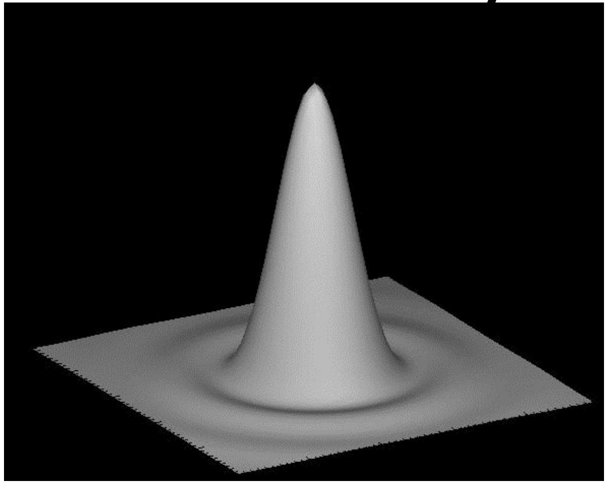
Observational Astronomy

Active and Adaptive optics

Point Spread Function

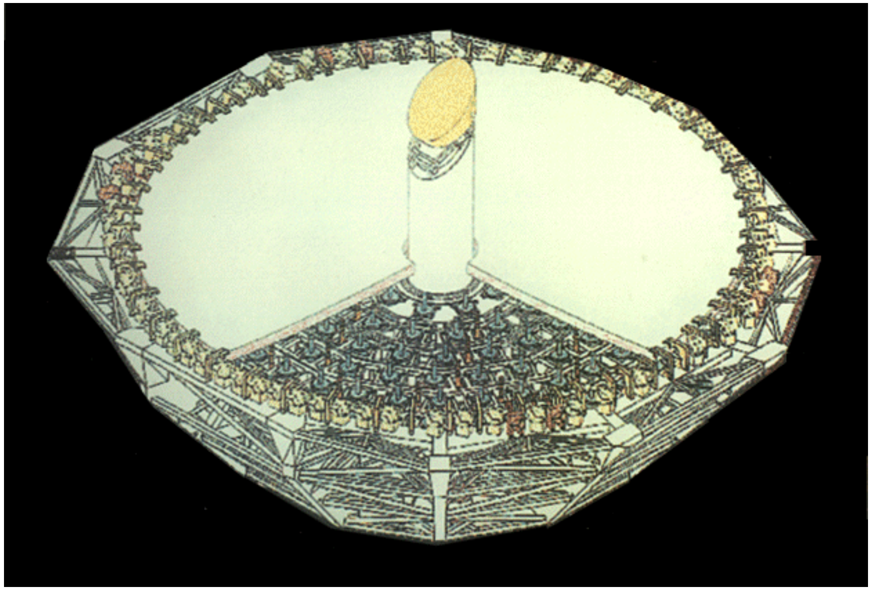
- PSF is the intensity distribution in the focal plane produced by the telescope+instrument looking at a point source.
- Ideal PSF of an axial system is a Bessel function)

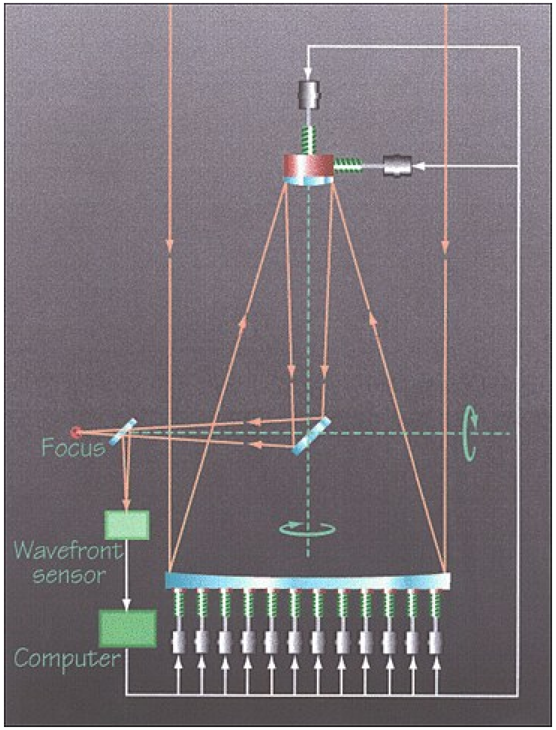


Active optics

Large thin mirrors are shaped by support system: VLT mirror is 8.2m in diameter

and only 18 cm thick!

