Phase-Shifting Zernike Wavefront Sensor

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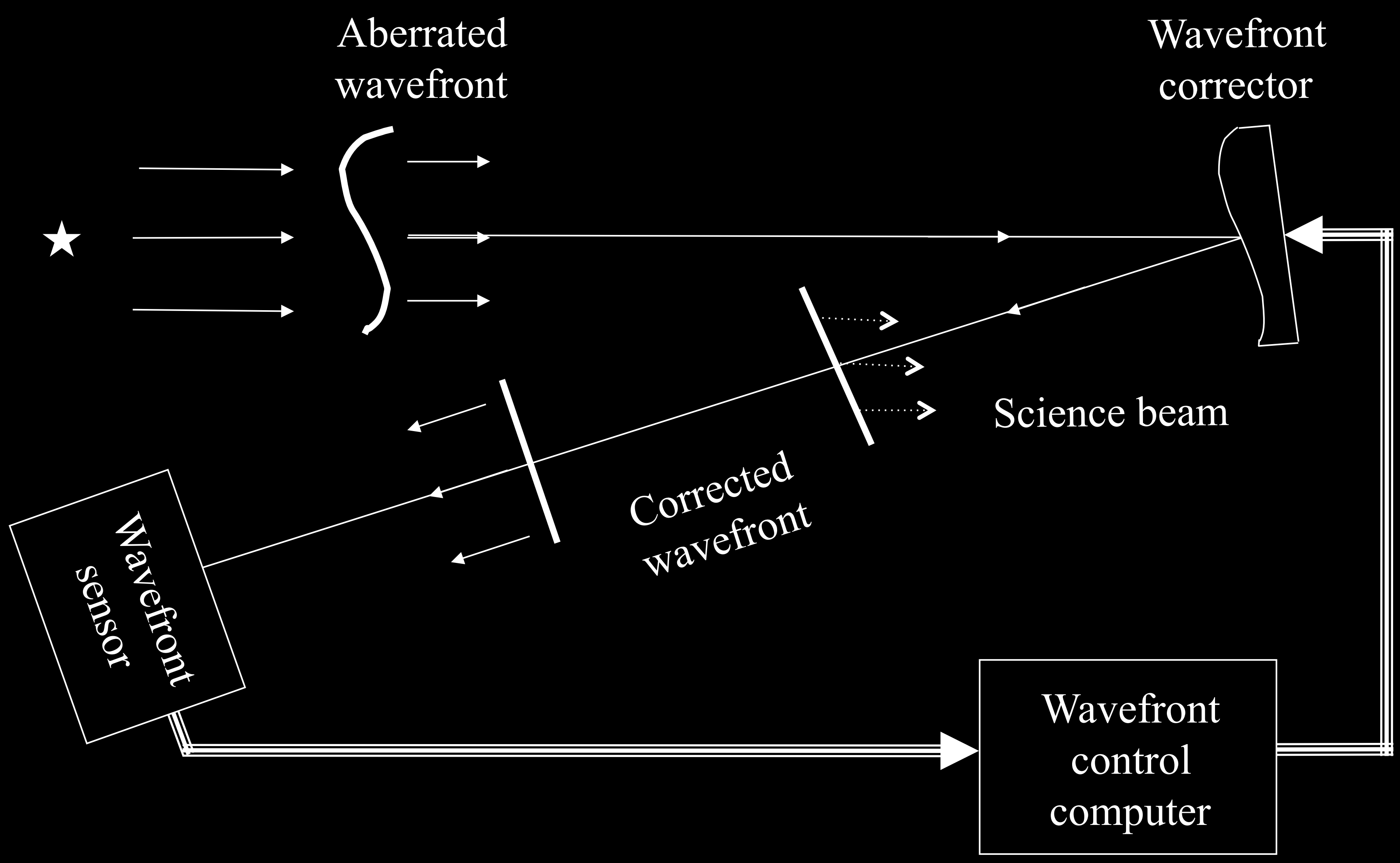
Supported by the JPL Research & Technology Development Fund

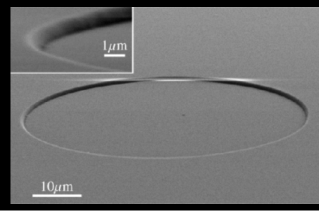
Overview

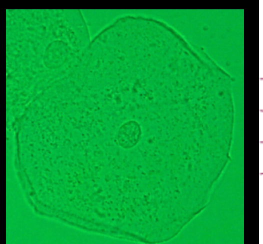
1. Background and theory
2. Testbed
3. Simulation
4. Telescope implementations

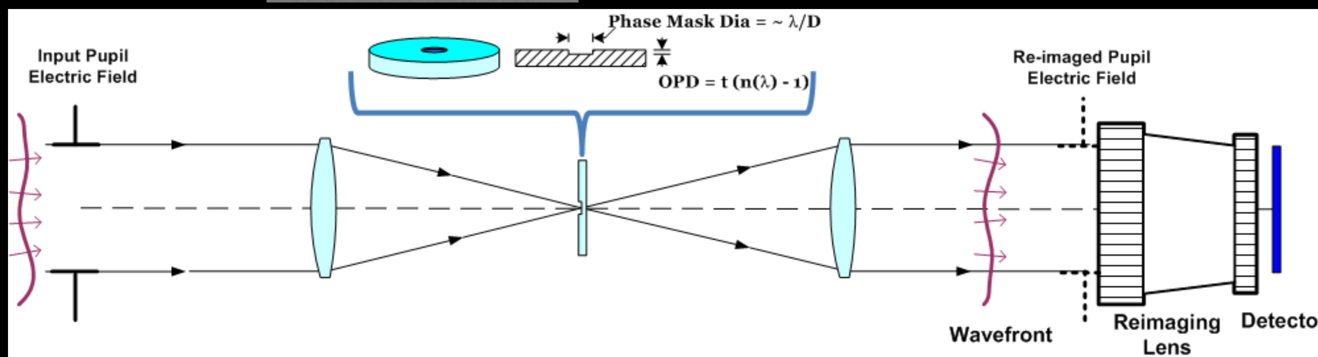
The Basics of Adaptive Optics

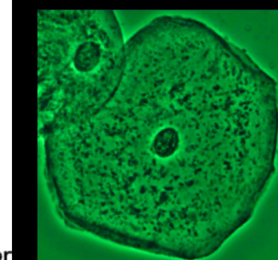


Transparent Specimens and Microscopy









- Properties of Classic Zernike Phase-contrast
  - Phase is converted to intensity
  - Very easy to implement, very robust
  - Limited dynamic range

Zernike Phase Reconstruction

Input Pupil

$$E(u,v) = P(u,v)\cdot A(1+\varepsilon(u,v))e^{i\varphi(u,v)}$$

$\downarrow$ $\Phi(u,v) << 1$ rad

$$E(u,v) \approx P(u,v)\cdot A(1+\varepsilon(u,v)+i\varphi(u,v))$$

Image Plane

$$E(\eta,\upsilon) = A\,PSF(\eta,\upsilon) + A\,PSF(\eta,\upsilon) * F[\varepsilon(u,v)+i\varphi(u,v)]$$

$\downarrow$ Phase Shift by $e^{i\theta}$

$$E(\eta,\upsilon) = A\,PSF(\eta,\upsilon)e^{i\theta} + A\,PSF(\eta,\upsilon) * F[\varepsilon(u,v)+i\varphi(u,v)]$$

Output Pupil

$$E(x,y) = A\,P(x,y)\cdot(e^{i\theta}+\varepsilon(x,y)+i\varphi(x,y))$$

$\downarrow$ Simplify notation

$$E = A(e^{i\theta}+\varepsilon+i\varphi)$$

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Static Zernike Phase Reconstruction

