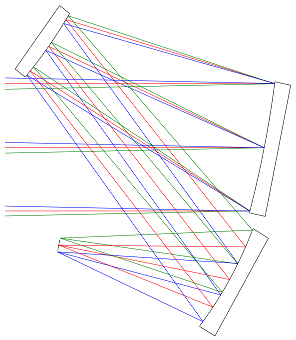
Freeform nominal full-field performance



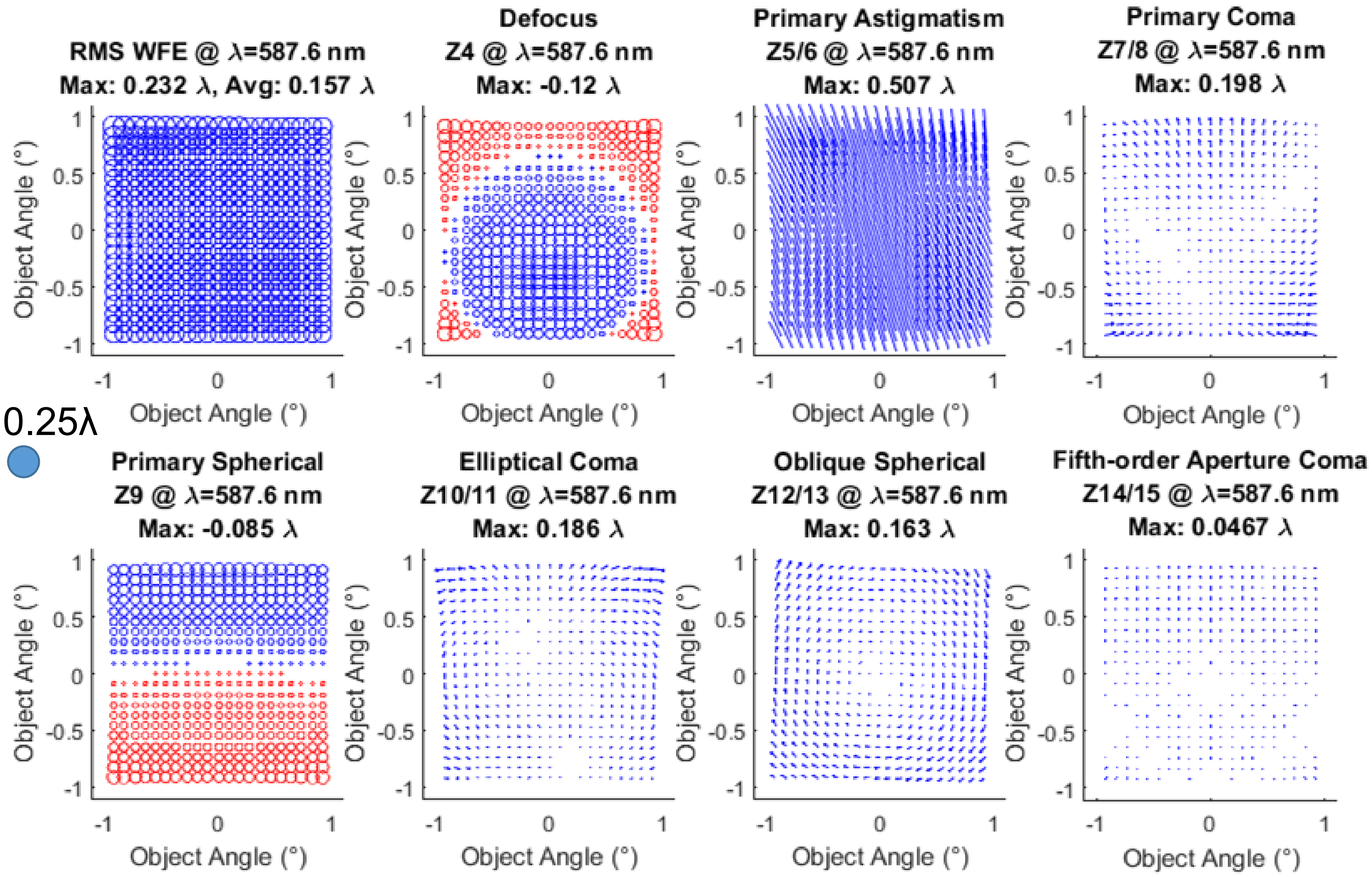


- Limited primarily by higher-order astigmatism (in field)
  - Uncommon field dependence

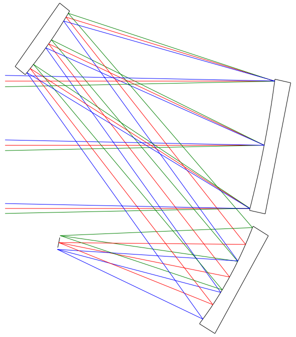
Freeform with tip/tilt and X-Y decenter, refocus



