HabEx Coronagraph Masks in Polarization Ray-tracing

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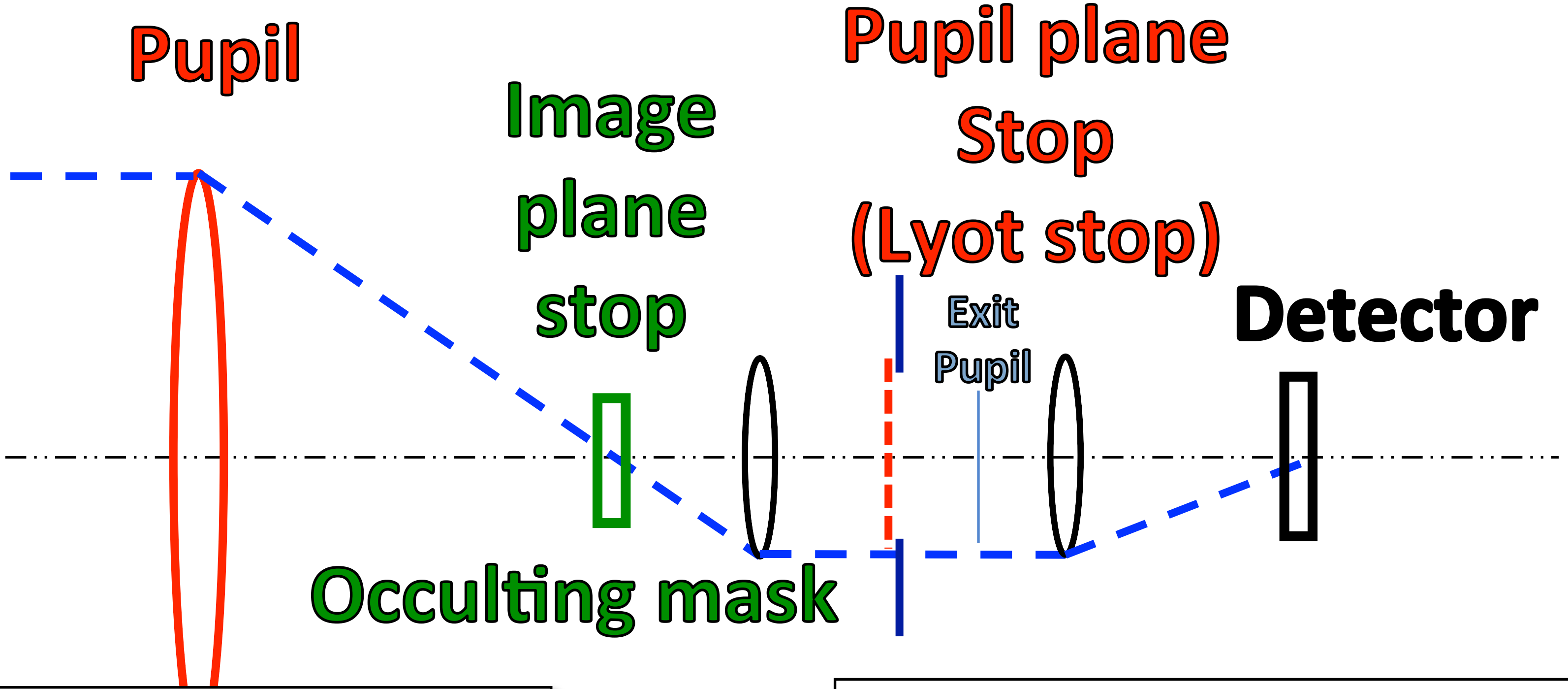
Presentation Outline

- Computational methods for using polarization ray tracing to study coronagraph designs with a Jones Pupil decomposition
- Measurements/modeling of form birefringence on primary mirror
  - Degrades contrast
- Future work:
  - Mitigation strategies in mask design
  - Sensitivity to mask fabrication errors

Assumptions in these Simulation Studies

- No deformable mirror optimization or EFC in HabEx prescription
- Measurements/modeling of form birefringence on primary mirror
  - Demonstration of capability to quantify degradation in contrast
  - Novel method for measuring form birefringence on a large optic
  - Test optic we measured is NOT HabEx mirror and given differences in coating technology our measurements are a worse case scenario (maybe 10x better is possible?)

Computing the HabEx Jones Pupil using Polaris-M



Jones Pupil is a 2x2 matrix at each spatial coordinate in the pupil. Maps E-field in Entrance Pupil (NP) to Exit Pupil (XP)

Compute System Jones Pupil:

40K (29 attributes/ray=1.16M) rays in Polaris-M

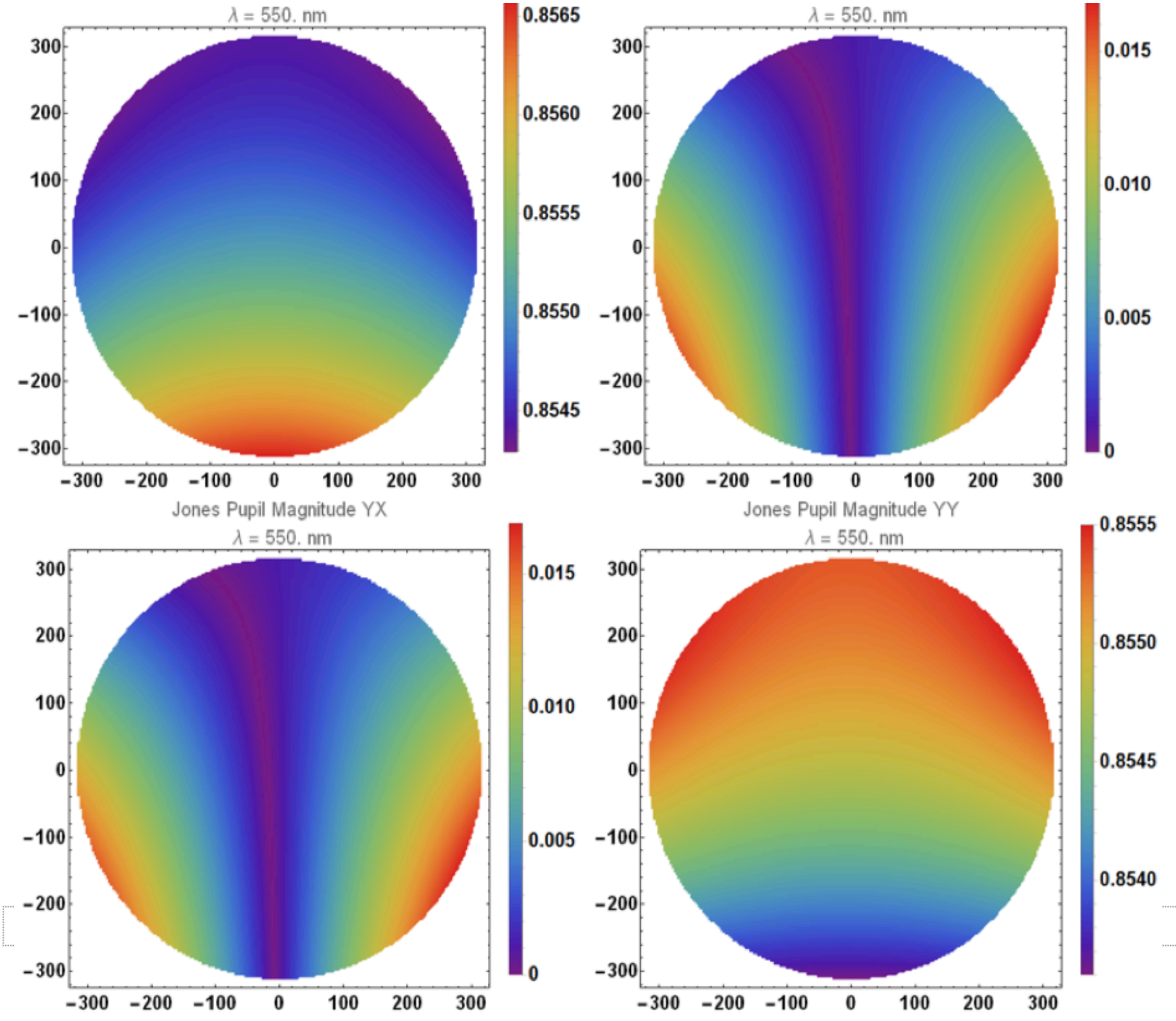
≈ 1 day per wavelength

Time prohibitive to study mask variations

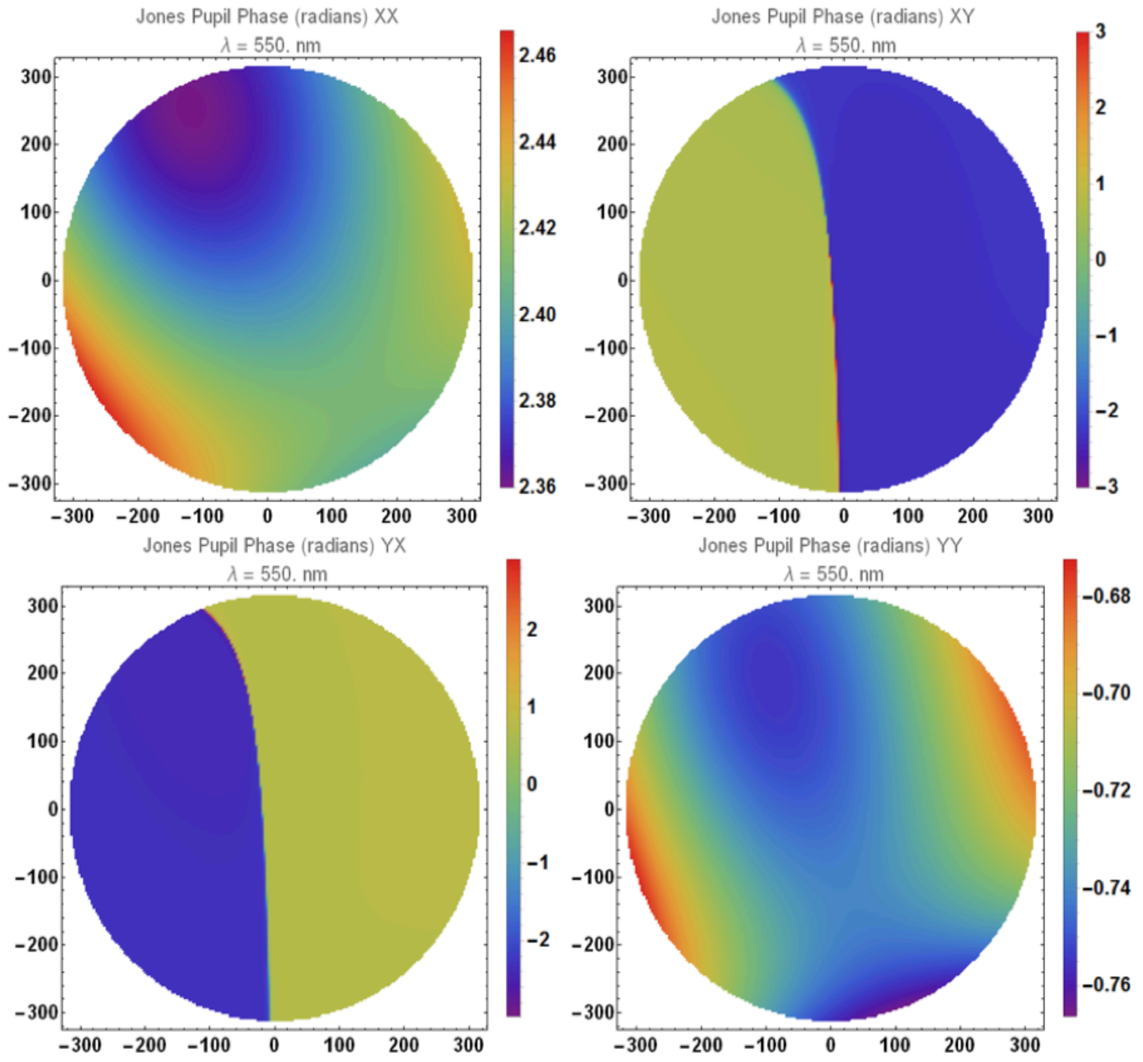
$$J(\xi, \chi) = \begin{pmatrix} J_{XX} & J_{XY} \\ J_{YX} & J_{YY} \end{pmatrix}$$

HabEx Jones Pupil from Polaris-M: detector plane @ 550 nm(no mask)

