Defining Pupil Knowledge Requirements for Roman Space Telescope Integrated Payload Assembly Testing

M.S. Thesis Defense

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Joint work with NASA Goddard Space Flight Center

Outline

The Nancy G. Roman Space Telescope
- Mission Background
- Integration & Testing
- Project Overview

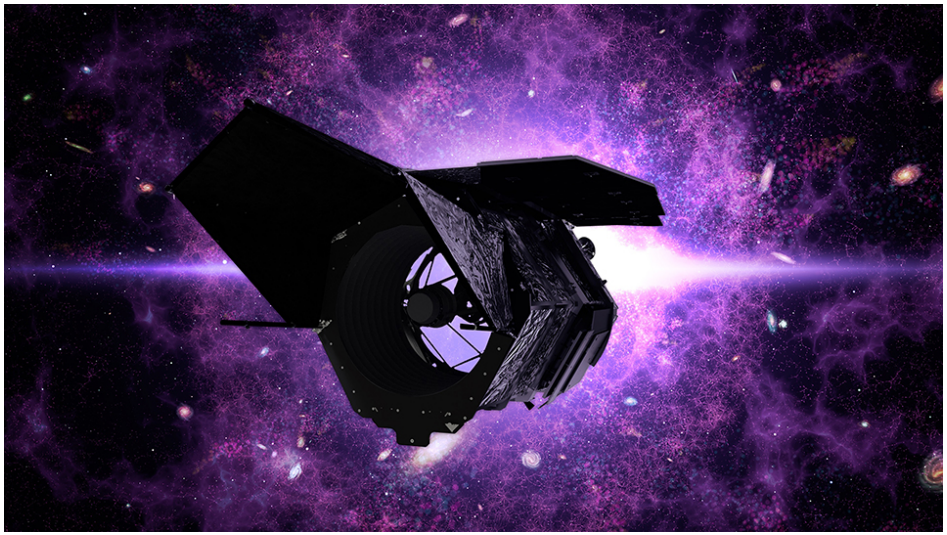
Phase Retrieval
- Background
- Algorithm
- Implementation

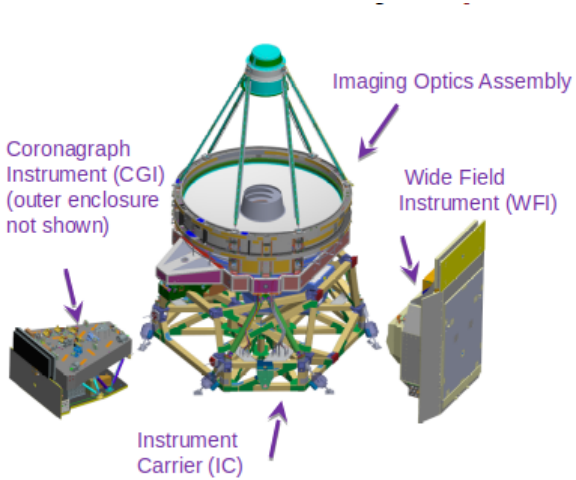
Simulation

Overview of Models
- Ideal Case
- Perturbed Models
- Gravity Sag

Results

The Nancy G. Roman Space Telescope (RST)





- NASA's next flagship observatory
- Will study multiple areas of astrophysics including universal expansion, dark energy, and exoplanets
- Two instruments on-board: the Wide-Field Instrument (WFI) and the Coronagraph Instrument (CGI)[a]

[a] Center, *Roman Space Telescope Mission Overview*.

Integrated Payload Testing

Test configuration in Space Environment Simulator

- Alignment verification of payload (WFI and imaging optics assembly)
- Pseudo double pass configuration using WFI detector and fiber sources adjacent to focal plane array (FPA)
- Conducted in Space Environment Simulator (SES) chamber at NASA Goddard[a]

[a] Bolcar et al., "Roman Space Telescope Optical System: Overview, Test, and Verification".

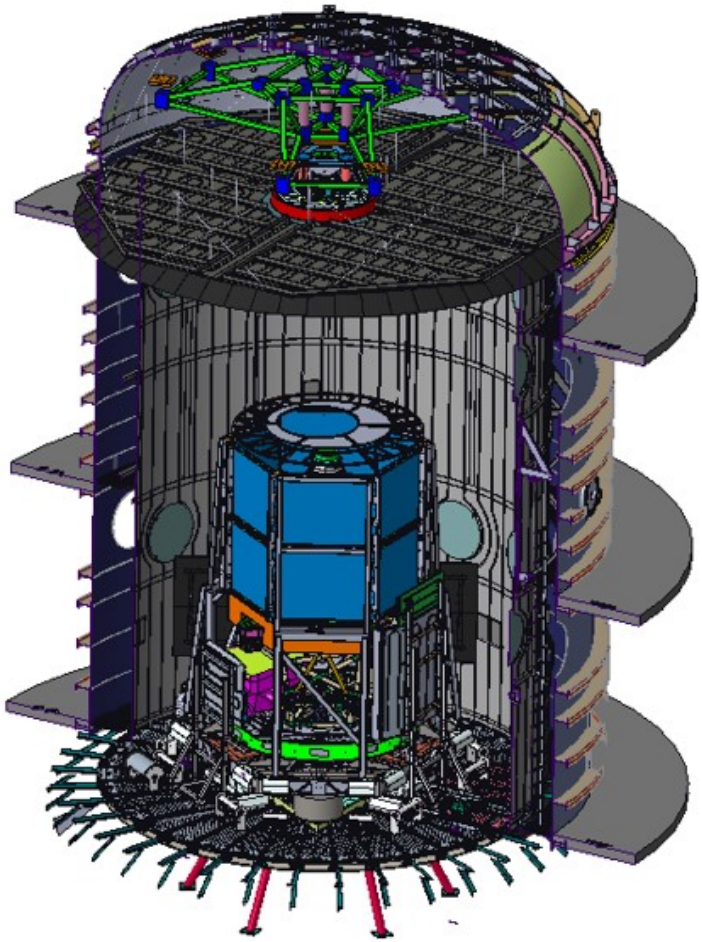


Figure: RST in Space Environment Simulator SES

Integrated Payload Testing

Telescope model not to scale

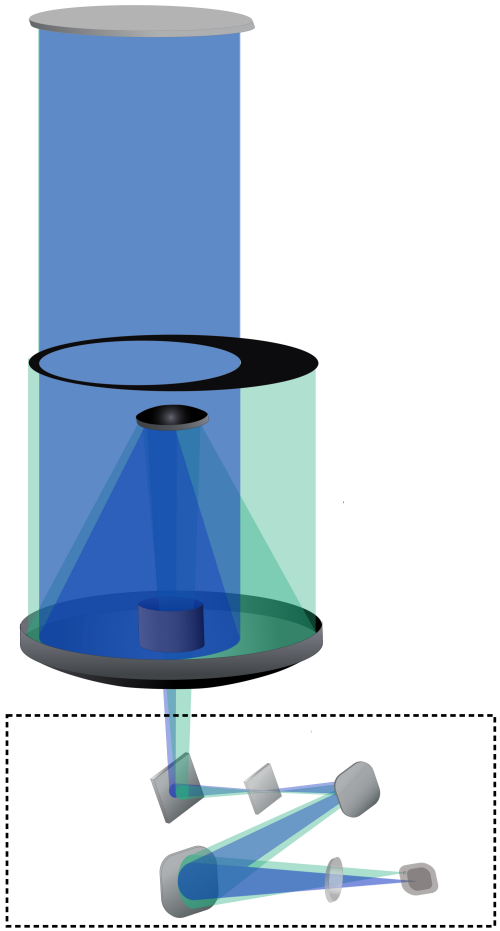


Figure: Wide-Field Instrument (WFI)

Integrated Payload Testing

Telescope model not to scale

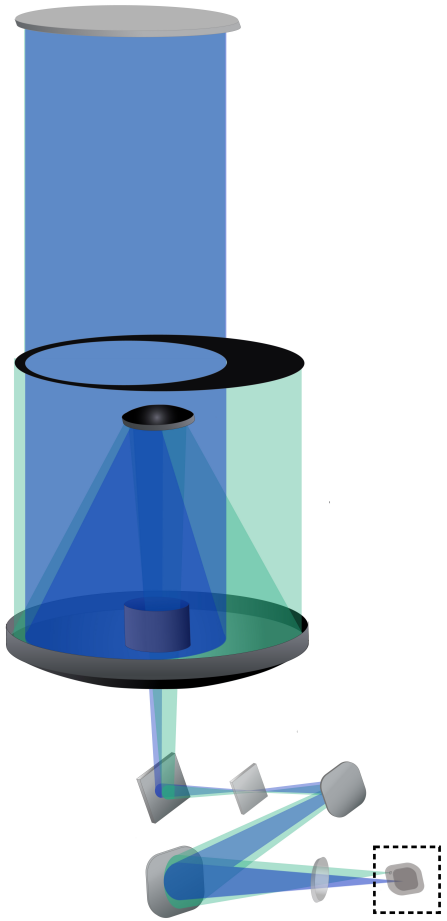


Figure: Focal Plane Array (FPA)

Integrated Payload Testing

Telescope model not to scale

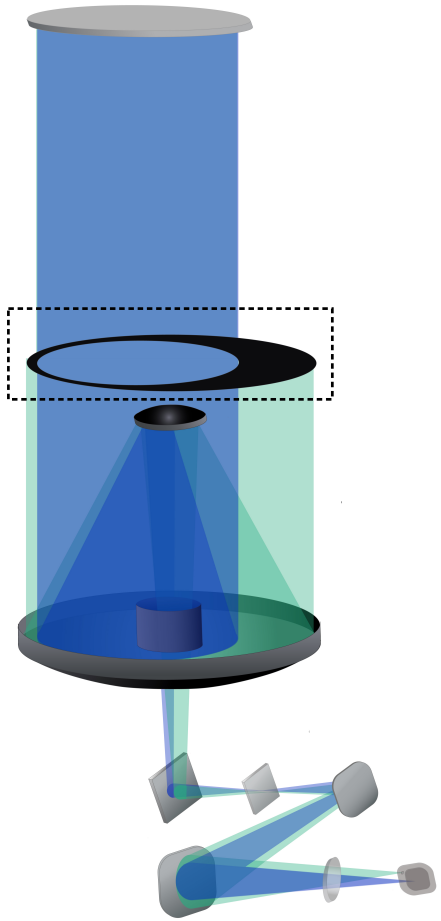


Figure: Subaperture Metrology System (SAMS)

Integrated Payload Testing

Telescope model not to scale

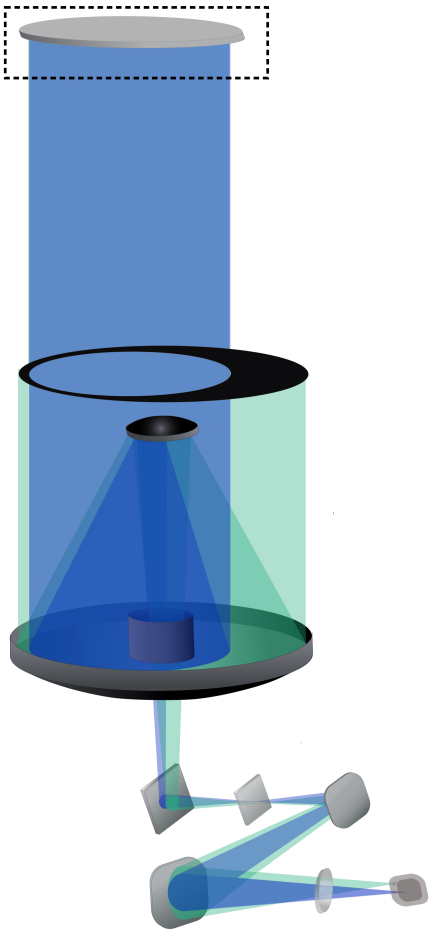
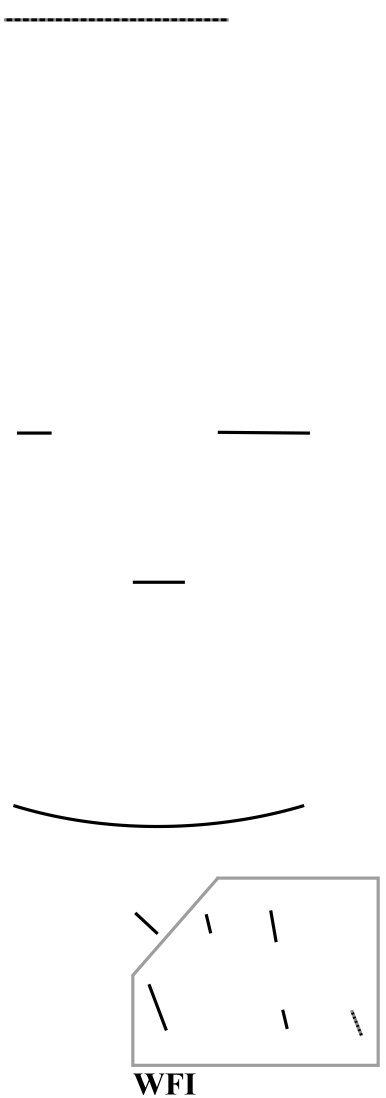


Figure: Optical Large Aperture Flat System (OLAFS)

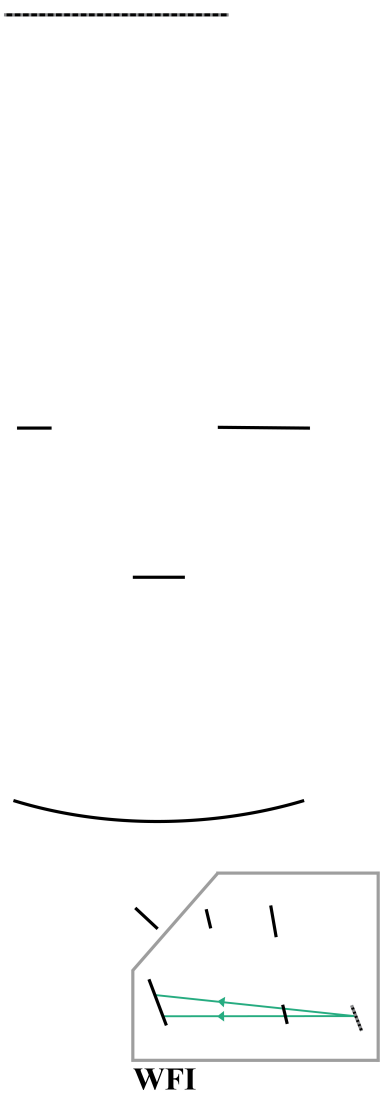
Integrated Payload Testing

Pseudo double pass beam path



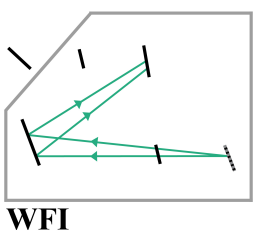
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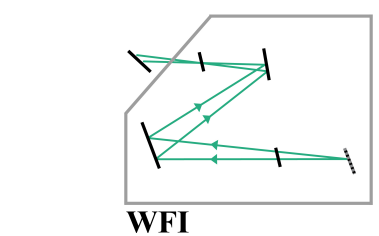
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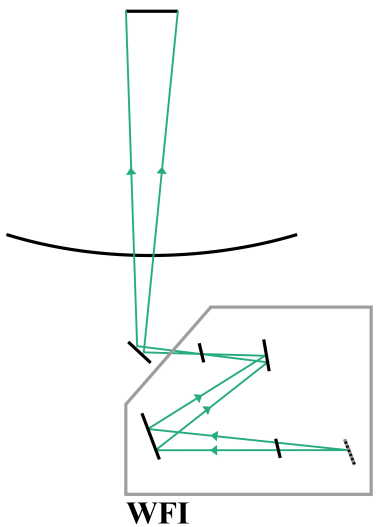
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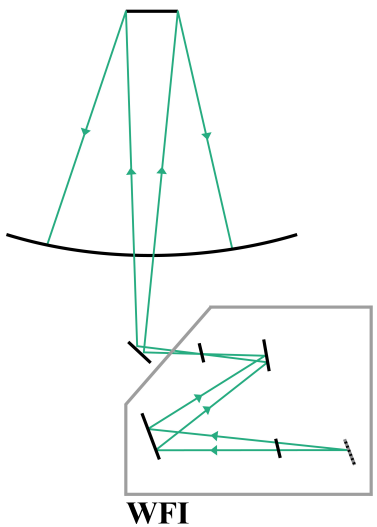
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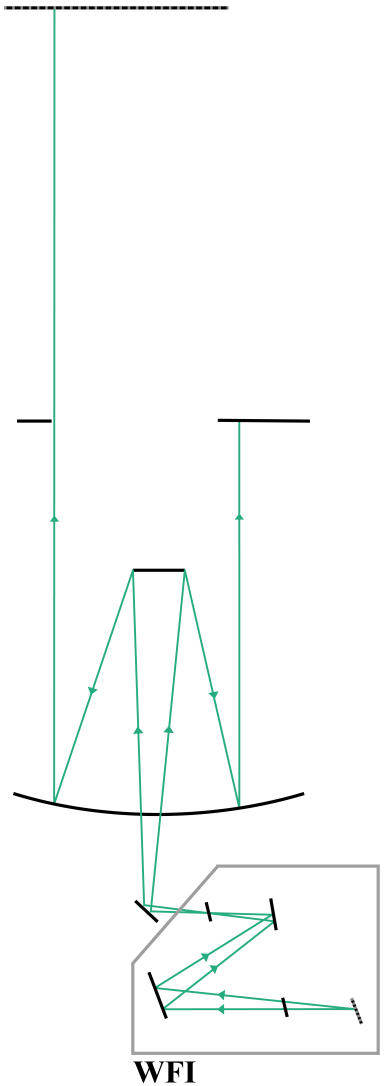
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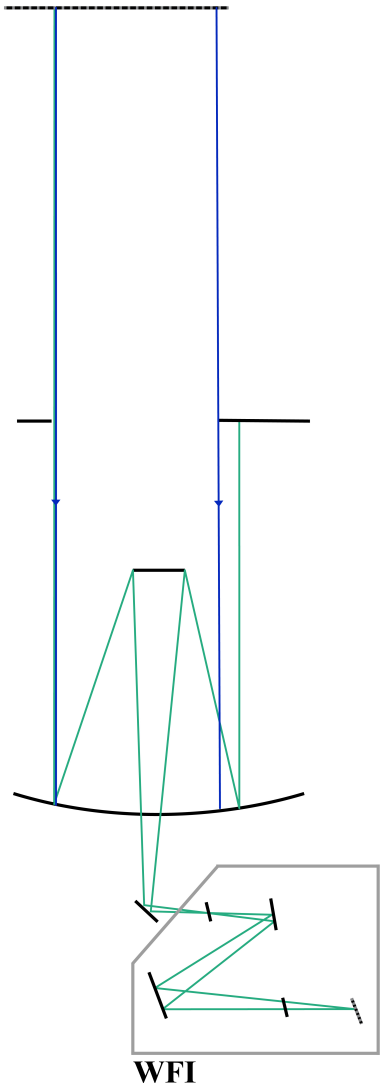
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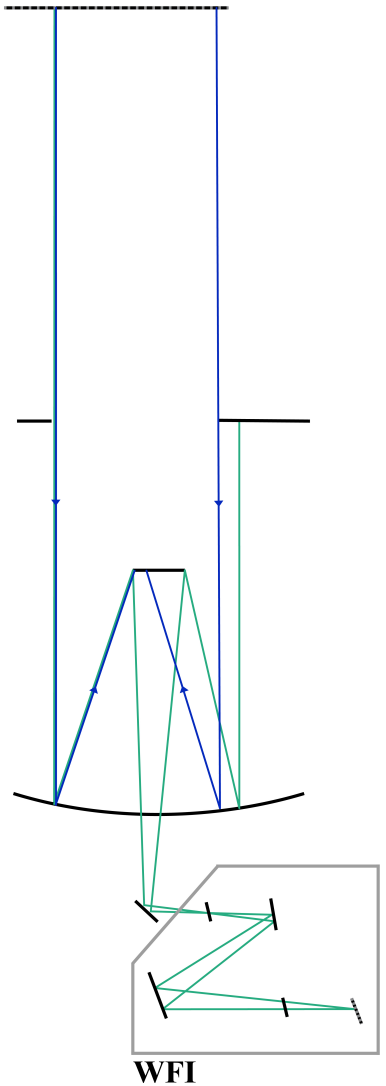
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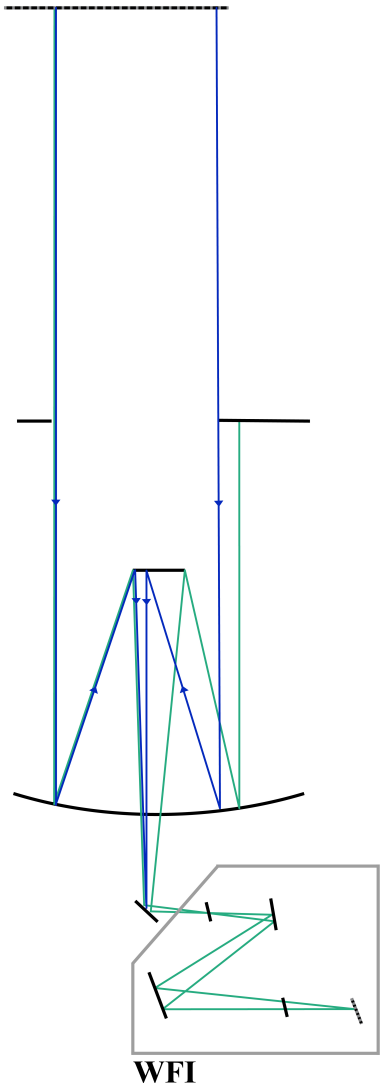
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Pseudo double pass beam path



