Telescopes – II. Domes and Mirrors

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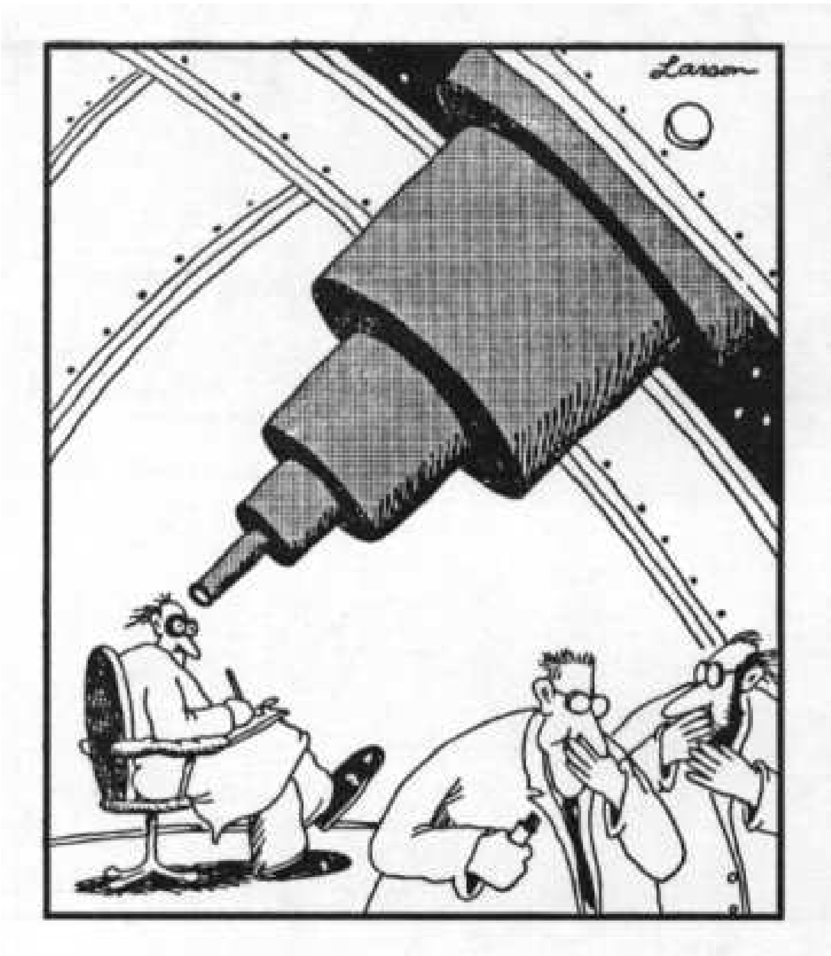

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1 The Telescope Environment

1.1 Telescope sites

Most ground-based optical telescopes – certainly all large instruments – are situated on mountain tops, because:

- these sites tend to have the best "weather". Peaks such as Mauna Kea (in Hawaii) at 4200m altitude are well above the local atmospheric inversion layer and thus often above local cloud;
- they are above a significant fraction of the atmosphere (in the case of Mauna Kea about 40%) so they are above much of the atmospheric dust and aerosols and tend to have very good atmospheric transparency;
- they are usually well above and away from industrial pollution and well away from light pollution (an increasing problem) - see figures 2 & 3 and look at *www.darksky.org/images/sat.html* for high-resolution Earth images.;
- they tend to have high atmospheric stability so that "seeing" is usually very good;
- and they are above most of the atmospheric water vapour – very important for infra-red work.

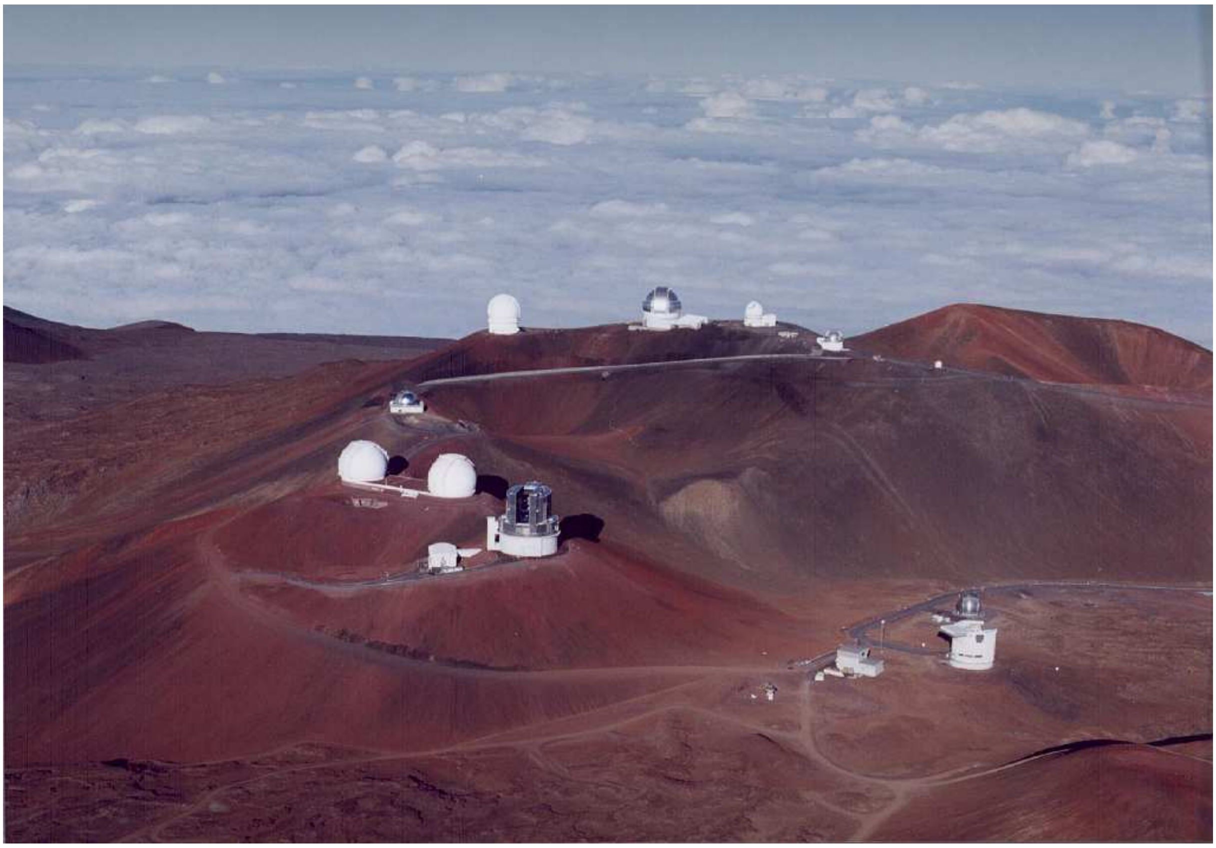

Figure 1: Summit of Mauna Kea, Hawaii. Note the distant cloud is *below* the mountain top.

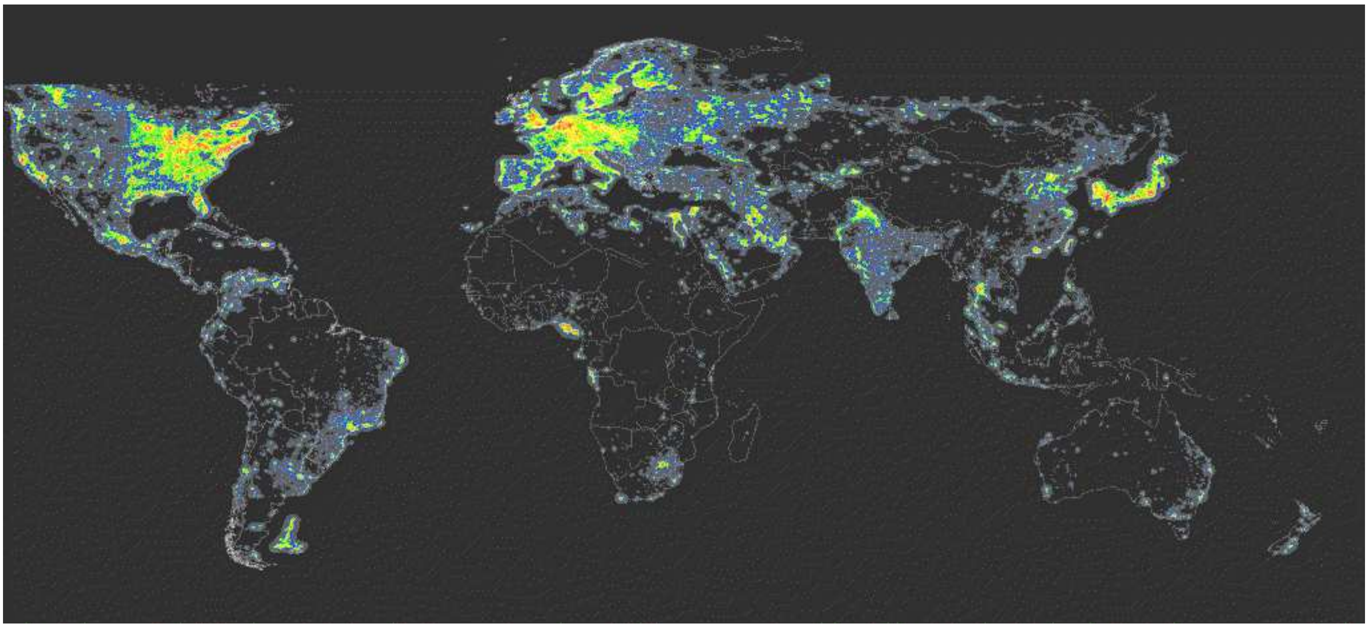

Figure 2: Map of sky brightness of the night-time Earth.

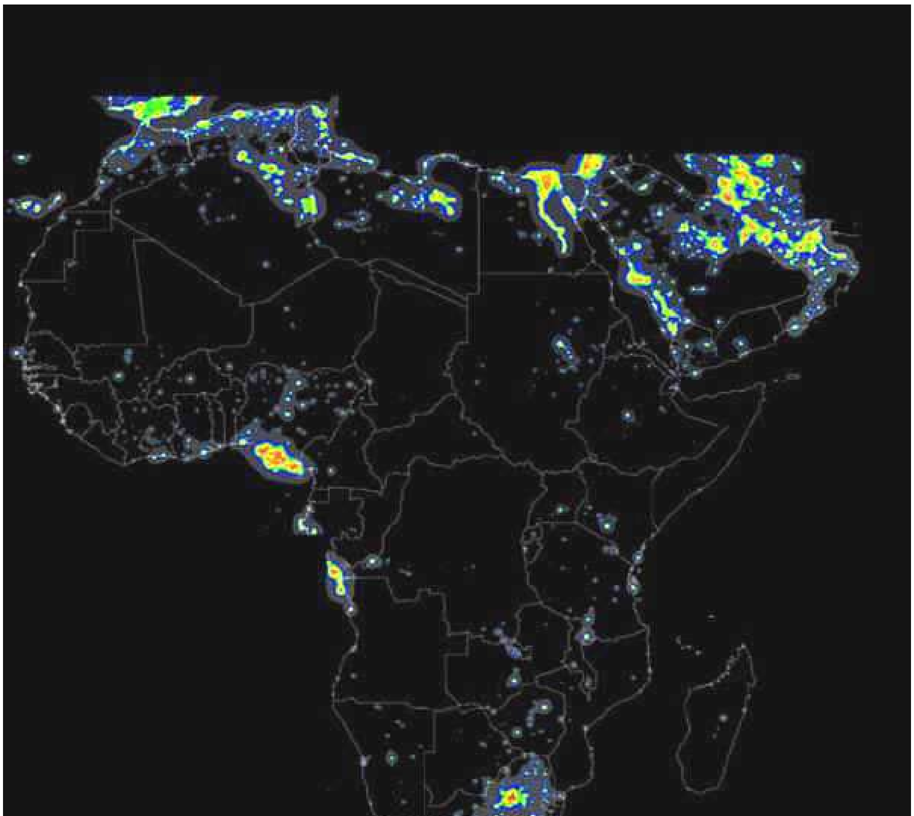

Figure 3: Map of sky brightness of night-time Africa.

1.2 Telescope enclosures (buildings & domes)

The design of enclosures (buildings and domes) for telescopes is important – and becomes increasingly important as telescopes get bigger. Such design involves the balancing of often conflicting requirements of optical, thermal, mechanical and structural engineering – and, of course, special requirements usually mean increased cost.

The Earth's atmosphere has a significant effect on image quality (scintillation and "seeing") but it is also the case that image quality can be affected by **dome seeing** and **mirror seeing**– the combined effects of perhaps many features of the building, dome and telescope itself.

