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RGB Wavefront Sensor for Turbulence Mitigation

STL-078-16, Year 1 of 2

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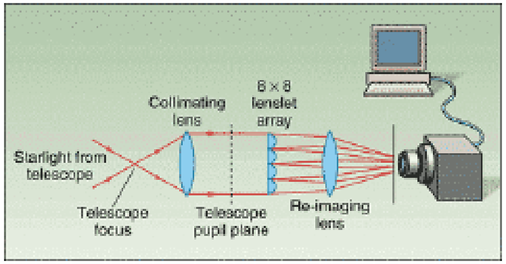
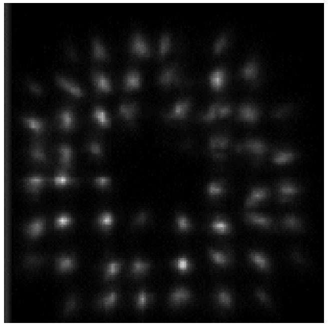
Background

- For high turbulence, algorithms alone cannot recover scene content especially for long-range horizontal paths
- STL has been working with ARL on combining Adaptive Optics 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 will result in higher f/# requiring high sensitivity cameras
  - Requires accurate and computationally lightweight image registration algorithms



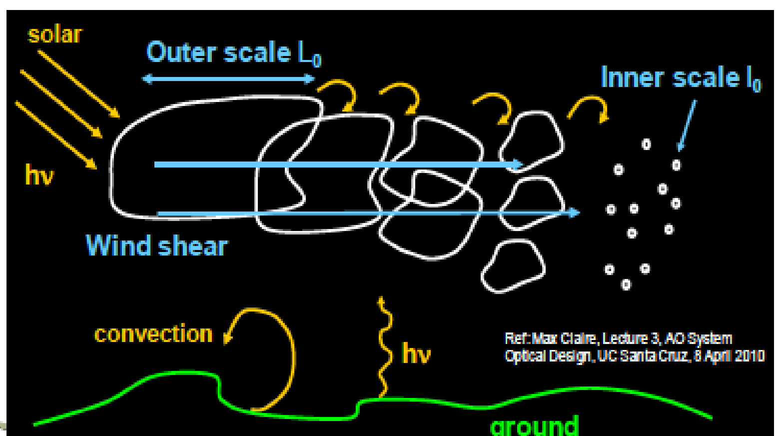


Out-of-focus star from AO system

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

Turbulence Theory

- Turbulent cell or eddy is created by mixing warm and cool air
  - Energy injection via ground heating the air layer adjacent to it
  - Energy transfer via wind mixing the buoyant warm bubble of air with the surrounding cooler air
  - Energy dissipation into the next layer of the atmosphere
- In general, cells act as lens elements
  - Large cells act as refractive elements
  - Small cells act as diffractive elements



