

RGB Wavefront Sensor for Turbulence Mitigation STL-078-16, Year 2 of 2

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Acknowledgments

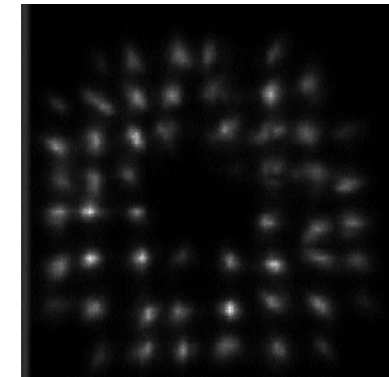
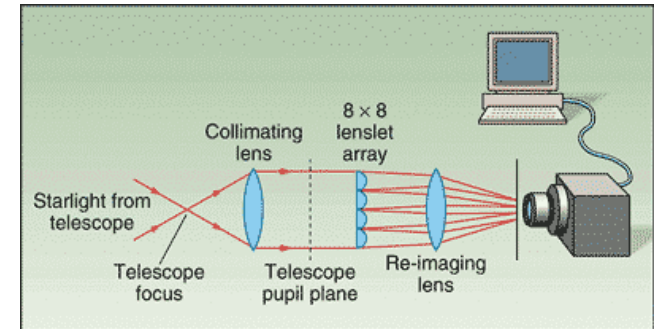
David Tofsted (ARL), Ben Valencia, Rick Allison

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Background

- For high turbulence, algorithms alone cannot recover scene content, especially for long-range horizontal paths
- STL has been working with ARL to combine adaptive optics (AO) with algorithms for long-range horizontal path imaging
- Shack-Hartmann adaptive optics—typically closed loop
 - Entrance aperture is split up into an array
 - From image, computer calculates pixelated map
