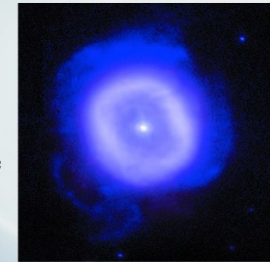


## Introduction to Adaptive Optics

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.



### Astronomical Adaptive Optics: The brief history (Sodium LGS on the largest telescopes)

Military Technology

Astro Science

Next Generation / Multi-guidestar

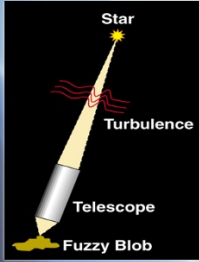
- 1980's Star Wars
- 1991 USAF research results and LGS AO technology declassified, released to the astronomical community
- 1992-1994 Sodium LGS experiments at LLNL
- 1994 LGS AO experiment started at Lick 3-m telescope
- 1996 first Sodium LGS closed loop image
- 2002 routine science observing at Lick
- 2004 SOR puts 50W NaLGS on the sky
- 2005 routine science observing at Keck
- 2005 Gemini North LGS operational
- 2007 Subaru LGS operational
- 2008 2<sup>nd</sup> Keck laser, Gemini South MCAO
- Keck Next Generation AO
- 30 meter telescopes, MCAO, MOAO

Slide courtesy of Don Gavel

SOR = Starfire Optical Range outside of Albuquerque, NM

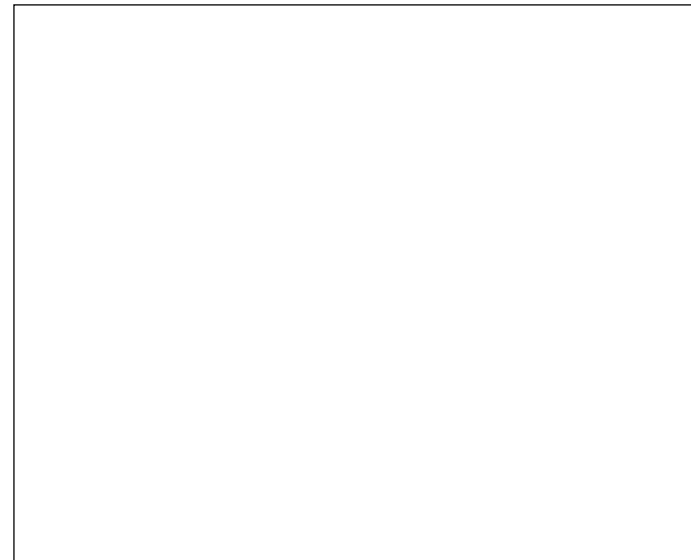
### Turbulence in the atmosphere limits the performance of astronomical telescopes



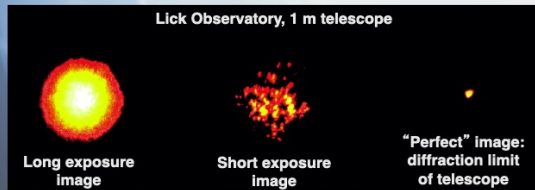
- Turbulence is the reason why stars twinkle
- More important for astronomy, turbulence spreads out the light from a star; makes it a blob rather than a point

**Even the largest ground-based astronomical telescopes have no better resolution than an 8" backyard telescope!**

Slide Courtesy Claire Max



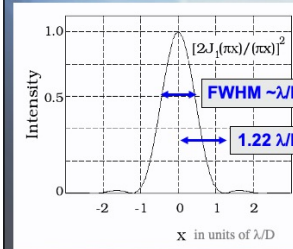
## Images of a bright star: Arcturus



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

Slide Courtesy Claire Max

## Imaging through a perfect telescope



With no turbulence, FWHM is diffraction limit of telescope,

$$\theta \sim \lambda / D$$

Example:

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

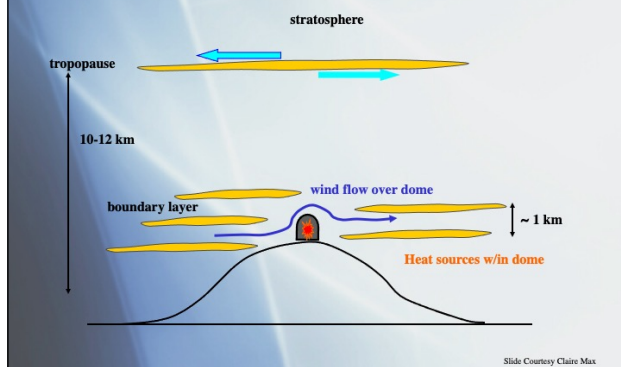
for  $\lambda = 1 \mu\text{m}$ ,  $D = 10 \text{ m}$

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

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

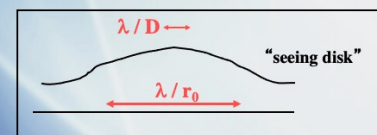
Slide courtesy of Claire Max

## Turbulence arises in several places



## Effect of turbulence on image size

If telescope diameter  $D \gg r_0$ , image size of a point source is  $(\lambda / r_0) \gg (\lambda / D)$

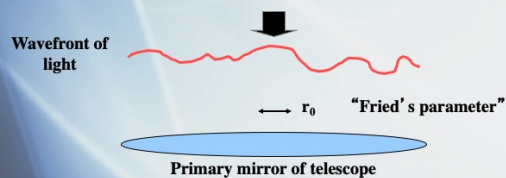


$r_0$  is diameter of the circular pupil for which the diffraction limited image and the seeing limited image have the same angular resolution.

