AGA0414
High Angular Resolution

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Why high angular resolution

Our goal is always to reach the highest resolution possible. This is to separate objects which would be otherwise resolved (binary stars or accretion discs) or separate components of an astrophysical object (separate the AGN from its host galaxy).

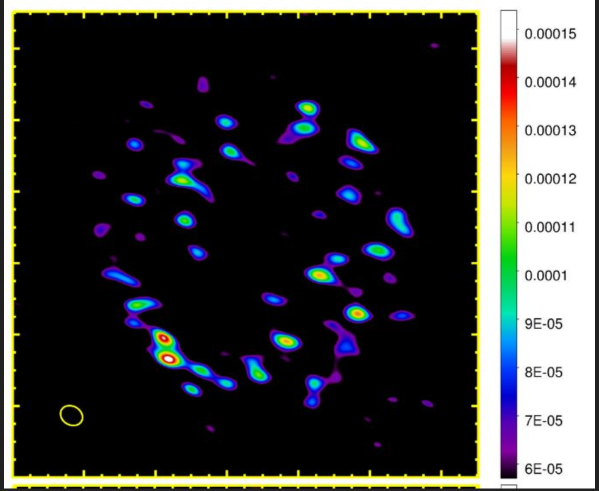
As we will see, this can be difficult and our main limiting factors are optics and the Earth's atmosphere.

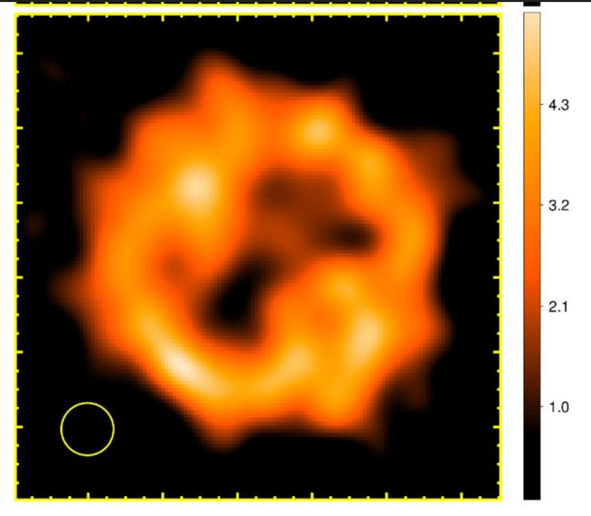
Example: Diaz et al. (2019)

[Observations of a nova ejecta with ALMA.]

Used radio interferometry to get high angular resolution of the ejecta (top).

A convolution (bottom) shows how the same physical structure would look in Hα through HST. Most of the clumps get lost and the image look much smoother.