1.2.1 Dome and mirror seeing

There are many features which might contribute to dome/mirror seeing (or "facility seeing"), mainly due to warm air from inside the dome mixing with colder outside air, usually in the dome aperture. For example:

- **Dome shape** can have a significant effect on seeing. Conventional domes are hemispherical because this shape encloses the maximum volume for the minimum surface area – which means the minimum material in the dome – and usually means minimum weight and cost. However, a hemisphere is not necessarily the best shape for minimising air turbulence – a cylinder would be better.
- **Dome shutters** often slide sideways leaving large surface areas exposed to wind and creating turbulence (and risking damage in high wind conditions). A shutter which slides over the top or sideways but remains essentially flush with the done would be preferable.
- **Heat sources** in the dome are almost unavoidable – motors are needed to move and track the telescope, for example, yet motors will produce heat "plumes" which degrade seeing.
- **The building and dome** act as a thermal trap, heating up during the day, especially in direct sunlight. At night, the interior heat will cause convection currents when the dome is opened.
- **The telescope and mirror** will also heat up during the day. The mirror, in particular, might be a substantially thick piece of glass with large heat capacity and poor conductivity, so convective plumes can last for hours.

1.2.2 Corrective measures

Many observatories have made extensive studies of dome seeing, particularly when constructing large telescopes. Because domes and buildings are often quite individualistic, it is becoming common to find telescopes in which air temperature and humidity are monitored inside and outside the dome. Temperature in particular might be monitored in many places – at various places inside the dome and on the telescope structure and mirror and its supports. (Temperature changes in the telescope structure will affect focus position as well as seeing).

A number of corrective measures have been used, for example:

- **Having no enclosure** – or an enclosure which folds away – leaving the telescope exposed to the elements. This is generally not so satisfactory as the telescope can suffer from wind "shake" and also, on larger telescopes, variable loading on the mirror and telescope structure which will affect image quality (though these can be countered with **adaptive optics**. For large telescopes, it is important to investigate the resonant frequencies of the structure – these are generally of lower frequency for bigger structures – which are therefore more susceptible to wind induced vibrations.

- At Sutherland, we have reduced building heating by **minimising artificial heating** inside the dome and **"cladding"** the dome with an outer layer which reduces solar heating of the building. These are only partial solutions.

Figure 4: Sutherland domes showing the "venetian blind" cladding.

- **Telescopes are often elevated** to raise the primary mirror above the layer of turbulent air that arises from wind shear – wind contact with the ground.
- **Many telescope domes are painted white** to reflect sunlight and emit in the infra-red to reduce daytime heating. This can backfire if the white surface emits too efficiently at night – cold plumes of air can fall into the dome.
- Modern large (and not so large) telescopes often have **air cooling** to keep the air inside the dome at a temperature close to what is expected for the outside air at the start of the night.
- During the night, strong **forced ventilation** – or channelling and controlling the **wind flow** through the dome by "louvres" (Venetian-blind like structures) in the dome wall – can be used to reduce convection plumes within the building and on the mirror.
- As well as wind flow through the dome, some observatories have mounted **powerful fans** on the telescope structure to blow air directly across the **mirror surface** to reduce mirror seeing.
- The most modern large telescopes have **"active" optics** – control of the shape of the primary mirror using feedback systems – to try to adjust for some of the temperature, flexure and vibrational variations. Some also have **"adaptive" optics** to correct for the effects of atmospheric seeing. We shall look at these later.

The SALT enclosure will use massive air cooling systems to control the air temperature inside the dome. In addition, all the heat sources inside the dome will be cooled – a large tank (the "swimming pool") contains $\sim$ 50 000 litres of coolant which will be used to cool motors, electronics and so on. Both SALT and the Japanese Infra-red Facility at Sutherland have extensive louvres in the walls. These can be opened to various extents to adjust the night-time air flow through the dome, so that cooling can be achieved whilst wind shake or vibration is minimised.

Figure 5: Air flow vents on the Cerro Tololo Interamerican Observatory (CTIO) 0.9m telescope.

Figure 6: Air flow vents on the CTIO 4m telescope.

Figure 7: Close up of air flow vents on the CTIO 4m telescope.

Figure 8: The Gemini (South) telescope showing the large vents opened. Note the much greater area of these designed vents compared to the “modification” fittings on the other CTIO telescopes.

2 Mirror Coating

We have looked at different telescope configurations – the arrangement of mirrors in the optical system. But it is necessary to pay some attention to the reflecting surfaces themselves. Consider the Nasmyth focus – this has three mirrors (before any additional reflecting surfaces in the instrumentation). If each mirror has a reflectivity of 95%, the three mirrors together will have $(0.95)^3 = 86\%$. If each mirror has a reflectivity of only 85%, the total is $(0.85)^3 = 61\%$ and you are losing close to half the light entering the telescope.

There have been (so far) three main "eras" of reflection technology:

- $\sim$ 1670 – 1860: Speculum metal mirrors. This Copper-Tin alloy was basically hammered into shape and then polished for shape and reflectivity. Speculum would only give about 65% reflectivity which decreased as the surface tarnished.
- $\sim$ 1860 – 1930: Chemical deposition of silver on glass. Silver is much more reflective (>90%) than speculum but tarnishes fairly quickly.
- $\sim$ 1930 – present: Vacuum deposition of aluminium (and other metals).

For some years there has been experimentation with dielectric coatings for glass mirrors, as well as using (vacuum deposited) silver with a transparent overcoating to prevent tarnishing, and a number of other possibilities. Currently vacuum deposition of aluminium is very widespread, but this could change in the next few years.

2.1 Chemical Silvering

First applied by Foucault (1857) to the coating of telescope mirrors, chemical deposition of a silver layer can be done quite successfully to a thickness of about 0.1 μm or about 100 nm ($\sim$ 0.2 of the wavelength of visible light). But there are a number of disadvantages to this process:

- The deposited layer is often uneven - in the case of a very accurately figured mirror surface, this would effectively degrade the figure.
- Silver tarnishes rapidly which substantially reduces the reflectivity.
- The tarnishing means that the mirror requires polishing frequently which produces many microscopic scratches which then scatter light and reduce image quality.

2.2 Vacuum aluminising

Vacuum deposition of aluminium on to glass mirrors was largely developed by John Strong (Publ. Astr. Soc. Pacific Vol. 46, p18, 1934).

In this process, small "riders" of aluminium are melted on to tungsten filaments in a vacuum tank. With the mirror in the tank, the pressure has to be down to around 10^{-5} mm of mercury (torr) or $\sim$ 1 to 0.1 pascals. In this case, the mean free path of molecules is comparable to the size of the vacuum tank, then the aluminium atoms are "evaporated" directly on to the mirror. Again, a layer of about 60 – 120 nm ($\sim$ 0.1 μm) can be easily produced.

Generally, the old aluminium coat is removed with a weak (5%) caustic soda (NaOH) solution and then the mirror is very carefully washed with water and then distilled water and dried. It is important to get a clean dry surface (and also to avoid scratching the optical surface).

Although the procedure requires (often expensive) vacuum technology and equipment, these are standard in modern observatories. The aluminium layer has the advantages that

- The vacuum-deposited aluminium layer gives almost perfect reproduction of the mirror surface – there is no degrading of the figure.
- The aluminium is very "weather" resistant, due to a very thin layer of transparent aluminium oxide (corundum) which rapidly forms on the surface. (Although the aluminium is susceptible to attack by atmospheric sulphurous acid, this is not usually a problem at "clean" sites, away from industrial pollution).
- The aluminised surface is hard and sticks to the glass very well. This enables the surface to be gently washed to clean off dust and dirt (eg batcrap). In Sutherland we have cleaned mirrors with distilled water, restoring the surface to very nearly the reflectivity of a newly aluminised mirror. Other observatories have used carbon dioxide "snow" to clean mirrors.
- Aluminium has superior reflectivity to silver in the ultraviolet and near ultraviolet and is almost as good in the visible.

2.3 Reflectivity

The figure shows the wavelength-dependence of reflectivity for silver (Ag) aluminium (Al) and gold (Au). Clearly, aluminium is superior to silver and gold in the ultraviolet (though the Earth's atmosphere absorbs strongly below $\sim$ 350nm, so that the gain over silver is not so great). Aluminium reflects better than gold up to about 600nm and is not very much worse than either up to at least 10 μm (10000 nm), where all reflect at 98 – 99%

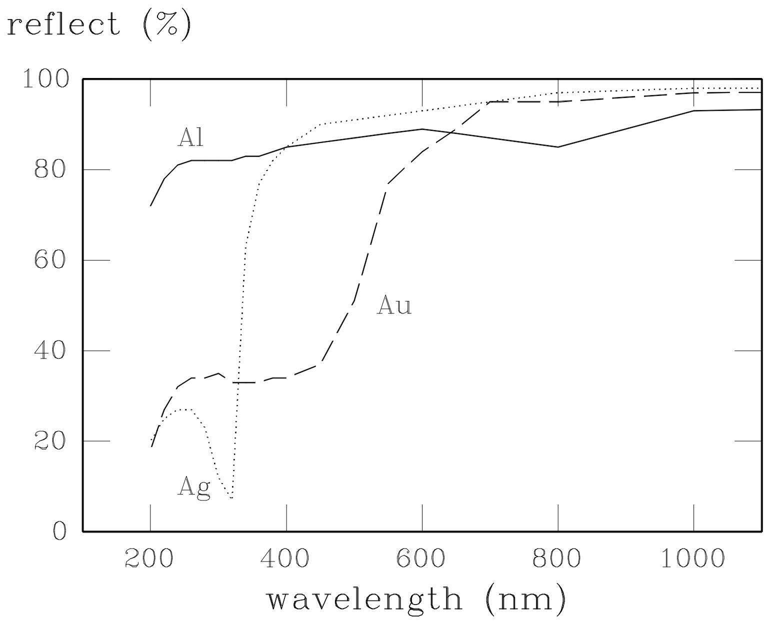

Figure 9: Reflectivity of Aluminium(Al), Gold (Au) and Silver (Ag).

Gold is sometimes used for mirrors which are used in infrared instruments because of its very high reflectivity in the infrared – and thus very low emissivity. (Observing in the infrared is observing at wavelengths where everything glows – including the observer, the telescope and the mirrors – special techniques are required).

Figure 10: An aluminising coil in the 1m tank

Figure 11: The SAAO 1m mirror being taken out of the aluminising tank ...

Figure 12: ... and lowered into the mirror cell (note mirror support elements).

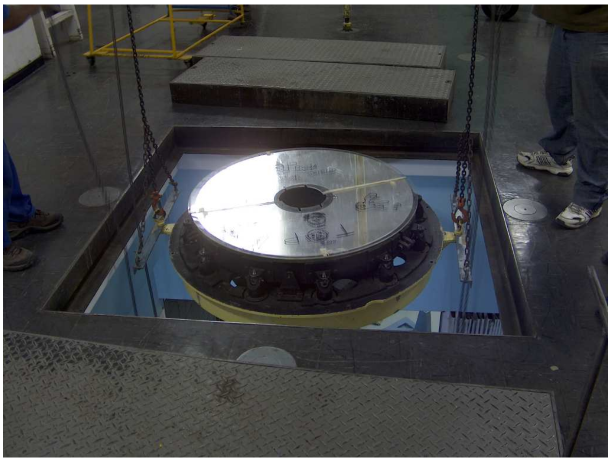

Figure 13: Mirror and cell being lifted to the observing floor for installation in the telescope.

Figure 14: SAAO 1.9m mirror being taken out of its aluminising tank ...

Figure 15: ... and lifted to the telescope.