 - Pixelated map of wavefronts is fed into a deformable mirror
 - Typically requires a point (or small) source in the scene
 - For long-range horizontal paths, a point source may not be available
- Advantages to this research
 - Use of color camera with filters to simultaneously capture shifted images
 - Added information in spectral content
 - New generation of compact handheld sensors
- Risks
 - Requires better measurement of statistics associated with turbulence
 - Sub-apertures result in higher f/# requiring high sensitivity cameras



Out-of-focus star
from AO system

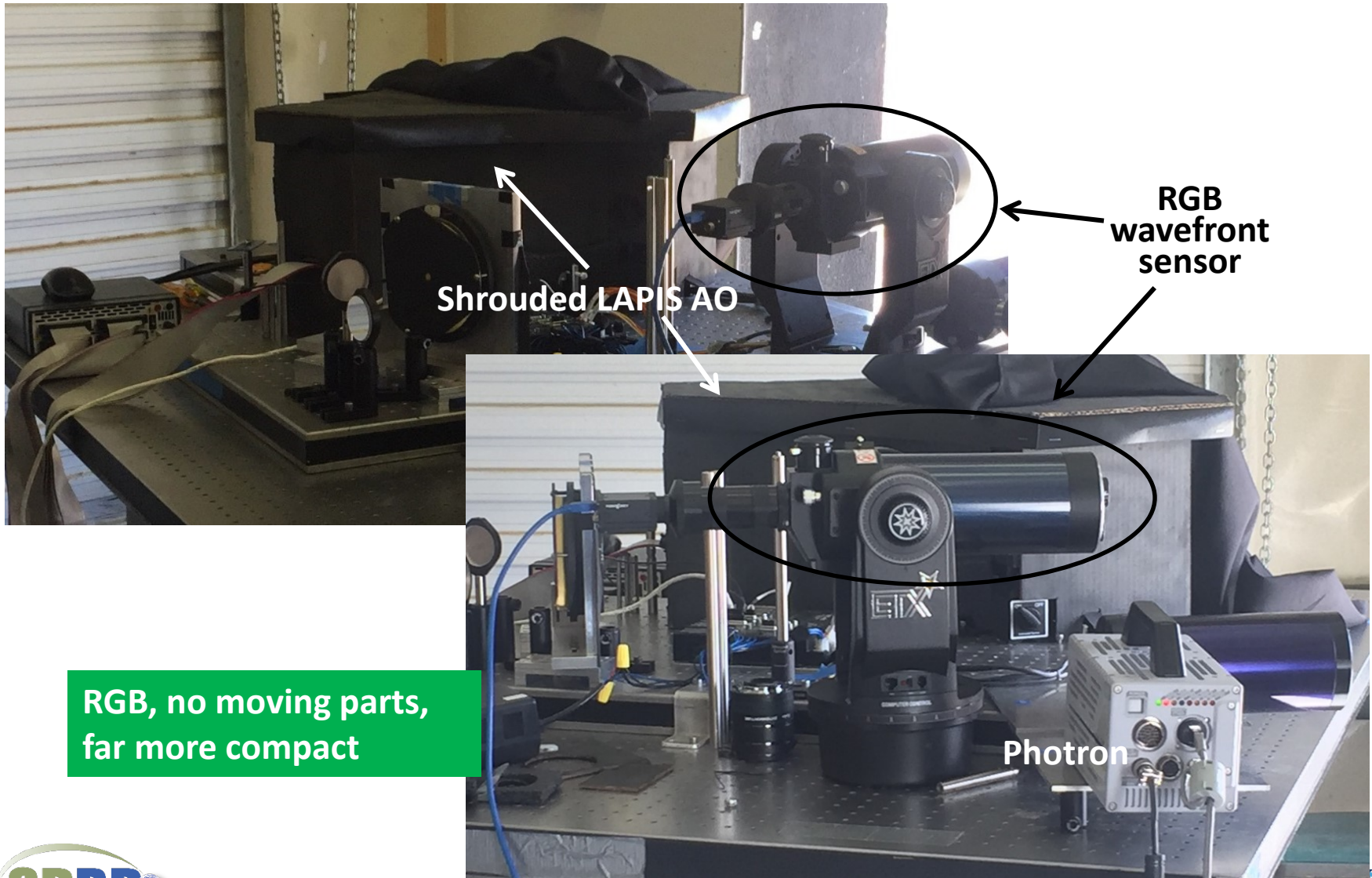
<http://www.ast.cam.ac.uk/research/instrumentation.surveys.and.projects/lucky.imaging/lucky.adaptive.optics>

