Laser Guide Stars for Adaptive Optics

Paul Withers - Part II Literature Review

Atmospheric turbulence degrades the resolution of a telescope. The resolution can be improved with the use of adaptive optics. This technique, which senses the distortions of a stellar wavefront and uses a deformable mirror to correct the wavefront, is only useful for images of small areas of sky. Important limitations of adaptive optics are that only a small proportion of the sky can ever be viewed with it, and that the improvement in resolution is limited by the faintness of the stellar object. Use of a laser guide star almost completely overcomes both these limitations. A laser guide star is a bright spot high in the atmosphere, created by a laser beam, which acts like a very bright star.

1 - The Need For Laser Guide Stars

1.1 - Atmospheric Turbulence

Kolmogorov turbulence in the atmosphere creates eddies. These eddies dissipate into smaller and smaller eddies, until molecular friction converts the eddy turbulence into heat. This heat causes spatial and temporal variations in temperature, density, and refractive index [1].

As a result of this refractive index variation, the phase and amplitude values of a stellar wavefront, as measured at a telescope pupil, vary across the pupil and fluctuate with time. Amplitude variations are small, and their effects are usually neglected [1]. The diffraction-limited visible resolution of an 8m telescope is 0.02 arcsec, but the phase variations limit the visible resolution of any telescope to 0.5 arcsec at best [2]. This maximum attainable visible resolution is called the “seeing angle”.

1.2 - Adaptive Optics

The astronomical technique of Adaptive Optics (AO) tries to bring the resolution of a telescope closer to its diffraction limit. It does this by measuring the phase variation of the wavefront across the telescope pupil, and using a deformable mirror to correct this distortion (fig. 1).

Due to the spatial variation of the refractive index, the wavefront must be sensed at many points across the telescope pupil, which demands a high photon flux incident on the telescope. These sensing points are usually arranged in a square grid, with roughly 20cm spacing when measured relative to the pupil size. This spacing is the diameter of a telescope whose diffraction-limited resolution equals the maximum resolution permitted by typical atmospheric turbulence [1,3,4].

Due to the spatial variation of the refractive index, distortions of the wavefront only remain correlated over a small angular range, and so only a small area of the sky can be corrected in a single image. This limits the area of the sky over which photons can be collected. If the object at the centre of the image is in focus, then the area of the sky over which other objects are acceptably focused is called the field of view (FOV). The FOV which can be corrected with AO is only a few arcsec across [1,4]. A typical astronomical image is a few arcminutes across, so this restricted FOV is a major limitation on the usefulness of AO. Techniques have been proposed to increase the FOV by placing the deformable mirror conjugate to the most turbulent atmospheric layer [1].

Due to the temporal variation of the refractive index, the wavefront must be sensed frequently, typically once every 10 ms. This is the time the wavefront takes to change significantly from its measured state [2,3]. This also demands a high photon flux.

The effects of turbulence are only mildly wavelength dependent. With the most common AO systems, wavefront sensing does not have to be performed at the wavelength of observation [5], nor in a narrow band [1]. Loss of resolution due to atmospheric turbulence is worst for visible wavelengths, and it ceases to be a problem for wavelengths above 4 μm [6], so AO is designed to work in the visible and near-IR bands. The size of the FOV, the maximum time between adjustments of the deformable mirror, and the maximum distance between points at which the wavefront is sensed are all proportional to $\lambda^{6/5}$. Hence visible observing is technically more challenging than IR observing[7].

The proportion of the sky that can be viewed with an AO system is called the sky coverage. The demand for photons, and the restricted area of the sky from which they can be collected, limits the sky coverage of AO systems.This sky coverage is finite (~1%) in the near-IR, but negligible in the visible. For example, only objects less than a few arcsec away from an object brighter than 7th magnitude can be imaged in the visible [8]. Even in regions of the sky where viewing with AO is possible, the limited number of photons restricts the accuracy of correction and the improvement in resolution. Improvements in the proportion of the sky which can be viewed with AO, and improvements in the resolution which can be obtained with AO, can be made with the use of Laser Guide Stars (LGSs) [9].