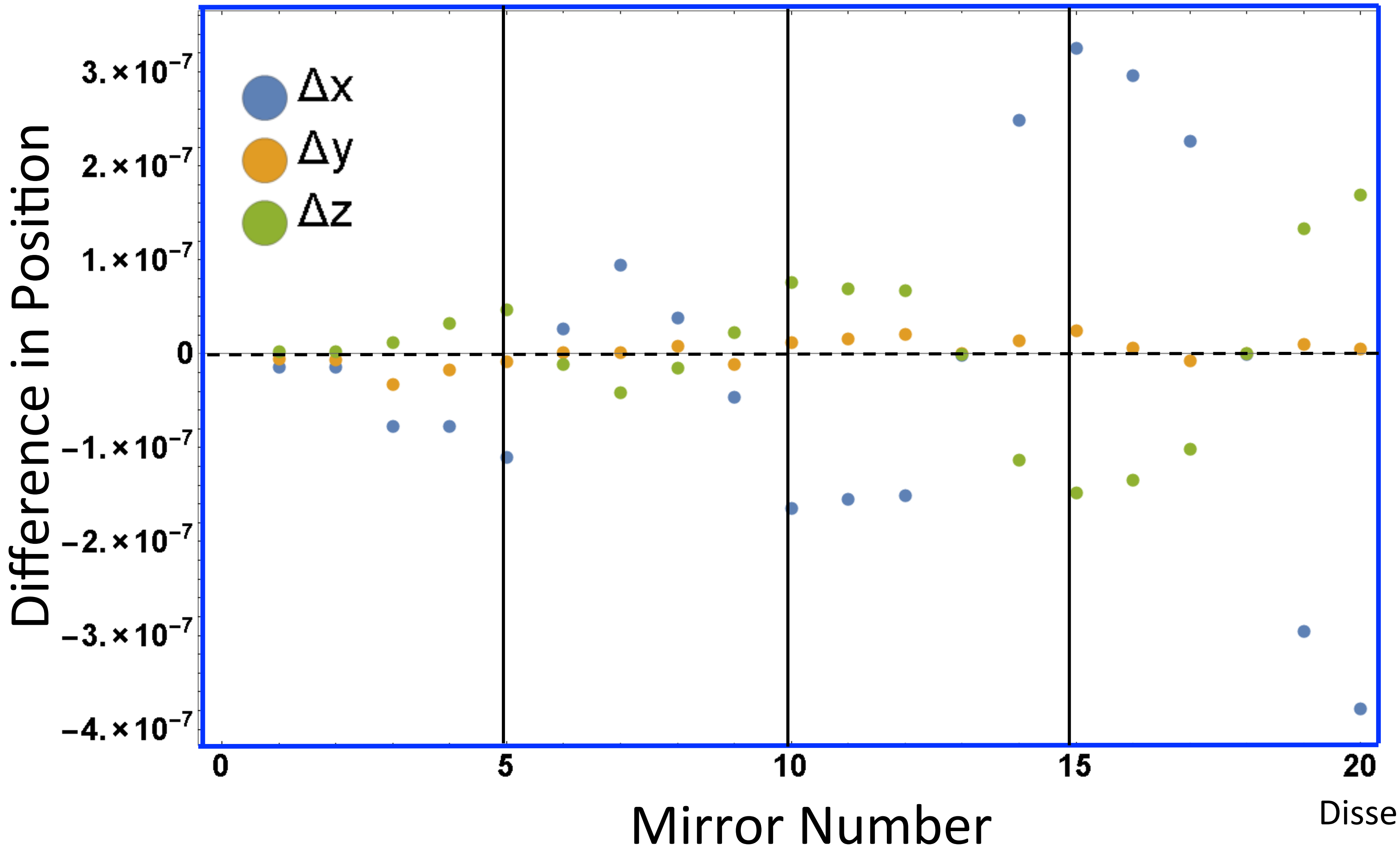
Amplitude



Phase [radians]



Code-V & Polaris-M Validation



k-vector residual
< 3X10^{-7} mm
on mirror surfaces
for WFIRST-CGI

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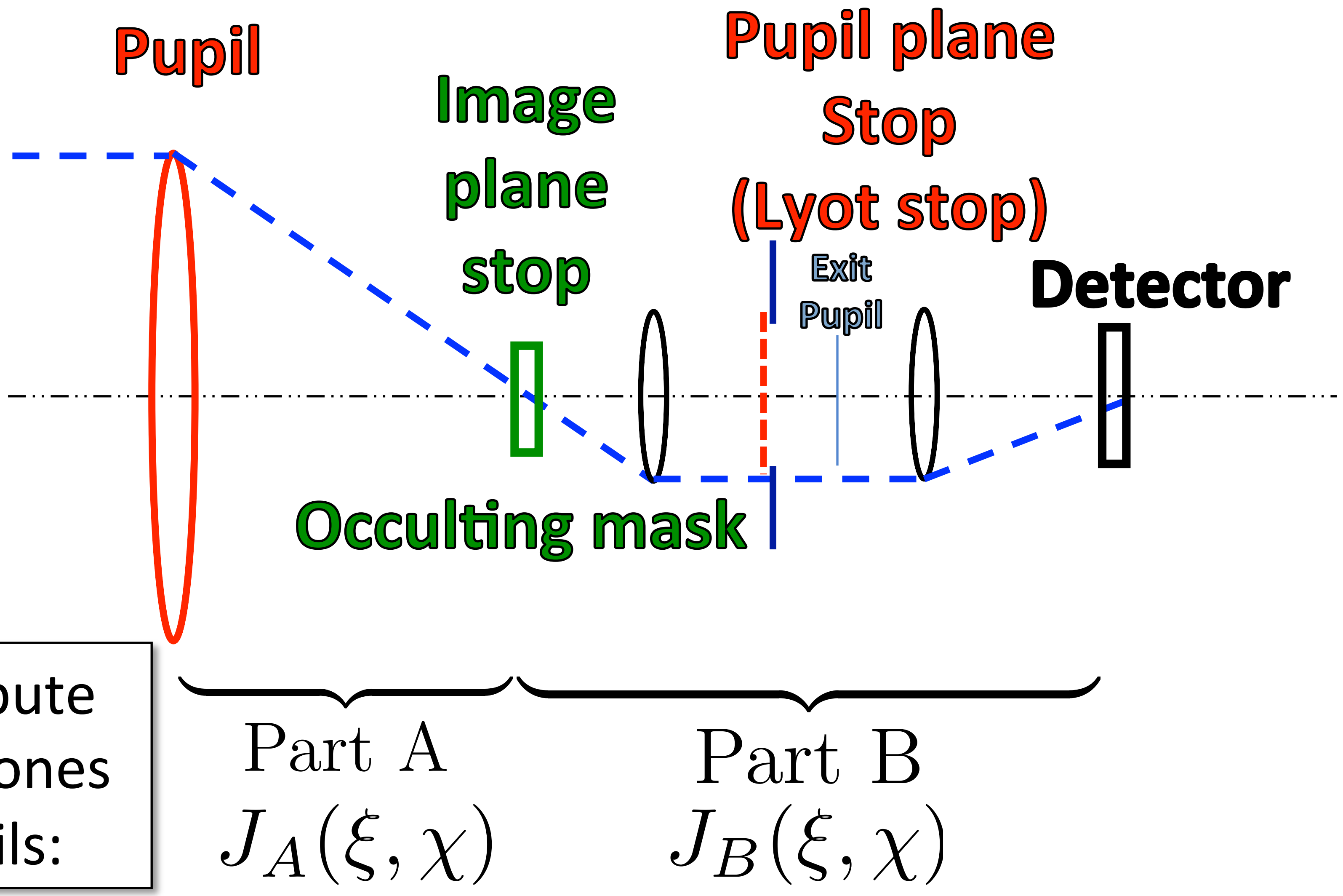
Computing the HabEx Jones Pupil with Mask

Pupil Decomposition Concept to Eliminate Redundancy

Compute Two Jones Pupils:



Implementing the HabEx Mask:
Pupil Decomposition Algebra

No Mask:

2x2 matrix-multiply

$$J(\xi,\chi) = J_B(\xi,\chi) J_A(\xi,\chi)$$

Insert Mask (**without redoing fore-optics & instrument ray trace!**):

$$J(\xi,\chi) = J_B(\xi,\chi)\mathcal{F}^{-1}\left\{M \odot \mathcal{F}\left\{J_A(\xi,\chi)\right\}\right\}$$

M : complex transmittance of the mask

Element-by-element multiply

Analyze the behavior of the Jones Pupil, PSF, system contrast for various mask designs:

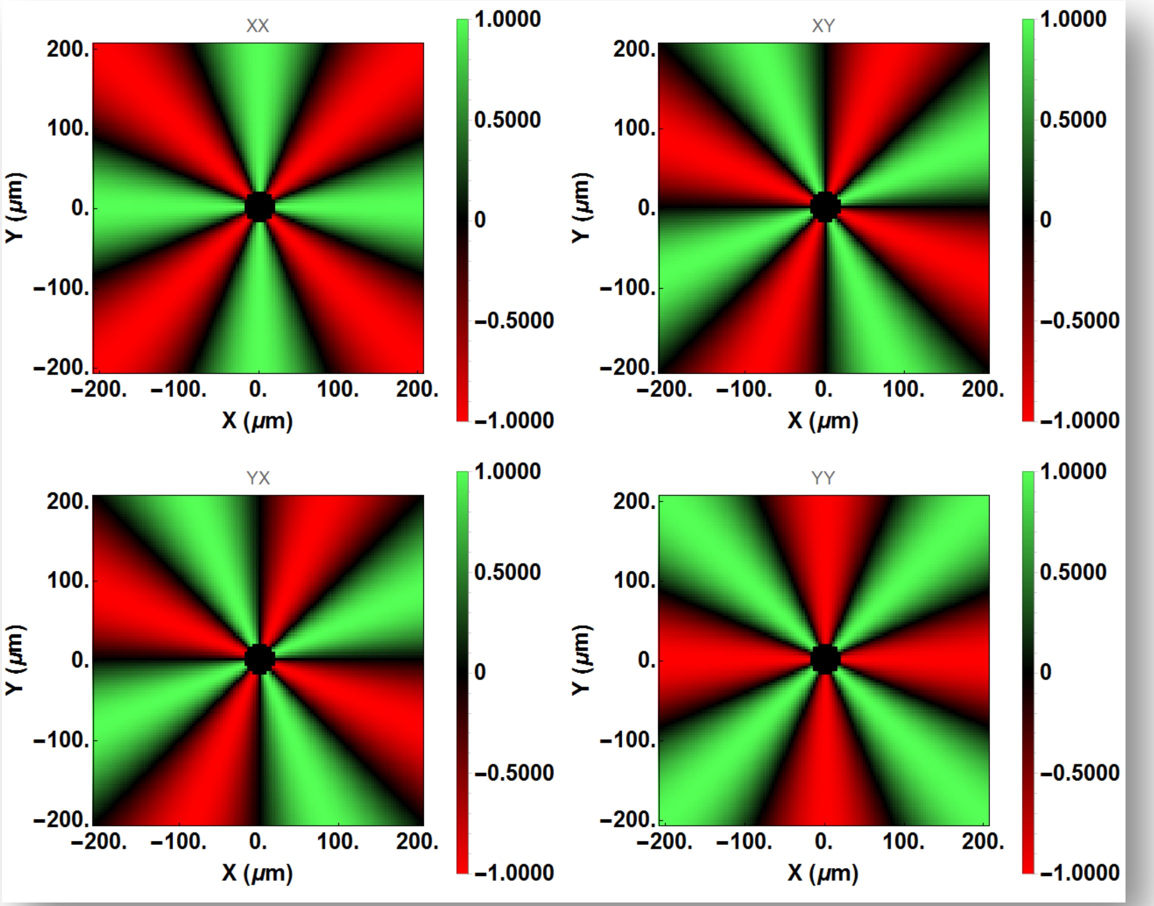
$$J(\xi,\chi;\mathbf{a}) = J_B(\xi,\chi)\mathcal{F}^{-1}\left\{M(\mathbf{a}) \odot \mathcal{F}\left\{J_A(\xi,\chi)\right\}\right\}$$

$\mathbf{a}$:mask attributes (e.g. size occulter, phase errors, fabrication tolerances)

Vector Vortex (VV) Transmittance

$$\begin{pmatrix} \cos(m\tan^{-1}(\frac{y}{x})) & \sin(m\tan^{-1}(\frac{y}{x})) \\ \sin(m\tan^{-1}(\frac{y}{x})) & -\cos(m\tan^{-1}(\frac{y}{x})) \end{pmatrix}$$

- Vector Vortex (charge, m=4)
- 40 micron diameter obscuration
- Future work:
  - Fabrication tolerances for liquid crystal VV



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Primary mirror form birefringence effects

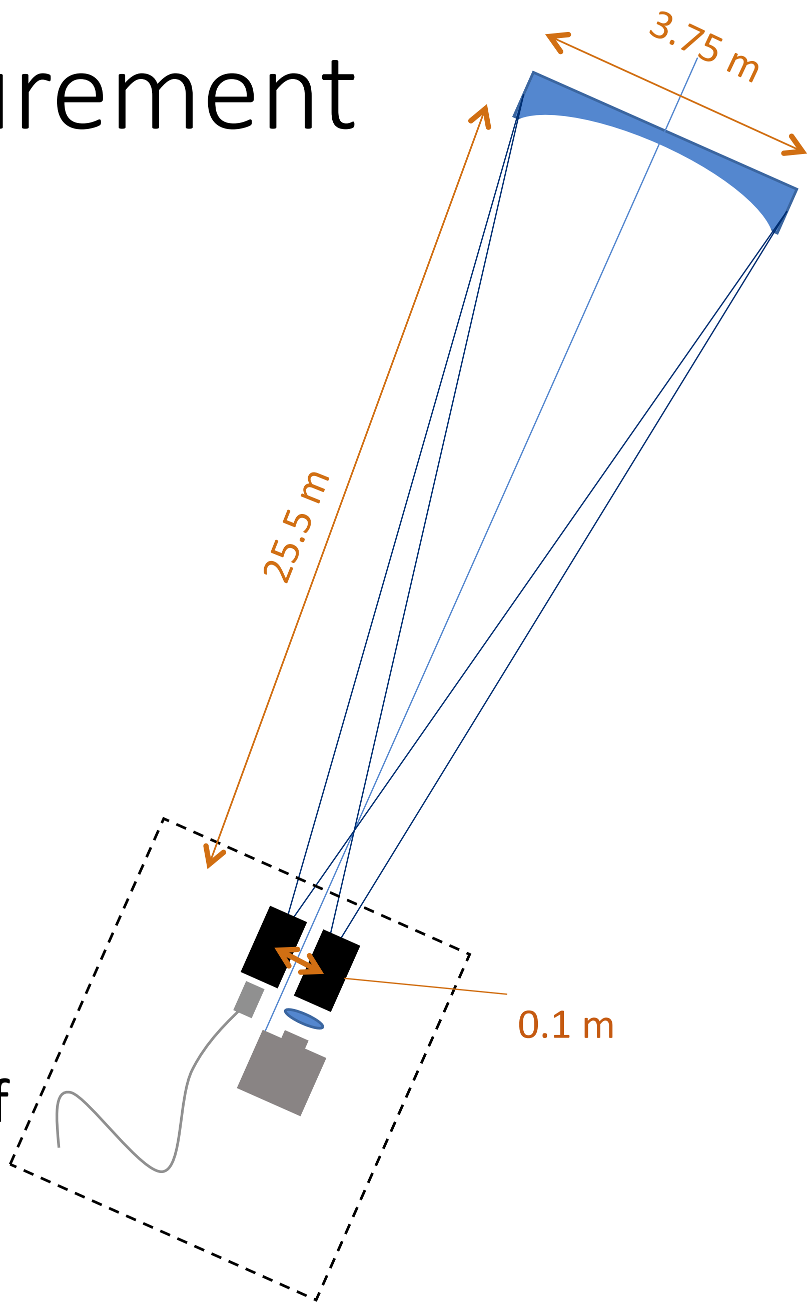
- Took advantage of a unique opportunity to measure spatial changes in polarization reflectivity across a large (3.75-m) astronomical mirror
  - Al coated in a vacuum chamber at Kitt Peak
  - Bare Al natural oxide layer about 4nm

- Developed a precision instrument and software to measure birefringence and diattenuation across a 3.75-meter mirror

- Placed the measured results into our HabEx model & modeled the effect on the noise-equivalent contrast.