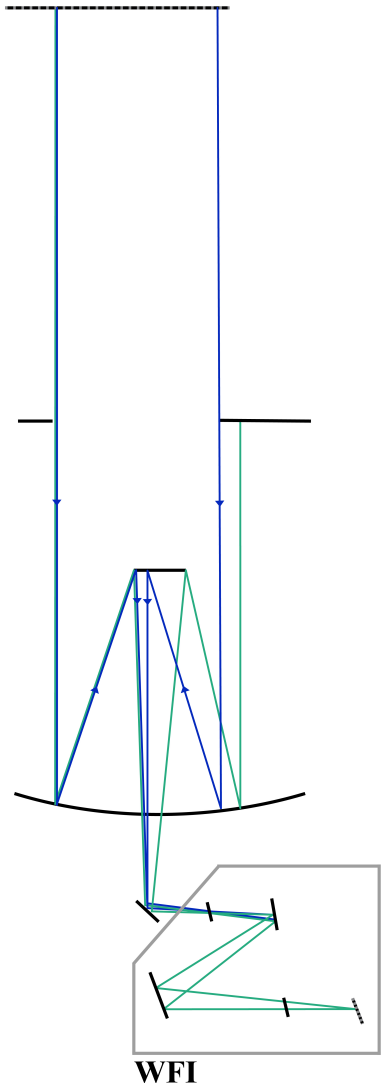
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Pseudo double pass beam path



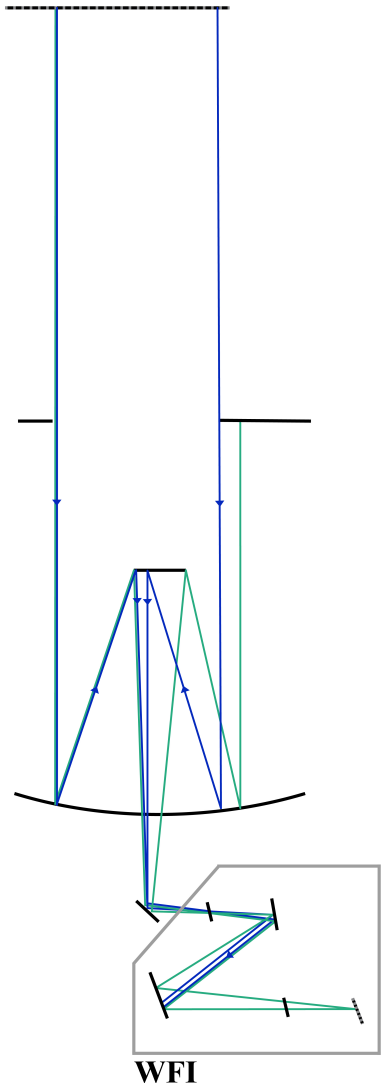
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Pseudo double pass beam path



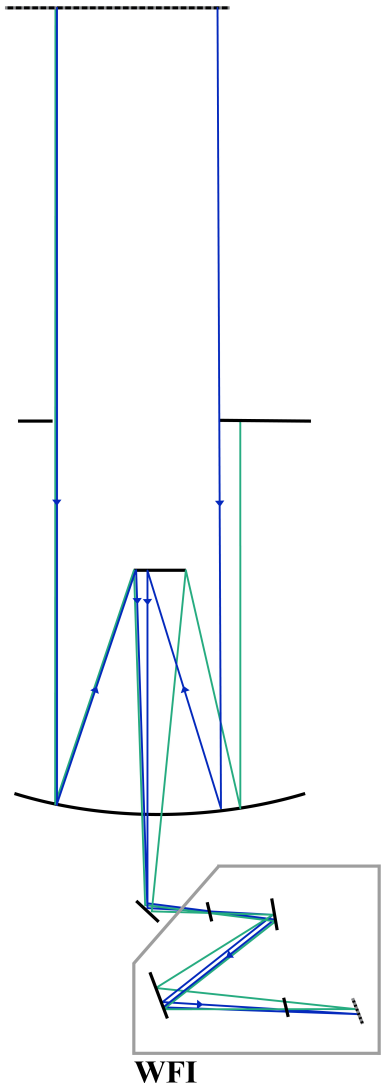
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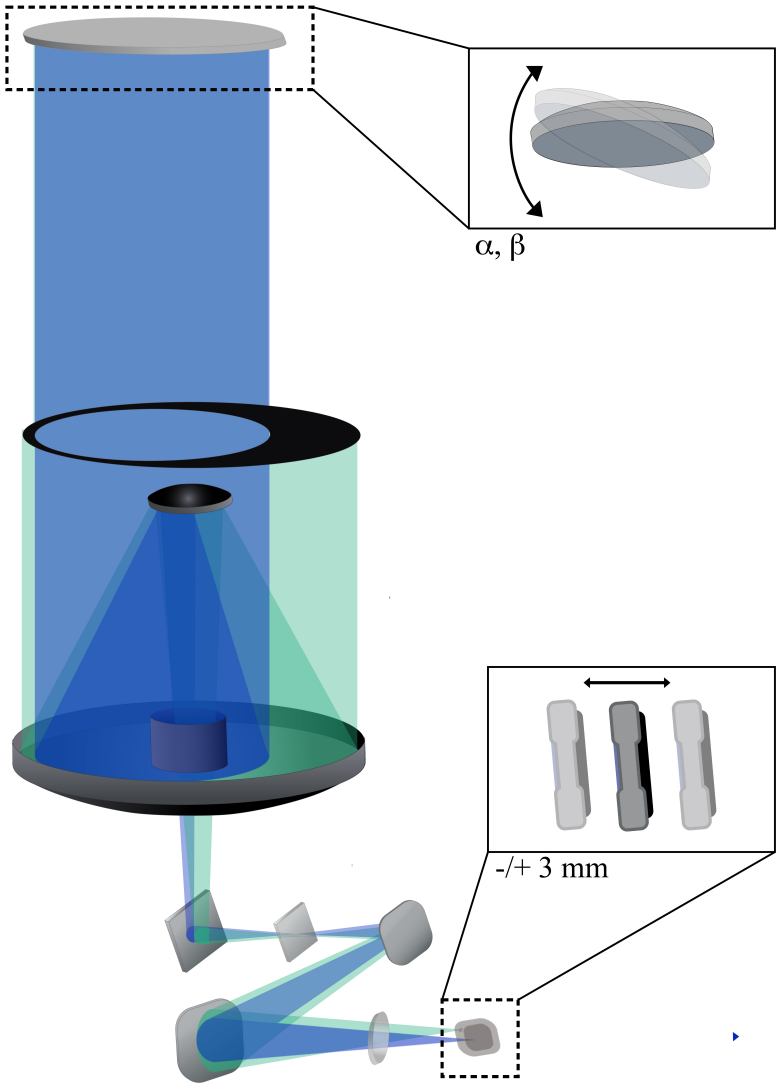
Integrated Payload Testing

Pseudo double pass beam path



Integrated Payload Testing

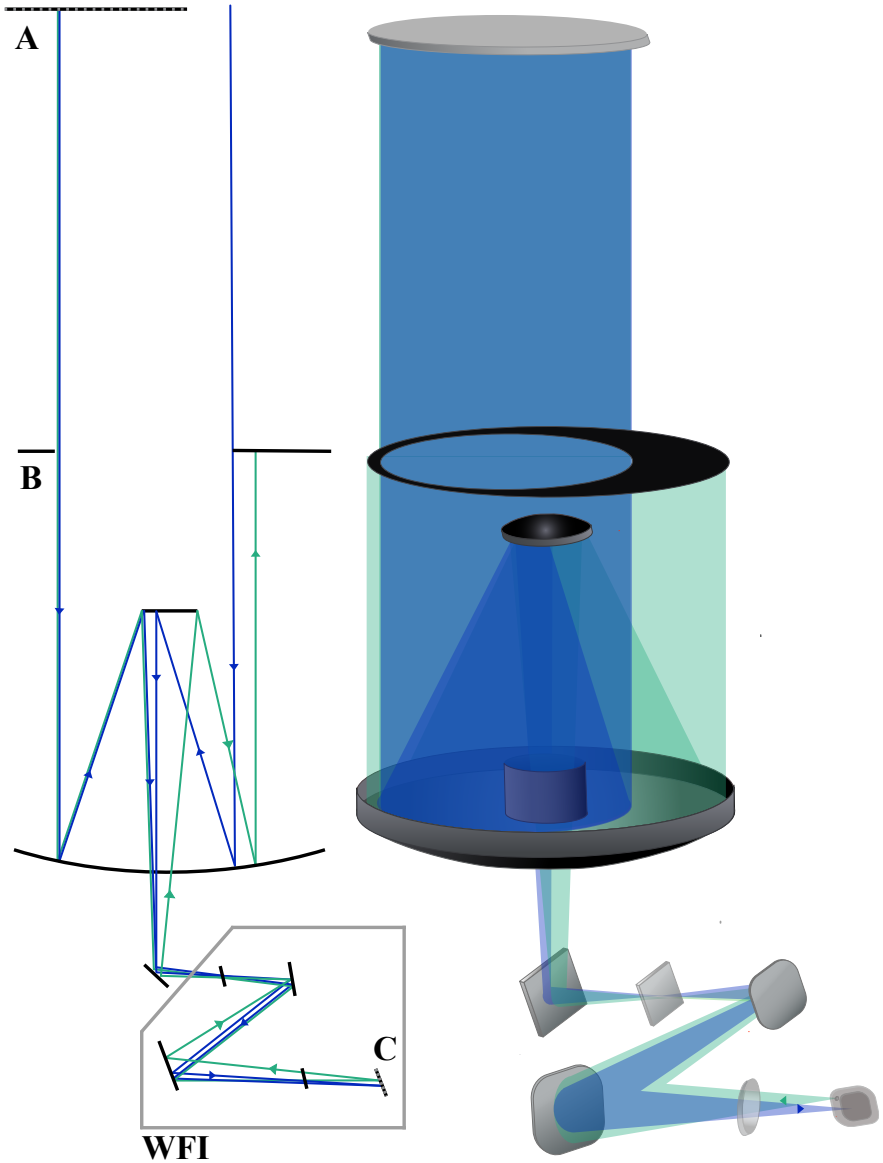
Active components



Integrated Payload Testing

Verify telescope alignment using image-based wavefront sensing

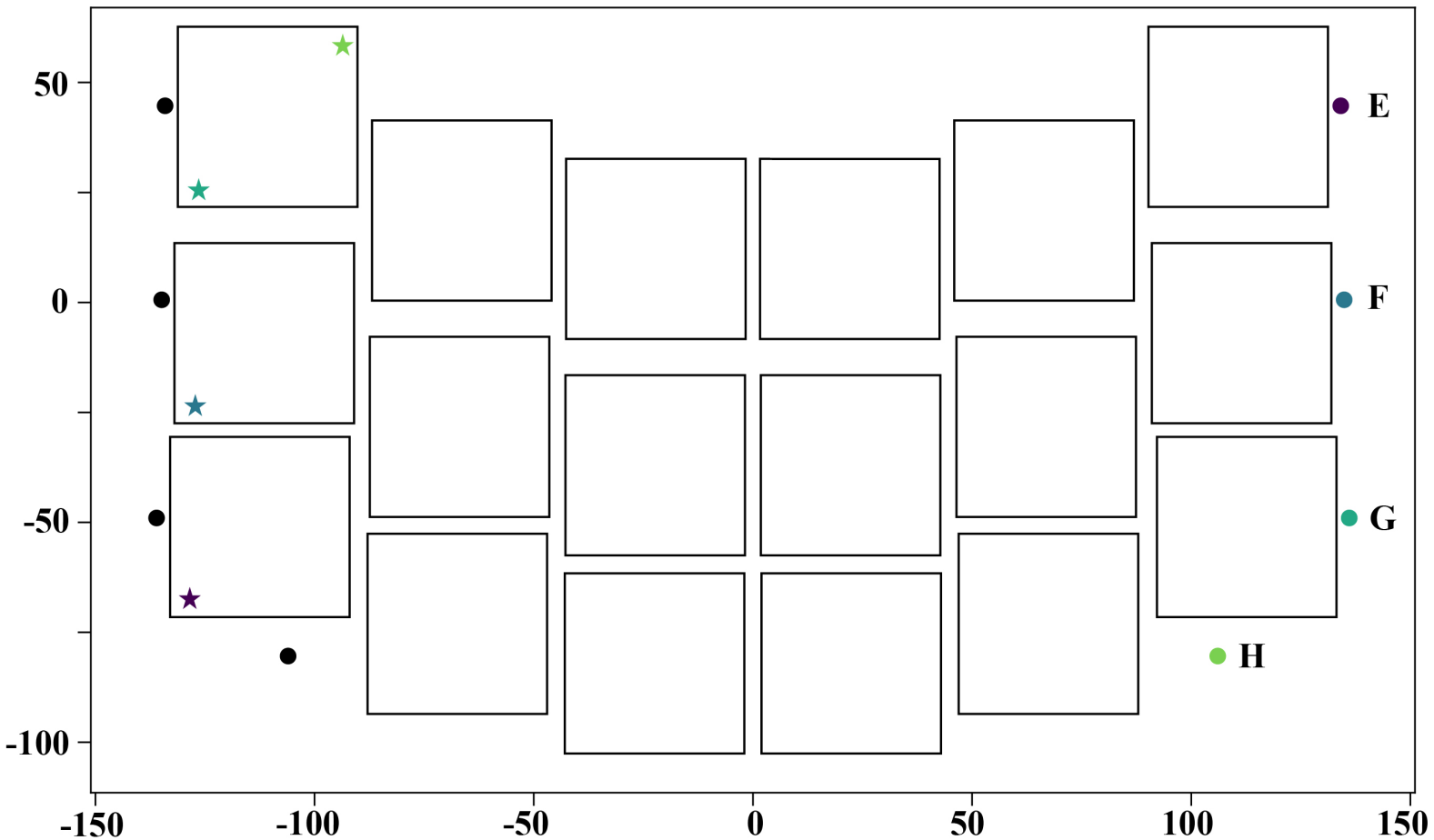
- Translate FPA through focus (three positions)
- Illuminate four fibers at once
- Tilt OLAFS to translate beams across the FPA and sample entire field of view
- Image point sources on the detector[a]



[a] Bergkoetter and Jurling, "Data analysis algorithm for double-pass testing of the Roman Space Telescope".

