Reduction of laser spot elongation in adaptive optics

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Abstract

Adaptive optics systems measure the wave front to be corrected by using a reference source, a star or a laser beacon. Such laser guide stars are a few kilometers long, and when observed near the edges of large telescopes they appear elongated. This limits significantly their utility. However, using more sophisticated launch optics, their shape and length can be controlled. We propose to string around the rim of the telescope a number of small telescopes, whose addition of laser beams in the scattering medium will create a compact spot. The method could also be adapted for ocular adaptive optics.

Keywords: adaptive optics - laser guide stars - phased arrays - spot elongation.

In the past several years a number of 8-10 m ground-based telescopes have been built and more are now under construction. Even larger ones, on the 25-100 m scale are being planned[1,2]. To encounter the distortions due to turbulence in the atmosphere, which limits their effective coherent aperture, they are provided with adaptive optics. Adaptive optics allows to measure and undo the effects of turbulence in real time, delivering near-diffraction-limited performance at the infra-red and visible wavelengths. Most observatories are planning to employ or already have laser guide stars (LGSs), which serve as reference beacons for precise measurement of the turbulence even when nearby stars are too weak for this purpose[3].

Essentially all laser beams to create guide stars are launched through a simple telescope, located on the telescope mount, either next to the telescope or above its secondary mirror. The diameter necessary to send this beam up is approximately 0.5 m, allowing focusing down to a 0.75-1.5 m spot at 15-100 km. The larger beam diameter is set by the turbulence distorting the beam going up. Most systems use the light scattered from dust below 30 km (Rayleigh beacon) or from sodium at the elevation of 87-95 km (sodium beacon). The light return is very low, and the power of today's lasers is barely sufficient for this purpose.

The problem of spot elongation becomes significant in the larger telescopes[4]. When the telescope is small, it essentially looks at the scattered light along its direction of propagation. If the telescope diameter is large, then even for 8 m telescopes and side-mounted laser launcher, the opposite side of the aperture perceives elongation of the spot. This reduces significantly the performance of the popular Hartmann-Shack and curvature wave front sensors, as well as others. Future telescopes in diameters larger than 10-15 m will run into this difficulty for all parts of the aperture distant from the launch beam by a few metres. There are a number of solutions to this problem[4]. One of them is time-gating[5], where the detector is active only during a short time interval, or length, of the scattered beam, thus losing the rest of the light. In another solution, the detecting telescope keeps focusing on the scattered light as it travels up the sky[6]. Other solutions use two crossed, elongated beams to measure consecutively both directions normal to these beams[7]. Finally, it is possible to relay each section along the beam on a different pixel of the detector and use it as a separate beacon[8].

Most of the described techniques accept the beacon as launched from a very simple projector, and attempt to make the wave front sensing accommodate the low quality beam. We propose here to shift the weight of the problem to the launching optics[9-11]. We employ a large number of launch telescopes, each sending a weak beam up, where all beams focus and combine at the required elevation, be it 25 or 93 km for Rayleigh or sodium beacons. Each is fed by a fiber leading from a central laser. Its diameter does not have to be much larger than Fried's parameter, $d \geq r_0$. The preferred locations of these launch telescopes is where they do not disturb the astronomical observation, while utilizing the same mount as the telescope itself. Thus they can be mounted just outside the periphery of the telescope primary, or just inside the periphery of the secondary. In an alternative approach, an annulus around the telescope is fed directly by a laser. This ring of mirrors does not have to be continuous, but its light path might have to be baffled so as not to interfere with the astronomical one. If the primary is made of segments, it is possible to replace some of the (smaller) segments with launch telescopes, at the price of a slightly worse point-spread-function for the telescope. Another alternative is to use the whole telescope[12], or masked sections of its primary, for launching the beam, directly from the focal position conjugate to the beacon (Fig. 1).