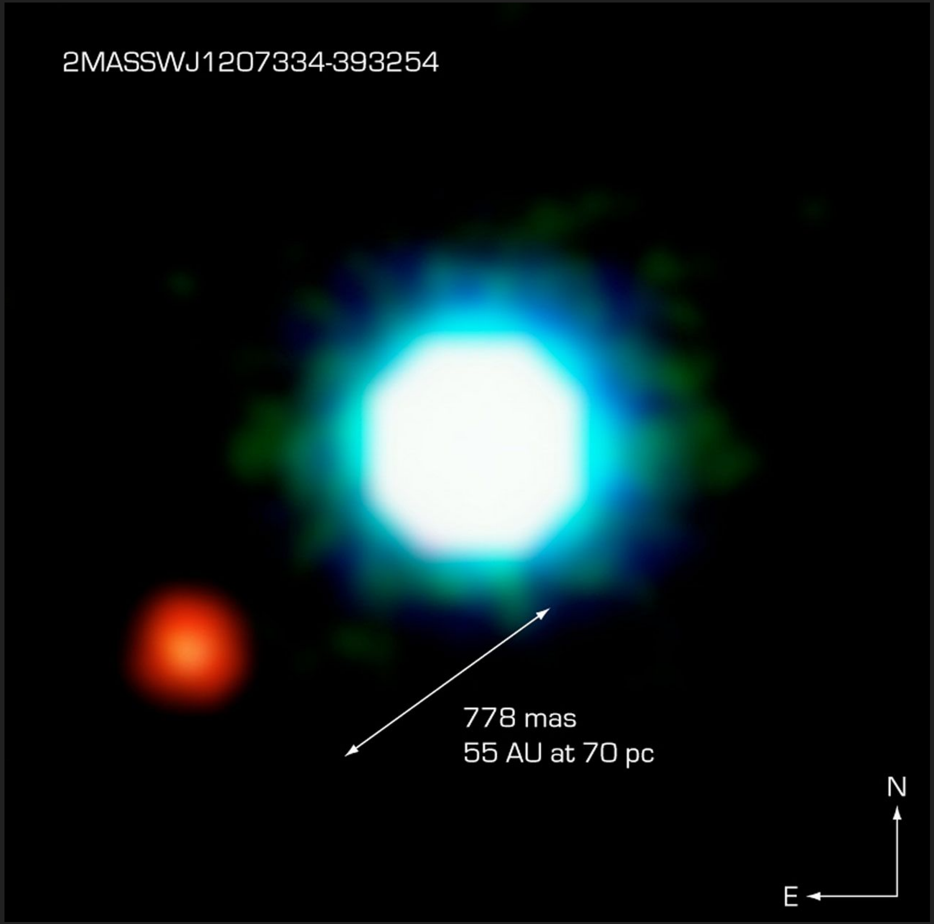




Exoplanet or Brown Dwarf

This image, obtained with the NAOS/CONICA (NACO) on VLT, was an icon of the search for planets.

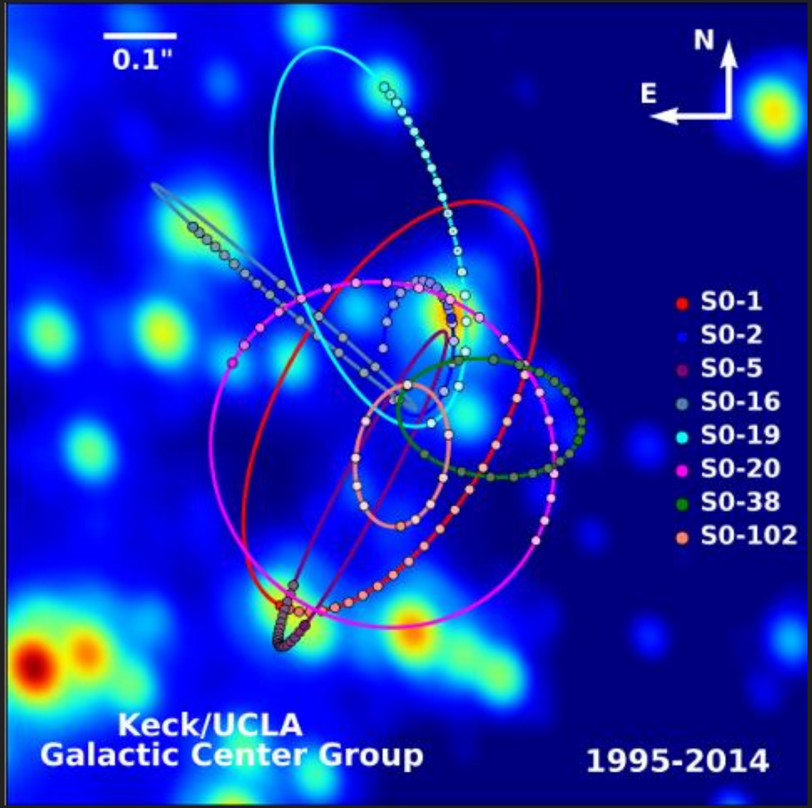
This allows the depth achievable with an 8m class telescope at the same time as its spatial resolution.



Stars orbiting Sgr A*

UCLA and the MPE have devoted a significant effort to the study of Sgr A* and much of their instrumentation development has been guided by this (e.g. MPE’s work on VLT/NaCo, VLT/SINFONI, VLTI/GRAVITY)

I very much like this video.



How do we do high angular resolution?

Play with optics:

Since the Airy criteria is 1.22 λ/r your resolution will be higher when the Airy ring will be smaller: shorter wavelengths or larger apertures

“Get rid” of the atmosphere:

- If you go out of the atmosphere (i.e. you go to space), your optics will reach diffraction limit 1.22 λ/r
- If you are on the ground, there are techniques that allow you to “freeze” the atmosphere or, pretend, that the atmosphere is not troubling you

Getting rid of the atmosphere

“Eppur si muove”

The main deal of the atmosphere is that it moves. The classical example is to watch an object at the bottom of a swimming pool.

