OBSERVATIONAL ASTRONOMY

AUTUMN 2023

Lecture 4

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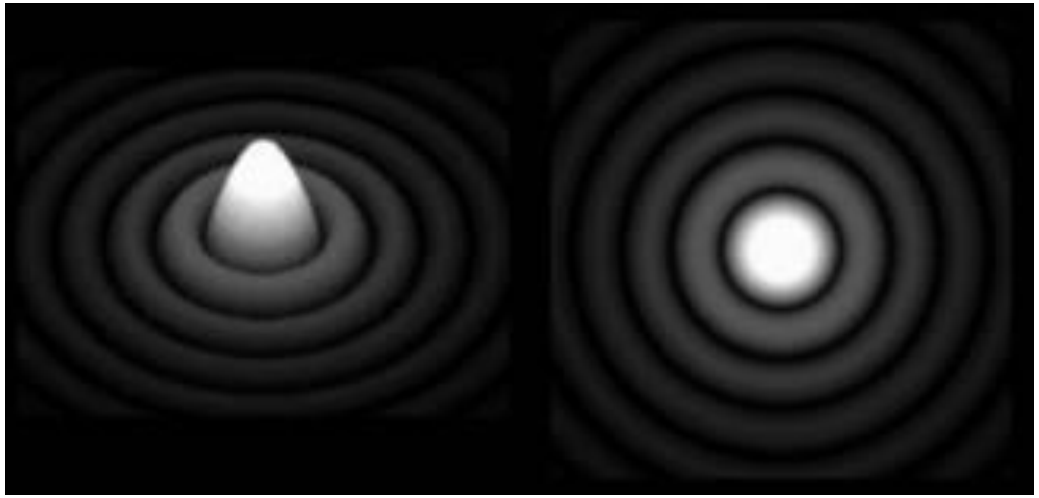
Diffraction and Spatial resolution

- Airy disk:



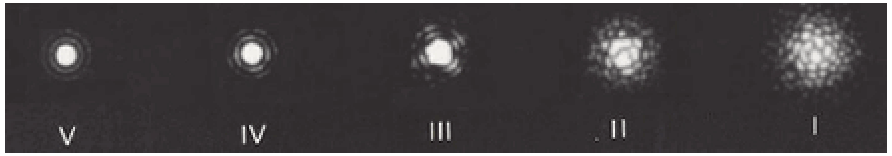
- The first dark ring is at an angular distance of 1.22 λ / d (radians) from the center. This is often taken as a measure of resolution in an ideal telescope.

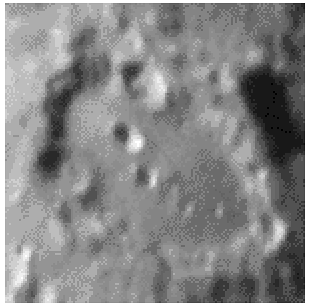
Diffraction and Spatial resolution

- The fundamental limit to the spatial resolution of a circular aperture telescope is set by the size of the Airy diffraction pattern, but in practice the resolution is often worse than that, particularly at wavelengths shorter than 10 µm (100000 Å). Causes are:
  - Imperfections in manufacture or support of the reflecting surface;
  - Aberrations;
  - **Distortion of the wavefront by the atmosphere (seeing)!**

Seeing and Scintillation

- The Earth's atmosphere is not a quiescent plane-parallel ideal region. It is, in fact, a turbulent mix of gasses, always in motion. Because the index of refraction varies with temperature and pressure motions in the atmosphere result in variations in refraction of the light passing through.
- This results in rapid fluctuations in the apparent brightnesses of stars (scintillation), and motions in the apparent positions or variations in the apparent sizes of stars (seeing).



