Laser guide star projection for large telescopes

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ABSTRACT

Perspective imaging of laser guide stars leads to their elongation. This effect is significant in future large telescopes, where many such beacons are necessary. Solutions to these problems include mechanical or electronic movement at the sensing devices, optical separation of the reference sources and more. Another solution is to shift the burden of analysis to the lasers and create a pattern which suffers less from perspective elongation when scattered back onto the detectors. Finally, different analysis methods can then be employed to solve for the wave front tomographically from this projected pattern.

Keywords: adaptive optics, laser guide stars

1. INTRODUCTION

Telescopes of diameter larger than 10 m are now being planned (for example, 30 m in the US, 42 m in Europe). These telescopes will be corrected by active and adaptive optics, to remedy slow and fast variations of the optics and of the atmosphere. In order to measure the quality of the wave front, the current solution is the usage of laser guide stars, in addition to natural guide stars. These beacons serve as reference optical sources at elevations of 20-100 km, in addition to the few weak natural stars in the telescope field of view.

Currently, the 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 or from sodium at the elevation of 87-95 km. The light return is very low, and the power of today's lasers is barely sufficient for this purpose.

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 launchers, 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. The main loss is in accuracy along the direction of the elongation, which, in addition, is not necessarily along a Cartesian direction of the detector. Another loss is in the division of the few photons along many detector pixels. 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 meters.

Some solutions[1-7] to the problem of spot elongation are:

1. Flexible focusing, where the detecting telescope[3], or parts thereof[4], keep focusing on the scattered light as it travels up the scattering medium. Unfortunately, during travel the beam samples also different parts of the turbulence.

2. Time-gating, where the detector is active only during a short time interval, or length, of the scattered beam. This entails loss of the rest of the light[1, 2].

3. Two crossed beams measure consecutively both directions normal to their elongation[5]. The read-out time is doubled, the number of pixels read is larger, and the two directions are not measured simultaneously. Moreover, each such pixel provides information on a separate turbulent volume and they are not mixed.

4. Height imaging, relaying each section along the beam (and turbulence volume) onto a different pixel of the detector and using it as a separate beacon[6].

5. Multiple weak beams launched from a large number of launch telescopes[7]. All beams focus and combine at 15 to 95 km. Only light from that small combination point is visible, while the rest of the scattered light is wasted. This option is developed more now.

2. TECHNICAL DETAILS

Each beam is fed by a fiber leading from a central laser or a number of weak lasers. The launch diameter does not have to be much larger than r_0. When using many lasers, the spot size is set by the average ascent path, and the location of the spot is the average of these paths. Since each laser is weak, feedback control for its separate jitter is difficult, and instead one must use of the average spot location. If a single laser is used for all beams, then the combination point will be of the same size, but highly speckled. This can be remedied by adaptive optics control of all the sub-beams (attitude control *and* phase control) and hence the formation of a single bright speckle. The size of this speckle is the diffraction size of the launch array, making it very tight.

The launch telescopes can be planted between panels of the primary. Another option is to have separate mirrors around the edges of the secondary and/or primary, focused at the right elevation (Fig. 1).

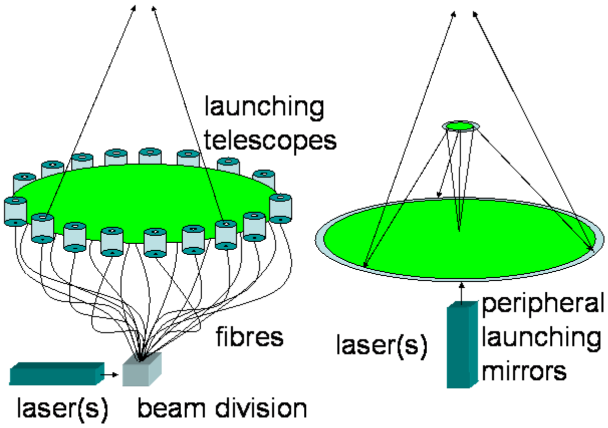

Fig. 1. Mounting the launch optics around the rim of the telescope allows for better focusing of the laser spot. Left: fibre feed from a single or many weak lasers with separate telescopes. The projection optics can ring the telescope primary or its secondary. Right: mirrors around the edges of the telescope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

3. SPOT SIZE

We examine the incoherent addition of all projected beams at the required altitude (Fig. 2). These beams overlap within a volume of two cones, whose angular width is λ/d, where $\lambda \approx 500$ nm. Since turbulence is the limiting factor, the diameter of the launch telescopes is $d \approx r_0$. The actual width of the spot at altitude H is

$$w = \lambda\, H / d$$

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

$$h = 2\, \lambda\, H^2 / d\, L$$

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

$$\theta\,(r) = h\, r / H^2 = 2\, \lambda\, r / d\, L$$

If the launch telescopes are around the periphery of the primary, $L = 2r = 2R$, 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, $L = R/2$, 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. For a 50 m telescope and secondary circumference projection it is 7 times longer for the Rayleigh case, 27 times for sodium.