Form Birefringence Measurement

- Measurement concept
  - Identify polarization properties intrinsic to coating
  - Incident angles near 0˚ achieved by placing point source adjacent to center of curvature of mirror
  - With this geometry Fresnel equations predict
    - retardance < 10^{-5}
    - diattenuation < 10^{-6}
- System description
  - Source: Fiber coupled monochromator
  - Polarimetry: Two crossed Glan-Thompson polarizers mounted on motorized rotation stages
  - Detector: Scientific grade 16-bit camera
  - Mounting: 3-axis translation to align system with center of curvature. 2-tilt axis to aim source and camera at mirror.
  - Rotation about center axis to provide different system orientations



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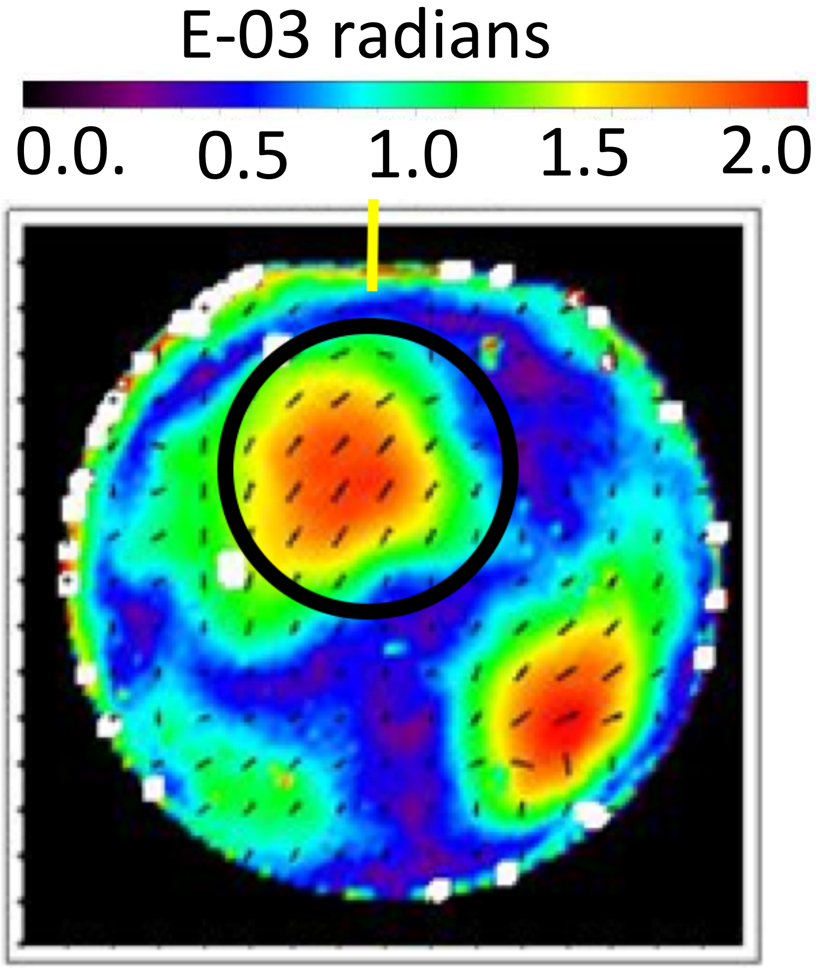
Form Birefringence Measurement



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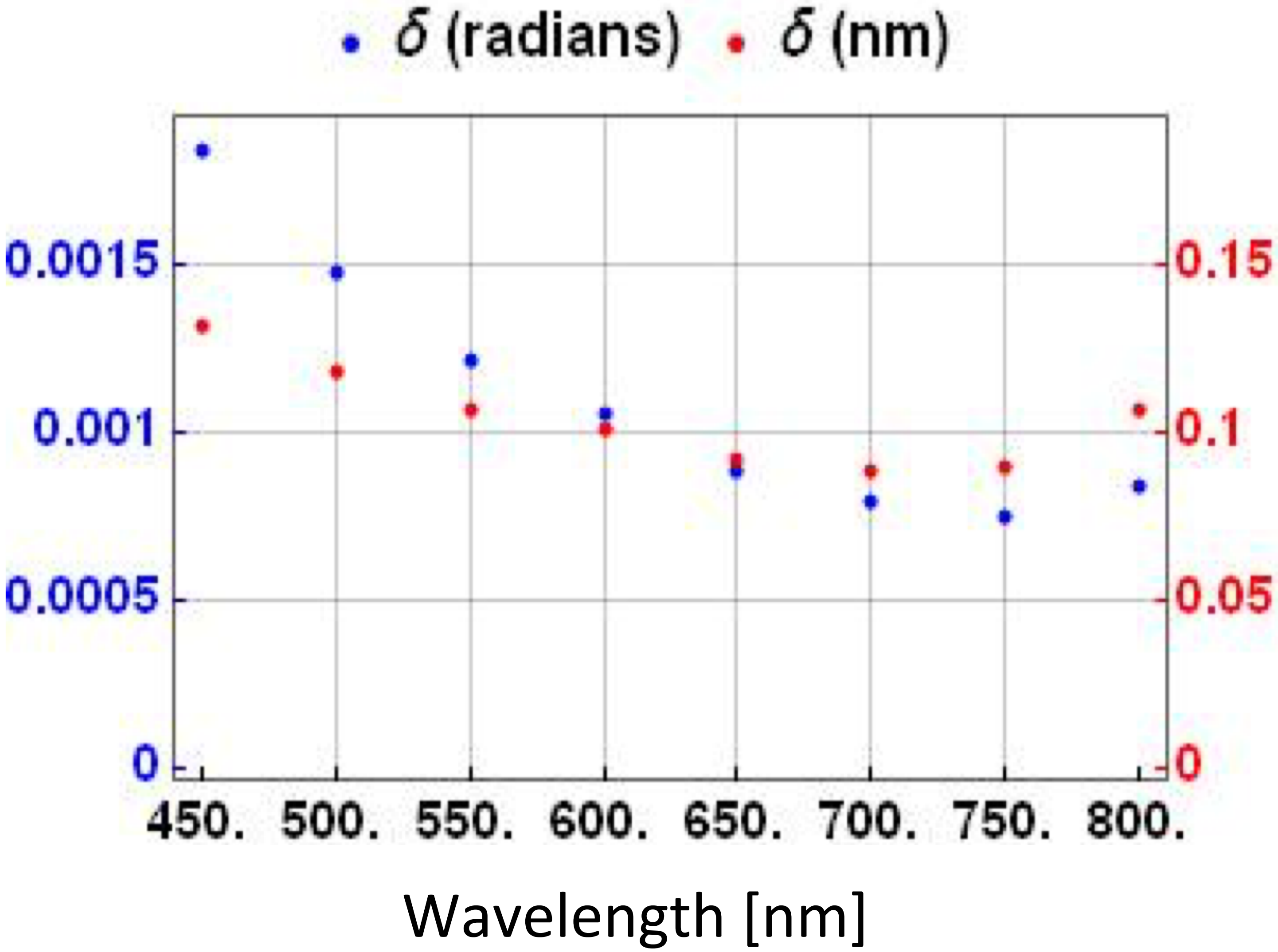