Apply a phase shift $e^{-i\pi/2}$ in the image plane

Propagate the electric field to the output pupil

$$E = A(e^{-i\pi/2} + \varepsilon + i\varphi) = A(-i + \varepsilon + i\varphi)$$

Convert to intensity

$$I = E \cdot E^{*} = A^{2}(1 + \varepsilon^{2} - 2\varphi + \varphi^{2})$$

Dropping second order terms, intensity is now proportional to phase

Static Zernike Phase Reconstruction

Advantages

1. Easy to interpret measurements
2. The sensor is common mode
3. Easy to control sampling

Disadvantages

1. Sensitive to any system error resulting in signal variation
2. Amplitude fluctuations cause spurious signals (e.g. atmosphere scintillation)

Dynamic Phase Reconstruction

Apply a series of phase shifts $e^{i\theta}$ in the image plane:

$\Theta = -\pi/2, 0, \pi/2, \pi$

Propagate the electric field to the output pupil:

$$E_1 = A(e^{-i\pi/2} + \varepsilon + i\varphi) = A(-i + \varepsilon + i\varphi)$$

$$E_2 = A(e^{i0} + \varepsilon + i\varphi) = A(1 + \varepsilon + i\varphi)$$

$$E_3 = A(e^{i\pi/2} + \varepsilon + i\varphi) = A(i + \varepsilon + i\varphi)$$

$$E_4 = A(e^{-i\pi} + \varepsilon + i\varphi) = A(-1 + \varepsilon + i\varphi)$$

Zernike Phase Contrast

Convert the output pupil electric fields to intensity

$$I_1 = E_1 \cdot E^*_1 = A^2(1+\varepsilon^2 - 2\varphi + \varphi^2)$$

$$I_2 = E_2 \cdot E^*_2 = A^2(1+\varepsilon^2 + 2\varepsilon + \varphi^2)$$

$$I_3 = E_3 \cdot E^*_3 = A^2(1+\varepsilon^2 + 2\varphi + \varphi^2)$$

$$I_4 = E_4 \cdot E^*_4 = A^2(1+\varepsilon^2 - 2\varepsilon + \varphi^2)$$

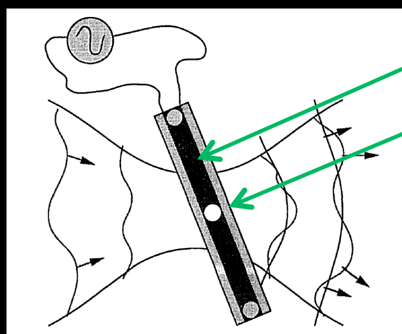
Solve for ϕ and ε

$$\varphi = \frac{I_3 - I_1}{4A^2} \qquad \varepsilon = \frac{I_2 - I_4}{4A^2}$$

Advantages of Dynamic Approach

- **Like Classic Zernike, it is common mode**
  - Not affected by non-common path optics
  - Insensitive to vibration, thermal drift
- **Optical system is reflective**
  - Works with broadband white light
  - Polarization insensitive
- **Phase shift is dynamic**
  - Synchronous-demodulation rejects noise sources not common with the phase-shifting frequency such as:
    - Detector noise
    - Stray light
- **Reconstruction is mathematically simple**
  - It can even be done on selective parts of the pupil

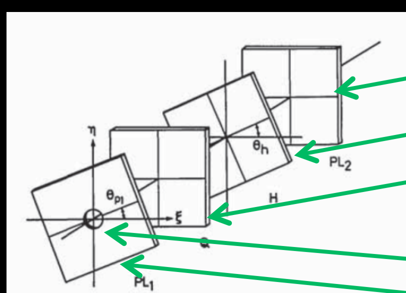
Phase Delay Techniques



Liquid crystal point-diffraction

Mercer and Creath

Applied Optics Vol. 35 No. 10 p. 1633 (1996)

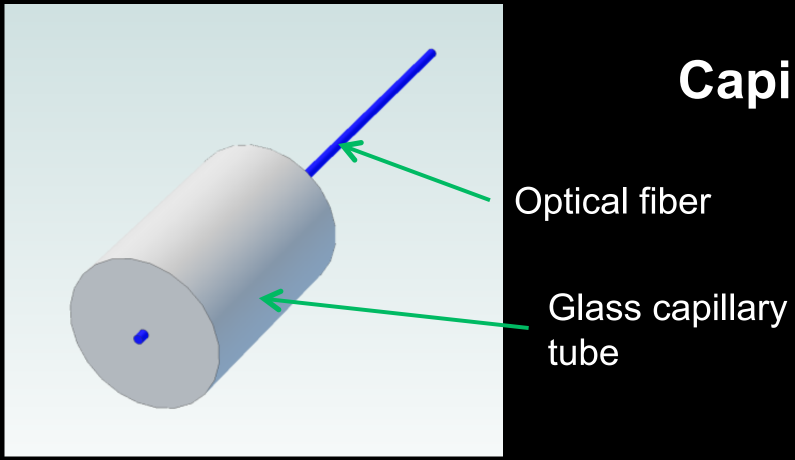


Polarization phase-shifting

Kadono, Takai, and Asakura

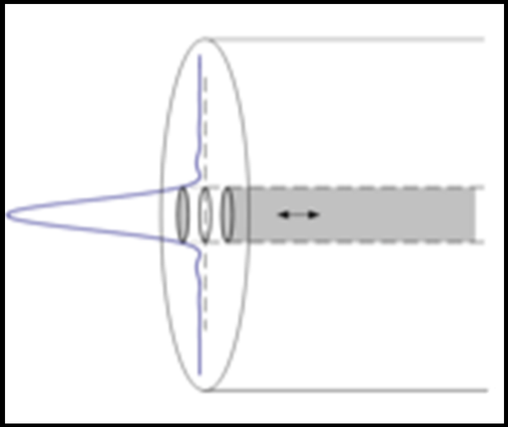
Applied Optics Vol. 26, No. 5 p. 898 (1987)

Phase Delay Technique



Capillary & fiber

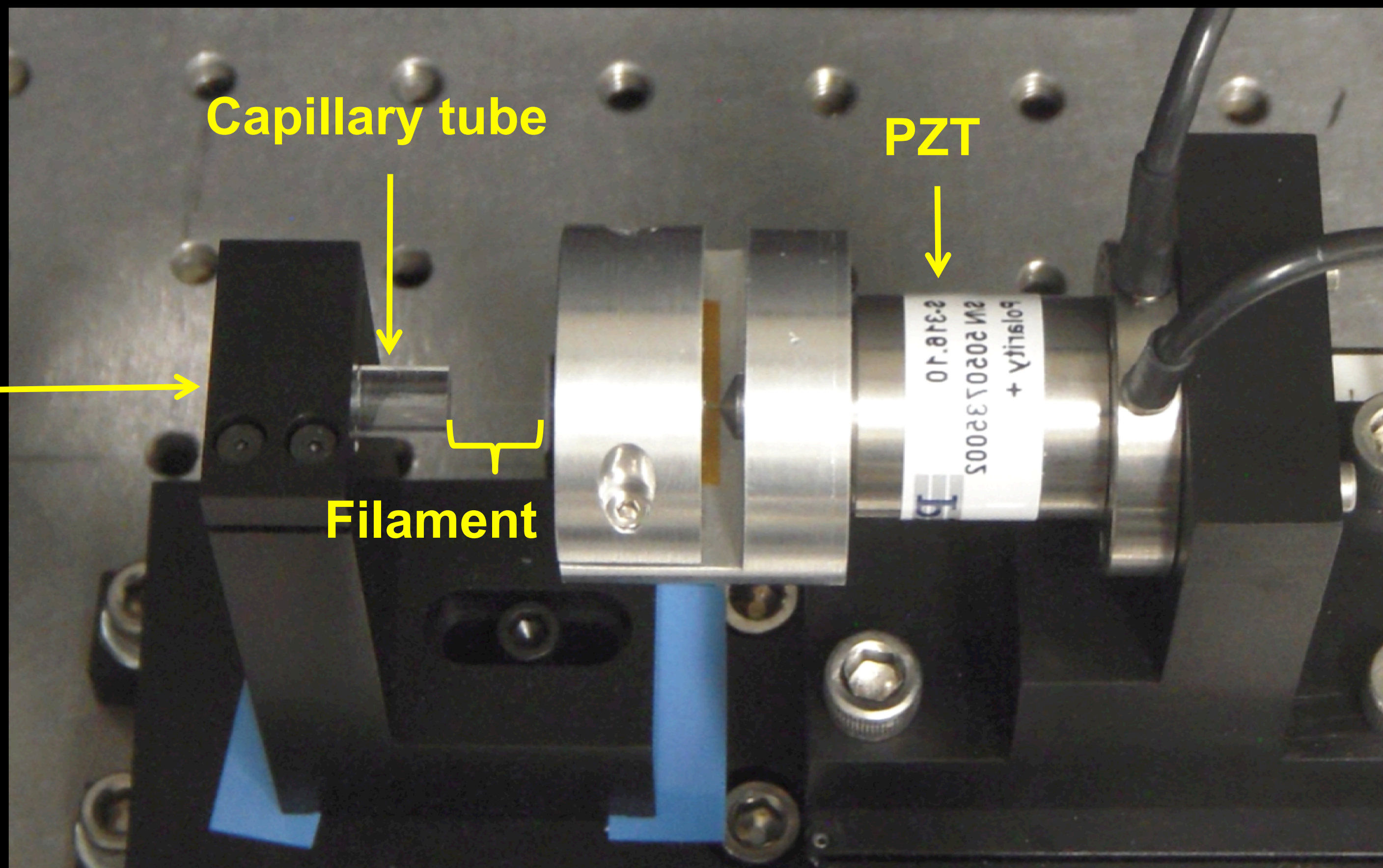
Proc. SPIE 6888 68880B (2008)



