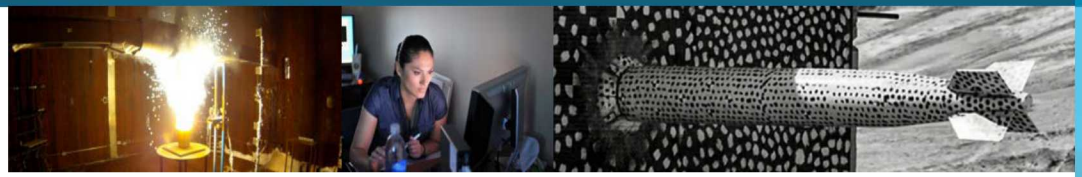
SAND2019-6126C

Sandia National Laboratories

Freeform Optical Surfaces for Field Biased and Decentered Aperture Reflective Optical Design



PRESENTED BY

Kyle Fuerschbach

Sandia National Laboratories

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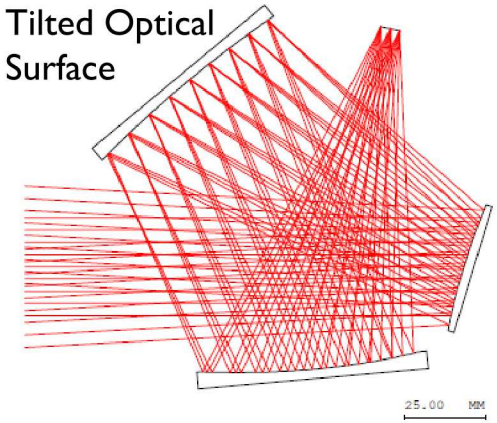
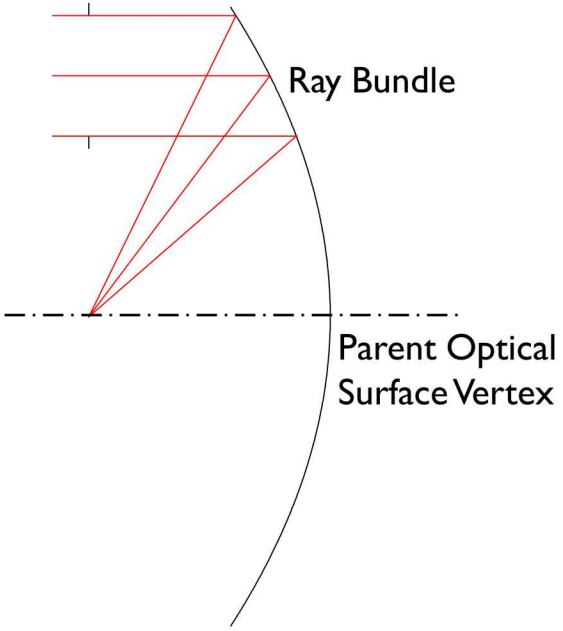
Introduction

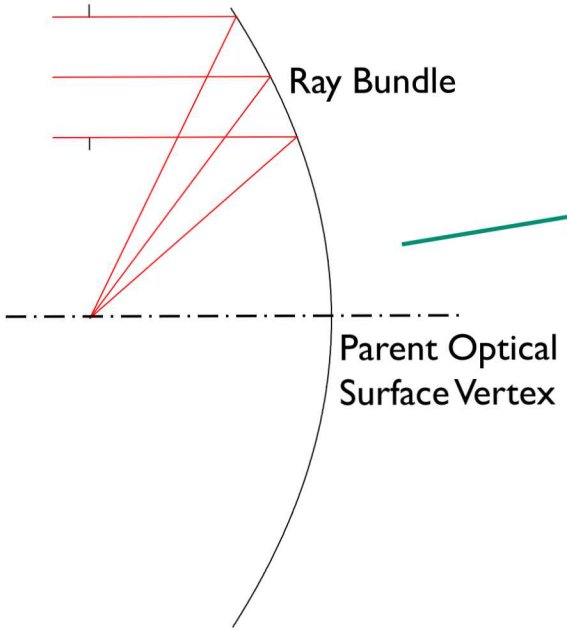
- Freeform optical surfaces yield additional degrees of freedom in off-axis reflective design
  - Two ways to yield an off-axis reflective design
    - Titled optical components
    - Field bias and/or decentered aperture
- For optical surfaces that are tilted
  - The vertex of the freeform overlay is coincident the vertex of the base conic
  - The ray bundle is nominally about this vertex
- For optical surfaces with a decentered aperture
  - There may be a large distance between the freeform overlay and the rays that interact with this overlay if the freeform overlay is added to the base conic at its vertex
  - This distance creates inefficiency in the freeform overlay and requires large freeform deformations to yield any appreciable impact