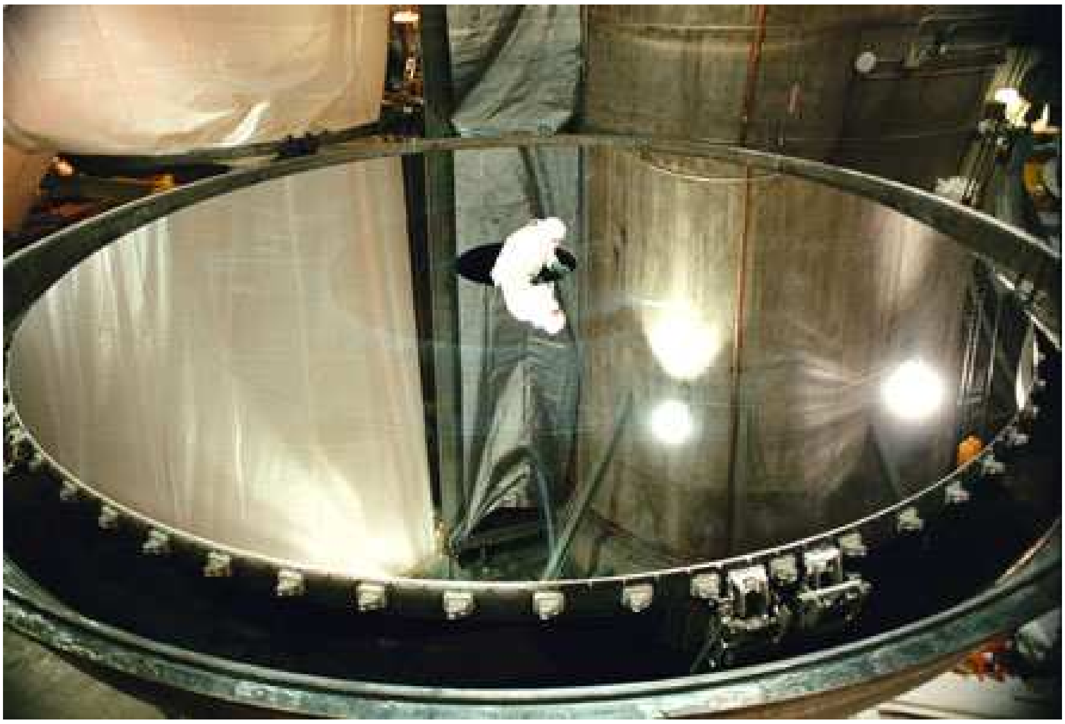

Figure 16: The 8m monolithic mirror from the Gemini (North) telescope just after aluminising.

3 Active and Adaptive Optics

Thirty years ago, in the early 1970s, "large" telescopes had apertures typically $\sim$ 4m. A number of such telescopes built around that time had thick, low-expansion glass mirrors (for optical stability), heavy rigid structures and massive equatorial mounts. These telescopes (eg. the AAT 3.9m) were beginning to take advantage of the new fast computers – at least for setting and guiding.

Ten years later, "new technology" telescopes of similar size were being built with lightweight mirrors, alt-az mounts and correspondingly smaller domes. The success of these NTTs (eg. the Australian National University 2.3m and the ESO 3.6m) led to the design of the much larger telescopes we have today (2 x Keck 10m; 4 x ESO 8.2m (the VLT); 2 x Gemini; Subaru; etc.)

With these larger telescopes came a real desire to improve image quality. We have seen how badly the effects of "seeing" can spread out an image. By improving the image, we not only improve the **spatial resolution** of our system, we also improve the **limiting magnitude** – we get to see fainter with the same instrument. This happens because if we concentrate the light into fewer detector elements ("pixels") we improve the signal/noise of the image.

One obvious way to improve image quality is to get ouside the atmosphere. It's easy to see the problem of this when you consider that the first 10m Keck telescope cost about US$ 200 million, whereas the 2.4m Hubble Space Telescope cost over US$ 2 billion – **Hubble cost about 200 times Keck per unit area of mirror.**

Active and adaptive optics are similar ways of trying to improve images. They both use some kind of wavefront sensor to measure the distortion of what should be a smooth wavefront and apply a correction via a deformable mirror or mirrors to restore the wavefront. The main differences are:

- **Speed** – active optics correct relatively slowly (minutes), adaptive optics are fast (milliseconds).
- **Size** – as a result of the different speeds, active optics can correct large optical elements (primary and secondary mirrors) whereas adaptive optics tend to work via a smaller "deformable" mirror.
- Active optics corrects mainly for mechanical and thermal effects of the telescope structure; adaptive optics for atmospheric effects (seeing).

3.1 Active Optics

Active Optics refers to a telescope system where the principal optical element – usually the primary mirror – can be adjusted to compensate for distortions introduced by a variety of effects such as

- Varying flexure of optical and mechanical components (main mirrors and the telescope structure itself) under gravity – due to orientation changes as the telescope.
- Any small optical errors inherent in the system. A consequence of active control is that the mirror need not be perfect, so long as it is smooth on small scales.
- Thermal effects due to ambient temperature changes.

and so on.

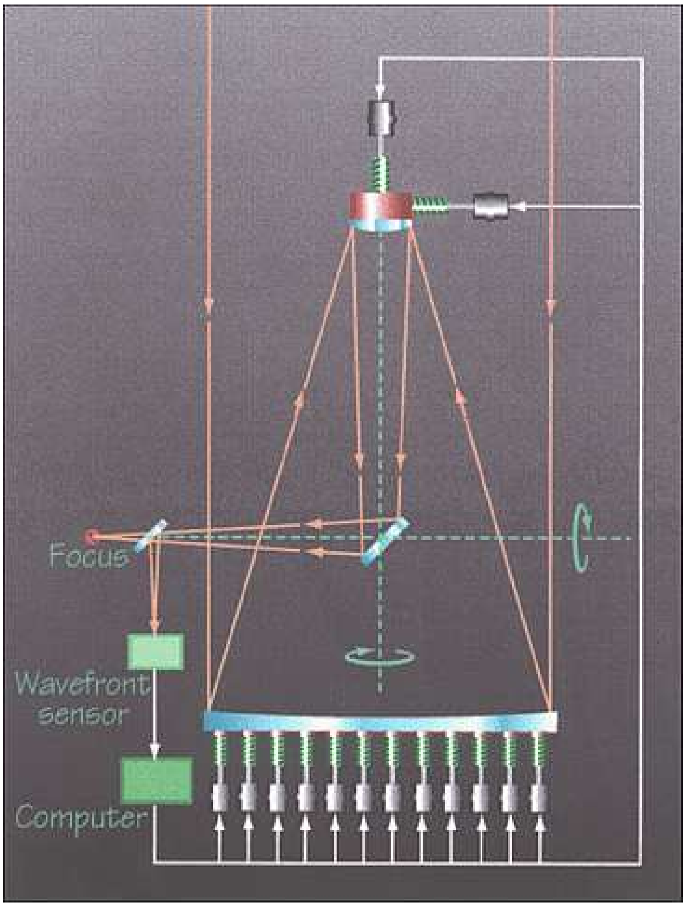

Figure 17: Schematic of the VLT active optics system.

An active optics system looks at the image quality of a bright star in the field of view and adjusts the shape of the primary and the position of the secondary mirror (focus) to remove, as far as possible, the errors. As noted earlier, the primary must be *relatively* thin for this to work.

Classical primary mirrors typically have a thickness about a sixth of the mirror diameter to maintain rigidity and image quality in the face of orientation and temperature changes. For example, the Palomar 5m telescope, made from low-expansion Pyrex, has a thickness of about a metre and weighs over 14 tons. The Very Large Telescope (VLT) of the European Southern Observatory (ESO) at Mt Paranal in Chile) is composed of four telescopes each with an 8.2m mirror. These would then need to be nearly 2m thick (and would weigh getting on for 200 tons) but in fact are only 17.5 cm thick. (but still weigh of 23 tonnes each) and are each controlled by 150 actuators which can modify the shape – typically at levels of fractions of a micron.

The system must work continuously, using a reference star in the field of view. Light from this star is measured by the wavefront sensor and a feedback loop adjusts the actuators on the primary and the position of the secondary.

Because the system corrects for telescope effects, it can work relatively slowly – every few minutes – this means the system can integrate for several tens of seconds, enabling quite faint stars to be used. This means that such a star can be found in the field of view. Any star can be used because the corrections are valid over the whole (small) field.

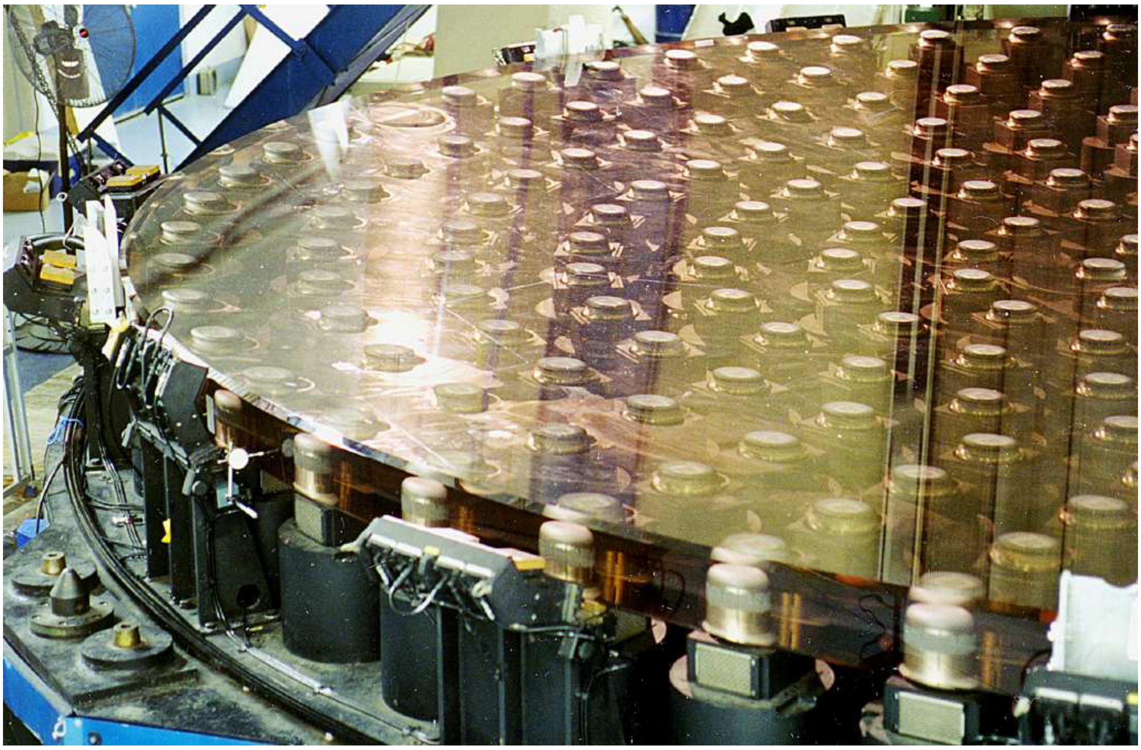

Figure 18: The actuators of the Subaru active optics system.

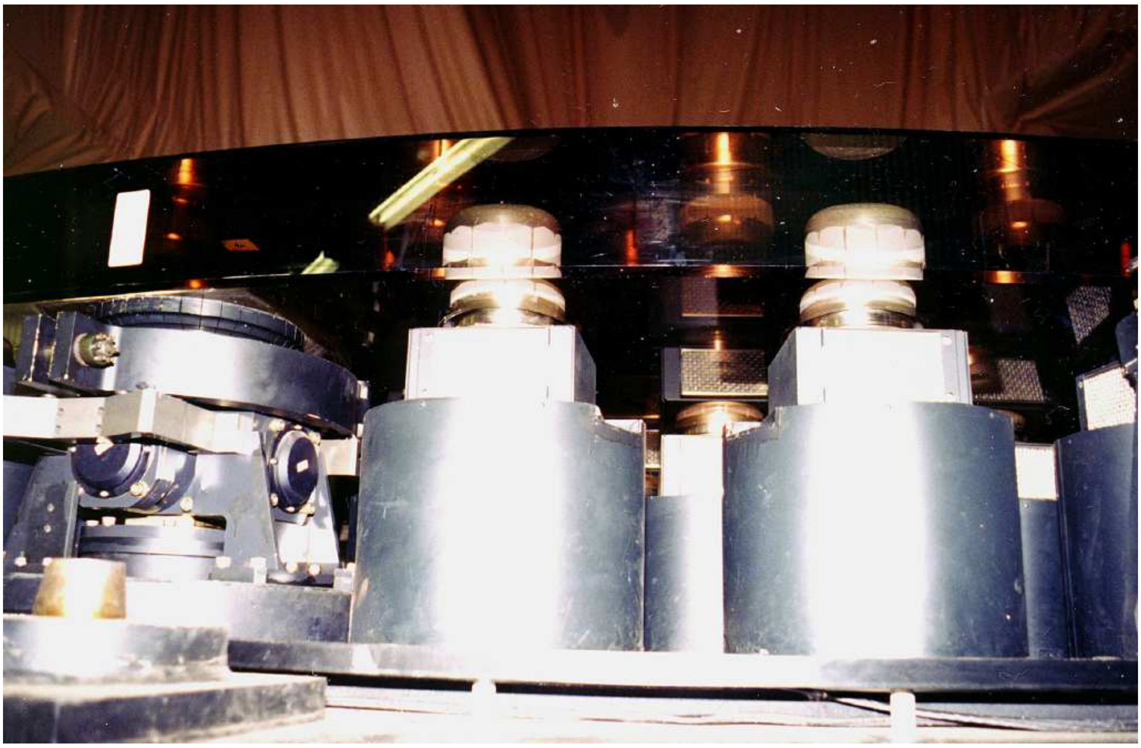

Figure 19: Close up of the Subaru actuators.

3.2 Adaptive Optics

An adaptive optics (AO) system is one where an optical surface of the telescope (often a small intermediary mirror) can be very rapidly adjusted to compensate for the distortions in incoming light caused by the Earth's atmosphere.