1.3 - Laser Guide Stars

A LGS is a bright spot high in the atmosphere whose photons are used to measure the effects of atmospheric turbulence. This spot can be placed as close as desired to the stellar object of interest, allowing the use of AO over all the sky, and can be made as bright as desired, maximising the improvement in resolution.

The spot is created by focusing a laser beam on a region of the sky. Molecules excited by the passing laser beam scatter photons in all directions. Photons scattered back along the path of the laser beam are collected by the telescope, along with photons from the stellar object of interest (fig. 2).

There are two types of LGS; one is created by Rayleigh scattering from atmospheric molecules, and the other is created by resonance scattering from a high layer of sodium atoms. I shall discuss Rayleigh LGSs first, together with general features of LGS AO systems, then discuss the more complicated sodium LGSs separately.

2 - Rayleigh Laser Guide Stars

2.1 - Introduction

A Rayleigh LGS is created by the Rayleigh scattering of laser light from atmospheric molecules. The physics of Rayleigh scattering is well understood, and the main points that we need to note are the simple proportionality between the number of photons sent up in the laser beam and the number of backscattered photons collected by the telescope, and the λ^{-4} dependence of the scattering cross-section.

The backscattered photons used to measure the effects of atmospheric turbulence should all scatter from about the same height in the atmosphere, so that they all experience the same turbulence. This height restriction can only be satisfied by using a pulsed laser and gating the wavefront sensing device. A Rayleigh LGS usually has a vertical size of ~1km and is located at a height of between 10 and 20km [3, 10]. Due to the exponential decrease in the density of scattering molecules with height, the current height limit is 20km. This is fixed by laser and wavefront sensing technology.

Due to distortions of the wavefront only remaining correlated over a small angular range (section 1.2), the Rayleigh backscattered photons must originate from a small area of the sky. This small area should be centred on the stellar object of interest and must be entirely within the few arcsec FOV. This means that the laser beam quality must be high, and the aiming excellent (fig.3).

Laser light must not contaminate the astronomical results. Either a filter is used, and hence the laser wavelength should be away from the wavelength band of observation, or the astronomical instrument is gated. If gated, the consequent loss of observing time is small.

2.2 - Laser Projection

The laser beam may be projected through the AO system and full telescope pupil, from a separate transmitter, or from behind the central obscuration of the telescope [11].

Projection through the AO system and full telescope pupil keeps the LGS centred on the stellar object of interest, increasing the accuracy of the wavefront correction and allowing the use of lower beam quality lasers [12]. However, optical components are caused to fluoresce strongly even when the astronomical instrument is collecting photons [12]. The fluorescent light will contaminate the astronomical observations and wavefront sensing. Even backscattered light alone causes fluorescence, and this is a major limitation on the use of LGSs [13]. If the laser itself is close to the optical path, then any dissipated heat will cause increased turbulence and image degradation.

Use of a separate transmitter eliminates heating in the path of astronomical starlight and simplifies incorporation of the laser into the telescope. The spot will be distorted by its angled projection, but will remain within the FOV for visible observing [14].

Projection from behind the central obscuration of the telescope is the ideal approach, but this is difficult to arrange in an already existing telescope.

2.3 - The Cone Effect

The LGS wavefront is not distorted in precisely the same way as the stellar wavefront. This is because turbulence above the LGS is not sampled by the backscattered photons, and turbulence below the LGS is sampled differently by the backscattered photons and the stellar photons (fig. 4). Turbulence is significant up to a height of 20km [8], which is the present maximum height of a Rayleigh LGS. This "Cone Effect" limits use of a single Rayleigh LGS to 2m-class telescopes for near complete correction in the visible [15], increasing to 4m in the IR [16], or if partial correction in the visible is acceptable [17].

2.4 - The Tilt Problem

Turbulence on the upward path of the laser beam randomly displaces the LGS from its aim point on the line-of-sight to the stellar object of interest (fig. 2). Hence, LGSs are unable to measure the "tilt" introduced to the stellar wavefront by atmospheric turbulence. Tilt refers to the distortion of a plane wavefront caused by simply tilting the plane. Unless the tilt of the stellar wavefront can be corrected, there is very little improvement in the image quality [3]. So some natural starlight is needed to measure this tilt. This measurement can take place across the whole pupil of the telescope, and so fainter natural stars can be used than are required for complete correction of a stellar wavefront without LGSs. The natural star can be further away from the stellar object of interest than if it was to be used for complete correction of a stellar wavefront.