K. Fuerschbach et al., Opt. Express **19**, (2011)



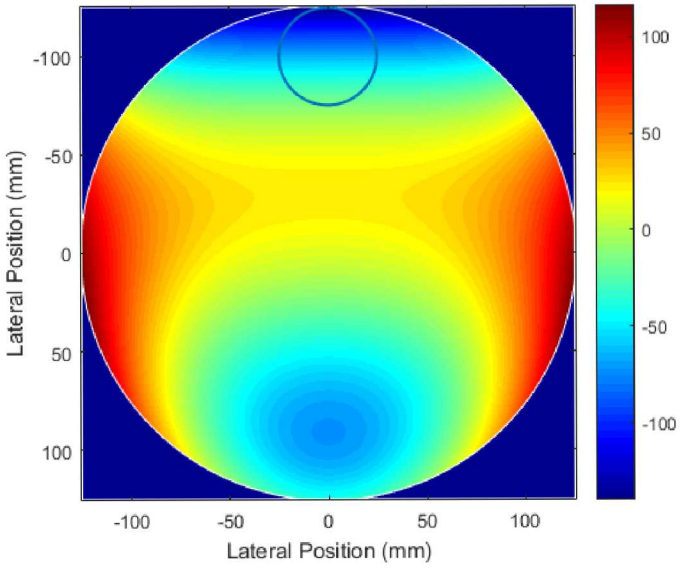
Freeform Overlays with Decentered Apertures



$$z = \underbrace{\frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}}}_{\text{Base Conic}} + \underbrace{\sum_{j=1}^{37} C_j Z_j\left(\frac{r}{R_{norm}}, \theta\right)}_{\text{Fringe Zernike Overlay}}$$

Fringe Zernike	Value (μm)
Z1	0
Z2	0
Z3	0
Z4	0
Z5	100
Z6	0
Z7	0
Z8	50
Z9	10

Fringe Zernike Overlay minus Base Conic μm



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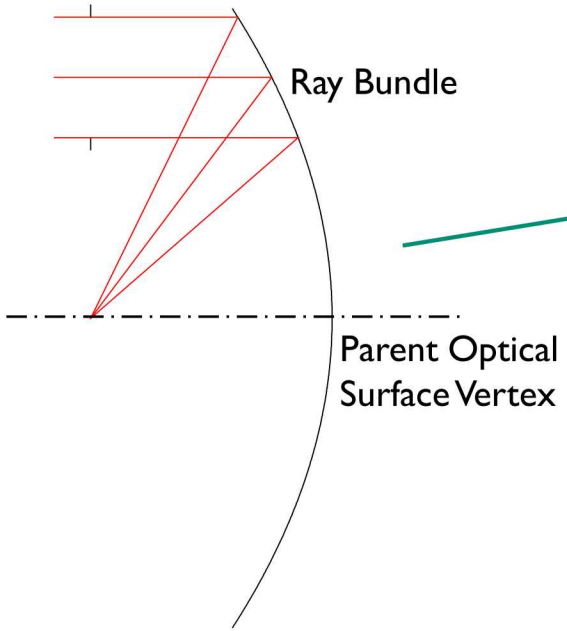

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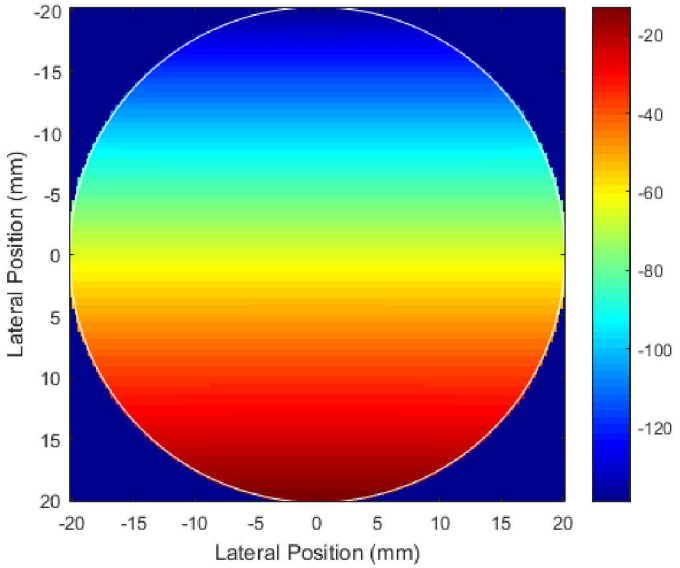
Fringe Zernike	Value (μm)
Z1	-67.69
Z2	0
Z3	63.14
Z4	-2.80
Z5	5.56
Z6	0
Z7	0
Z8	-0.11
Z9	0.02