Future telescopes will certainly employ wide-field-of-view adaptive optics (also known as multi-conjugate adaptive optics, or MCAO)[13,5]. While natural guide stars alone might be sufficient for larger telescopes[14-16], we have to keep in mind smaller telescopes observing in sky areas devoid of stars. In these regions several LGSs[17,18] or fringes[9,10] might be necessary for atmospheric tomography. Such patterns of LGSs can be produced with the method described here, as direct images of the arrangement of fibers or interference in the foci of the projecting telescopes. In the central beam approach, where the beams are projected from the periphery of the telescope, this guide star pattern has to be produced at the position conjugate to the laser position (Fig. 1).

In a coherent option, which is much more difficult to realize, a phased array tailors the beam shape at positions matched to our needs. The method proposed previously was a simple interference of three nearby apertures to create fringes over a large area to better sample the atmospheric turbulence[9,10]. However, this design may suffer even more from the spot elongation effect, as the fringes, when observed obliquely, hide each other: this is the Venetian blind effect[19]. But interference allows adding coherently the beams at chosen locations. For example, a hologram (or a computer-generated one) can be designed to create a specific three-dimensional pattern in the sky, including tilted laser beams[20] which should reduce the spot elongation. Because of the complexity of the design, which also requires adaptive correction of the ascending beams[21], we leave it for a further study.

An advantage of the light piling approach is the reduction of the problem of global tip-tilt, which usually arises when the ascending and descending beams traverse the same aberrated path and hence cannot remove the degeneracy caused by these aberrations[22]. By virtue of the multiplicity of paths and of the larger diameter of the telescope (near or larger than the outer scale), it is possible to average out these contributions. In a more complex scheme, where each launch telescope projects a few beams (all with the same tip-tilt error), they can be separated temporally or at a lower altitude and even corrected.

We examine the incoherent addition of all projected beams at the required altitude. These beams overlap within a volume of two cones (Fig. 2), whose angular width is λ/d, where d is the diameter of the launch telescopes and $\lambda \approx 0.5\mu$m is the wave length. Since turbulence is the limiting factor, the diameter is usually chosen to match it, $d \approx r_0$. The actual width of the spot at altitude H is