The Tilt Problem means that sky coverage is not complete for LGS AO systems. It is practically complete in the IR and finite (a few percent) in the visible [18]. It can be substantially increased in the visible by use of LGS AO on both the stellar object of interest and the bright natural star used for tilt correction. This "Dual Adaptive Optics" technique requires duplication of the expensive LGS system. Other, more exotic, methods have been proposed to give practically complete sky coverage in the visible [19,20,21].

2.5 - Types of Lasers

Lasers suitable for Rayleigh LGS AO should pulse at up to a few hundred pulses per second, have a high average power (~50 W), excellent beam quality and long term reliability. Such lasers are readily available.

By balancing atmospheric opacity with a λ^{-4} dependence in the Rayleigh scattering cross-section, and maximising the number of return photons for a given laser power, it has been shown that the laser wavelength should be between 350 and 430nm [22]. UV excimer lasers are ideal, with a longest wavelength of 351nm. They are common in other fields, and are of proven quality [3].

Work has also been done with green copper-vapour lasers [23]. These can deliver high powers of a few hundred Watts, and consequently more backscattered photons, and can generate a higher LGS, which gives a greater correlation between the measured LGS wavefront and the actual stellar wavefront. These lasers have a poor beam quality and must be projected through the full AO system [10]. The problems this causes for observation have been discussed previously (section 2.2).

2.6 - Current Status

Many tests on 1m-class telescopes have demonstrated the viability of Rayleigh LGS AO [eg 23,24,25] and astronomical papers are just beginning to be published using it [eg 26,27]. Practically all the necessary equipment is available off the shelf for a Rayleigh LGS AO system which can provide performance close to the Hubble Space Telescope over a narrow FOV [3].

3 - Sodium Laser Guide Stars

3.1 - The Sodium Layer

The mesospheric sodium layer [3] provides an excellent scattering medium for the creation of LGSs because of its high altitude, which reduces the cone effect, and large resonant backscattering cross section, which creates many backscattered photons. The sodium layer is believed to be created by meteoric deposition, and to be depleted at its lower boundary by chemical processes. The layer lies at a mean altitude of 92 km and its average thickness is 10-15km [28]. The sodium column density varies on both daily and annual time scales, with its winter maximum approximately three times its summer minimum. Hence the amount of backscattered light generated by a LGS AO system varies seasonally. Other atomic species are deposited in the mesosphere by the same process, but none has as good a combination of column density and backscattering cross section [3].

3.2 - Sodium Spectral Lines

Of all the sodium spectral lines, the D_2 line at 589nm creates the most backscattered photons, and is hence used for creation of the sodium LGS (fig. 5).

Unlike Rayleigh scattering, the physics of the sodium atom has a strong influence on the number of resonant backscattered photons. The 16ns lifetime of the excited state, which is long on atomic timescales, means that saturation occurs at an instantaneous power output of >5kW. The brightness of the LGS then ceases to increase as stimulated emission begins to occur, radiating forward out of the atmosphere. Saturation will occur at a lower instantaneous power output unless the laser is accurately tuned to the D_2 family of lines, with a linewidth of 3GHz.

3.3 - Characteristics of Sodium LGSs

Due to the cone effect, a single sodium LGS can only provide near complete correction in the visible on 4m-class telescopes, increasing to all telescopes in the IR or if partial correction is acceptable [10].

For a given laser power output at the D_2 wavelength, the sodium LGS is as bright as a Rayleigh LGS at a height of 20km [11]. This is the current limit on Rayleigh LGSs, so the laser must be high powered, ~50W for near complete correction in the visible on a 4m-class telescope [30]. Only a few Watts are needed for near complete correction at 2.4μm on a 4m-class telescope [16], due to the $\lambda^{6/5}$ dependence of many facets of atmospheric turbulence (section 1.2).