Fringe Zernike Overlay
minus Base Conic
In Region of Ray Bundle μm



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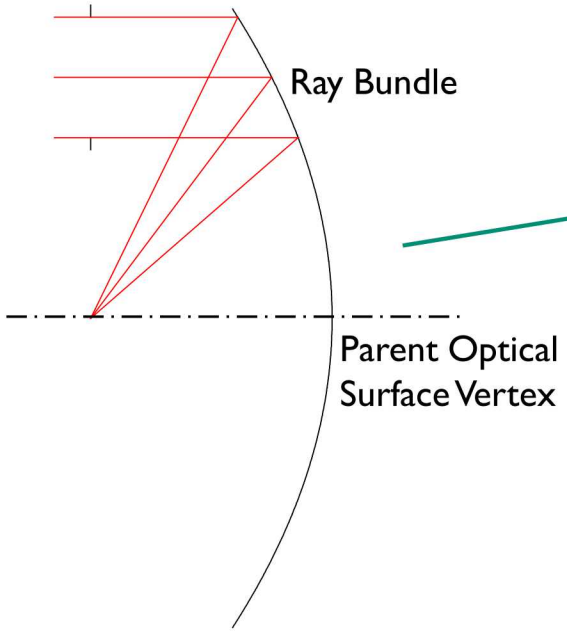

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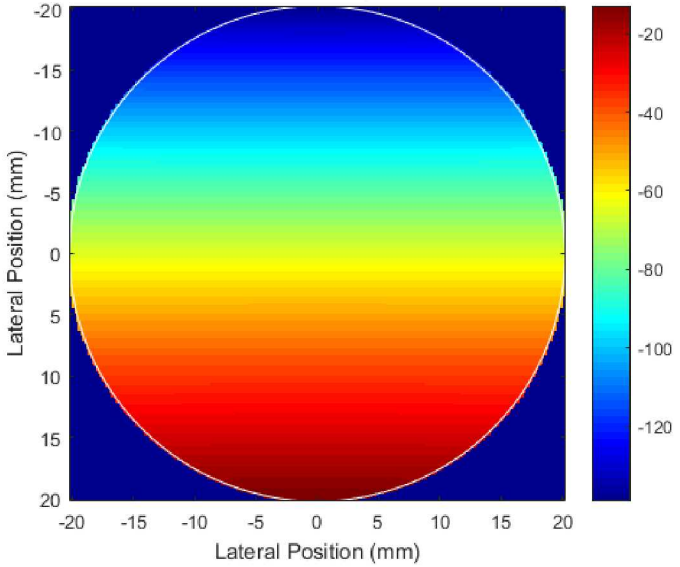
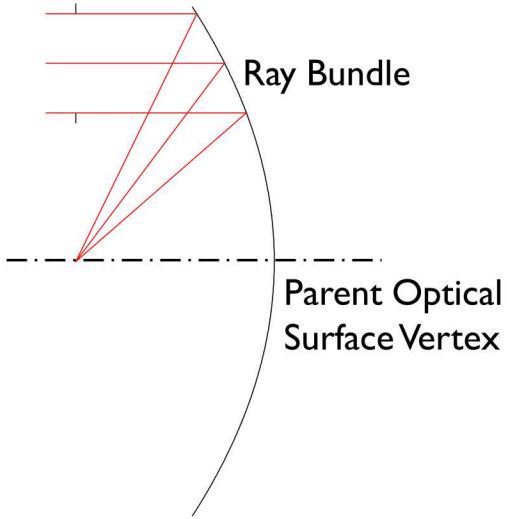