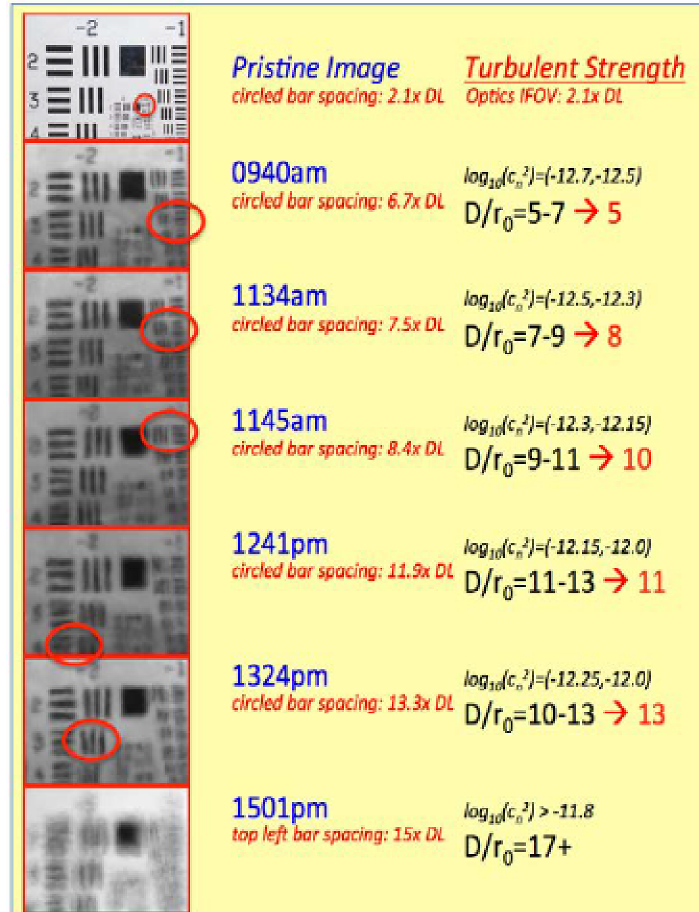
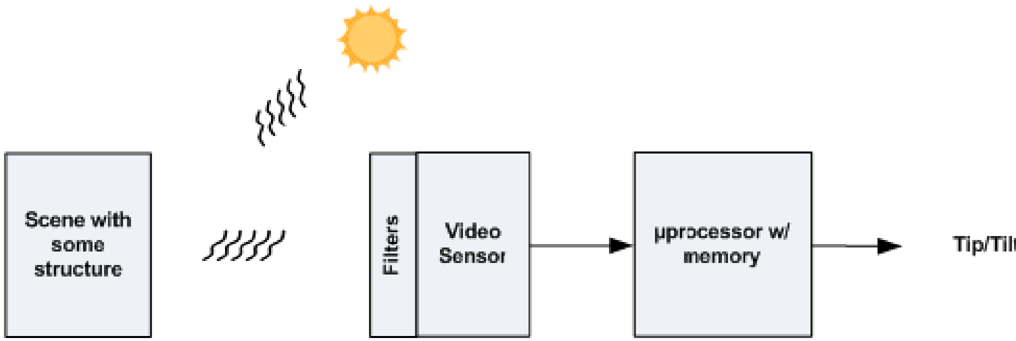
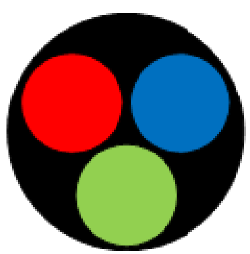


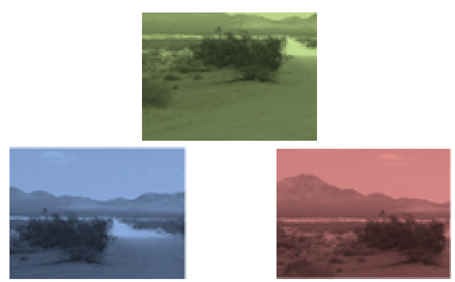
Image quality decreases both with turbulence strength and range to target, unitless measure D/r_0