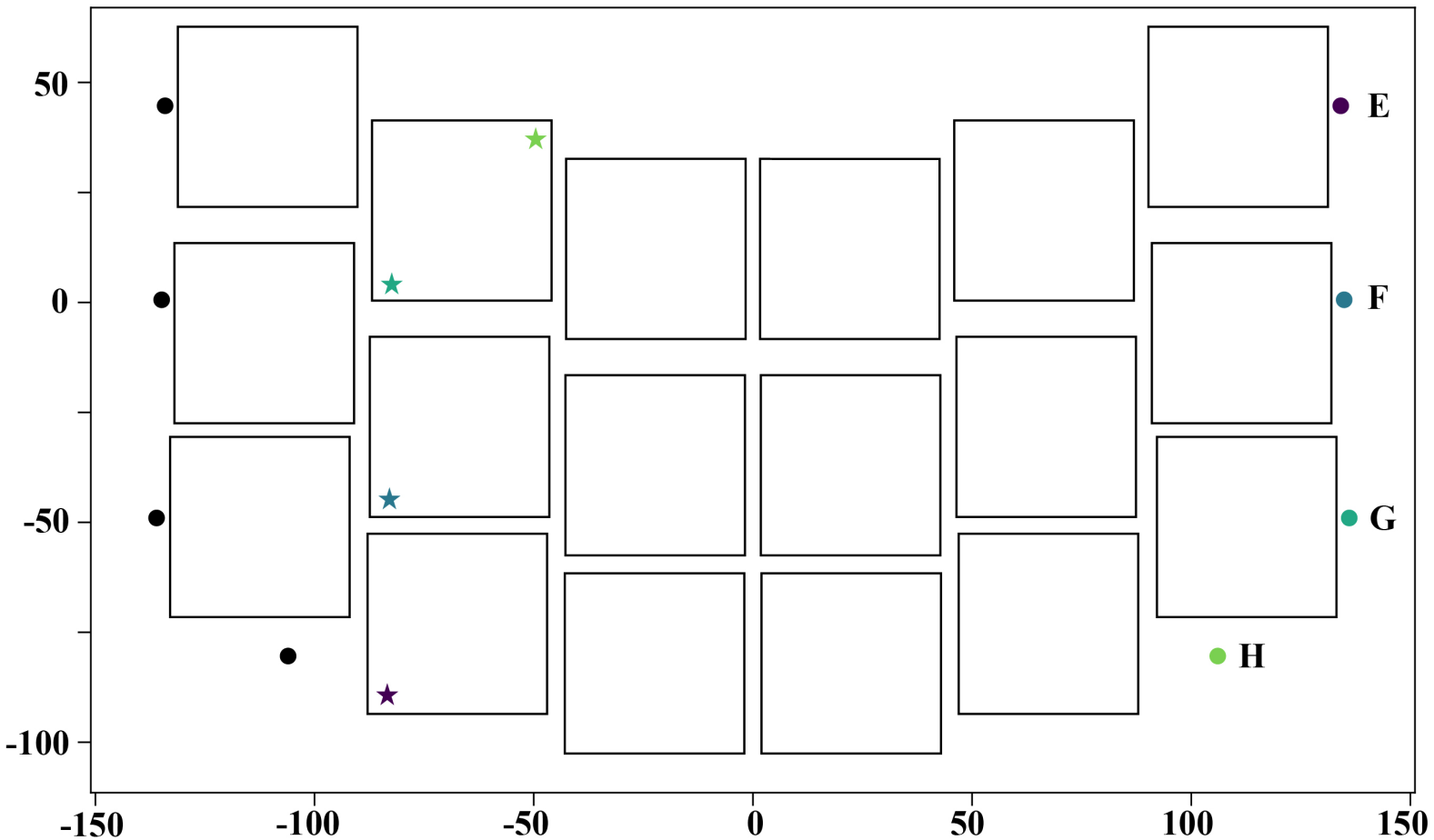
Integrated Payload Testing

Point sources on detector through test pass for 6 OLAFS tilts



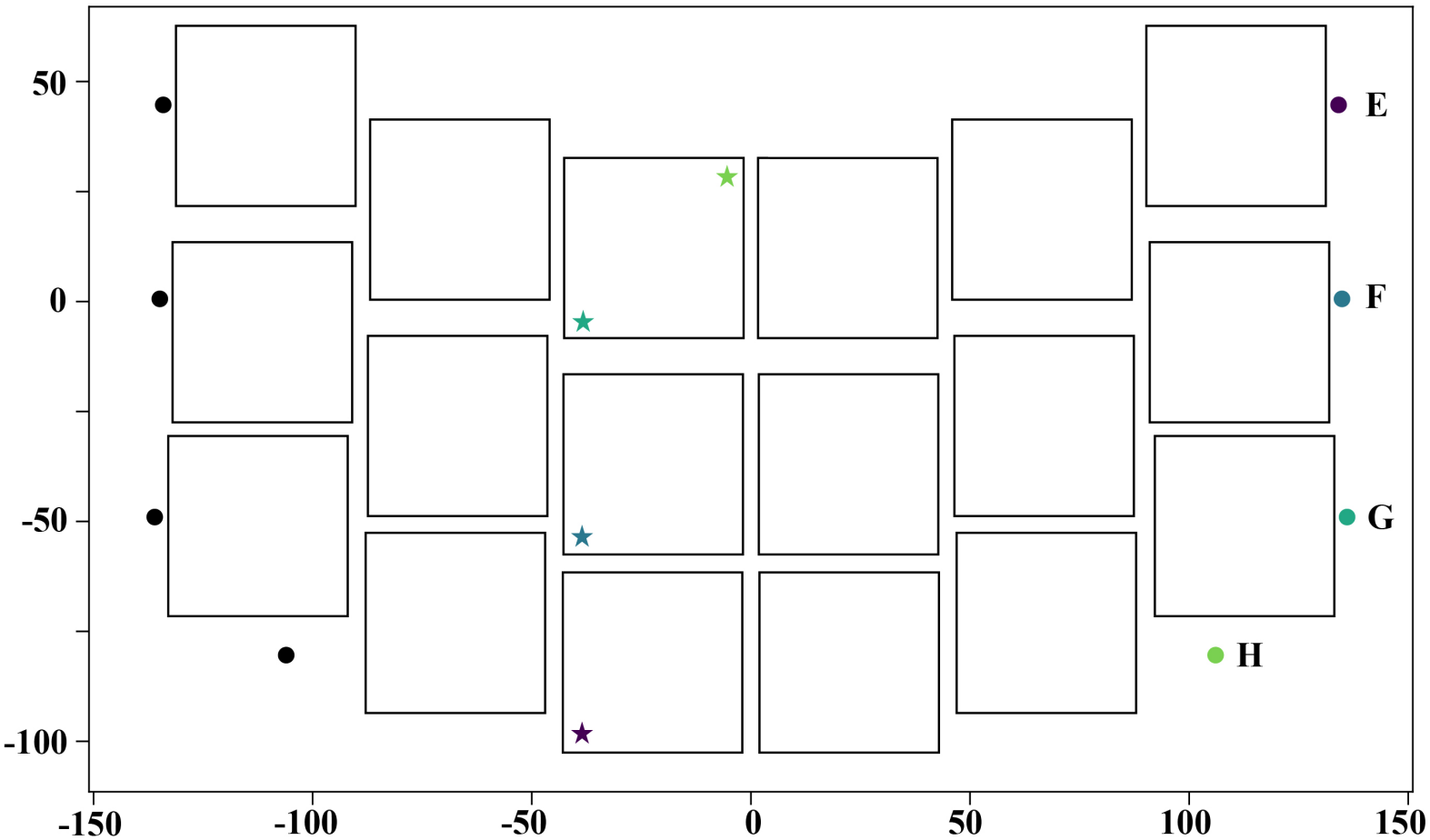
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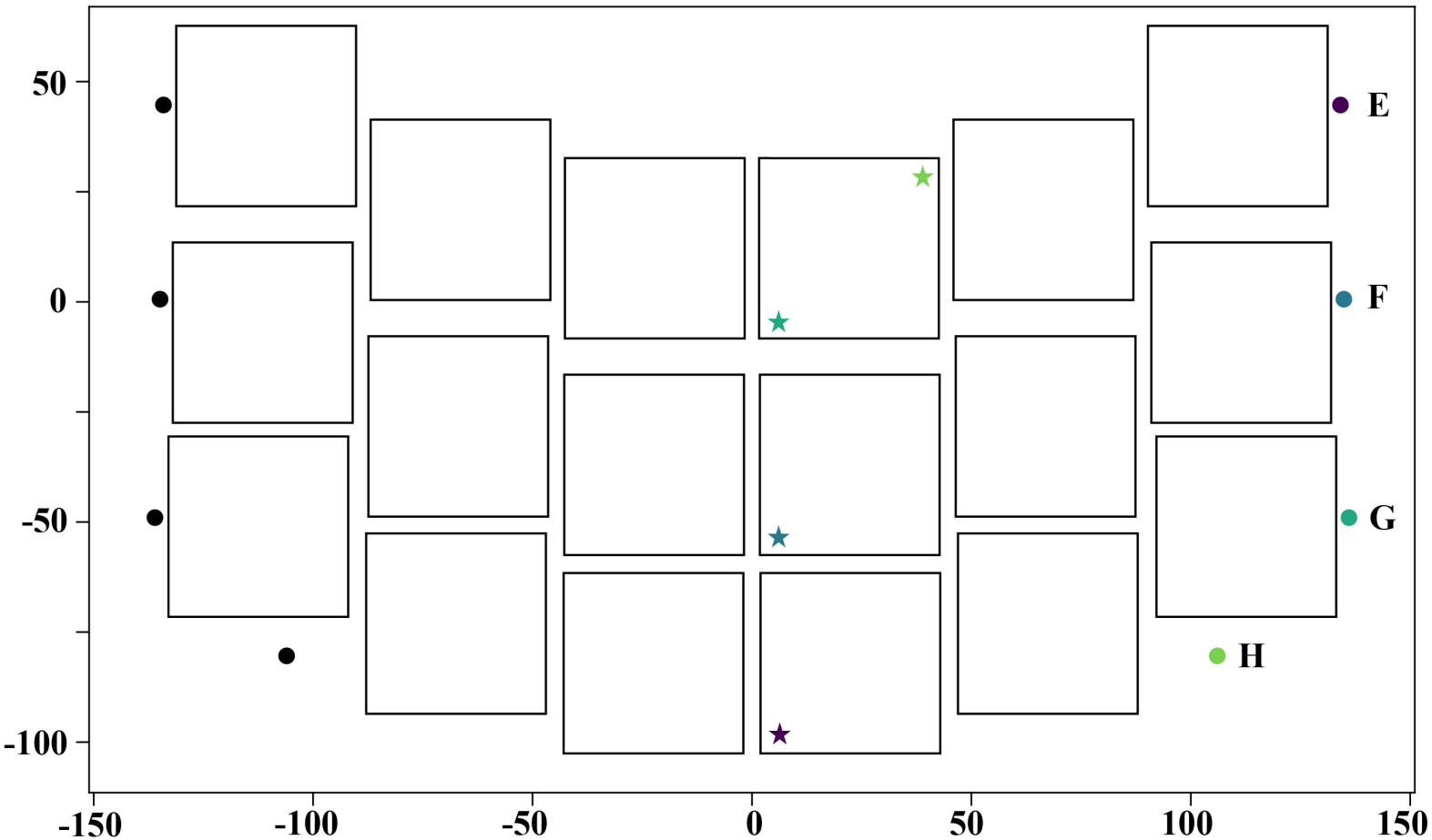
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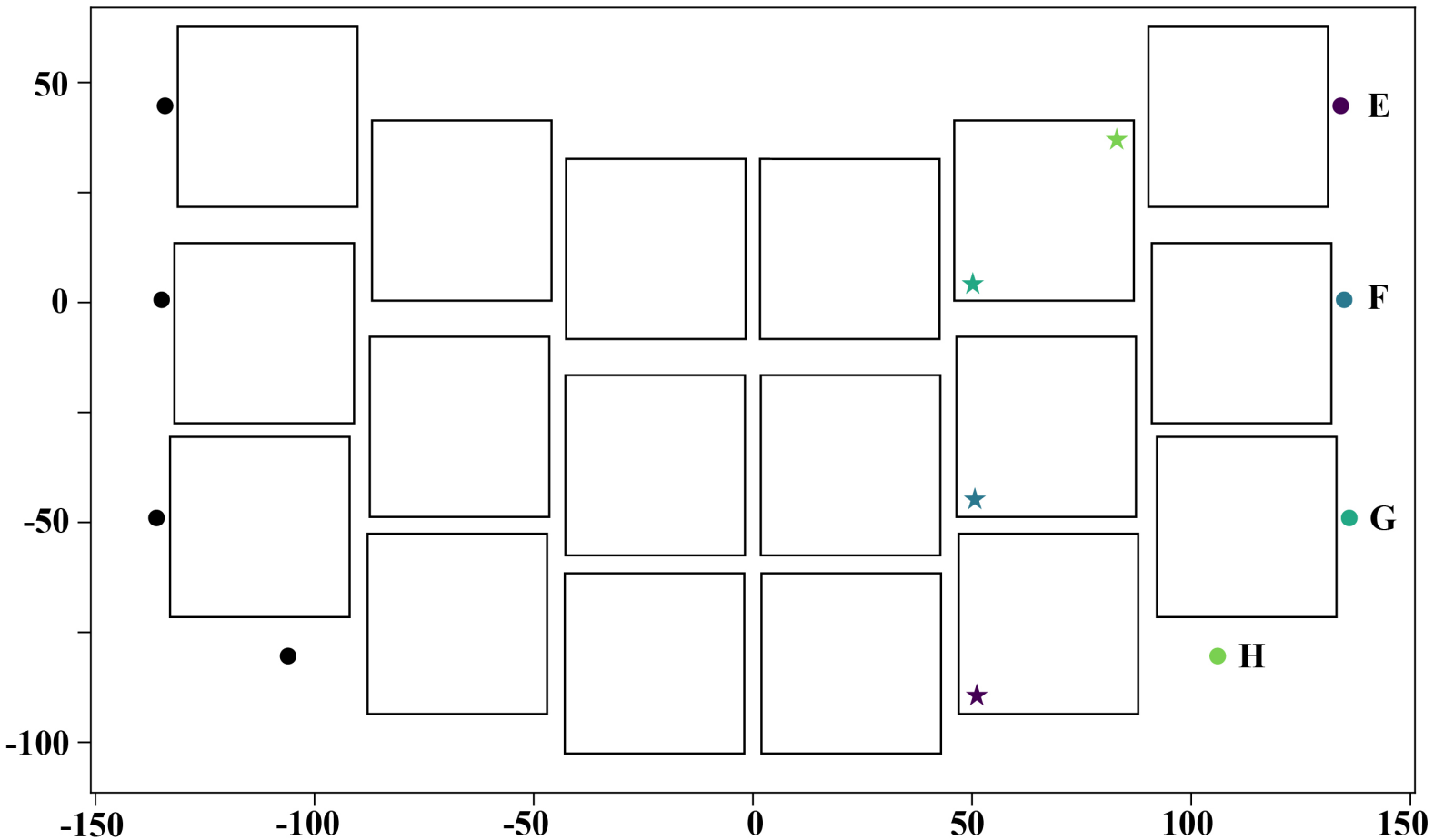
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Point sources on detector through test pass for 6 OLAFS tilts



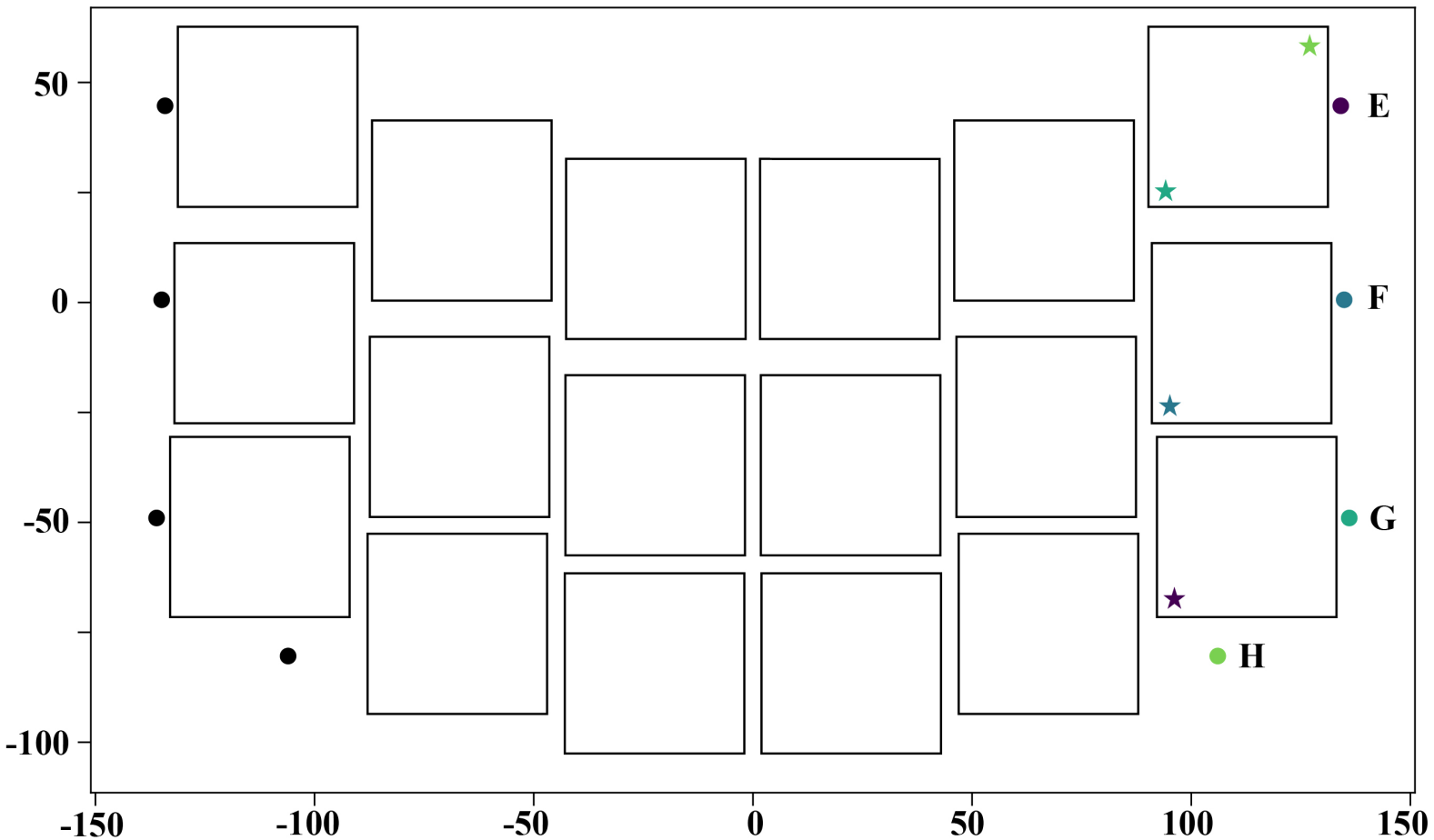
Integrated Payload Testing

Point sources on detector through test pass for 6 OLAFS tilts



Integrated Payload Testing

Point sources on detector through test pass for 6 OLAFS tilts



Integrated Payload Testing

Wavefront Sensing

Phase retrieval was used to characterize Hubble mirror flaw[a]

James Webb Space Telescope demonstrated that phase retrieval is a useful and necessary method of wavefront sensing that can be used through the stages of integration to on-sky alignment[b c d]

- Used for verification in ground testing
- Sole method of wavefront sensing for on-sky alignment

Phase retrieval will be used throughout RST integration

- Will not be able to offload gravity on the primary mirror after integrating payload
- Phase retrieval is most realistic option for wavefront sensing that can accommodate gravity induced aberrations

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[a] Fienup, "Phase-retrieval algorithms for a complicated optical system".

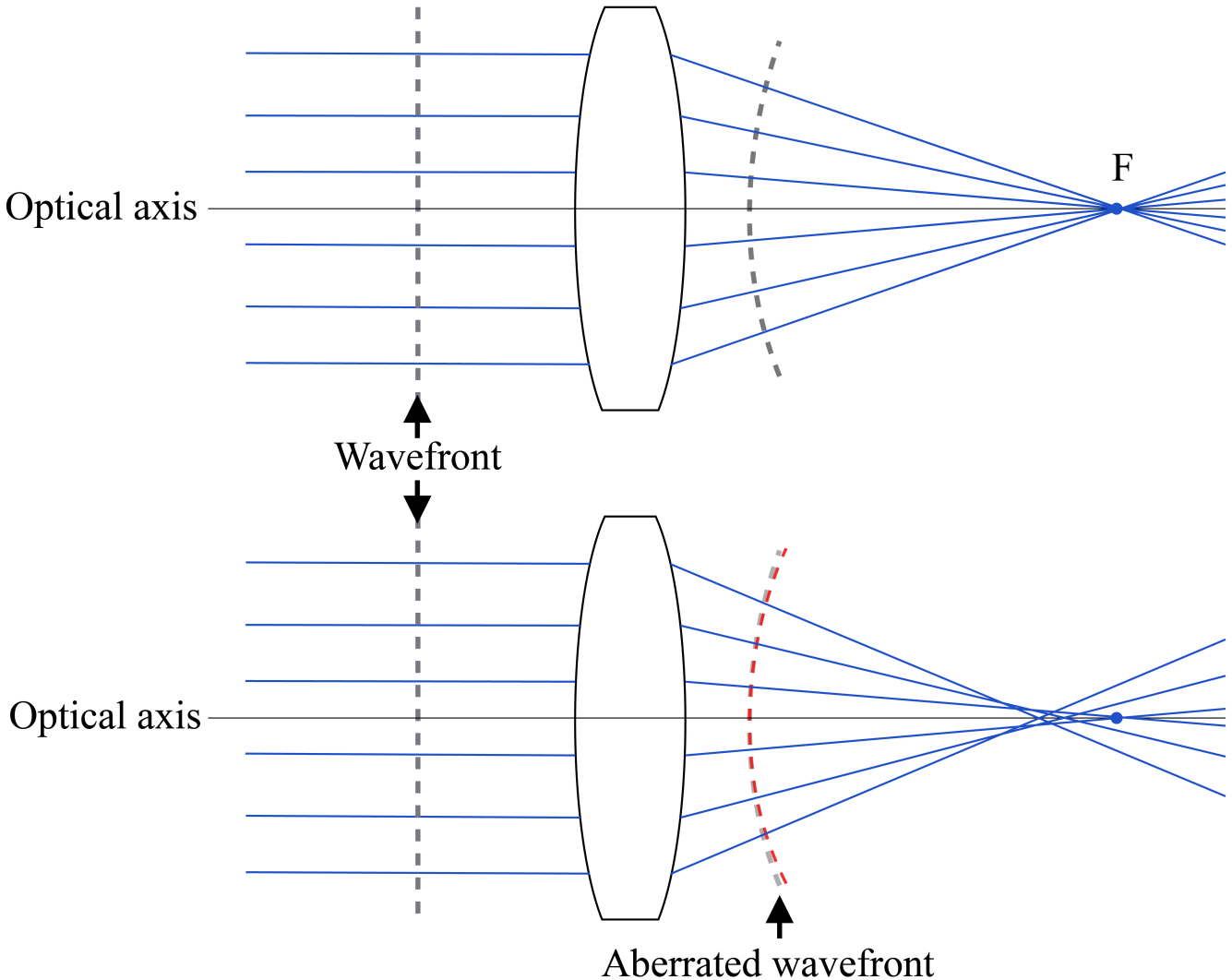
[b] Smith et al., "METHODOLOGY AND RESULTS OF JAMES WEBB SPACE TELESCOPE THERMAL VACUUM OPTICAL SYSTEM ALIGNMENT TESTING AND ANALYSIS".

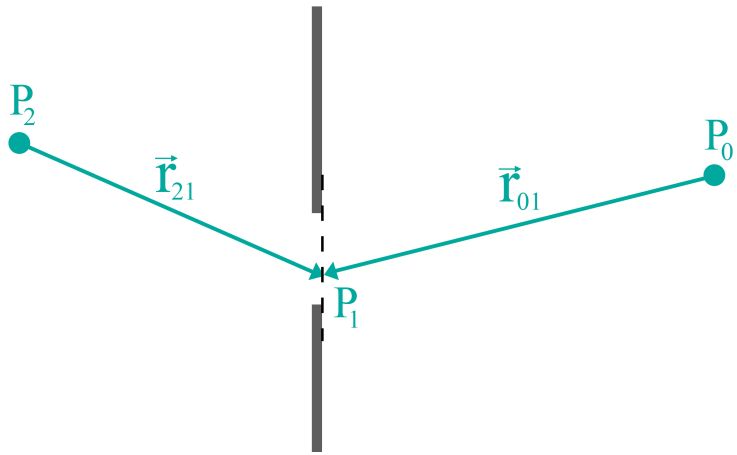
[c] Dean et al., "Phase retrieval algorithm for JWST Flight and Testbed Telescope".

[d] Aronstein et al., "Wavefront-error performance characterization for the James Webb Space Telescope (JWST) Integrated Science Instrument Module (ISIM) science instruments".

Background

What is a wavefront?





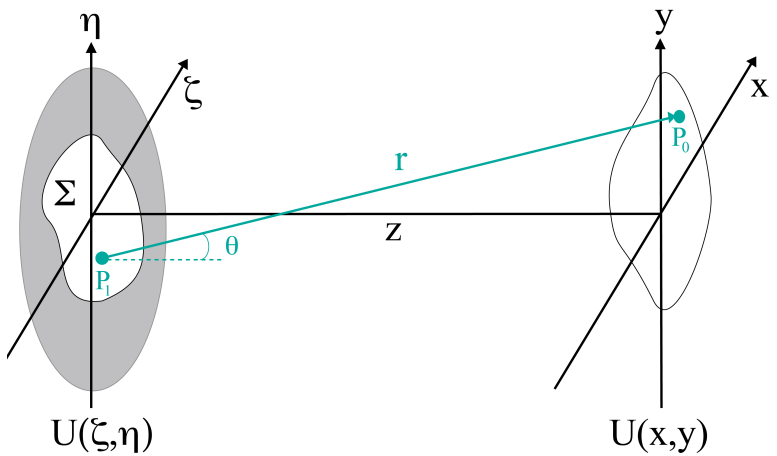
$$U(P_1) = \frac{Ae^{jkr_{21}}}{r_{21}} \tag{1}$$

$U(P_1)$ aperture illumination from single spherical wave diverging from a point source P_2[a]

[a] Goodman, *Introduction to Fourier Optics*.

