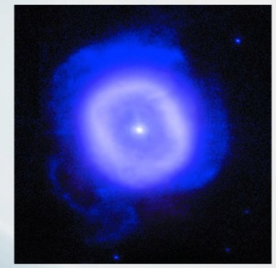
Introduction to Adaptive Optics

Observational Astronomy Workshop
Elinor Gates

Adaptive Optics

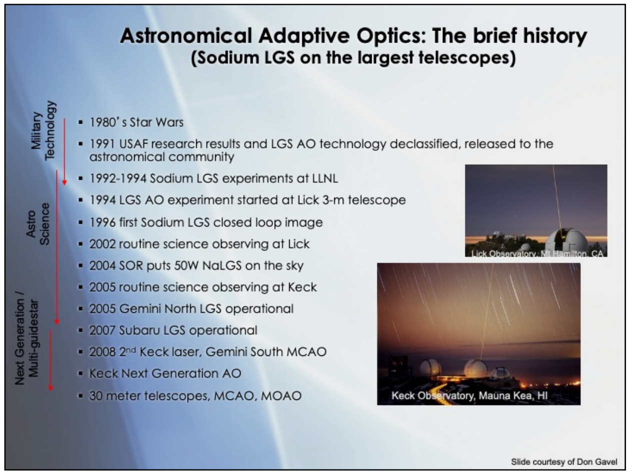
- High resolution and contrast imaging and spectroscopy
- Corrects blurring from atmospheric turbulence mechanically in real time
- NIR science, but moving into the optical regime



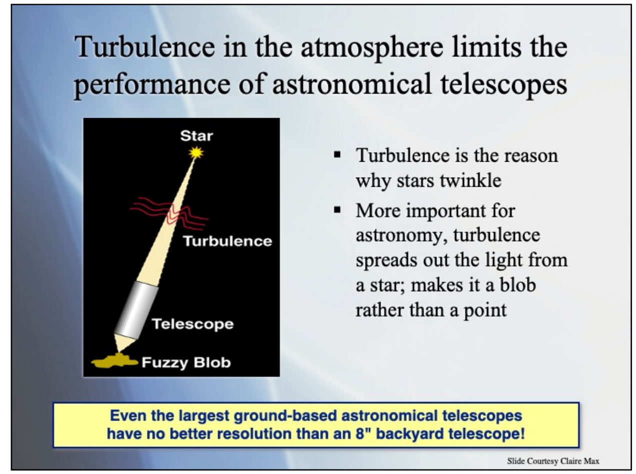
Campbell's Hydrogen Star

Planetary Nebula BD+30 3639 - discovered by W.W. Campbell in 1893 with 36" refractor.

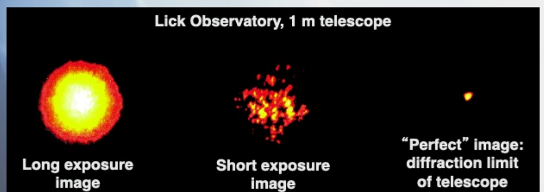
AO image from Gemini North Telescope, June 1999.



SOR = Starfire Optical Range outside of Albuquerque, NM



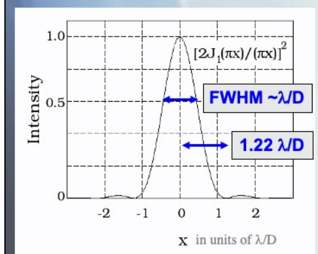
Images of a bright star: Arcturus



Distant stars should resemble "points," if it weren't for turbulence in Earth's atmosphere

Slide Courtesy Claire Max

Imaging through a perfect telescope



Point Spread Function (PSF): intensity profile from point source

With no turbulence, FWHM is diffraction limit of telescope,

$$\vartheta \sim \lambda / D$$

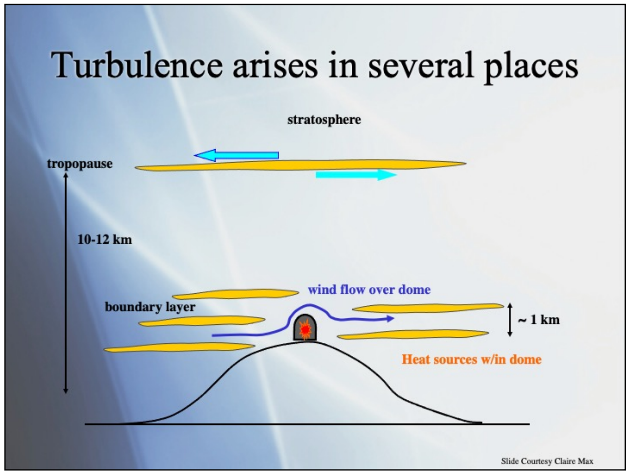
Example:

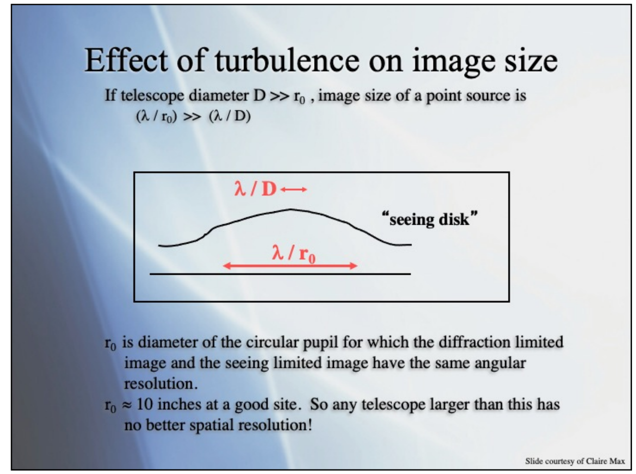
$$\lambda / D = 0.02 \text{ arc sec}$$

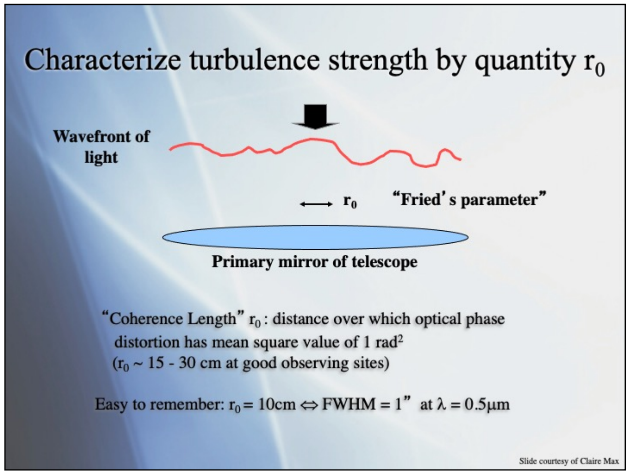
for $\lambda = 1\ \mu m, D = 10\ m$

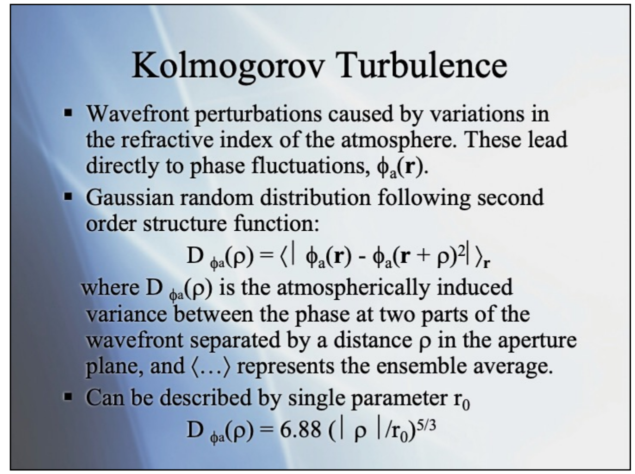
With turbulence, image size gets much larger (typically 0.5 - 2 arc sec)

Slide courtesy of Claire Max


Turbulence arises in several places
stratosphere
tropopause
10-12 km
wind flow over dome
boundary layer
~ 1 km
Heat sources w/in dome
Slide Courtesy Claire Max


Effect of turbulence on image size
If telescope diameter D >> r_0 , image size of a point source is
(λ / r_0) >> (λ / D)
λ / D
"seeing disk"
λ / r_0
r_0 is diameter of the circular pupil for which the diffraction limited image and the seeing limited image have the same angular resolution.
r_0 ≈ 10 inches at a good site. So any telescope larger than this has no better spatial resolution!
Slide courtesy of Claire Max





Amplitude fluctuations are a second-order effect while wavefronts propagate from perturbing atmospheric layer to the telescope.

Kolmogorov Turbulence

- r_0 indicates the “strength” of the phase fluctuations as it corresponds to the diameter of a circular telescope aperture at which atmospheric phase perturbations begin to seriously limit the image resolution.
- r_0 also corresponds to the aperture diameter for which the variance σ^2 of the wavefront phase averaged over the aperture comes approximately to unity

$$\sigma^2 = 1.0299(d/r_0)^{5/3}$$

C_n^2 Profile

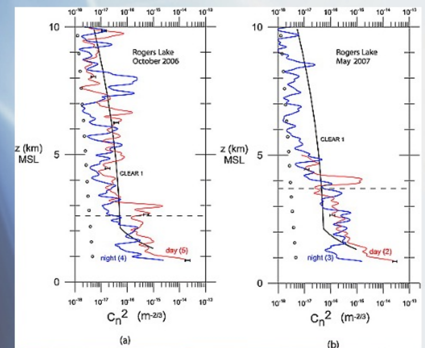


Figure from Roadcap, Tracy 2009

Dry convective. (a) Rogers Lake, California campaign, October 2006. (b) Rogers Lake, California campaign, May 2007. Circles mark noise floor. Error bars indicate instrumental uncertainty. Thermosonde measurements – 1 meter horizonal separation between two unheated tungsten fine wire probes.

C_n^2

- r_0 can be determined from a measured C_n^2 profile (described below) as follows:

$$r_0 = (\,16.7\,\lambda^{-2}\,(\cos\gamma)^{-1}\int_0^{\infty} dh\;C_n^2(h)\,)^{-3/5}$$

where the turbulence strength C_n^2(h) varies as a function of height h above the telescope, and γ is the angular distance of the astronomical source from the zenith.

Cn2 can be measured many ways, e.g., lidar, scidar

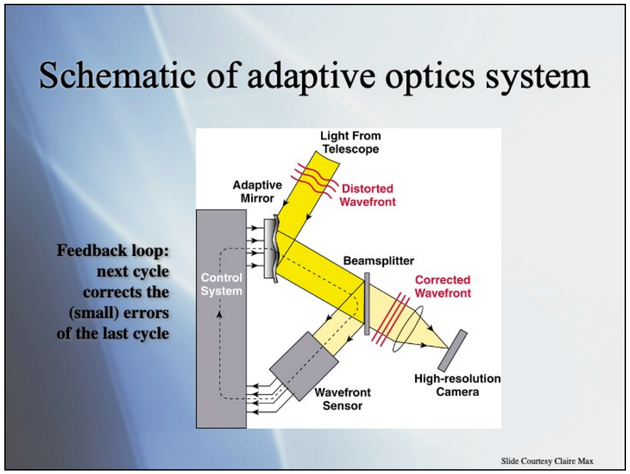
Often measured as part of astronomical site testing and selection.

Note that as you look through more atmosphere (greater zenith distance or airmass), you will see more turbulence, so r0 generally decreases with increasing zenith distance (airmass).

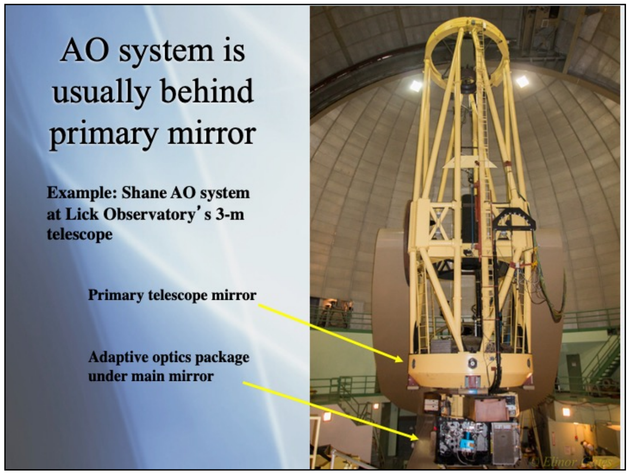
Basic AO Concept

- Use a bright natural reference star to measure turbulence in the atmosphere using a Wavefront sensor.
- Correct the turbulence in real time with a Deformable Mirror.
- First order corrections done by a separate Tip/Tilt Mirror.
- Current systems optimized for NIR science.

New systems, such as ShaneAO, are moving into optical wavelength correction.