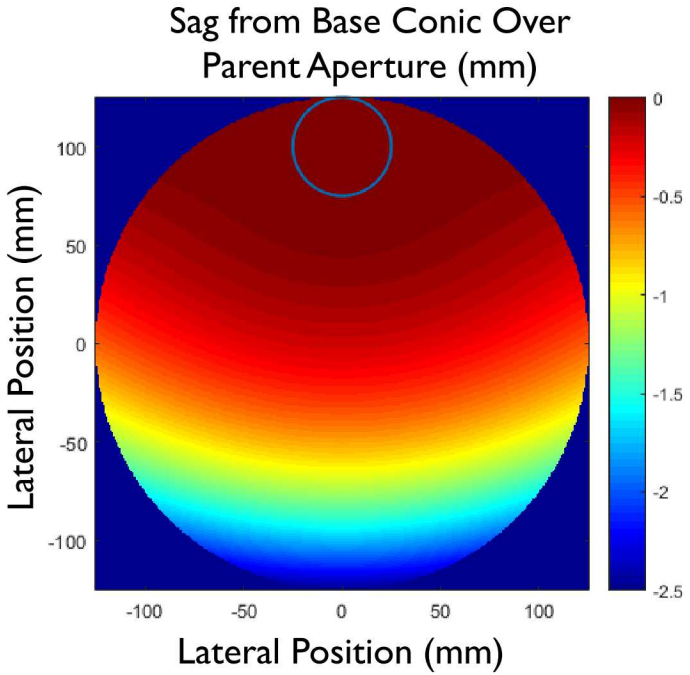
New Surface Description

- Propose surface description where the Fringe Zernike Overlay is offset from the parent vertex

$$z = \underbrace{\frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}}}_{\text{Base Conic}} + \underbrace{\sum_{j=1}^{37} C_j Z_j\left(\frac{r-r_0}{R_{norm}}, \theta-\theta_0\right)}_{\text{Offset Fringe Zernike Overlay}}$$

Parameter	Value
ROC (mm)	-200
k	-1
r_{off} (mm)	100
θ_{off} (deg)	90
Z8 (mm)	0.002





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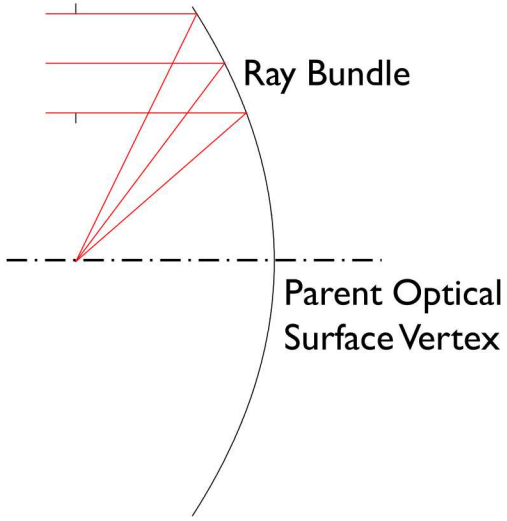
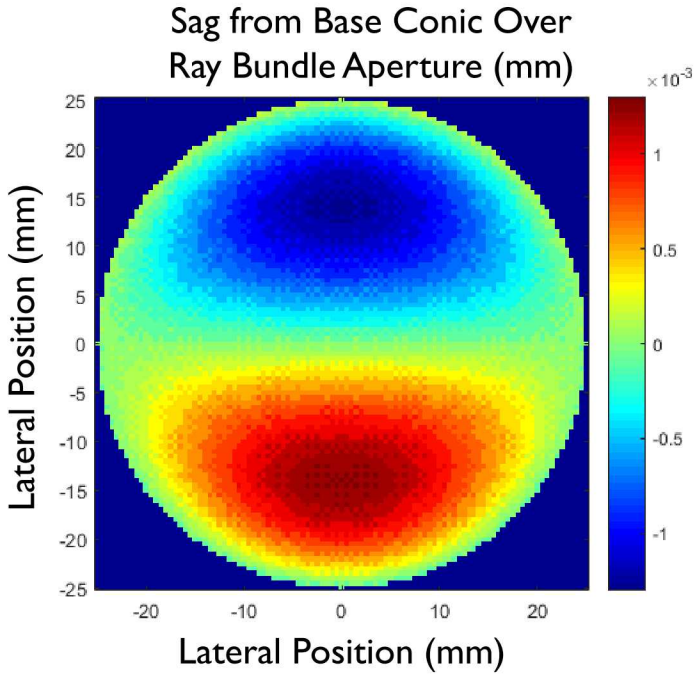
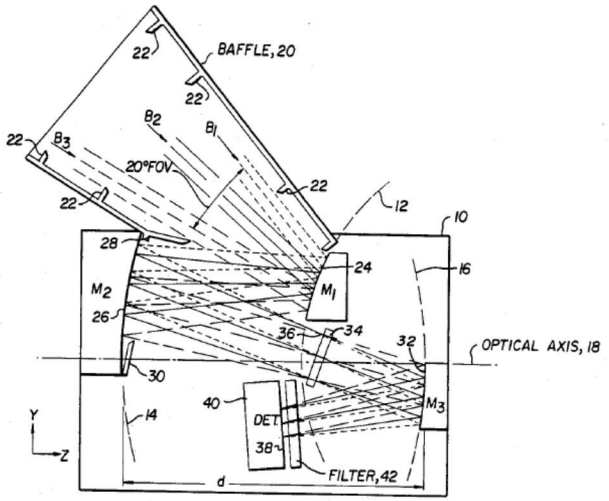