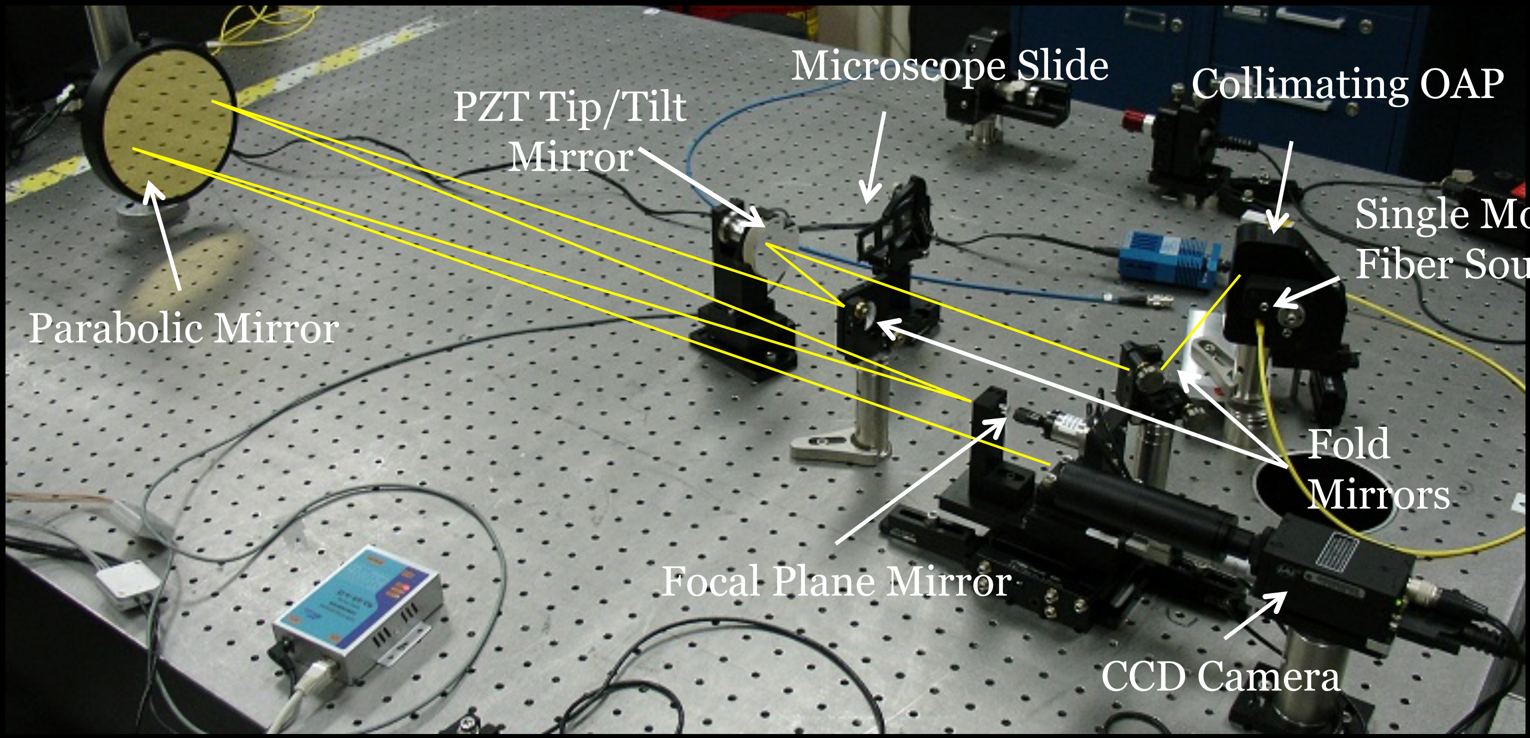
Cleaved fiber inside a polished glass capillary

- Both silver-coated
- Central core of PSF shifted by the fiber

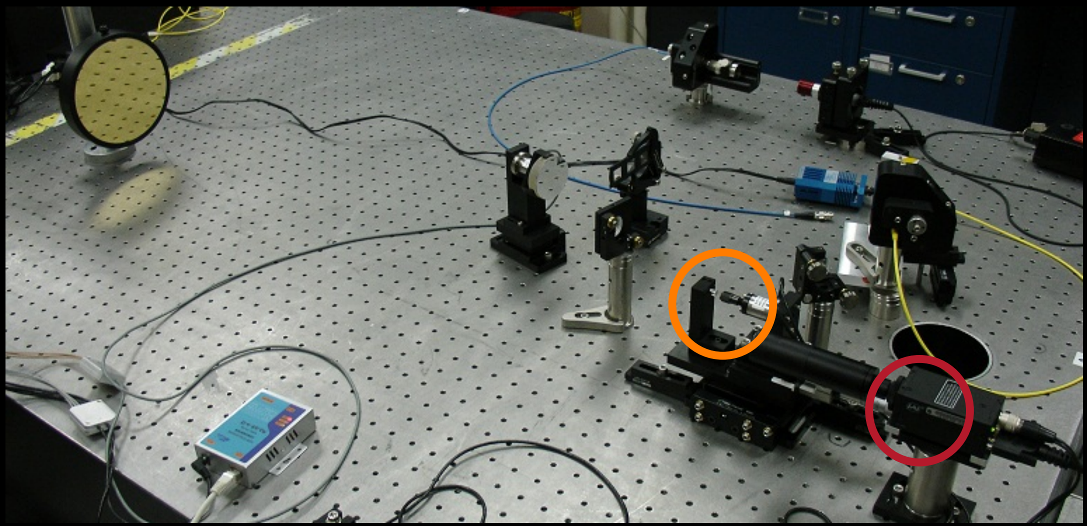
Phase Delay Implementation

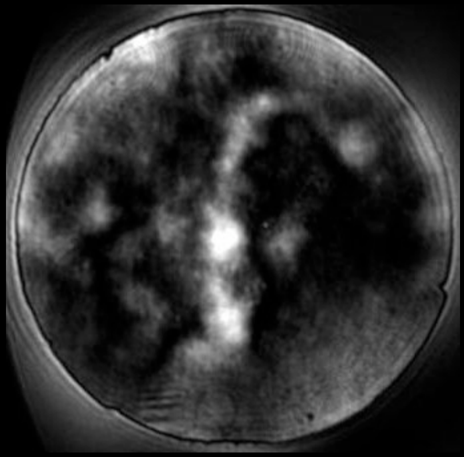


Dynamic Zernike Testbed



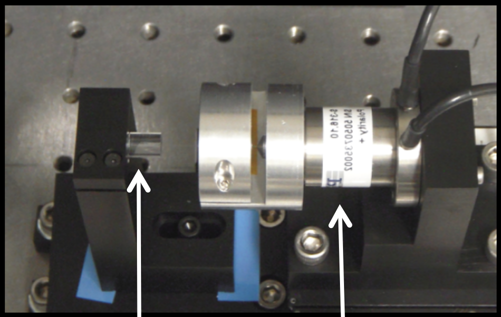
Dynamic Zernike Testbed





Focal Plane Assembly:

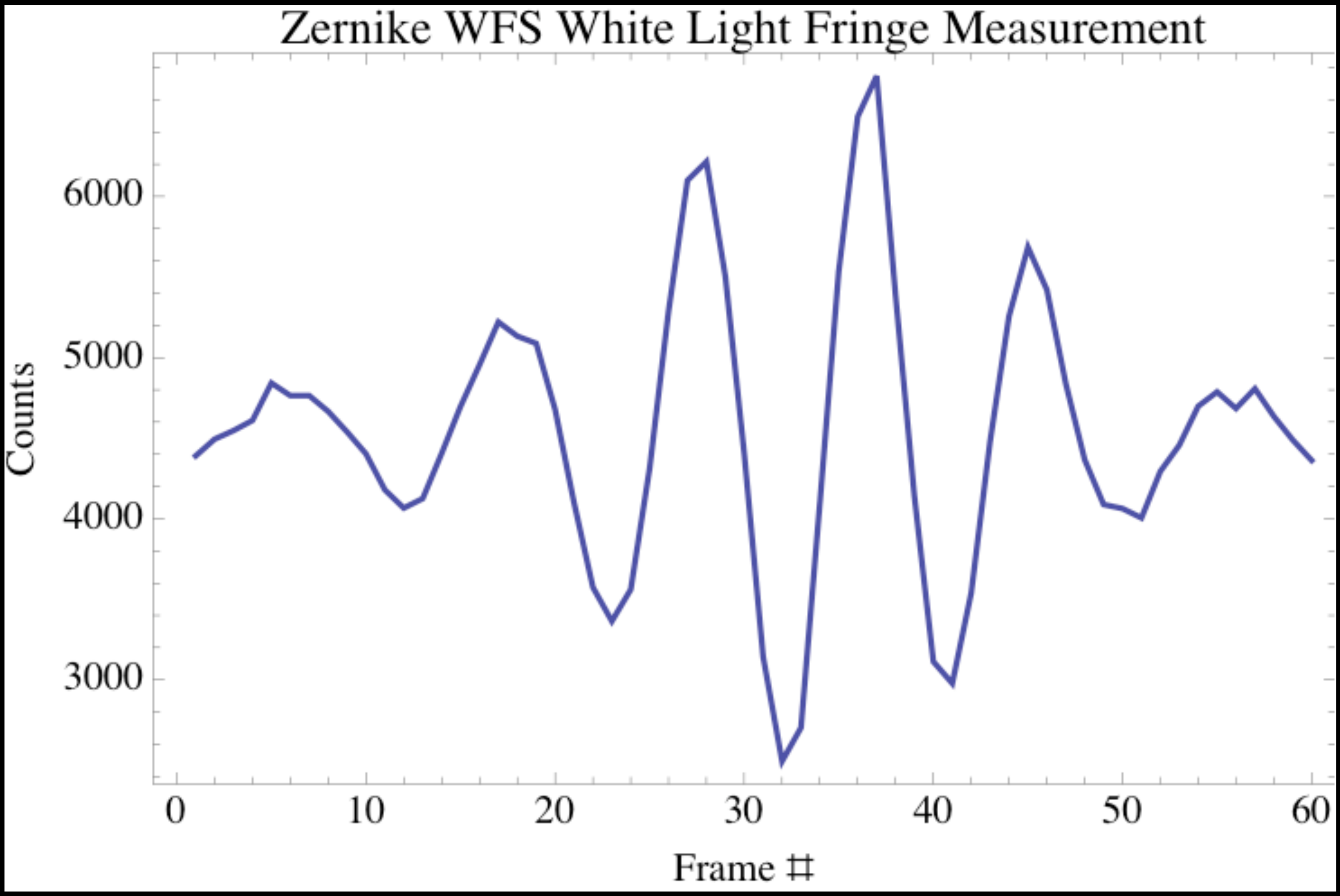
- Capillary tube
- Optical fiber
- PZT



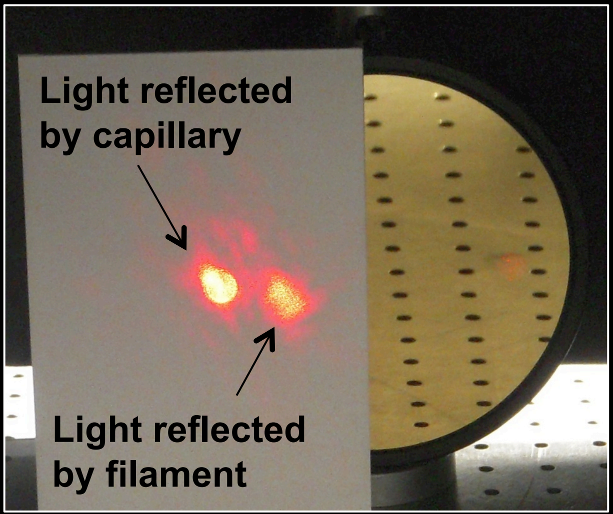
Output pupil Results:

- Pupil viewing CCD
- Intensity reflects microscope slide phase information

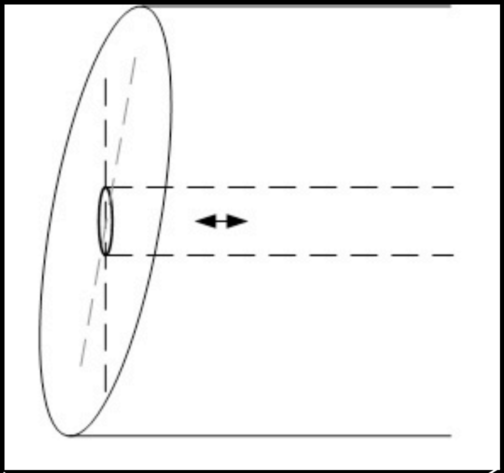
White Light Fringe

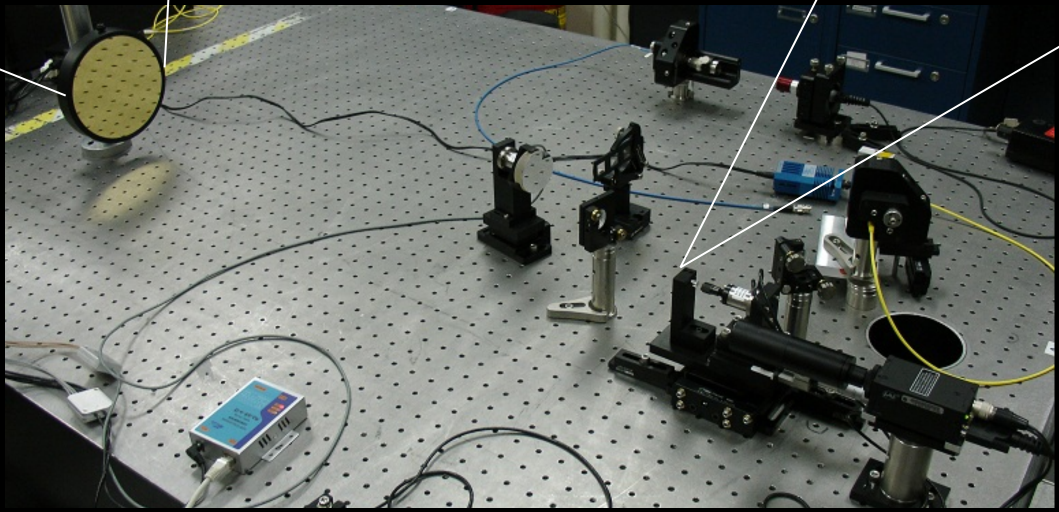


Mechanical Challenges

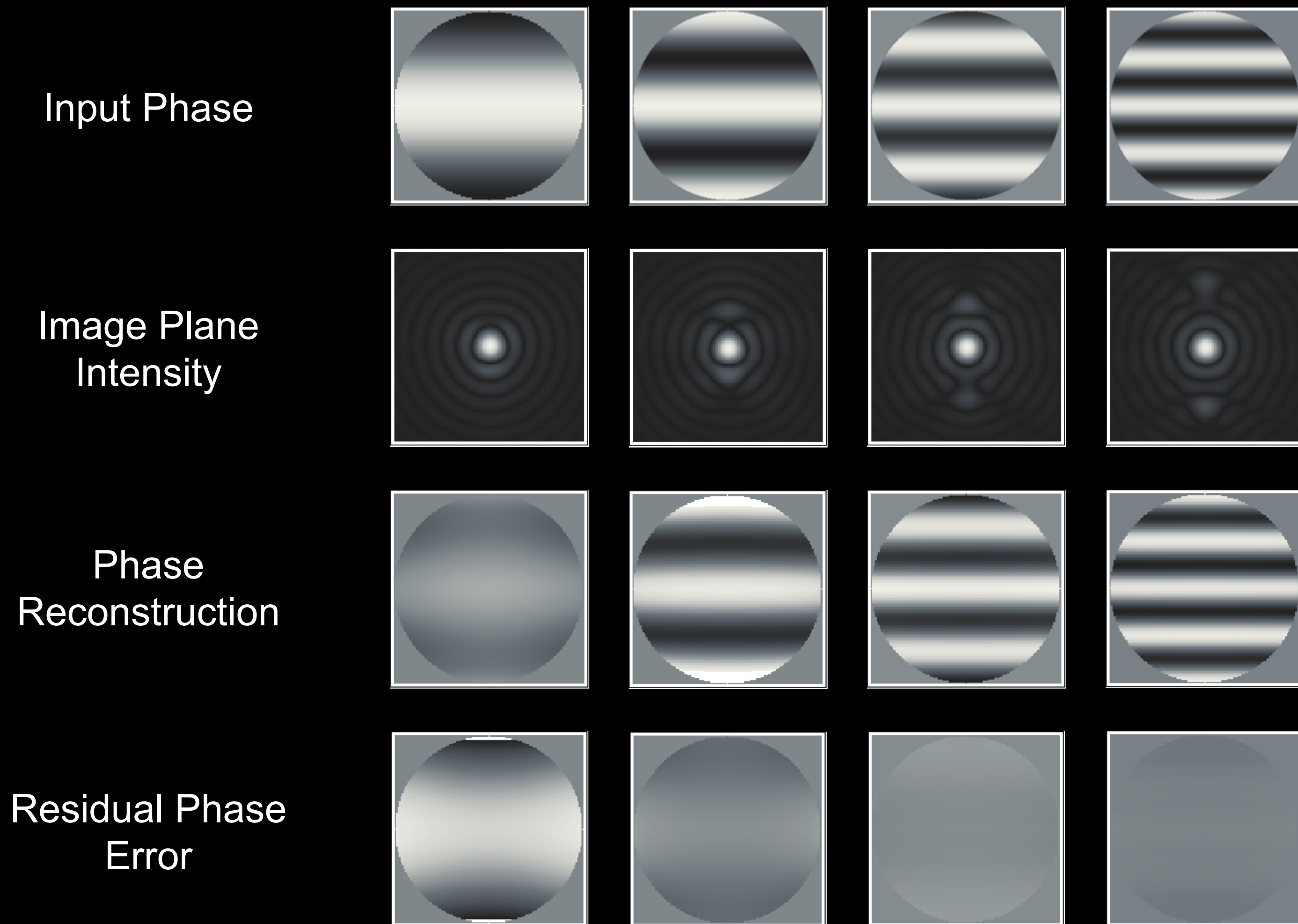


Relative capillary/fiber tilt offsets the light spots in output pupil

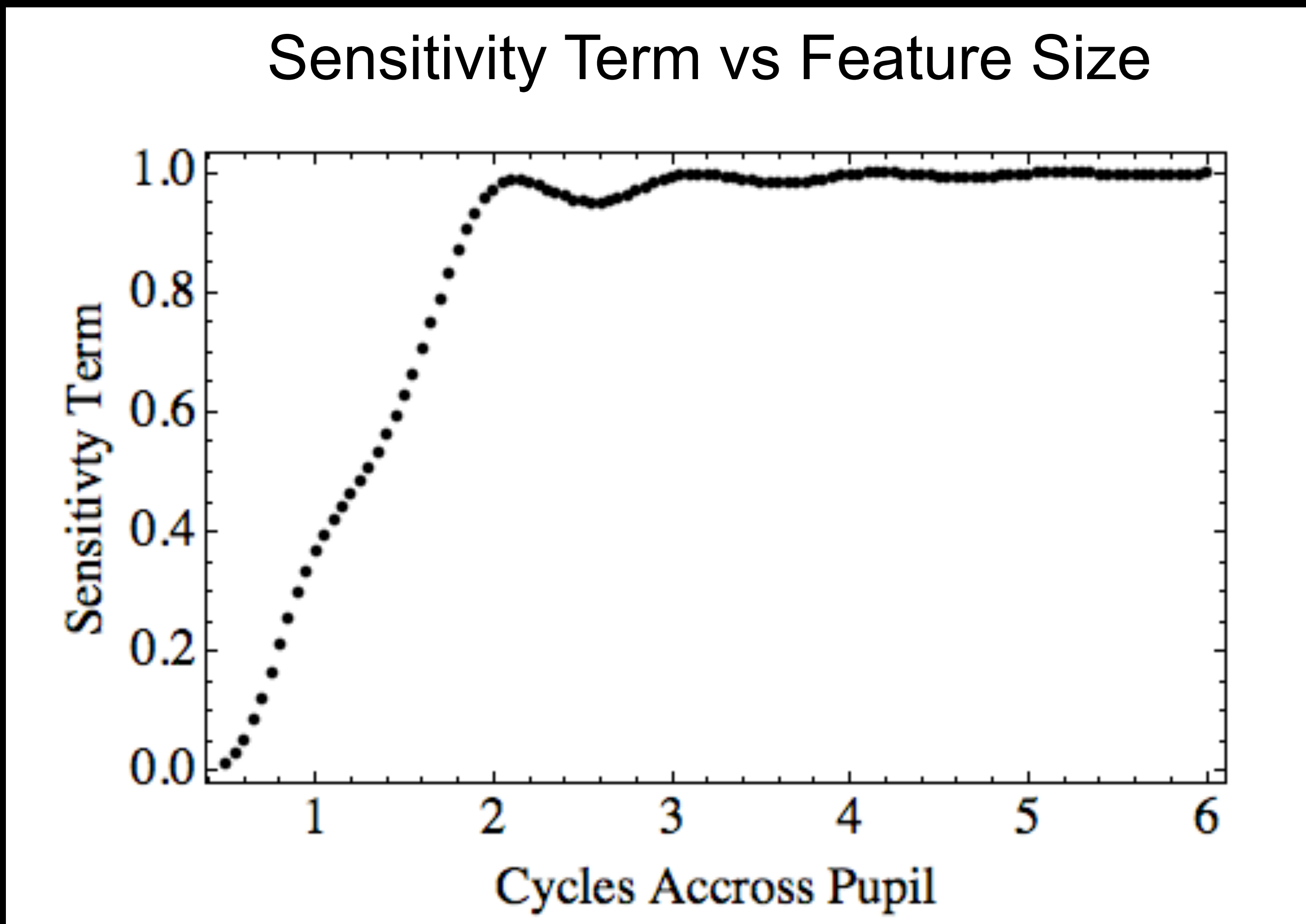