Use of a separate transmitter to generate a sodium LGS has an advantage not available to Rayleigh LGSs. If situated more than a few metres from the telescope aperture, Rayleigh scattered light is blocked out by the telescope dome. Very high pulse repetition rate lasers, and CW lasers, can now be used, as the height and vertical size of the LGS no longer needs to be controlled by the pulsing of the laser and gating of the wavefront sensor. CW lasers cannot be used with gated wavefront sensors, and so light in the centre of the visible band must be filtered out. This, and problems with the required power, make CW lasers unsuitable for work in the visible [30]. It is difficult to make low pulse repetition rate lasers, of a few 100 pulses per second, with long pulses, and so their power is delivered in sharp spikes which may saturate the sodium layer. This problem can now be alleviated with the use of very high pulse repetition rate lasers, which contain less energy per spike for a given power output, and are less likely to saturate the sodium layer.

The angled projection into the 10km thick sodium layer will cause elongation of the spot outside the FOV for visible, but not IR, observing. Beckers has proposed a technique to remove this problem for pulsed lasers [14].

Foy has proposed a polychromatic sodium LGS, using a number of sodium spectral lines, which may remove the need for a natural star in tilt measurements [31].

3.4 - Types of Lasers

Unfortunately, lasers suitable for sodium LGS AO are not readily available. High powered 0.6μm lasers have not been widely used previously, and the trade-off between excellent beam quality, high average power and non-saturating instantaneous power is challenging to satisfy [3]. In most astronomical work, dye lasers are used, but these are unable to supply sufficient power at an adequate beam quality for visible observations, although sufficient for many demonstrations of concept [3]. The lack of a suitable laser is impeding progress in the field and the best candidate, the NdYaG laser, is still in its trial stages [30].

NdYaG lasers have excellent beam quality, a suitable linewidth and a high ratio of average to instantaneous power [3, 30]. One such laser tuned to 1.06μm, and a second tuned to 1.32μm, are aimed into a non-linear (eg lithium niobate) crystal. This generates "summed frequency" laser light at the sodium D_2 frequency [32].

In early prototypes, these NdYaG lasers were flashlamp pumped. This is not ideal, as beam quality is low at the necessary power levels. Designs using diode pumping improve the beam quality and give greater control of the temporal nature of the laser beam (reducing the likelihood of saturation) [11]. This appears to be the only way to generate sodium LGSs suitable for near complete correction in the visible [30].

3.5 - Current Status

Sodium LGSs are still in their infancy and insufficient laser power prevents astronomical work in the visible. Most programs are concentrating on investigating the behaviour of sodium LGSs or designing improved lasers, rather than on performing astronomical work.

4 - Multiple Laser Guide Stars

The cone effect on a single LGS limits near complete compensation in the visible to telescopes up to 2m in diameter for Rayleigh LGSs, increasing to 4m for sodium LGSs [10]. Use of multiple LGSs will reduce the cone effect, and should allow near complete correction in the visible on all telescopes [34]. However, there are many practical difficulties with this concept [7], and little experimental work has been reported [35]. Less than 10 sodium LGSs would be necessary for near complete correction in the visible on an 8m-class telescope [1, 15]. Many tens of Rayleigh LGSs would be necessary for correction in the visible on an 8m-class telescope, and unsampled turbulence above the LGSs will make diffraction-limited resolution unattainable [15].

5 - Summary and Conclusions

Atmospheric turbulence limits a telescope's resolution to that of a 20cm telescope. This resolution limit can be improved with the use of adaptive optics (AO), but only on images of small areas of the sky . Important limitations of AO are that only a small proportion of the sky can ever be viewed with AO, and that the improvement in resolution is limited by the faintness of the stellar object. Use of a Laser Guide Star almost completely overcomes both these limitations.

Single Rayleigh LGSs, which are readily available, offer near complete correction in the visible on 2m class telescopes (and on 4m class telescopes in the IR) over images a few arcsec across. Sodium LGSs are not yet available with sufficient power, at an adequate beam quality, to demonstrate near complete correction in the visible, and this problem is the single largest barrier to progress in AO.

Techniques to provide complete sky coverage, images of larger areas of the sky, and near complete correction on the largest telescopes are not likely to be available soon. Inherent problems like the cone effect and fluorescence of optics pose fundamental limitations to the use of LGSs.