Noise Equivalent Contrast
Definition

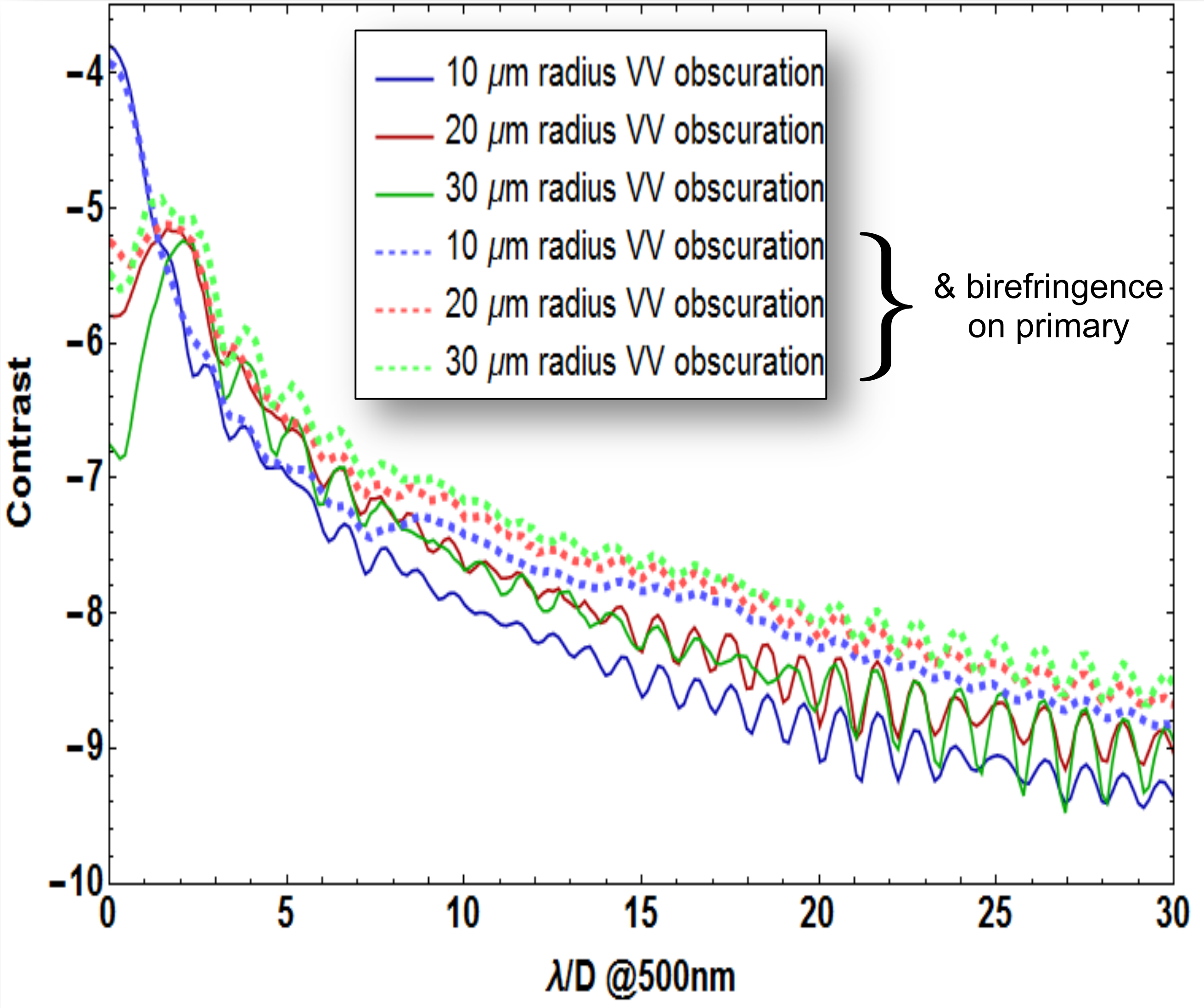
$$C^{P}_{\Delta(500)}(\mathbf{r}) = \log_{10}\left[\frac{1}{2}\left(\frac{\sum_{\lambda=450}^{\lambda=550}\langle I_{XX}(\mathbf{r};\lambda) + I_{YY}(\mathbf{r};\lambda)\rangle_{\mathbf{r}}}{\sum_{\lambda=450}^{\lambda=550} I_{XX}^{NoMask}(0;\lambda) + I_{YY}^{NoMask}(0;\lambda)}\right)\right]$$

where

$$PSF(x,y) = \begin{pmatrix} I_{XX}(x,y) & I_{XY}(x,y) \\ I_{YX}(x,y) & I_{YY}(x,y) \end{pmatrix}$$

- Sum the on-diagonal polarimetric elements
- Numerator is poly-chromatic PSF with occulting mask
- Denominator unmasked PSF at origin

HabEx 1709; Contrast [450, 475, 503, 525, 550 nm] with and without birefringence on primary mirror



Approximately 5x degradation in contrast when including form birefringence on primary mirror