In our case, you are at the bottom of a pool and you are trying to see something which is outside. The air, optically, acts like the water in this example.

If one could “freeze” the air, the light path would not change over time and the wavefront would always be deformed by the same amount.

The Fried Parameter

The scale length over which we can assume that the atmosphere is not affecting our images is called the “Fried Parameter” (or Fried Length Scale) and it is usually denoted with r_0 .

The coherence time scale is the Fried Parameter divided by the wind speed.

Typical numbers for these parameters are 10-20cm and a few hundredths of seconds, respectively.

r_0 goes as $\lambda^{6/5}$ which tells you that it is larger in the NIR than in the optical

Lucky Imaging

Considered the “Poor Men’s Adaptive Optics”.

You take thousands of images with very short exposure times (less than a coherence time). Over a short exposure time, there is a chance that the atmosphere **may** not vary.

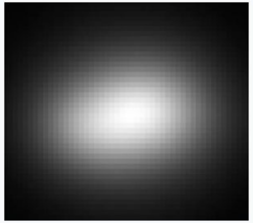
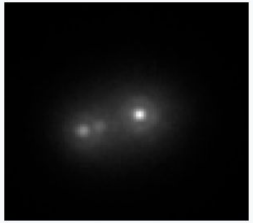
You only save a small percentage (normally less than 1%) of the best images and that can give you a diffraction limited image.

PROs: you only need a fast readout CCD, lots of storage and a good computer for processing.

CONs: you can only observe bright objects and it makes it hard to observe extended ones

Here is an example of how to use Lucky Imaging to resolve a multiple stellar system.

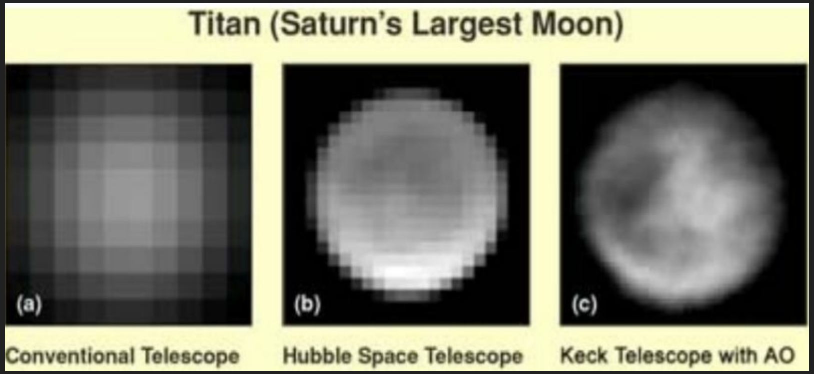
Image from https://en.wikipedia.org/wiki/Lucky_imaging

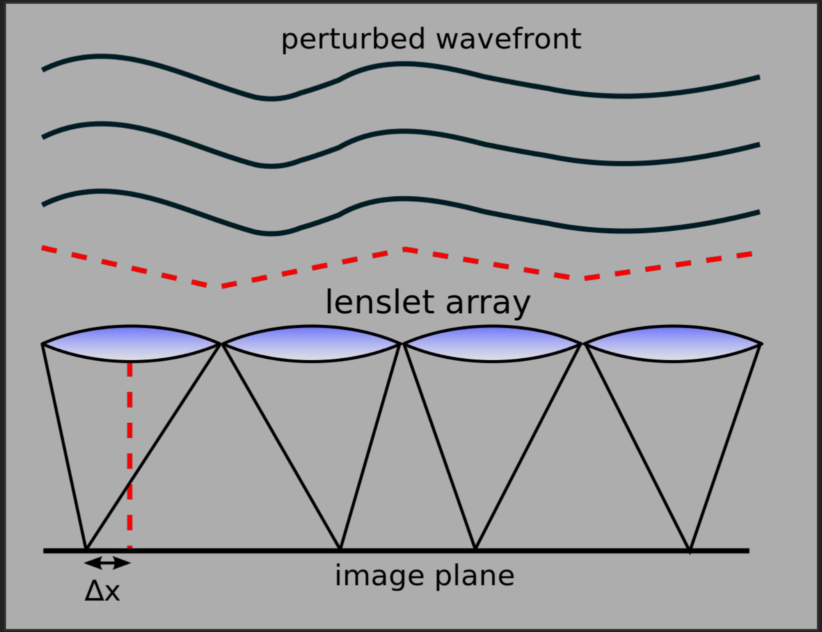
	Single exposure with low image quality, not selected for lucky imaging.
	This image shows the average of all 50,000 images, which is almost the same as the 21 minutes (50,000/40 seconds) long exposure seeing limited image. It looks like a typical star image, slightly elongated. The full width at half maximum (FWHM) of the seeing disk is around 0.9 arcsec.
	This image shows the 25,000 (50% selection) best images averaged, after the brightest pixel in each image was moved to the same reference position. In this image, we can almost see three objects.
	This image shows the 500 (1% selection) best images averaged, after the brightest pixel in each image was moved to the same reference position. The seeing halo is further reduced. The signal-to-noise ratio of the brightest object is the highest in this image.