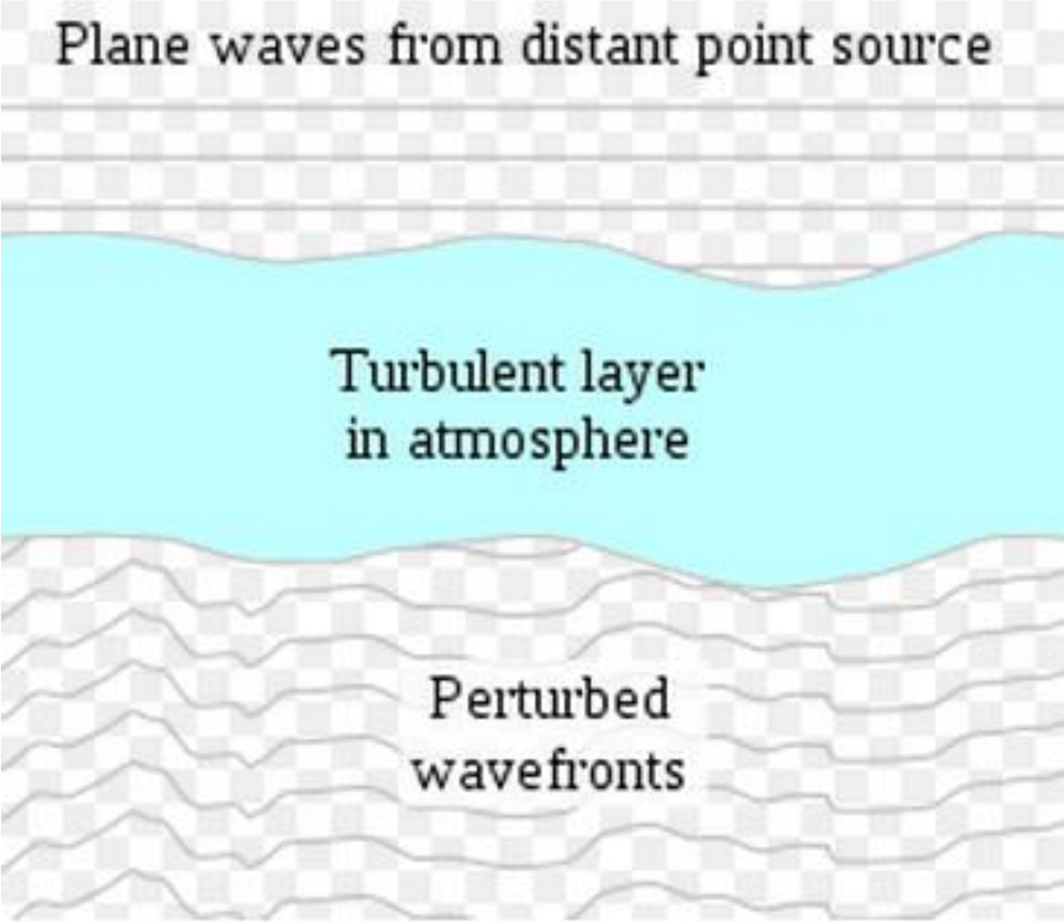


Distortion of the wavefront

- At optical and near infra-red wavelengths the spatial resolution is not set by the diffraction limit.
- Distortion of the wavefront by the atmosphere causes phase errors, therefore small errors in the direction that the light appears to come from.
- Turbulence combined with temperature gradients causes some pockets of the atmosphere to have different temperature and hence different refractive index.

Turbulence in atmosphere

How optical wavefronts from a distant star may be perturbed by a layer of turbulent mixing in the atmosphere.



Adaptive Optics

- In **Adaptive** Optics, mirrors are deformed to correct for distortions of the wavefront by the atmosphere.
- Not to be confused with Active Optics, in which the distortions corrected are those caused by mechanical or thermal deformation of the telescope.
- Adaptive optics corrections need to be calculated and applied at a frequency up to hundreds of Hz (c.f. ~ 1 Hz for active optics).

Kolmogorov theory

- The theory of atmospheric turbulence is due to the Russian physicist Kolmogorov.
- The turbulence above a telescope occurs at different scales and heights.
- It can be characterised with a single scale length parameter, usually called the Fried parameter, denoted by r_0.

Kolmogorov theory

- Fried’s coherence length r_0 is the distance over which the phase difference is one radian:

$$r_0 \approx 0.114\, \lambda^{6/5} \left(\frac{\cos z}{550^2}\right)^{0.6} \text{ m}$$

λ is the operating wavelength in nm
z is the zenith angle

- Fried’s parameter defines the maximum diameter of a telescope before it becomes seriously affected by atmospheric turbulence:
- In visual wavelengths, telescopes with a diameter >11.5 cm is always have their images degraded by turbulence.

The seeing disc

- Full Width Half Maximum (FWHM) of the point spread function due to atmospheric turbulence (the seeing) is given by:

$$\beta = 0.98\, \lambda / r_0 \quad \text{(radians)}$$

- This is quite close to the diffraction radius of a telescope of diameter $D=r_0$:

$$\vartheta \cong 1.22\, \lambda / D \text{ (radians)}$$

- For larger telescopes we need to use **adaptive optics**.