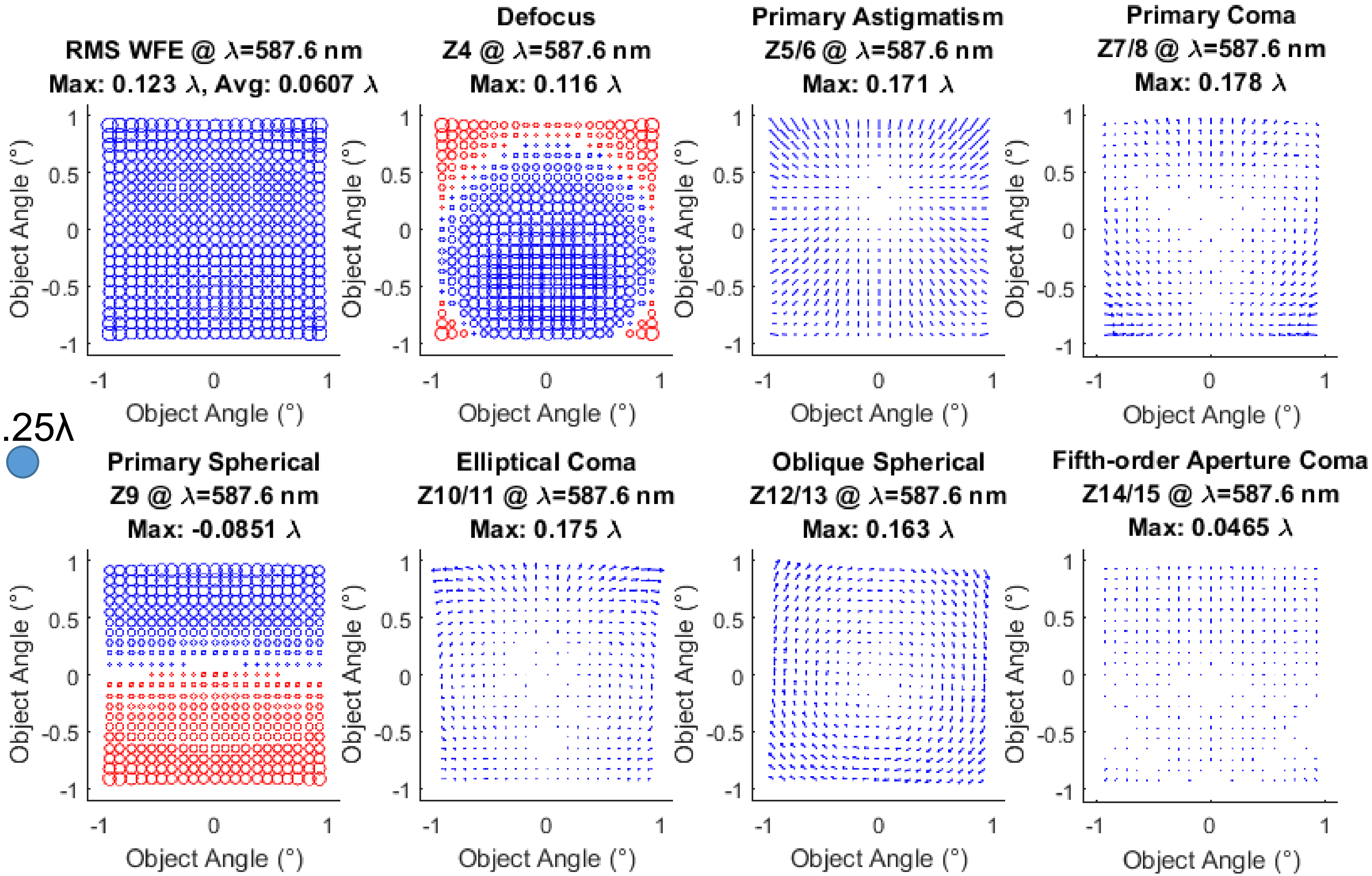
- Tip/tilts: 87 µrad
- Decenter/Despacing: 18 µm
- All mirrors perturbed to extreme values of tolerances
    - Image plane allowed to refocus
- Result: field-constant astigmatism
- Average RMS WFE over full field is not diff. lim.