Fourier Optics

Huygens-Fresnel Principle



$$U(P_0) = \frac{1}{j\lambda} \iint_{\Sigma} U(P_1) \frac{e^{jkr}}{r} \cos\theta ds \tag{2}$$

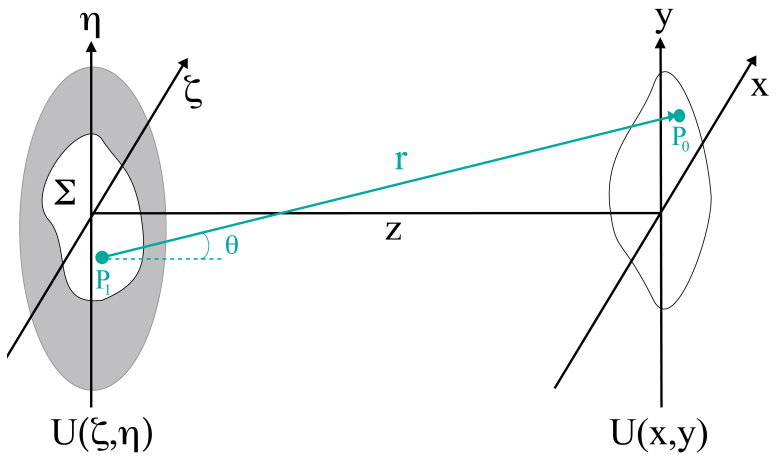
$U(P_0)$ complex field disturbance at P_0

λ wavelength

k wave number

Σ enclosed space around P_1[a]

[a] Goodman, *Introduction to Fourier Optics*.



$$\cos\theta = \frac{z}{r} \tag{3}$$

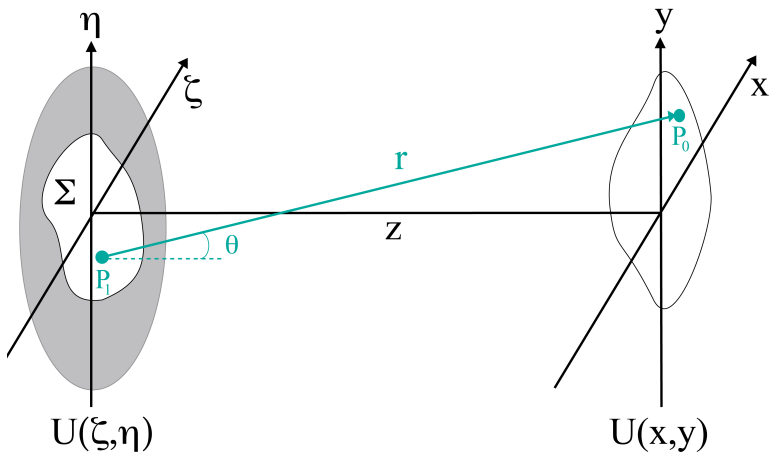
Rewrite as [a]

$$U(x,y) = \frac{1}{j\lambda z}\iint_{\Sigma} U(\xi,\eta)\frac{e^{jkr}}{r^2}ds \tag{4}$$

[a] (Goodman, *Introduction to Fourier Optics*)

Fourier Optics

Fresnel approximation



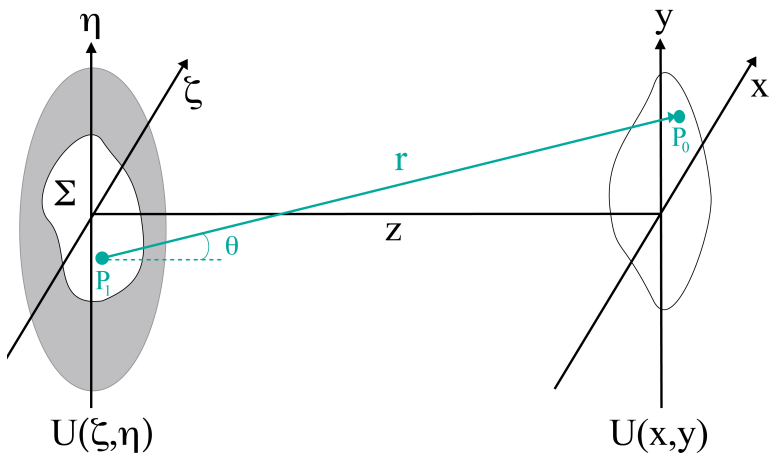
$$U(x,y) = \iint_{-\infty}^{\infty} U(\xi,\eta)\frac{e^{jkr}}{r}\frac{z}{j\lambda r}d\xi d\eta \tag{5}$$

$$r = \sqrt{z^2 + (x-\xi)^2 + (y-\eta)^2} \tag{6}$$

$$r \cong z + \frac{(x-\xi)^2 + (y-\eta)^2}{2z} \tag{7}$$

a

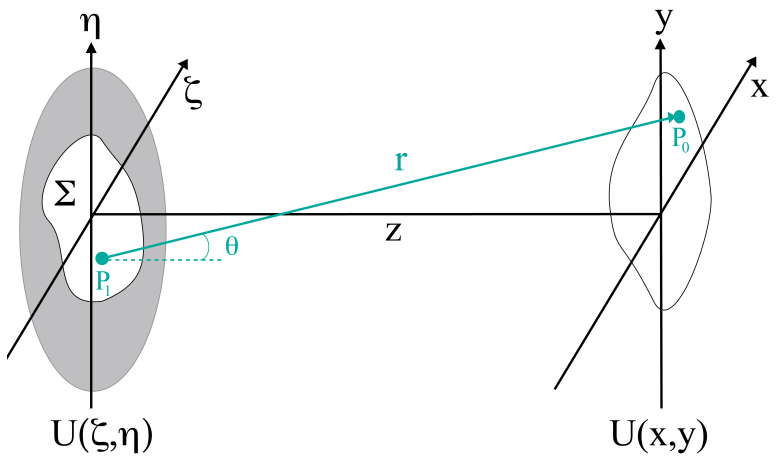
[a] Goodman, *Introduction to Fourier Optics*.



Plugging in the approximation for r, we get the Fresnel diffraction integral[a]

$$U(x,y) = \frac{e^{jkz}}{j\lambda z} e^{\frac{jk}{2z}(x^2+y^2)} \iint_{-\infty}^{\infty} U(\xi,\eta) e^{\frac{jk}{2z}(\xi^2+\eta^2)} e^{\frac{-j2\pi}{\lambda z}(x\xi+y\eta)} d\xi d\eta \qquad (8)$$

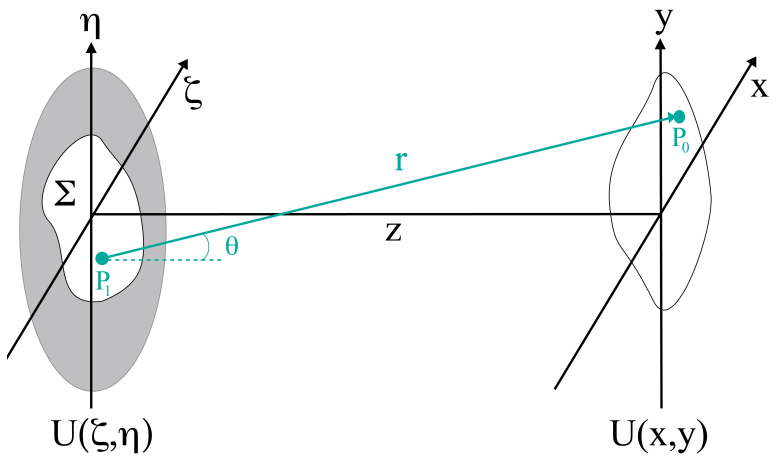
[a] Goodman, *Introduction to Fourier Optics*.



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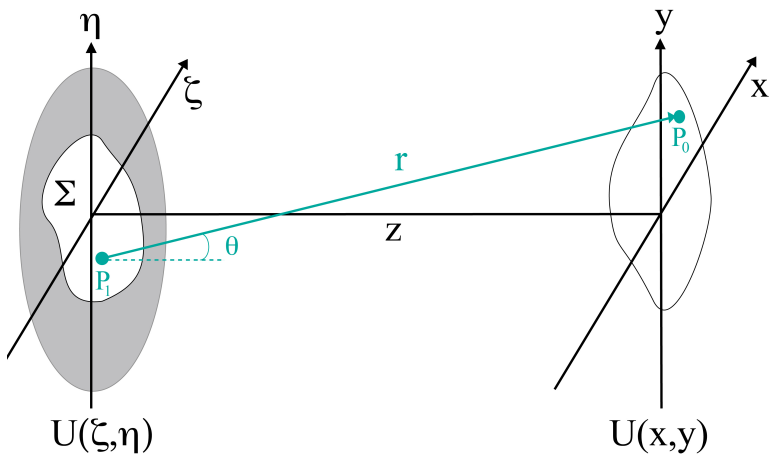
[a] Goodman, *Introduction to Fourier Optics*.



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[a] Goodman, *Introduction to Fourier Optics*.



Plugging in the approximation for r, we get the Fresnel diffraction integral[a]

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[a] Goodman, *Introduction to Fourier Optics*.



Figure: Pupil function

Wavefront is defined as

$$W = \sum_n a_n Z_n, \tag{12}$$

where a_n are coefficients of a basis Z_n
Using W we define the pupil function g

$$g = A \circ e^{\left(\frac{i2\pi}{\lambda} W\right)} \tag{13}$$

with A being the amplitude function and $\circ$ being element-wise multiplication[a]

[a] Fienup, "Phase retrieval algorithms: a comparison".

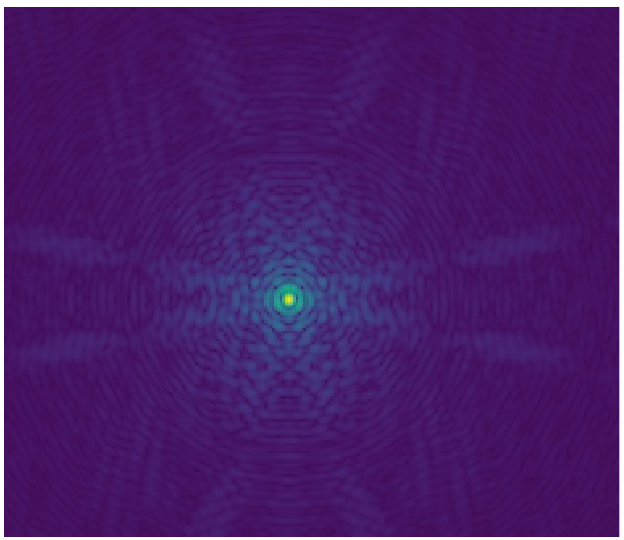


Figure: Modeled point spread function

We propagate from the pupil plane to the image plane G with a Fourier transform

$$G = \mathcal{FFT}\{g\} \tag{14}$$

The intensity I is the modeled point spread function for the forward model[ab]

$$I = |G|^2 \tag{15}$$

[a] Fienup, "Phase retrieval algorithms: a comparison".

[b] Fienup, "Phase-retrieval algorithms for a complicated optical system".

Phase Retrieval

Iterative algorithm (Gerberg-Saxton)

- Starts with wavefront guess and performs field propagation, adjusts parameters, and uses Fourier transform to propagate back and forth from pupil to image plane until the model sufficiently matches the measured data[a]
- Can be straightforward to implement- few lines of code
- Difficult to scale algorithm for complex problems
- Can be prone to stagnation

[a] Gerchberg, "A practical algorithm for the determination of phase from image and diffraction plane pictures".

Phase Retrieval

Nonlinear optimization approach

The error metric ϵ is the sum of squares difference between our modeled point spread function and the measured data D

$$\epsilon = \frac{\sum w \circ (\alpha I + \beta - D)^2}{\sum w \circ D^2}. \tag{16}$$

where w is a weighing function to account for noise and bad pixels in the measured data

α and β are model parameters to account for gain and bias in the measured data

Error metric is minimized using nonlinear optimization

Gradients are constructed using algorithmic differentiation[a][b]

[a] Jurling and Fienup, "Applications of algorithmic differentiation to phase retrieval algorithms".

[b] Fienup, "Phase retrieval algorithms: a comparison".

a

$$\bar{I} = 2\alpha w \circ (I_m - D_m) \tag{17}$$

$$\bar{G} = 2G \circ \bar{I} \tag{18}$$

$$\bar{g} = /\mathcal{IFFT}\{\bar{G}\} \tag{19}$$

$$\bar{W} = \frac{2\pi}{\lambda}\Im[\bar{g} \circ g*] \tag{20}$$

$$\bar{a_n} = \sum_m (\bar{W_m} \circ Z_n)_m \tag{21}$$

$$\bar{A} = \bar{g} \circ exp(\frac{-i2\pi}{\lambda}W) \tag{22}$$

[a] Jurling and Fienup, "Applications of algorithmic differentiation to phase retrieval algorithms".

Phase Retrieval

Nonlinear optimization approach

- Less simple to implement than iterative approach
- Forward model can account for advanced features and is easier to scale with system complexity
- Error metric can be adjusted to account for data artifacts[abc]

[a] Fienup, "Phase-retrieval algorithms for a complicated optical system".

[b] Jurling, "Advances in algorithms for image based wavefront sensing".

[c] Bergkoetter, "Phase retrieval for chromatic aberrations and wide-field detectors".

Phase Retrieval

Challenges

- Phase retrieval is generally dependent on a well understood system
- The ground support equipment (SAMS and OLAFS) position will effect this system understanding
- The extreme environmental changes within the chamber can lead to temperature deformation of the SAMS which introduces knowledge error in the phase retrieval

Phase Retrieval

Algorithm for study

- Goal is characterization not compensation
- Want to fully understand the effects of pupil knowledge error
- Optimized over tip/tilt, low-order Zernike functions, and a point-by-point fit[a]

[a] Jurling, Bergkoetter, and Fienup, "Techniques for arbitrary sampling in two-dimensional Fourier transforms".

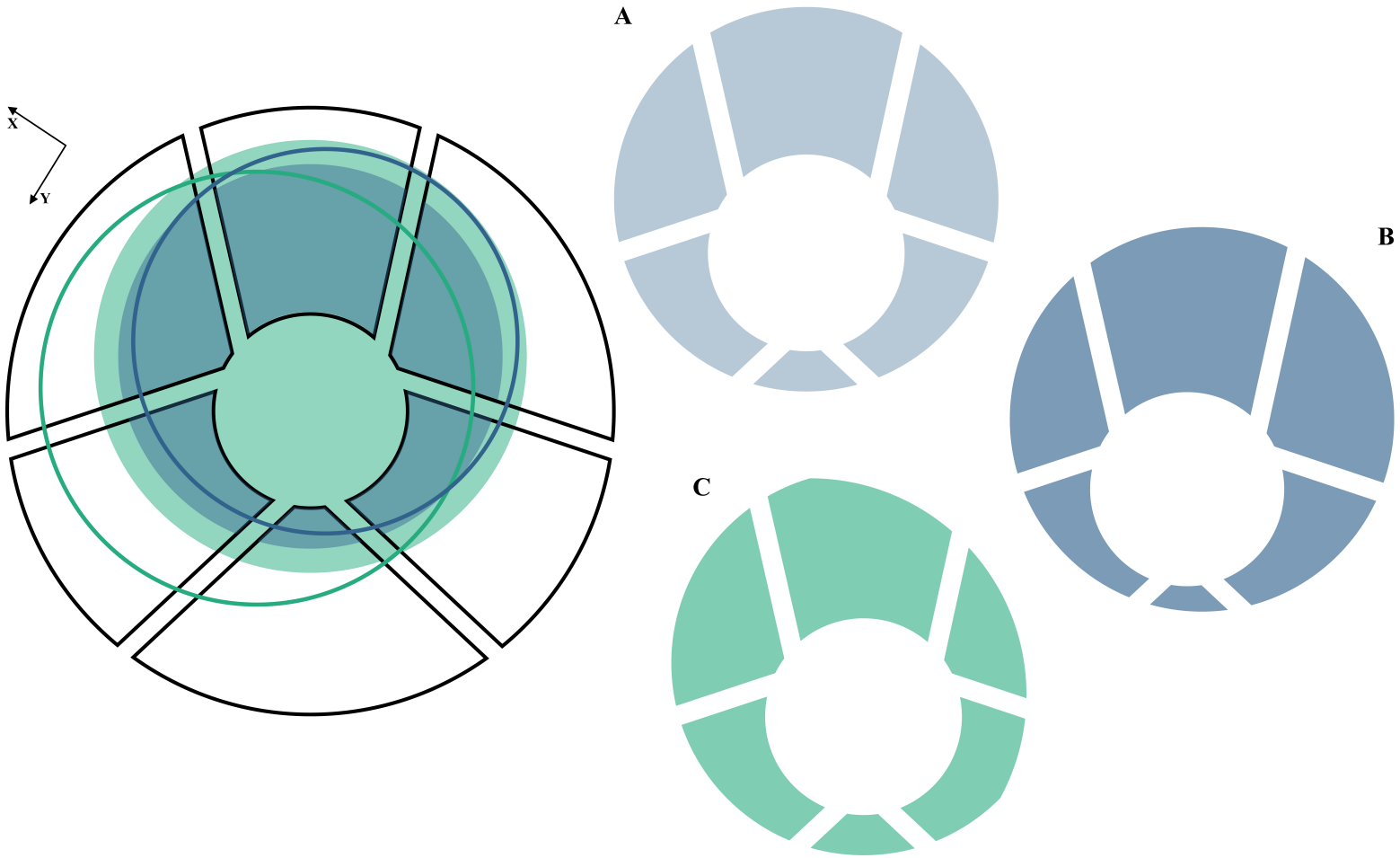
Ideal model
- No surface aberrations or misalignments

Monte Carlo perturbed models
- 30 models generated with perturbed surfaces
- Simulates possible misalignment/surface errors
- No gravity sag

Gravity sag model
- Simulates aberration due to gravity sag on primary mirror

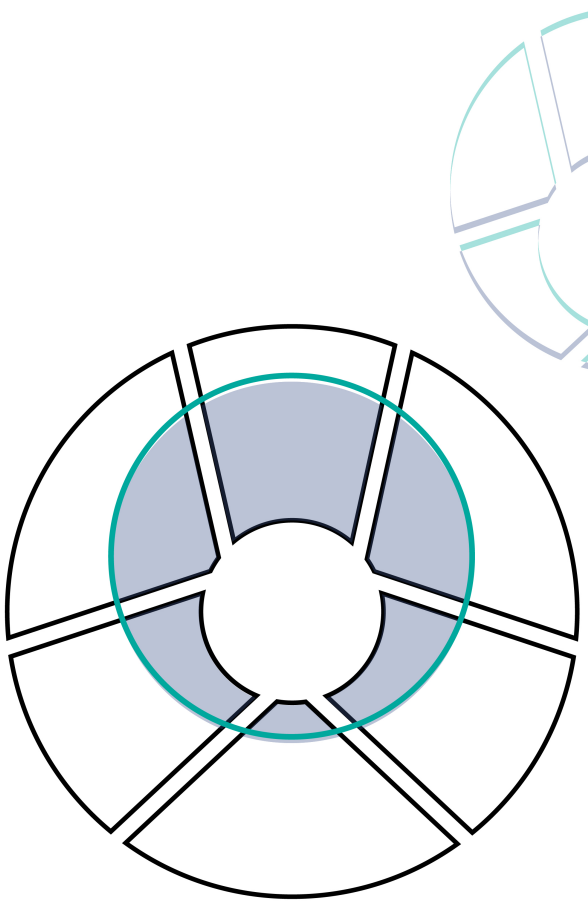
Simulation

Effect of component decentering on pupil

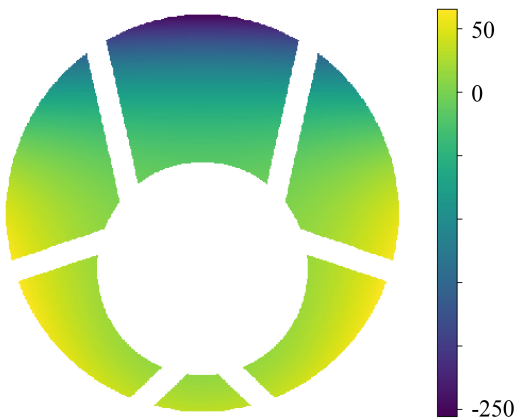


Simulation

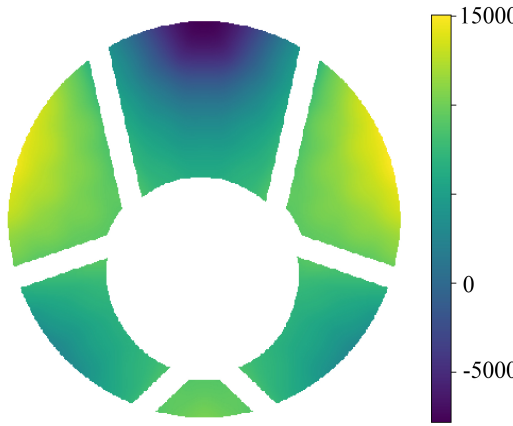
Effect of component decentering on fitting