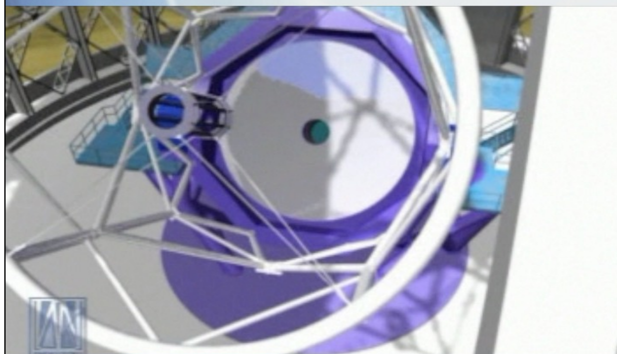


Note: Define Wavefront for public talks



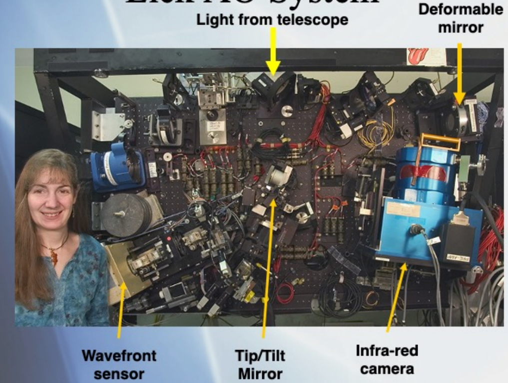
Some AO systems have a deformable secondary mirror, rather than having the DM being after the Cassegrain, Coude, or Naysmith focus.

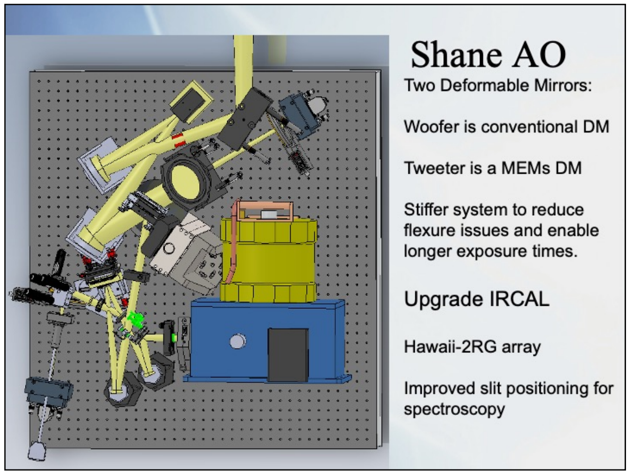
Gemini North AO Animation



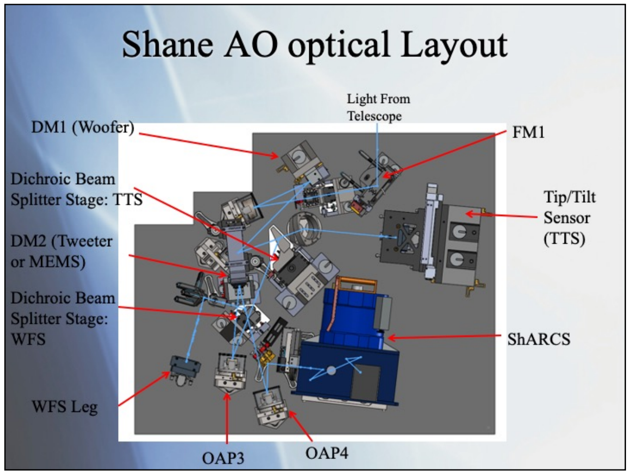
More extensive animation at
https://www.youtube.com/watch?v=3BpT_tXYy_I

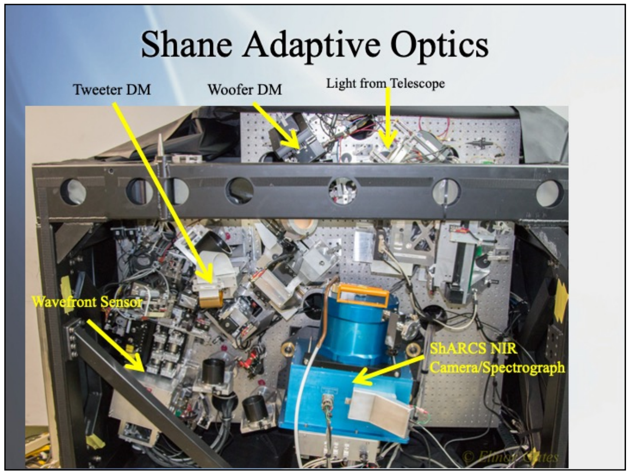
Lick AO System

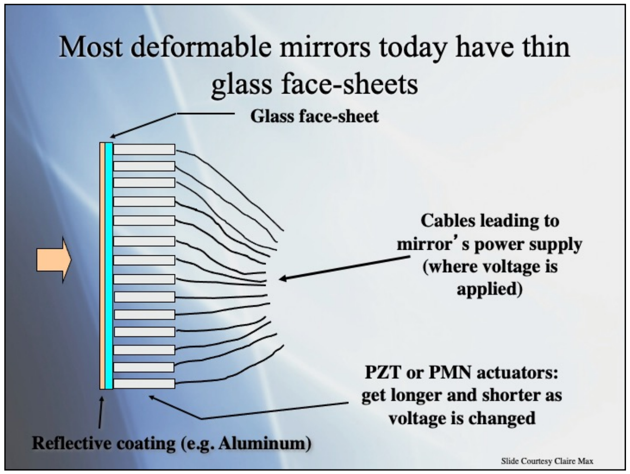




New system installed April 2014. Has 8x8, 16x16, and 30x30 subaperture WFS options.





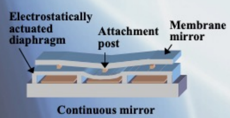


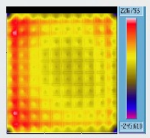
Other technologies for DMs are in use, such as MEMs and bimorph mirrors.

Shane AO woofer DM uses voice coils as actuators. Shane AO tweeter MEMS DM uses electrostatic forces.