Despite these technological obstacles, the future of LGSs looks promising; diffraction limited imaging over the whole sky at all wavelengths is an achievable goal, even on the largest telescopes.

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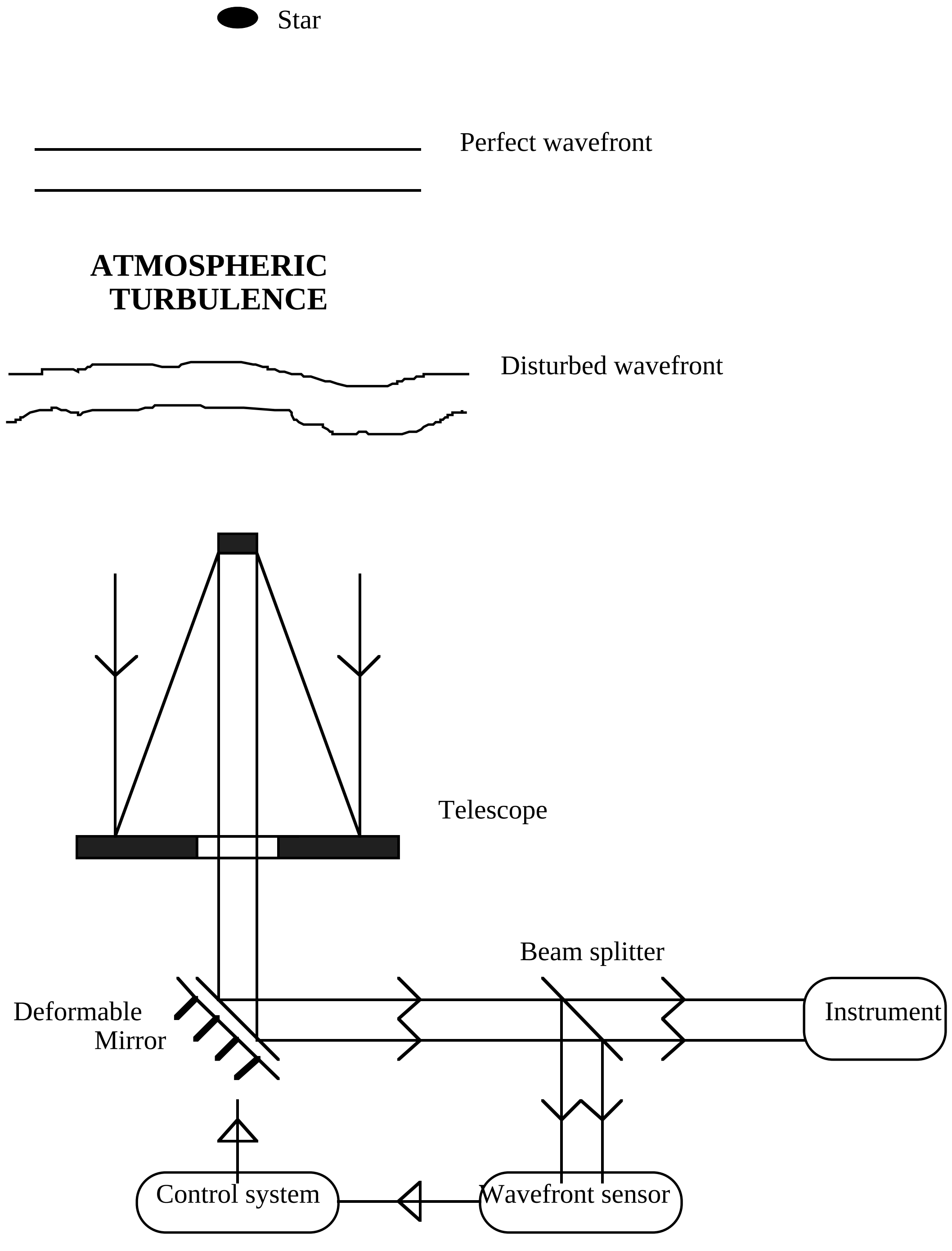


Figure 1. Schematic Adaptive Optics System

Starlight passes through the turbulent atmosphere, and some of it is directed to the wavefront sensor. There, the phase variation of the wavefront is measured, and the distorted wavefront reconstructed. The control system uses the reconstructed wavefront to decide how the deformable mirror should be altered to correct for the distortion in the wavefront. Whilst this is going on, some of the starlight is being corrected by themirror, and this forms a sharp image in the instrument.