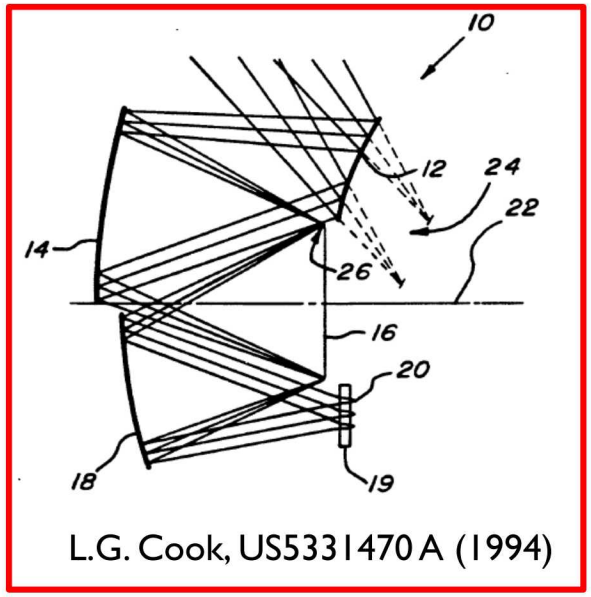
Design Example

Specification	Value
Entrance Pupil Diameter (mm)	25
Focal Ratio	2
Full Field of View (deg.)	30
Waveband	IR
Image Quality	Diffraction Limited at 10 μm

WALRUS Starting Point Designs: 20 x 20 degree FFOV at ~F/1



K.L. Hallam et al., US4598981 A (1986)