Light waves from a distant source arrive at the top of the atmosphere as parallel waves and are subsequently distorted by the varying temperature layers and "cells" of different refractive index. The waves as they arrive at the telescope are then slightly distorted from plane and give a less than perfectly focussed image. The adaptive optics system tries to compensate for this by using a bright star in the field of view to measure the distortion and then removes it by applying a correcting "figure" to a thin flexible mirror somewhere in the optical path. Clearly, as the atmospheric distortions can change quite rapidly, the computer must be very fast and the physical response time of the system has to be around a millisecond ($\sim$ 1000 Hz).

One problem with the very rapid sampling time is that it requires a quite bright star somewhere in the field. This is rarely possible and we discuss a possible solution to this later.

A common adaptive optics method is to have two mirrors:

- A flat mirror which can be rapidly tilted in x and y by piezo-electric actuators. This is usually called a "tip–tilt" mirror and takes out the mean tilt in the wavefront. Actually, correcting this alone can make a big improvement to the images.
- A thin flexible or deformable mirror to correct higher order effects. This can either be a small mirror controlled by many actuators or can be a "bimorph" – made of two thin plates of piezo-electric material bent by applied voltage (the principle of some tiny audio speakers).

The idea of adaptive optics was first suggested by H.W. Babcock (Publ. Astr. Soc. Pacific Vol. 65, p229, 1953) but research was classified for some years as the ideas were usable for the US "Strategic Defensive Initiative". (If you can clean up the image looking up through the atmosphere, you can also clean it looking down !)

In principle, adaptive optics systems should be able to approach the theoretical resolution limits, making ground-based telescopes competetive with space telescopes - and perhaps better because although adaptive optics systems are complex and expensive, telescopes fitted with them are still many times less expensive than satellite systems – and, of course, ground-based telescopes can be of much bigger aperture.
A good general article can be found in Sky & Telescope Oct 2001 p30 and some useful web sites (there are many) are:

`www.eso.org/projects/aot/introduction.html`
`www.cfht.hawaii.edu/Instruments/Imaging/AOB/local_tutorial.html`
`www.cfht.hawaii.edu/Instruments/Imaging/AOB/other-aosystems.html`
`www.ing.iac.es/PR/newsletter/news1/adaptive.html`

and a more advanced "tutorial" at:

`www.ctio.noao.edu/~atokovin/tutorial/intro.html`

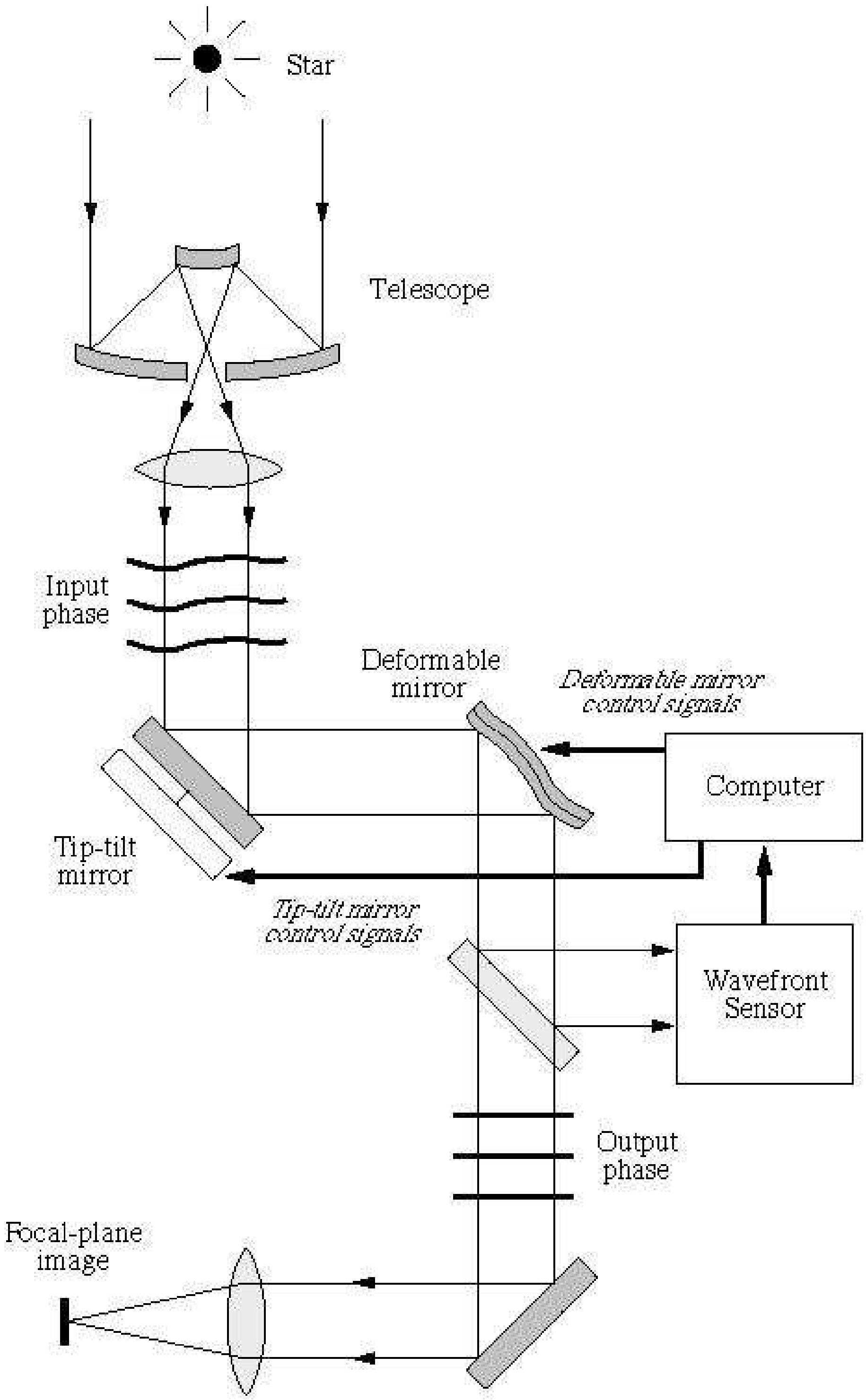

Figure 20: Schematic of a typical adaptive optics system.

3.3 Images

We have looked at the concept of **diffraction limited** images and defined **resolution** in terms of the **Airy disk** – the **Rayleigh criterion**.

We have also seen that, with a typical "large" telescope of even a couple of decade ago, diffraction-limited images would be completely unattainable – the atmospheric effects would completely smear out the diffraction limited image. Active and adaptive optics combined with CCD imaging, substantially improve this situation, and here we define some terms which you will come across repeatedly.

3.3.1 Point spread function

A star is effectively a point source. By the time its image is recorded on an area detector (eg a CCD), it can be represented as an (x,y,intensity) plot thusly:

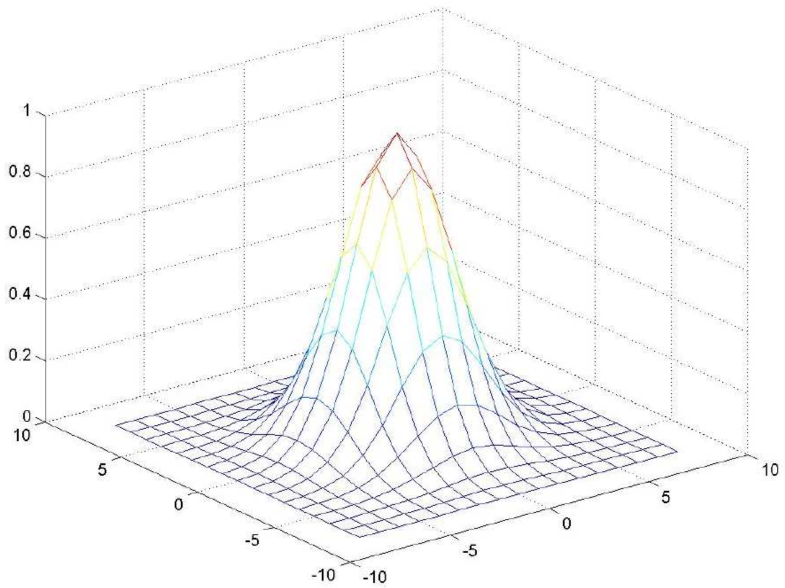

Figure 21: Representation of a star image on a digitised area detector.

The **point spread function (PSF)** describes the way in which a point source is degraded (spread) by an optical system. In astronomy, the PSF usually refers to the image on the detector and therefore includes not only the optics but also atmospheric effects – which, as we have seen, really dominate.

The actual function, of course, can be anything – Gaussian, Lorentzian or something more complex. It need not even be symmetric, for example, it just fits (or tries to fit) the data.

Note that the PSF is often assumed to be constant over the whole field of view (isoplanatism). **This is not necessarily the case, particularly when adaptive optics are involved**.

3.3.2 Full Width at Half Maximum (FWHM)

Whatever the function used, a common measure is the width of the function at half peak value – the **Full Width at Half Maximum or FWHM**

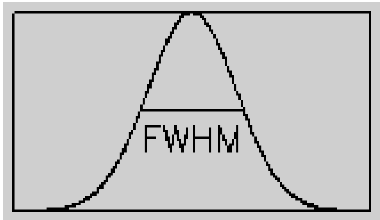

Figure 22:

3.3.3 Strehl Ratio

Another parameter widely used in active/adaptive optics to measure performance is the **Strehl ratio**. This can be defined as the ratio of the peak intensity of the observed image to the peak intensity of the theoretical image which would be produced by the same telescope with perfect optics and no atmospheric distortion. It is, therefore, more simply defined as:

$$\text{Strehl ratio} = \frac{\text{Peak intensity of the PSF}}{\text{Peak intensity of the Airy function}}$$

The Strehl ratio is clearly $\leq$1, though it is often expressed as a percentage. Systems currently in operation are achieving (at best) Strehl ratios of about 0.5 – 0.6 – extraordinarily good.

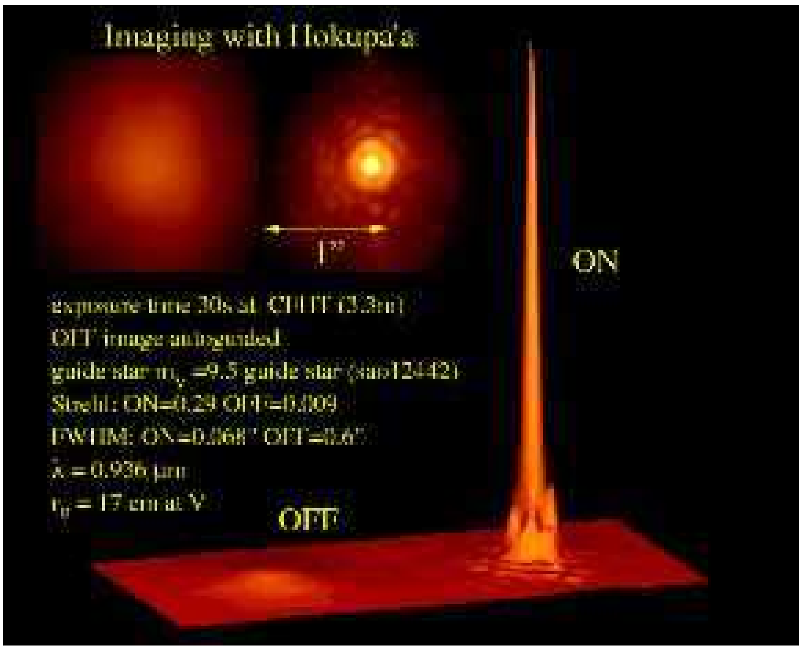

Figure 23: Adaptive optics system on the CFHT. With AO off, the image has a FWHM = 0.6” and a Strehl ratio S = 0.009. With AO on, FWHM = 0.068” and S = 0.29. The update frequency was 1.3 kHz.

