Long-Range Adaptive Passive Imaging Through Turbulence

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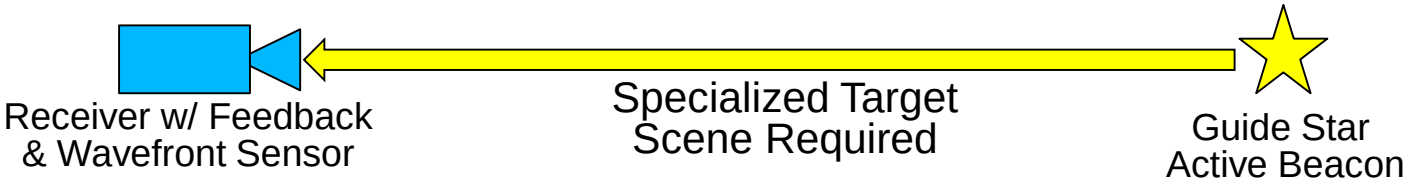
Overview of Talk

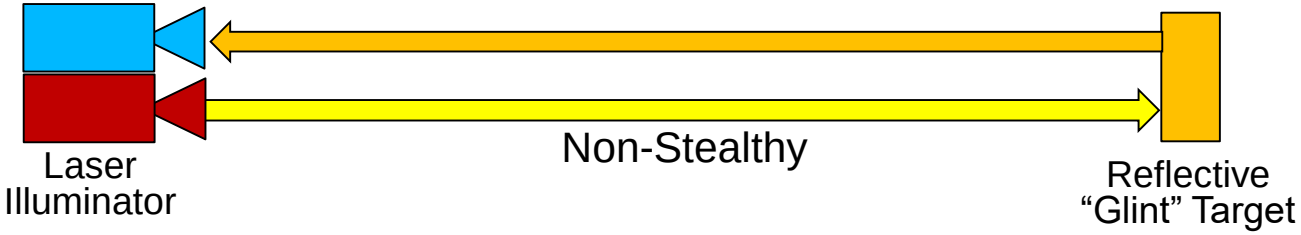
- Outline Problem
  - Comparison to Standard Methods
  - Turbulence Image Effects
  - Annular Aperture Short-Exposure Modulation Transfer Function
  - Variable Aperture Responses to Turbulence
- Generalized Proposed Solution
  - Zernike Expansion and Hufnagel Theory
  - Solution Components
- Solution Phase Control
  - Adaptive Aperture, Modes, Deformable Mirror Control
  - Decorrelation Issues, System Speed, Camera
- Conclusions

Adaptive Imaging Methods

Most Adaptive Optics Systems are Active

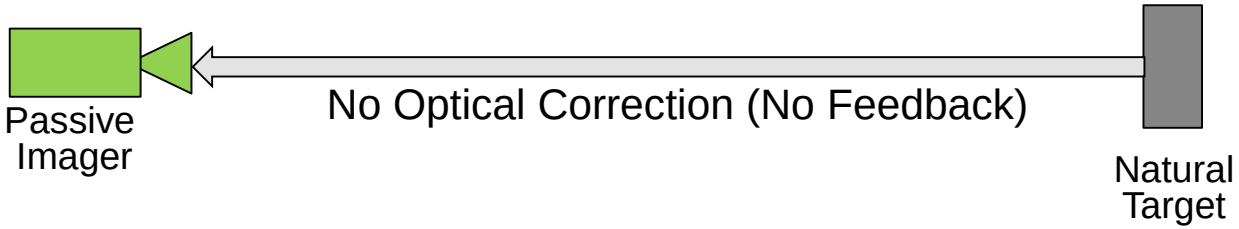


Examples:
LASER COMS
ASTRONOMY



Examples:
Active SWIR
HEL Beam Control

Or use only Post-Processing



Examples:
Lucky Patch
De-Warping
Segmentation

We Propose Combining a Passive Imager with Adaptive Elements = Passive Adaptive

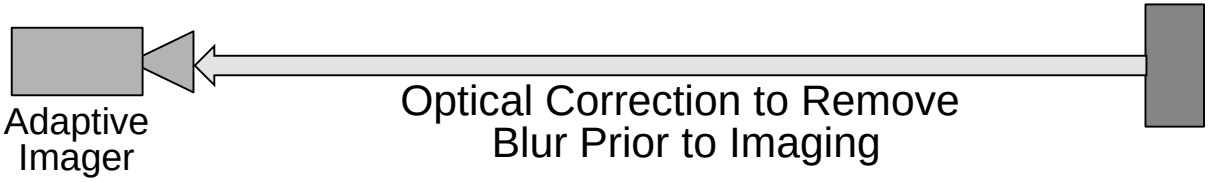
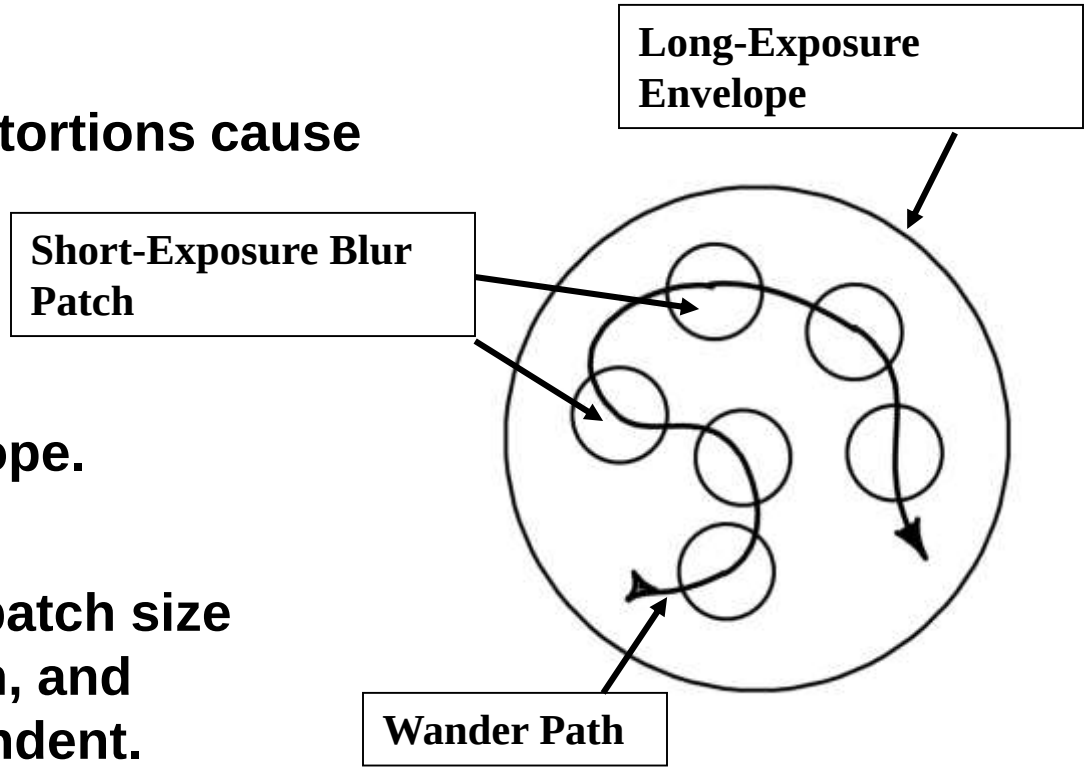


Image Blur & Distortion

- Distortion effects divide into long-exposure (>100 s) and short-exposure (~1ms) cases based on pixel integration times. Short-exposure blur effects are caused by smaller scale turbulence distortions.