Adaptive Optics

This technique aims at correcting the deformation of the wavefront due to the atmosphere.

There are various “declinations” of AO but here we only cover the general aspects of this technique.





Active vs. Adaptive Optics

Active optics

Adjust the optics to compensate its deformation under gravity and temperature.

It is done every few minutes or even hours. Sometimes every few seconds. In any case, on time scales larger than the coherence time scale.

Normally, it is done by deformation of the primary or by adjustment (not deformation) of the secondary.

Adaptive optics

Correct for the distortion of the wavefront due to the turbulence of the atmosphere.

It is done on time scales shorter than the coherence time.

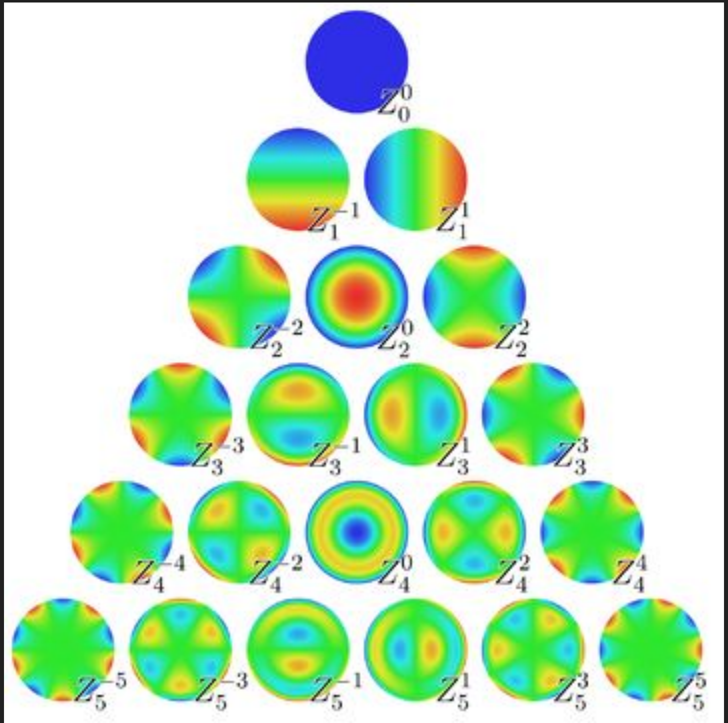
Normally it is done with a specific optical system in the exit pupil. Some new devices (e.g. VLT "Adaptive Optics Facility") use an "adaptive secondary" (i.e. the secondary is the deformable mirror).

The Zernicke coefficients

This is a mathematical base to describe a function in a circular aperture.

The first one are piston, then tip, tilt, then focus, astigmatism, coma, spherical aberration, and so on.

Piston can normally be neglected.