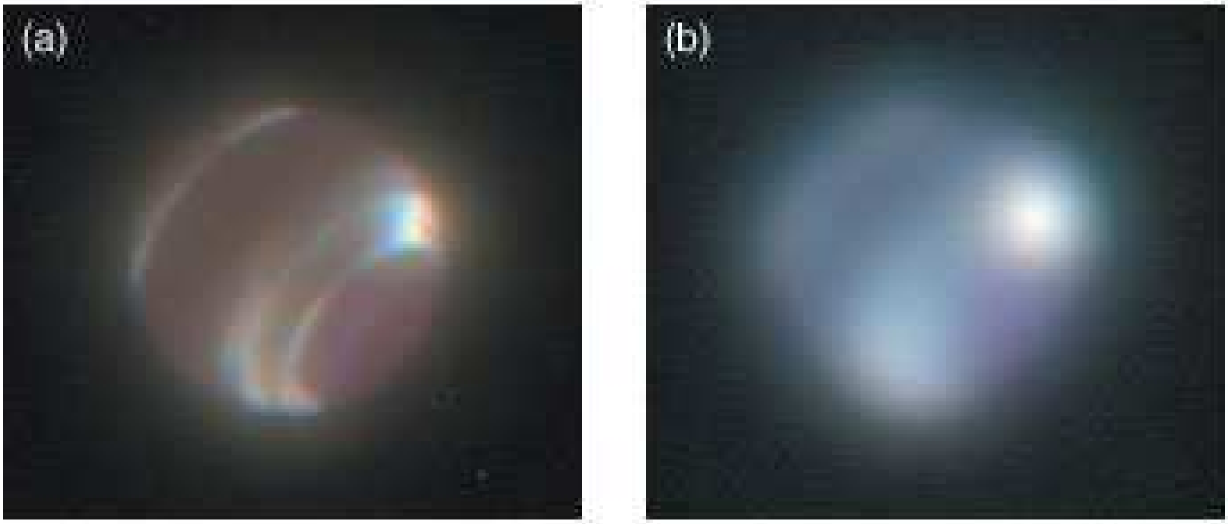

Figure 24: Illustration of the effect of adaptive optics on the planet Neptune (Keck Telescope).

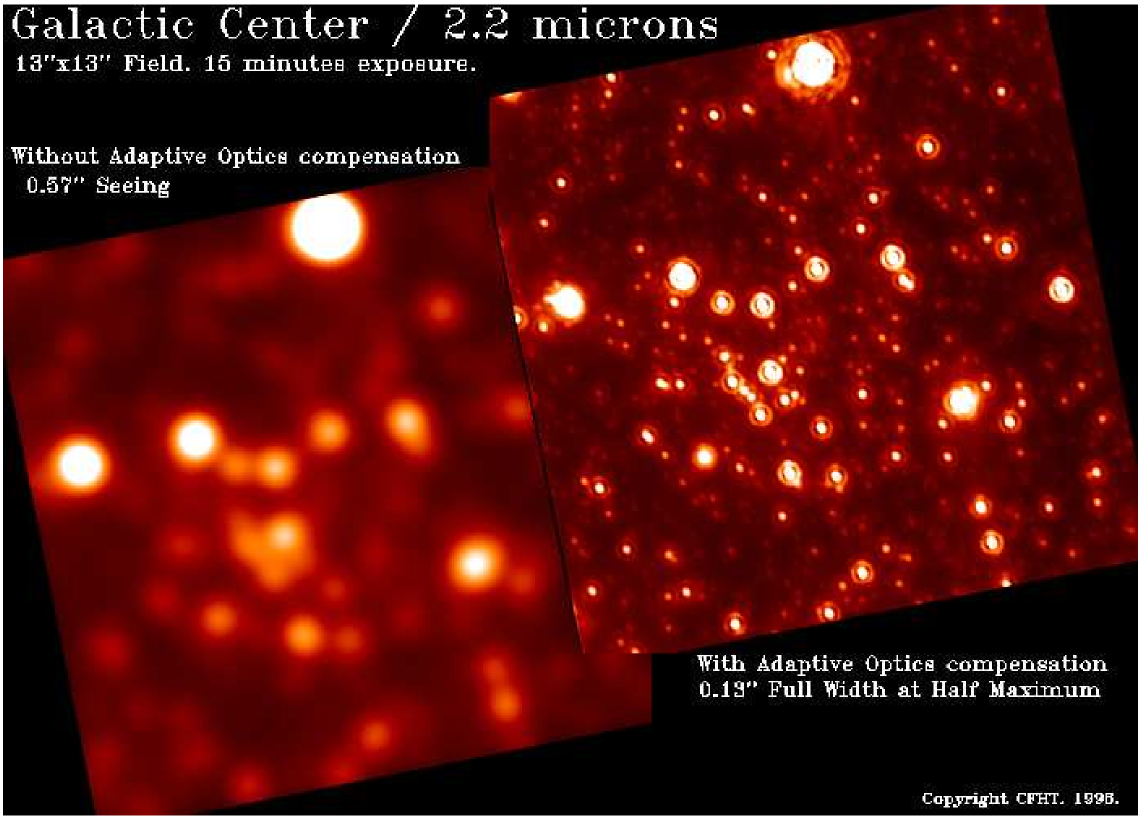

Figure 25: Illustration of the effect of adaptive optics on a crowded field (CFHT).

4 The Wavefront sensor

Active and adaptive optics systems require a "wavefront sensor" which has not yet been described. There are a number of methods in use or under development, but a commonly used wavefront sensor is the Shack-Hartmann sensor, based on the Hartmann test.

4.1 The Hartmann Test

The classical Hartmann test – first carried out by Hartmann in 1900 – uses a screen with many small holes in a collimated beam, to produce discrete "rays".

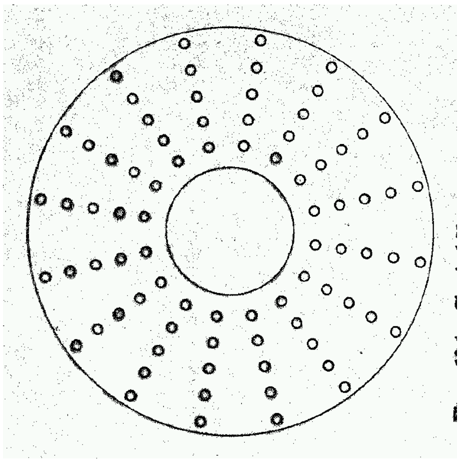

Figure 26: Typical "Hartmann screen" for Hartmann testing of mirrors.

It is then possible to perform "ray tracing" experiments by obtaining an image of the rays just inside (intrafocal) and just outside (extrafocal) the focus. This makes it possible to map the mirror surface and measure spherical aberration, coma and astigmatism – and also residual peaks and troughs which might arise in the mirror figuring process.

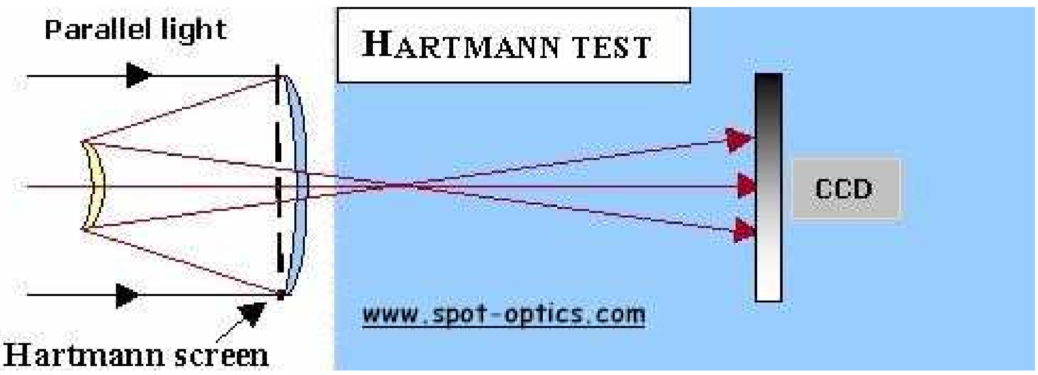

Figure 27: Schematic of Hartmann test. Note that in practice, the Hartmann screen is often placed at the "front end" of the telescope – attached to the secondary support, for example.

Initially this was done with photographic plates and was a time-consuming (though accurate) process. With the advent of CCDs and high-speed computers, this can be a much faster process (see the SBIG schematic).

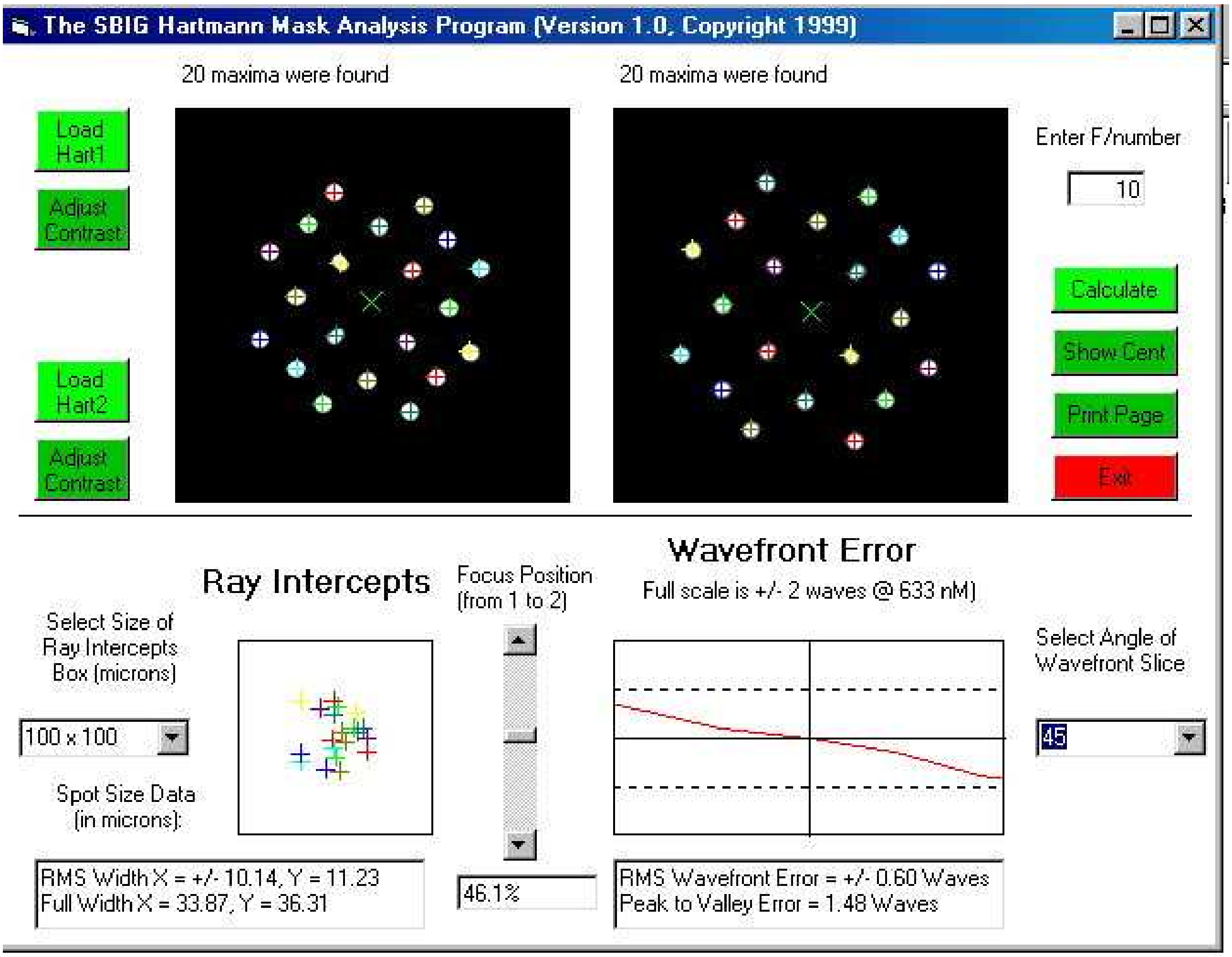

Figure 28: Schematic from Santa Barbara Instruments Group (SBIG) software for analysis of Hartmann tests.

The Hartmann test:

- is simple and robust – insensitive to atmosphere and vibration because these are averaged out by the exposure;
- can be used directly without auxiliary optics (such as interferometers);
- cannot be used for segmented mirrors if phase errors are present.

4.2 The Shack-Hartmann Sensor

In the late 1960's, the Optical Sciences Centre of the University of Arizona was working on a (classified) project for the US Air Force to improve the imaging of artificial satellites. The director of OSC, Dr Aden Meinel, had the idea of using a beam splitter to steal some of the collimated light so that measurement and focus adjustment could be done at the same time. There were problems with this approach and Dr Roland Shack assisted by Dr Ben Platt investigated the use of small lenses to replace the Hartmann screen holes. After much experimentation, it was realised that the required lenses needed to be much smaller and with longer focal lengths than anything commercially available at that time. In the end, Platt produced the first useful lens arrays in his kitchen and for about 5 years, all lens arrays used in wavefront sensors were made in the Platt family kitchen !

In the early 1970's, Shack had given lens arrays to Ray Wilson at ESO. Wilson built a wavefront sensor and tested it, finding all the larger ESO telscopes to be somewhat misaligned, and that he could significantly improve them with the new test unit. Wilson published the results of this work in 1984, coining the term **"Shack-Hartmann sensor"** for the first time.