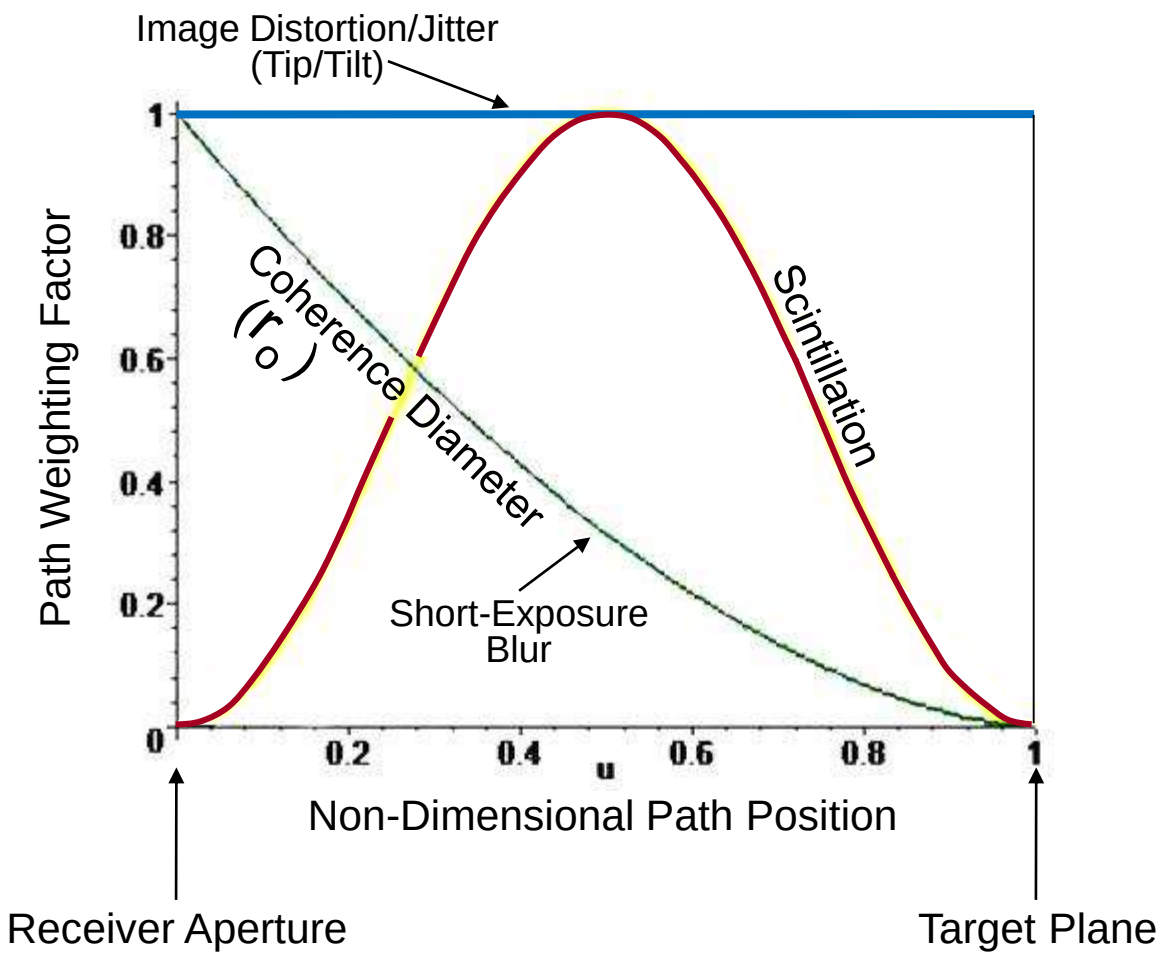
- Larger scale turbulent distortions cause the short-exposure image of a point source to wander as a function of time within the overall long-exposure blur envelope.

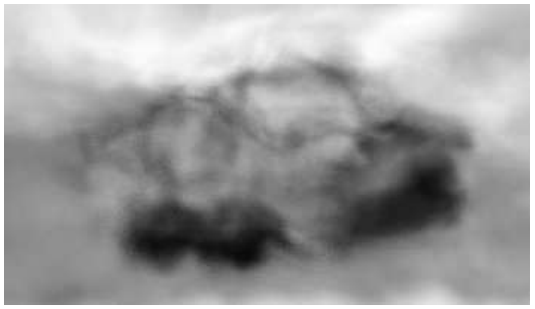
- The short-exposure blur patch size is wavelength, path length, and turbulence strength dependent.



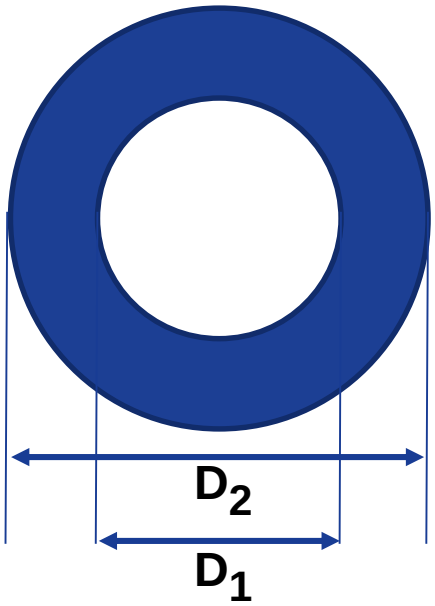
Path Weighted Effects

Initially, turbulent distortions dominate. As turbulence strength increases, blur effects dominate. Short-exposure blur is weighted most strongly at receiver.