$r_0 \approx 10$  inches at a good site. So any telescope larger than this has no better spatial resolution!

Slide courtesy of Claire Max

## Characterize turbulence strength by quantity $r_0$



"Coherence Length"  $r_0$ : distance over which optical phase distortion has mean square value of  $1 \text{ rad}^2$   
 ( $r_0 \sim 15 - 30 \text{ cm}$  at good observing sites)

Easy to remember:  $r_0 = 10 \text{ cm} \Leftrightarrow \text{FWHM} = 1''$  at  $\lambda = 0.5 \mu\text{m}$

Slide courtesy of Claire Max

## Kolmogorov Turbulence

- Wavefront perturbations caused by variations in the refractive index of the atmosphere. These lead directly to phase fluctuations,  $\phi_a(\mathbf{r})$ .
- Gaussian random distribution following second order structure function:

$$D_{\phi_a}(\rho) = \langle |\phi_a(\mathbf{r}) - \phi_a(\mathbf{r} + \rho)|^2 \rangle_r$$

where  $D_{\phi_a}(\rho)$  is the atmospherically induced variance between the phase at two parts of the wavefront separated by a distance  $\rho$  in the aperture plane, and  $\langle \dots \rangle$  represents the ensemble average.

- Can be described by single parameter  $r_0$

$$D_{\phi_a}(\rho) = 6.88 \left( |\rho| / r_0 \right)^{5/3}$$

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  $\sigma^2$  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

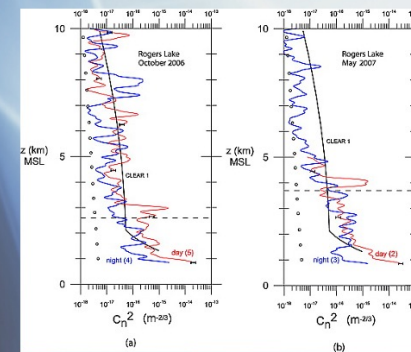


Figure from Roadcap, Tracy 2009

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 horizontal 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  $\gamma$  is the angular distance of the astronomical source from the zenith.

$C_n^2$  can be measured many ways, e.g., lidar, scidar  
Often measured as part of astronomical site testing and selection.

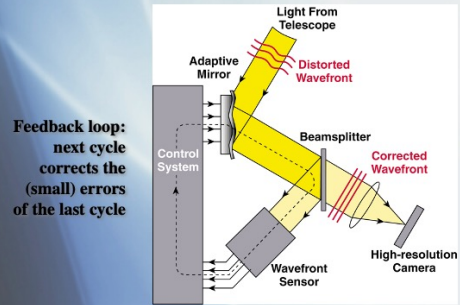
Note that as you look through more atmosphere (greater zenith distance or airmass), you will see more turbulence, so  $r_0$  generally decreases with increasing zenith distance (airmass).