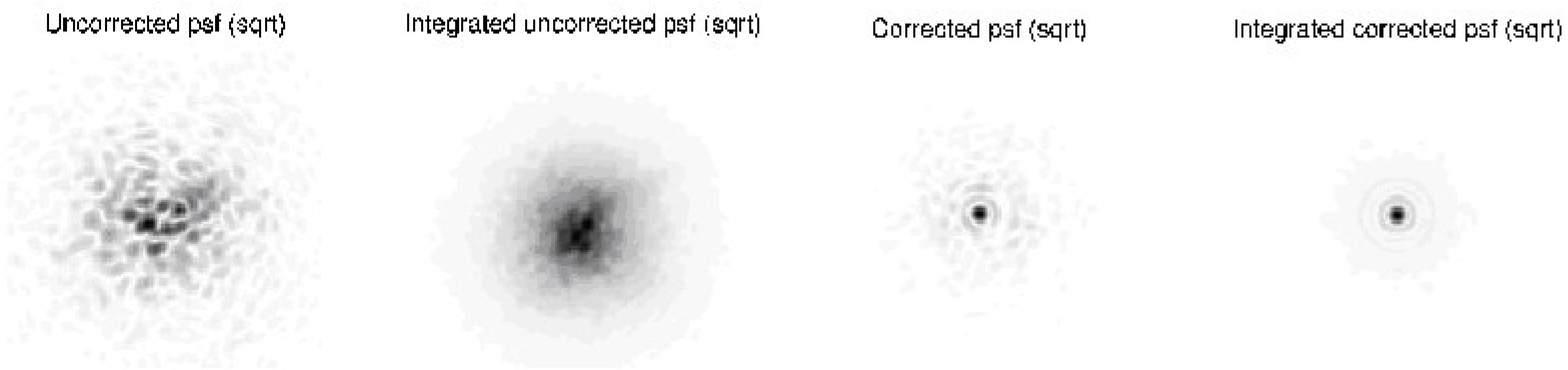




- Compensate for thermal and orientation distortions
- Close loop operation during adjustment
- Low frequency: 30 s cycle
- VLT: 150 actuators

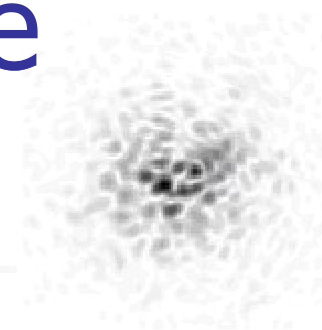
Adaptive optics

Seeing corrections (PSF):

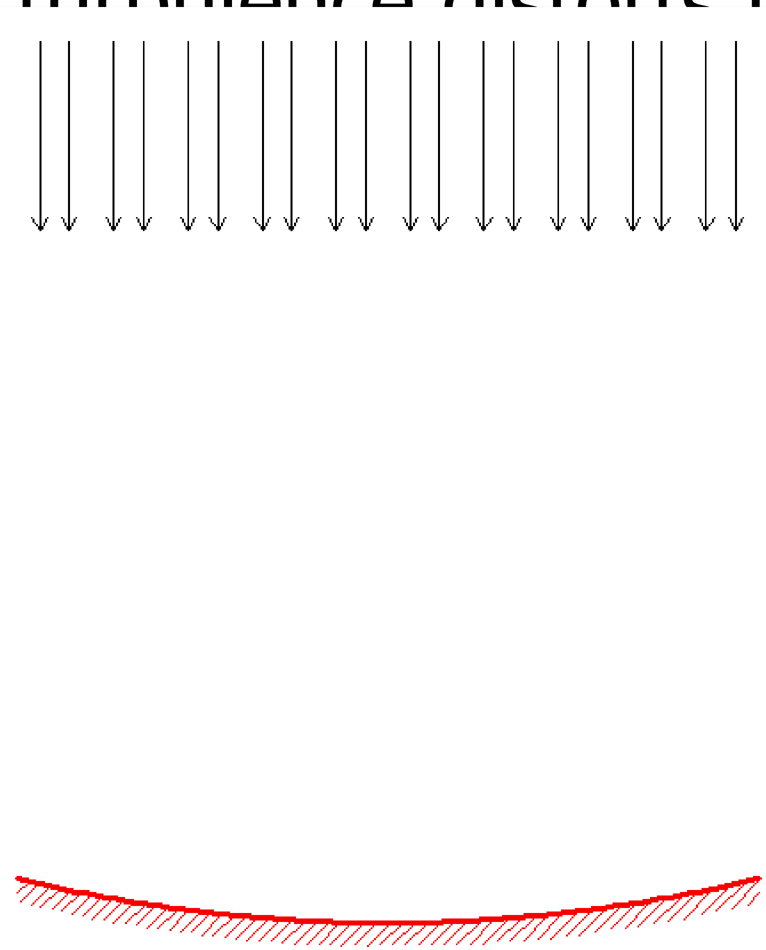


The *Strehl ratio* is *the ratio of peak intensities in the aberrated and ideal point spread functions in the focal plane* (Born and Wolf 1999).

Why do we need adaptive optics?