The Shack-Hartmann sensor has many uses, in optical testing and opthalmology, as well as adaptive optics in astronomy. A schematic layout is shown in the figure.

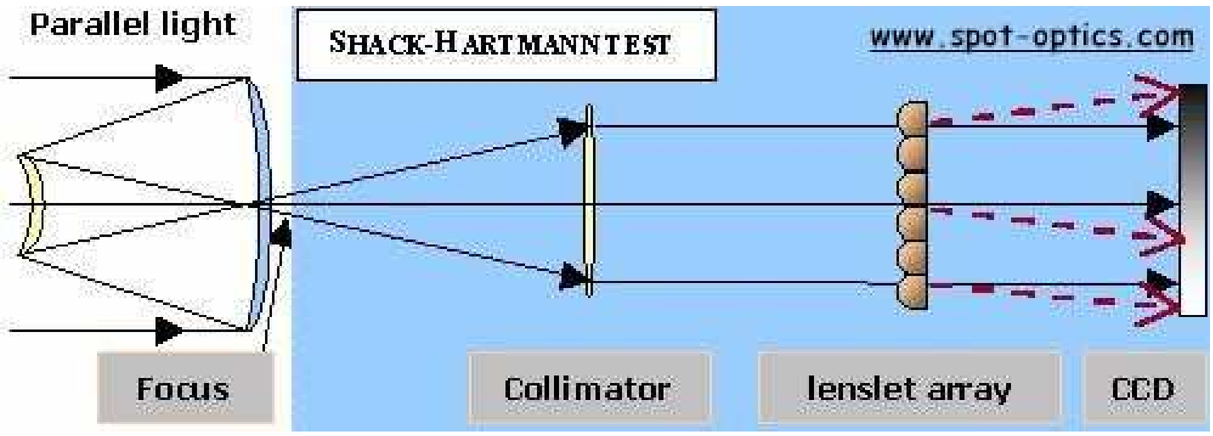

Figure 29: Schematic Shack-Hartmann sensor.

Elements of the Shack-Hartmann are:

- A collimator which effectively images the mirror system on to the lenslet array;
- the lenslet array itself, which produces a set of point images on
- a fast-readout detector, typically a CCD.
- Software is required to measure (very rapidly) any shifts in the image positions and to calculate corrections to be fed to the deformable mirror to correct those shifts back to a perfect grid.
- Recall that **all** of the above stages have to be done on a timescale of around a millisecond.

A plane (collimated) wave entering the lenslet array is focussed on to the CCD detector as a grid of **evenly spaced** points. Aberrations from the optics and distortions to the wavefront caused by the atmosphere, shift the points relative to the perfect grid. Software measures the centres of the shifted points and calculates corrections to be fed to the "tip–tilt" and deformable mirrors.

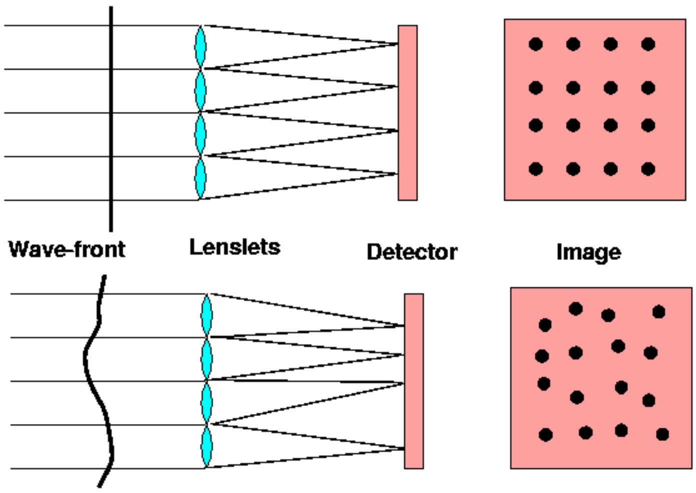

Figure 30: Schematic showing Shack-Hartmann CCD output.

The analysis process is shown in schematic form in the figure. The "frame grabber" is hardware that transfers data from each CCD frame to the computer; the centroid must then be found of each point formed by a lenslet in the lenslet array and a comparison made of these to the positions of the points formed by a perfect plane wave. Some way of inverting the displacements must be employed so that adjustments to the deformable mirror can be made to correct the actual wavefront.

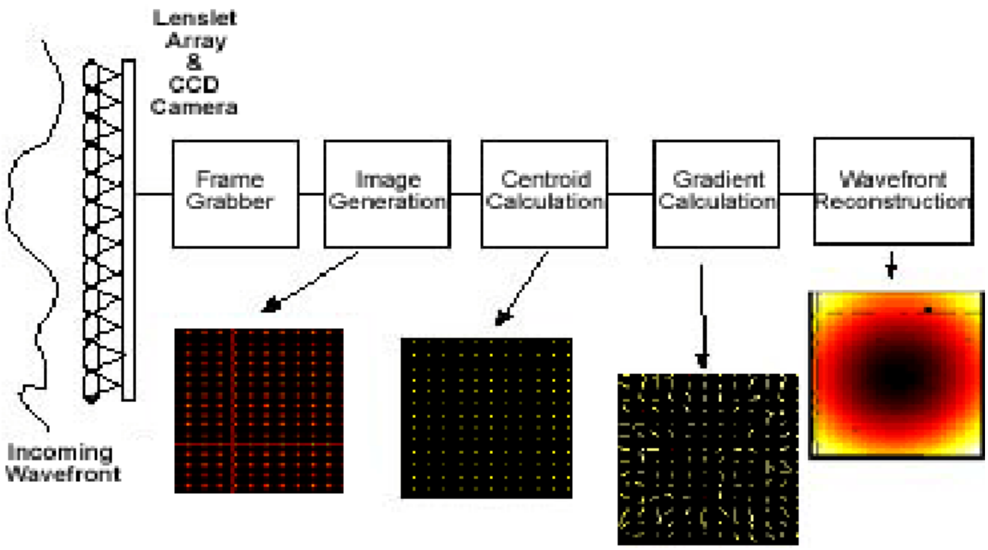

Figure 31: Schematic of Shack-Hartmann data analysis process.

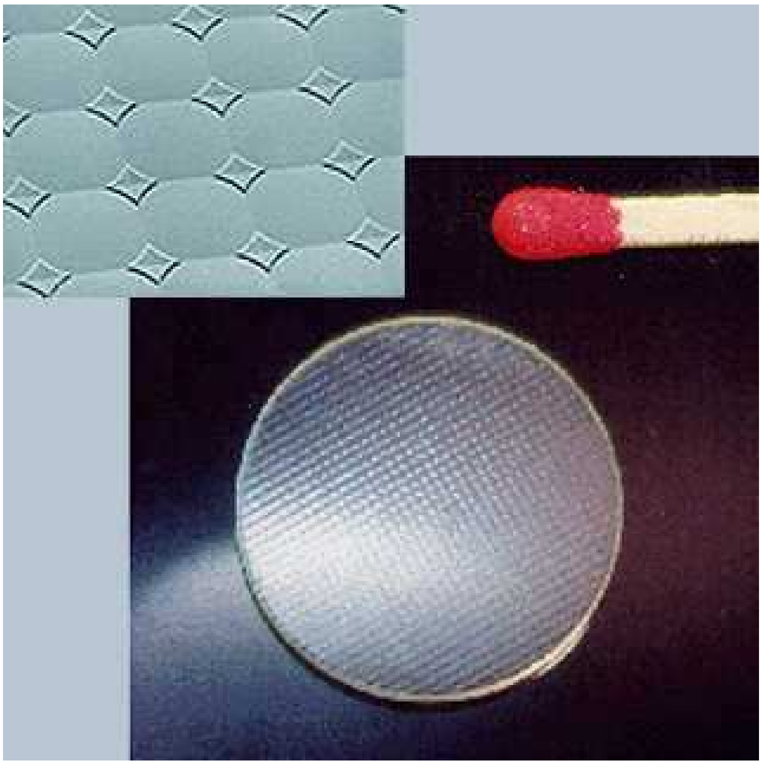

Figure 32: Lenslet array made by **Heptagon** for ESO. The array has 40 x 40 lenslets, each 500 μm (0.5 mm) in size.

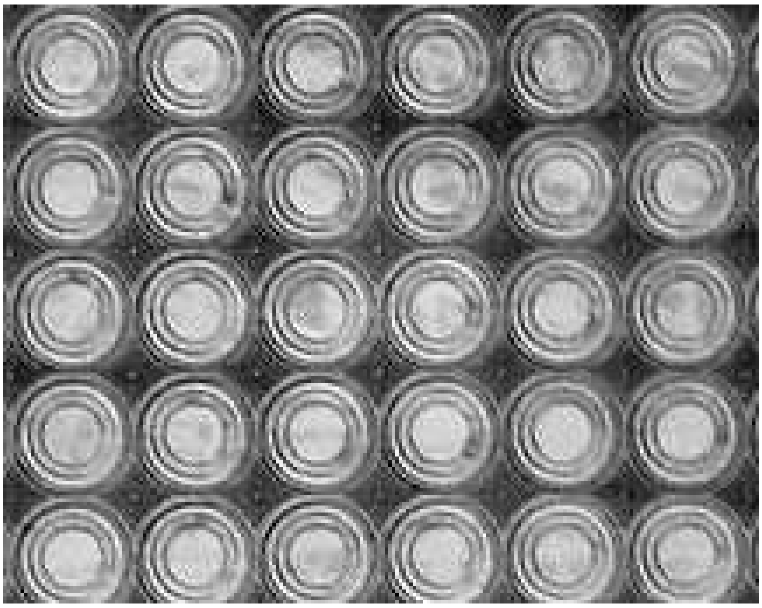

Figure 33: Part of lenslet array made by WaveFront Sciences. Each lens is 144 μm in diameter.

4.3 Zernike polynomials

To correct the incoming wavefront, some fit or representation of the wavefront must be calculated – and fast ! One way of doing this is with **Zernike polynomials**. These are often used in optical testing because they are similar in form to the wavefront shapes induced by aberrations. They take the form:

$$f(\rho)\ g(\theta)$$

where $g(\theta)$ is a continuous function that repeats every 2π

The nomenclature for Zernike polynomials is not always the same from source to source, neither is the ordering of the polynomials. The figure shows and the table lists some of the lower order polynomials.

The second and third polynomials can be easily seen to be the "tip" and "tilt" of the wavefront, so fitting these to the wavefront immediately gives a correction which can be fed to the "tip-tilt" mirror. With modern computers, many polynomials can be simultaneously fitted to the measured wavefront; the coefficients of the polynomials will be changing rapidly, of course.

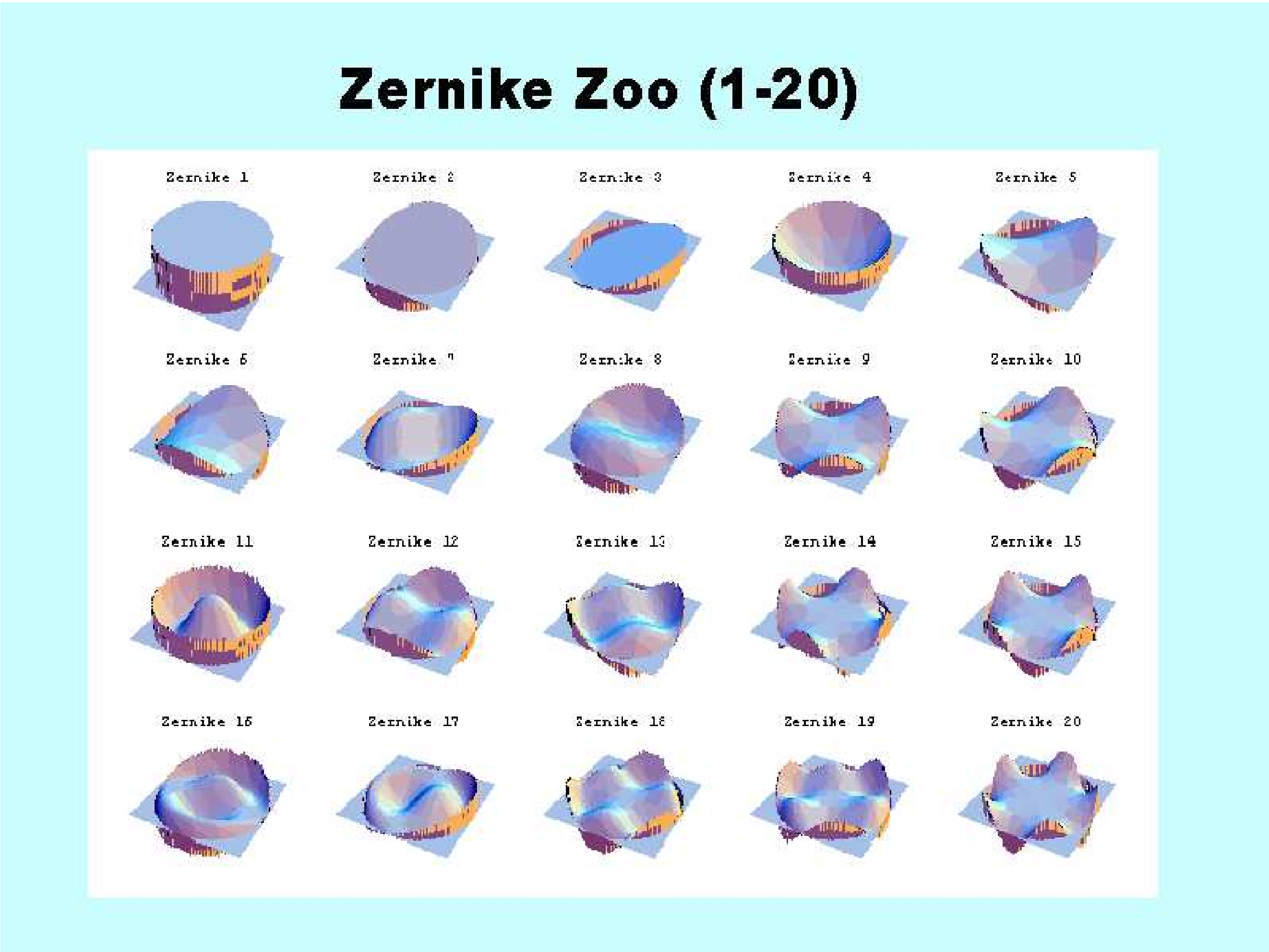

Figure 34: Illustration of the first 20 Zernike polynomials.