Leveraging work on Gibraltar

- Gibraltar WFO project
 - Combines AO with processing
 - Dr. David Tofsted of ARL developed the AO concept called Long-Range Adaptive Passive Imaging System (LAPIS)
 - Theory is strong, but implementation is complex
 - Sub apertures not sampled simultaneously but via a spinning reticle
 - Fits on 3' × 4' bench with moving parts
- RGB AO system
 - Compact, fully time correlated sub aperture data, 4" telescope
 - Leveraging previous SDRD work and ARL AO theory
 - Additional work required since full aperture image (all colors simultaneously) cannot be collected

**Gibraltar project recognized the need for
a hybrid AO and algorithm solution**

Sept. 2016 Gibraltar Test, LAPIS and RGB Equipment



RGB, no moving parts,
far more compact

Test imagery from LAPIS, Sept. 14, 800 m, frame 673,
 $C_n^2 = 2.4 \times 10^{-13} \text{ m}^{-2/3}$, 3" aperture

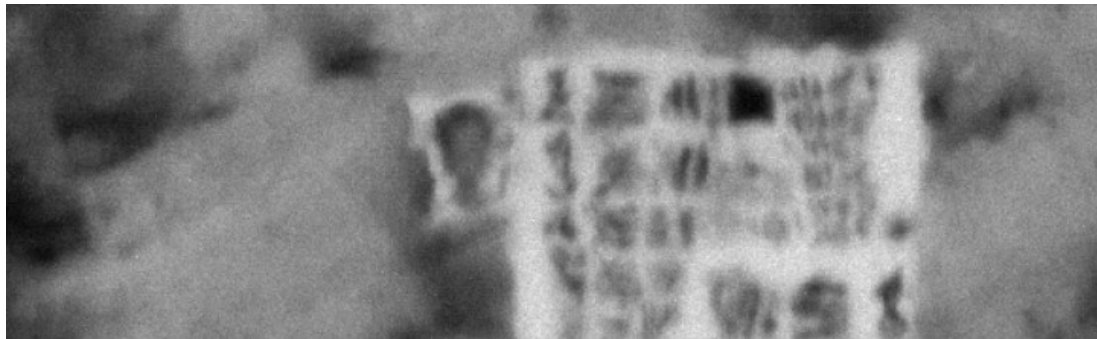
No Correction



Tip/Tilt



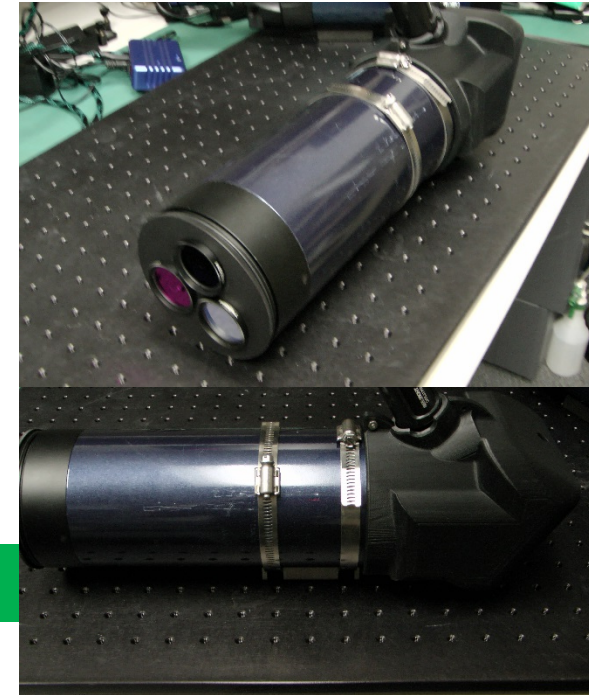
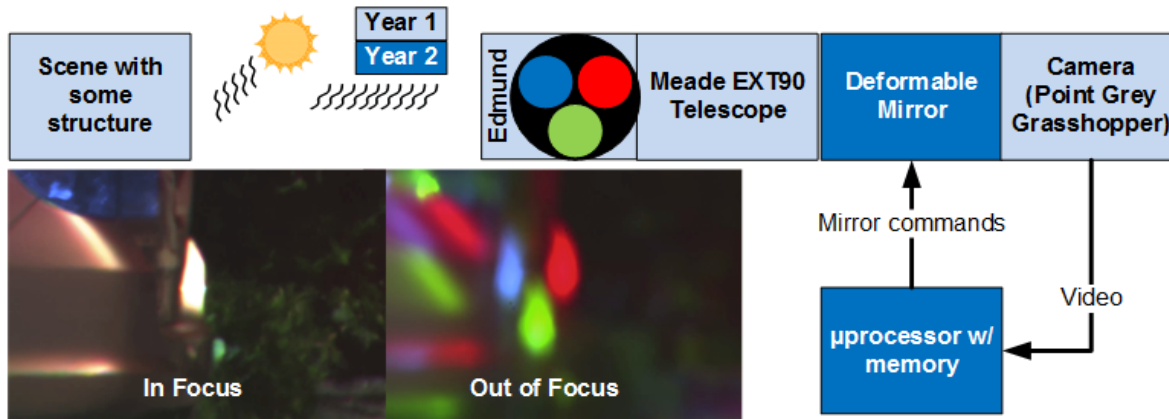
LAPIS System