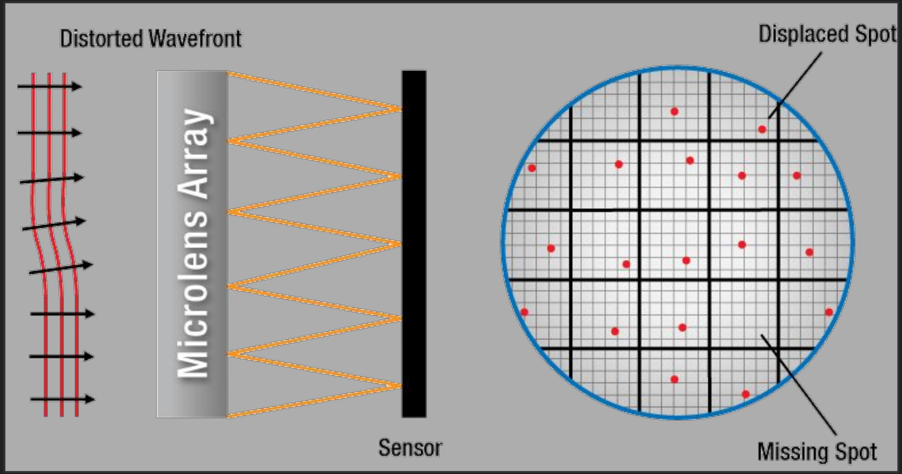
Tip-tilt

Tip and tilt carry most of the distortion of the wavefront. They represent the "inclination" of the wavefront, if you like.

Typically you use a bright star and a flat mirror to compensate for this effect.

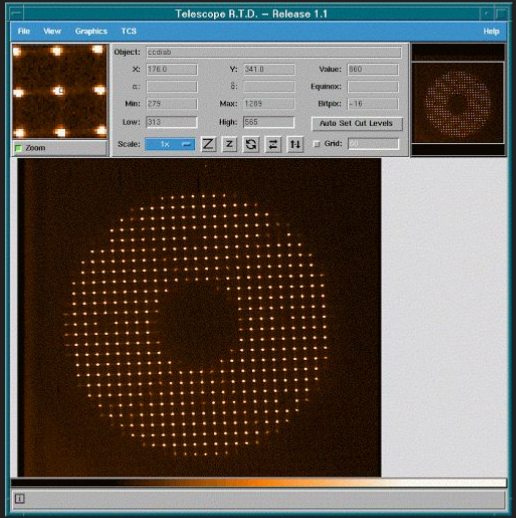
The main effect of tip-tilt is the displacement the image in the focal plane.

The Shack-Hartmann WFS



This is one very common type of wave front sensor (WFS).

An array of lenslets focusses the pupil on a detector. Before we start observing, we obtain a reference image with the optics in perfect shape. While observing, we want the pupil to be imaged exactly as in our calibration.



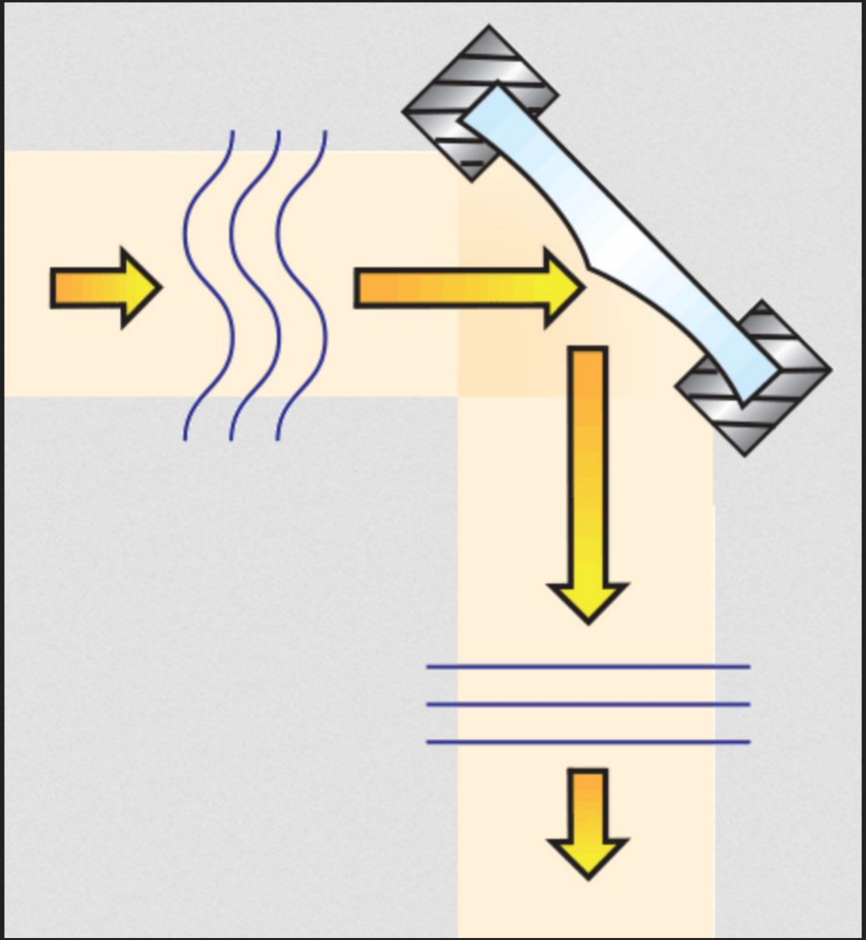
Bottom: SH of the NTT; that is the image of the pupil through the SH WFS.