## 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.

## Schematic of adaptive optics system



Slide Courtesy Claire Max

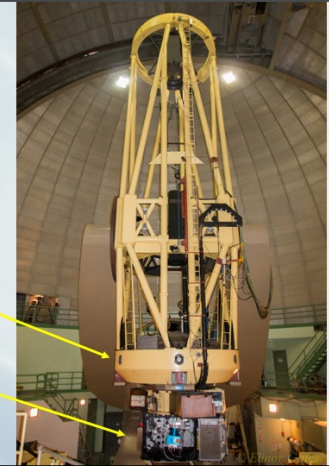
Note: Define Wavefront for public talks

## AO system is usually behind primary mirror

Example: Shane AO system at Lick Observatory's 3-m telescope

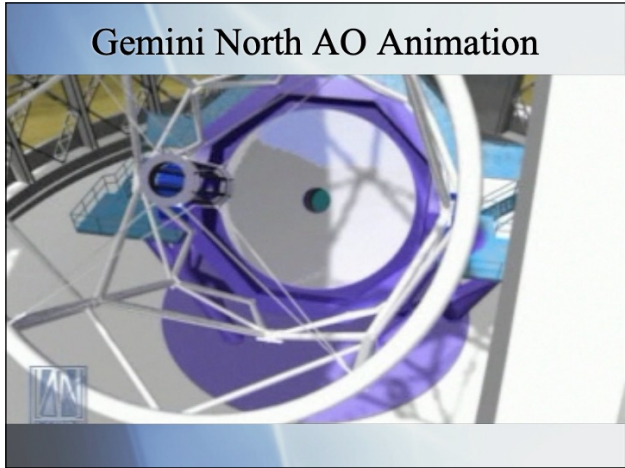
Primary telescope mirror

Adaptive optics package under main mirror

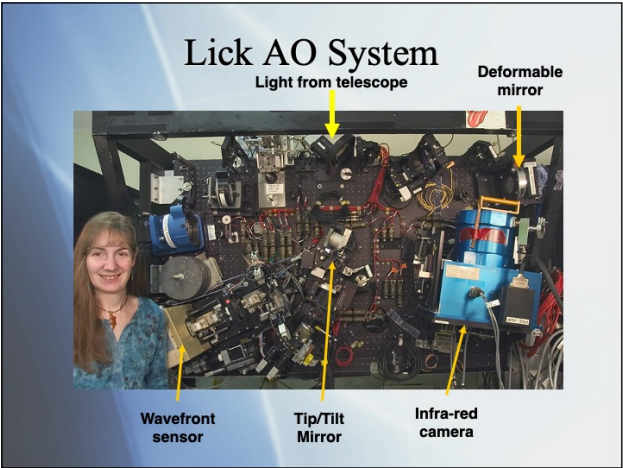


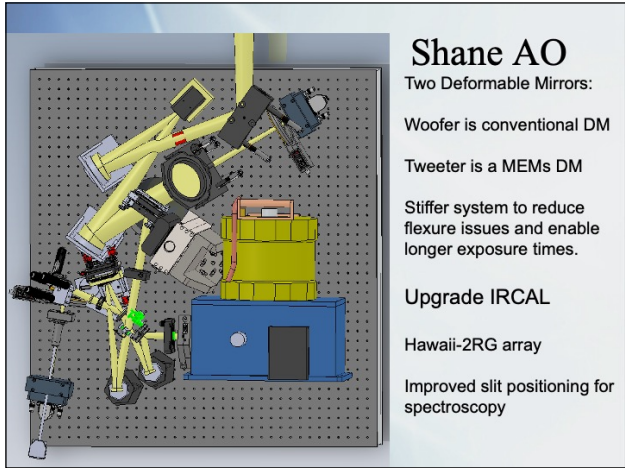
Some AO systems have a deformable secondary mirror, rather than having the DM being after the Cassegrain, Coude, or Naysmith focus.



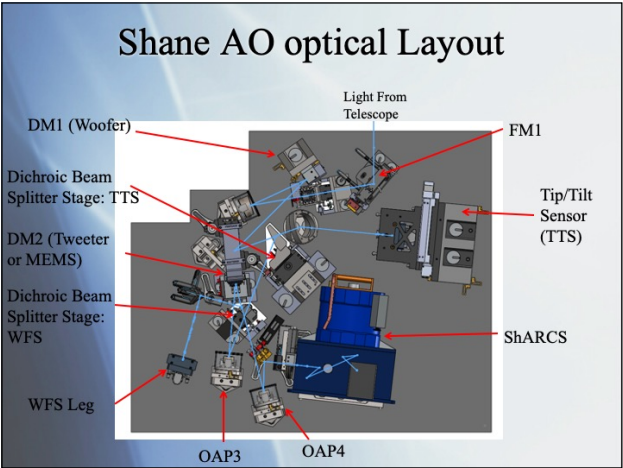


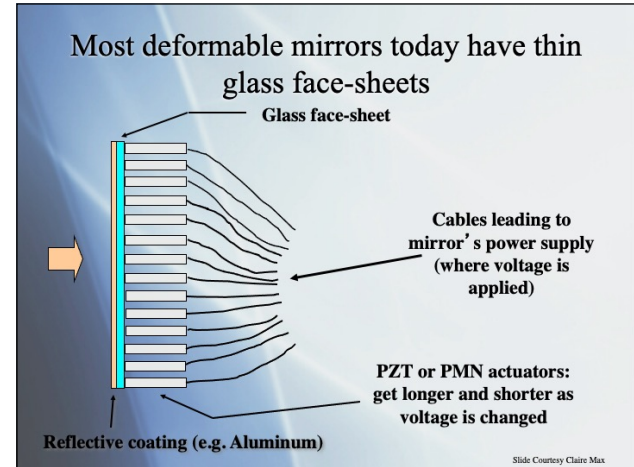
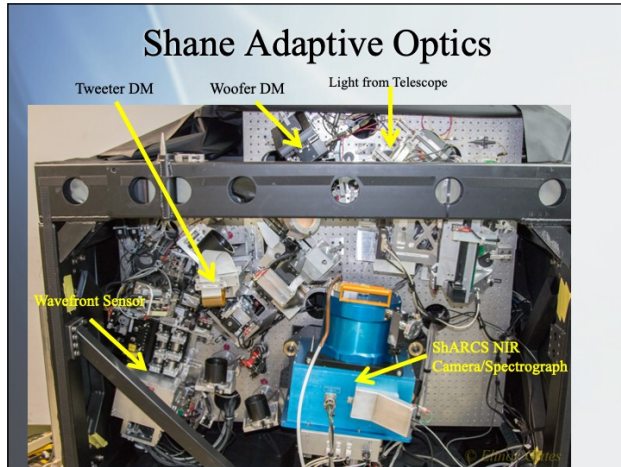
More extensive animation at  
[https://www.youtube.com/watch?v=3BpT\\_tXYy\\_I](https://www.youtube.com/watch?v=3BpT_tXYy_I)





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

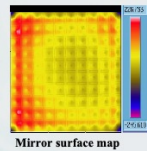
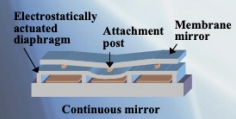




Other technologies for DMs are in use, such as MEMs and bimorph mirrors.  
 Shane AO woofer DM uses voice coils as actuators. Shane AO tweeter MEMS DM uses electrostatic forces.