ARL AO data for Gibraltar project shows promise of RGB concept

Portable COTS RGB AO Concept

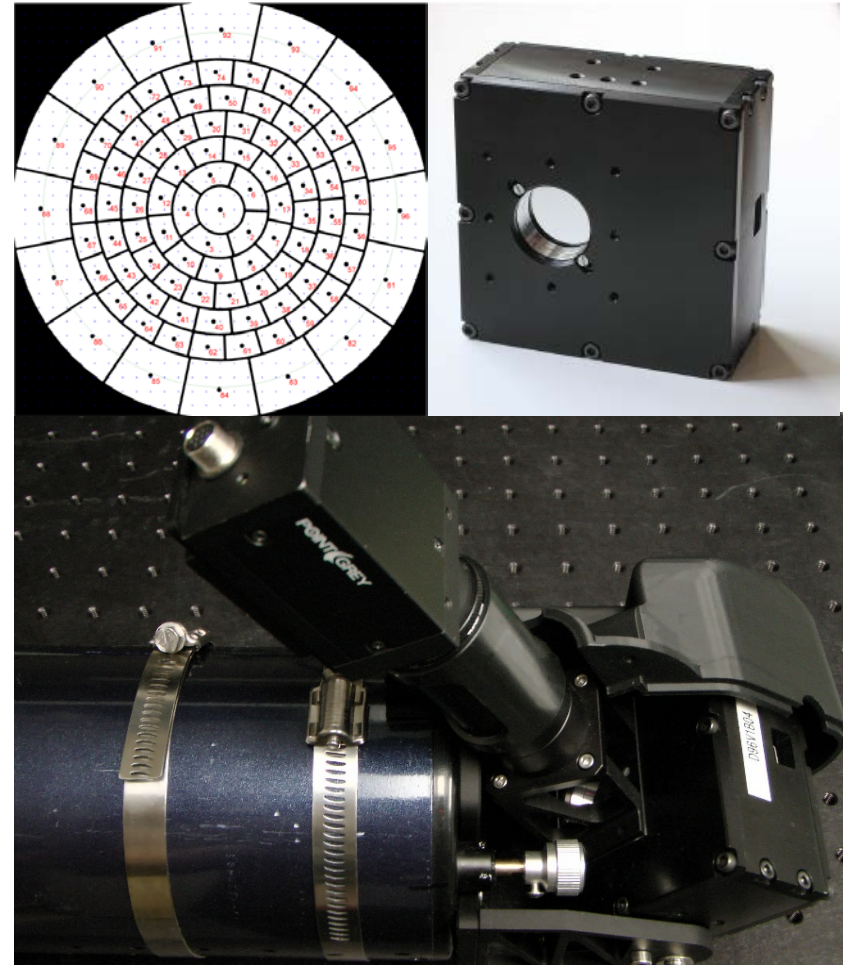
- Objects in the scene are illuminated
- Three filters are placed on the entrance to the telescope
- The corresponding received scenes are shifted based on the turbulence
- Pixel shifts are used to determine tip/tilt, etc., for controlling a deformable mirror



Inspired by Gibraltar work as a low-cost COTS interim solution

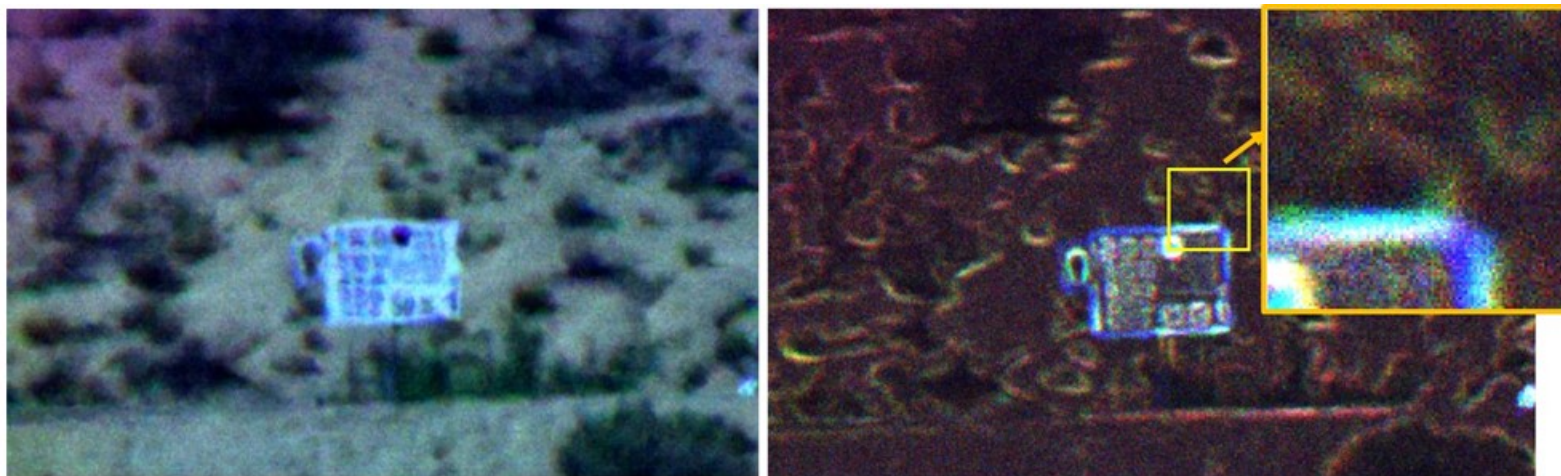
Deformable Mirror

- Limited selection due to cost constraints
- Selected continuous Al-coated membrane by OKO (Netherlands), lowest cost
 - Clear aperture, 1" (same as Meade telescope mirror at exit pupil)
 - 96 actuators
 - Maximum retardation 19 μm
 - 2 kHz refresh rate
 - USB control with SDK
 - Software drivers integrated into ODroid software