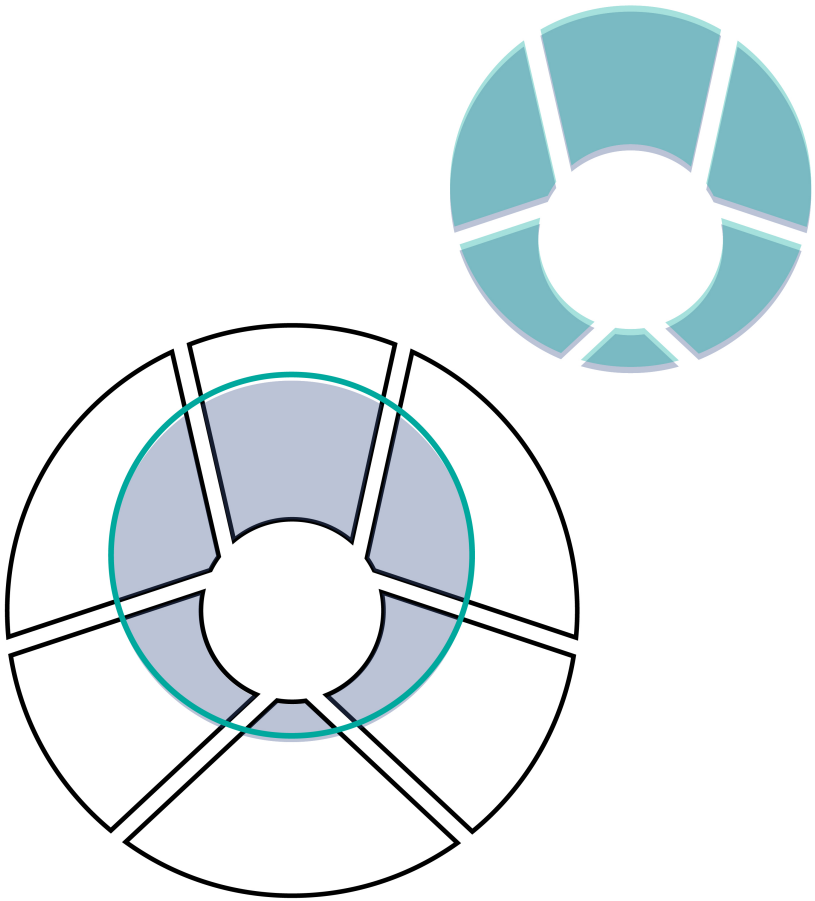
73.1 nm RMS WFE

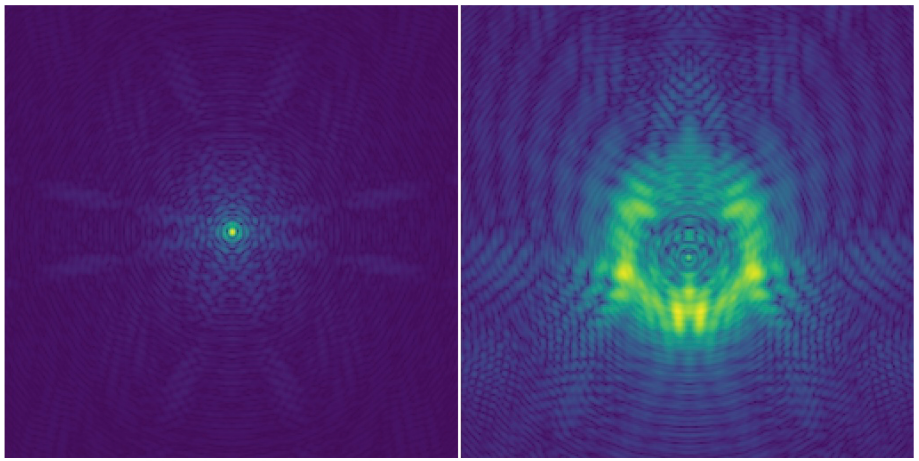


8238.1 nm RMS WFE

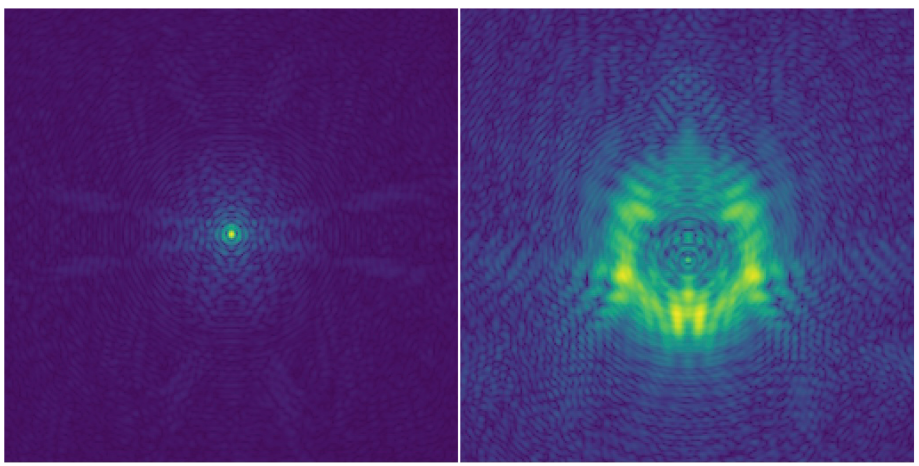
Simulation

Effect of component decentering on fitting



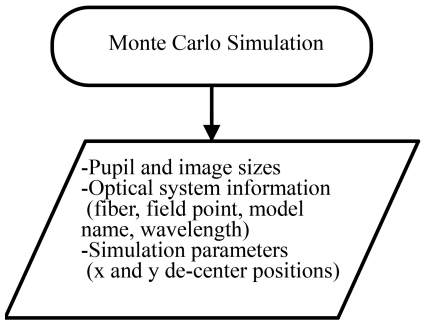


Measured Point Spread Function



Fitted Point Spread Function

Simulation

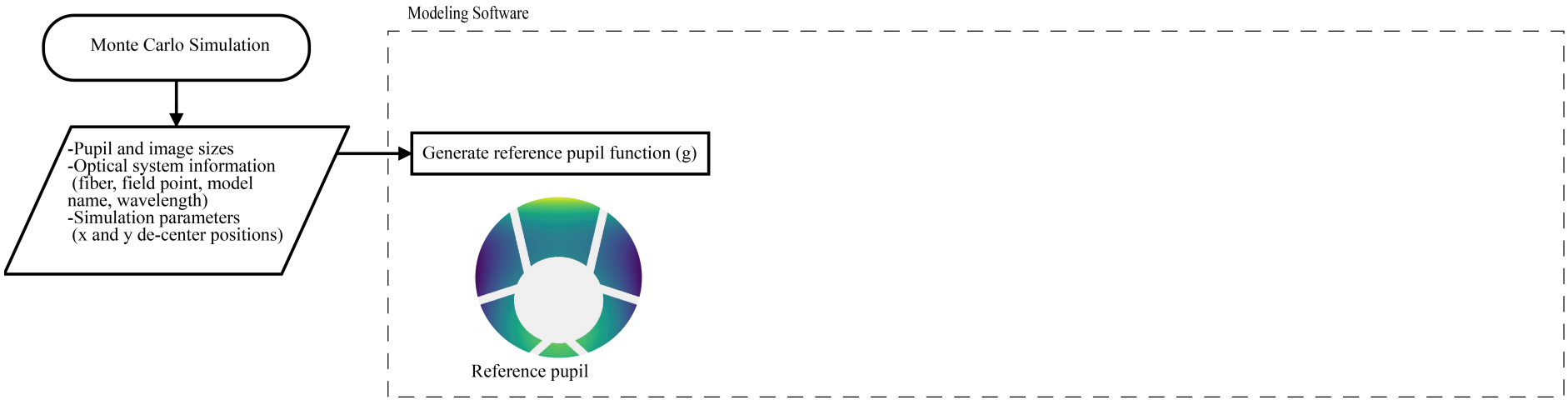


ab

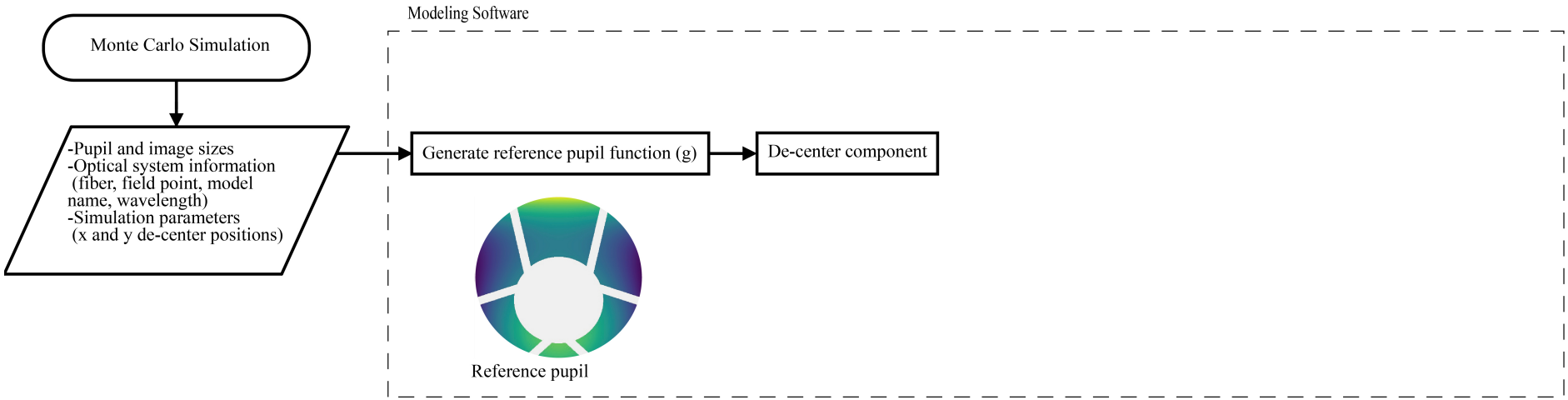
[a] Jurling, "Advances in algorithms for image based wavefront sensing".

[b] Bergkoetter, "Phase retrieval for chromatic aberrations and wide-field detectors".

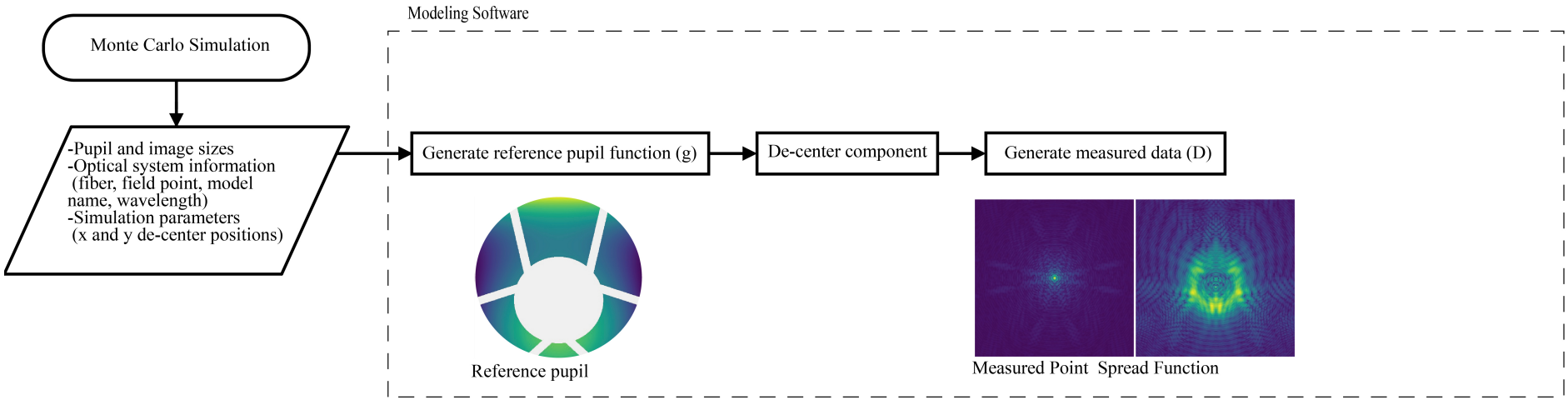
Simulation


Monte Carlo Simulation
-Pupil and image sizes
-Optical system information
(fiber, field point, model
name, wavelength)
-Simulation parameters
(x and y de-center positions)
Modeling Software
Generate reference pupil function (g)
Reference pupil

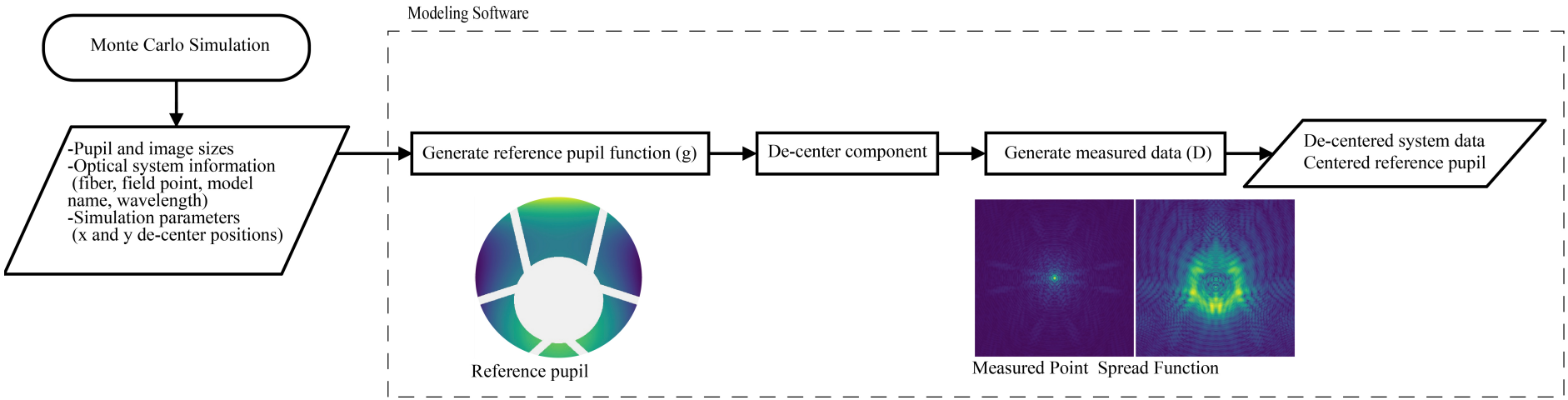
Simulation


Monte Carlo Simulation
-Pupil and image sizes
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-Simulation parameters
(x and y de-center positions)
Modeling Software
Generate reference pupil function (g)
De-center component
Reference pupil

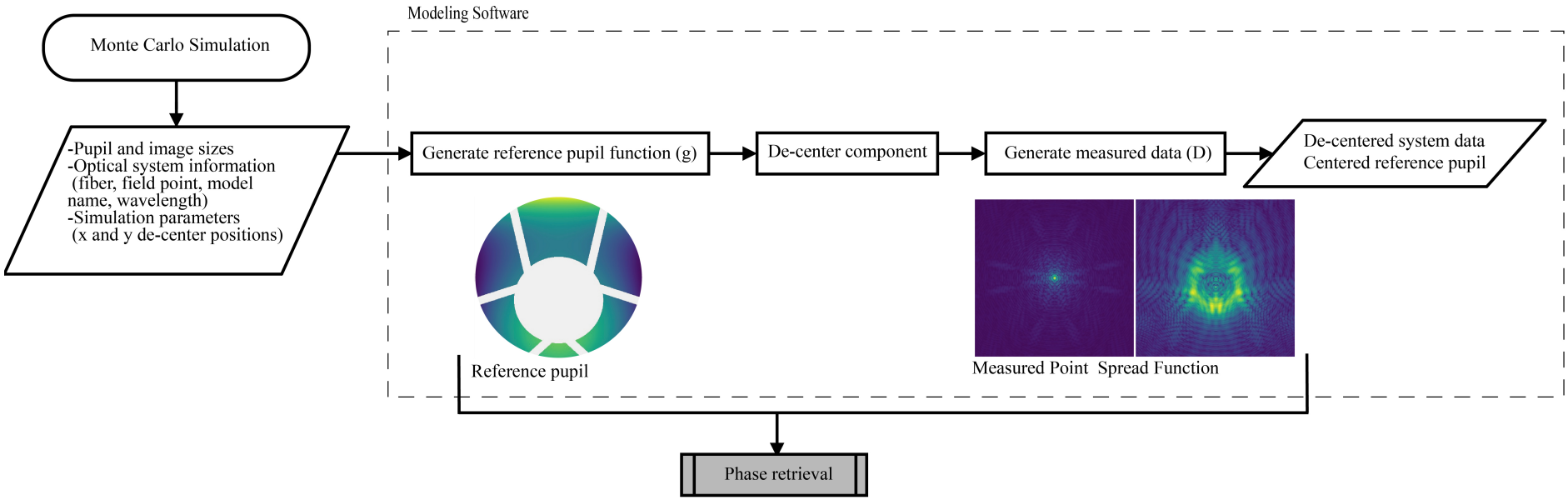
Simulation


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Modeling Software
Generate reference pupil function (g)
De-center component
Generate measured data (D)
Reference pupil
Measured Point Spread Function

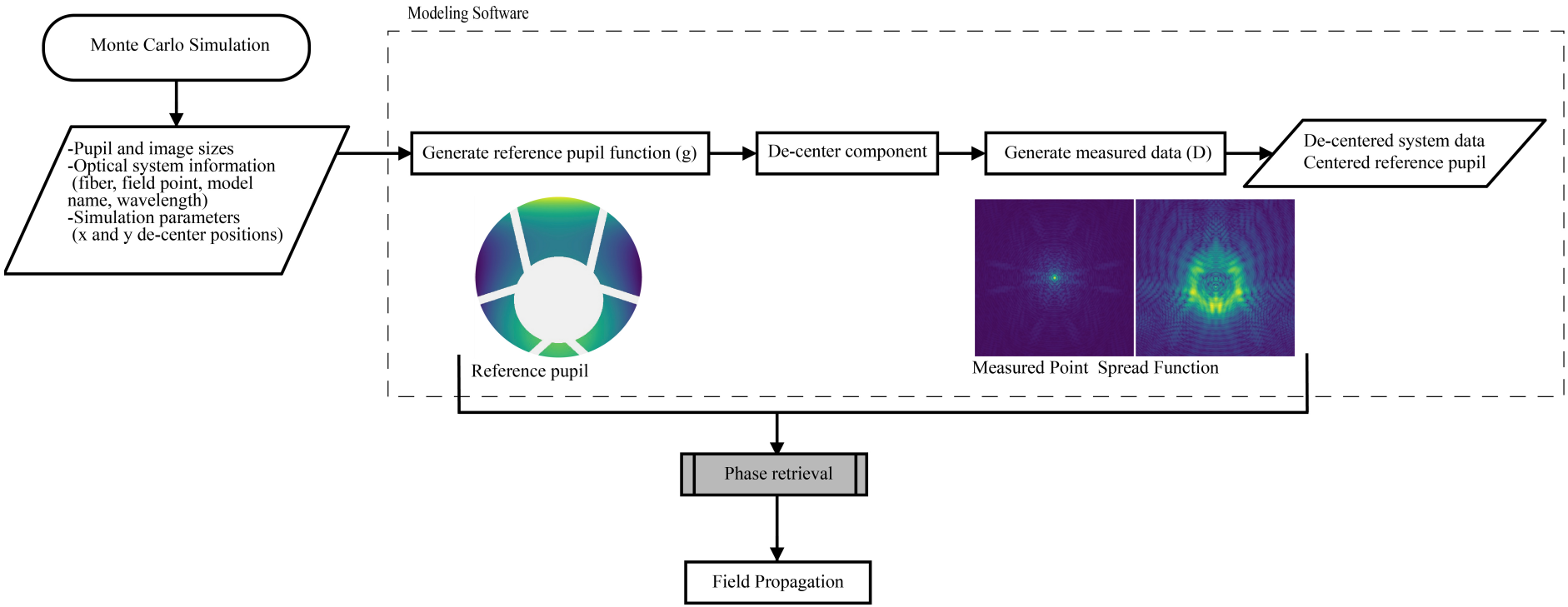
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Generate reference pupil function (g)
De-center component
Generate measured data (D)
De-centered system data
Centered reference pupil
Reference pupil
Measured Point Spread Function

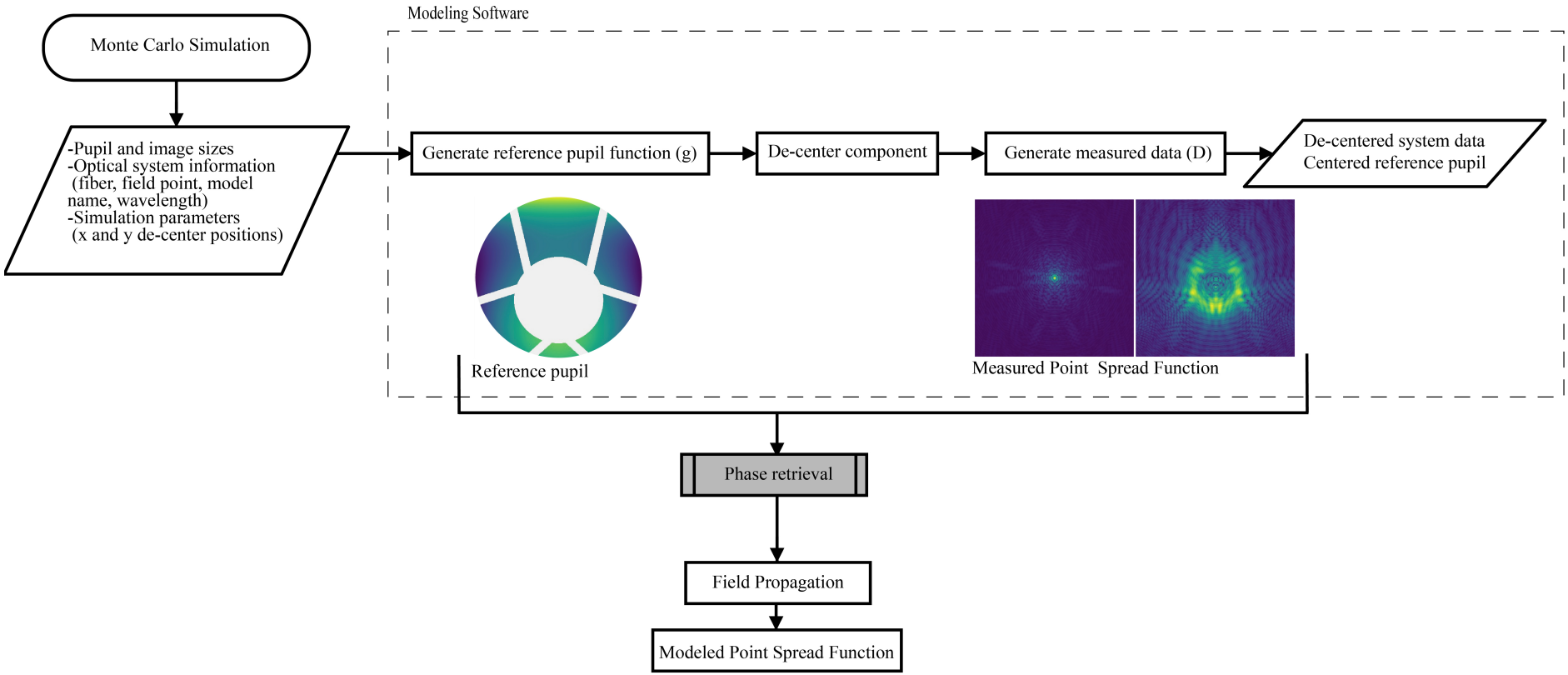
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Generate reference pupil function (g)
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Phase retrieval