## 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)



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

Piecewise linear fit

Phase  $\Phi$

Primary mirror

$D \gg r_0$

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  $\sim r_0$   
Number of subapertures  $\propto (D / r_0)^2$

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

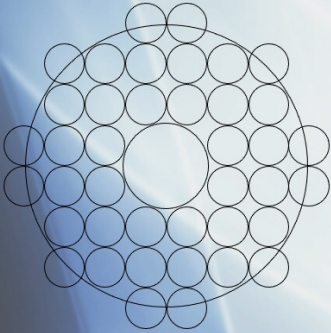
Deviation of spot position from a perfectly square grid measures shape of incoming wavefront

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

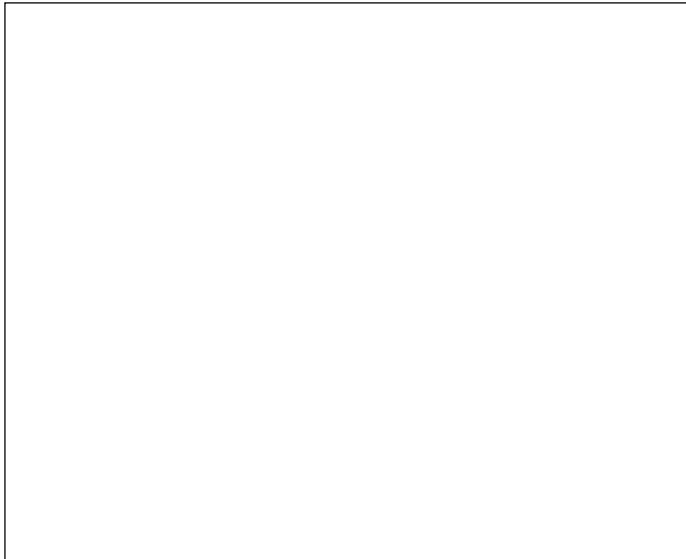
Slide courtesy of Claire Max

**Lick AO System**

3 m primary  
0.8 m secondary

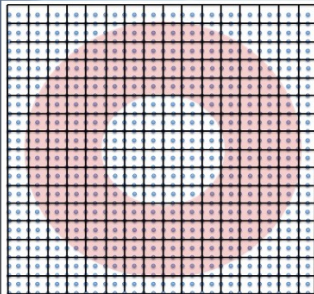


- 40 subapertures,  $d=43\text{cm}$
- 61 actuators, hex grid,  $d_s=50\text{cm}$
- Max sample rate: 1000 Hz
- Sodium layer LGS
- IR Cam:  $256^2$  HgCdTe, 0.076 arcsec/pixel (Nyquist in K) with Direct Imaging, Polarimetry, and Spectroscopic capabilities



**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.



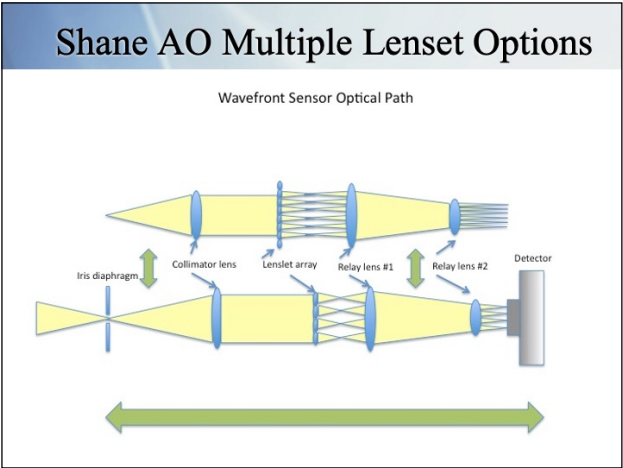
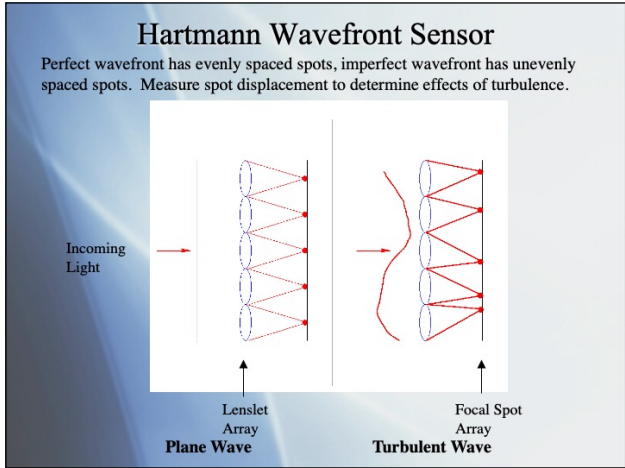
Sub-apertures modes: 8x, 16x, and 30x across  
Corresponding to 15, 7.5, and 4 inch (38, 19, and 10 cm) diameter r0 sub-apertures on the 120" primary

Max sample rate: 1500 Hz

Sodium layer LGS

IR Camera: 1024x1024k H2RG  
0.033 arcsec/pixel  
Nyquist sampled in J

Direct Imaging, Polarimetry, and Spectroscopic capabilities

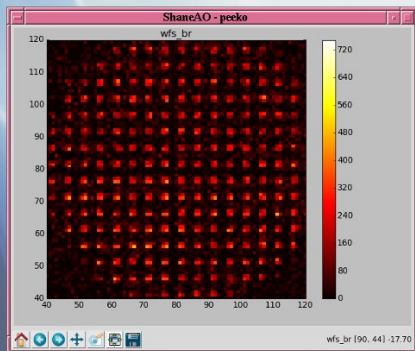


Other wavefront sensing techniques:

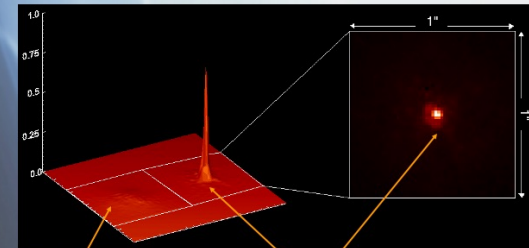
Curvature Sensing

Pyramid Sensors

## ShaneAO Wavefront Sensor



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



Without AO  
width = 0.34 arc sec

With AO  
width = 0.039 arc sec

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.