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

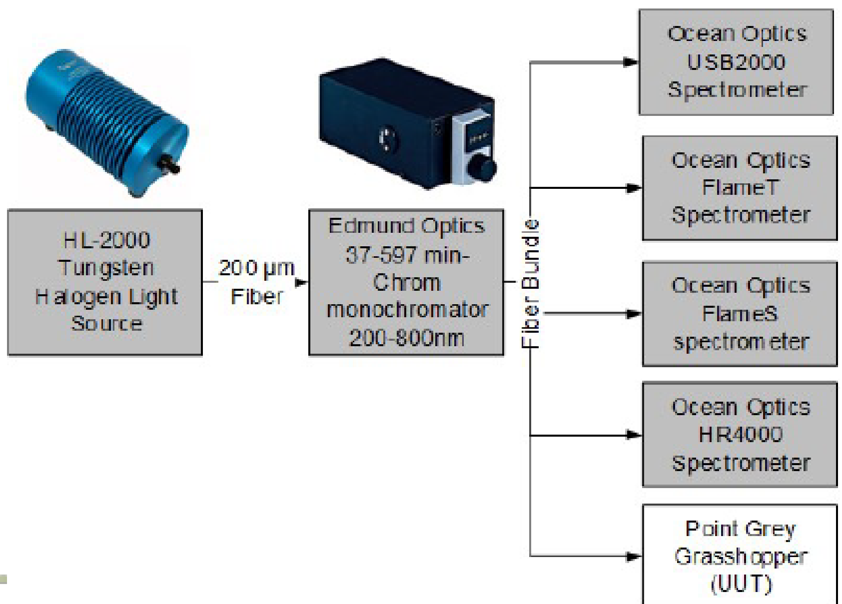


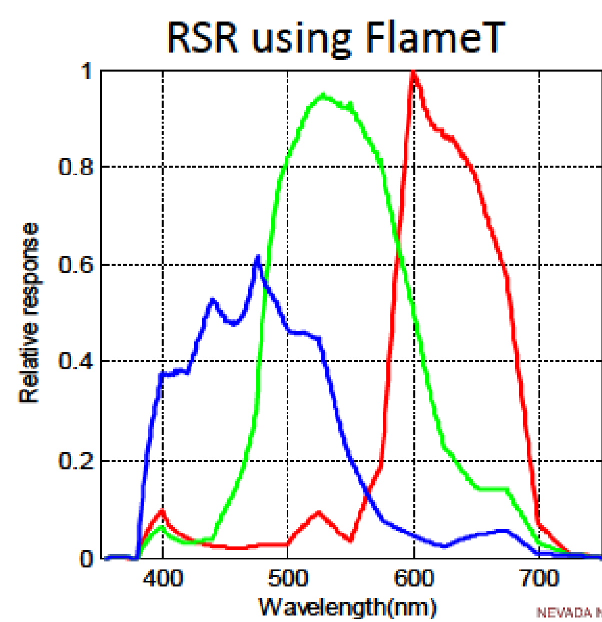




Relative Spectral Response (RSR)

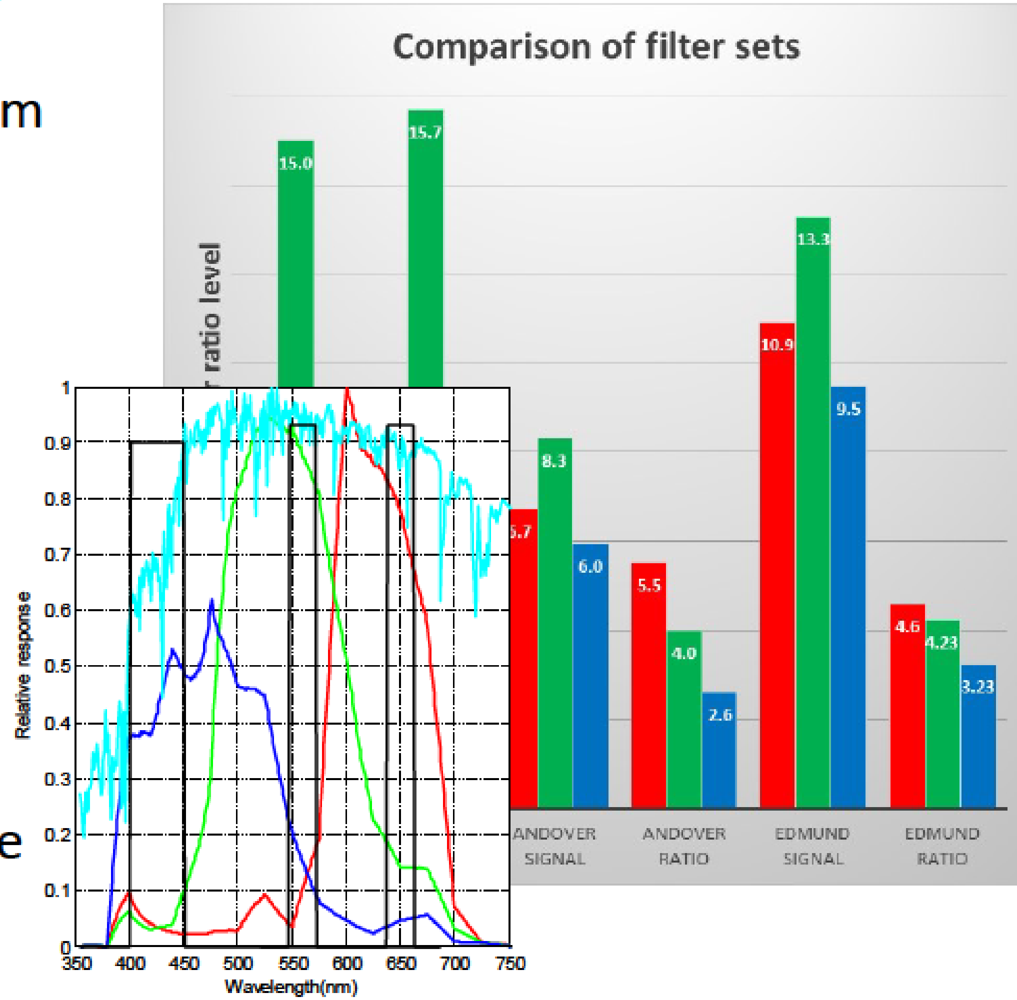
- Redundant spectrometers
- Raw images analyzed
  - At spectral edges, low signal
  - Spectrometers agreed at 'crossover points'
  - Significantly different RSR from response found on internet