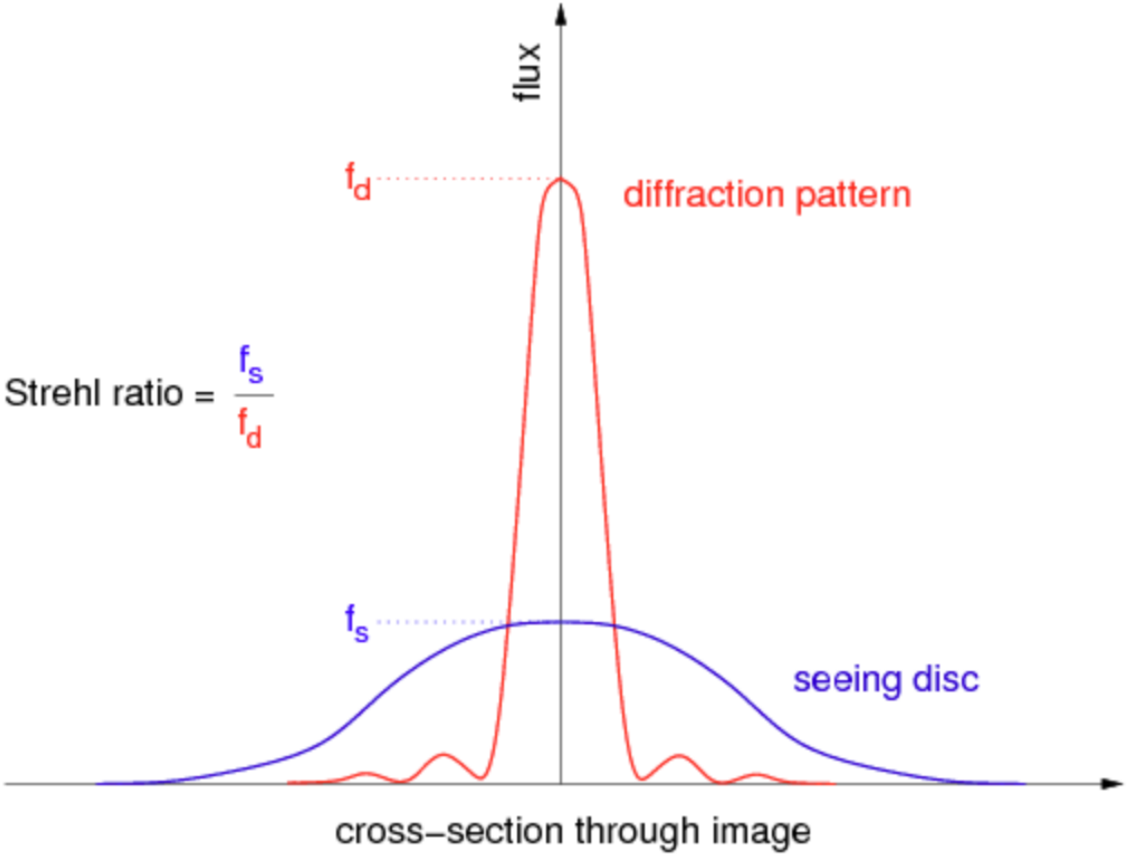
The Strehl Ratio

- Performance of an adaptive optics system is characterized by the **Strehl Ratio**, which is the ratio of the central intensity in the real point spread function, to that in the ideal point spread function for that telescope
  (i.e. the Airy or diffraction function).

- For a seeing limited telescope the Strehl ratio is given by:

$$S = (r_0/D)^2$$

D is the telescope diameter.



The seeing disc of a star superposed on the theoretical diffraction pattern (figure from Vik Dhillon’s lectures).

Adaptive Optics

- The aim of an adaptive optics system is to produce a Strehl ratio as close as possible to 1.
- The higher the Strehl ratio, the more the image is concentrated and hence the higher the spatial resolution.
- The Strehl ratio recorded by a telescope without adaptive optics is typically only a few per cent.
- In general, the higher the ratio of the telescope diameter D to r_0 the more difficult it is to correct the wavefront.
- If D/r_0 is not too high (2-5) then considerable improvement in the image quality can be obtained using a **tip-tilt** corrector.
  - This is the lowest order adaptive optics corrector, which is a flat mirror which can be tilted in two orthogonal planes, to keep the image centred.

Adaptive Optics

- Adaptive optics is more difficult at shorter wavelengths.
  - r_0 is dependent upon wavelength, in the sense that it is larger for longer wavelengths (slide 187):

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

  - The timescale on which the properties change is faster at shorter wavelengths.

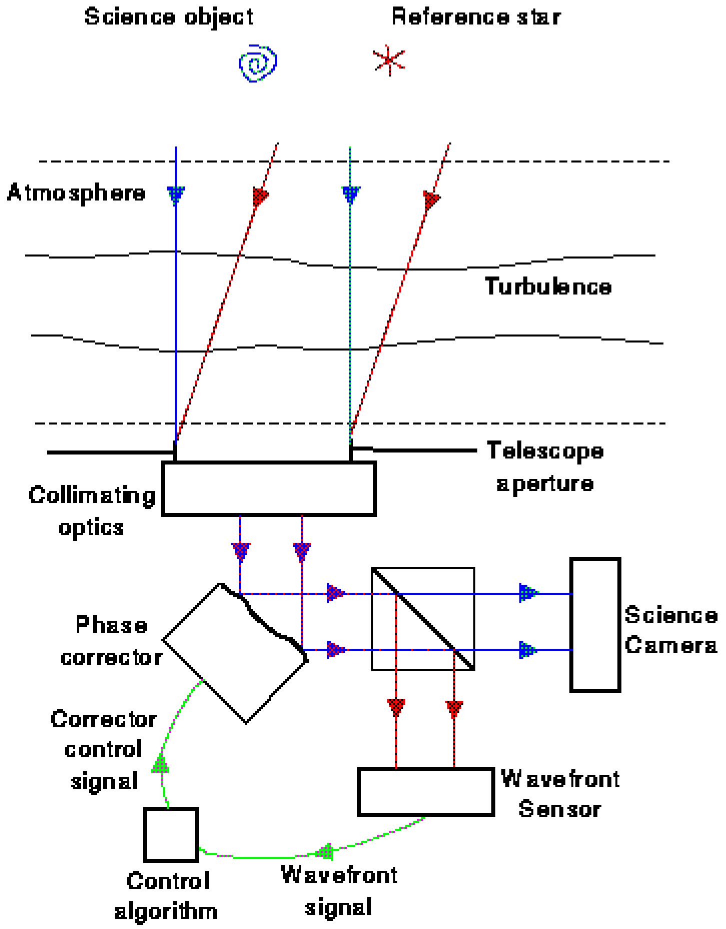
$$\tau_0 = 0.31\ r_0\ /\ \langle V \rangle$$

$\langle V \rangle$ is the altitude averaged wind velocity, typically 10 m/s.

- For this reason, most practical adaptive optics systems work in the near infra-red.

r_0 at 20000 Å is 5.9 times what it is at 5000 Å.

Practical Adaptive Optics system



- **Collimating optics** – to ensure phase correction is correct for all parts of the wavefront.
- **Phase corrector** – deformable mirror with a number of piezoelectric actuators.
- **Beam Splitter** – either dichroic filter (to reflect blue and transmit red) or a pickoff to send only the reference star to the wavefront sensor.
- **Wavefront sensor** – usually a fast frame transfer CCD to detect the wavefront from the reference star.
- **Control loop** – to calculate the phase corrections from the output of the wavefront sensor.
- **Science camera** – CCD or IR hybrid array.