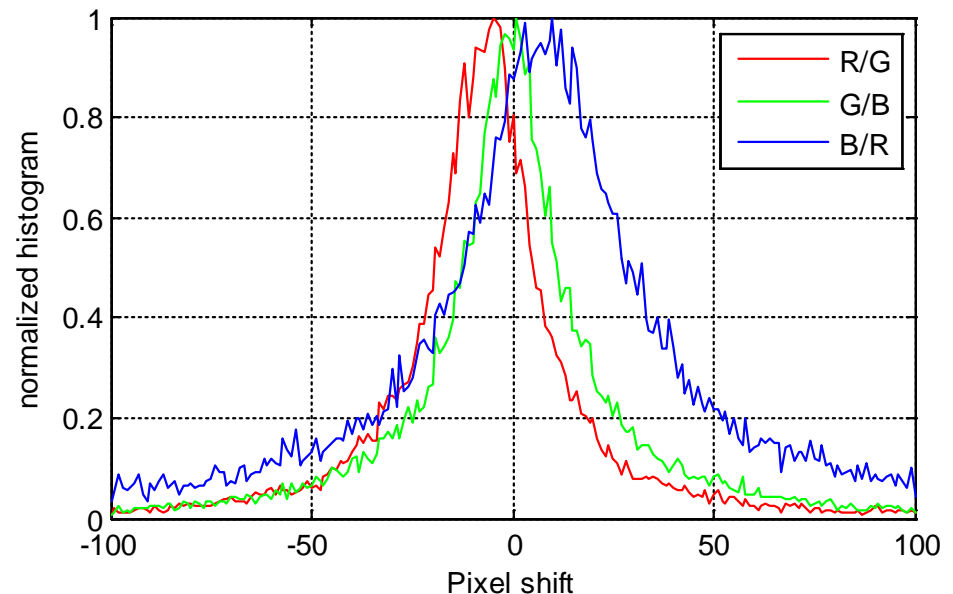
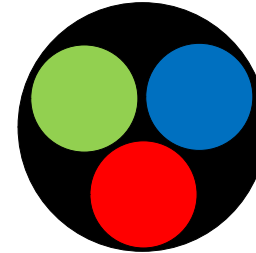
RGB variance image, Sept. 14, 800 m to target, $C_n^2 \sim 2.4 \times 10^{-13}$

- As turbulence increases, high spatial frequency content is lost
- Variance image enhances turbulent flows
 - Provides high spatial frequency content even in high turbulence
 - Updates on each frame allow frame to frame variations to be computed
- Pixel shifts have been extracted from unprocessed imagery using
 - Phase correlation and Fifth Gait block shift methods
 - Implemented in real time on a Linux SBC
 - Extrapolation of variance image is straightforward

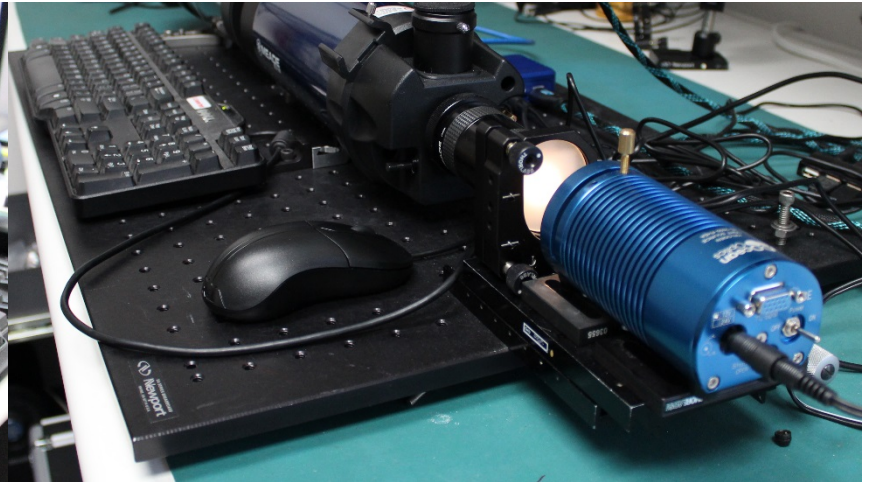
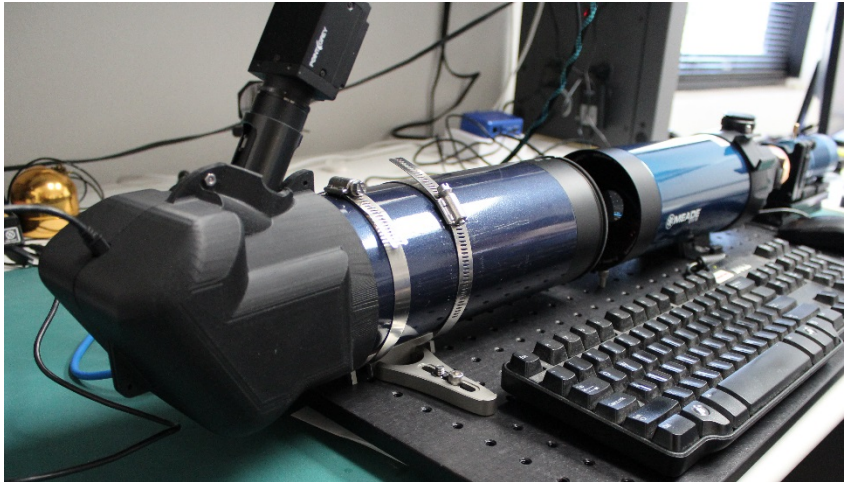