New developments: tiny deformable mirrors

- Potential for less cost per degree of freedom
- Liquid crystal devices
  - Voltage applied to back of each pixel changes index of refraction locally
- MEMS devices (micro-electro-mechanical systems)





Mirror surface map

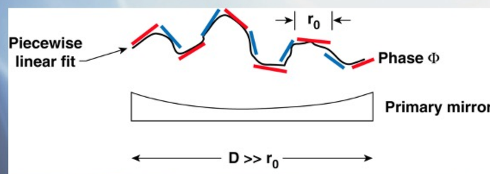
Slide Courtesy Claire Max

Shane AO Deformable Mirrors

Woofer, Voice-coil Actuated
Silver Coated
52 Actuators

Tweeter, MEMS
Gold Coated
32x32 array

Real deformable mirrors have continuous surfaces



In practice, a small deformable mirror with a thin bendable face sheet is used

Placed after the main telescope mirror

Slide courtesy of Claire Max

Fit mirror shape to measured wavefront based on actuator influence functions and spacing. This information is contained in the DM control matrix. Fit of wavefront to mirror is never perfect.

Can also use deformable secondary mirror, for example, the MMT, LBT, VLT.

Shack-Hartmann wavefront sensor measures local “tilt” of wavefront

Divide pupil into subapertures of size ~ r_0

Number of subapertures α $(D / r_0)^2$

Lenslet in each subaperture focuses incoming light to a spot on the wavefront sensor's CCD

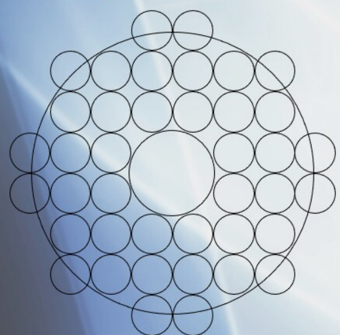
Deviation of spot position from a perfectly square grid measures shape of incoming wavefront

Wavefront reconstructor computer uses positions of spots to calculate voltages to send to deformable mirror

Slide courtesy of Claire Max

Lick AO System

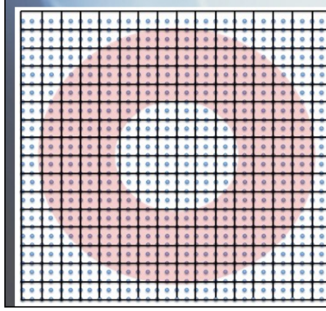
3 m primary
0.8 m secondary



- •40 subabertures, d=43cm
- •61 actuators, hex grid, d_a=50cm
- •Max sample rate: 1000 Hz
- •Sodium layer LGS
- •IR Cam: 256^2 HgCdTe, 0.076 arcsec/pixel (Nyquist in K) with Direct Imaging, Polarimetry, and Spectroscopic capabilites

Shane AO

Pupil mapping on MEMs, below, blue dots are actuators, grid is wavefront sensor sub-apertures in 16x16 mode, pink annulus is pupil image.



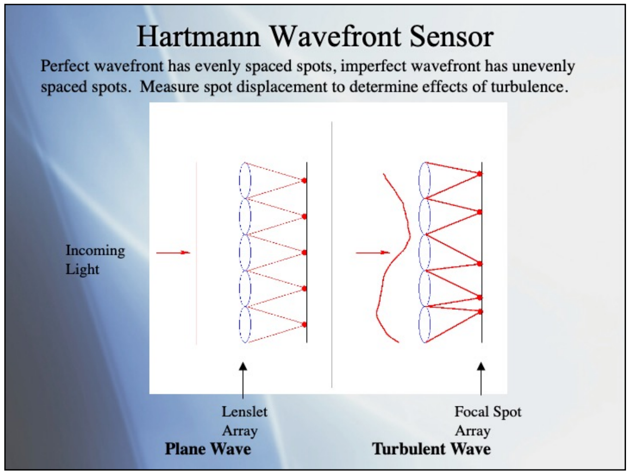
Sub-apertures modes:
8x, 16x, and 30x across
Corresponding to
15, 7.5, and 4 inch (38, 19, and 10 cm) diameter r0 sub-apertures on the 120" primary

Max sample rate: 1500 Hz

Sodium layer LGS

IR Camera: 1024kx1024k H2RG
0.033 arcsec/pixel
Nyquist sampled in J

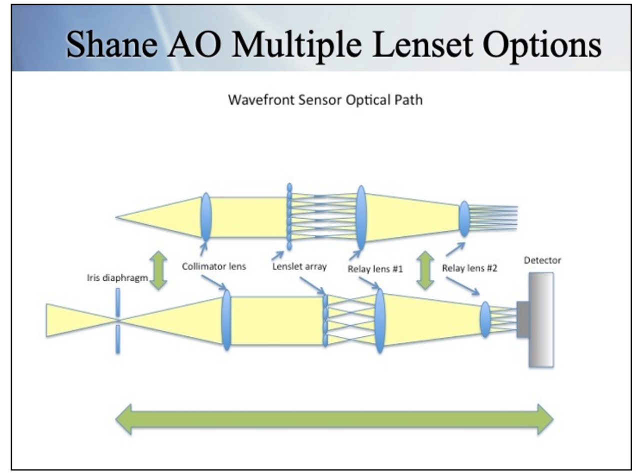
Direct Imaging, Polarimetry, and Spectroscopic capabilities



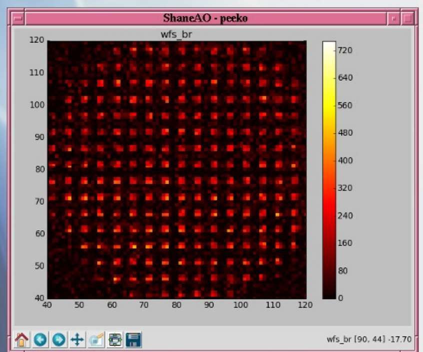
Other wavefront sensing techniques:

Curvature Sensing

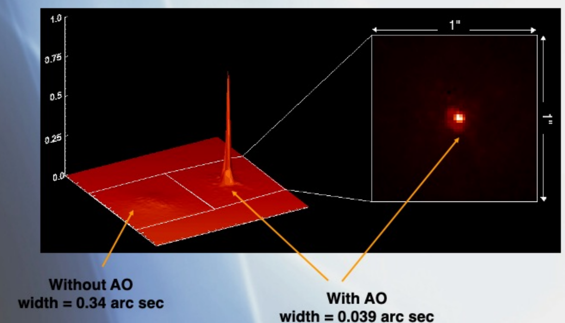
Pyramid Sensors



ShaneAO Wavefront Sensor



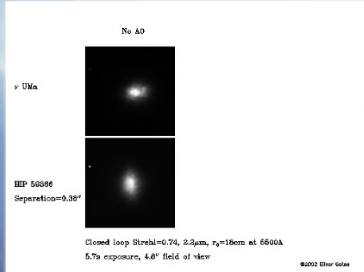
Adaptive optics on 10-m Keck II Telescope: Factor of 10 increase in spatial resolution