The deformable mirror

The analysis of the WFS provides the deformation of the wavefront. If I have a deformable mirror in the parallel beam, I can use it to compensate for the defromation.

In figure, from [here](), distorted WF is flattened by the deformable mirror.

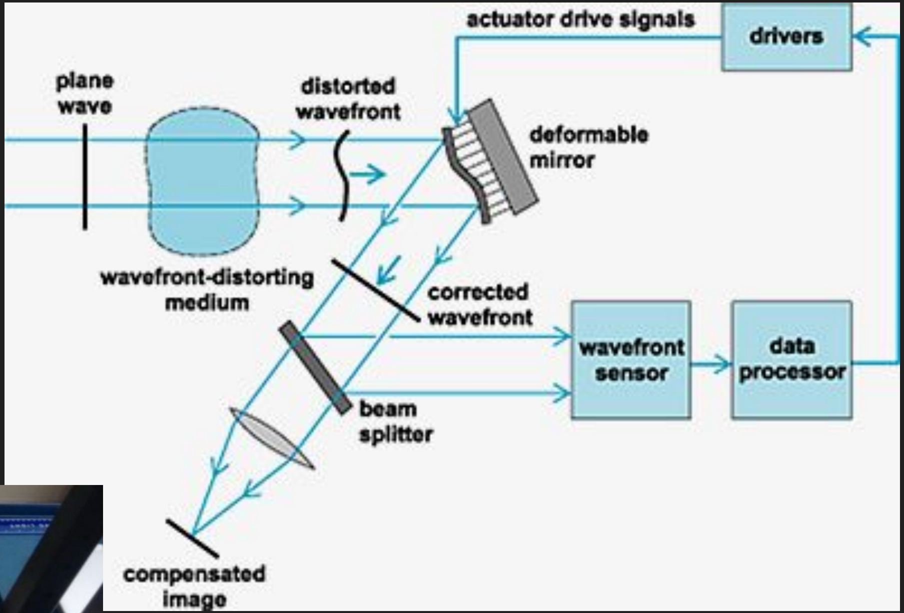
Each compensation must be done on time scale shorter than the coherence time scale.

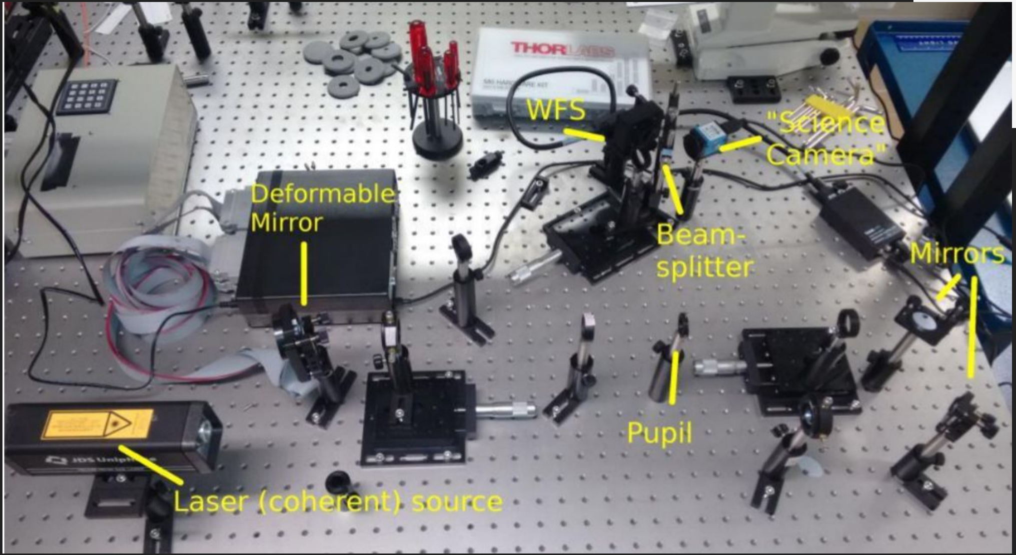


SAMPlus

If we were at IAG, we would be able to see a real AO system in development.