Vertical Pixel Shifts from Variance Image

- Relative shifts used
 - Stable even with platform motion
- Histogram of pixel shifts for entire image, ~10 pixels
 - Green to blue, no shifts because these were inline
 - Width of histogram indicates variation throughout image
- Mirror motion measured
 - About 8–10 pixels for min to max voltage all actuators

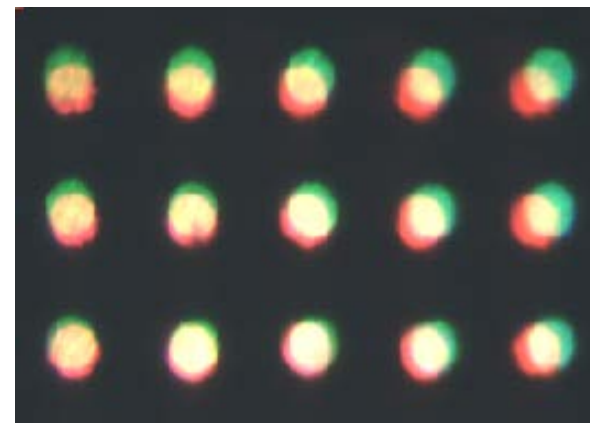


Bench Test

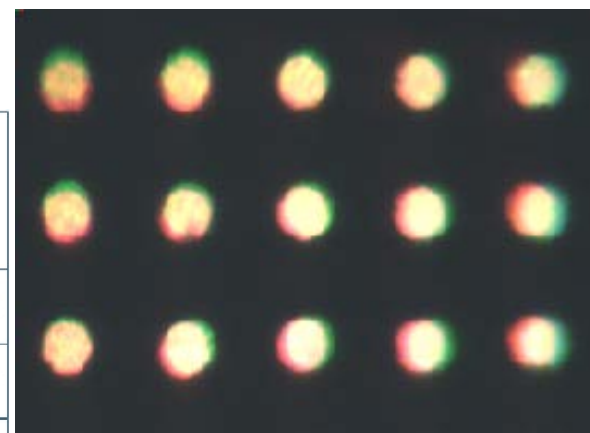
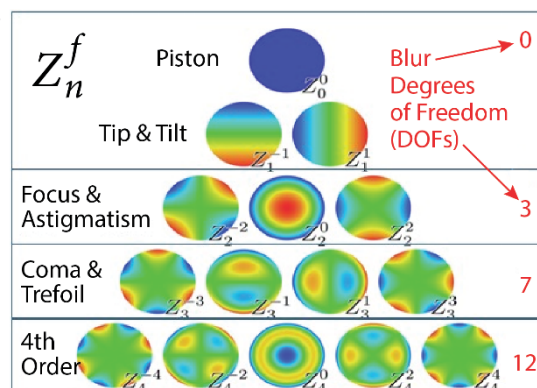
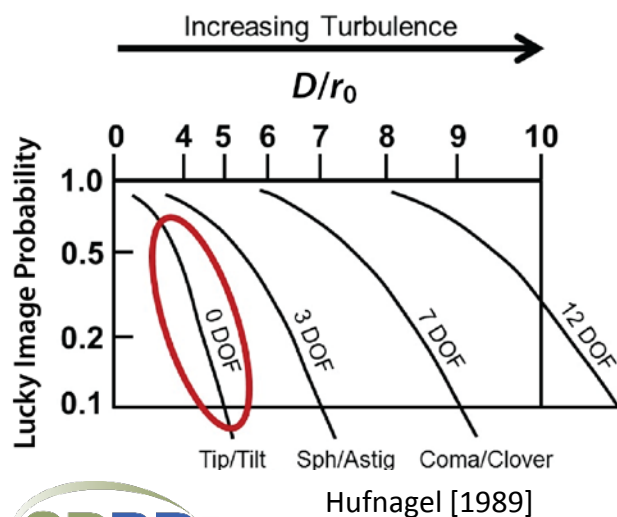