Closed loop Strehl=0.74, 2.5 $\mu$ m,  $r_0$ =18cm at 6500Å  
5.7s exposures, 4.0' field of view

©2002 Elnor Gates

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

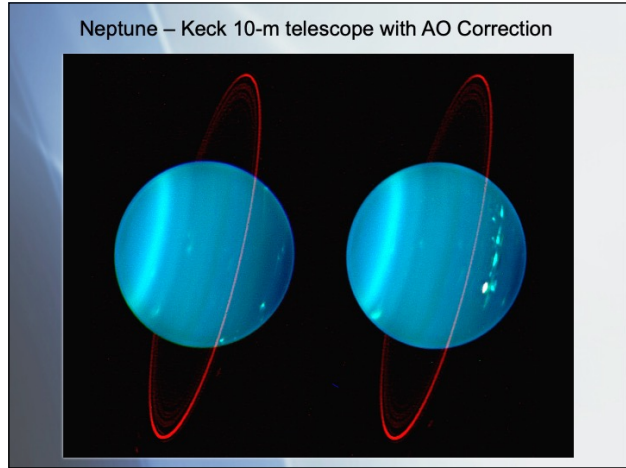
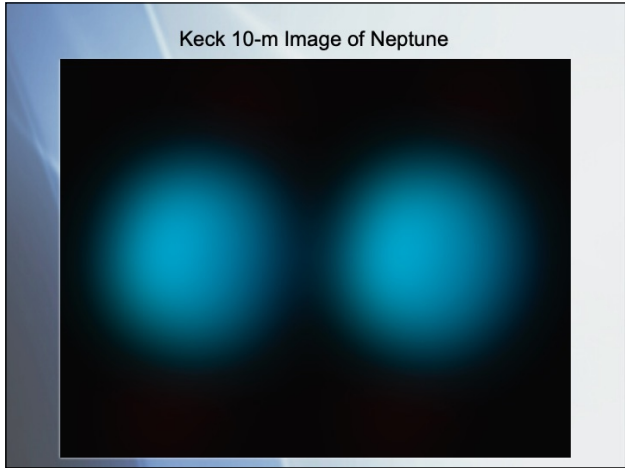
## Adaptive optics in action

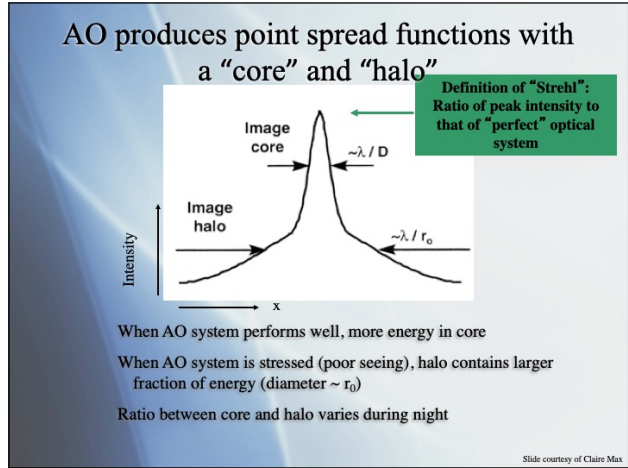
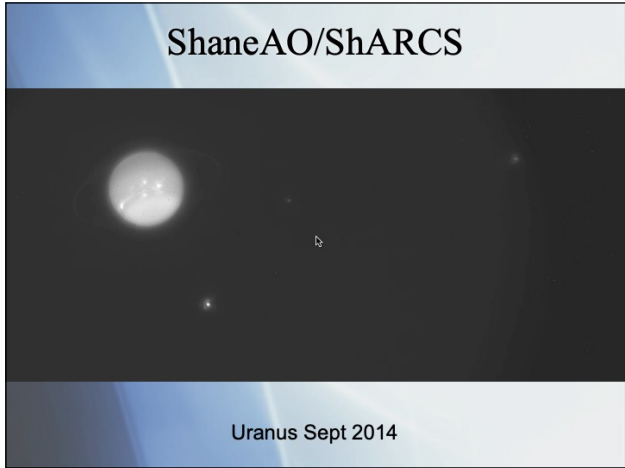
Lick Observatory Adaptive Optics System

	No AO	Tip/Tilt	AO
$\nu$ UMa			
HIP 56986 Separation=0.38"			

Closed loop Strehl=0.74, 2.5 $\mu$ m,  $r_0$ =18cm at 6500Å  
57ms exposures, 4.9' field of view