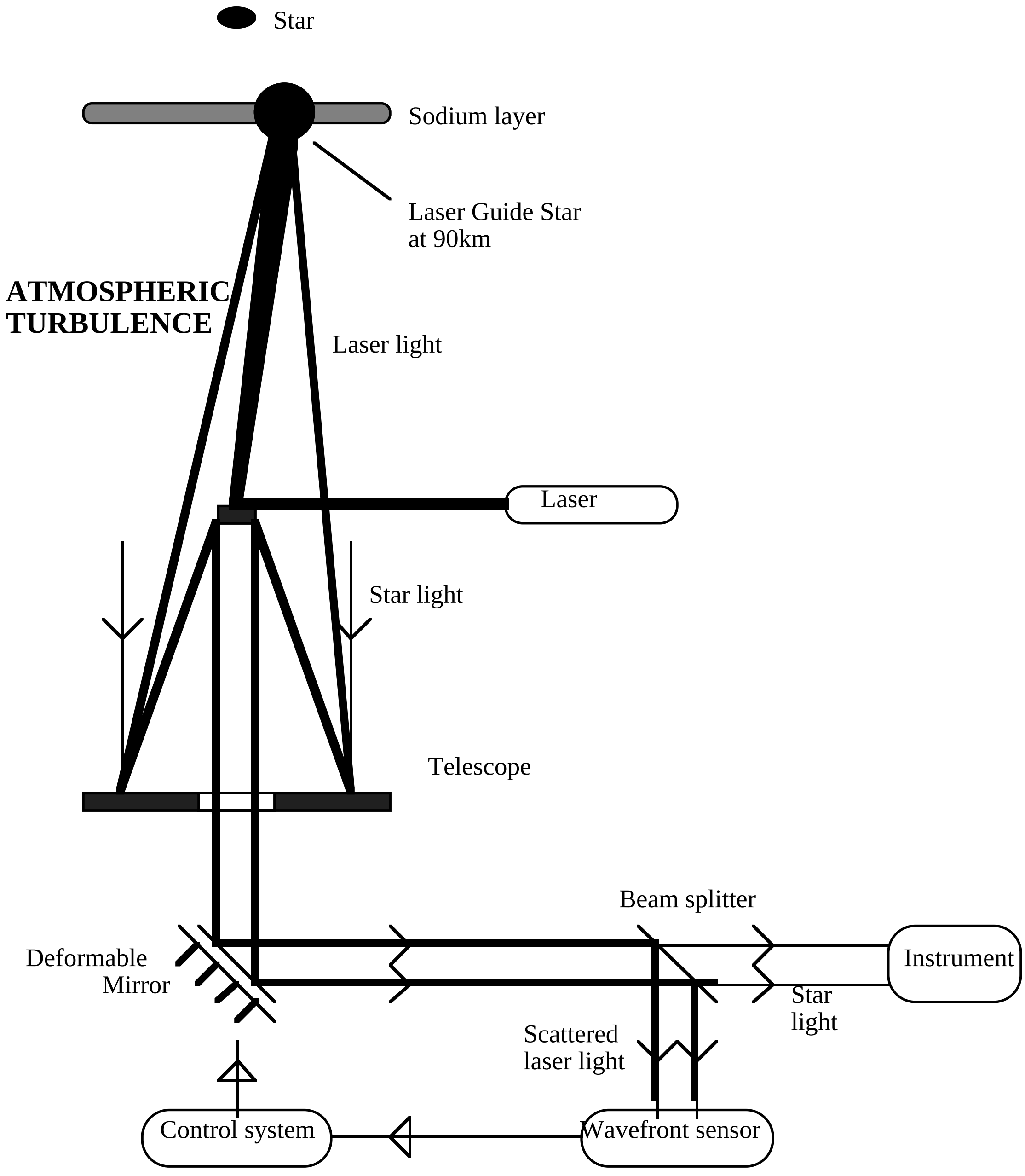


Figure 2. Schematic Laser Guide Star Adaptive Optics System (Sodium LGS)