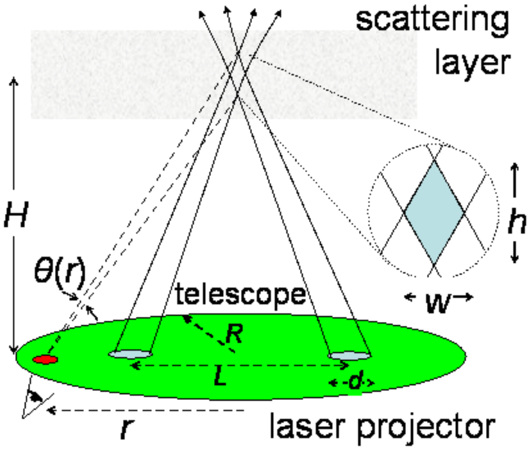

Fig. 2. The geometry of the projected beams. The angular extent of the spot subtends the two-cone overlap area of all side beams. In case of coherent addition, the width of the central section of this volume drops by d/L.

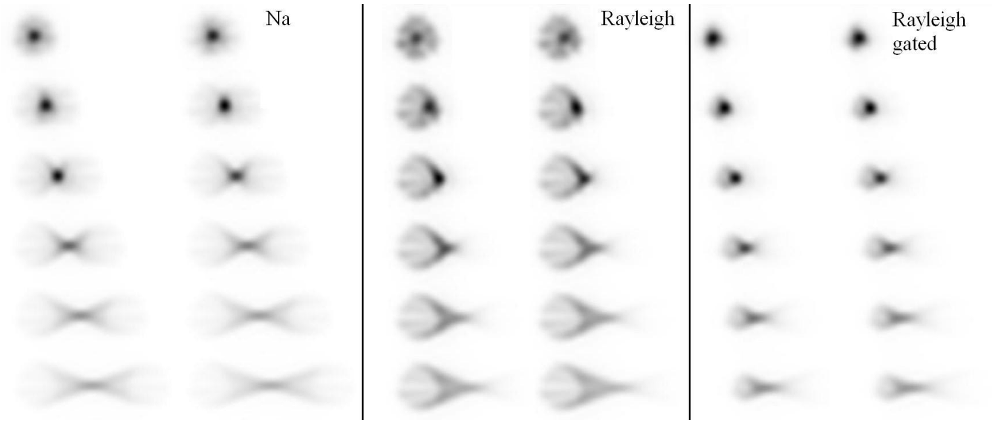

Fig. 3. Appearance of a spot created by incoherent addition from a projection circle of 13 apertures, for $D/r_0 \approx 200$ and $D/d = 64$. We begin to discern spot elongation as we step out from the telescope centre (left to right, top to bottom), and cross the circle of apertures (5th image and on). 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).

4. SIMULATION

We show a spot as created by incoherent addition from a projection circle of 13 apertures, which can be on periphery of either the primary or the secondary. More scattered lasers will create a more uniform spot. To remove low scattering, gating was applied during the lower 50% of the optical path (sodium spot), 90% and 92.5% (Rayleigh and Rayleigh gated in Fig. 3). Single layer turbulence was included[7]. The series shows the same spot as viewed though different lenslets from the center of the telescope (top left, each sequence) to the ring of lasers (fifth spot) and to 2.4 radii out (bottom right).

5. EXTENDED PROJECTIONS

How does this solution mesh in with other projection schemes? First, we look at the simple case of single beams, so designed to create single spots, at low (Rayleigh) or high (sodium) elevations. Each telescope now has to project a few (say five to ten) beams, using the same holographic beam divider. The chance that two beams will be observed to overlap unintentionally is minute, and this scheme also assumes separate wave front sensors looking only at the designated spots, so extra points can easily be neglected.

