Design of Wide-Field Imaging Shack Hartmann Testbed

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Abstract

Adaptive Optics systems developed by astronomers measure the aberrations in the wavefronts of beacon guide stars, which limits the corrected field of view to the isoplanatic angle. Imaging systems that require a larger corrected field must rely on tomographic analysis of aberrations measured along multiple lines of sight. [1]. The foundations of this method are derived from techniques used in adaptive optics imaging of the sun. [2] Small regions containing high contrast, high frequency spatial information replace guide stars as the reference beacons for the 3D reconstruction of aberrations. Extending the solar AO technique, we report early results from a laboratory prototype in which a single imaging Shack Hartmann sensor is used to fully characterize the wavefront over a field of view an order of magnitude larger than the isoplanatic angle. A first order design of the system was done in Zemax, and currently under alignment. The system has two arms, connected through a beam splitter. The imaging arm has an $F_{\#}$= 18.87, and provides the reference image used in the wavefront sensing. The wavefront sensor arm contains a 5x5 Shack Harmann lenslet array of the same $F_{\#}$, with a focal length that will depend on the back focal distance of the finished imaging arm. Each sub-aperture provides an image of the scene from a slightly different sight line. The sub-apertures of the sensor see the scene from slightly different angles. Warp maps of the images seen by all the sub-apertures are calculated by cross-correlation of small regions of the scene provided by the imaging arm that contain high contrast, high spatial frequency information. The warp maps can then be used to construct the 3D distributions of aberrations of the wavefront using tomosynthesis. [1] Future work entails finishing the alignment and characterization of the imaging arm, and obtaining a precise measurement of the back focal distance to finish the design of the lenslet array and start building the second arm. A turbulence simulator designed by colleague, R. Phillip Scott, will be placed in front of this system upon its completion, to be used as the light input to the system.

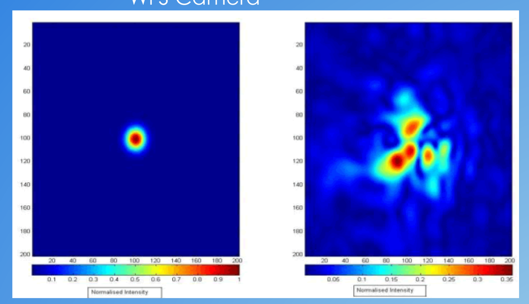
Background

Cartoon of an application of the WFS Camera

- Aberrations caused by atmospheric turbulence distort and blur the image.

Sources of Aberration: (depends on aperture size!)

- Small scales: Refraction of light causes speckling and blurring.
- Large scales: Refraction of light by the atmosphere randomly shifts the apparent line of sight of each point in a scene.

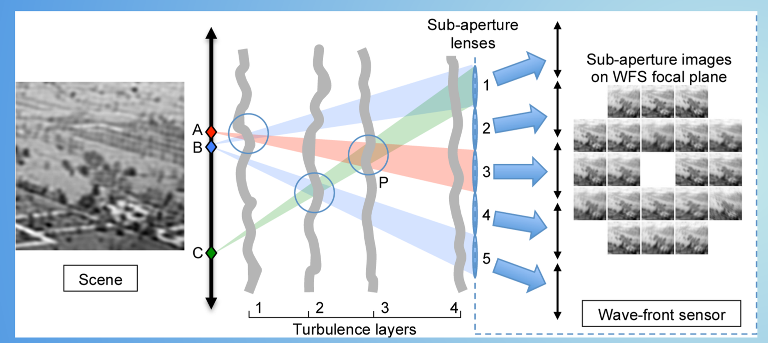


PSF with no turbulence. [3] PSF with strong turbulence. [3]

Solution: Correct for aberrations using Adaptive Optics or Post Processing.

- Need to characterize the wave front first!

Imaging Shack Hartmann Wavefront Sensor. [2]



- Imaging a scene with discrete features.
- FOV>> isoplantic angle

- WFS divides the pupil into a grid of 5x5 sub-apertures
- Entire scene is imaged in each sub-aperture
- Phase gradients in the atmosphere warp each image differently, due to the different perspective of each sub-aperture

- Each sub-aperture image compared against a reference
- Displacements of high spatial frequency information used to calculate a grid of gradients across entire FOV
- The 3D wavefront gradients can be integrated to estimate the 3D distribution of aberrations in the wavefront

Design

Two Arms, same $F_{\#}$

- Imaging Arm:
  - Provides reference image.
  - Provides the basis for the final high resolution image
- Shack Hartmann Arm:
  - Divides the pupil using lenslet array.
  - Provides sub-aperture images to sense off of.