The Isoplanatic Angle

- You can see from the diagram that the light from the reference star travels through the atmosphere at a slightly different angle to that from the science object.
- How far off does this have to be before the reference star does not any more sample the relevant path through the atmosphere?
- This depends upon a number of things including the height of the turbulent layer in the atmosphere.

$$\vartheta_0 \approx 0.31\, r_0 / \langle h \rangle$$

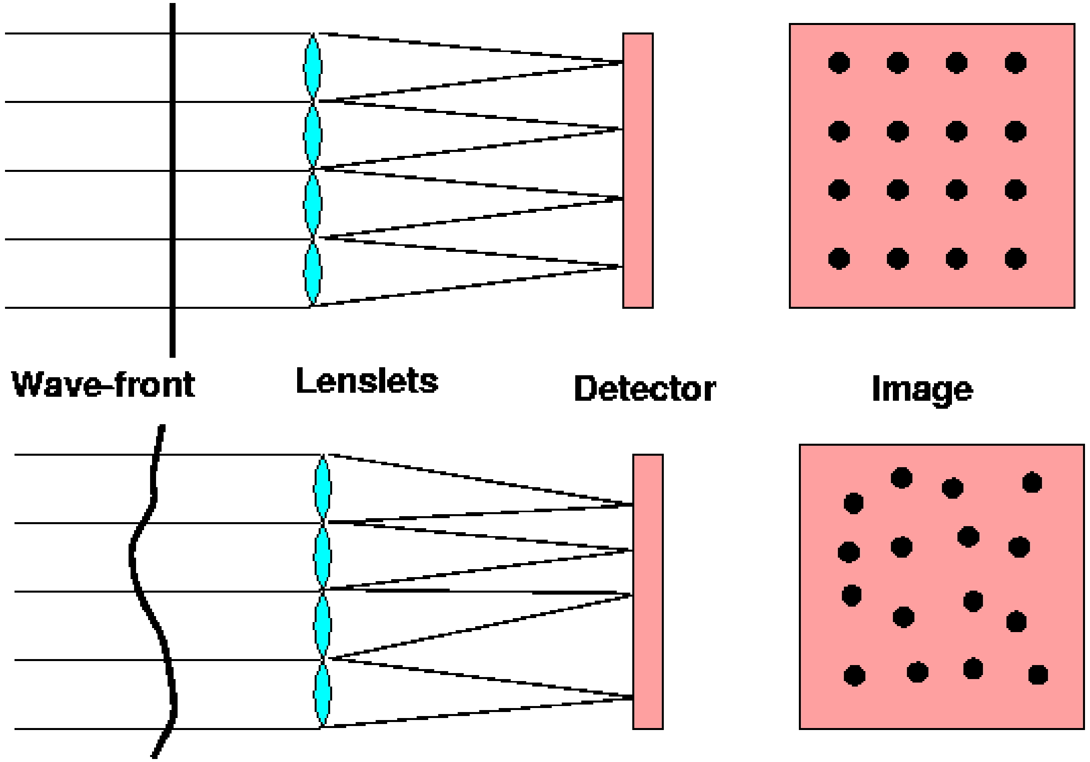
$\langle h \rangle$ is some average turbulence altitude. Typically $\langle h \rangle \approx 5$ km.
So, if $r_0 = 20$ cm, then $\vartheta_0 = 8.25$ arcseconds.

The field of view is very small! Again, much larger in the infrared.

Wavefront sensors

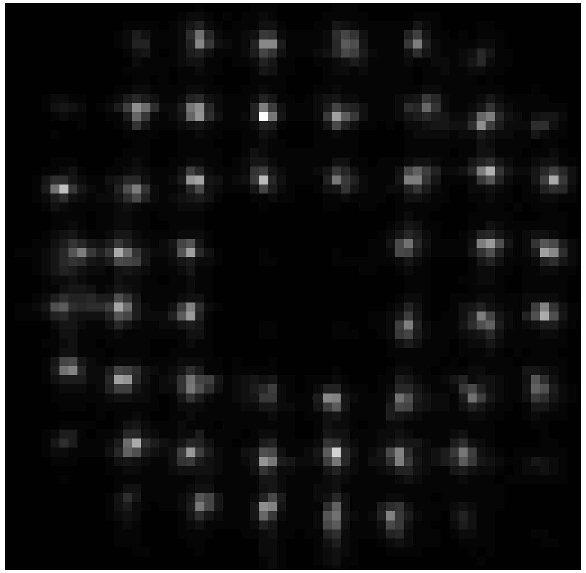
Simplest type is
a Shack-Hartmann wavefront sensor.