Slide courtesy of Claire Max

IR Image Quality

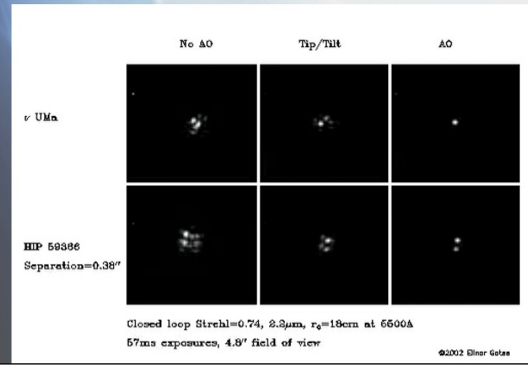
- IR Camera image Strehl or FWHM is final determination of image quality. Often we take short exposures during setup to determine if changes to AO or TT loop gains, control matrix, centroider, etc. have improved or degraded image quality.



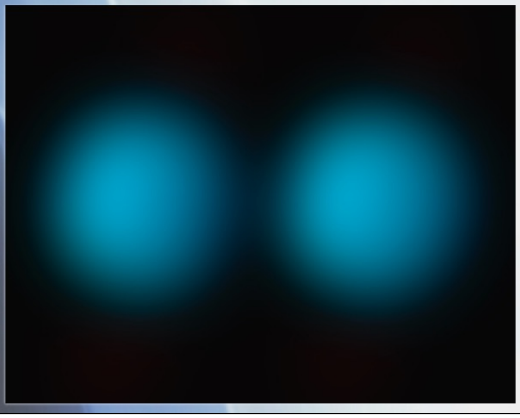
Example of very best performance. Typical Strehl under good seeing is 0.4-0.5. Under excellent seeing 0.6-0.7.

Adaptive optics in action

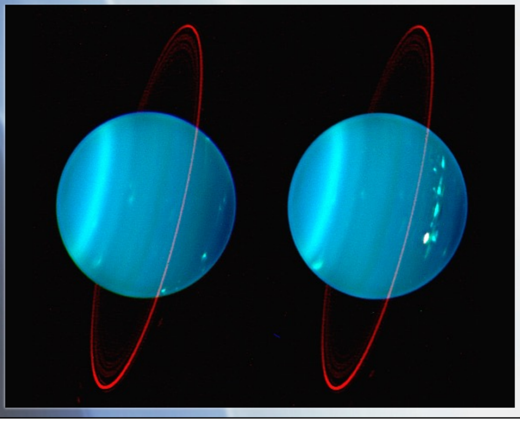
Lick Observatory Adaptive Optics System



Keck 10-m Image of Neptune



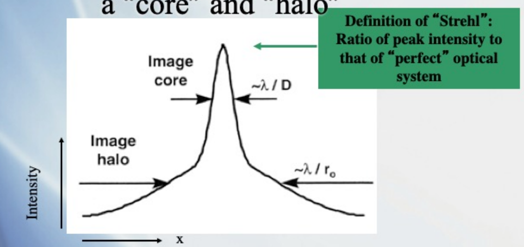
Neptune – Keck 10-m telescope with AO Correction



ShaneAO/ShARCS

Uranus Sept 2014

AO produces point spread functions with a "core" and "halo"



- When AO system performs well, more energy in core
- When AO system is stressed (poor seeing), halo contains larger fraction of energy (diameter ~ r_0)
- Ratio between core and halo varies during night

Slide courtesy of Claire Max

Strehl Ratio

Measure of Image quality

Two definitions of Strehl ratio (equivalent):

- Ratio of the maximum intensity of a point spread function to what the maximum would be without aberrations

- Strehl is equal to the "normalized volume" under the optical transfer function of the aberrated optical system

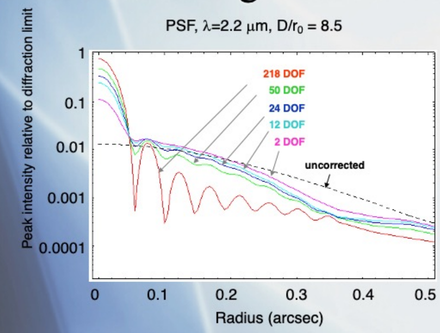
$$S = \frac{\int OTF_{aberrated}(f_x, f_y)\, df_x df_y}{\int OTF_{un-aberrated}(f_x, f_y)\, df_x df_y}$$

where $OTF(f_x, f_y) = Fourier\ Transform(PSF)$

Slide courtesy of Claire Max

Recommend Goodman's "Fourier Optics"

Point-spread function for different # of degrees of freedom



Slide courtesy of Claire Max

How many degrees of freedom is determined by number of subapertures on the wavefront sensor and the number of actuators on the DM.

Zernike Polynomials

- Orthogonal set of polynomials oft used to describe optical aberrations in a circular pupil
- Even Zernikes:

$$Z_n^m(\rho,\phi) = R_n^m(\rho)\cos(m\phi)$$

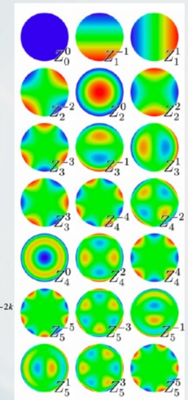
- Odd Zernikes:

$$Z_n^{-m}(\rho,\phi) = R_n^m(\rho)\sin(m\phi)$$

- Radial Function:

$$R_n^m(\rho) = \sum_{k=0}^{(n-m)/2} \frac{(-1)^k (n-k)!}{k!((n+m)/2-k)!((n-m)/2-k)!}\rho^{n-2k}$$

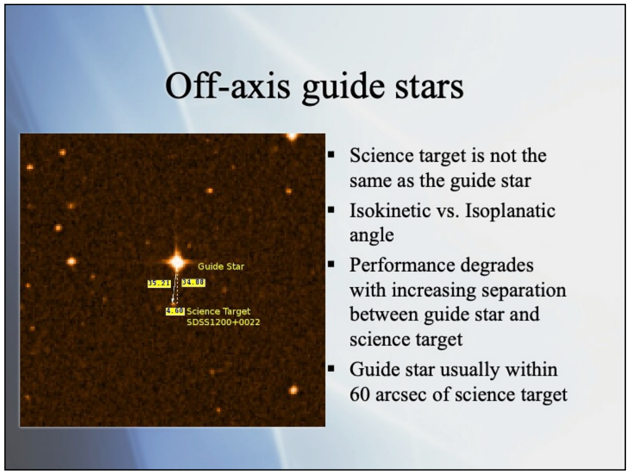
for $n \geq m \geq 0$ and n-m even.
For n-m odd, then $R_n^m(\rho) = 0$