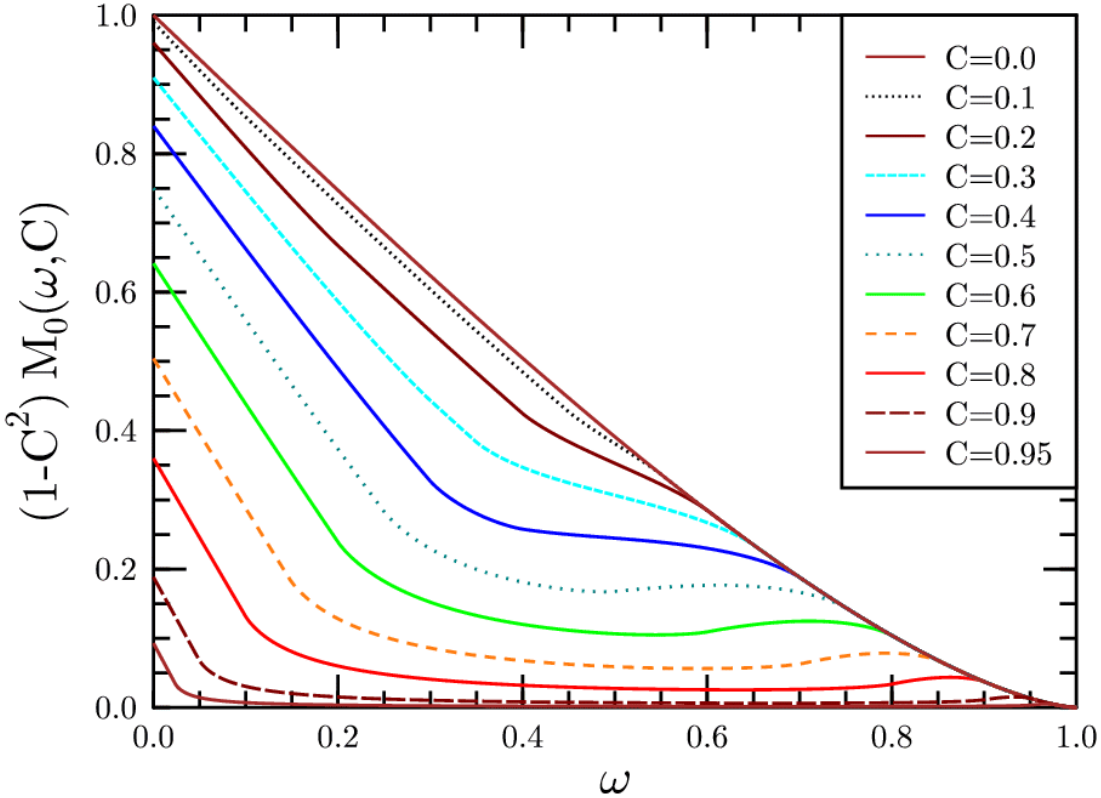




Annular Aperture MTFs



$$M_S(\omega) = M_0(\omega, C)\, M_{SA}(\omega, S, Q, C)$$



$C = D_1/D_2$

$$S = D_2/\rho_o$$

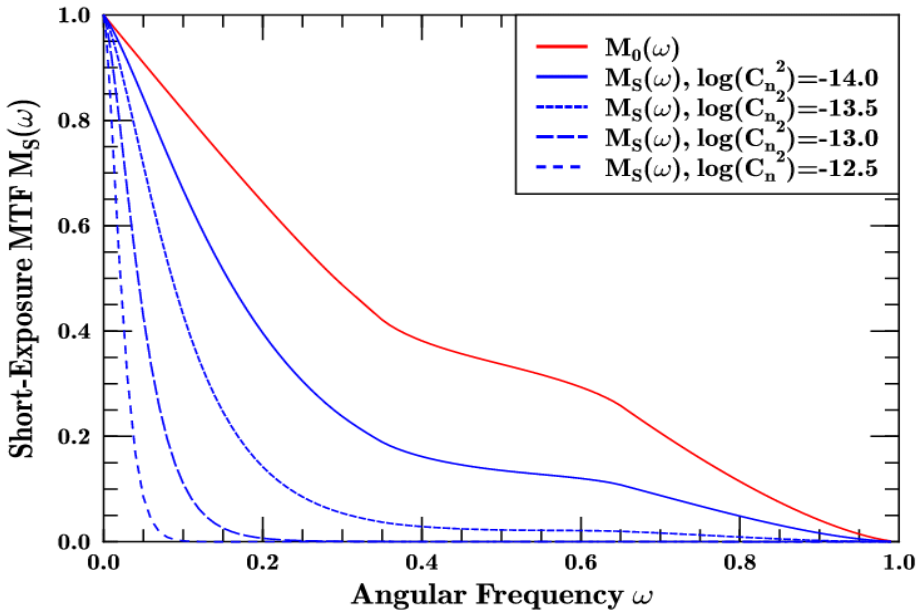
$$Q = D_2/(\lambda L)$$

$$\rho_o = 1.437\,(k^2 L C_n^2)^{-3/5};\; k = 2\pi/\lambda$$

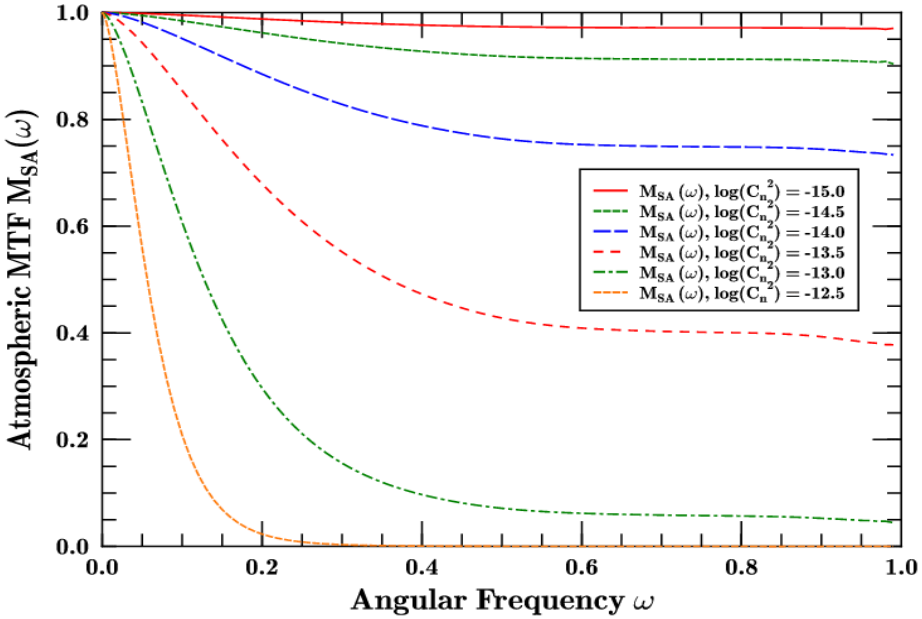
$\omega = \Omega/\Omega_o$, $\Omega_o = D/\lambda$

AnAp Atmospheric MTF

$$M_S(\omega) = M_0(\omega, C)\, M_{SA}(\omega, S, Q, C)$$



- Net atmosphere plus system MTF is monotonically decreasing.
- Short-exposure influences produce a plateau region at mid-band spatial frequencies.



- Function V(w,S,Q,C) reflects removal of phase tilt, dominated by a tilt-phase correlation term.

$$M_{SA}(\omega, S, Q, C) = \exp\left\{-S^{5/3}\left[\omega^{5/3} - V(\omega, S, Q, C)\,\omega^2\right]\right\}$$

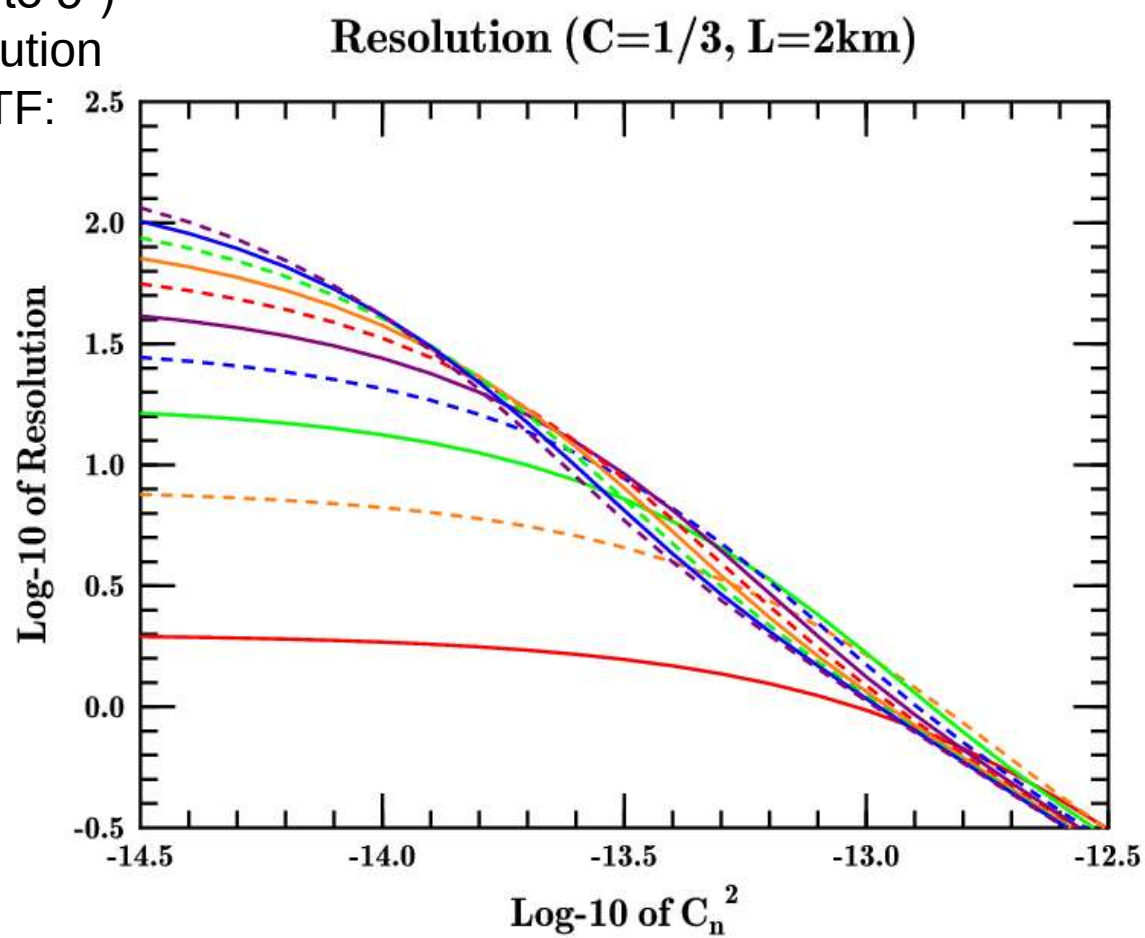
Variable Aperture Effects

- Consider turbulence effects as a function of aperture size (1/2” to 5”) measured using Fried’s Resolution function, the volume under MTF:

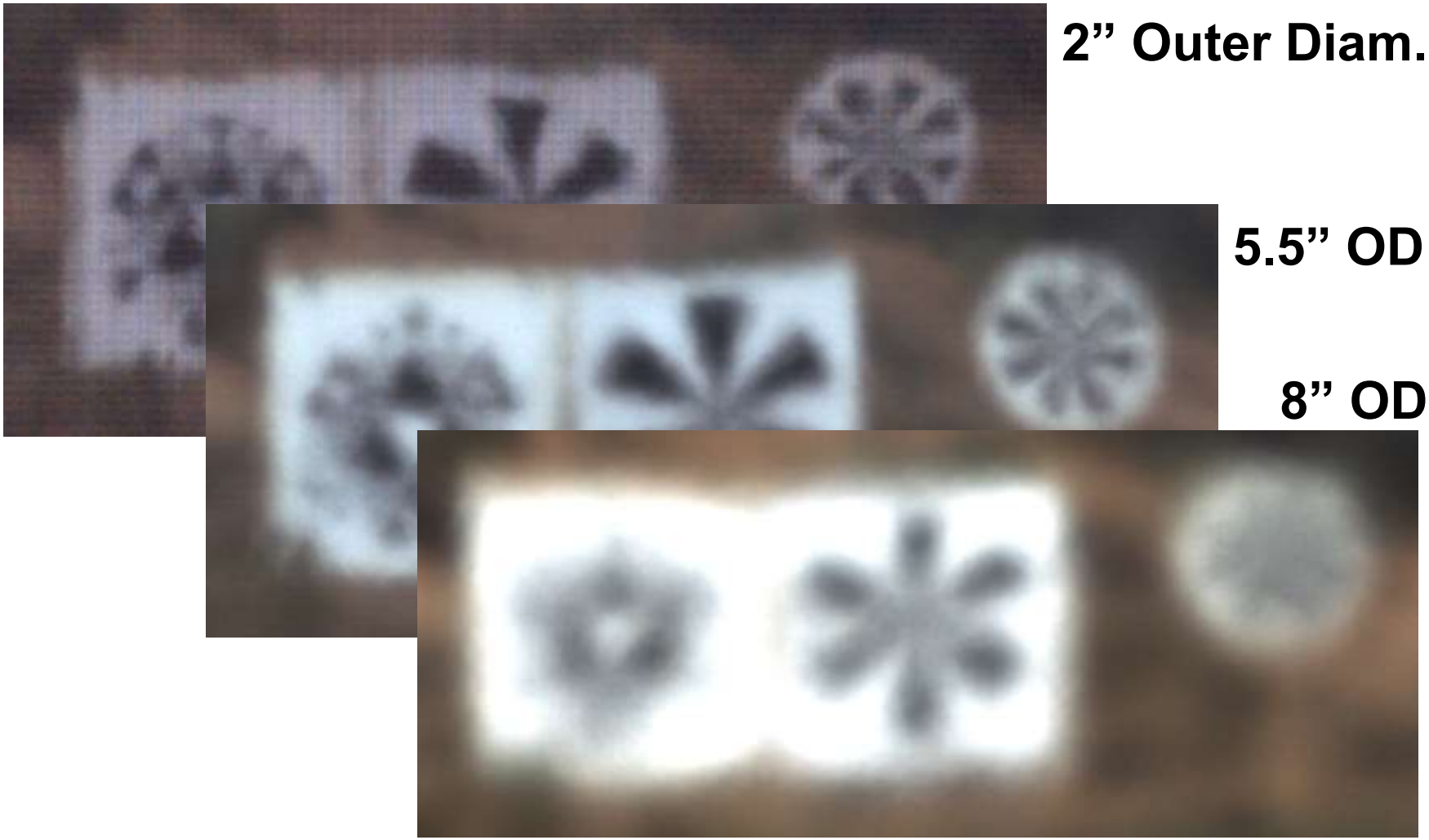
$$\mathcal{R} = \int \pi \, \omega \, M_S(\omega) \, \mathrm{d}\omega$$

- Smaller apertures outperform larger by factors up to 3 under increasing turbulence strength.

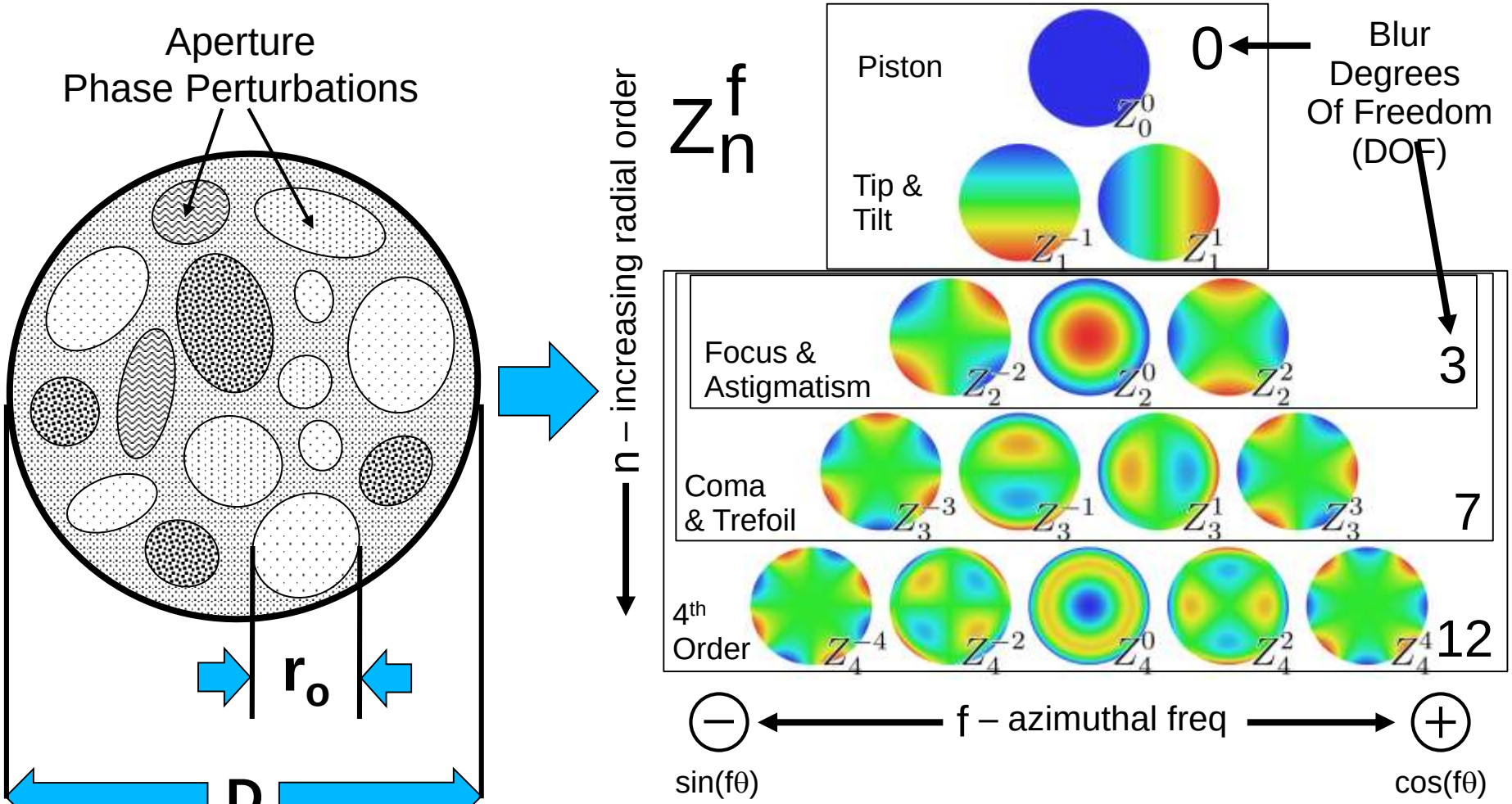
- Suggests aperture control key to improved image quality.