Imaging Arm

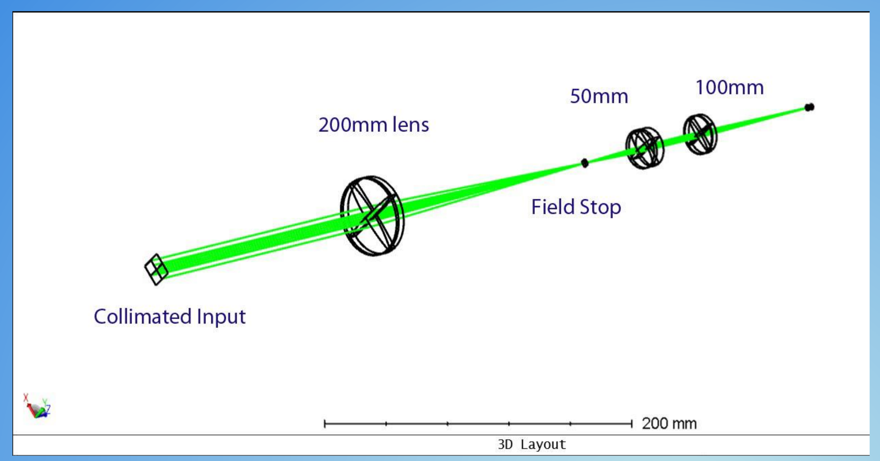


Figure 1. Design of Imaging arm done in Zemax.

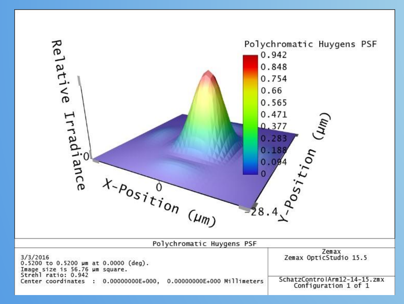


Figure 2 A. PSF of on-axis ray bundle.

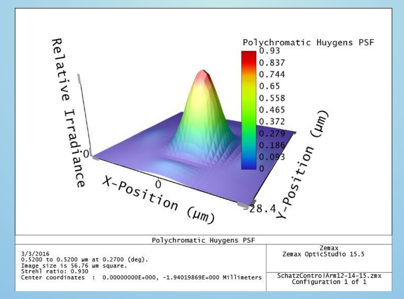


Figure 2 B. PSF of off-axis ray bundle.

- $F_{\#}$= 18.87
- 0.5 degree FOV
- 4X Keplerian Relay
  - 21.2 mm beam input
  - 5.3 mm output
  - 2.5 mm field stop at shared focus
- 100 mm focusing lens
- Point Grey Flea3 camera
- Strehl greater than 93% across all fields.
- Field stop will eventually be square.
- PSF is a sinc^2 function.

Shack Hartmann Arm (In Progress)

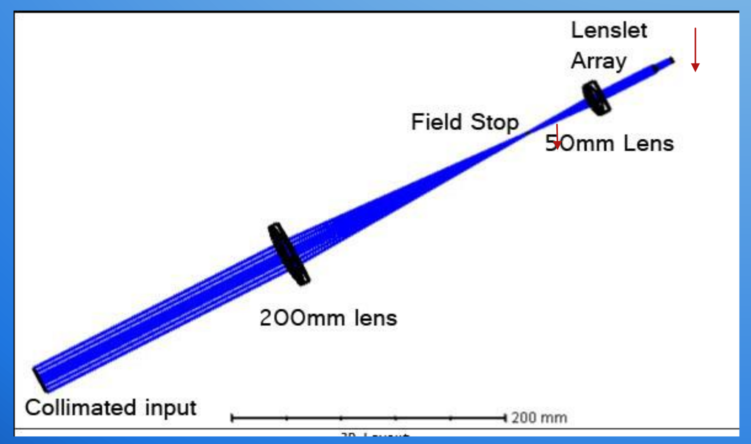


Figure 3. Design of Shack Hartmann arm done in Zemax.