This spot is offset from its aimpoint (section 2.4). The laser beam is projected from the telescope and scatters back from molecules in the atmosphere, here a layer of sodium atoms. The path of the backscattered photons is close to that of the natural starlight.
The AO system proceeds as figure 1, with the laser light excluded from the observations

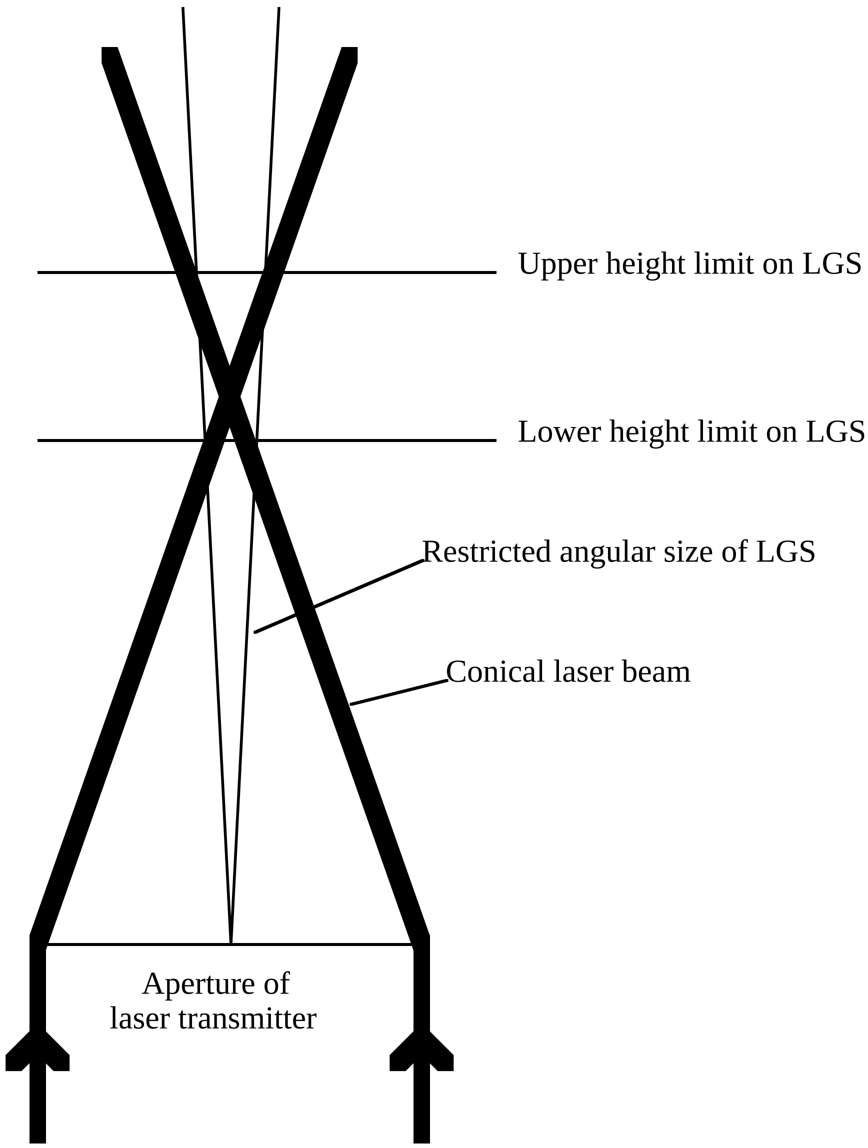


Figure 3. The need for high quality lasers

To satisfy both the height restriction and the angular size restriction, the laser must only illuminate a restricted region of the atmosphere. If the beam quality is poor, then the illuminated region is larger than the allowed region, and the LGS is rendered useless. If the aiming is poor, then part of the illuminated region lies outside the allowed region, and the LGS is rendered useless.