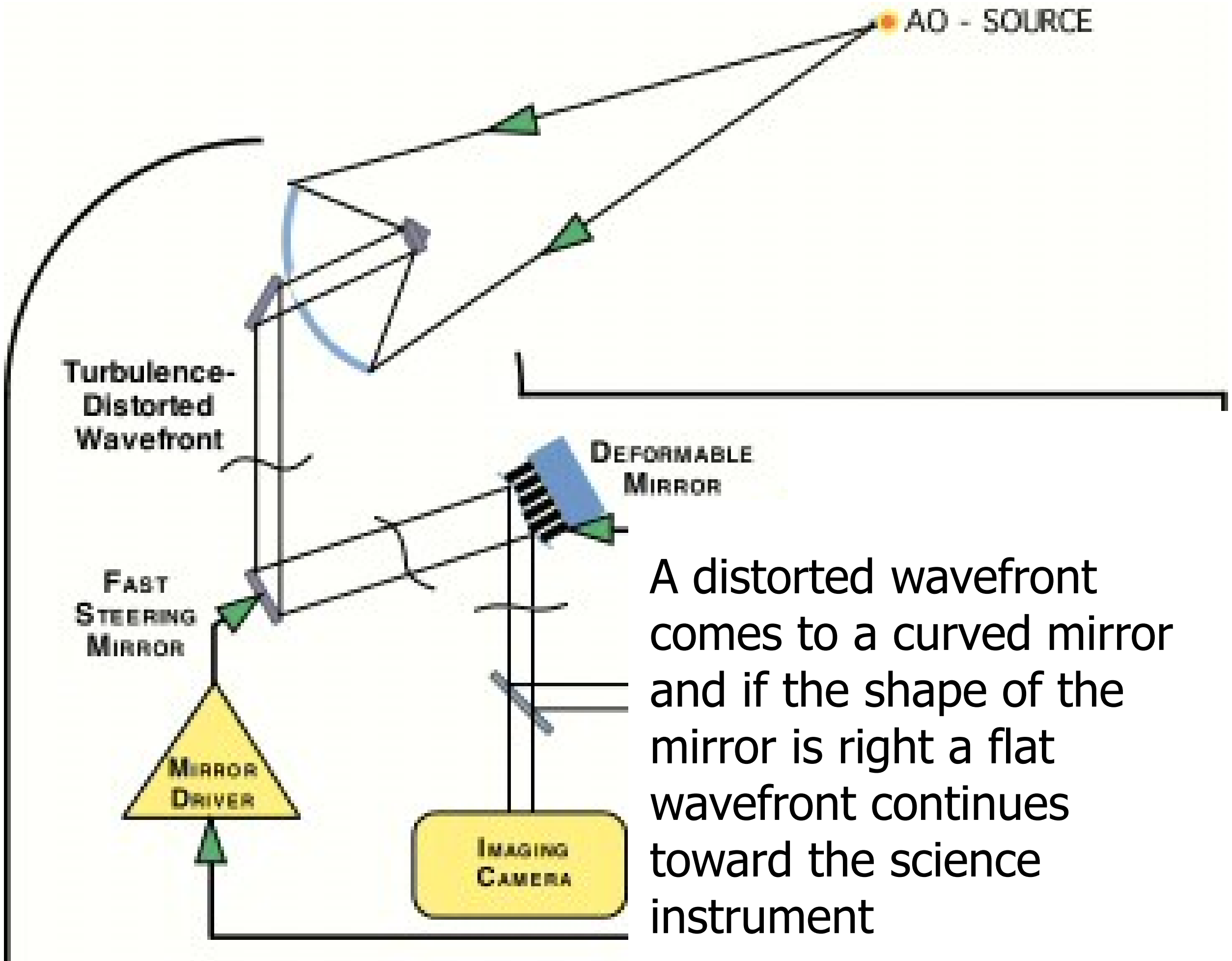
Atmospheric turbulence distorts the wave fro



Three ways of looking at the focal plane image:

1. Non-collimated beams (speckles)
2. Curved wavefront (phase shifts)
3. Changing intensity distribution

How adaptive optics work?



A distorted wavefront comes to a curved mirror and if the shape of the mirror is right a flat wavefront continues toward the science instrument

A bit of theory…

- Amplitude of turbulence spectrum $\Phi(k) \propto k^{-2/3}$ where $k = 2\pi / r$ (Kolmogorov spectrum)
- Refraction index in the atmosphere is affected by the temperature: (Oboukhov's law)

$$\delta n = -7.8 \cdot 10^{-2} \frac{P \delta T}{T^2}$$

- Typical variations are of the order of 10 mK and thus refraction changes ≈10^{-8}
- Phase shift is:

$$\Delta\phi(x,y) = \frac{2\pi}{\lambda} \int \delta n(x,y,z)dz$$

… and some more …

What is important for the actual observations is the accumulated phase difference as a function of **angular** distance and therefore $\Delta\phi$ is proportional to the scale of perturbation in the power 5/3:

$$\Delta\phi = \left(r / r_0 \right)^{5/3}$$

where r_0 is Fried radius defined as the radius where the phase shift is 1 radian. Fried radius shows:

- size of the isoplanatic patch
- the aperture size which can reach diffraction limit

… and some more …

- Fried radius is related to the wavelength:

$$r_0 \propto \lambda^{6/5}$$

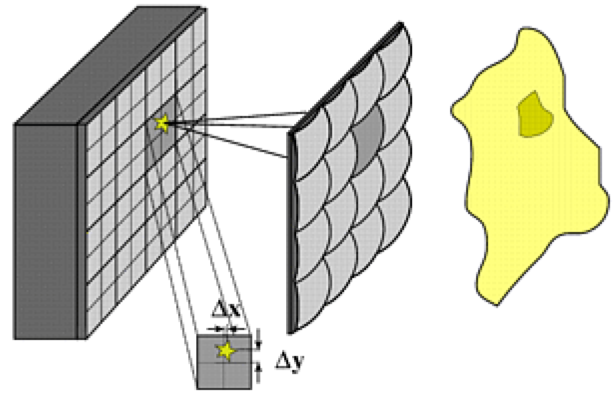
and to the diameter of the PSF:

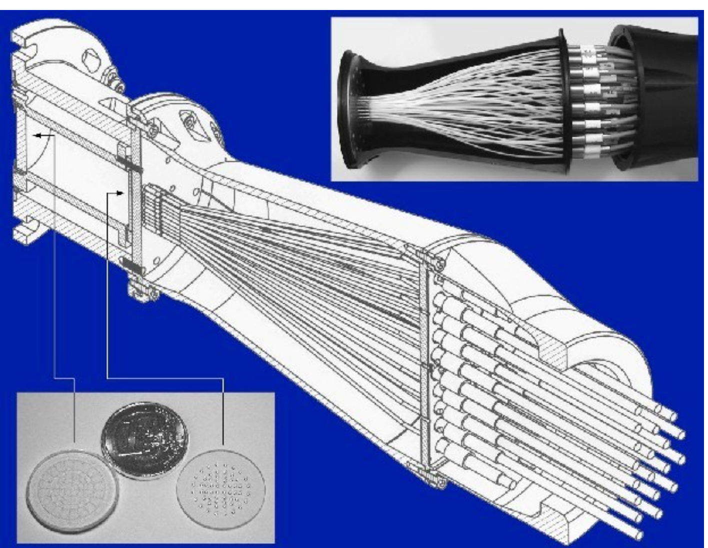
$$\mathrm{FWHM} \approx \lambda / r_0$$

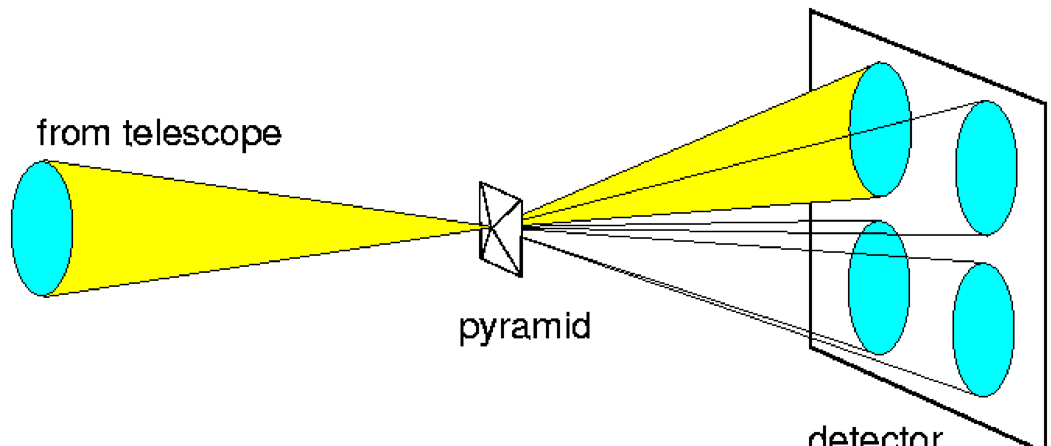
- Time scales: *0.001 seconds*
- Typical r_0 are around *10 cm in the visible light*
- How would you measure r_0?

Wavefront sensor

- Shack-Hartmann
- Curvature sensor
- Pyramid WFS





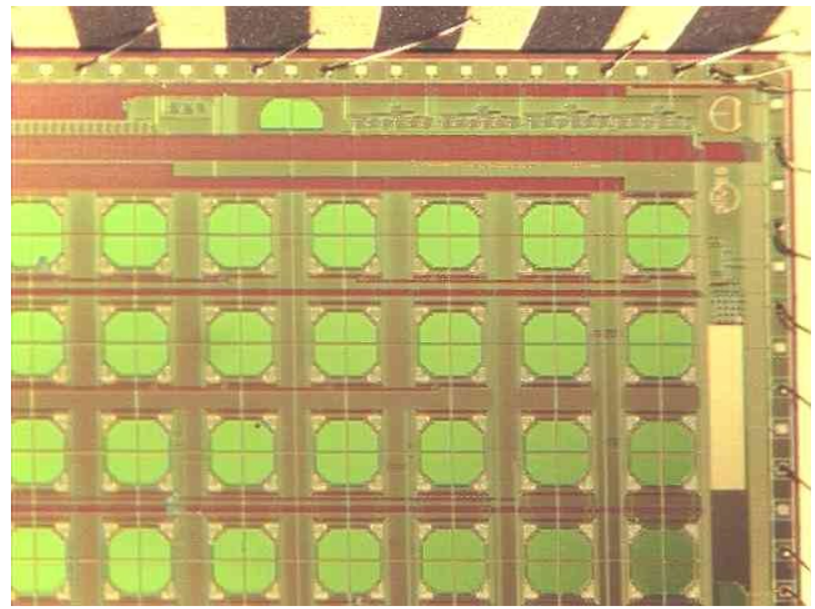


Fast steering mirror is needed
to get all pixels in focus

Sensor implementation

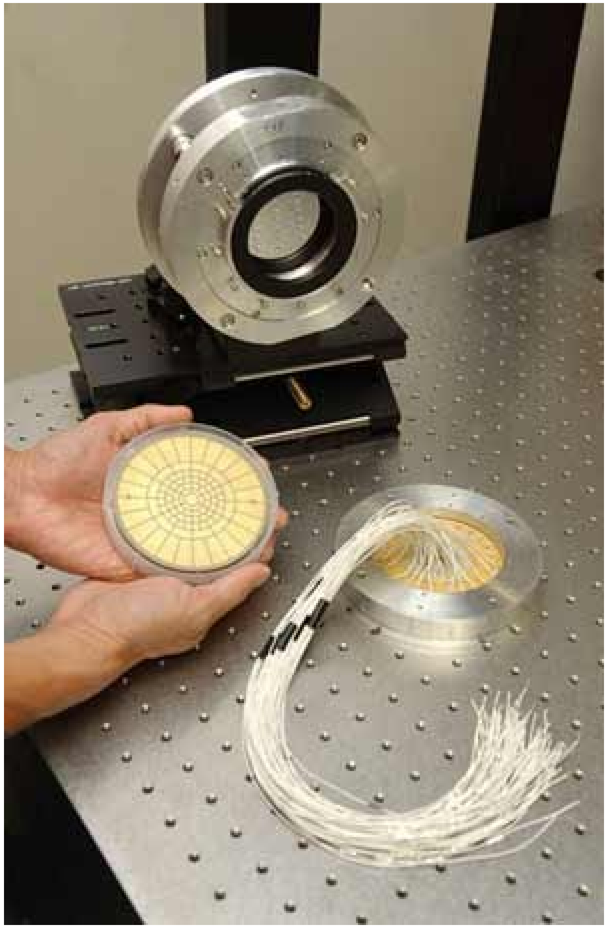
Wavefronts must measured many at 100 kHz rate!