Aperture Influences



Zernike Phase Expansion



- Aperture reduction can reduce the number of active modes, but what about additional mode corrections?

Hufnagel DOF Corrections

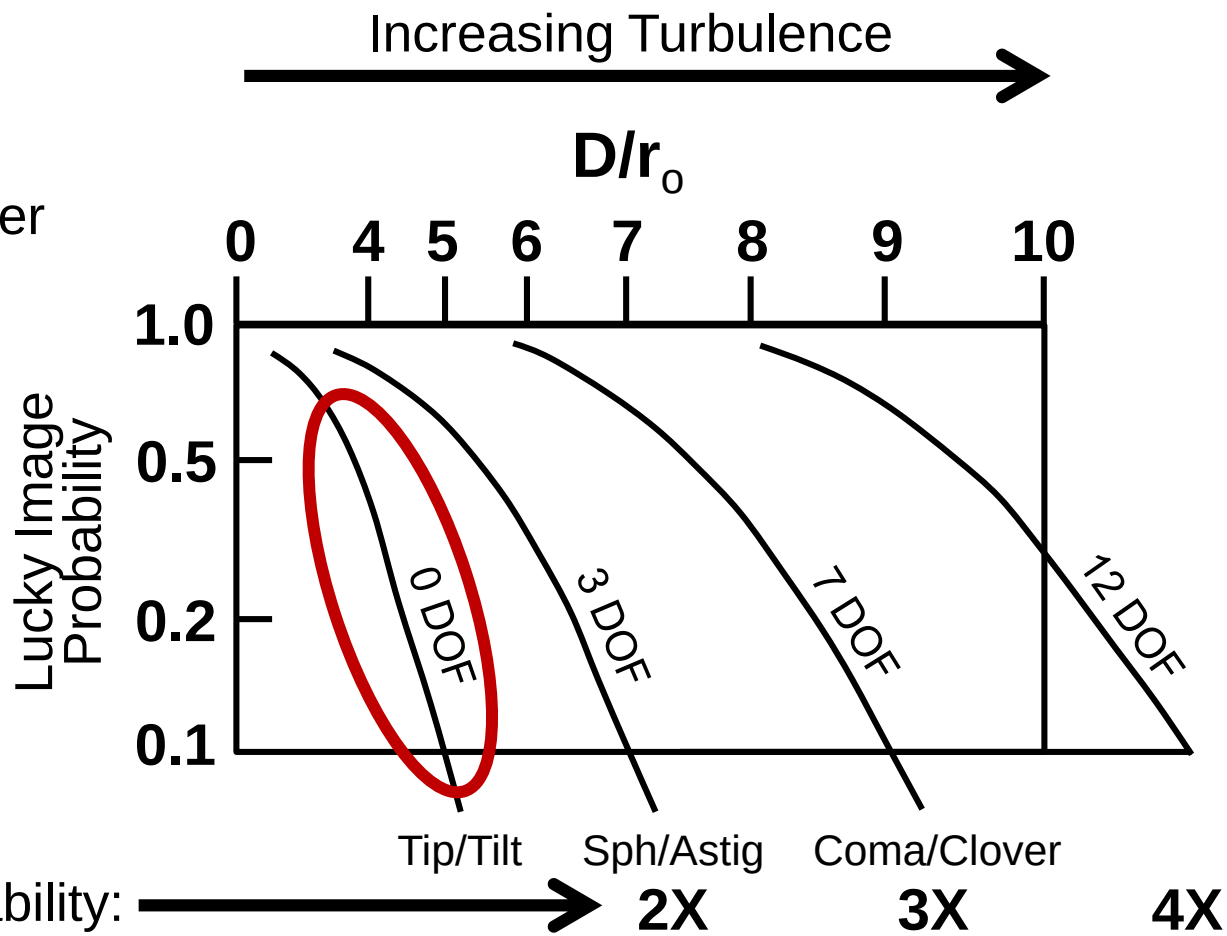
Figure from Hufnagel [1989]

D = Aperture Diameter

r_o = Coherence Diameter

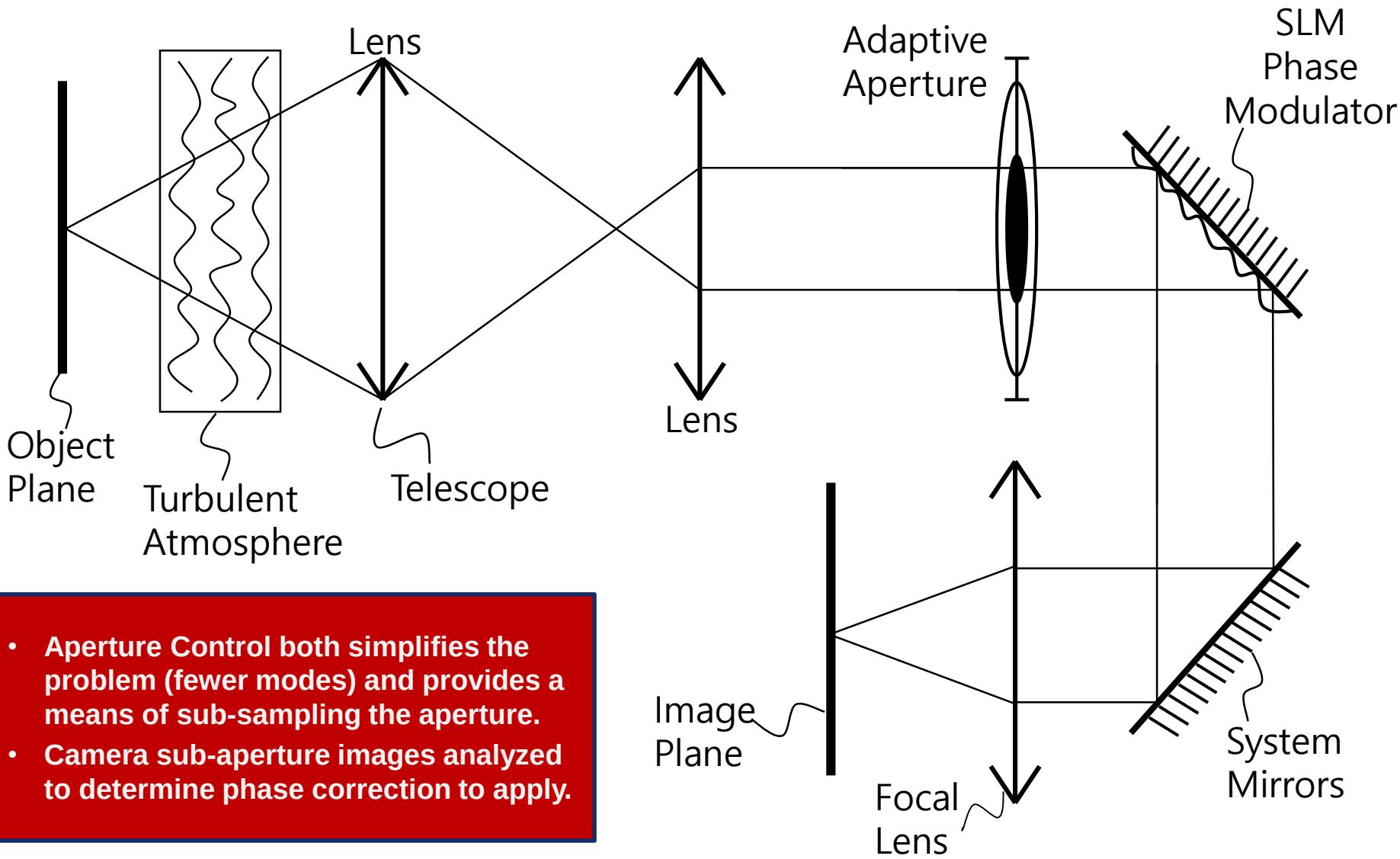
Basic "Lucky Patch"