Fourier Mode Sensitivity



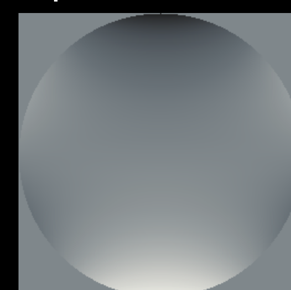
Fourier Mode Sensitivity



Input Phase

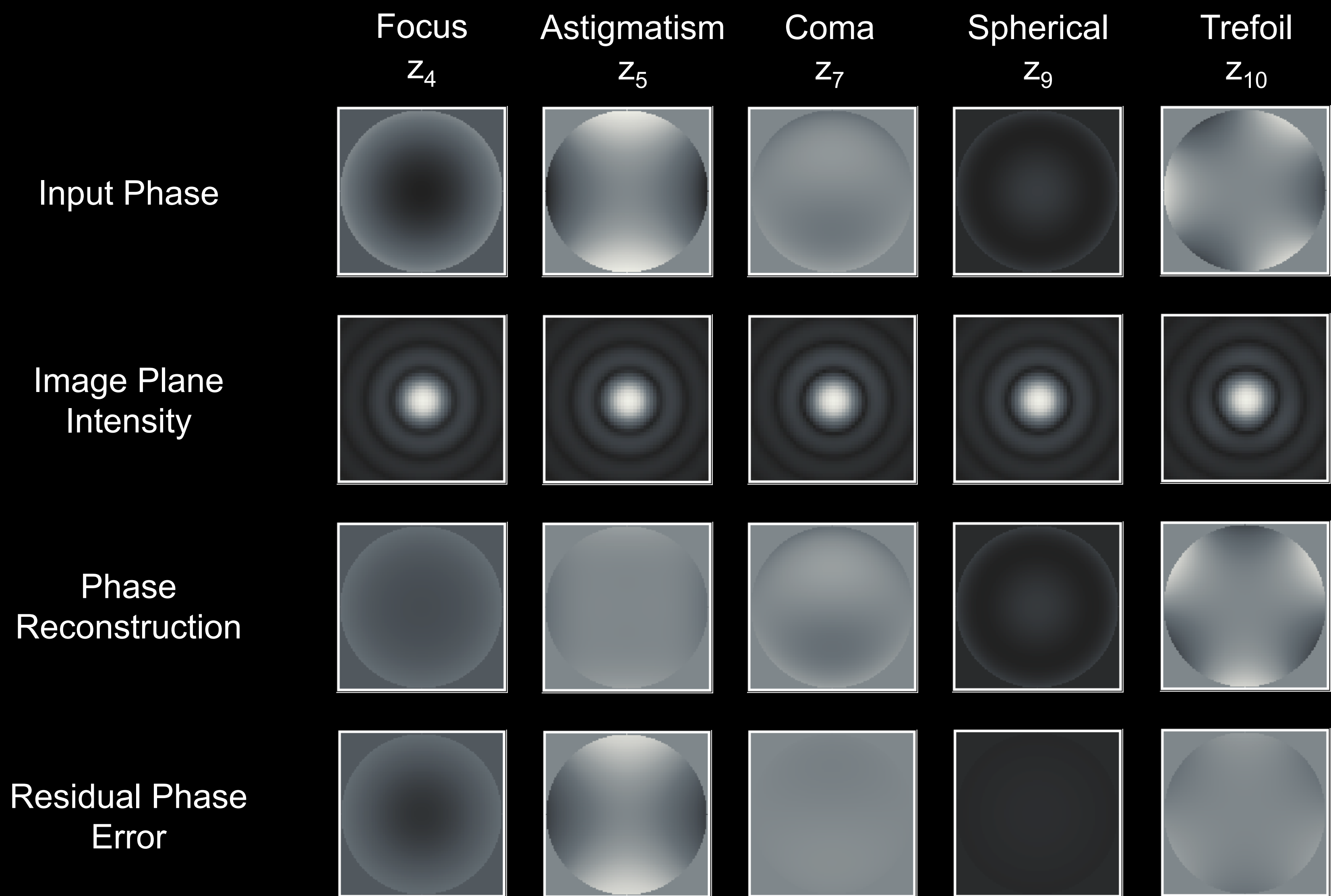
Phase Estimate

Input – Estimate

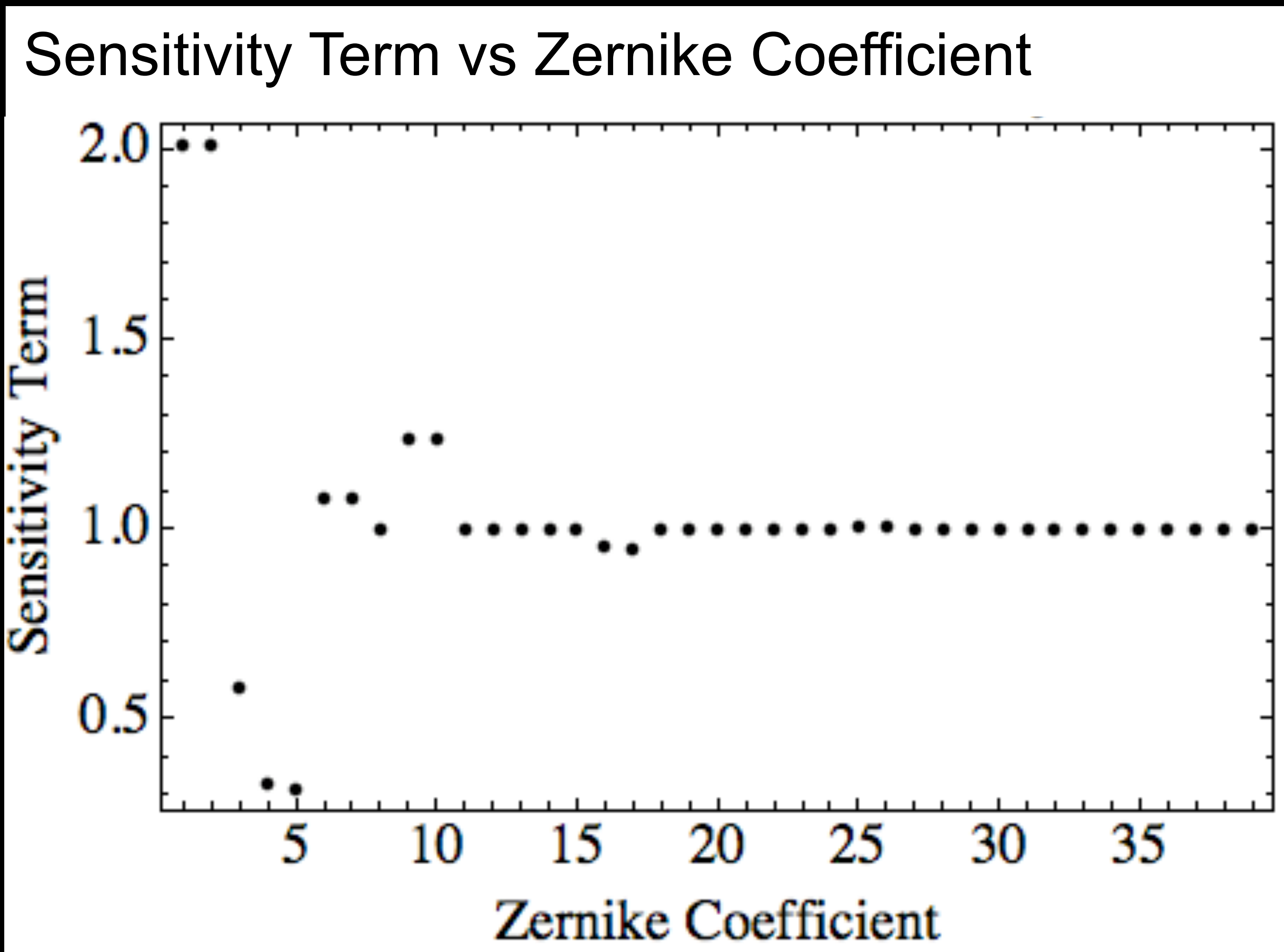


Amp=0.01λ
RMS=0.002λ
PV=0.003λ

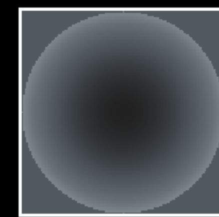
Zernike Mode Sensitivity



Zernike Mode Sensitivity



Input Phase