$$w \approx \frac{\lambda H}{d}$$

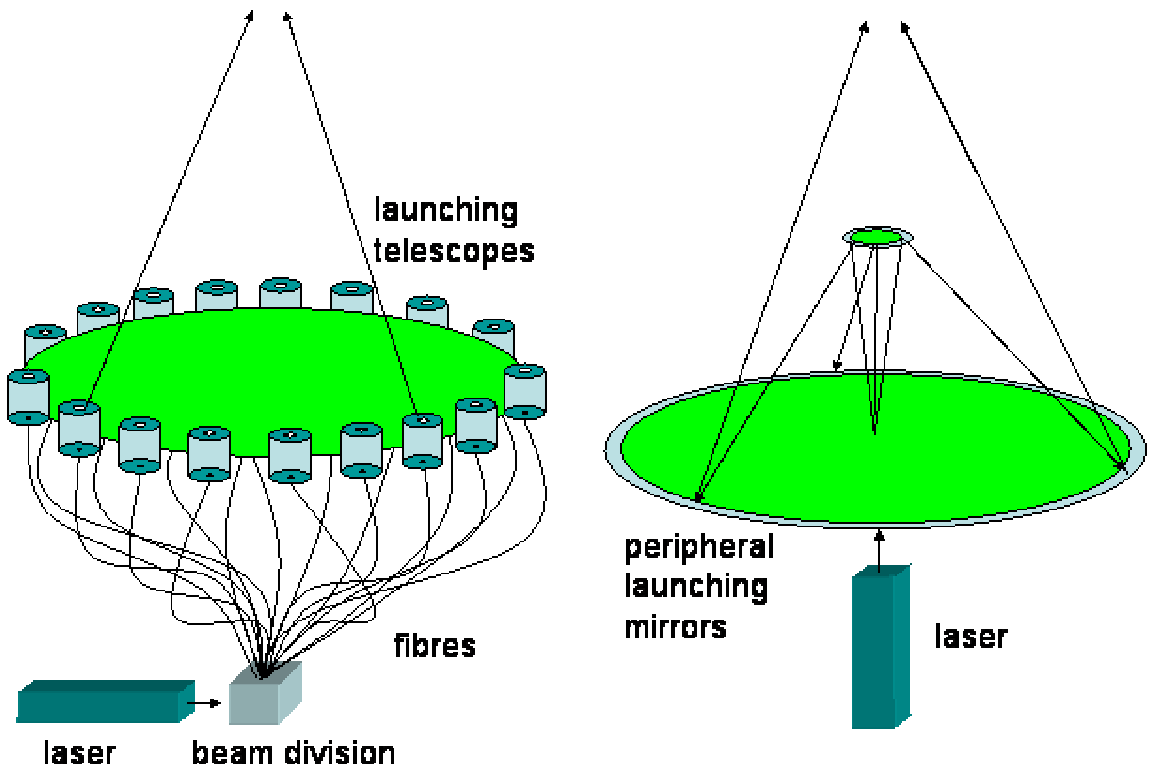

Figure 1: Mounting the launch optics around the rim of the telescope allows for better focusing of the laser spot. Left: fibre feed from a single laser with separate telescopes The projection optics can ring the telescope primary or its secondary. Right: mirrors around the edges of the mirrors are focused at therequired position.

If the distance between launching telescopes is L, then the height of the spot is

$$h \approx \frac{2\lambda H^2}{dL}$$

This is much larger then its width w, and it limits the spot size as seen from the ground. At a distance r from the centre, the subtended angle is

$$\theta(r) \approx \frac{hr}{H^2} \approx \frac{2\lambda r}{dL}$$

If the launch telescopes are around the periphery of the primary, $L \approx 2r \approx 2R$, and the spot size is λ/d or smaller as we approach the centre of the telescope. Even if they are around the periphery of the secondary, $L \approx R/2$, the worst spot elongation will be only $4\lambda/d$. For comparison, the single-beam spot elongation is also hr/H^2, where h is now the layer thickness[4,14]. For a 100 m telescope (secondary circumference projection) it is 9 times longer for the Rayleigh case, 35 times for sodium.