This is the SAMPlus project.





Laser guide star(s)

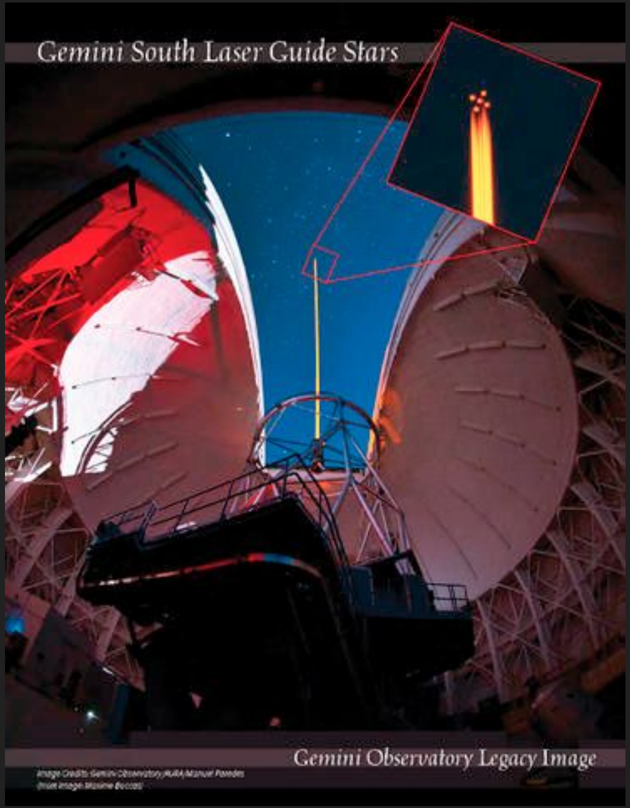
Originally, the light to be used as a reference was coming from a star. In some cases, the science target is the reference itself!

This is not always possible though. In order to increase the sky positions where AO can be used, we can shoot a laser, which excites a layer of sodium in the upper atmosphere and use that “artificial star” as reference.

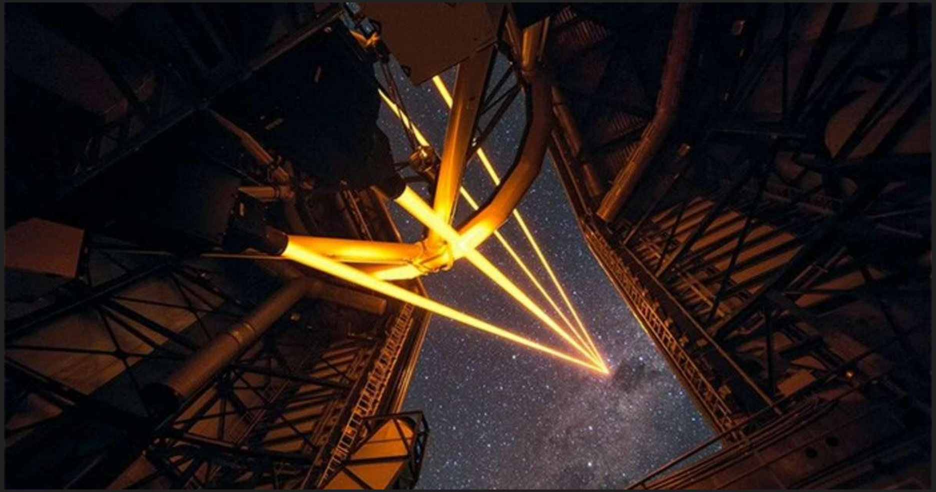
Gemini South was the [first] to be able to shoot a constellation of (four) stars.