Freeform after refocus and M3 tip/tilt compensators



- Added M3 tip/tilt as compensator
- Average RMS WFE recovers to within 0.002 λ of nominal
- Coma node returns to center

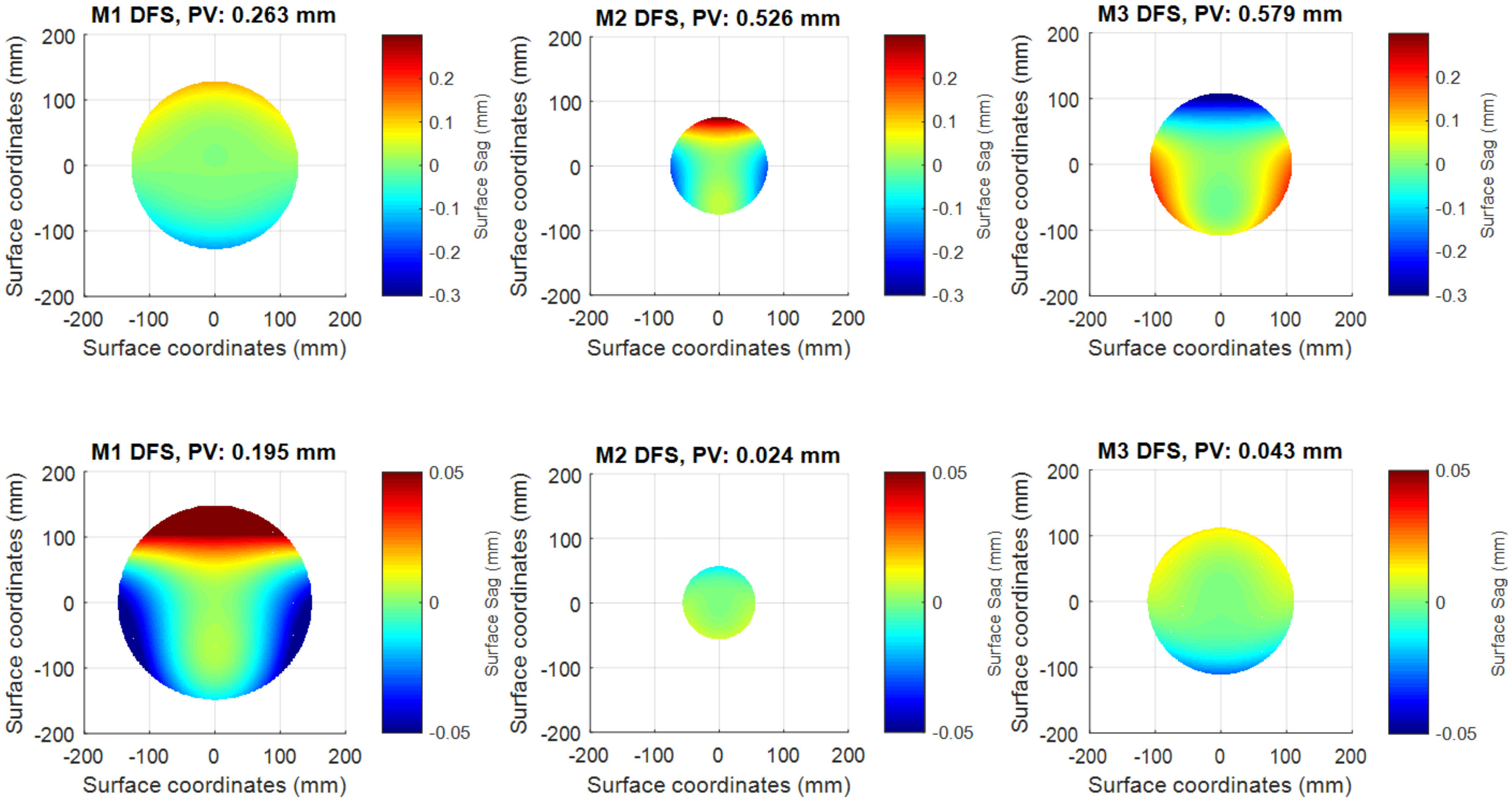


M3 compensation:
X-Axis: 0.00016°
Y-Axis: 0.0011°

Surface departure-from-sphere

Freeform
Color range: [-0.3, 0.3] mm

TMC
Color range: [-0.05, 0.05] mm



Summary

- In this early comparison:
    - Freeform is more compact by 22%
    - Both designs (compact freeform and TMC) require a compensator
    - Both designs can recover performance
    - Freeform exhibits primarily field-constant astigmatism with perturbation, which can be easily compensated
    - TMC also exhibits (less) field-constant astigmatism, requires more compensator movement to correct (design tradeoff?)

- Study is on-going
    - This first-iteration compact freeform may benefit from methods developed by Bauer (2015) which may reduce DFS and slope (reducing sensitivity to alignment)

A. Bauer, J. P. Rolland. *Optics express* 23.22 (2015)

Acknowledgements

NSF I/UCRC Center for Freeform Optics (CeFO)
www.CenterFreeformOptics.org

Thanks to Synopsys for the student license of CODE V ®

Backup slides

Compact freeform design