A very nice demonstration of Zernike polynomials can be found at:

wyant.opt-sci.arizona.edu/zernikes/zernikes.htm

where you can add them together and display (and rotate) the results.

`z1 = 1;`	Piston or Bias
`z2 = ρ Cos[θ];`	Tilt x
`z3 = ρ Sin[θ];`	Tilt y
`z4 = -1 + 2 ρ^2;`	Power
`z5 = ρ^2 Cos[2 θ];`	Astig x
`z6 = ρ^2 Sin[2 θ];`	Astig y
`z7 = ρ (-2 + 3 ρ^2) Cos[θ];`	Coma x
`z8 = ρ (-2 + 3 ρ^2) Sin[θ];`	Coma y
`z9 = 1 - 6 ρ^2 + 6 ρ^4;`	Primary Spherical
`z10 = ρ^3 Cos[3 θ];`	Trefoil x
`z11 = ρ^3 Sin[3 θ];`	Trefoil y
`z12 = ρ^2 (-3 + 4 ρ^2) Cos[2 θ];`	Secondary Astigmatism x
`z13 = ρ^2 (-3 + 4 ρ^2) Sin[2 θ];`	Secondary Astigmatism y
`z14 = ρ (3 - 12 ρ^2 + 10 ρ^4) Cos[θ];`	Secondary Coma x
`z15 = ρ (3 - 12 ρ^2 + 10 ρ^4) Sin[θ];`	Secondary Coma y
`z16 = -1 + 12 ρ^2 - 30 ρ^4 + 20 ρ^6;`	Secondary Spherical
`z17 = ρ^4 Cos[4 θ];`	Tetrafoil x
`z18 = ρ^4 Sin[4 θ];`	Tetrafoil y
`z19 = ρ^3 (-4 + 5 ρ^2) Cos[3 θ];`	Secondary Trefoil x
`z20 = ρ^3 (-4 + 5 ρ^2) Sin[3 θ];`	Secondary Trefoil y
`z21 = ρ^2 (6 - 20 ρ^2 + 15 ρ^4) Cos[2 θ];`	Tertiary Astigmatism x
`z22 = ρ^2 (6 - 20 ρ^2 + 15 ρ^4) Sin[2 θ];`	Tertiary Astigmatism y
`z23 = ρ (-4 + 30 ρ^2 - 60 ρ^4 + 35 ρ^6) Cos[θ];`	Tertiary Coma x
`z24 = ρ (-4 + 30 ρ^2 - 60 ρ^4 + 35 ρ^6) Sin[θ];`	Tertiary Coma y
`z25 = 1 - 20 ρ^2 + 90 ρ^4 - 140 ρ^6 + 70 ρ^8;`	Tertiary Spherical
`z26 = ρ^5 Cos[5 θ];`	Pentafoil x
`z27 = ρ^5 Sin[5 θ];`	Pentafoil y
`z28 = ρ^4 (-5 + 6 ρ^2) Cos[4 θ];`	Secondary Tetrafoil x
`z29 = ρ^4 (-5 + 6 ρ^2) Sin[4 θ];`	Secondary Tetrafoil y
`z30 = ρ^3 (10 - 30 ρ^2 + 21 ρ^4) Cos[3 θ];`	Tertiary Trefoil x
`z31 = ρ^3 (10 - 30 ρ^2 + 21 ρ^4) Sin[3 θ];`	Tertiary Trefoil y
`z32 = ρ^2 (-10 + 60 ρ^2 - 105 ρ^4 + 56 ρ^6) Cos[2 θ];`	Quatenary Astigmatism x
`z33 = ρ^2 (-10 + 60 ρ^2 - 105 ρ^4 + 56 ρ^6) Sin[2 θ];`	Quatenary Astigmatism y
`z34 = ρ (5 - 60 ρ^2 + 210 ρ^4 - 280 ρ^6 + 126 ρ^8) Cos[θ];`	Quatenary Coma x
`z35 = ρ (5 - 60 ρ^2 + 210 ρ^4 - 280 ρ^6 + 126 ρ^8) Sin[θ];`	Quatenary Coma y
`z36 = -1 + 30 ρ^2 - 210 ρ^4 + 560 ρ^6 - 630 ρ^8 + 252 ρ^10;`	Quaternary Spherical

Figure 35: The first 36 Zernike polynomials.

5 Deformable Mirrors

The (typically small) deformable mirror is a crucial part of an adaptive optics system. As noted earlier, there are currently two main types of deformable mirror (though this is a rapidly developing area of technology).

5.1 Actuator controlled mirrors

Early deformable mirrors consisted of discrete segments, each controlled by three piezo-electric actuators so that "piston", tip and tilt movements could be used to form the shape of the overall mirror. More recently, it is common to bond a thin faceplate to an array of actuators.

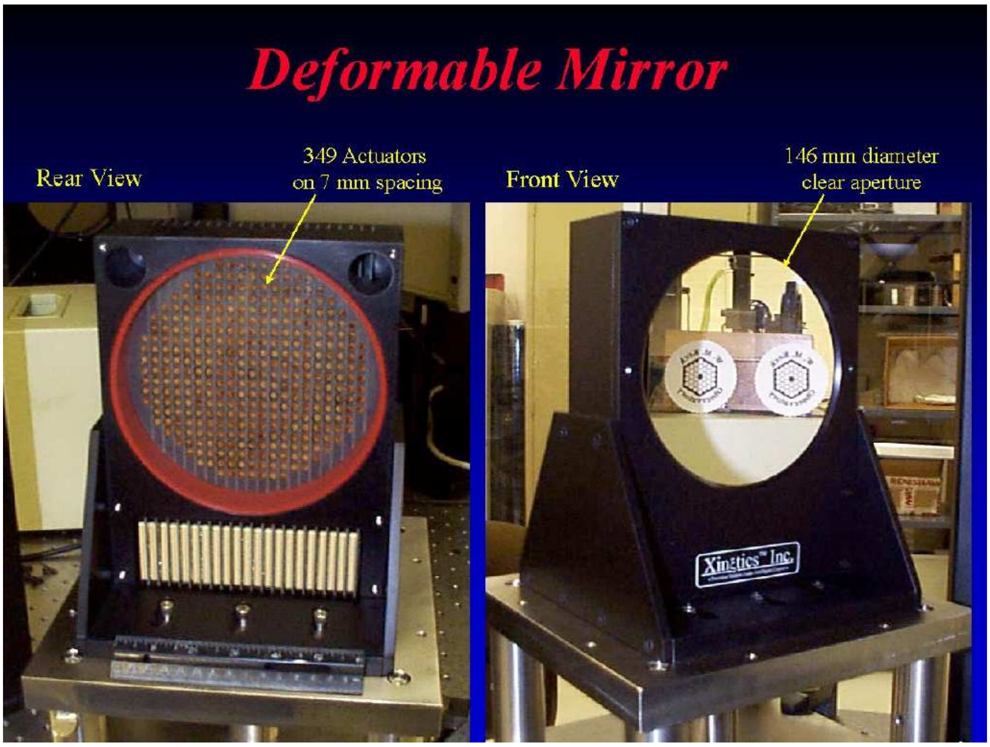

Figure 36: Deformable mirror from the Keck II adaptive optics (AO) system.

- These are not cheap; typically about US$1000 per actuator. (The Keck II AO system has a deformable mirror with 349 actuators at a cost of $\sim$ US$ 350 000.
- The stroke of these actuators is typically about a micron which means they don't give tip-tilt correction – hence the need for a separate tip-tilt mirror.
- The actuators have some hysteresis which makes control tricky
- Nonetheless, most AO systems use a **continuous faceplate** deformable mirror.

5.2 Bimorph mirrors

A **"bimorph"** mirror consists of two piezo-electric wafers bonded together with opposite polarity, so that application of an electric field causes one layer to shrink slightly while the other expands.

This causes a local curvature in the wafers. The front surface of the sandwich has a high reflection coating and is the deformable mirror.

In some cases, the piezo-electric layers are bonded to a substrate which forms the mirror (a **semi-passive** bimorph mirror). In this case, a number of electrodes can be used to control the mirror without any discontinuities at the edges of the electrodes.

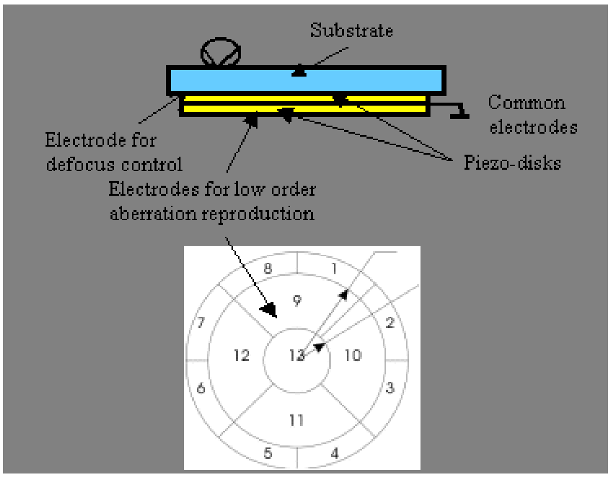

Figure 37: Semi-passive bimorph mirror. The lower figure indicates the distribution of electrodes on the substrate.

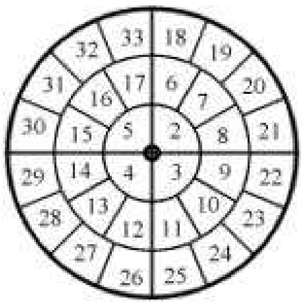

Figure 38: Distribution of electrodes on a larger mirror.

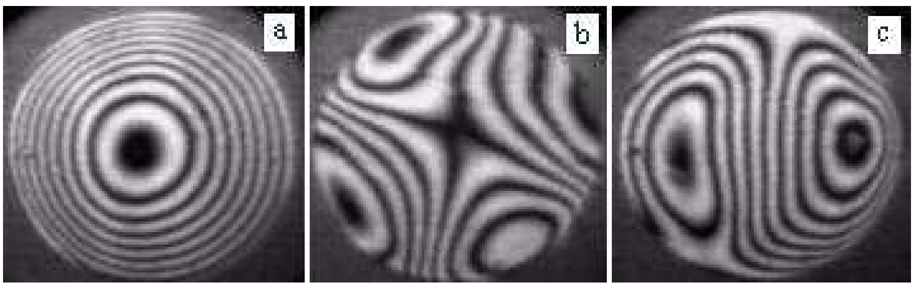

Figure 39: Interferograms showing the reproduction of the effects of (a) defocus, (b) astigmatism and (c) coma using a bimorph mirror.