Filter selection based on camera RSR

- Selected filters based on crossover points
- Computed integrated sum of sun, filter and RSR for each band
- Equalized signal in each color
- Maximized ratio of band color to leakage from other bands
- Both Andover and Edmund filter sets ordered
- Edmund filters provided the best signal to leakage ratio



Edmund Filters

Data Collection

- 4/13/16 using prototype RGB device in STL parking lot
  - Dr300 License plate, both in-focus and out-of-focus
  - Honda Odyssey van glint, moving from *out-of-focus through focus* and back

- 6/7/16 using prototype RGB WFS in STL parking lot
  - Dr300 License plate, both in-focus and out-of-focus
  - Toyota Prius glint, both in-focus and out-of-focus
- Planned collection 9/12-14/16 at WSMR

Defocus case showing pixel shifts related to Tip/Tilt

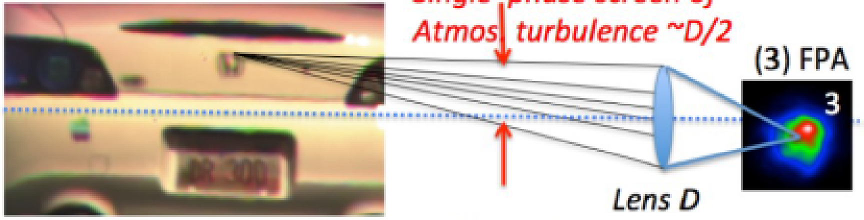
- Left: Original video, showing RGB through focus
- Right: Simple RGB analysis to get relative pixel shifts
- Defocused, objects naturally separate by color

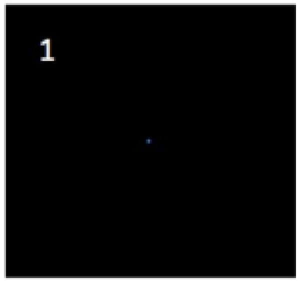
Hybrid Ray Optics

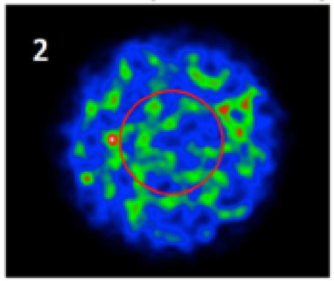
- Turbulence is between scene & lens
- When in focus, all rays land on image plane
- When out of focus, rays from different parts of the aperture end up in front or behind image plane resulting in pixel shifts
- We have simultaneous collection of three parts of the aperture with the three colors

Lens point (r,ϕ) defocus shifts by $\left(r\frac{\Delta z}{f},-\phi\right)$

$$x \approx p_x \frac{\Delta p}{f} z \quad \text{where pixel } |p_x| \leq \frac{N_x}{2}$$