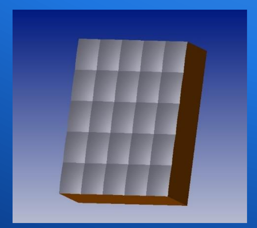
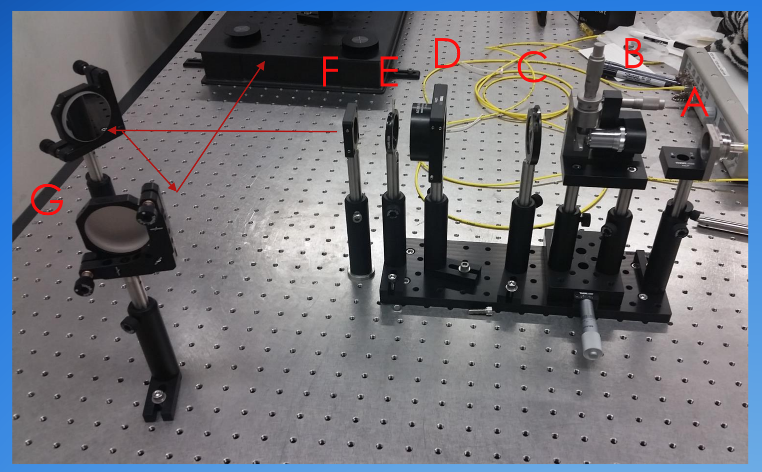
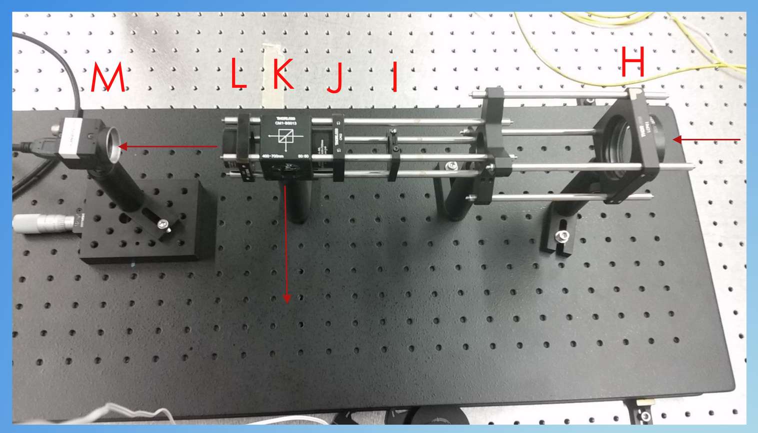


Figure 4. Design of lenslet array done in Zemax

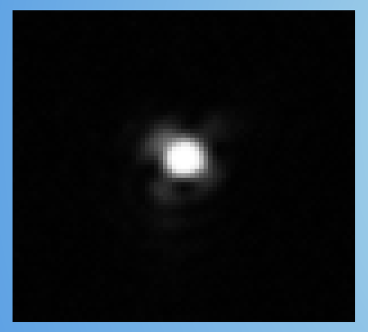
- Connected to imaging arm by beam splitter
- 5x5 lenslet array
- .75mm by .75 mm lenslets
- F= 14.15 mm (approximately)
- $F_{\#}$= 18.87
- Final focal length determined by precise measurement of back focal distance of imaging arm. (Still to be done)

Current Progress: Alignment and Characterization





A. Collimating fiber port
B. Spatial Filter with 5 micron pinhole
C. Iris
D. 150 mm collimating lens
E. Iris
F. 4.0 ND filter
G. 2" flat lens periscope
H. 200 mm lens (start of Keplerian relay)
I. Field stop
J. 50 mm lens (end of Keplerian relay)
K. Beam Splitter
L. 100 mm focusing lens
M. Flea3 camera



Current PSF! (Placeholder)

Strehl Program

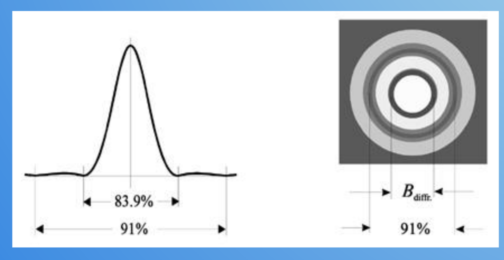
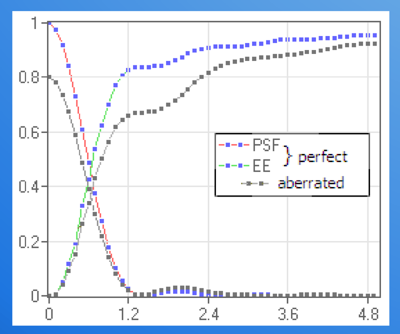


Figure 4. Encircled energy plots of the Airy Pattern.



- ~84% of energy in the core of a perfect airy pattern.
- Degrades with aberrations
- Comparing the energy inscribed in the core versus the total energy gives the Strehl Ratio

Future Work:

- Finish Alignment and Characterization
- Measure BFD
- Finish Lenslet Array Design
- Create a Scene Generator

References

[1] M. Hart. S. M. Jefferies. J. G. Nagy. D. A. Hope. "Tomographic wave-front sensing without cooperative beacons," in review for Optics Express, OSA, (2015).

[2] G. Moretto, M. Langlois, P. Goode, N. Gorceix and S. Shumko, "Design for solar multi-conjugate adaptive optics at the New Solar Telescope/Big Bear solar observatory," in Adaptive Optics for Extremely Large Telescopes, Third AO4ELT Conference, Florence, Italy (2013).

[3] M. Ismail. M. Sathik. "A Study on atmospheric turbulence with Shearing Interferometer wavefront sensor," in Research & Reviews, (2015)