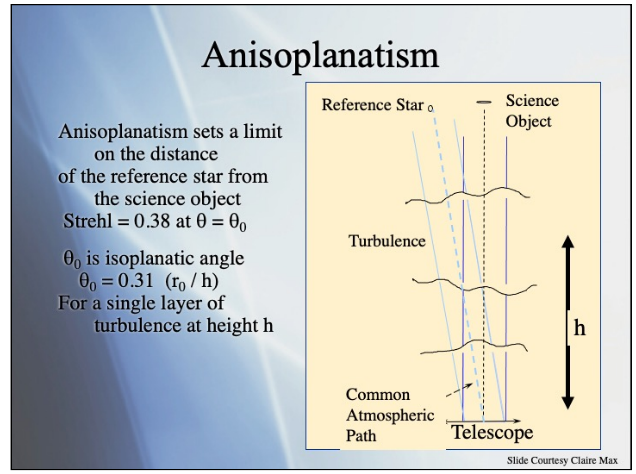
List of first 35 Zernike polynomials in polar coordinates at
http://www.optics.arizona.edu/jcwyant/zernikes/ZernikeEquations.htm

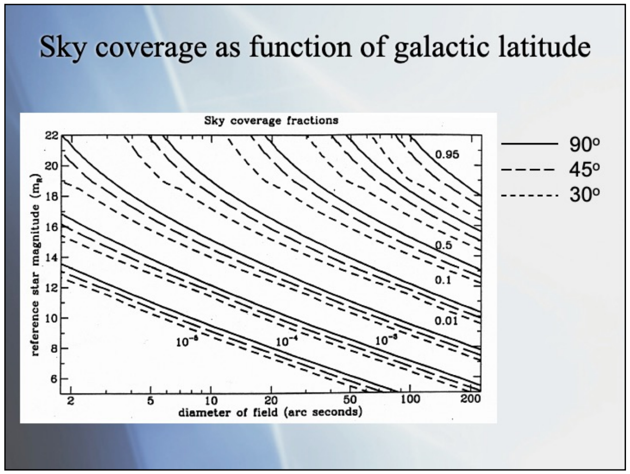
Natural Guide Stars

- Best case - science target is its own guide star
- Off-axis guide stars work, but anisoplanatism effects
- Science target may not have a suitable guide star nearby - need Laser Guide Star
- Laser Guide Star operations still require natural tip/tilt star

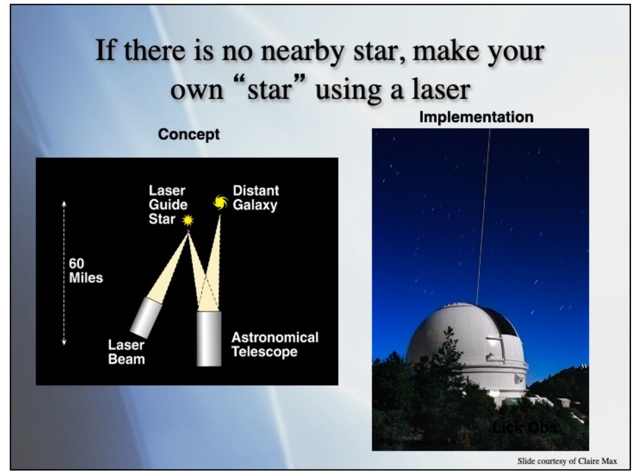


Isokinetic angle is angle for which tip/tilt correction is still ok.





Not always a guide star available where you need one. Harder to find guide stars for objects further from the galactic plane.



Less than 1% of the sky is near enough to a suitably bright natural guide star (V<12).

How does a Sodium Laser make an Artificial Star?

60 miles up is a layer in the mesosphere containing metals, sodium, potassium, calcium.

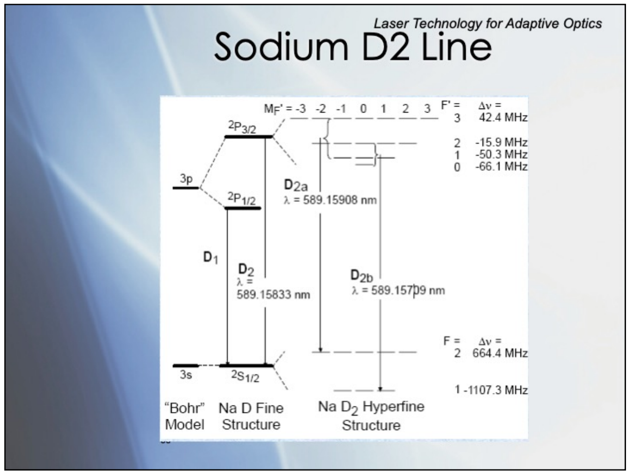
These metals are deposited by meteors burning up in the Earth's atmosphere.

Tune laser to emit 589 nm wavelength light.

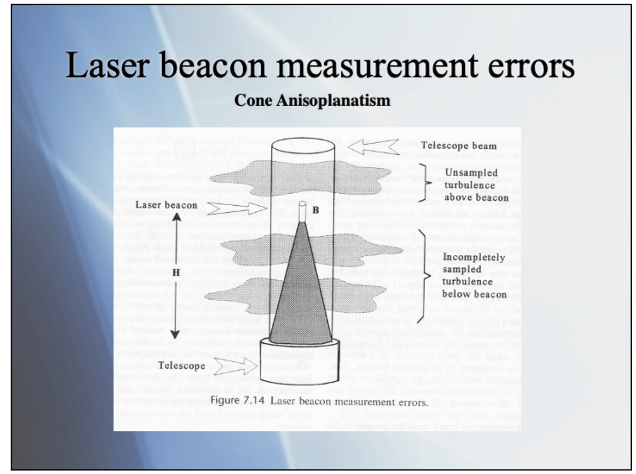
Sodium atoms absorb and are excited by laser.

The atoms quickly de-excite, re-emitting the light, and create an artificial star wherever you need one.