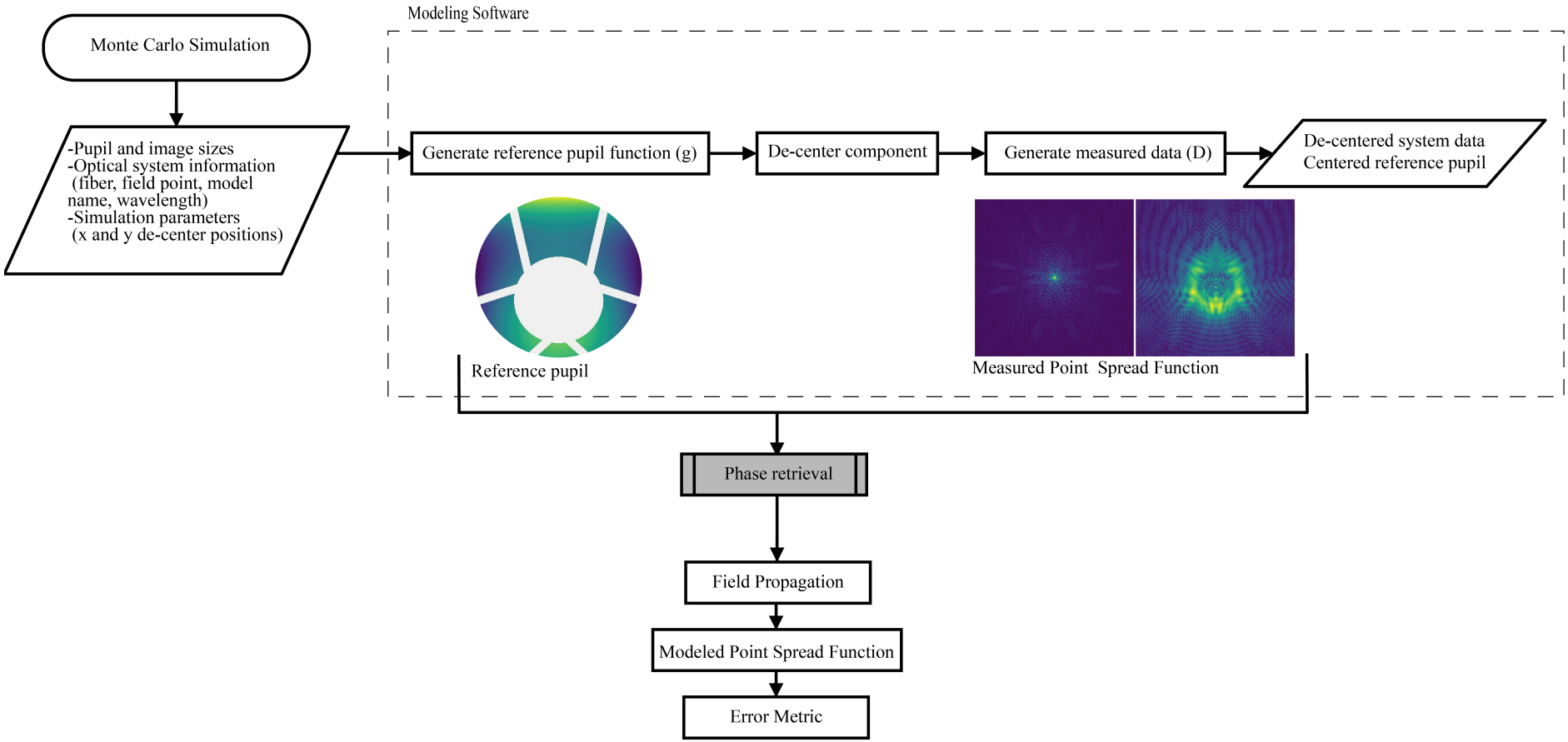
Simulation


Modeling Software
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Centered reference pupil
Reference pupil
Measured Point Spread Function
Phase retrieval
Field Propagation

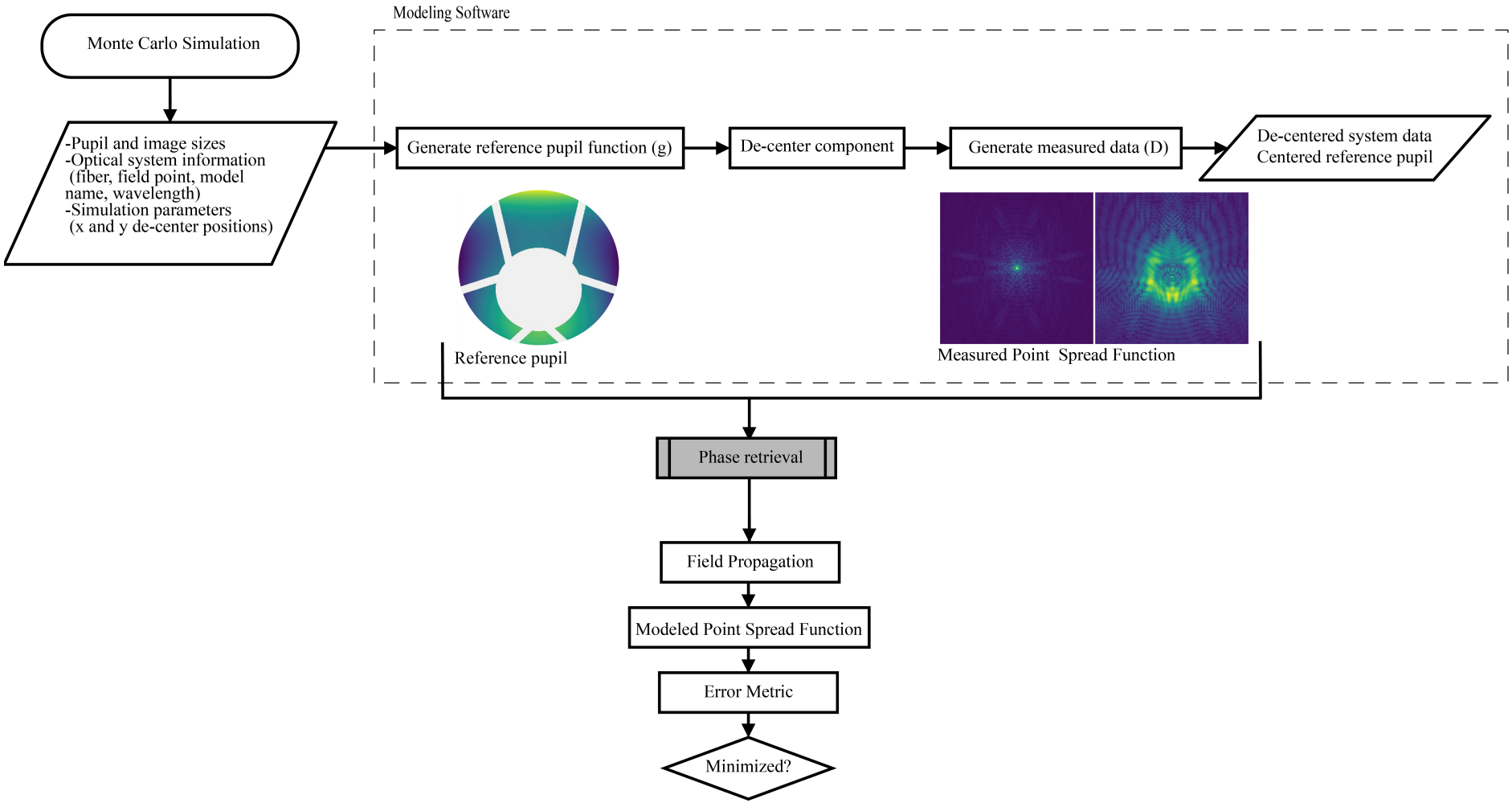
Simulation


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Reference pupil
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Phase retrieval
Field Propagation
Modeled Point Spread Function

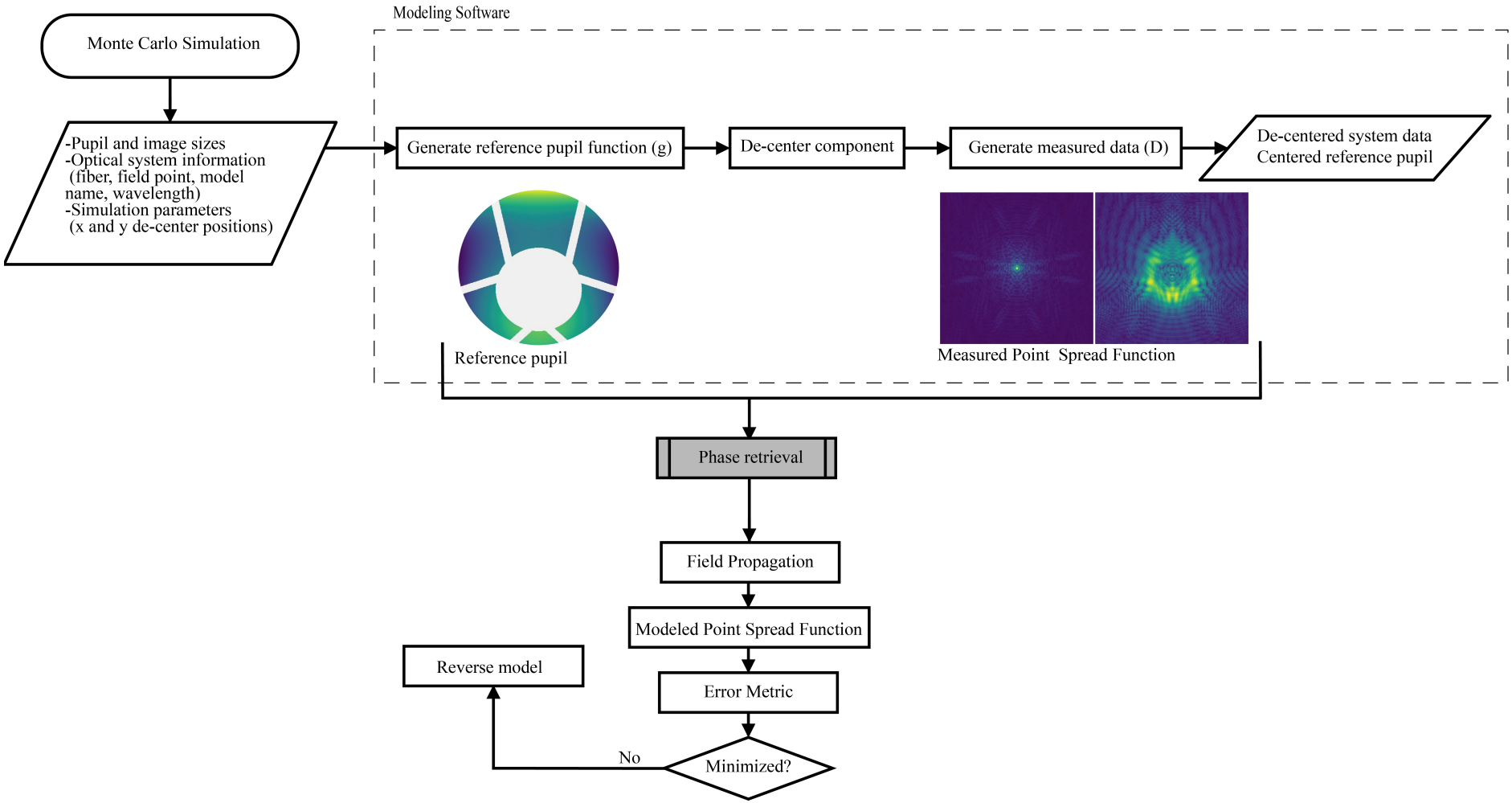
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Field Propagation
Modeled Point Spread Function
Error Metric

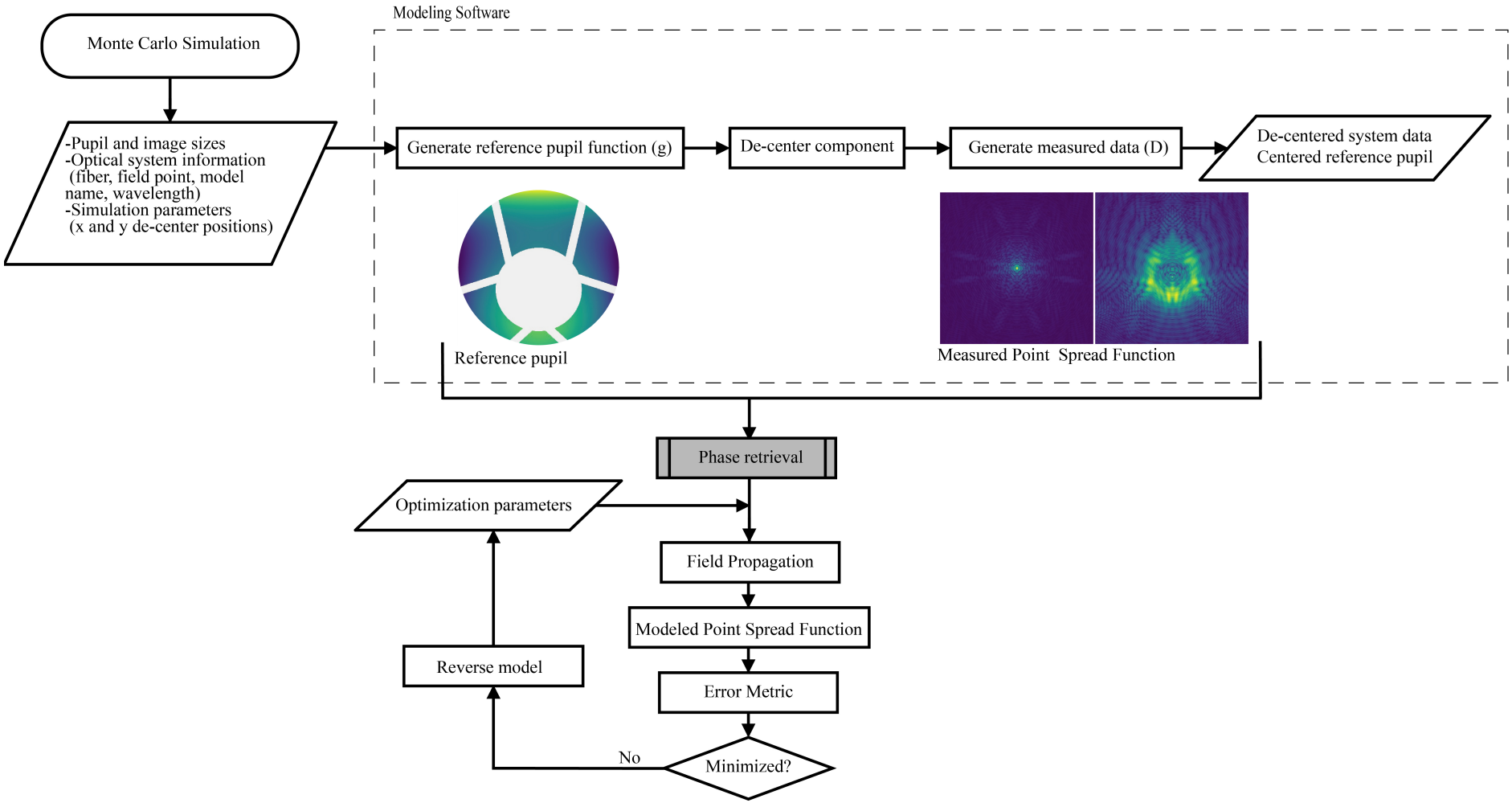
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Phase retrieval
Field Propagation
Modeled Point Spread Function
Error Metric
Minimized?

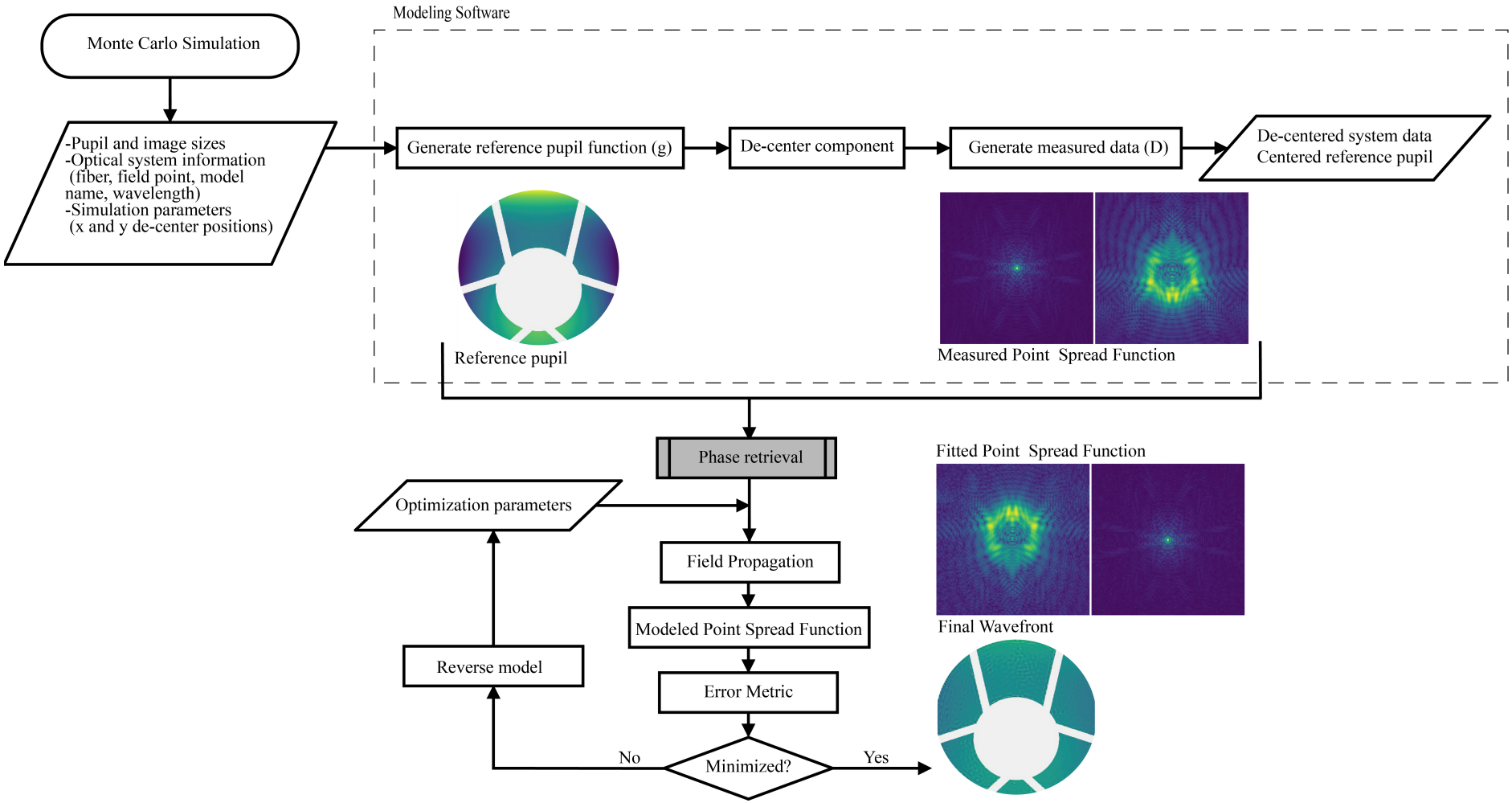
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Reference pupil
Measured Point Spread Function
Phase retrieval
Field Propagation
Modeled Point Spread Function
Error Metric
Minimized?
No
Reverse model

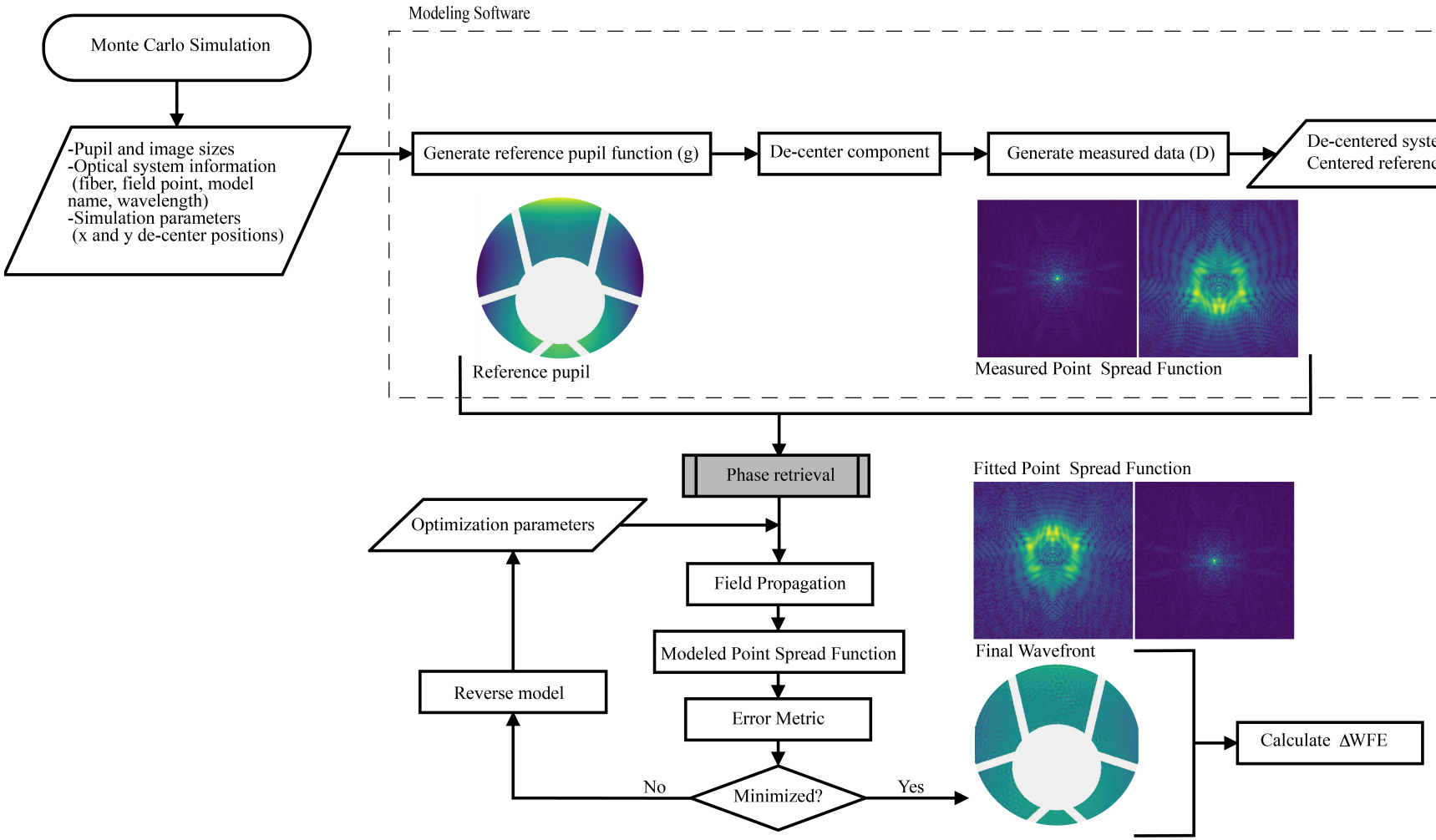
Simulation


Modeling Software
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Modeled Point Spread Function
Reverse model
Error Metric
No
Minimized?