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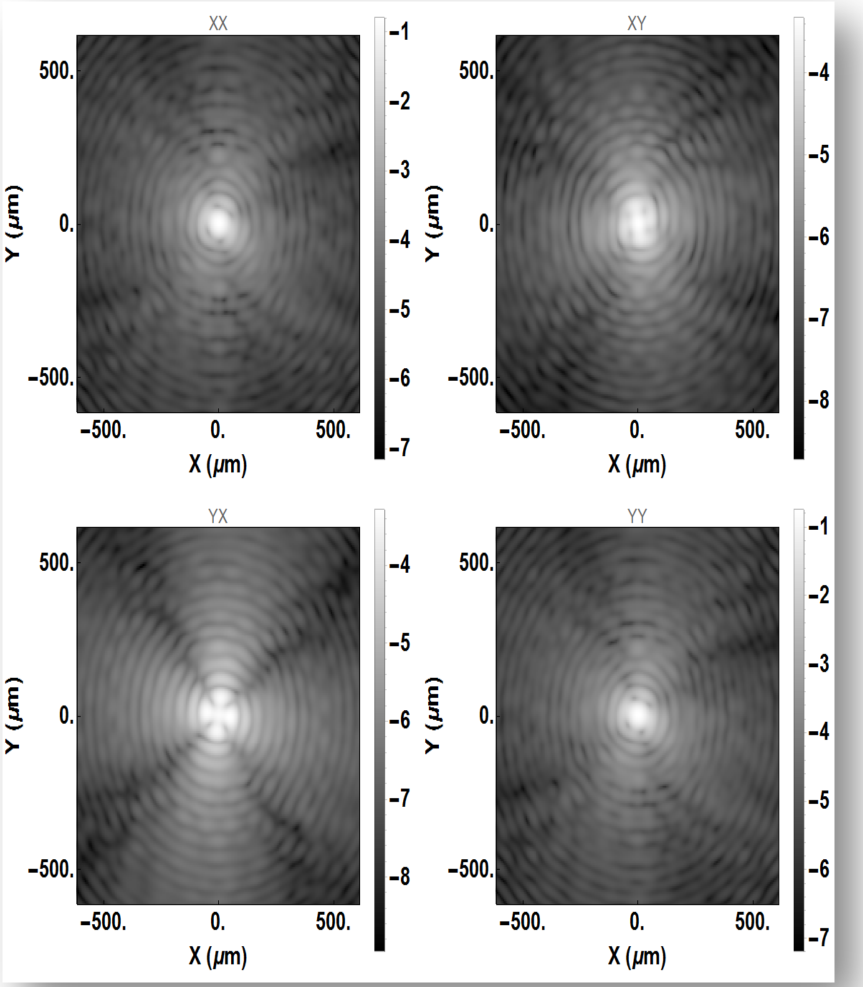
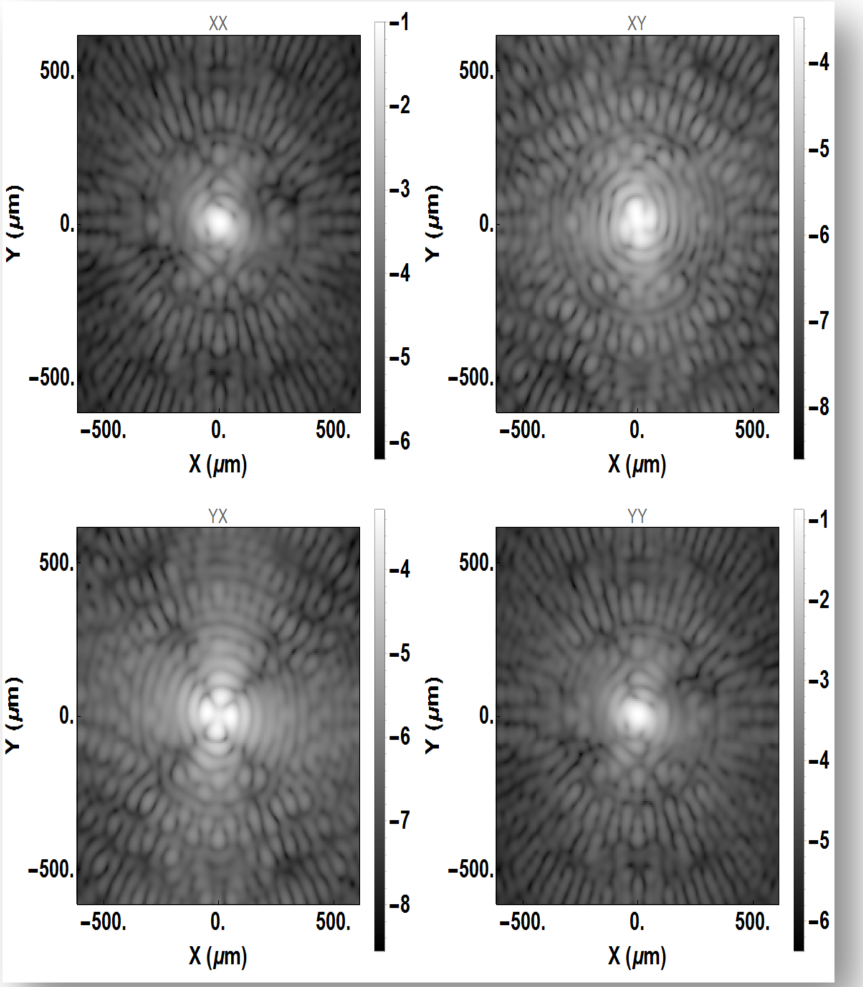
HabEx 1709; Log10 PSF [450=>550 nm]
VV4 (obscuration radius 10 microns)

No Birefringence on primary



Birefringence on primary



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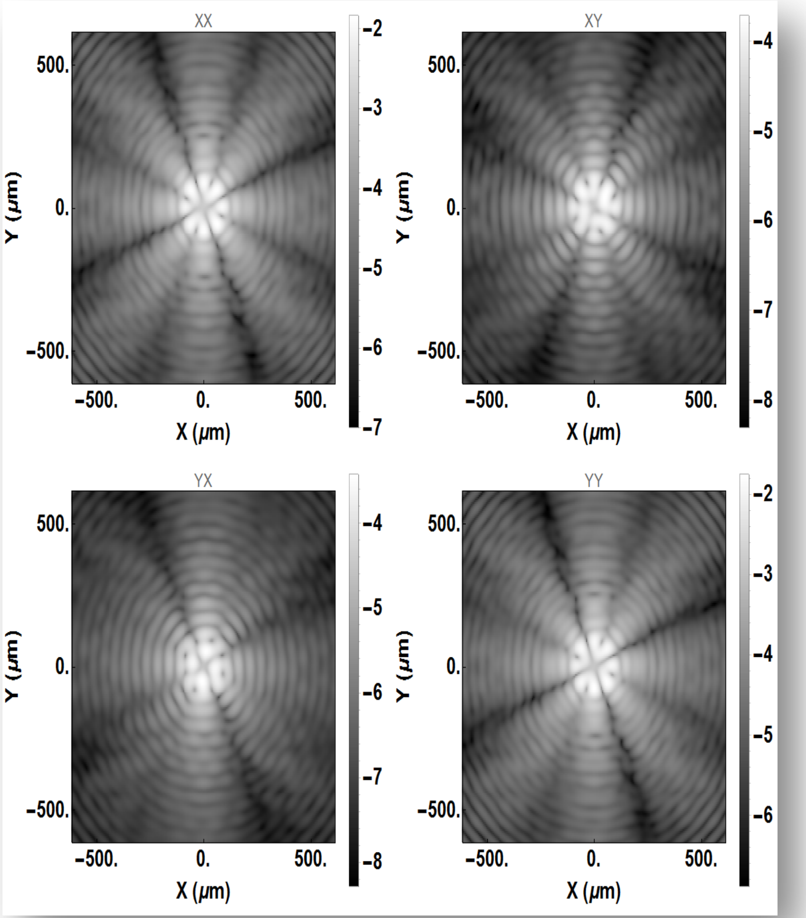
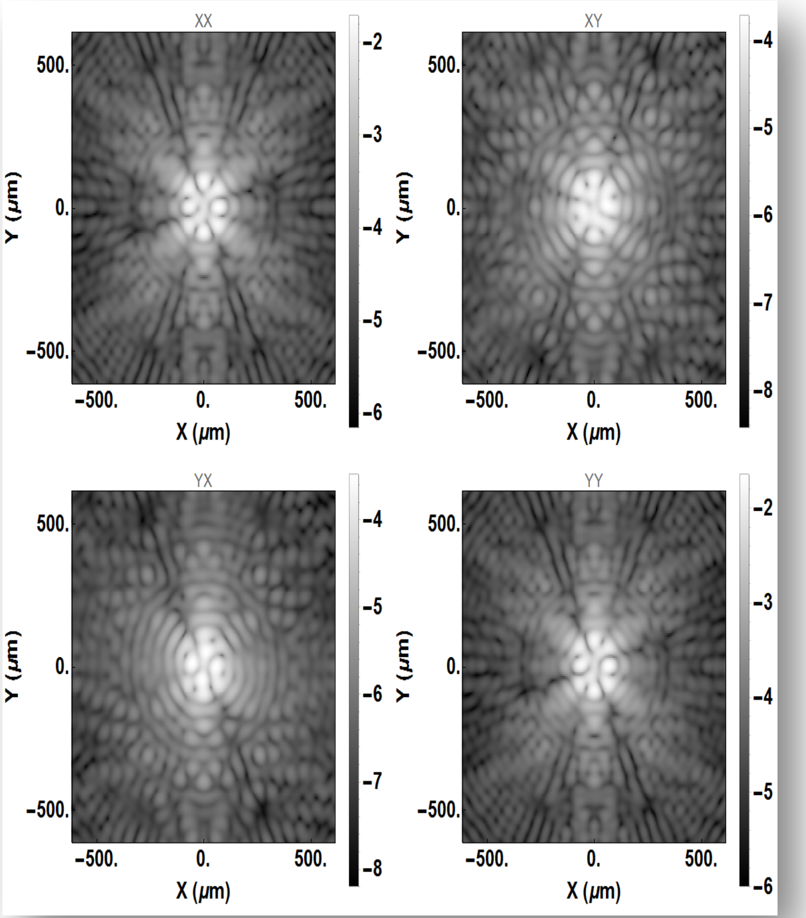
HabEx 1709; Log10 PSF [450=>550 nm]
VV4 (obscuration radius 20 microns)