Slide courtesy of Claire Max



24 level Bloch equations describe rates of transition between States in Hyperfine structure



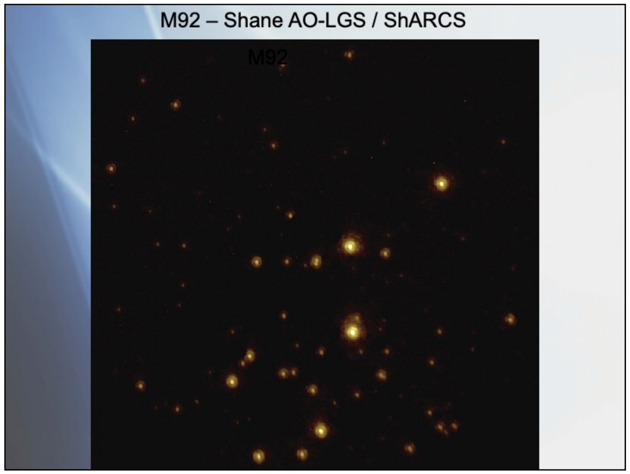
Sodium vs. Rayleigh beacons:

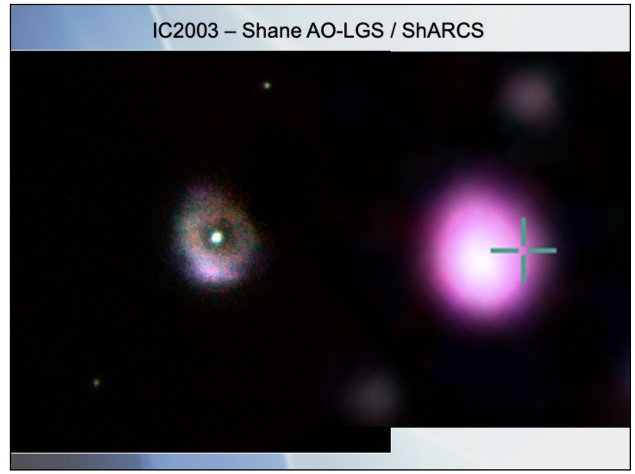
Rayleigh at 12-14 km altitude - gated systems

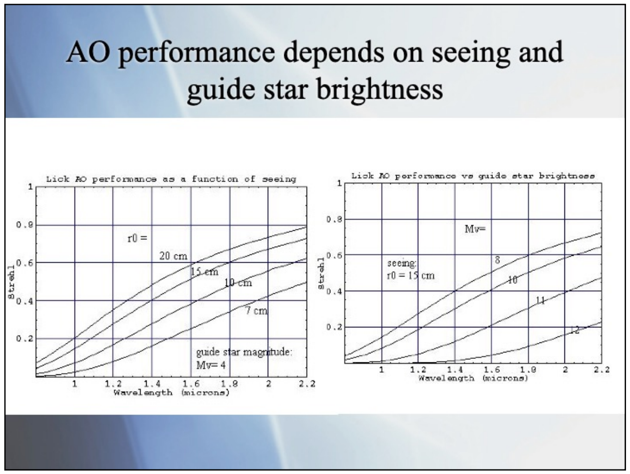
Sodium at 90 km altitude - harder technology but much better performance

Also, laser guide star operations still need a faint tip/tilt star since the laser can't measure the tip/tilt aberration.

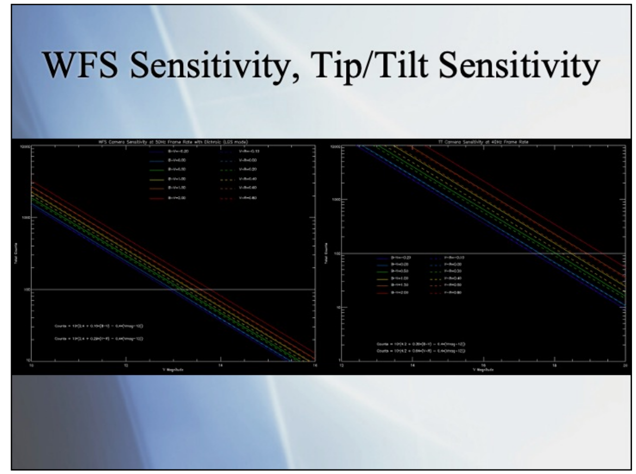
Tip/tilt star can be significantly fainter (at Lick V~16).


M92 – Shane AO-LGS / ShARCS
M92


IC2003 – Shane AO-LGS / ShARCS

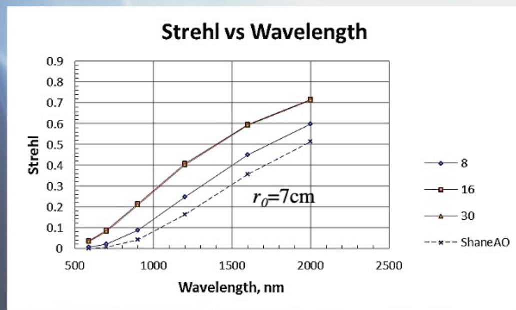


The brighter the star, the faster the AO system can measure the wavefront. Also, with brighter stars you can use more subapertures on the Hartmann sensor and measure the wavefront on a finer spatial scale. As the seeing degrades (r0 gets smaller) the turbulence is more severe and harder to correct, so the Strehl will decrease.



The fainter the star the slower you need to run the camera to collect enough photons to make an accurate measurement of the wavefront. The horizontal line is at 100 DN, giving a S/N = 10 for each subaperture. With ShaneAO the slowest rate for the WFS camera is 50Hz, so this limits the magnitude of natural guide stars to r<13.5 (with some dependence on the color of the star). The tip-tilt camera can run as slow at 40Hz, limiting the guide stars to r<18.

Strehl varies as a function of Wavelength



Actually, dotted line is for old Lick AO system, but it underestimates the strehl. Lick AO system matched the 8 line.

PSF Calibration

- Guide star (on or off-axis) should be of similar magnitude and color so AO performance same
- PSF calibration star data should be at similar airmass as science target
- PSF - Guide star pair should have similar separation and position angle as Science target - Guide star
- Can be difficult to find suitable PSF - guide star pairs. Often have to compromise

Compromises on finding suitable PSF - guide star pairs depend on whether separation, position angle, guide star color and/or magnitude Is most important. I.e., usually more important to have similar separation than position angle.

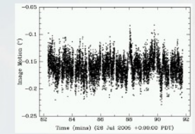
PSF Issues

- Always choose at least two possible PSF stars - most stars are binaries, some turn out to be galaxies
- Roy's PSF Pair Finder
  http://catserver.ing.iac.es/aotools/pairfind.html
- Off-axis PSF measurements done in various ways.