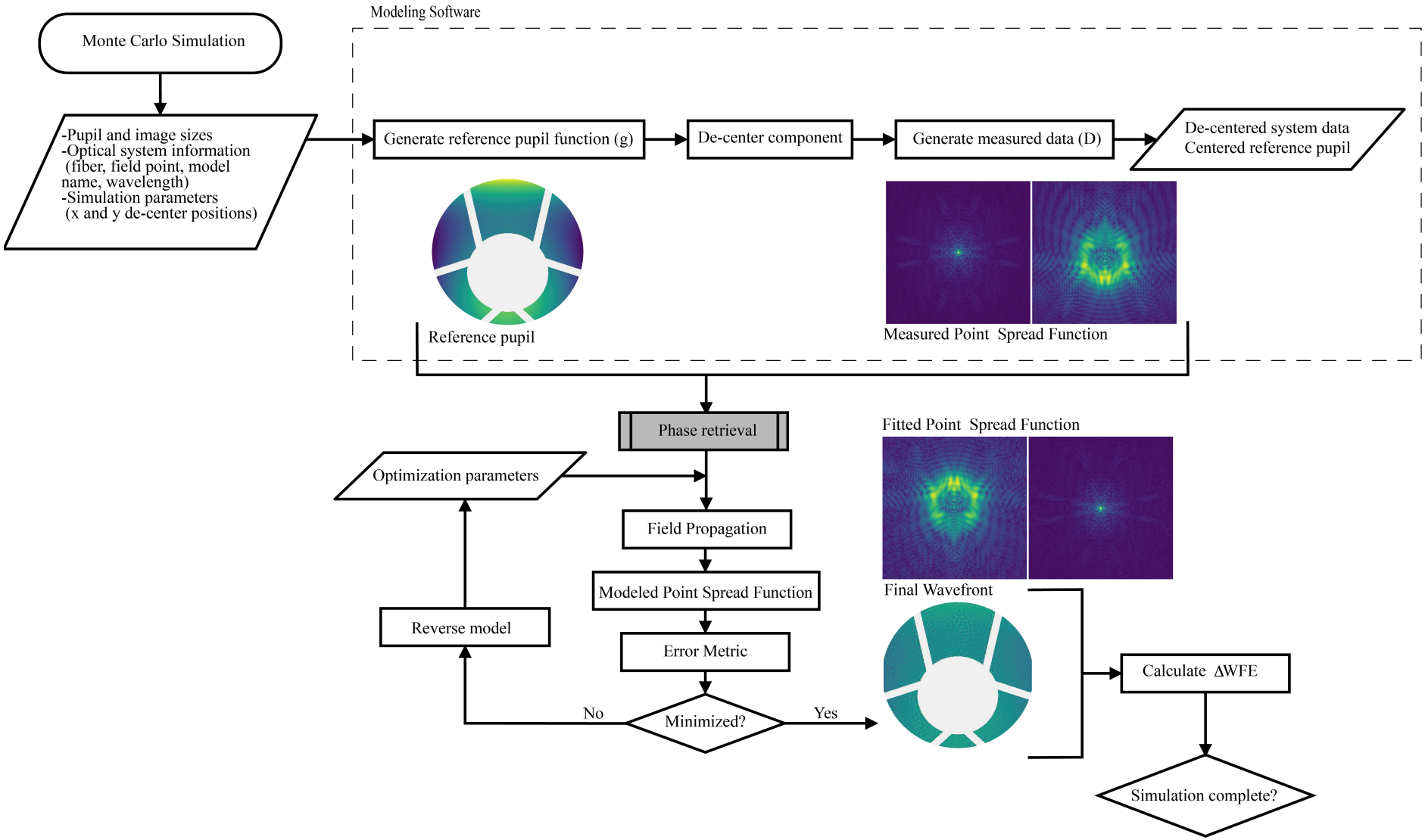
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Measured Point Spread Function
Phase retrieval
Optimization parameters
Field Propagation
Modeled Point Spread Function
Error Metric
Reverse model
No
Minimized?
Yes
Fitted Point Spread Function
Final Wavefront

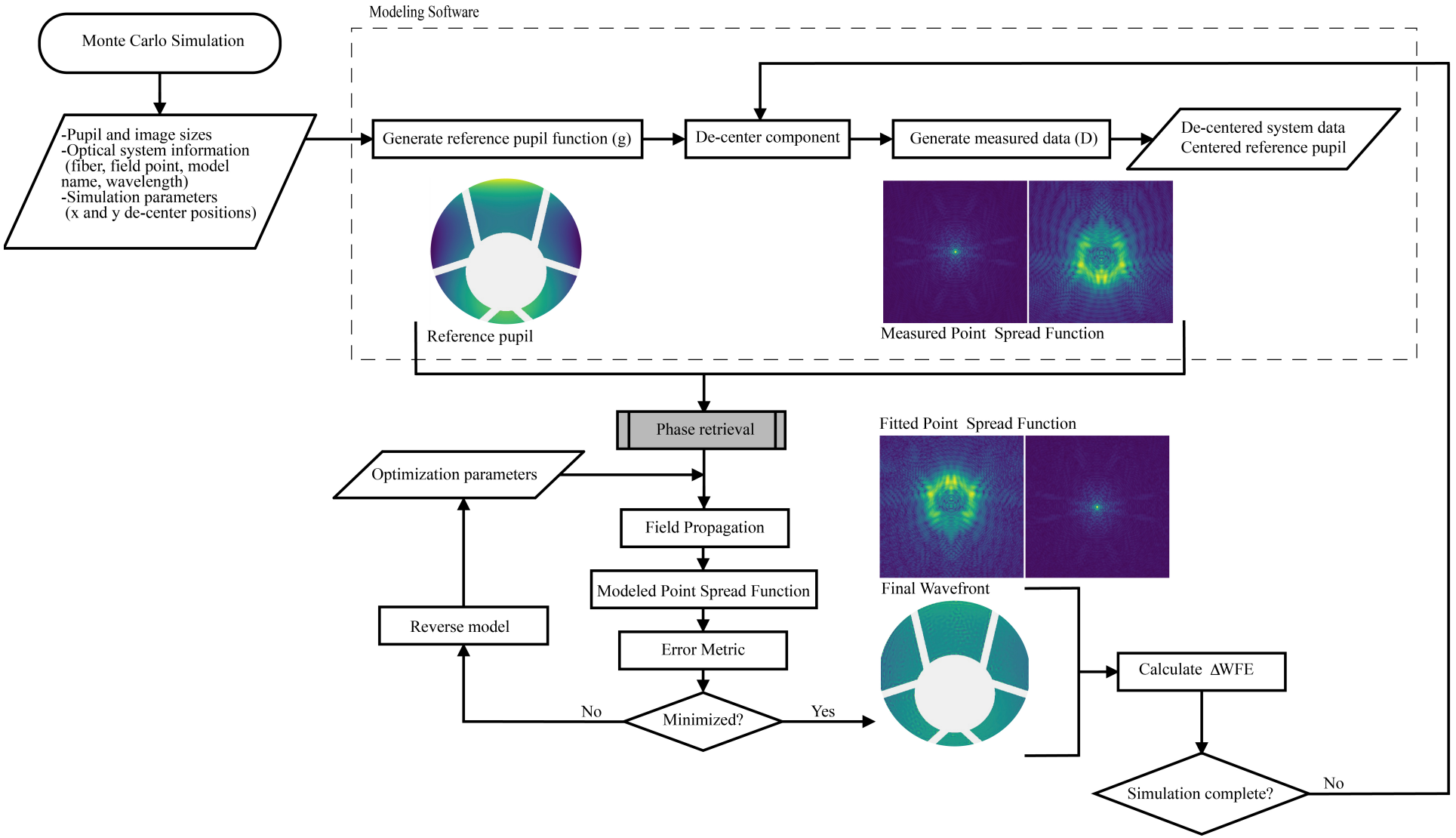
Simulation


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Measured Point Spread Function
Phase retrieval
Optimization parameters
Field Propagation
Modeled Point Spread Function
Error Metric
Minimized?
No
Yes
Reverse model
Fitted Point Spread Function
Final Wavefront
Calculate ΔWFE

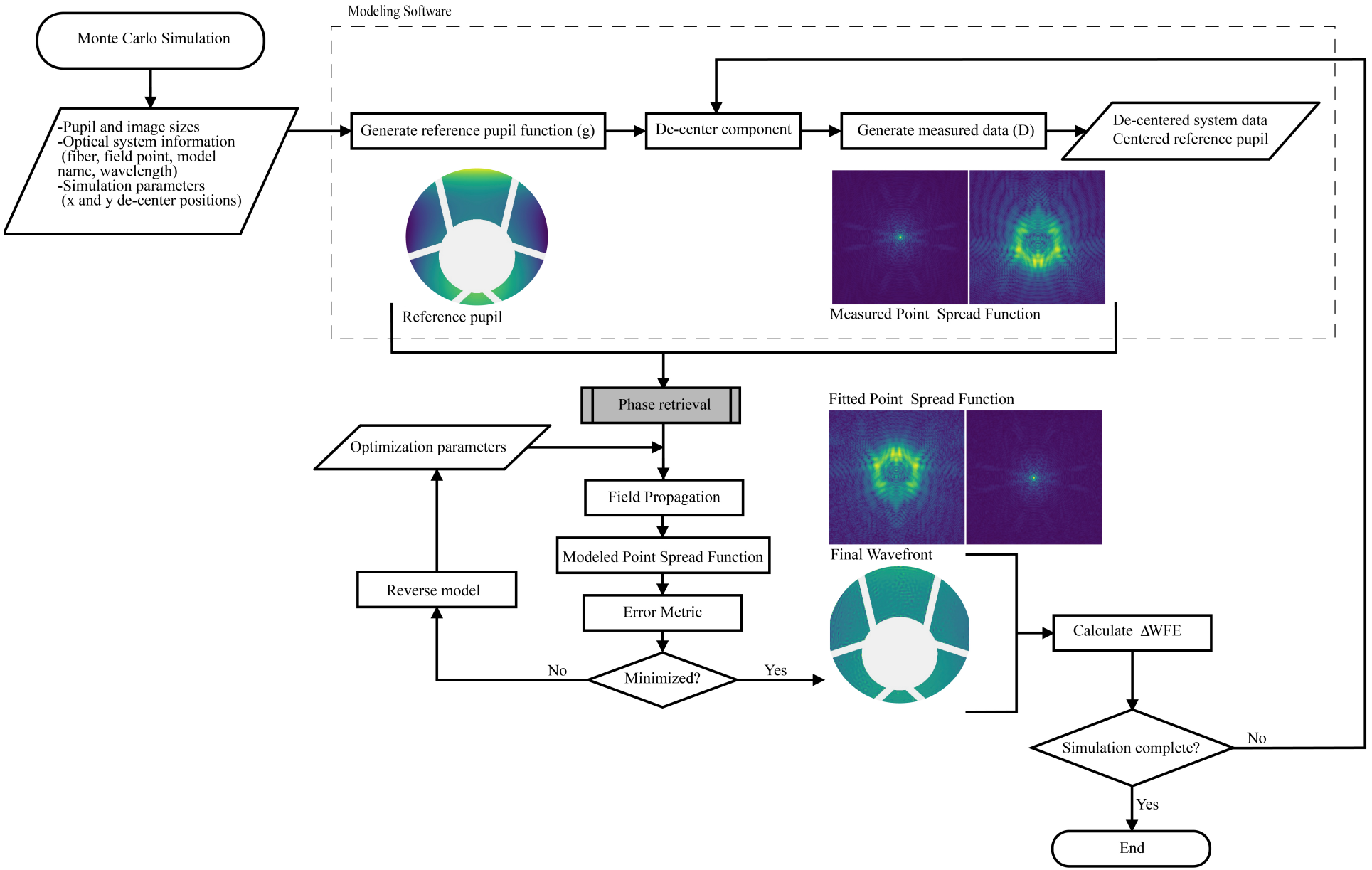
Simulation


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Reference pupil
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Phase retrieval
Optimization parameters
Field Propagation
Modeled Point Spread Function
Error Metric
Reverse model
No
Minimized?
Yes
Fitted Point Spread Function
Final Wavefront
Calculate ΔWFE
Simulation complete?

Simulation


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Error Metric
Reverse model
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Minimized?
Yes
Fitted Point Spread Function
Final Wavefront
Calculate ΔWFE
Simulation complete?
No

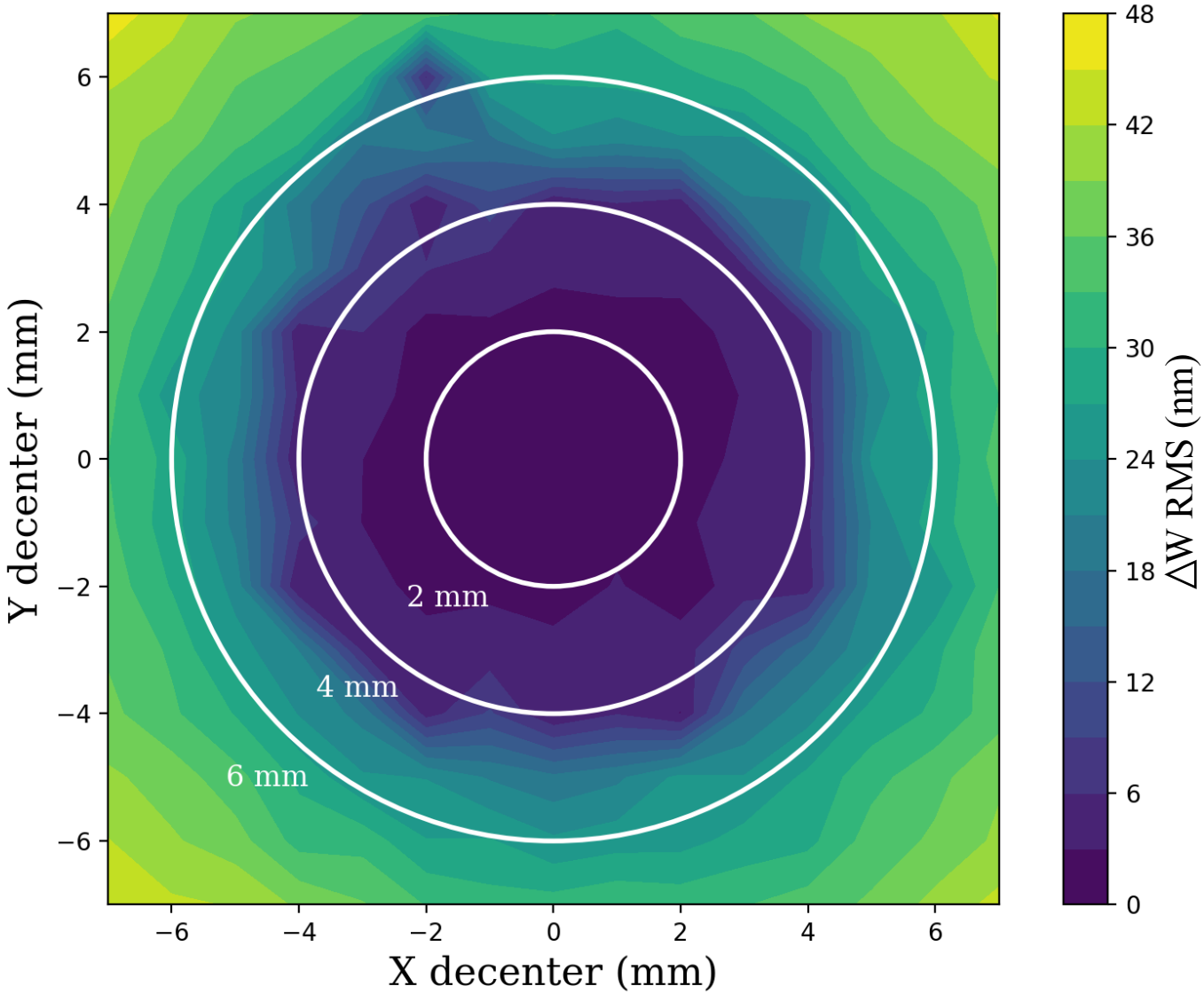
Simulation


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Optimization parameters
Field Propagation
Modeled Point Spread Function
Error Metric
Minimized?
No
Yes
Reverse model
Fitted Point Spread Function
Final Wavefront
Calculate ΔWFE
Simulation complete?
No
Yes
End