Blur DOFs Removed



Improved Range Capability: → **2X** **3X** **4X**

Passive Adaptive Solution



- **Aperture Control both simplifies the problem (fewer modes) and provides a means of sub-sampling the aperture.**
- **Camera sub-aperture images analyzed to determine phase correction to apply.**

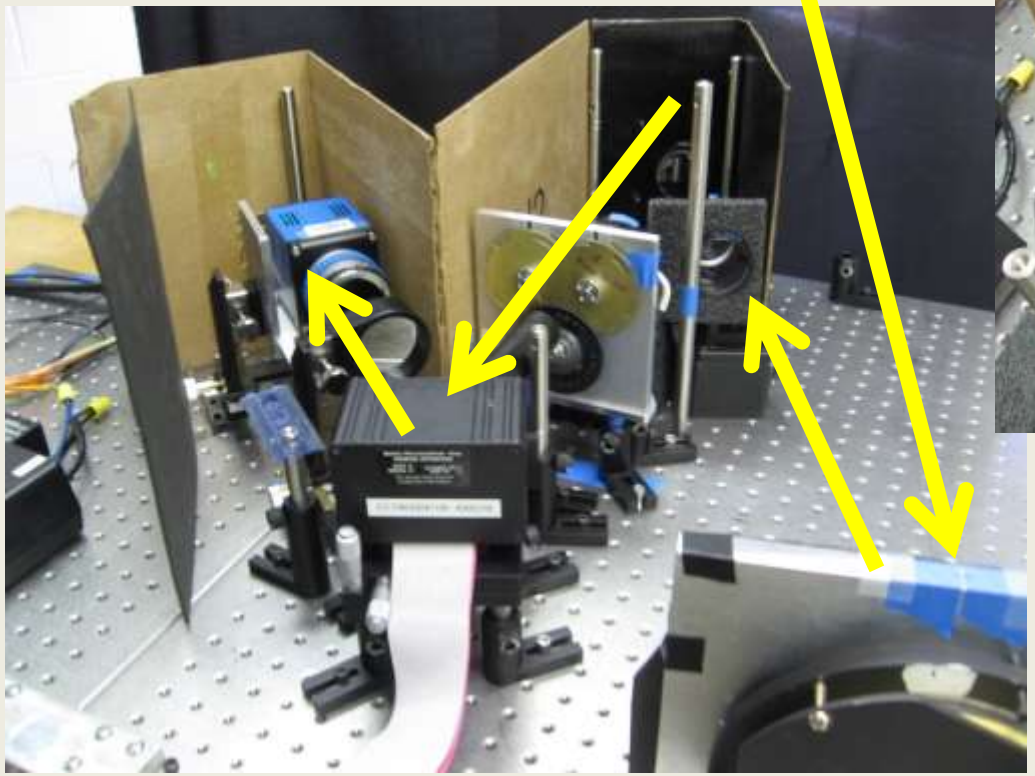
Prototype System

System Camera

Adaptive Aperture

Spatial Light Modulator

System Light Path



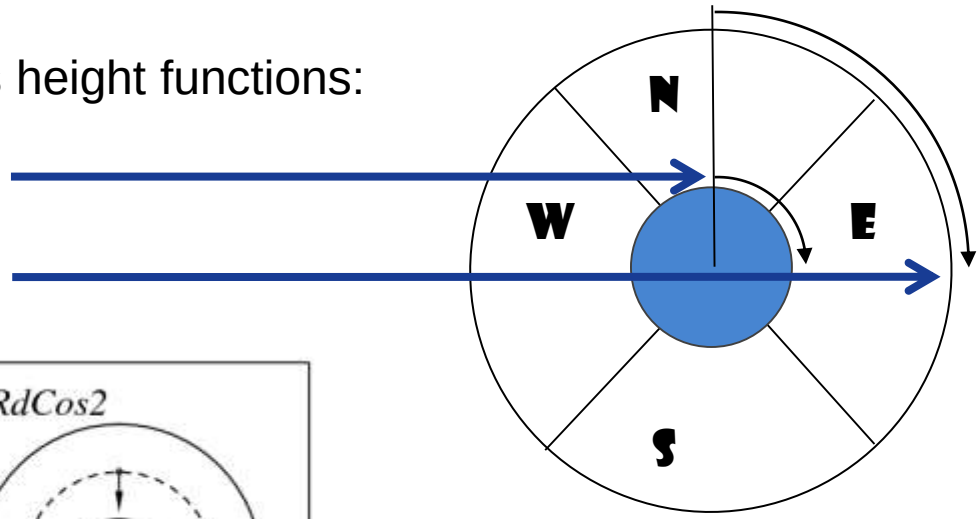
Main Mirror

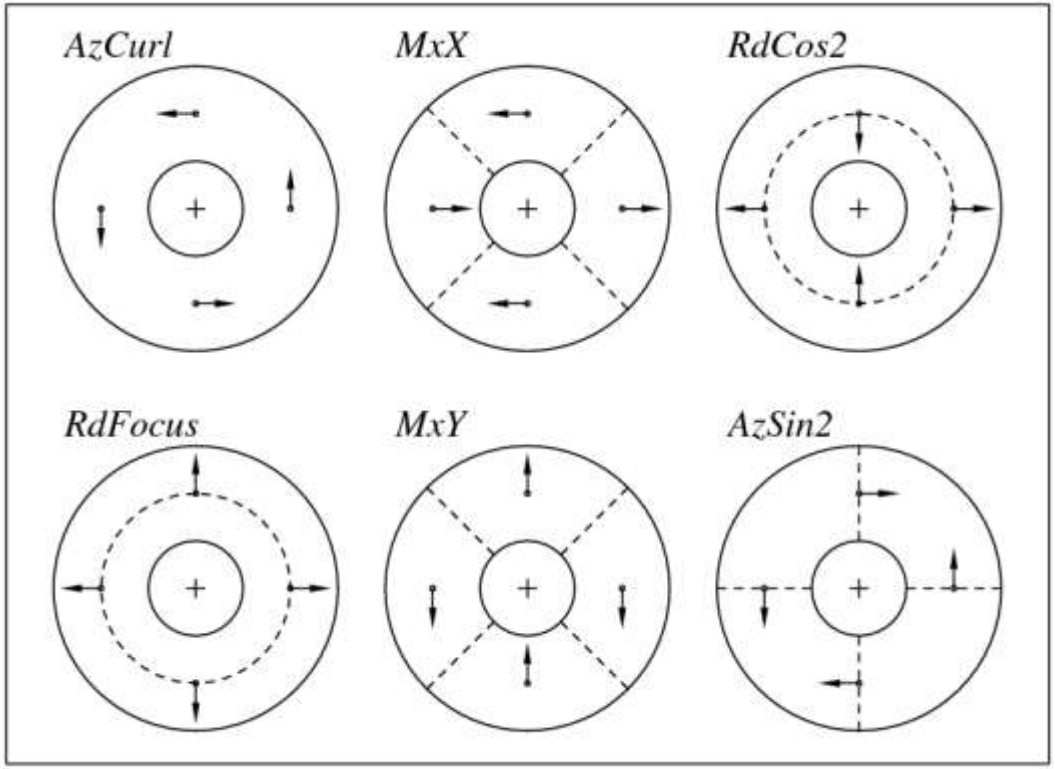
Phase Decomposition

First, model inner and outer radius height functions:

$$\Phi_{inner} = A0 + A1\cos(1\theta) + A2\cos(2\theta) + B1\sin(1\theta) + B2\sin(2\theta)$$

$$\Phi_{outer} = C0 + C1\cos(1\theta) + C2\cos(2\theta) + D1\sin(1\theta) + D2\sin(2\theta)$$

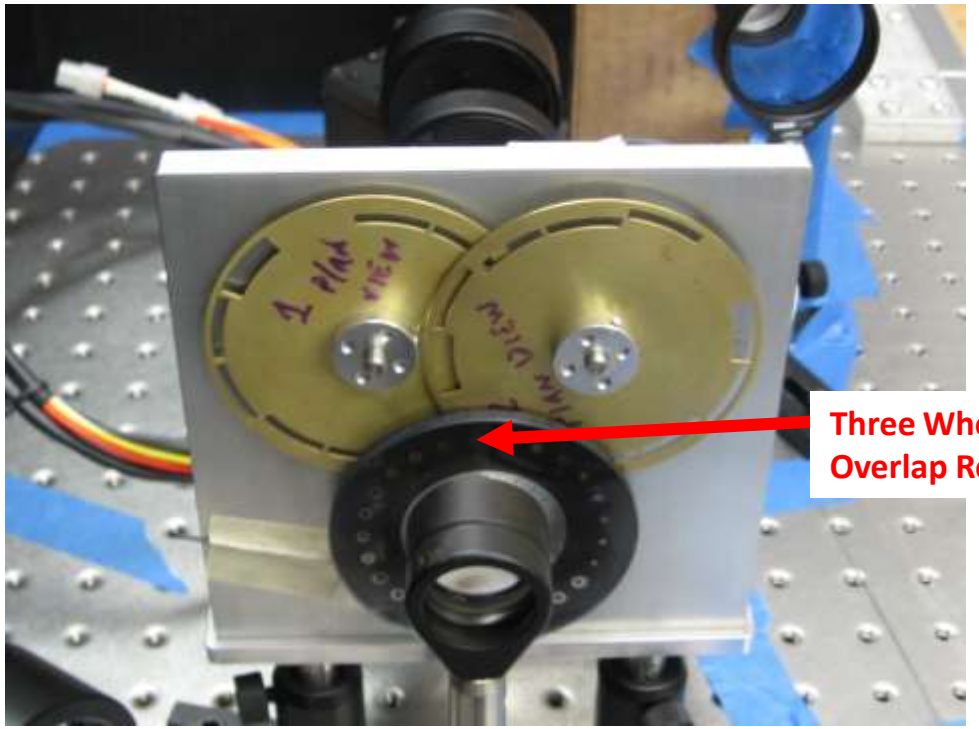




The resulting model can be expressed using eight “modes”. Of these, two are the tip and tilt linear terms that do not affect image quality. The remaining terms are shown at left.

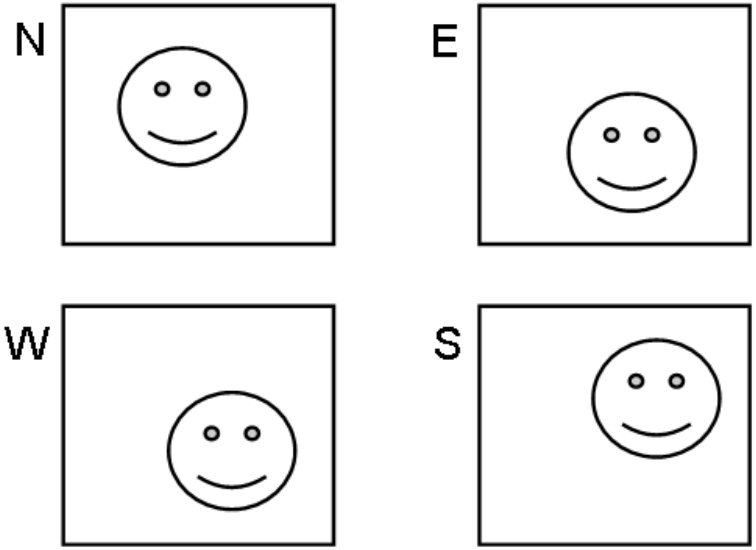
AzCurl is unrealizable, reflecting the inaccuracy of the current size of the outer and inner diameters of the system vs. turbulent state.

Adaptive Aperture



- In the current prototype version, four subaperture images are collected using a flywheel apparatus.
- The four sample images are collected, then a full aperture image is collected.

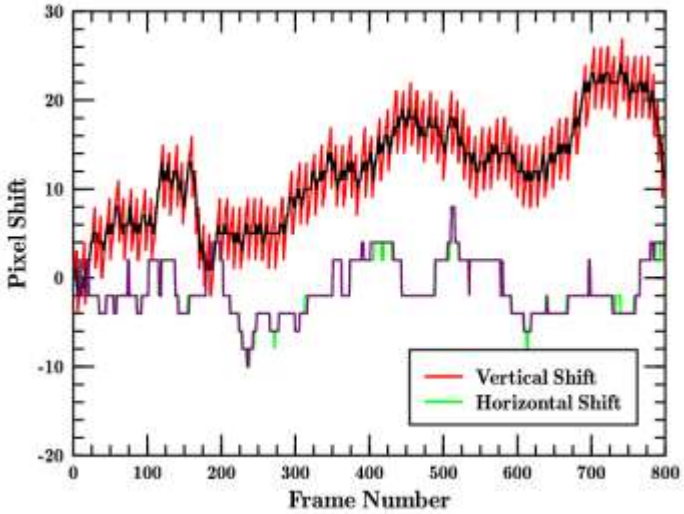
- Image shifts are calculated via a cross-correlation procedure to determine the relative tilt of the incoming light in each portion of the aperture.