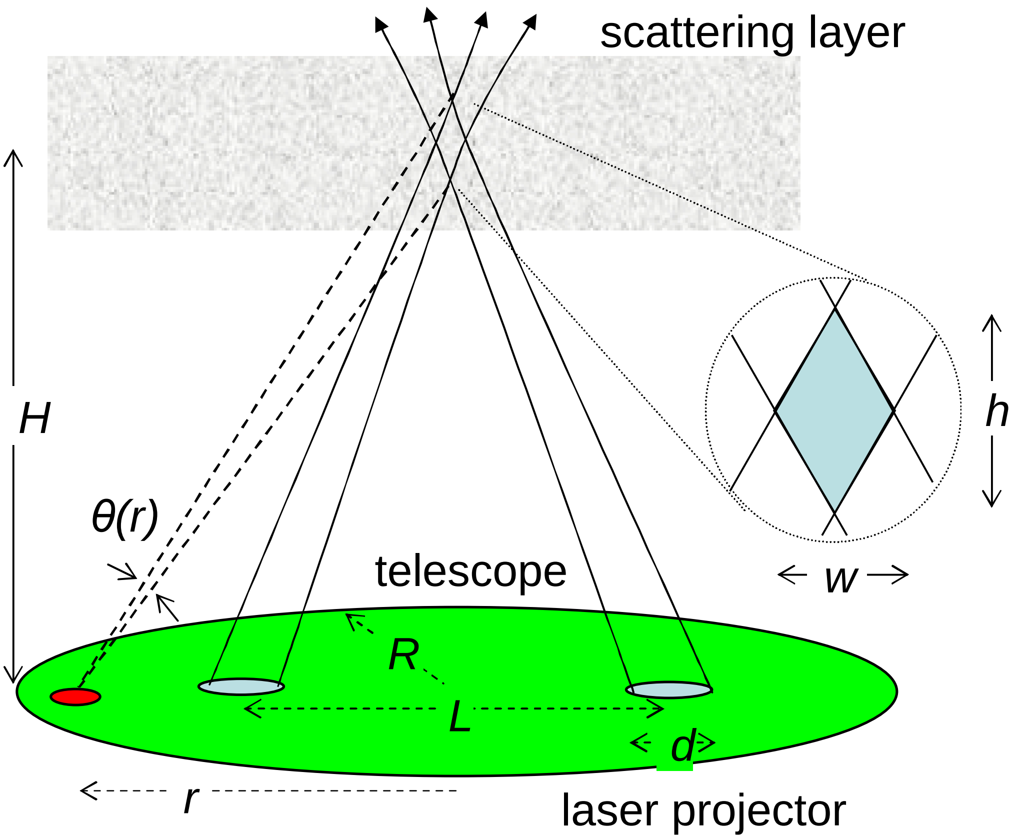

Figure 2: The geometry of projected beams. The angular extent of the spot subtends the two-cone overlap area of all side beams. In case of coherent addition, the width of the central section of this volumedrops by *d/L*.

To check out the proposed approach we ran many computer simulations. An array of 9-15 round apertures was placed around a telescope, and their pattern was calculated at infinity by simple Fourier transformation. In a typical simulation, the array size was 1024^2, the telescope diameter was 512 pixels, and the projectors' diameters 8 pixels. A spherical term was added to the whole array, corresponding to slight focal shift, and the pattern was calculated again. This was repeated for a range of distances. Finally, the three-dimensional set of intensity data was analysed from the view point of different sub-apertures on the observing telescope: from directly below the centre, from the periphery, and from points in between. We found that indeed we do get the expected tight spot from all viewing directions.

The results shown in Figures 3 and 4 include turbulence, which was a single Kolmogorov phase screen, added to the apertures before propagation. The outer scale was assumed to be larger than the telescope diameter. We found some deterioration of the spot shape, and a lateral shift (tip-tilt) resulting from the global slope of all the turbulence-affected wave front. In the case of coherent addition of the spots, the spot envelope was of the same size, but strongly speckled. Only a full adaptive correction of each aperture and all apertures can reduce this pattern to a single speckle.

We also simulated the insertion in the focal plane of each launching telescope a few fibres, each fibre coming from a different laser and so mutually incoherent. In this case we projected on the sky a magnified image of the fibres in the focal plane, which was shifting in unison, because of the equal effect of the atmosphere on all beams in each telescope. Looking at each such spot from different positions, we found that indeed there was a very limited beam elongation, in most cases below 2-3 times λ/d .Thus the Venetian blind effect is insignificant here.