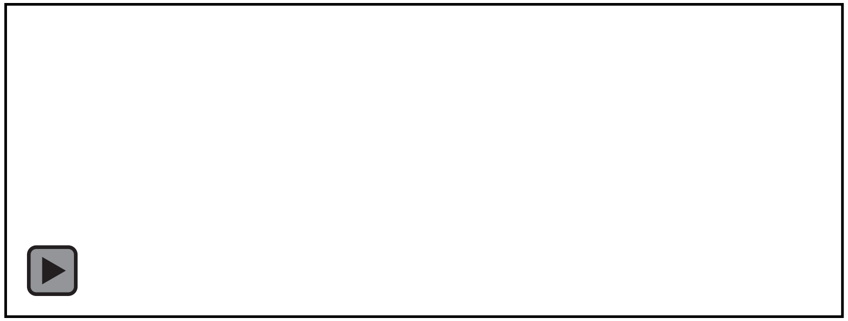


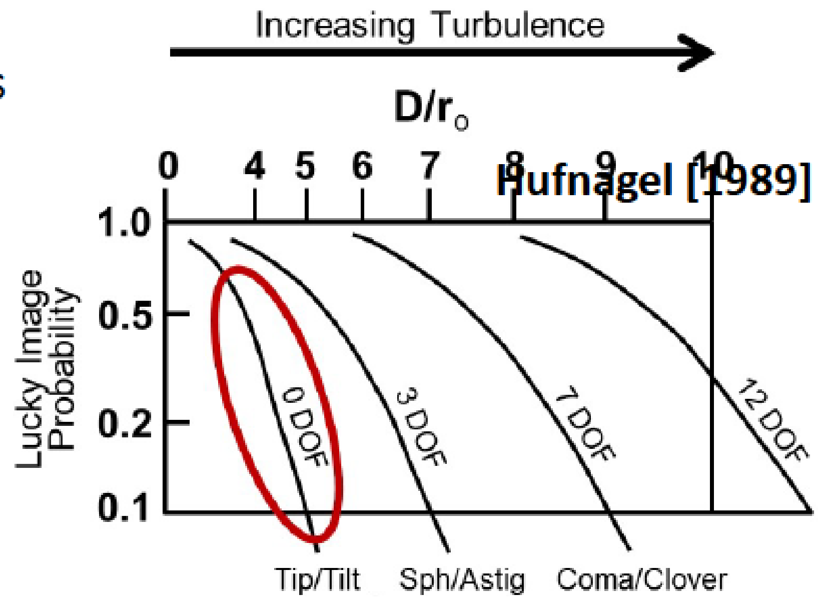


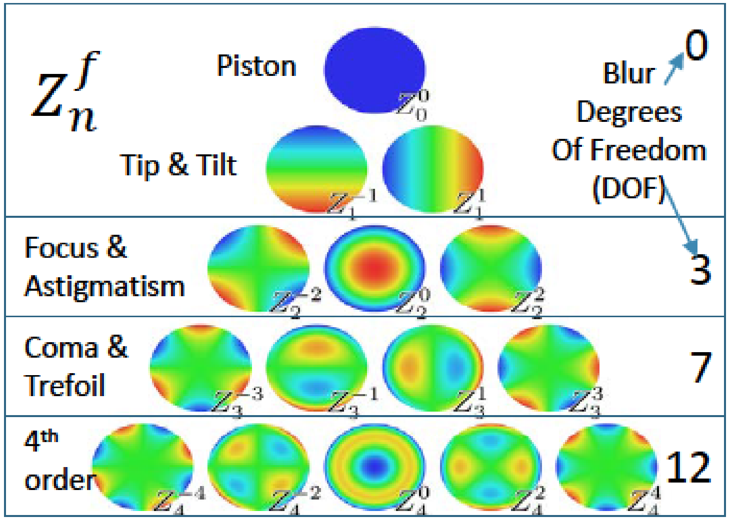


Wavefront error correction modes

- Zernike polynomials describe aberrations associated with phase errors
  - Used in Adaptive Optics to cancel atmospheric distortion
  - More DOF result in a higher probability of getting a good (Lucky) image
- Tip/tilt derived directly from image shift differences between colors
- Work on deriving other DOF from statistics related to STL-10-2013 need to be verified with a deformable mirror
- Second year will couple this sensor with a deformable mirror







Summary

- Method to derive tip/tilt determined – extrapolating to multiple regions
- Leveraging SDRD STL-10-13 method for other DOFs
- Paper on work so far to be presented at Military Sensing Symposium (MSS) Passive sensors in November 2016
- Gibraltar sponsor interest if 2017 SDRD funded and successful

Future Plans

- Select deformable mirror
- Refine methods to derive Zernike polynomials
- Develop mirror interface control, ideally implement in small computer with Linux OS
- Integrate RGB wavefront sensor with deformable mirror
- Test to verify image correction