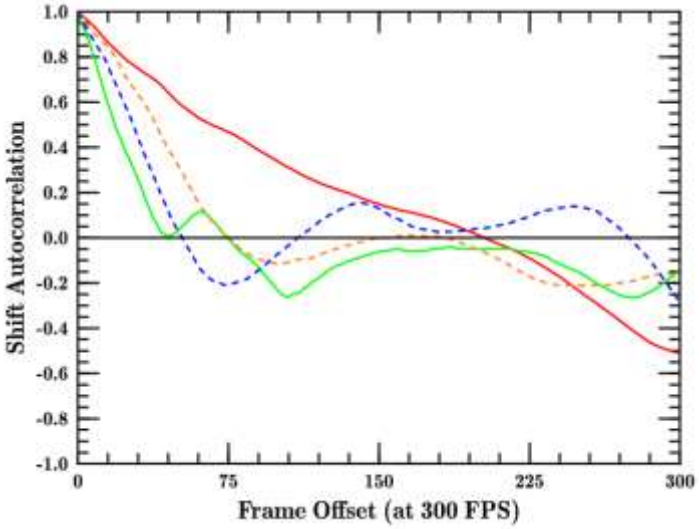
Tracking Image Shifts

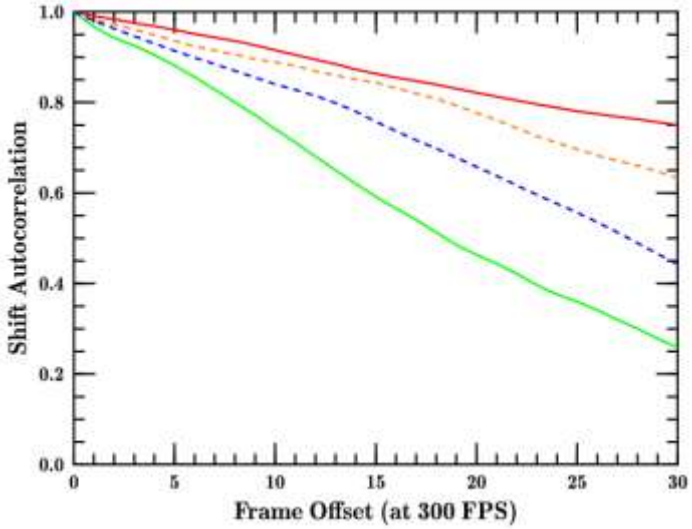
Use cross correlation techniques to determine angle-of-arrival shifts:

- For computational speed:
  - Sum both in Vertical and Horizontal Dimensions
  - Correlate to determine pixel shift



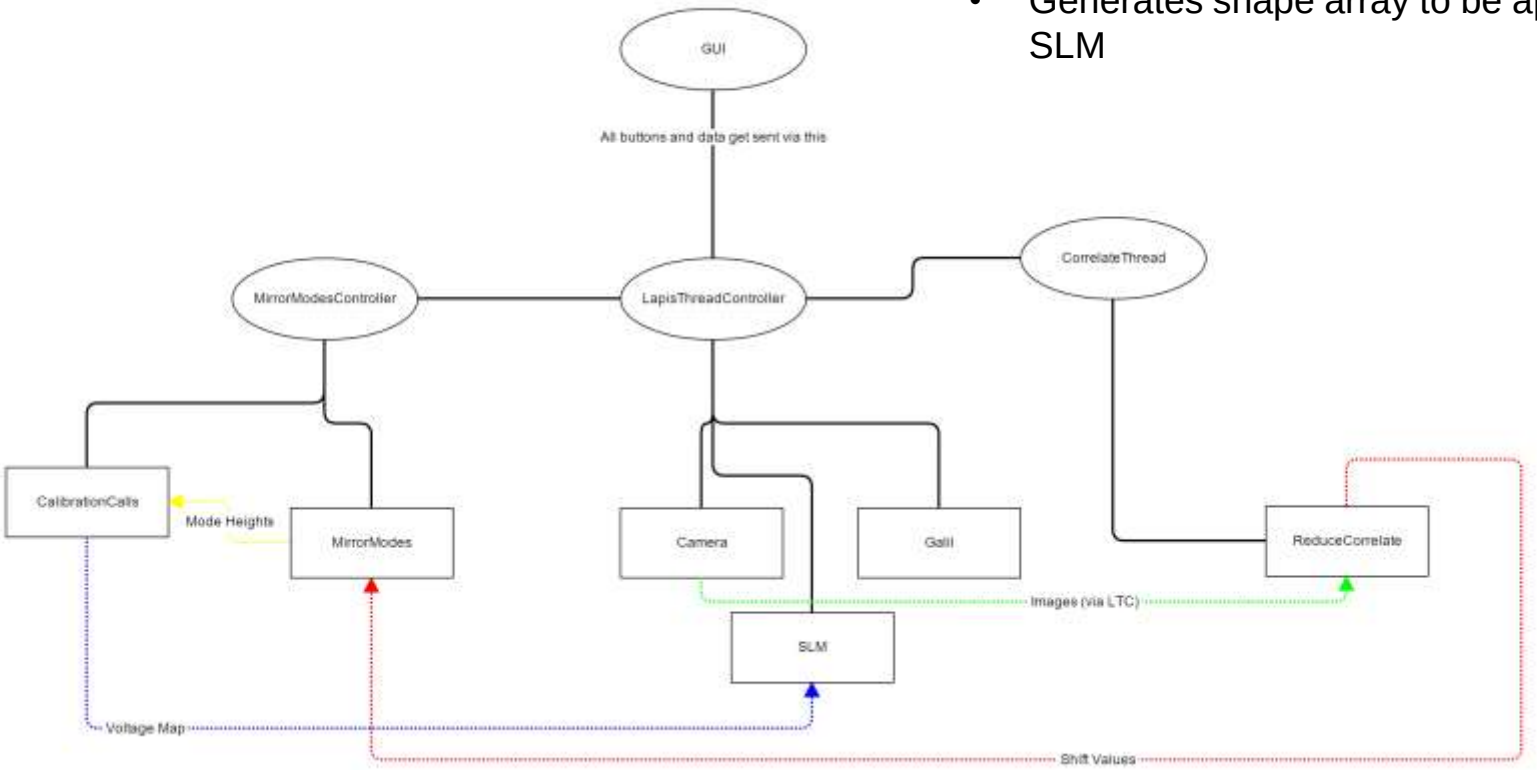
Based on observed shift sequences, derive decorrelation information… 90+% @ <20ms





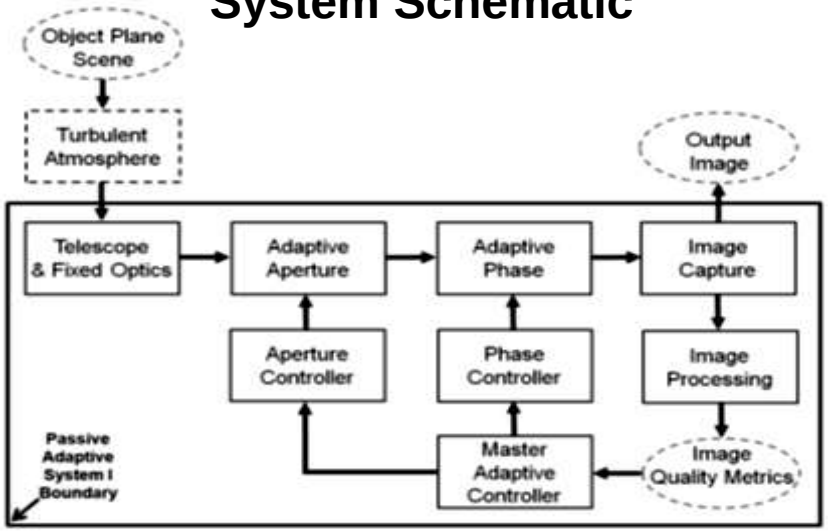
Basic Software/Hardware Interface Design

- Layout of underlying threading design
  - GUI
  - Thread Controller
    - Sync all threads and GUI
    - Control flow of incoming images
    - Control SLM and Motor Controllers
- Correlation Thread
  - Handles reduction and correlation to output pixel shifts
- Mirror Modes Thread
  - Models mirror shape according to 4 image shifts
  - Generates shape array to be applied to SLM



Conclusions

System Schematic



- System testing awaiting completion of software checkout.
- Preliminary results indicate near linearity of phase across annular rings.
- Timing of the system dependent on maintaining adequate cross-correlation between full frames & image exposure.

- Aperture size dictated by photon availability.
- Turbulence strength also controlled by relative light level.
- Improved performance through additional innovations needed.