Wavefront Error Correction Modes

- Not at exit pupil; Zernikes are not be directly applicable
- Initial method was unconstrained linear solution using bench test data
 - Mirrors have non-linear response
 - Solution from fixed starting point Zernike polynomials describe aberrations associated with phase errors
- Implementation progressing
 - Requires careful calibration via bench set up
 - Monte Carlo test proved ability to correct defocus
 - Working on improved method



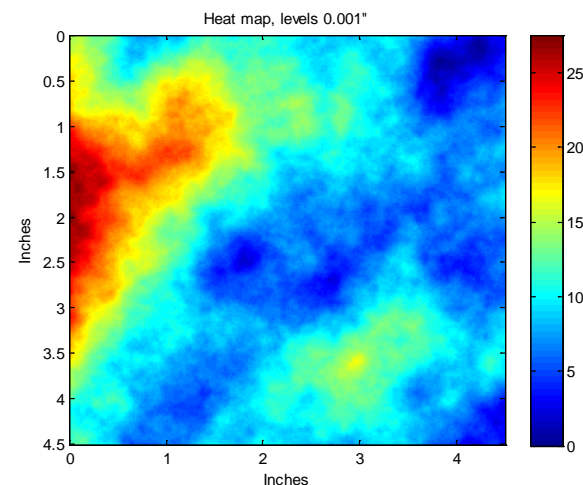
Defocused image >7 pixels



Monte Carlo to minimize RSS error in box to <1.2 pixels

Phase plate mimicked the distortion due to turbulence

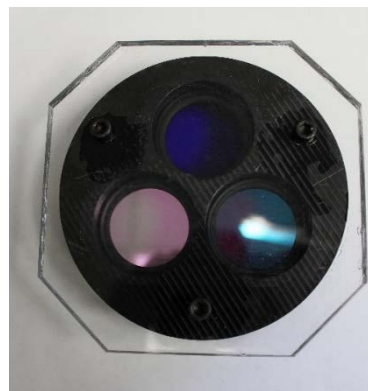
- Allows bench test with simulated turbulence
- Phase pattern was computed that followed the known statistics of turbulence (scaled for 1 km propagation distance, with C_n^2 of $10^{-13} \text{ m}^{-2/3}$)
- Pattern was replicated for each sub aperture of the RGB wavefront sensor
- Pattern depth based on index match of 'glue' and desired turbulence level
- Composite pattern was milled into acrylic using CNC
- Filled with index matching fluid (UV epoxy or corn syrup for reuse of plate)



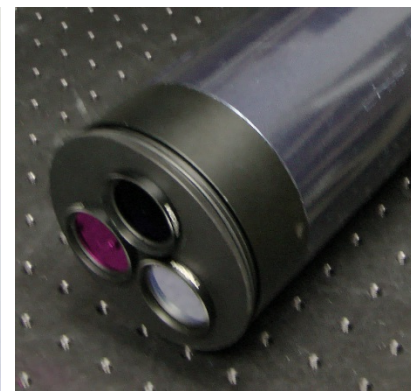
Phase plate
with holder



RGB filter holder



Assembled phase
plate/RGB filter holder



RGB filter holder
on telescope

Summary

- Incorporated deformable mirror into low-cost Meade telescope
- Developed closed-loop software and incorporated on ODroid for measuring pixel shifts and controlling mirror
- Developed bench test to allow calibration of deformable mirror motion with pixel shifts and testing with simulated turbulence
- Developed preliminary methods for calibrating mirror
 - Monte Carlo to verify mirror capability
 - Unconstrained linear solution
- Finalizing nonlinear, constrained method that may allow a demonstrable solution before the end of the FY
- Sponsor requested a February 2018 demo