©2002 Elnor Gates





## 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

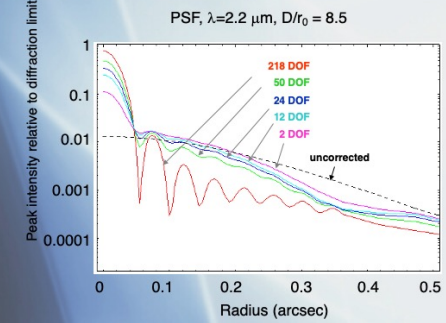
$$S = \frac{\int OTF_{aberrated}(f_x, f_y) df_x df_y}{\int OTF_{un-aberrated}(f_x, f_y) df_x df_y}$$

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

Slide courtesy of Claire Max

Recommend Goodman's "Fourier Optics"

## Point-spread function for different # of degrees of freedom



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:

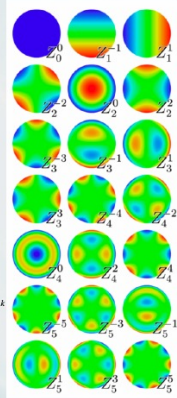
$$Z_n^m(\rho, \phi) = R_n^m(\rho) \sin(m\phi)$$

- 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  $R_n^m(\rho) = 0$

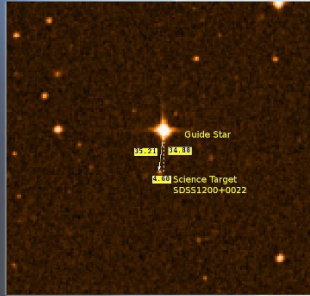


## Natural Guide Stars

- 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

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

## Off-axis guide stars



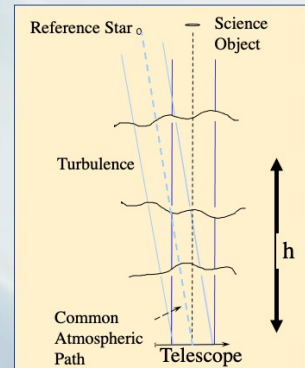
- Science target is not the same as the guide star
- Isokinetic vs. Isoplanatic angle
- Performance degrades with increasing separation between guide star and science target
- Guide star usually within 60 arcsec of science target

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

## Anisoplanatism

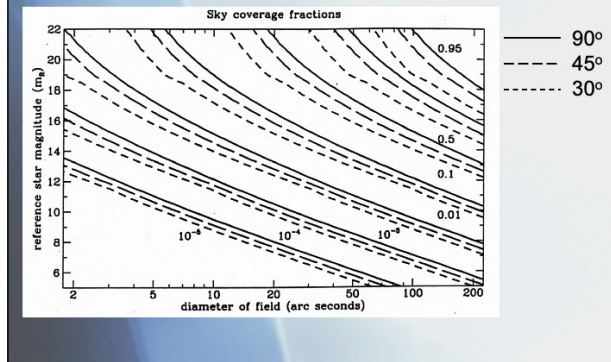
Anisoplanatism sets a limit on the distance of the reference star from the science object  
 $\text{Strehl} = 0.38$  at  $\theta = \theta_0$

$\theta_0$  is isoplanatic angle  
 $\theta_0 = 0.31 (r_0 / h)$   
 For a single layer of turbulence at height  $h$



Slide Courtesy Claire Max

### Sky coverage as function of galactic latitude



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

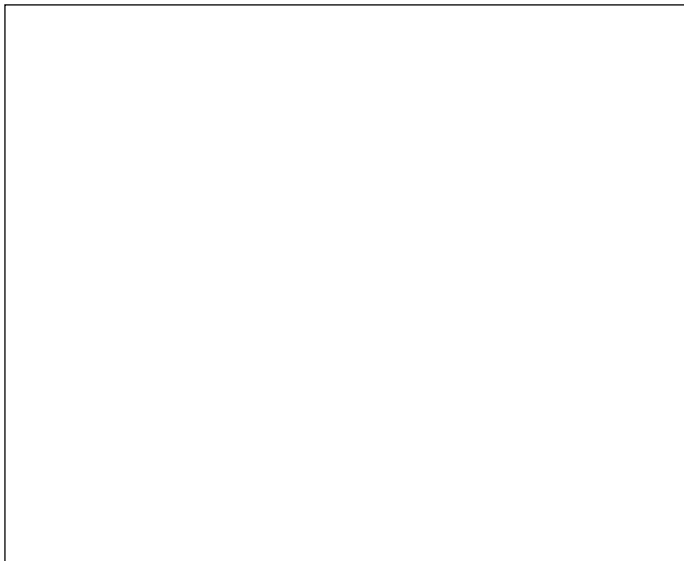
### If there is no nearby star, make your own "star" using a laser

**Concept**

**Implementation**

Slide courtesy of Claire Max

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.

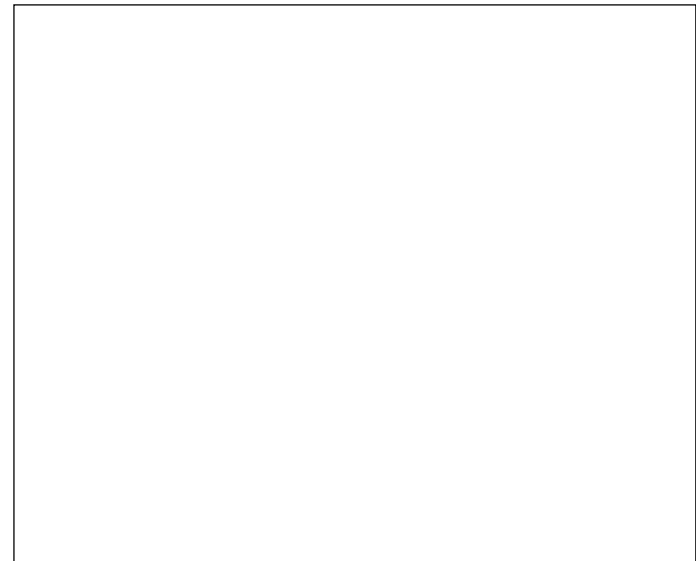
These metals are deposited by meteors burning up in the Earth's atmosphere.