Results

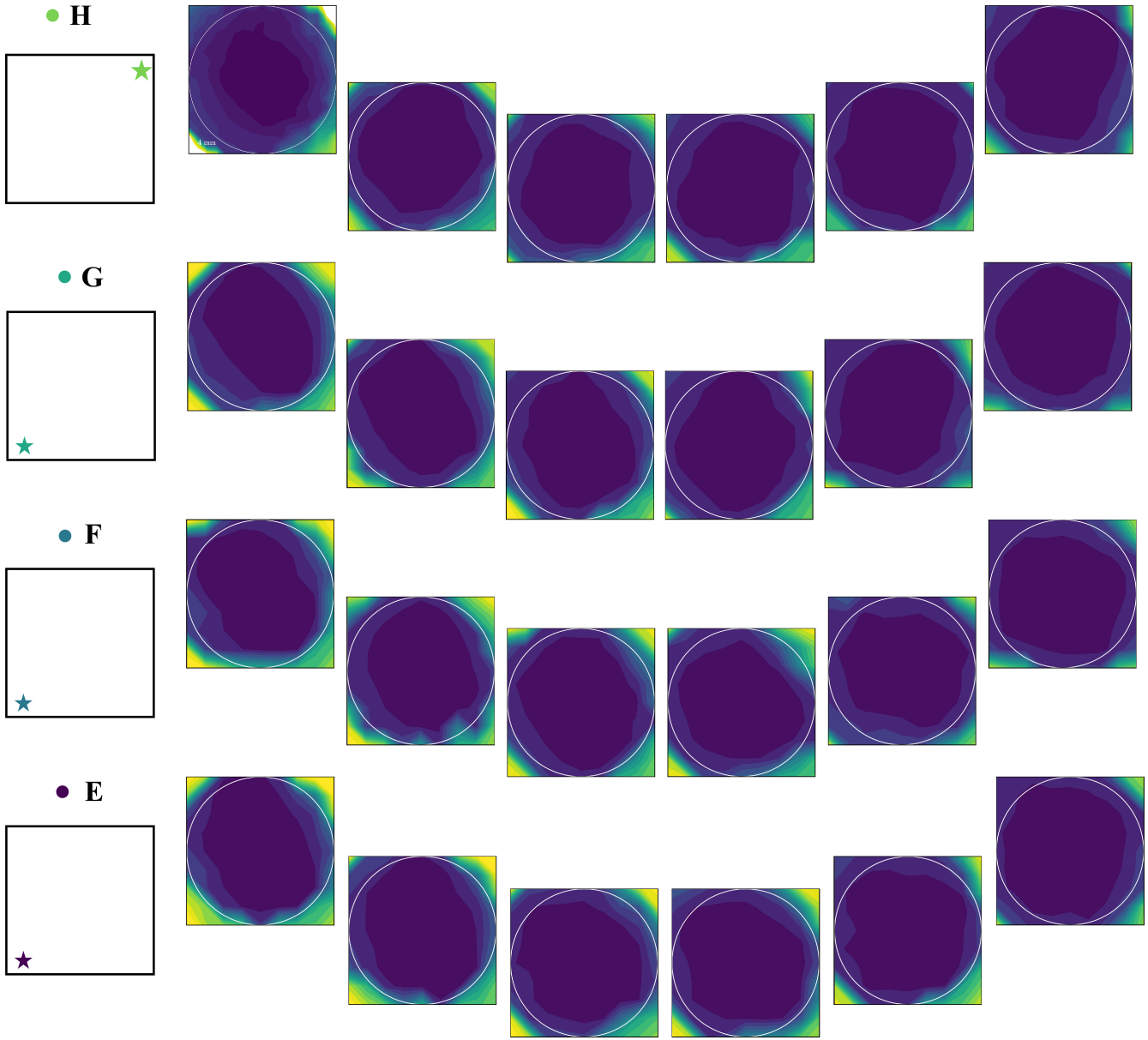
Results

Ideal model baseline decentering study



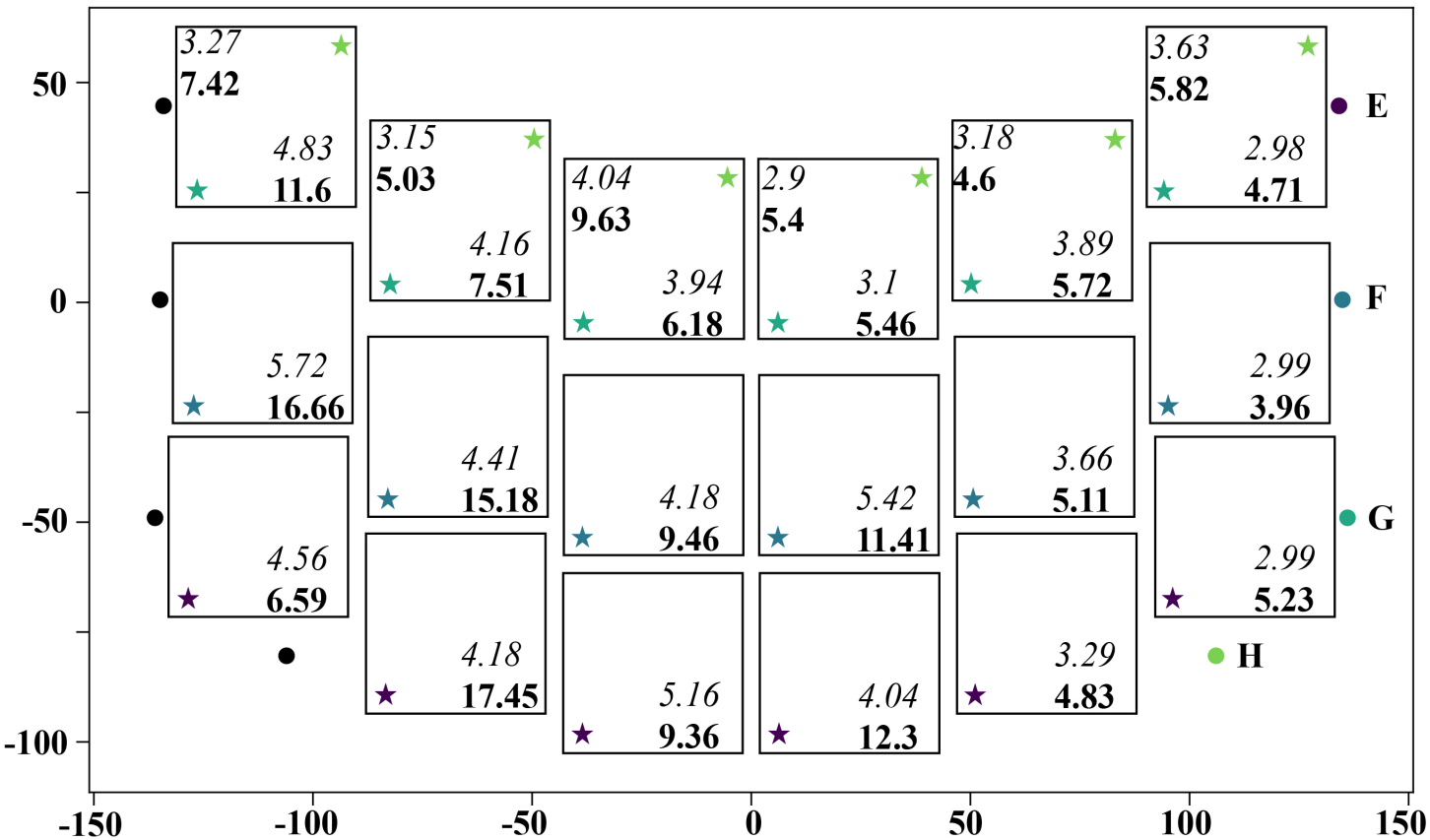
Results

Decentering contours across fied of view



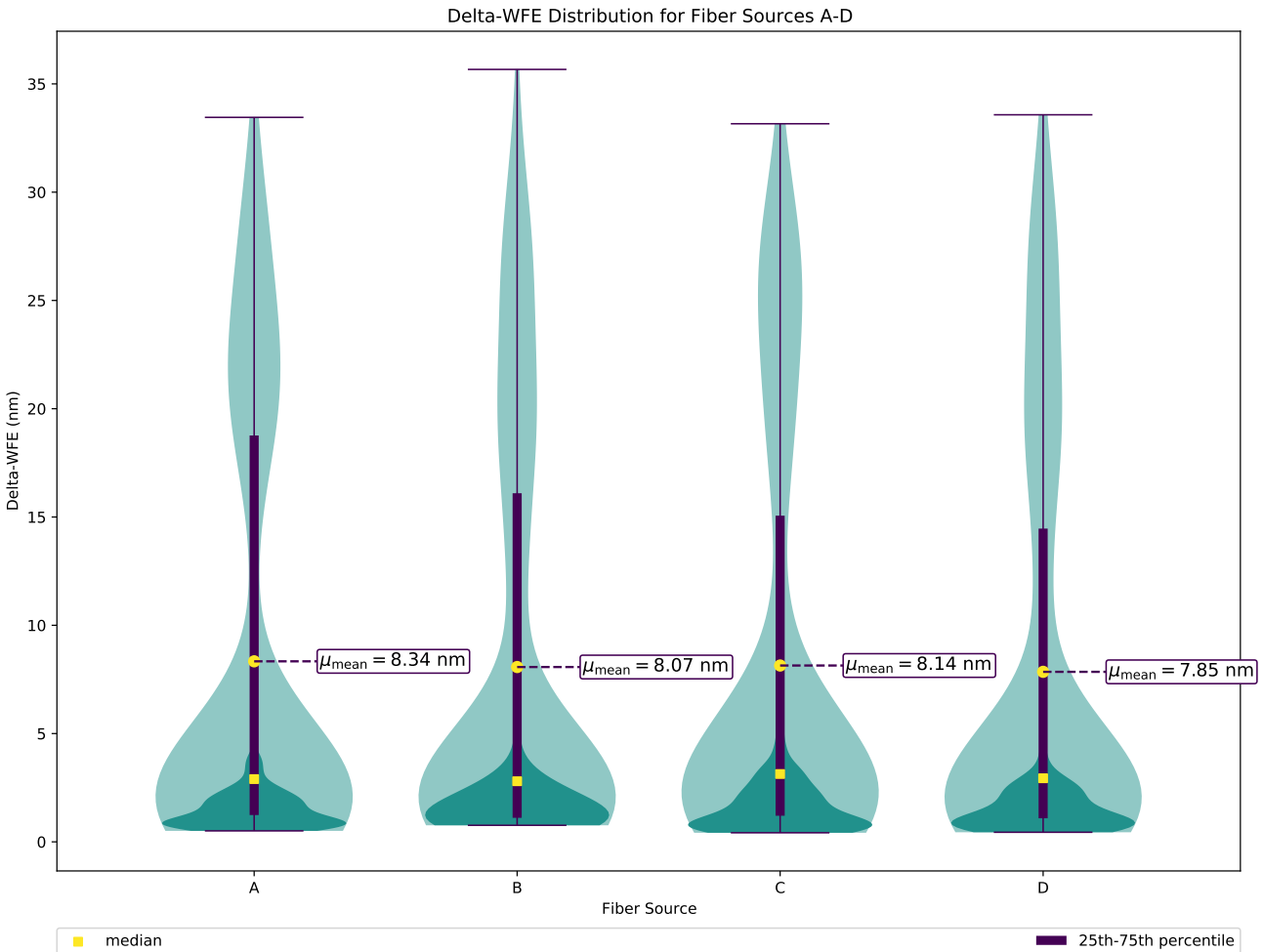
Results

95th percentile and max WFE within 4 mm decentering radius



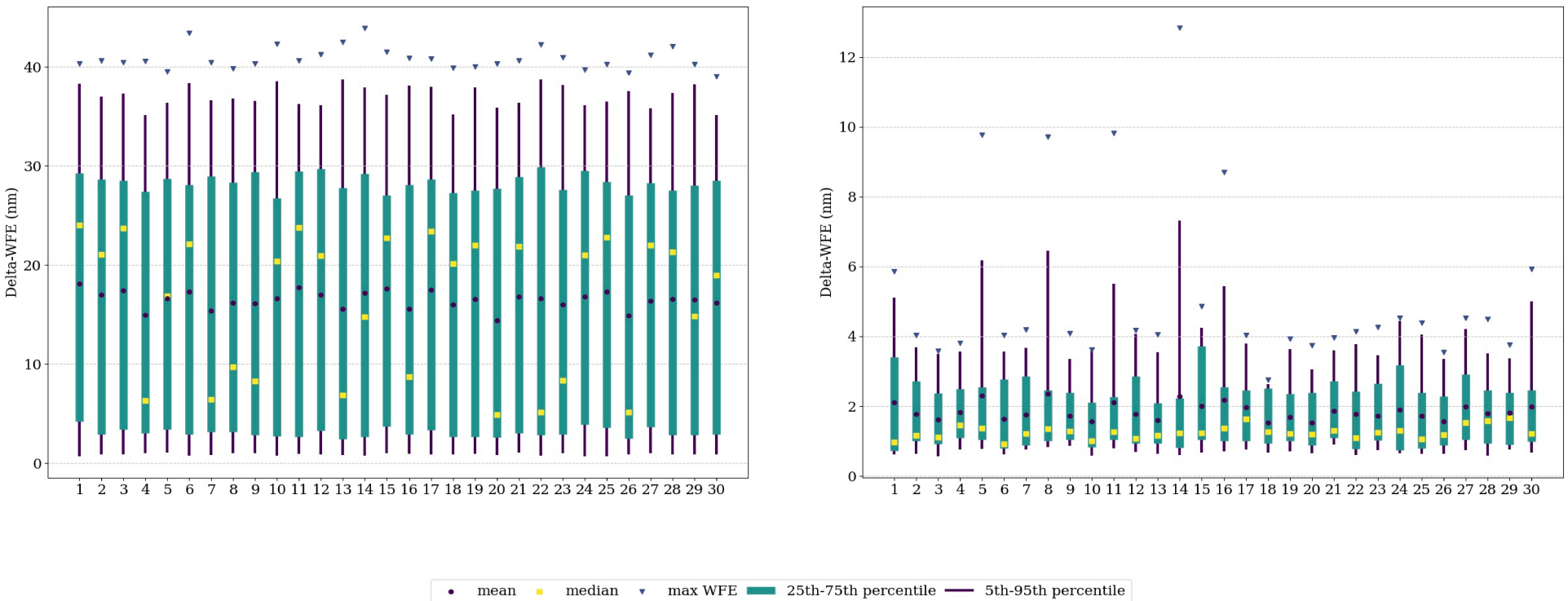
Results

Violin plot of 7 mm and 4 mm decentering radius WFE



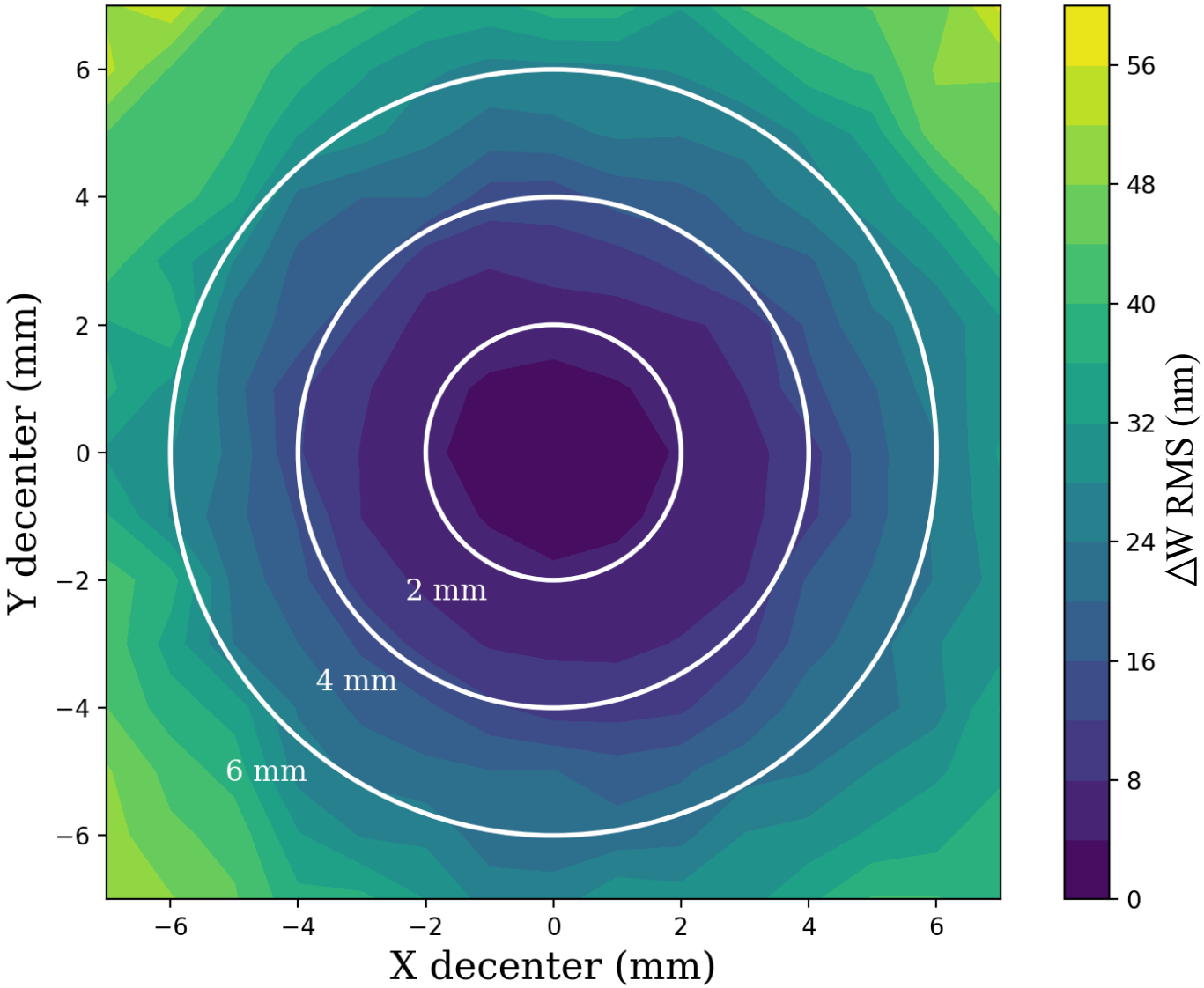
Results

Plot of 6 mm and 4 mm radius of decentering for 30 models



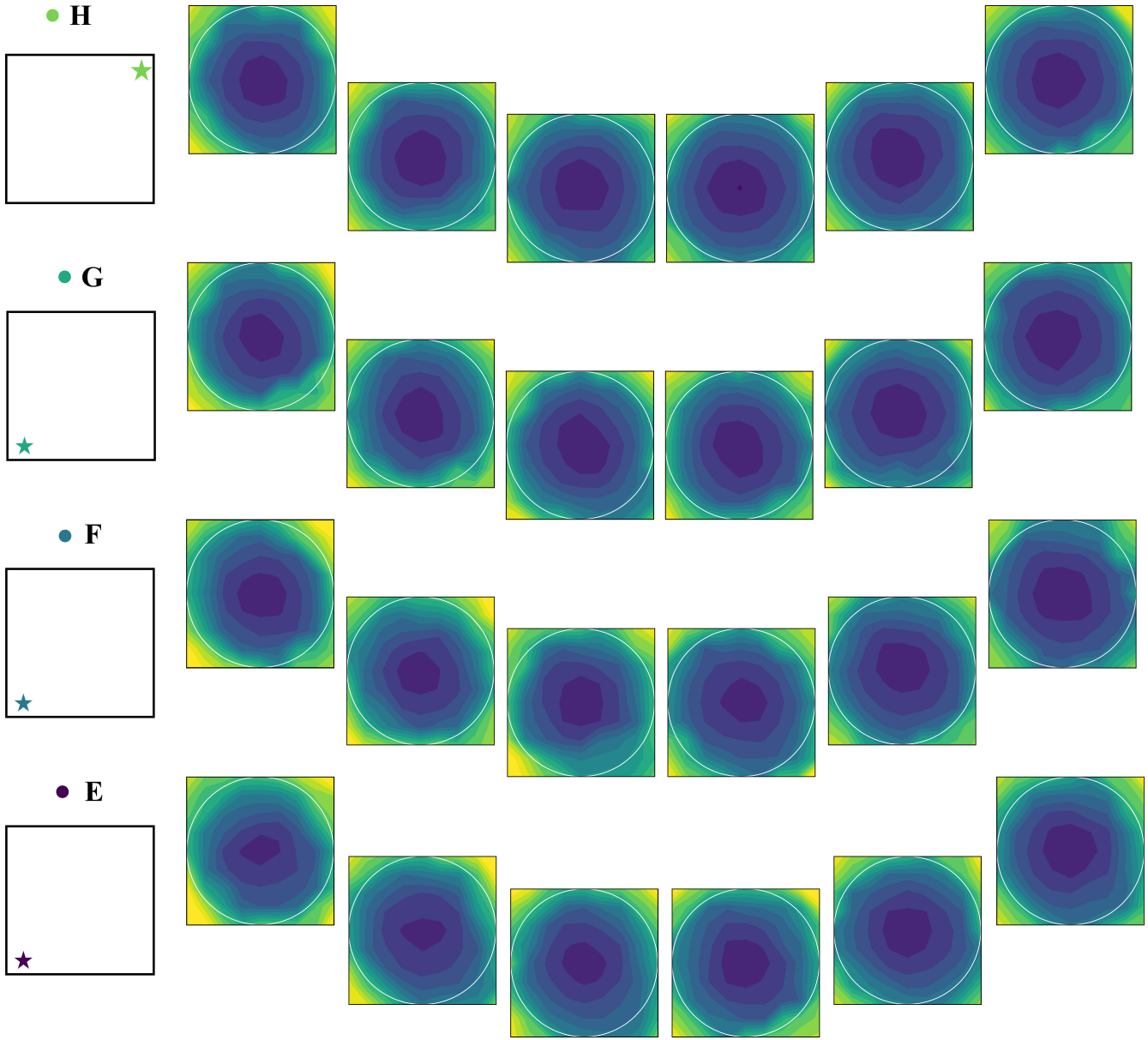
Results

Gravity sag model baseline decentering study



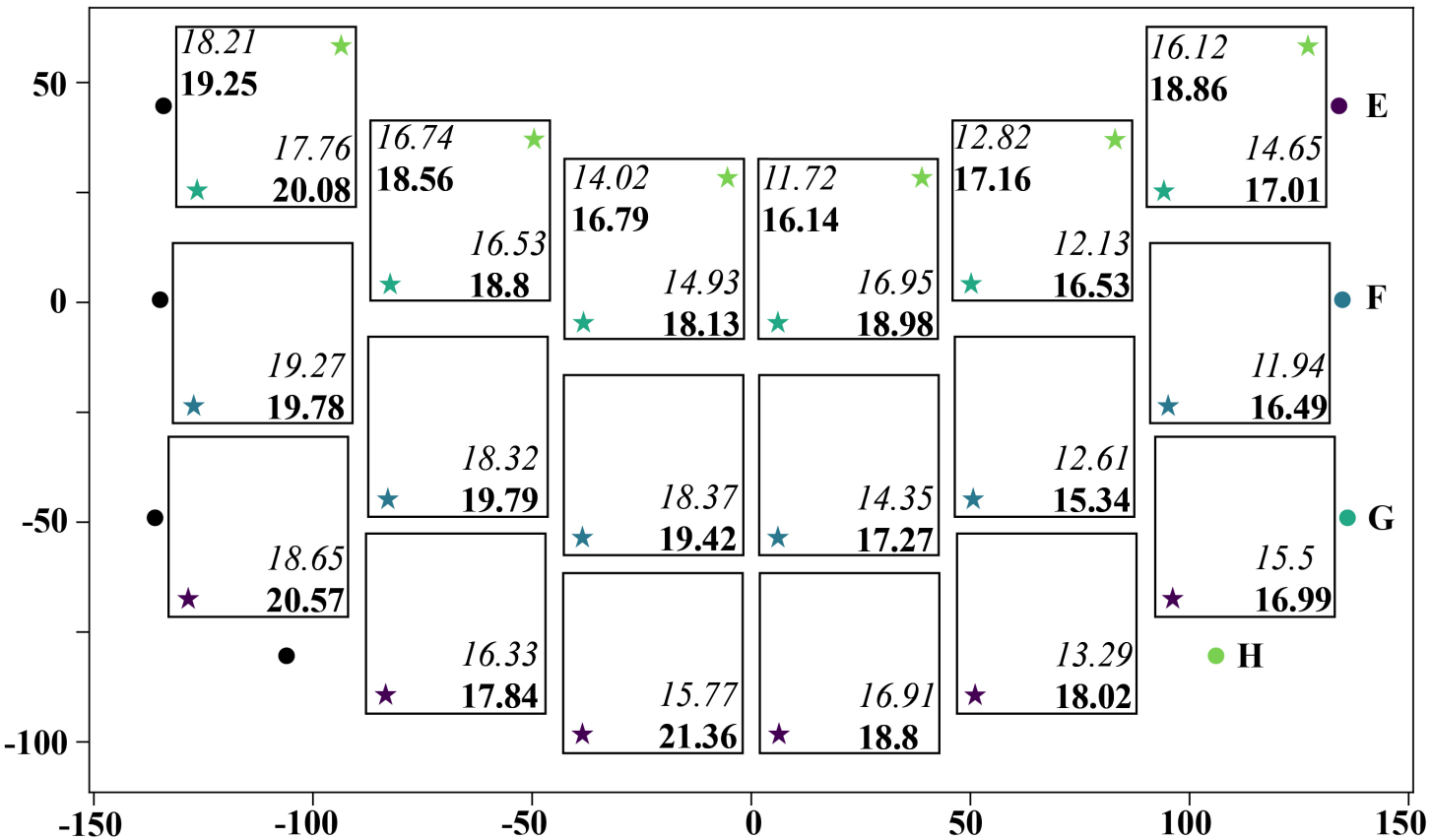
Results

Decentering contours across fied of view



Results

95th percentile and max WFE within 4 mm decentering radius



Conclusion

- 4 mm decentering radius fits within error budget for test
- Gravity sag results slightly effected by clipping
- Despite decentering dependent wavefront error and clipping, gravity sag results share similar trends across field of view
- Can confidently use phase retrieval in presence of pupil knowledge error and gravity sag
- Next step is full test simulator

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Thank you for listening!

Special thanks to...

- Advisor Prof. Dmitry Savransky
- NASA Goddard & RST WFSC Groups
- My family
- My dog