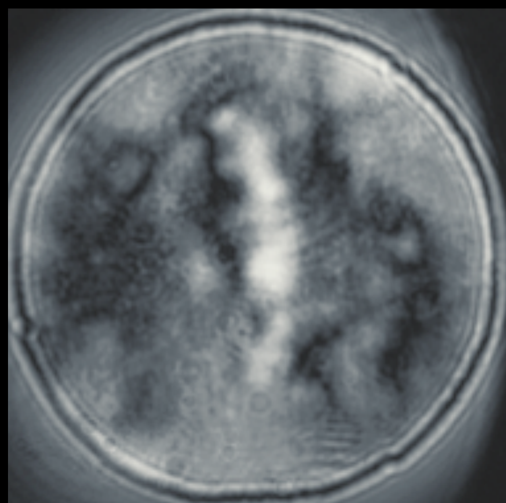


Phase Estimate

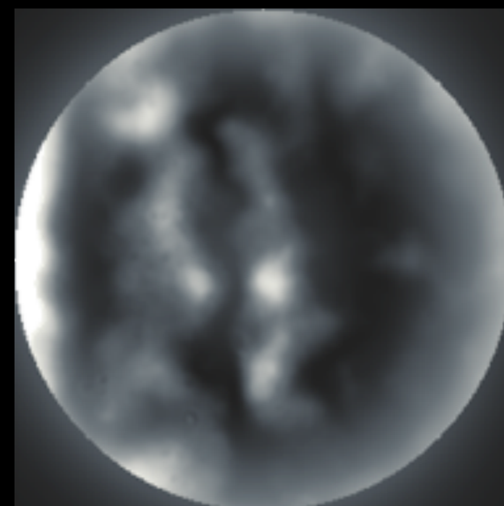
Input Phase – Phase Estimate

Simulation and Testbed Comparison

Testbed



Simulation

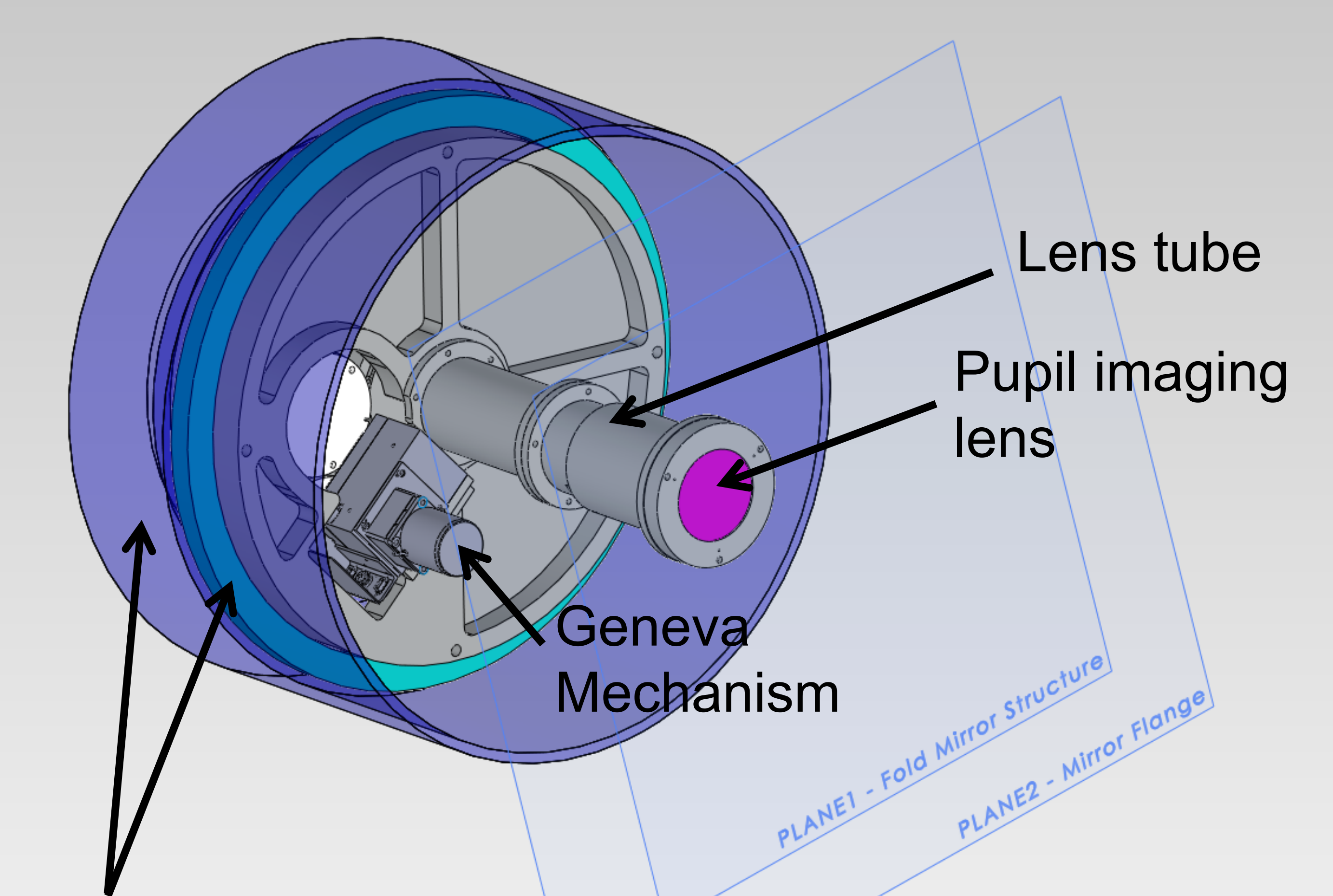


- The output pupil intensity reported by the testbed andsimulation share qualitative features
- Testbed focus and alignment will improve agreement