Tune laser to emit 589 nm wavelength light.

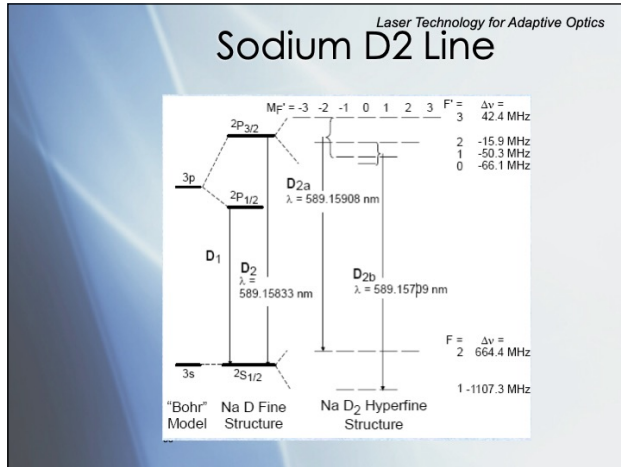
Sodium atoms absorb and are excited by laser.

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

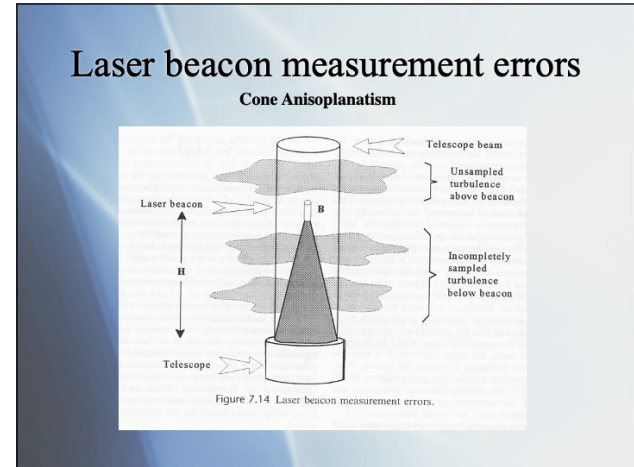
Slide courtesy of Claire Max







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



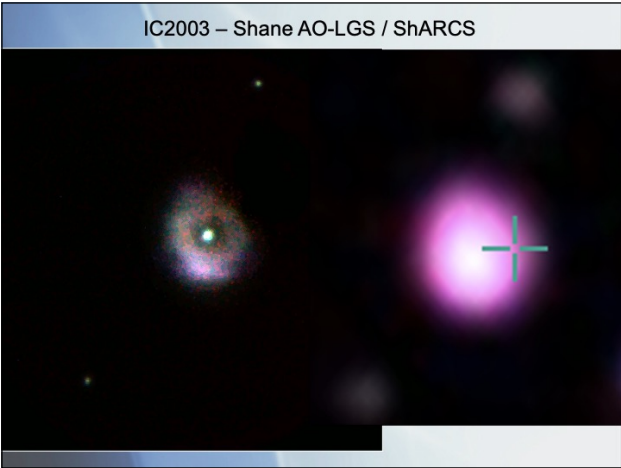
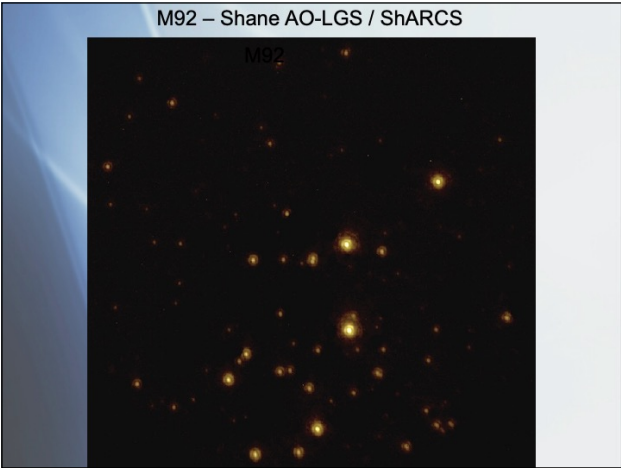
Sodium vs. Rayleigh beacons:

Rayleigh at 12-14 km altitude - gated systems

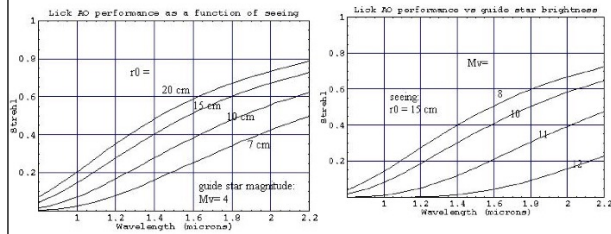
Sodium at 90 km altitude - harder technology but much better performance

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).