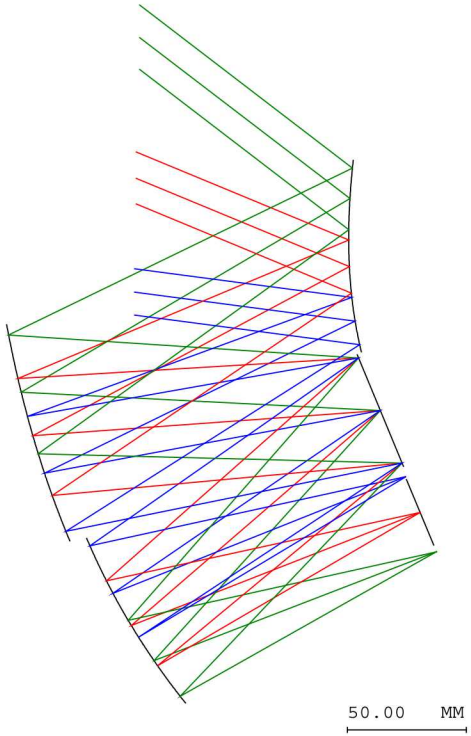


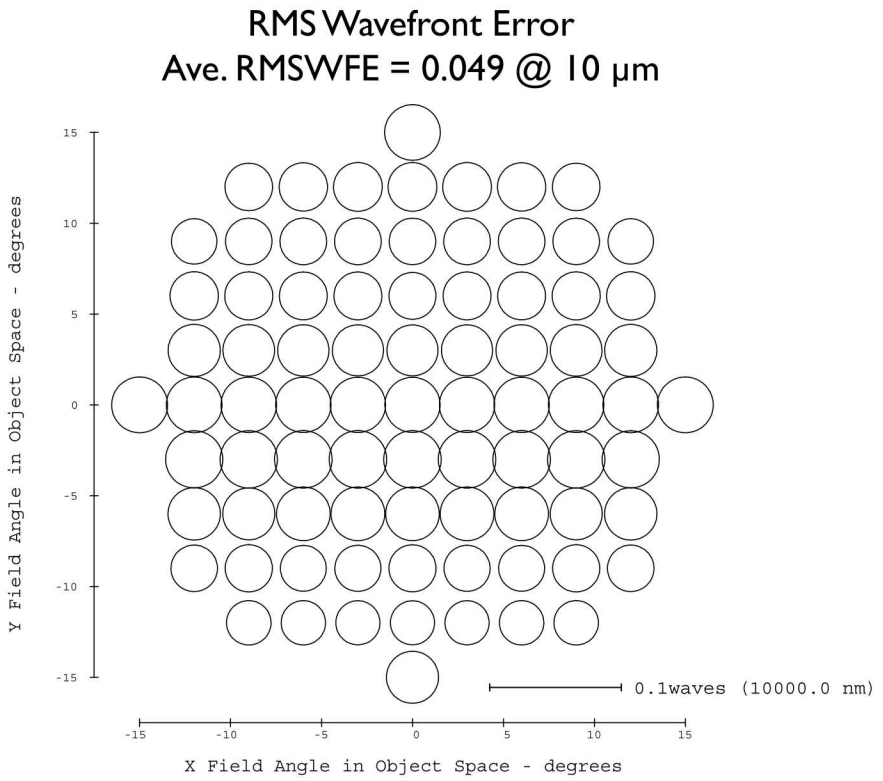
L.G. Cook, US5331470 A (1994)

Selected for Compact Geometry

Conic Only Solution

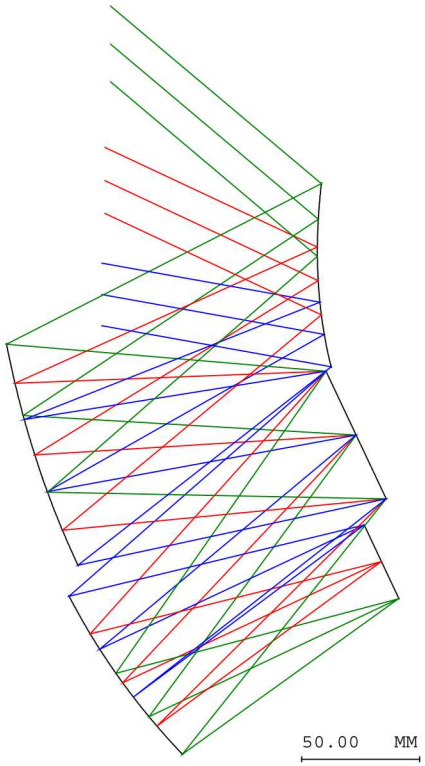
- Using Cook form as starting point
  - Design is optimized where each mirror surface is only allowed to be an off-axis conic
  - Fold Mirror at stop surface is kept flat
  - The FOV is fixed at 30° while the entrance pupil diameter is slowly increased towards the target of 25 mm - **Achieved only 20 mm**