Sensor chip on a printed-circuit board.

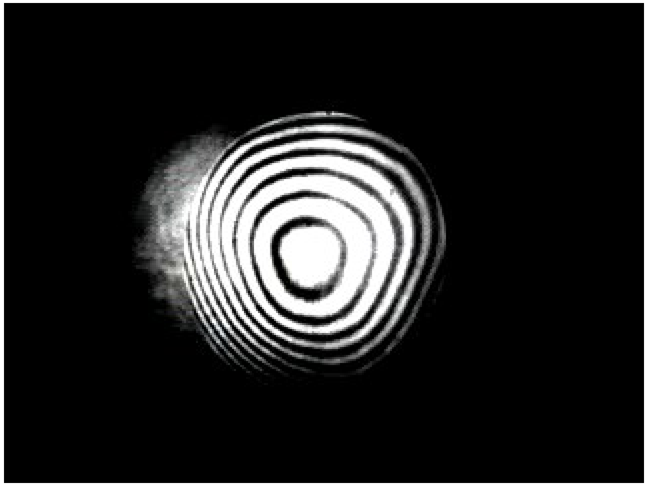


Photograph of a corner of the 1cmx1cm wavefront-sensor chip implemented in standard CMOS. The green elements are the position-sensitive detectors.

Deformable mirror