The problem becomes more complicated if one wishes to use an extended fringe pattern, which is then to be deciphered by either an extended Hartmann-Shack sensor[8], a pyramid array[9], or shearing interferometers[10, 11]. Some of these designs also require gating to avoid low-lying Rayleigh scattering for Rayleigh or sodium beacons. In this case the light density, even for weak beams, is rather high, and occasional cross beams should be avoided. Add to that the need to avoid the Venetian blind effect[9] (separate beams overlap when viewed from a large side angle), and the problem becomes even more complex.

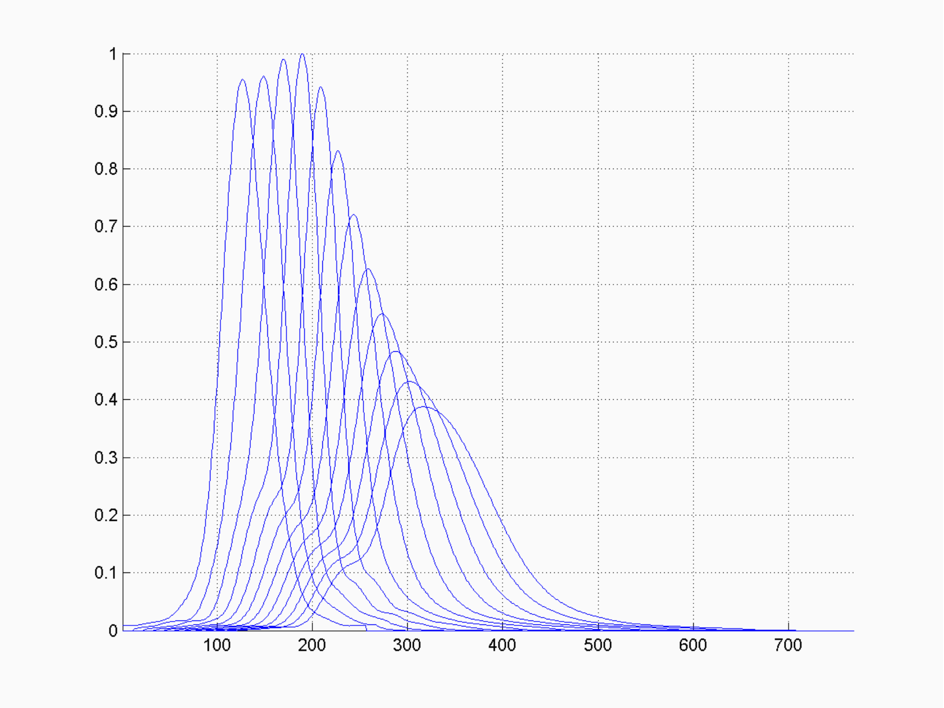

Fig. 4. Cuts along the Rayleigh spots, gated for the last 7.5% of the path (right panel of Fig. 3). The diffraction size is ~50 pixels FWHM (as in the leftmost cut). A single Rayleigh beacon would be 9 times longer than the rightmost cut. A single Na beacon would be 35 times longer.

6. SUMMARY

Comparing the single bright beacon with the multiple-weak-lasers, some issues are:

Disadvantages:

- Complex housekeeping: the separate lasers and fibres need power lines and fibres to connect to the telescopes.
- Telescope point-spread-function depends on the shape of the aperture. If some central panels are missing for the sake of laser launchers, they might scatter more light near a stellar image.

- Variable spot shape might occur when observing from different parts of the telescope aperture, and can reach up to about twice the bore-sight spot size (still much smaller than other schemes).
- Gating still required: in some instances, the scattering from lower altitudes cannot be blocked by the telescope secondary, and so have to be gated away.
- Care should be taken to avoid Venetian blind effects when multiple laser spots or some pattern are required.
- The weak beams do not allow jitter control, and make initial adjustment complicated. Thus the spot location is the average wave front tilt from all the launchers, and for a smaller outer scale, this tilt might not be so large.
- Outside the overlap region, the scattered light is not used.

Advantages:

- Reduced spot elongation: from most locations in the aperture, the spot is slightly larger than the diffraction limit.
- Reduction of global tip-tilt problem: averaging of multiple lasers reduces the collinearity of the ascending and descending beams.
- Simpler lasers: since the beams do not have to be coherent, they can be sent from weaker lasers, instead of a single bright one.
- Simpler Optics: weaker beams can be sent through fibres without worry for non-linear effects. They can all be in a central location or near the launch telescopes.

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