No Birefringence on primary



Birefringence on primary



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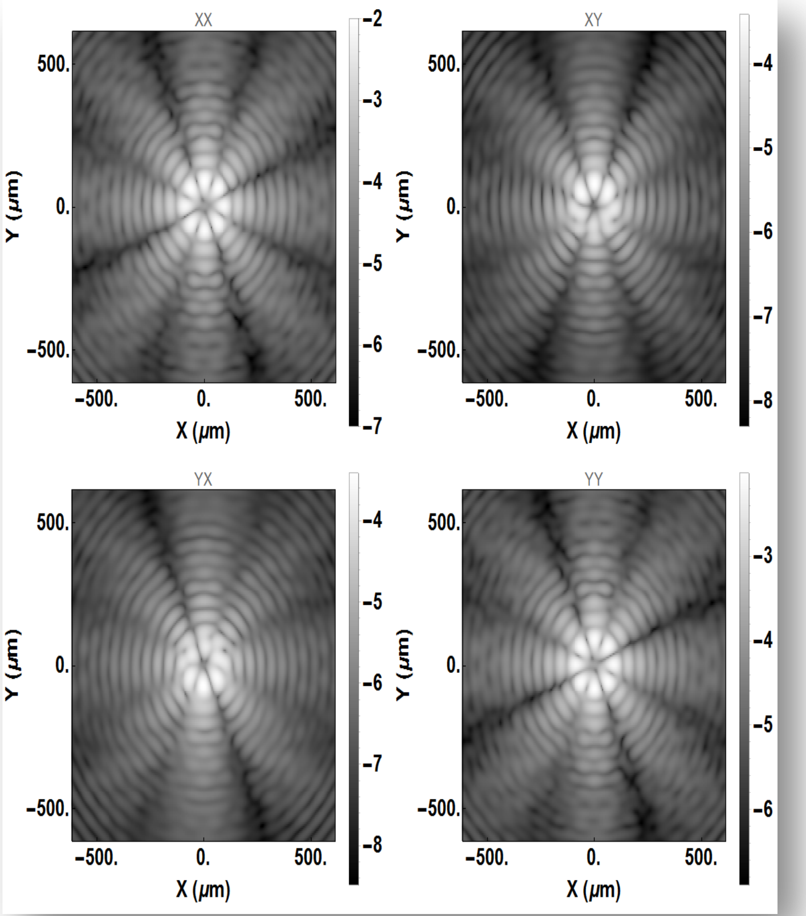
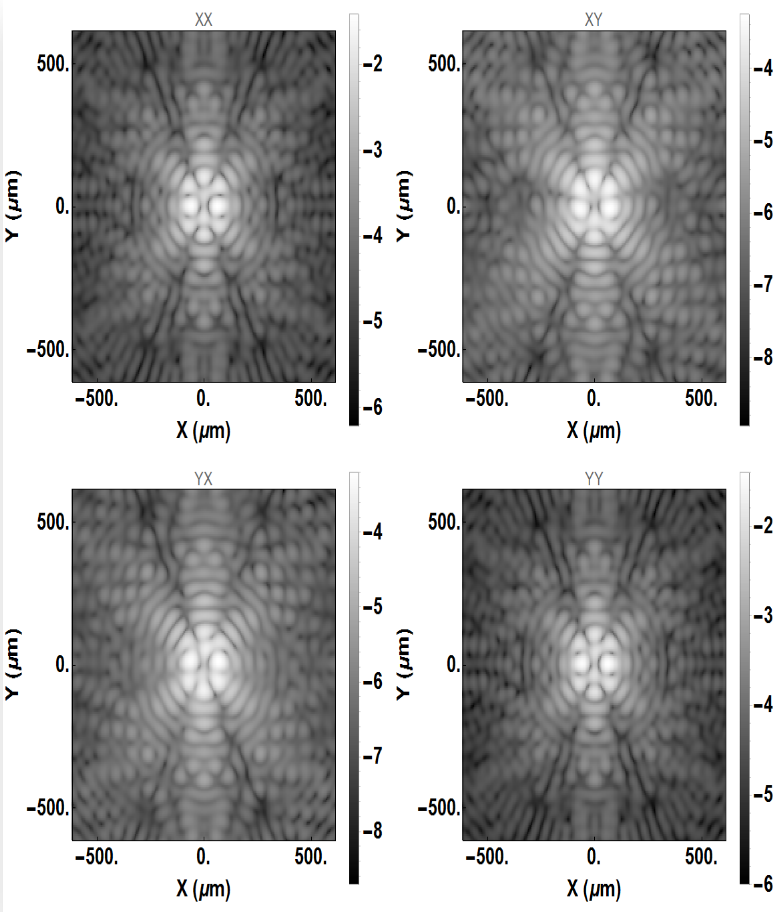
HabEx 1709; Log10 PSF [450=>550 nm]
VV4 (obscuration radius 30 microns)

No Birefringence on primary



Birefringence on primary



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Conclusions

- Polarization ray tracing can be made computational feasible for studying mask designs and polarization properties of large optics with Jones Pupil decomposition

- Polarization and form birefringence degrades contrast

- Future work:
    - Are mitigation strategies in mask design possible?
    - Sensitivity to mask fabrication errors
    - Treat polarization properties of surfaces as random processed

Future Work

Optimize Linear System between E-field at entrance pupil (NP) and exit pupils (XP):

$$E_{XP} = J(\xi, \chi; \mathbf{a}) E_{NP}$$

- Create Scene Models (spectra-polarimetric) for E_{NP} under 2 hypotheses, eg: exoplanet present, exoplanet habitable, atmospheric dust/disk types
- Optimize mask attributes for discriminating these 2 hypotheses from E_{XP}
- Expertise in this type of optimization problem for scientific imaging:
  - Use Kullback-Leibler divergence between $pr(E_{XP}|1)$ and $pr(E_{XP}|2)$ as merit function
  - Closed-form gradient wrt mask attributes for normal $pr(E_{XP}|1)$ and $pr(E_{XP}|2)$