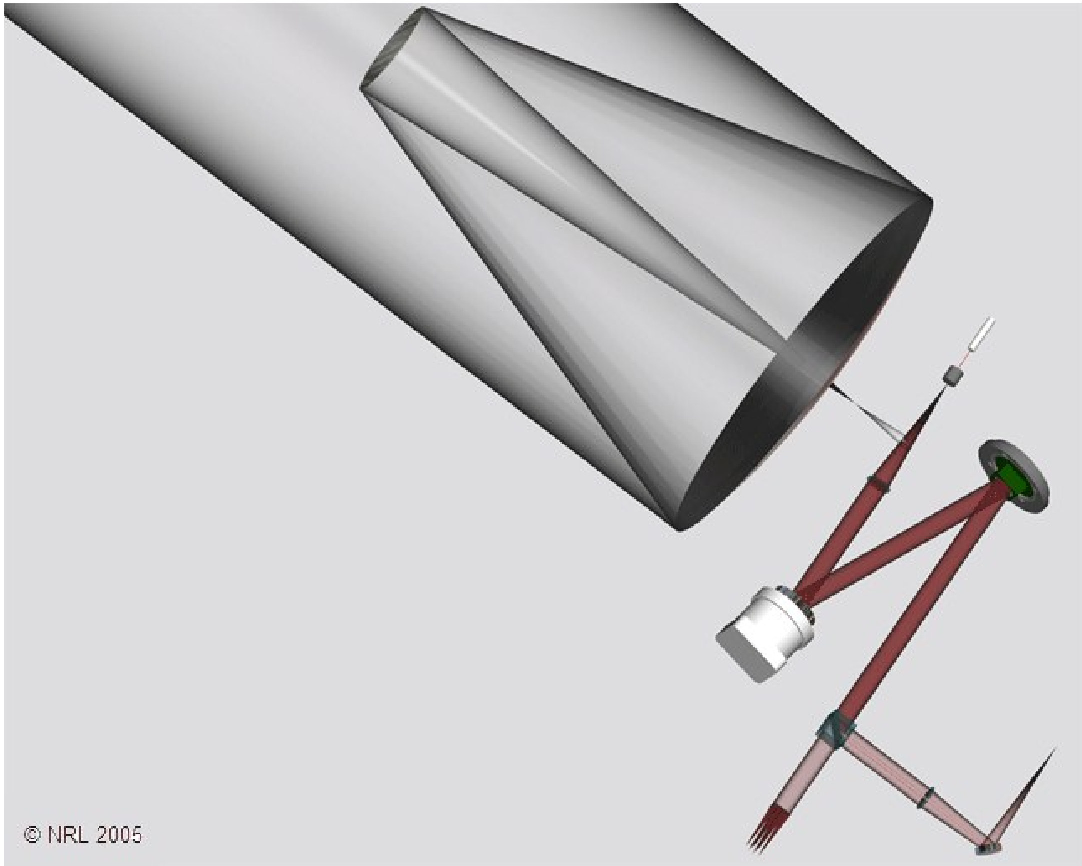


Various Zernike mode corrections performed with 37 actuator mirror

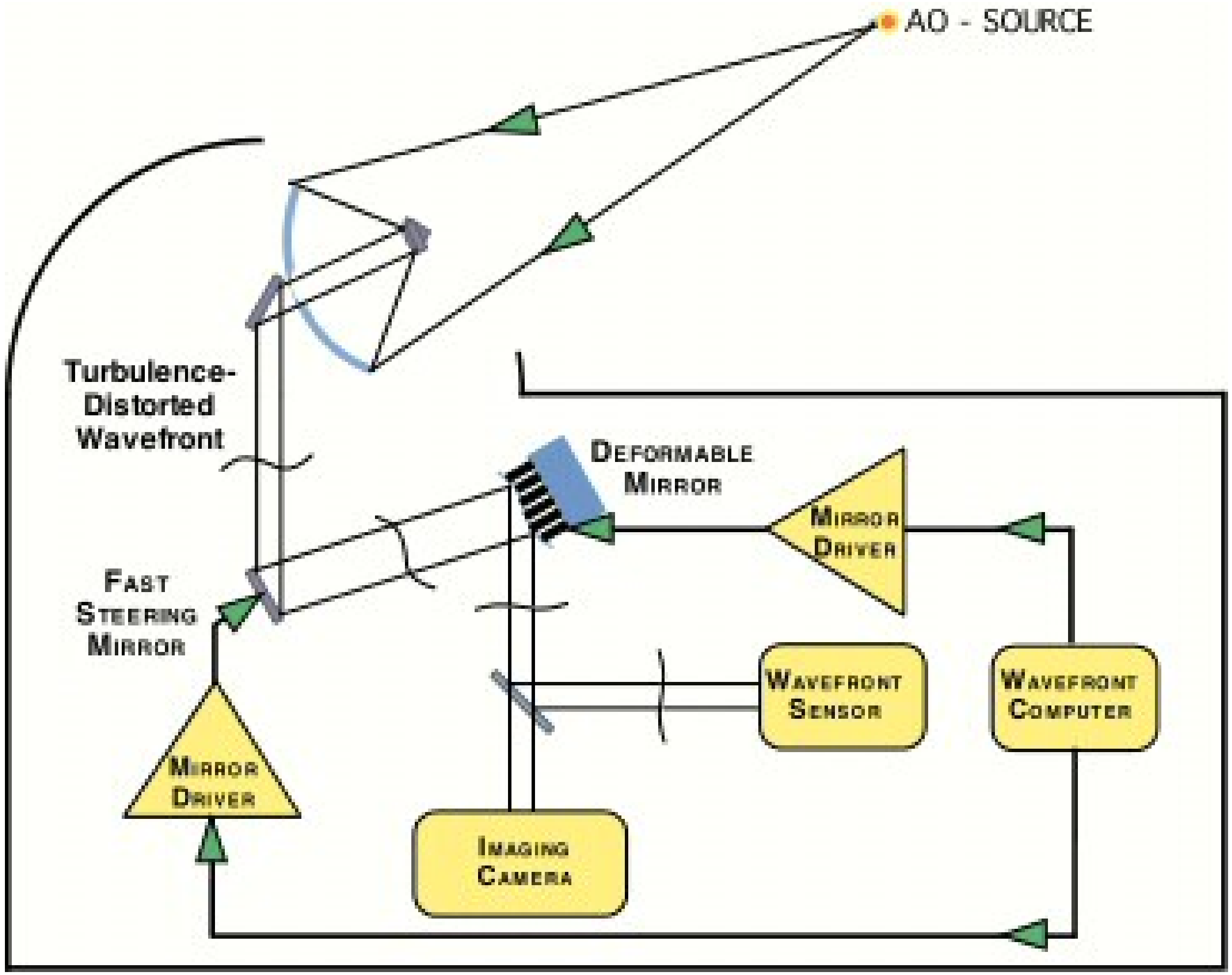


Calibrations

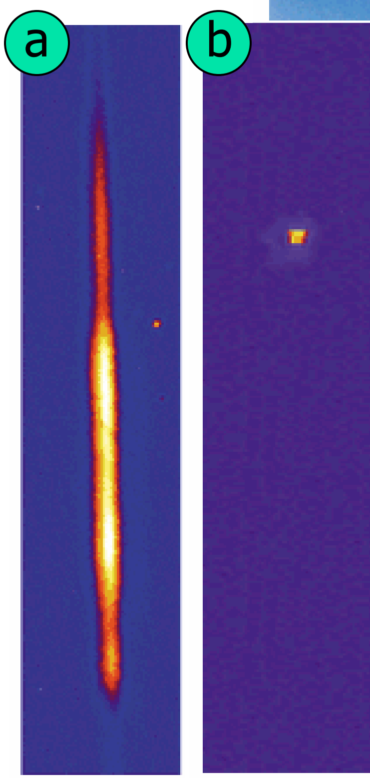
Looking for a zero-point of DM:



Closing the loop



Laser Guide Star



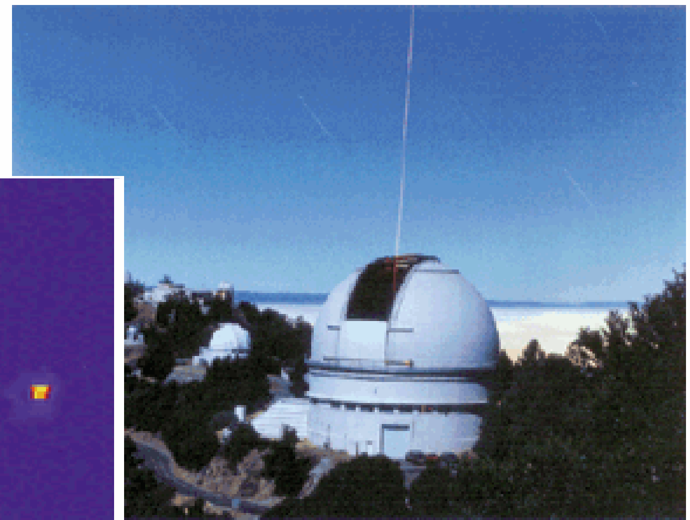
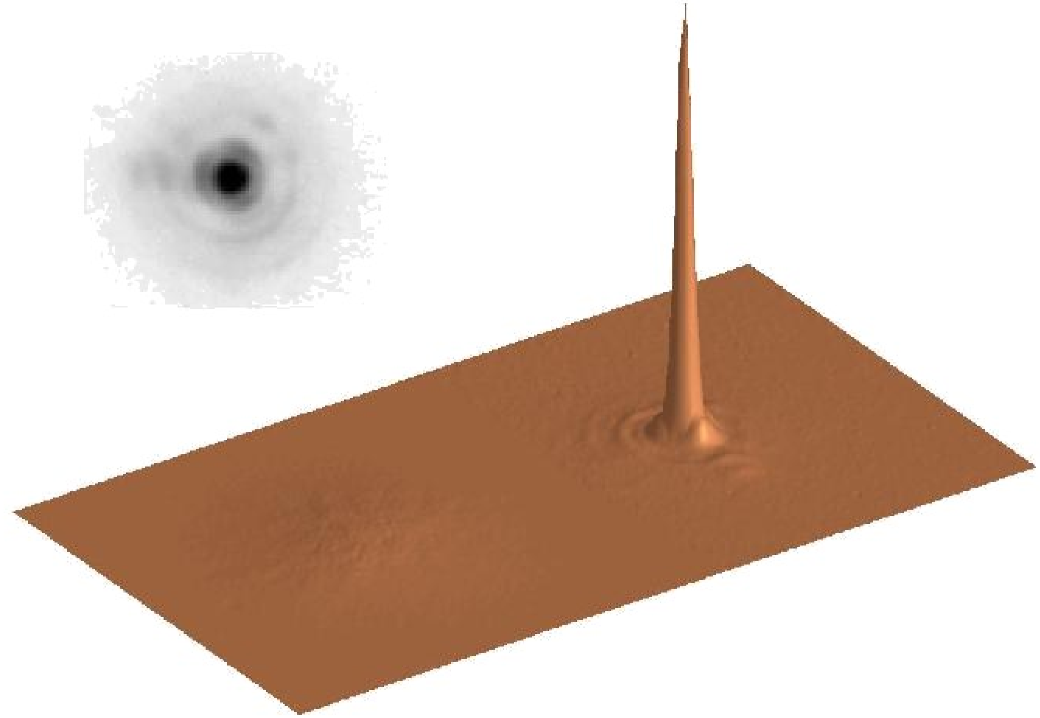
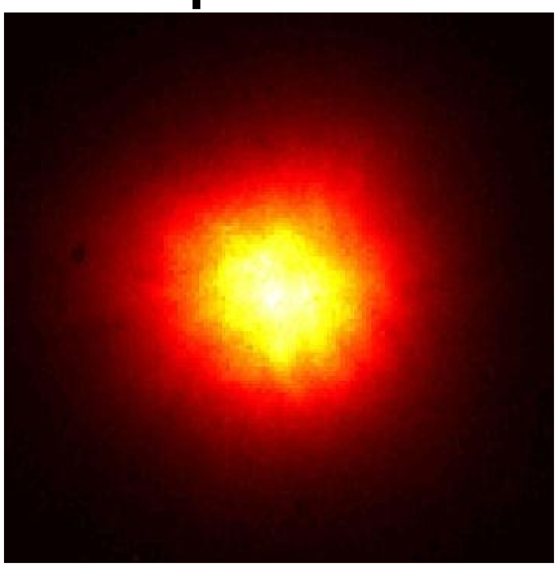


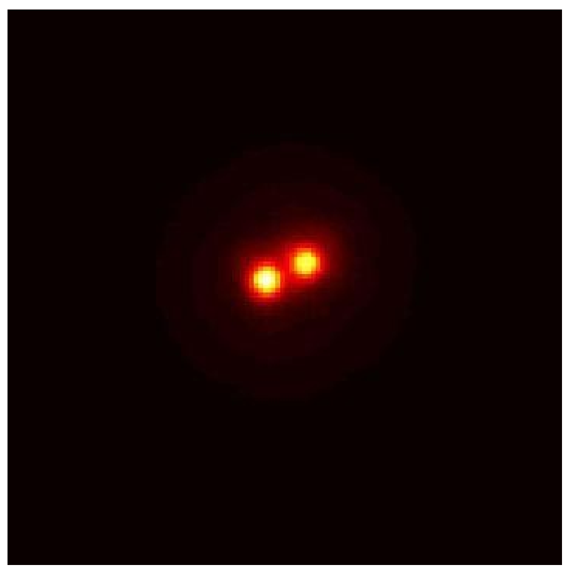
Figure 3. Views of the laser guide star at the Lick Observatory. (a) From another telescope at Lick, the guide star appears as a streak. (b) From the Shane telescope, the guide star looks like another star in the sky.

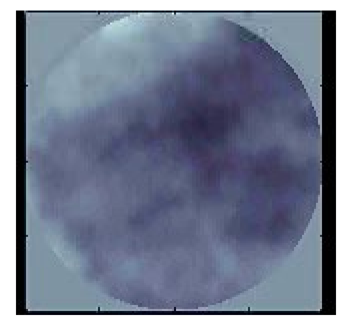
Final result



VLT NACO:
  PSF and resoluti
  improvements

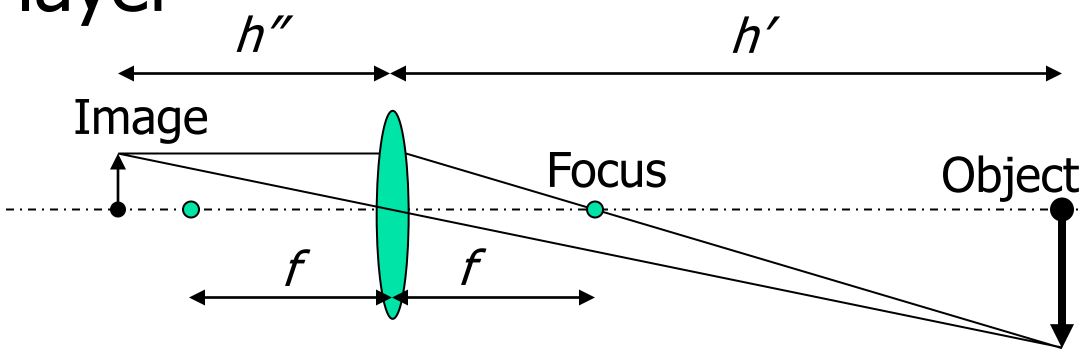






Multi-Conjugate Adaptive Optics

- Main problem of AO: assumption of a single thin turbulent layer
- Fundamental formula of a lens:



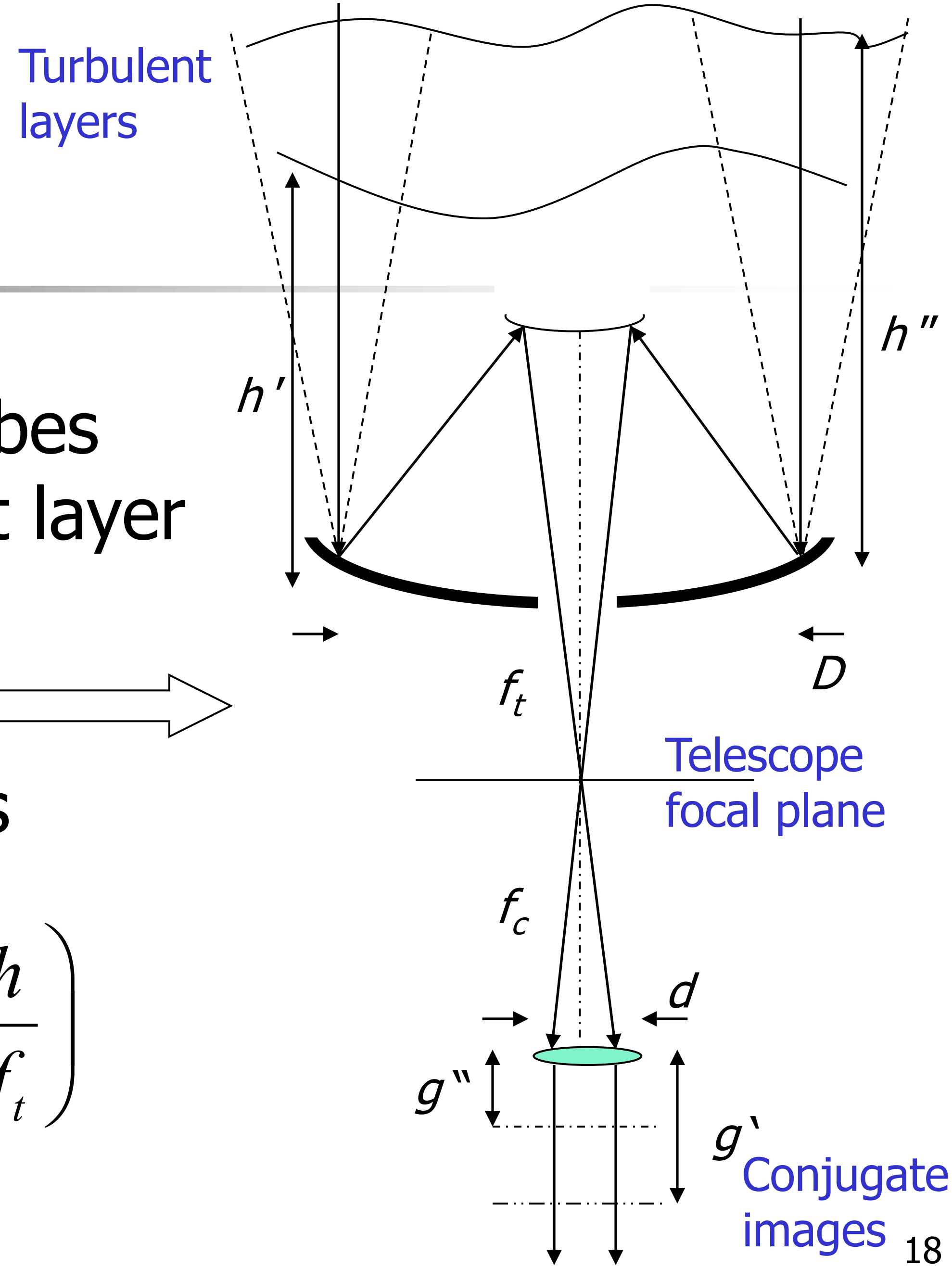
$$\frac{1}{f} = \frac{1}{h'} + \frac{1}{h''}$$

- Thus, we can create the image of the turbulent layer at the deformable mirror
- This allows to have multi-layer AO

MCAO

- Single guide star probes only part of turbulent layer
- Here is how it may look for two layers:
- Conjugate distance is given by:

$$\frac{g}{f_c} = \left(1 + \frac{d}{D}\right) - \left(\frac{d}{D}\right)\left(\frac{h}{f_t}\right)$$



Home work

- Take one WFS and prepare concise 3 minute presentation summarizing advantages and disadvantages of a given WFS design
- Look up the race for implementing laser-guide star and multi-conjugate AO: who has the lead? What are the instruments using LGS and MCAO on large telescopes?
- Derive the formula for conjugate distances remembering that: $f_c / f_t = d / D$

Next time…

- Direct Imaging
- Angular resolution
- Focal Reducers
- Photometry