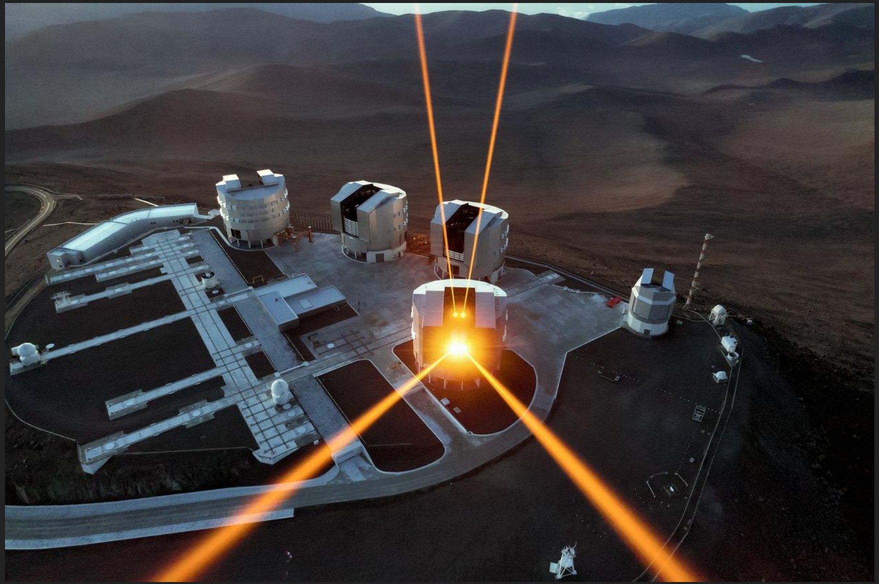
VLT’s UT4 is now routinely operating with a constellation of lasers.

This is how the 30m class telescopes will operate (all but GMT which is the only one which has been designed to be able to operate with natural seeing).



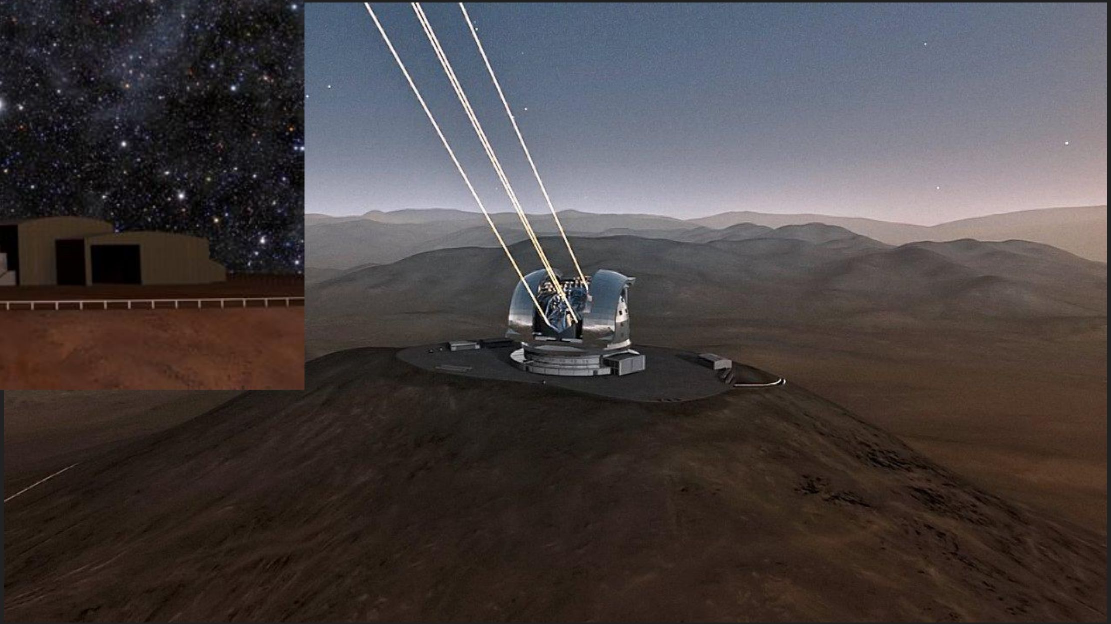
UT4 “deploying” the laser





Rendering of GMT and ELT

<irony> note that ELT is so good it can shine the lasers during daytime. </irony>



I figured that some concepts of interferometry are in common with radio, so I will cover optical/NIR interferometry together with radio.