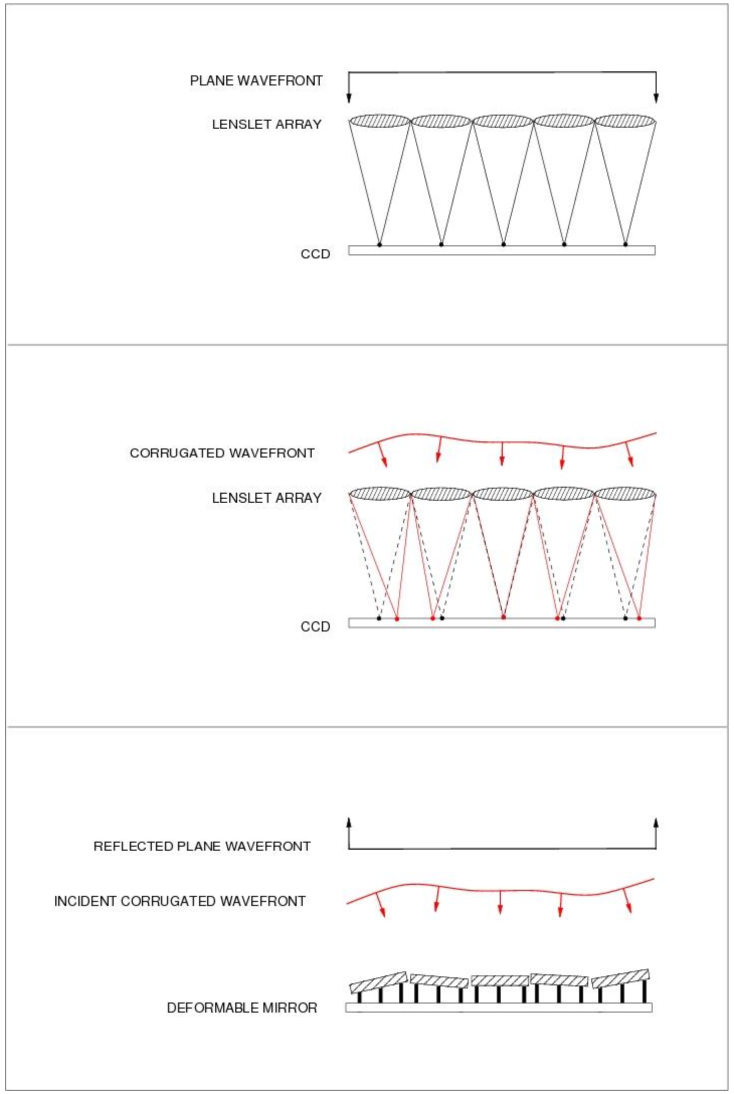
- ☐ Series of lenslets which each image part of the pupil plane onto a detector.
- ☐ Spots from the lenslets move around as the wavefront changes.



Shack-Hartmann Wavefront Sensor

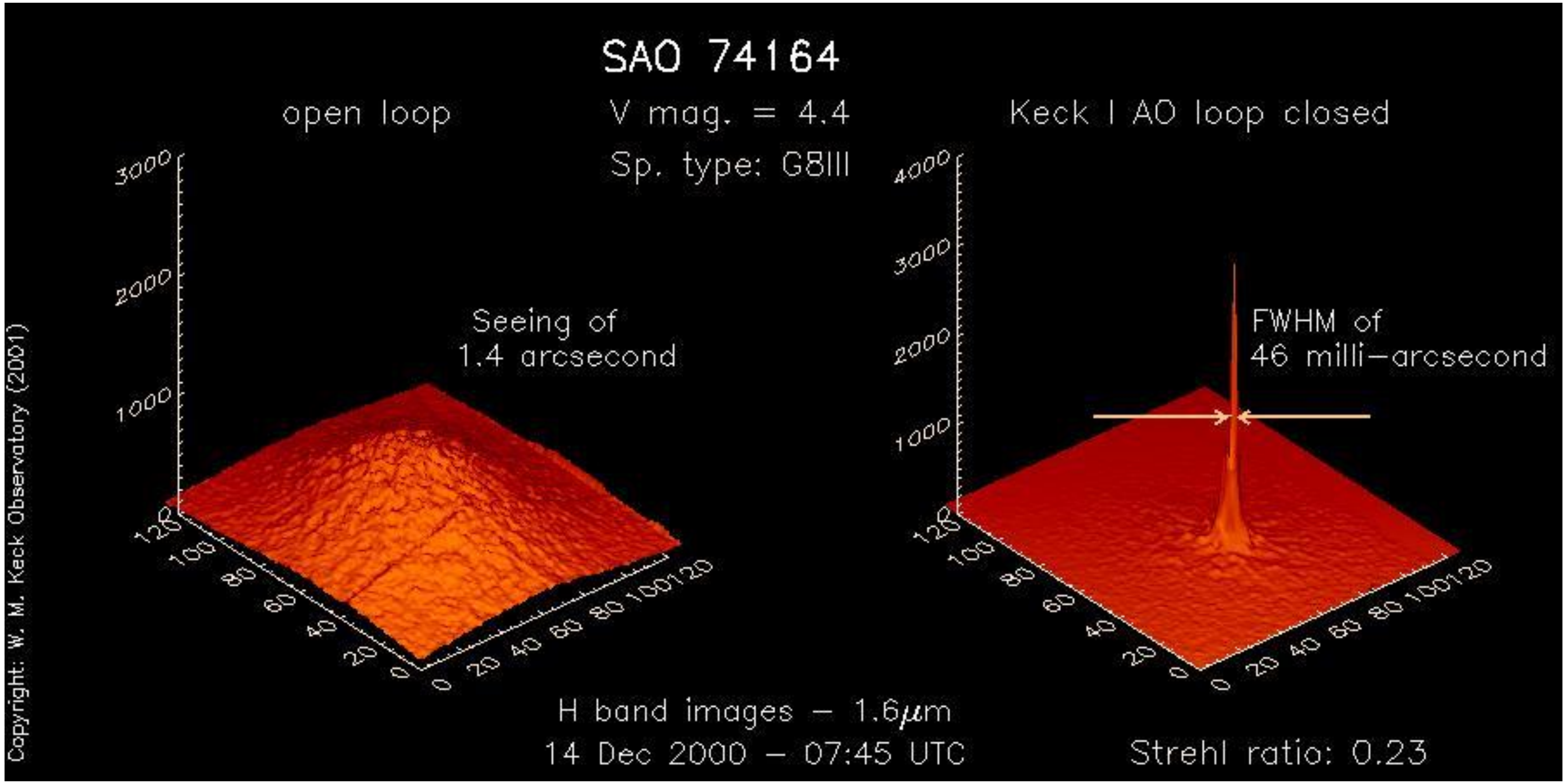
- Software detects the centroid of each spot.
- Then it models the wavefront distortions using a set of functions called Zernicke polynomials.
- Feedback to a membrane mirror to alter shape to correct the wavefront distortion.