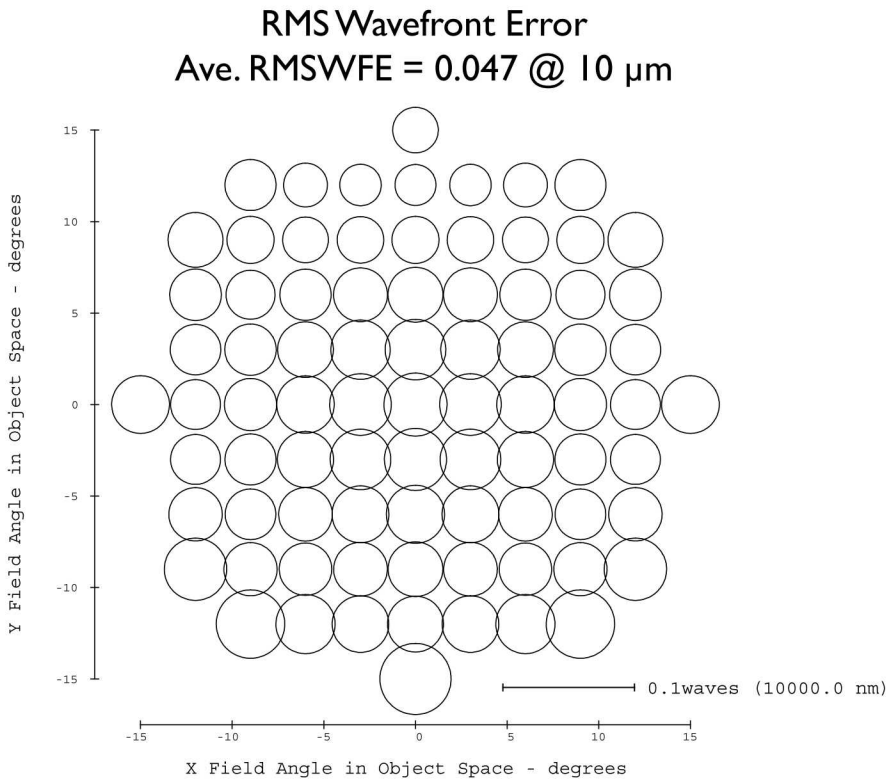




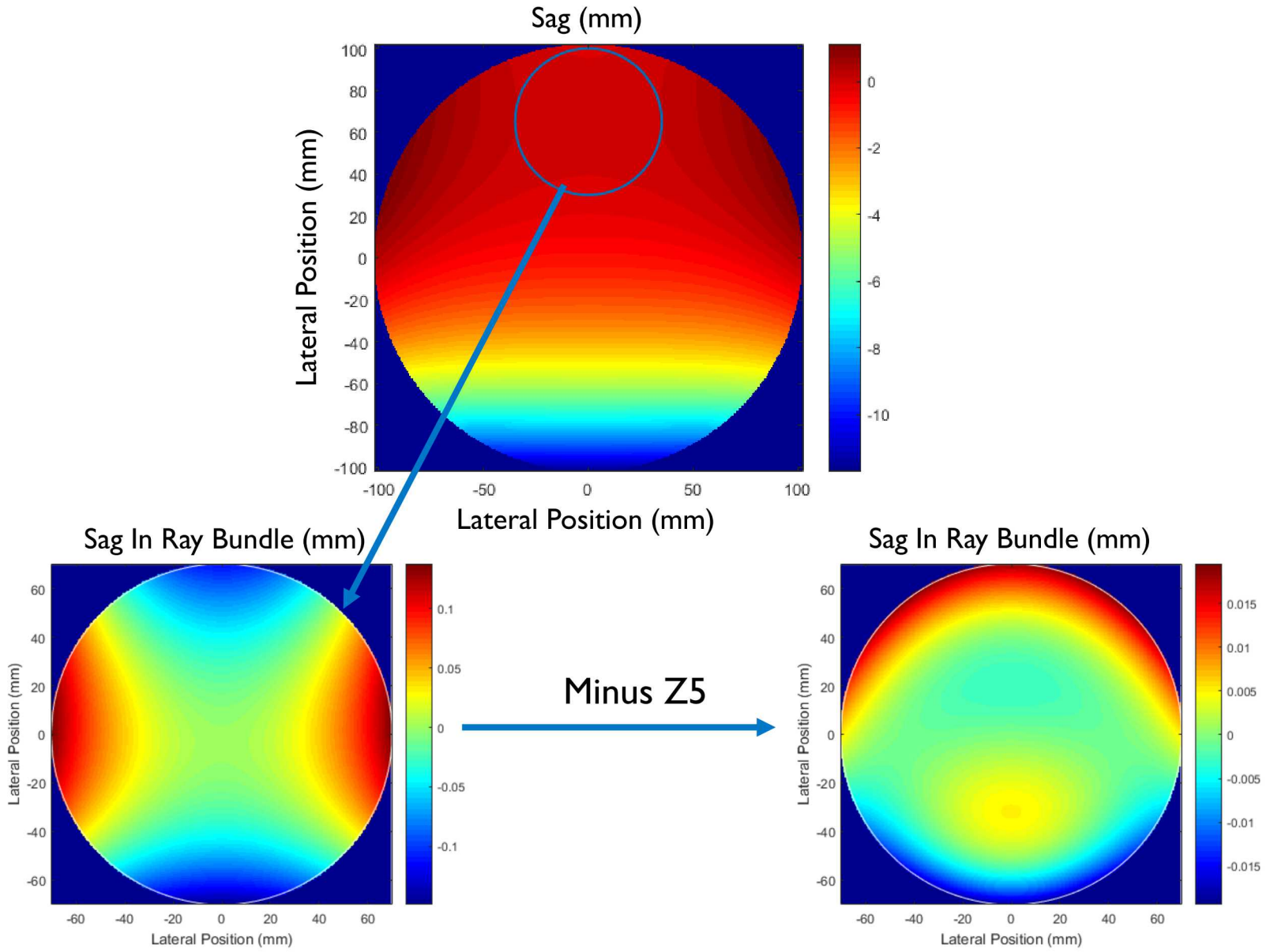
Offset Zernike Surface Solution

- Added decentered Zernike surface on each off-axis conic mirror
  - Zernike distribution added on each mirror is a combination of Zernike astigmatism (Z6), Coma (Z8), Trefoil (Z11), Oblique spherical aberration (Z12)
- After optimization, the entrance pupil has been expanded to meet the entrance pupil requirement of 25 mm while meeting the image quality metric



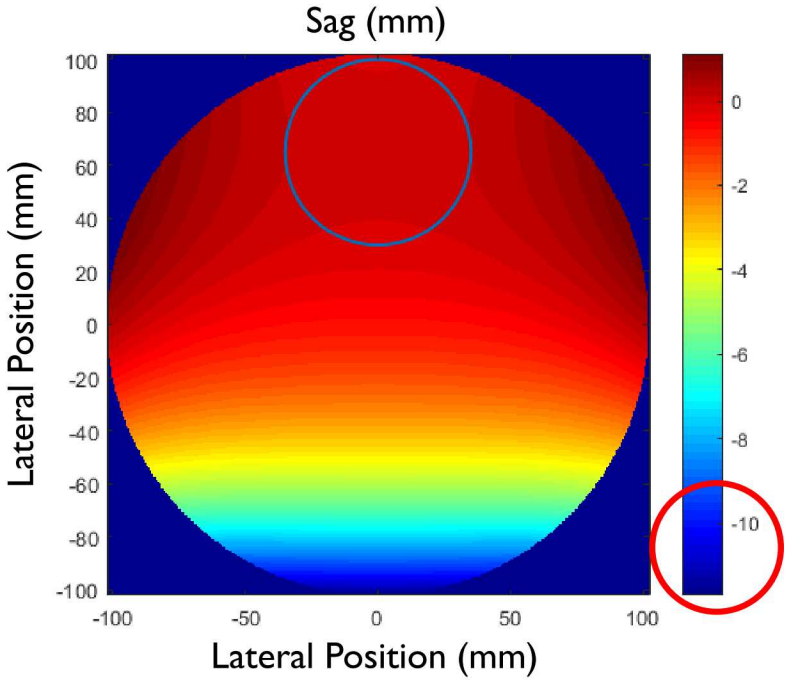


Primary Mirror Surface Sag



Shortcomings of Design Description

- Since the offset Zernike overlay is defined over a norm. radius that may be small and an offset that may be large:
  - The sag far away from the parent may be very large
  - Can lead to raytracing errors unless apertures are correctly utilized
- Similar surface descriptions (XY Polynomial based) are beginning to appear
  - D. Reshidko and J. Sasian, *Optical Engineering*, Vol. 57, (2018)



Conclusions

- For optical designs that utilize tilted and/or decentered apertures, the distance between the parent optical surface vertex and incident ray bundle may be large
  - If a freeform overlay is added to the parent surface vertex, the overlay will be inefficient
  - One method is to utilize a offset Zernike overlay where the overlay can be decentered to the ray bundle vertex
- The offset Zernike overlay has been utilized in conjunction with a base conic to improve the optical performance of a field biased off-axis wide field of view imaging system
  - With the offset Zernike overlay, the entrance pupil diameter of the design was expanded 25% and yielded similar performance to the conic only solution

Acknowledgements

- Eric Shields for creating and allowing me to use his MATLAB Object toolbox that allows for quick analysis of Zernike surfaces
- This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

Questions?