Abstract

A method is presented to overcome the sensitivity loss resulting from the perspective elongation in a laser guide star caused by the displacement of the laser transmitter from the telescope. It uses a rapid motion of the images formed of the laser guide star by the Hartmann-Shack wavefront sensor on the detector to compensate for the laser guide star motion (with the velocity of light) across the mesospheric sodium layer. The resulting limitations for the offset distance of the laser transmitter to the telescope are analyzed. The possible application of this technique to the ESO Very Large Telescope is described.

1. INTRODUCTION

It has been suggested\(^1\) to use the spot formed by the scattering of a laser beam tuned to the sodium D lines of the 90 km (h\(_{\text{Na}}\)) high mesospheric sodium layer for the sensing of the wavefront disturbances introduced by the atmosphere. Figure 1 shows the geometry of such an arrangement. Experiments have established the validity of this concept and the correction of atmospheric seeing by adaptive optics using such a laser guide star for modest sized telescopes has been demonstrated\(^3, 4, 5, 6\). Because of its relatively high brightness, the use of a laser guide star promises to remove the star brightness limitations and sky coverage limitations which exist when using natural stars\(^7\). As a result its implementation for astronomical telescopes like the four 8 meter diameter telescopes and the 1.8 meter auxiliary telescopes of the ESO Very Large Telescope (VLT)\(^8, 9\) is being seriously considered.

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Fig. 1 Sketch of the telescope – laser transmitter – laser guide star geometry. Plane of the figure corresponds to the plane containing these three objects. For simplicity it is shown for a zenith pointing telescope. Notations: \( h_{Na} \) = height of mesospheric sodium layer (taken here as 87 km); \( \delta h_{Na} \) = full width at half maximum (FWHM) of sodium layer (taken as 11.5 km); \( H \) = average height of the seeing layer (taken as 3.5 km for the 2.6 km high VLT site); \( D \) = telescope diameter (8 meter for the VLT); \( d \) = distance of the telescope to the laser transmitter; \( \alpha \) = pointing difference between telescope and laser transmitter.
2. THE FINITE DISTANCE OF THE LASER GUIDE STAR: EFFECTS

As a result of the finite distance of the laser guide star its use presents a number of complications which are absent in the use of natural stars for wavefront sensing and which have to be taken into account in their implementation. These are: (i) the so-called focus anisoplanatism, also referred to as the laser guide star parallax effect, which results from the different light paths followed by the natural and laser guide star radiation. At the average height \( H \) of the seeing layer the lateral displacements amount to \( 0.6D/H/h_{N\alpha} \), or 17 cm for the edge of the VLT mirrors using the values given in figure 1. At the top of the seeing layer the displacement is substantially larger. At visible wavelengths it compares with or exceeds the Fried's parameter \( r_0 \), and therefore has to be corrected. The proposed method is to use multiple laser guide stars displaced from one another and to "stitch" the resulting wavefronts together. The same pattern of multiple laser guide stars may be used to increase the size of the isoplanatic patch through multi-conjugate adaptive optics, (ii) the elongation of the laser guide star resulting from the thickness \( \delta h_{N\alpha} \) of the sodium layer and the offset \( d \) of the laser transmitter from the center of the telescope. This results in a pointing offset for the transmitter of \( \alpha = d/h_{N\alpha} \) and an angular elongation in the telescope-transmitter direction of the laser guide star of \( \beta = d \cdot \delta h_{N\alpha} / h_{N\alpha}^2 \) as seen from the telescope. This extension exceeds the \( \approx 1 \) arcsec laser guide star diameter for \( d > 3.2 \) meters and hence substantially decreases the sensitivity of wavefront sensing in this direction for photon limited applications. I will refer to it as the "perspective elongation effect". Unless compensated it sets an upper limit to the distance \( d \) of the laser transmitter to the telescope. For the VLT 8 meter telescopes this limit is less than the telescope radius, forcing the transmitter to be included in the telescopes. The description of a way to compensate the perspective elongation effect, and thus to separate the transmitter(s) from the telescope, is the topic of this publication.