Figures from Vik Dhillon's lectures.

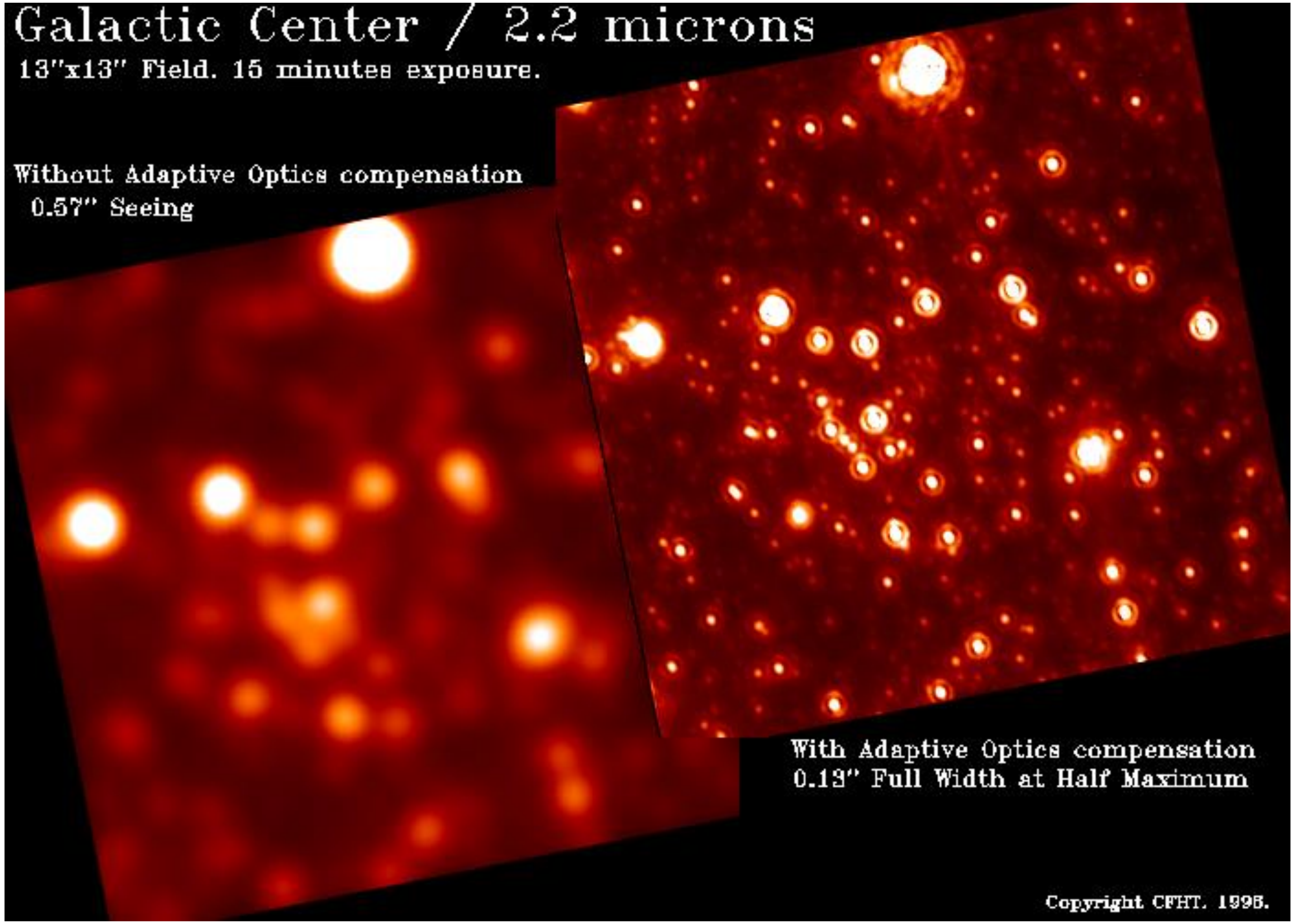
Effect of adaptive optics on a star image at the Keck telescope



This is cheating a bit because the star is its own guide star!

Effect of adaptive optics (real, not cheating)

Infrared image of the centre of our galaxy, without (left) and with (right) adaptive optics



Problems of adaptive optics

- You need a bright star as a guide star
- The wavefront is only corrected for objects near that star, within the isoplanatic angle.
- So, if there isn't a star near the objects you are interested in, why not put one there?