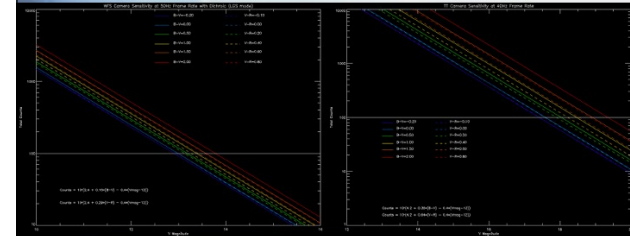


## AO performance depends on seeing and guide star brightness



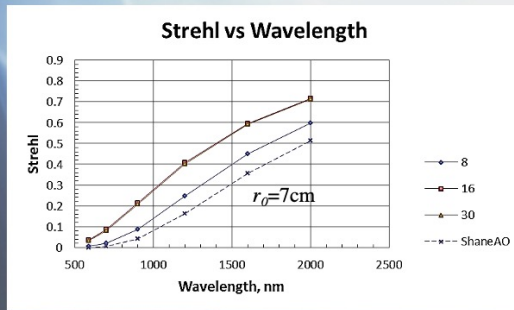
The brighter the star, the faster the AO system can measure the wavefront. Also, with brighter stars you can use more subapertures on the Hartmann sensor and measure the wavefront on a finer spatial scale. As the seeing degrades ( $r_0$  gets smaller) the turbulence is more severe and harder to correct, so the Strehl will decrease.

## WFS Sensitivity, Tip/Tilt Sensitivity



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 as 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.

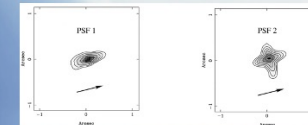
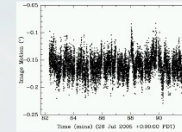
## PSF Issues

- 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.

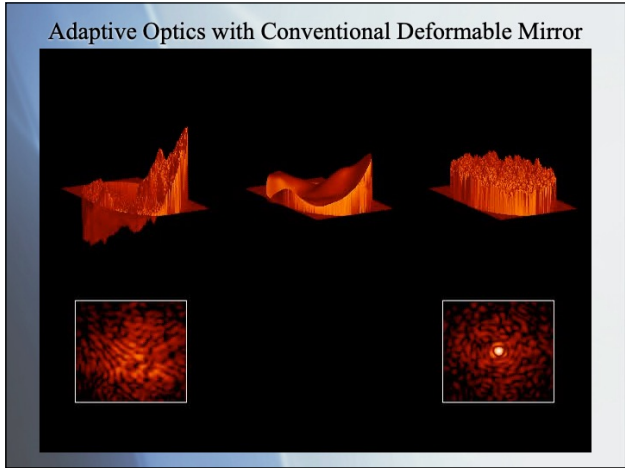
## Strehl, FWHM, and Science

- 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.

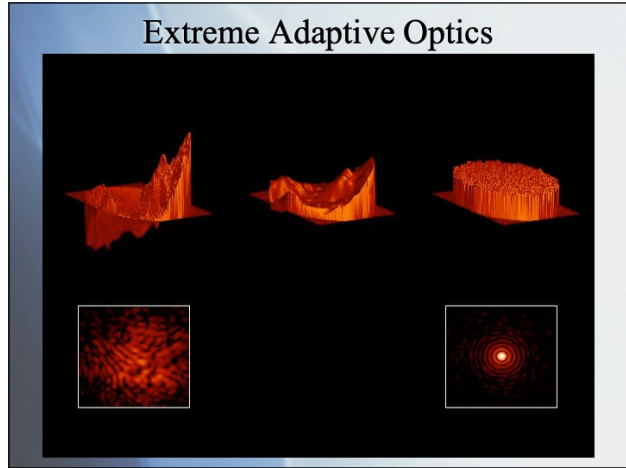
Info for old Lick AO system. Will depend on AO system.

## AO Run Planning

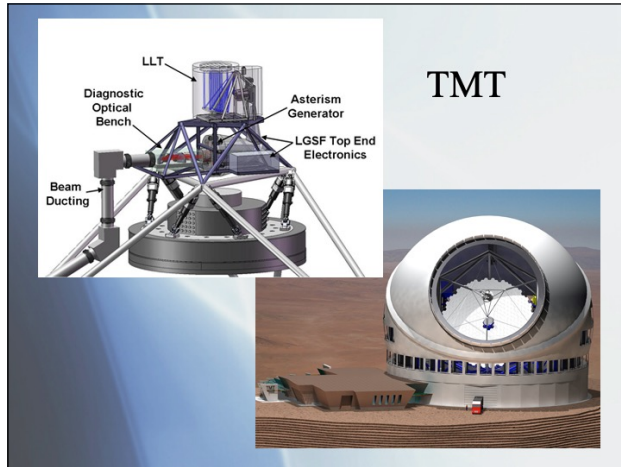
- Targets - Is the target also the guide star (NGS or LGS TT)? If not, is there a suitable guide star within range? NGS or LGS program?
- Photometric and/or Spectral Standard Stars
- PSF stars - Do you need a single star or a PSF - Guide Star pair?
- What Strehl or FWHM required to accomplish the science 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.

### AO with Multiple Guidestars

- Advantages
  - Widens the field of correction
  - Corrects the cone-effect error
- Requires
  - Tomography reconstructor algorithms
  - Multiple Sodium LGS
  - Multiple DMs
  - Complicated tip/tilt strategy

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.