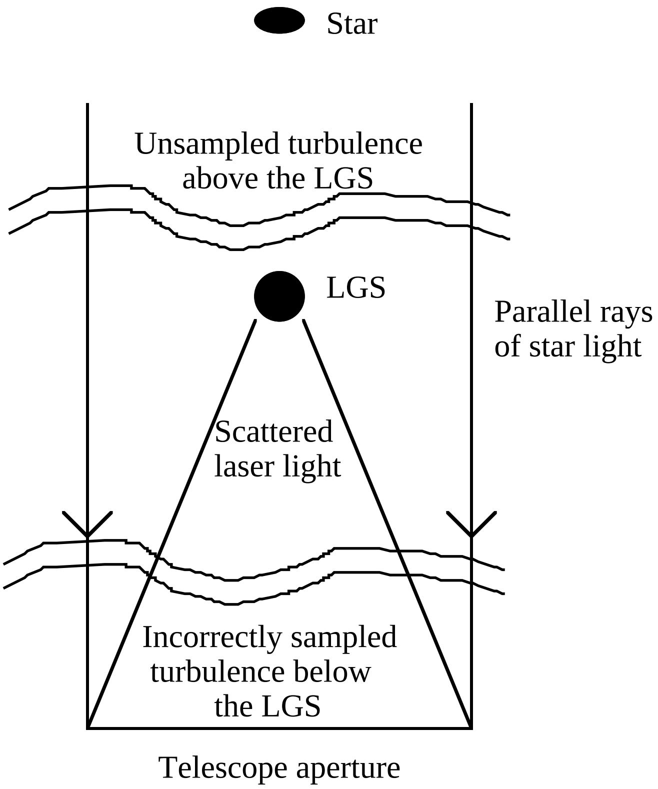
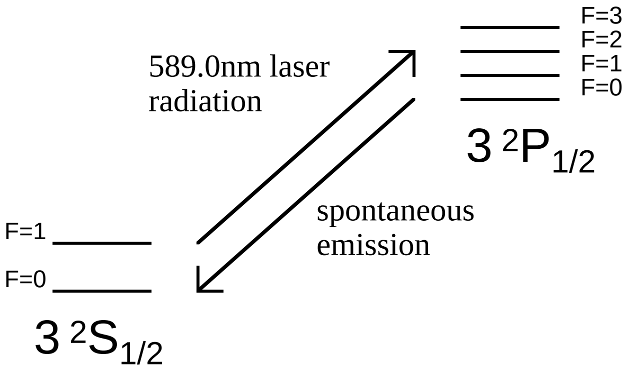
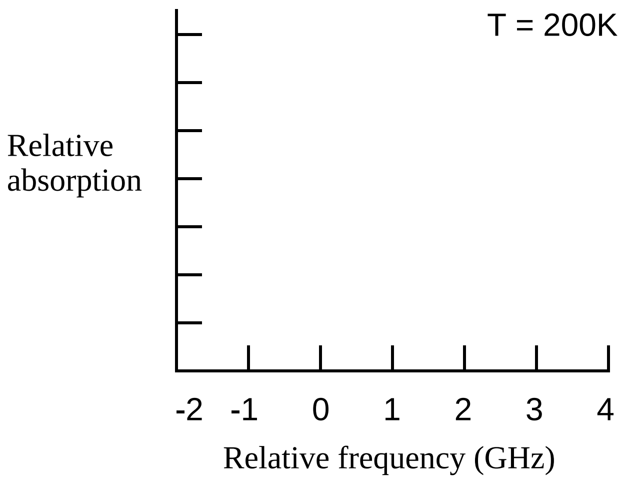


Figure 4. The Cone Effect

The path of LGS photons differs from that of stellar photons. LGS photons do not sample any turbulence above the LGS, and sample turbulence below the LGS differently to stellar photons. The LGS wavefront is therefore distorted differently to the stellar wavefront. The correlation between the two wavefronts is better for a high LGS.



a) Energy levels for the sodium D_2 transtion.
Separation of the 3 $^2S_{1/2}$ ground state energy levels is 1.77 GHz.
Separations of the 3 $^2P_{1/2}$ excited state energy levels are
16, 35, 60 MHz from lowest pair to highest pair.



b) Absorption profile of the D_2 transition versus frequency for mesospheric sodium at a temperature of 200K. Transitions from the F=1 and F=2 ground states are well resolved. The ratio of areas under the two peaks (5:3) is controlled by the 2F+1 degeneracies of each state.

Figure 5.