Caltech Submillimeter Observatory (CSO) Implementation

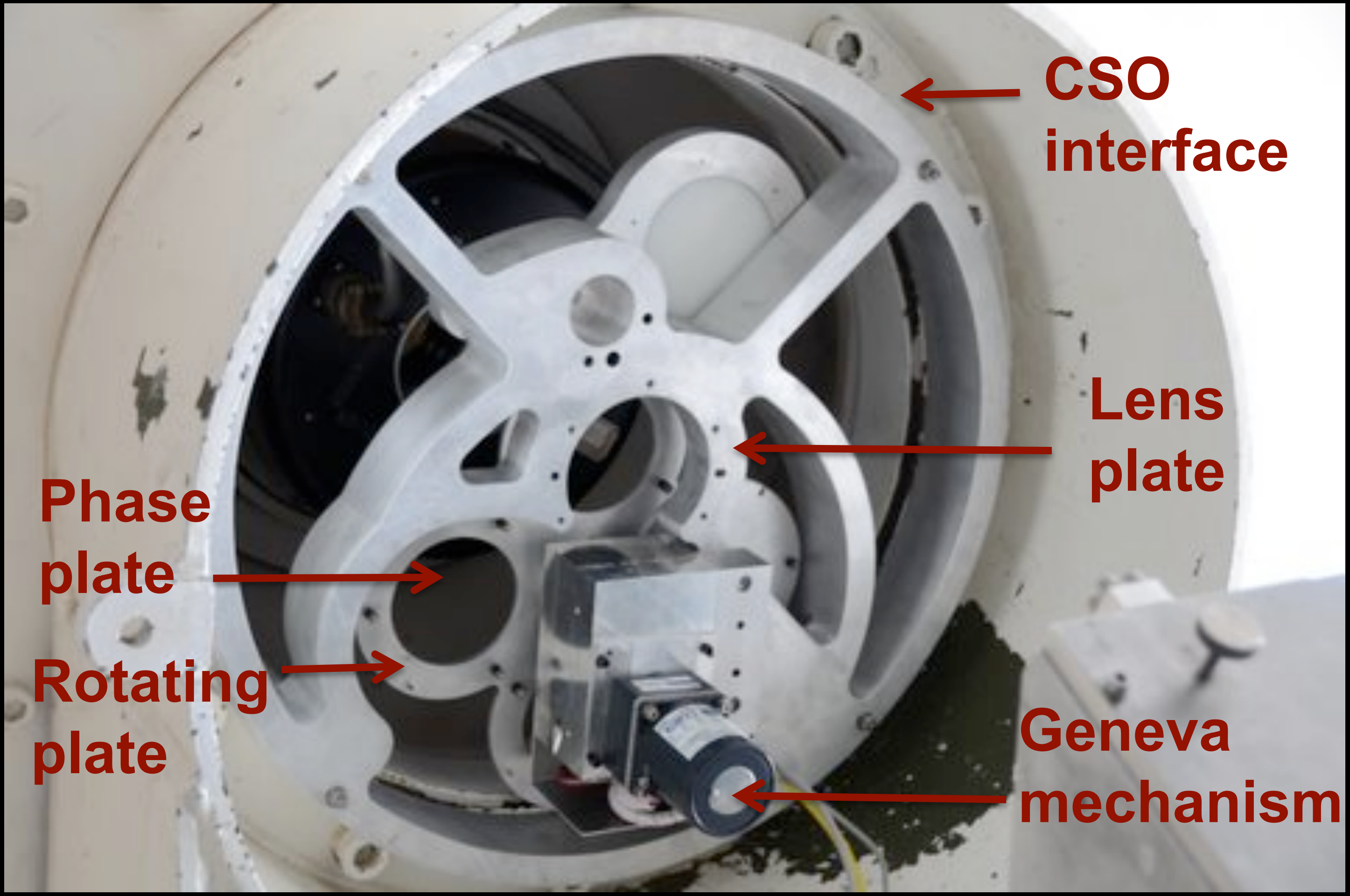
- Use ZWFS to measure a fraction of the CSO pupil
- Compare ZWFS with MGS on short time scales
- Acquire experience with ZWFS in preparation for CCAT phasing.

CSO Implementation



CSO Interface blue is the bearing well, light blue is keep out zone for bolts.

CSO Implementation



Mount Palomar Implementation

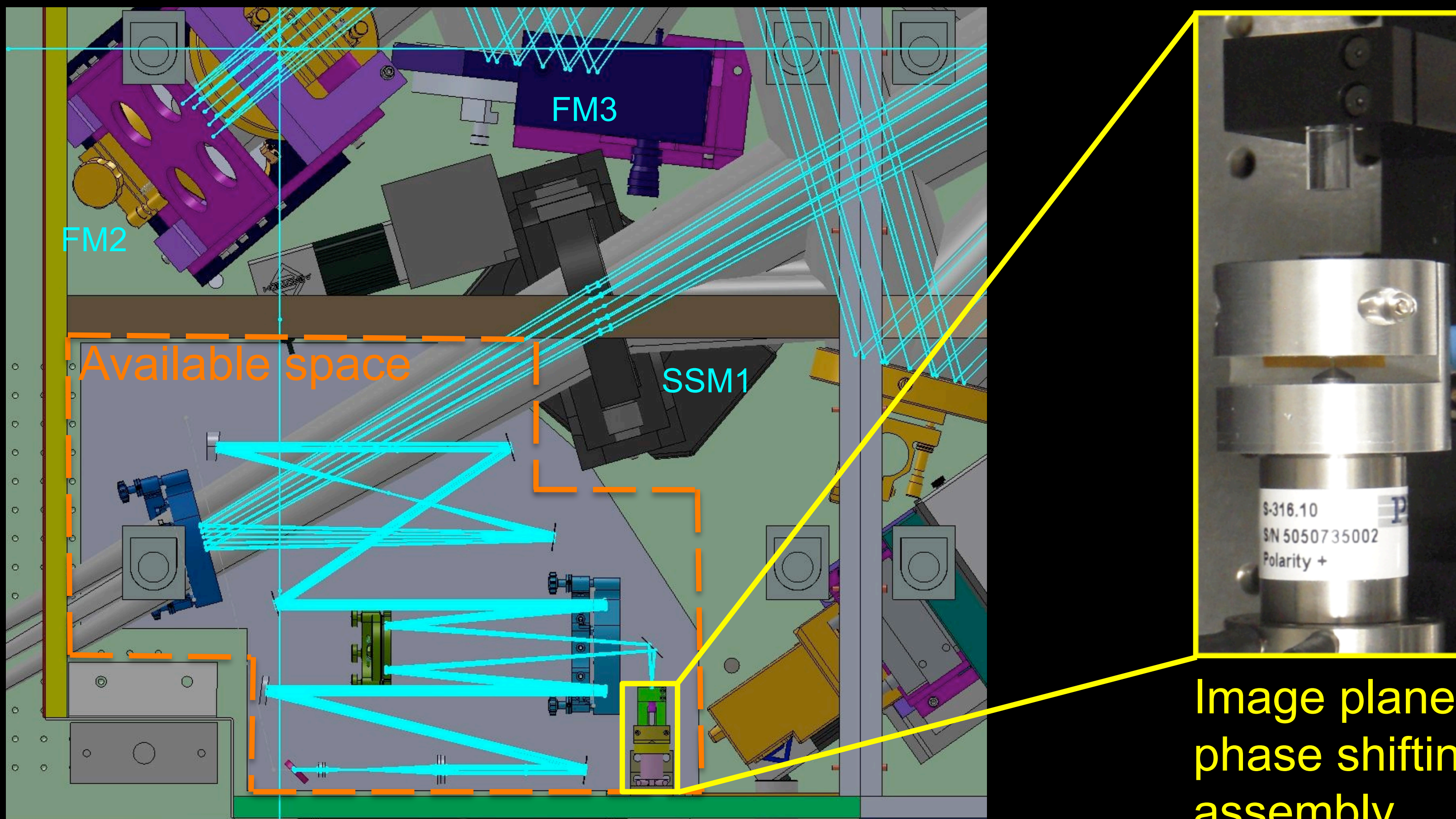


Image plane phase shifting assembly

Conclusion

- Zernike phase contrast maps phase to intensity in the output pupil
- The Zernike wavefront sensor uses dynamic Zernike phase contrast to measure phase for telescope applications
- Future applications
  - Mount Palomar adaptive optics system
  - Phasing segmented mirrors (CCAT, space-based telescopes)

Acknowledgements

- **Project Funding:**
  - JPL Research & Technology Development Fund
- **Student Funding:**
  - Massachusetts Space Grant
  - Dr. Gerald A. Soffen Memorial Fund for the Advancement of Space Science Education
  - MIT Department of Physics