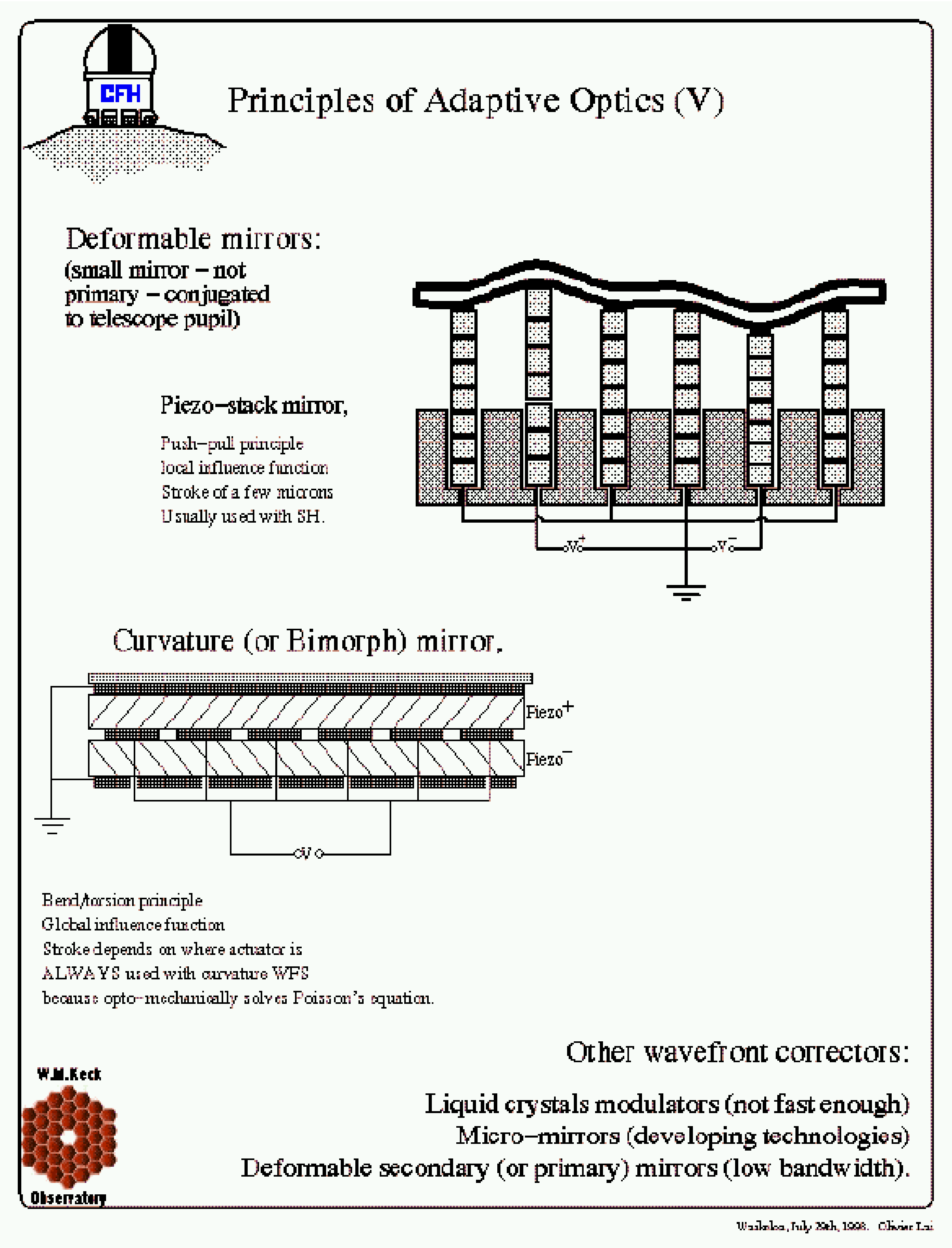
CFH
Principles of Adaptive Optics (V)
Deformable mirrors:
(small mirror – not primary – conjugated to telescope pupil)
Piezo–stack mirror,
Push–pull principle
local influence function
Stroke of a few microns
Usually used with SH.
Curvature (or Bimorph) mirror.
Piezo+
Piezo−
Bend/torsion principle
Global influence function
Stroke depends on where actuator is
ALWAYS used with curvature WFS
because opto–mechanically solves Poisson's equation.
Other wavefront correctors:
Liquid crystals modulators (not fast enough)
Micro–mirrors (developing technologies)
Deformable secondary (or primary) mirrors (low bandwidth).
W.M.Keck
Observatory

Figure 40:

6 Laser Guide "Stars"

Many AO systems use light from stars in the field under observation. The problem with AO systems is that they need to operate so quickly that light can only be collected for about a millisecond before the CCD is read out. This means that even with the largest telescopes, fairly bright stars are needed for the system to have sufficient light (signal/noise) to work. In general, a small area of sky will not have such a bright star, so this limits the targets for which AO can be used to those which, by chance, have a bright enough star near enough.

Some adaptive optics systems are getting around this by creating artificial light sources high in the atmosphere using a laser. These are called **laser guide stars** or, perhaps more accurately **laser beacons**. At present, there are two ways of doing this:

- Using **Rayleigh scattering** from air molecules of light from a pulsed laser focussed at a height of $\sim$ 15 km. Because Rayleigh scattering is proportional to λ^4, this is usually done with blue/uv lasers.
- Using **resonant fluorescence** of sodium atoms. Sodium (and other metals) exist in a layer at around 90 km, probably created and maintained by the evaporation of micro-meteorites. Generally, dye lasers which are tuned to excite the sodium 'D' lines near 589 nm are used.

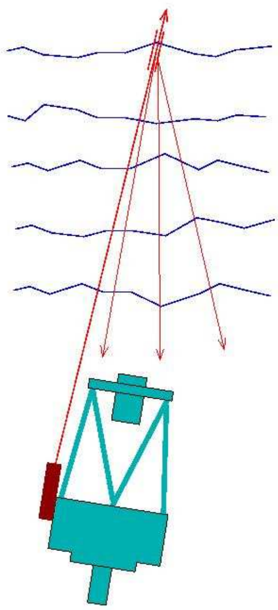

Figure 41: Creating laser guide stars.

Of course, there are problems:

- Because the laser beacon and the stars are not at the same distance, the light does not travel along exactly the same path and this leads to the **"cone effect"**.
  - Turbulence above the laser beacon is not sampled.
  - The outer portions of the stellar wave front are not sampled.
  - The laser and stellar wave fronts are scaled differently.

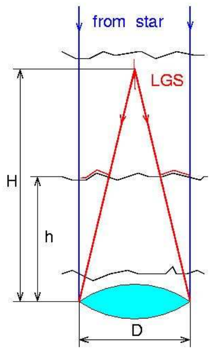

Figure 42:

- Laser guide stars are not well-suited to measuring tip-tilt effects, because the laser light is travelling through the atmosphere twice.
- The sodium layer shows rapid, diurnal and seasonal variations which affects performance.
- There is a considerable amount of Rayleigh scattering associated with the sodium fluorescence method (see figure).

Figure 43: Sodium "guide star" with associated cone caused by Rayleigh scattering.

This can be controlled by "range gating" (fast electronic shutters in front of the wave-front sensor). Also, if the beam is launched from the top of the telescope, the secondary mirror blocks most of the scattered cone.

Laser systems also have potential problems:

- Care must be taken with the location of aircraft and satellites when firing powerful laser beams into the atmosphere.
- They add to "light pollution" at what should be very dark sites.
- Laser beacons cannot be used in even very thin cloud conditions because of back-scattering problems.

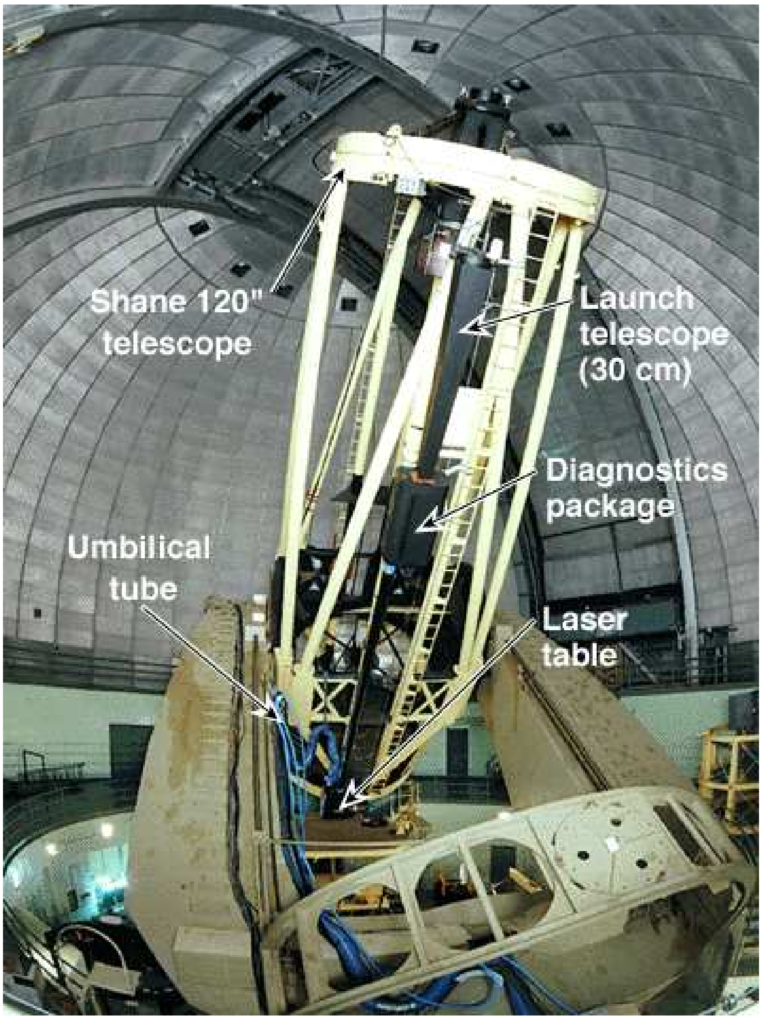

Figure 44: 3m “Shane” telescope of Lick Observatory with adaptive optics system.

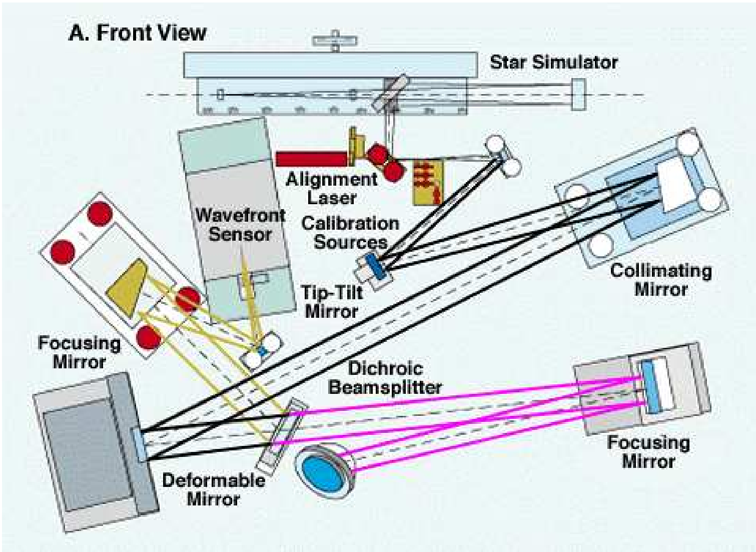

Figure 45: AO system of Lick 3m telescope.

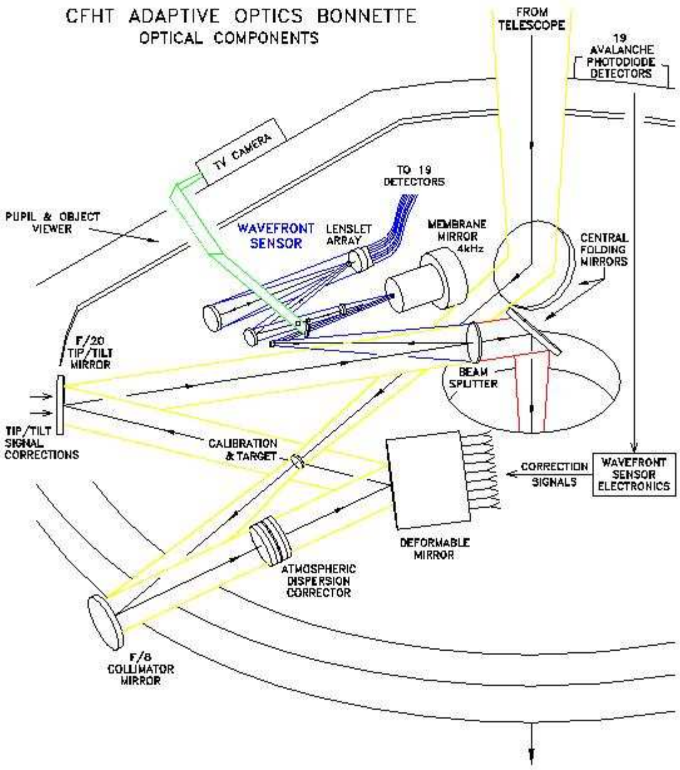

Figure 46: AO system ("PUEO") of the Canada-France-Hawaii Telescope (CFHT).