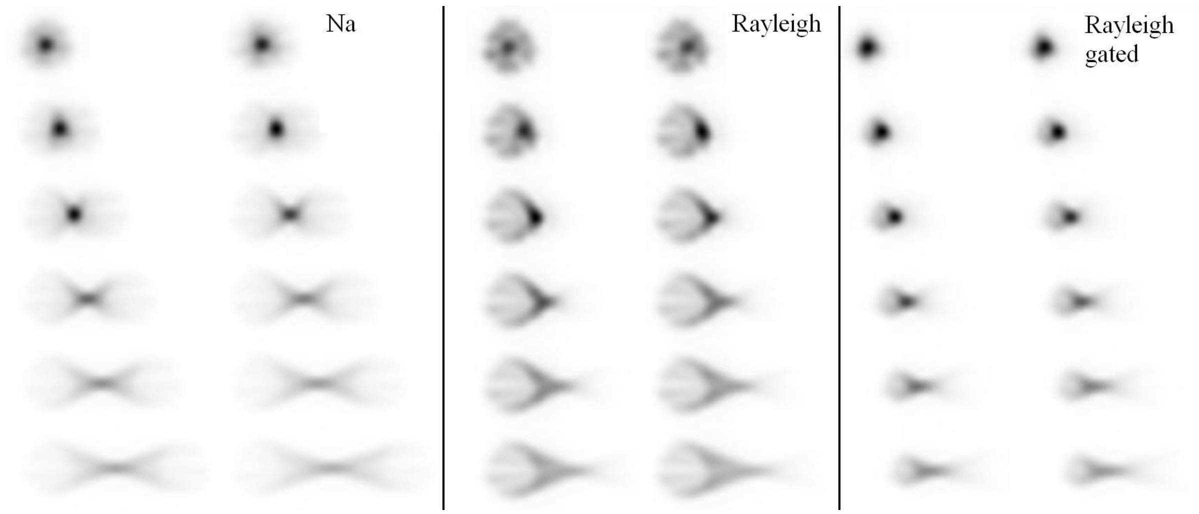

Figure 3: Appearance of a spot created by incoherent addition from a projection circle of 13 apertures, for $D/r_0 \approx 200$. We begin to discern spot elongation as we step out from the telescope centre (left to right, top to bottom), and cross the circle of apertures (5^{th} image and on). The spots were gated to show scattering only from the sodium layer (left). The central sequence shows Rayleigh scattering, gated for the last 10% of the optical path, and for the last 7.5% (right).

Finally we looked at the obscuring effects of low-altitude Rayleigh scattering on sodium or Rayleigh beacons. We added an exponential height profile to the scattered light, to match approximately the reduced scattering as a function of height[23]. Indeed now low-altitude scattering might block the higher beacons for some parts of the aperture[12] (inside the ring of launch telescopes, the pattern is different from that visible outside it all the way to the rim of the primary, Figs. 3, 4). Thus the laser light has to be pulsed, and range-gating is necessary to limit the scattering off lower elevations[12]. If the laser is continuous, then it can be switched serially between the different launch telescopes and guide stars. Suitable delay lines will be necessary in order to launch them simultaneously, so that the last (*N*th) telescope has no delay, the previous telescope a delay equal to the light train duration τ and the first telescope, a delay of $N\tau$. The actual spot length will be $c\tau$, and a short 1km beam will require $\tau = 3.3\mu s$. Notice that gating is performed in this case on the ascending beams, not at the detection stage.

To summarise, we presented a novel technique that allows compacting the elongated laser spot into a much shorter volume. A possible limitation which we did not consider at this stage is power saturation at the sodium layer, especially for the case of coherent addition of the spots. There might not be a need for such a high, saturating power, if all separate beacons are combined optically in a layer-oriented wave front sensor[14,19]. Notice also that the division into many ascending beams allows using parallel, synchronised weaker lasers, as technology barely provides a single high power laser for this application.

The solution outlined here is also valid in wave front sensing in the eye, where the reference spot is created by an external beam which scatters from the retina along ~1mm. If the beam enters through the pupil periphery (to avoid spurious reflections from the cornea), spot elongation might occur which reduces the quality of wave front measurement. Thus adding a few beams from various entrance points will create an effectively shorter reference spot.

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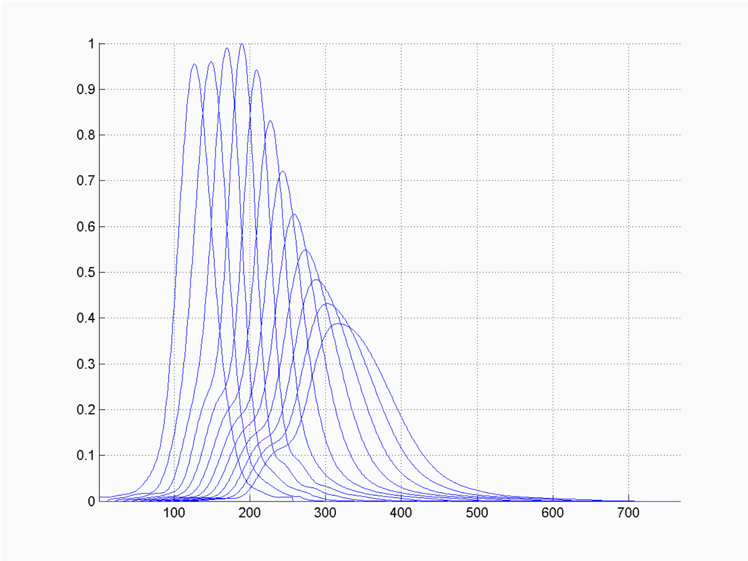

Figure 4: Cuts along the Rayleigh spots, gated for the last 7.5% of the path, as in the right sequence in Figure 3. The diffraction size is approximately 50 pixels FWHM (as in the leftmost cut). A single beacon would be nine times longer than the rightmost cut, and for Na, 35 times longer.

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