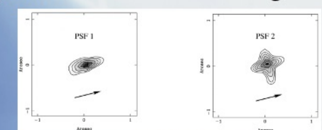
Need to check any pair to make sure stars are real rather than artifacts, not galaxies or binary stars. Select pairs based on proximity to science target, magnitude of Guide Star, magnitude of PSF star, separation and position angle of the pair. It is rare to find exact match, so need to know what limits or errors are most relevant or constraining.

IR Image Quality

- Residual Tip/Tilt errors



- Uncorrected static aberrations in the PSF
- Anisoplanatism - off-axis guide stars
  Elongation of PSF in direction of guide star



Uncorrected static aberrations can be from higher order Zernikes in AO system or primary mirror. Tend to change with zenith distance at Lick.

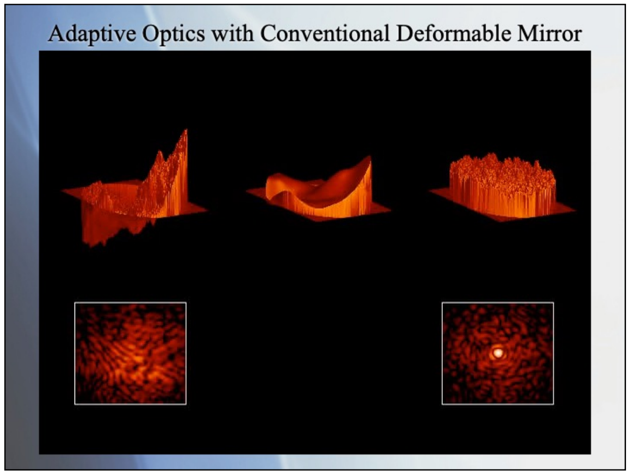
Strehl, FWHM, and Science

- Up to observers to know what Strehl or FWHM is necessary to achieve science goal. We can take 3″ seeing and make it 1″, but is that scientifically useful?
- Useful science results difficult to obtain if
  - NGS $r_0 < 6$ cm
  - LGS $r_0 < 11$ cm
  - Wind speed > 20 mph (looking into wind)
  - Wind speed > 35 mph (crosswind or downwind)
- Backup projects with brighter guide stars or less rigid FWHM requirements are recommended if not doing queue scheduling of telescope time.

Info for old Lick AO system. Will depend on AO system.

AO Run Planning

- Targets - Is the target also the guide star (NGS or LGS TT)? If not, is there a suitable guide star within range? NGS or LGS program?
- Photometric and/or Spectral Standard Stars
- PSF stars - Do you need a single star or a PSF - Guide Star pair?
- What Strehl or FWHM required to accomplish the science goals?
- What filters and exposure times do you need?
- Lick 3-m LGS AO also requires 10th mag alignment stars near each target for laser pointing and focus calibration.



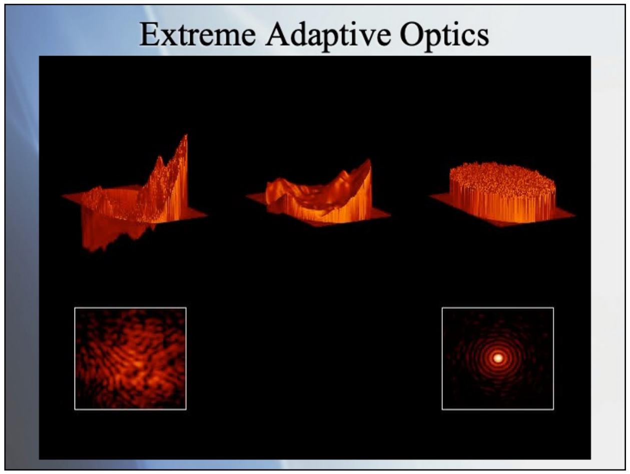
Top left: Actual Wavefront Bottom left: Uncorrected image

Top middle: DM fit

Bottom right: Corrected image

Top right: Residuals of fit

Note that corrected PSF has incomplete first Airy ring and only hints of more Airy rings with conventional AO.



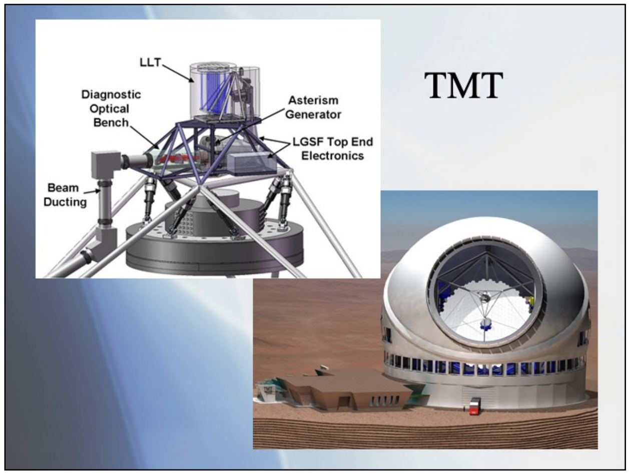
Top left: Actual Wavefront Bottom left: Uncorrected image

Top middle: DM fit

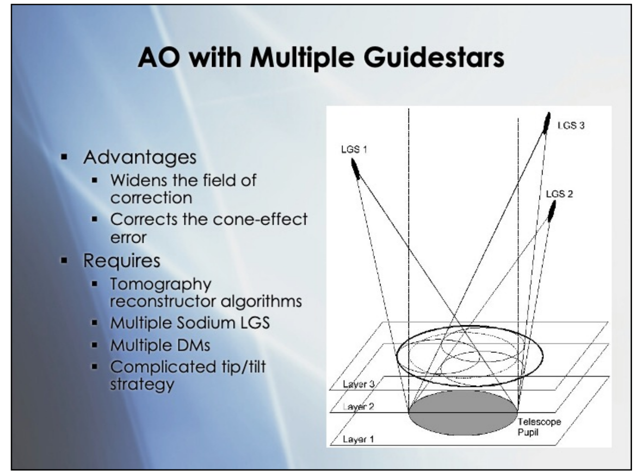
Bottom right: Corrected image

Top right: Residuals of fit

Note that corrected PSF image shows many complete Airy rings as well as less incomplete outer Airy rings.



TMT = Thirty meter telescope. Selected site is Mauna Kea, Hawaii.



CfAO Yr2, Theme 2 formed and kicked off a multi-institution collaborative project and a series of workshops (2002-2005) on analysis modeling and simulation of AO for ELTs. Special problem was the size of the problem (30 m aperture) which precluded scaling the Gemini MCAO reconstructor.