Laser guide stars

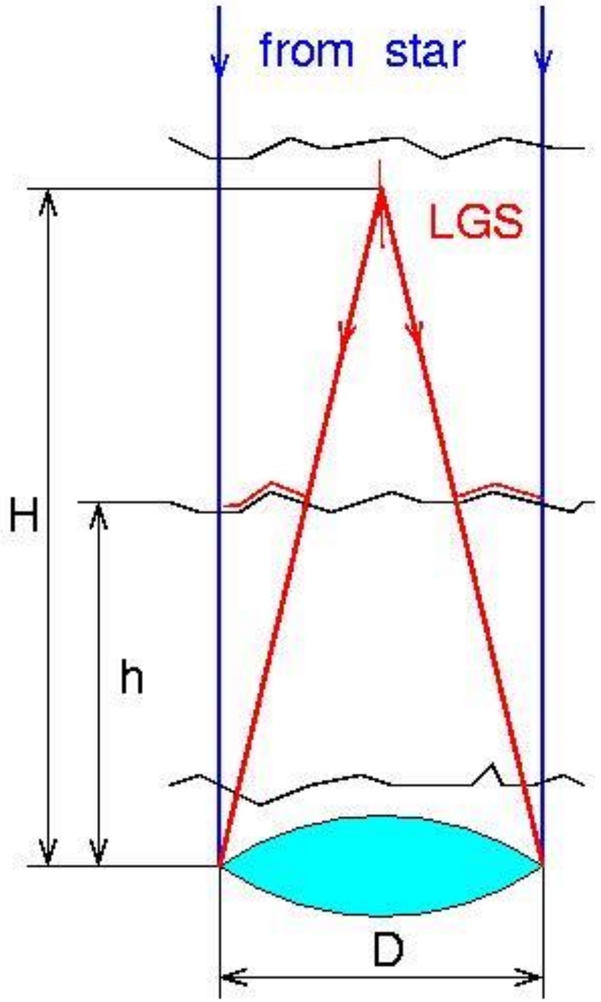
- Two types of laser used to create artificial guide stars:
  - Sodium lasers – Sodium layer at about 90 km altitude is produced from micrometeorites. This can be excited by a laser beam tuned to one of the D lines (usually D2 at 5890Å).
  - Rayleigh Scattering Lasers – light from the laser is back scattered by air density fluctuations. The laser beam is focused at an altitude of ~20 km, in addition the beam is pulsed and the return is gated with a fast shutter, so that the altitude is defined by the light travel time to and from the layer.

Rayleigh Scattering lasers

- Rayleigh scattering is more efficient in blue and ultraviolet wavelengths (hence the sky is blue). The return beam is therefore bluer than the outgoing beam.
- There is a tradeoff between the rate of the pulses and the altitude that the laser is gated to. If the altitude is 20 km, then the light travel time there and back is $(4 \times 10^4) / (3 \times 10^8)$ seconds, and the laser guide star cannot be used for atmospheric fluctuations faster than this.

The cone effect

- The Laser Guide Stars are not at infinite altitude, and therefore the light from the guide star does not pass through the same atmosphere as the beam from the astronomical target.
- The beam from the star suffers different wavefront distortions to the beam from the laser guide star.
- This problem is worse for lower altitudes and for larger telescopes.



The cone effect

- The maximum size of telescope that can be used with a laser guide star at altitude H is given by:

$$d_0 \approx 2.9\ \theta_0\ H$$

where ϑ_0 is the isoplanatic angle.

- For realistic values of the isoplanatic angle at optical wavelengths, d_0 is about 1 metre for Rayleigh scattering lasers (gated at 20 km altitude) and 4-8 metres for a sodium laser.

The tilt problem and its solution

- The laser beam passes through the atmosphere twice, once on the way up and once on the way down.
- The lowest order terms in the wavefront correction, called Tip and Tilt, cancel out and measurement of the Laser Guide Star does not sense them.
- Use a natural guide star for tip and tilt only. You can do this in the infrared as the isoplanatic angle is larger.
- Use a polychromatic Laser Guide Star. Sodium can be excited to higher levels to emit other lines (in the ultraviolet and infrared). Using the wavefronts at more than one wavelength the atmospheric tilt can be calculated.

Practical problems of laser guide stars

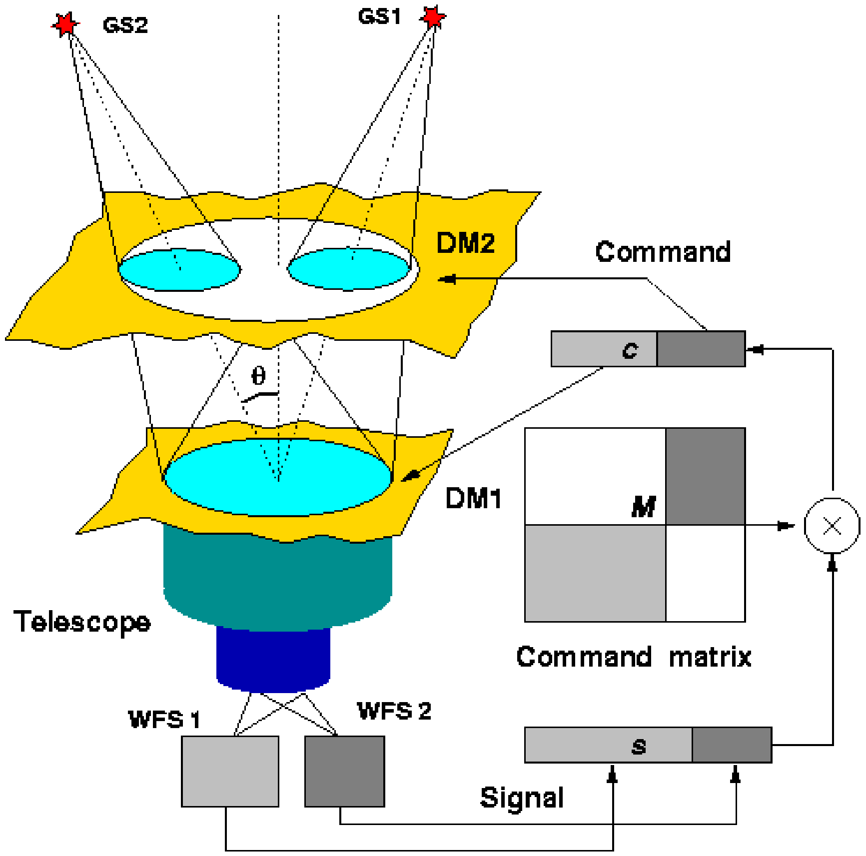
- Sodium lasers are expensive and unreliable.
- Require high power consumption.
- Can make yourself very unpopular with other telescopes on the mountain looking in the same direction.
- Want to be very sure you have no planes flying overhead as you can blind a pilot.

Sodium (left) and Rayleigh (right) laser guide stars in action.

Multi Conjugate Adaptive Optics

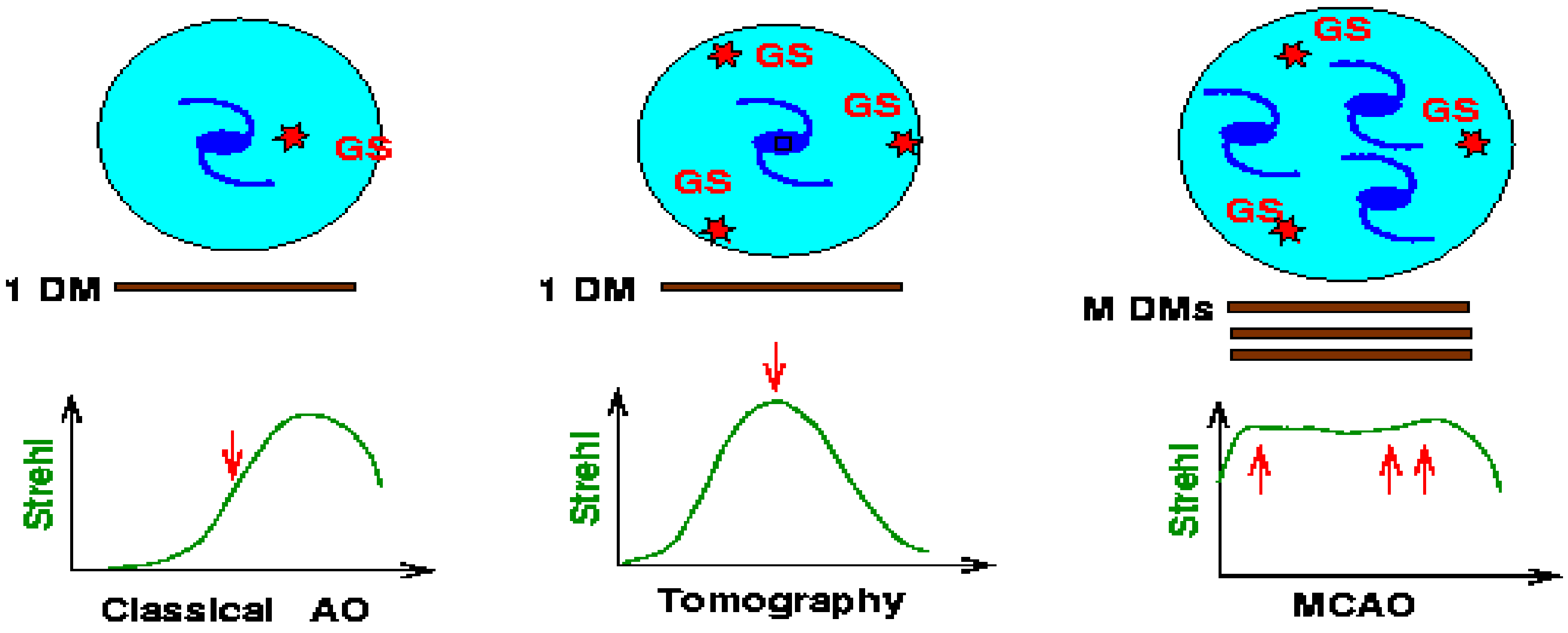
- With only one guide star, we can only model a height averaged wavefront distortions.
- With more guide stars, we can begin to make a three dimensional model of the turbulence, and correct the turbulence in different layers.
- This also helps correct the cone effect, as you can now model each layer and know which part of that layer a particular beam passes through.
- In Turbulence Tomography you use a number of guide stars to model the 3 dimensional turbulence and work out better what to do with your deformable mirror.
- In Multi Conjugate Adaptive Optics you have a number of deformable mirrors which correct the distortions for a number of turbulent layers.

Multi Conjugate Adaptive Optics



- MCAO with 2 laser guide stars and 2 deformable mirrors. In the high layer the light from each LGS passes through a different parft of the atmospheric layer.

Tomography and MCAO



Horizontal axis is across the image in each case, vertical axis is Strehl ratio.

Tomography and MCAO

- In classical AO your correction is strictly valid for the position of your guide star, and is less valid for your objects
- In tomography, you use a three dimensional model to make the right corrections for the object you are interested in.
- In MCAO you have many deformable mirrors, and your corrections are valid over a much wider field.
- MCAO greatly increases the isoplanatic angle.