3. COMPENSATION OF THE PERSPECTIVE ELONGATION EFFECT

3.1 Description of Concept

The concept for the compensation of the perspective elongation effect is exceedingly simple. Because of the finite velocity of light \( c \) and because of the short time scales \( \approx 10^{-8} \) sec involved in the resonance scattering by the neutral sodium, the instantaneous laser guide star formed by a pulsed laser will be a spot about 1 arcsec in size which moves in height across the neutral sodium layer in \( (\delta h_{N\alpha}^2 + d^2) \cdot 5/c \) seconds. As seen by the
Hartmann-Shack wavefront sensor in the telescope this motion takes twice as long, or 77 usec for $\delta h_{na} = 11.5$ km. The direction and angular velocity of this instantaneous laser guide star motion depends solely on the geometry of the telescope-transmitter configuration, and not on the height and atom distribution in the sodium layer. If a way can be found to compensate for this laser guide star motion in the Hartmann-Shack sensor, the elongation of the laser guide star can be removed.

Many ways can be thought of to remove this small but fast motion in Hartmann-Shack sensor, among which: (i) opto-mechanical scanners using wedges or mirrors, (ii) acousto-optical scanners, (iii) motion of the detector in the Hartmann-Shack sensor, (iv) magnetic deflection in the intensifier preceding the detector, and (v) movement of the charges along the columns of the Hartmann-Shack sensor CCD detector by reading the CCD out at the appropriate clock rate. The latter requires the alignment of the CCD columns in the perspective elongation effect direction. It appears to be the most straightforward and attractive of the laser guide star elongation compensation methods.

In the discussion above I have assumed that one wants to use all the resonance scattered radiation for the mesospheric sodium layer in order to obtain maximum sensitivity for the wavefront measurement. If that is not the case a fast shutter can of course be used in the Hartmann-Shack sensor to provide an additional limitation to the laser guide star elongation.

Fig. 2 Minimum wavelength at which adaptive optics can be used as a function of the distance $d$ between the telescope and the laser guide star transmitter for varying seeing conditions. Also shown is the number of adaptive elements required at these wavelengths.
3.2 The Isoplanatic Patch Limit to the Transmitter Offset

With the perspective elongation effect compensated the distance $d$ between telescope and transmitter can be increased. The size of the isoplanatic patch sets now the upper limit to that distance. I will assume that the elongation $\Delta$ of the laser guide star cannot exceed the diameter of the isoplanatic patch (taken as $0.62 \cdot r_0/H$). Since $r_0$ increases with wavelength this condition makes the maximum allowed distance $d$ dependant on both the seeing quality and the wavelength used for the adaptive optics. Inversely, a given distance $d$ results in a minimum wavelength at which the adaptive optics can be used. Figure 2 shows this relationship for 1, 1/2 and 1/3 arcsec seeing. Also given in figure 2 is the number of adaptive elements ($N$) required at this minimum wavelength. Since $N = (D/r_0)^2$ it turns out to be directly related to $d$, independent of the seeing quality. Thus for $N = 200$, as planned for the initial implementation of the VLT, $d$ can be as large as 71 meters. For $N = 2000$ $d$ cannot exceed 22.5 meters.

It may be possible to allow a slightly larger elongation for the laser guide star than the isoplanatic patch. Figure 3 shows the same diagram as Figure 2, but for a maximum elongation of $r_0/H$.

![Diagram showing the relationship between wavelength, distance, and number of adaptive elements for different seeing conditions.](image)

Fig. 3 As Figure 2 but for a maximum laser guide star elongation of $r_0/H$ radians.

3.3 Effect of Laser Pulse Length

At $d = 71$ meters a 1 arcsec elongation of the instantaneous laser guide star results from a laser pulse length of 1.7 usec. At smaller distances proportionally less. This pulse length
elongation should be avoided by keeping the individual pulse length sufficiently short.

Table 1 summarizes the properties of the lasers used for laser guide star generation. Two of the three lasers meet the pulse length requirement at 71 meters quite well. The other has a 4 \( \mu \)s pulse length, which would restrict its use to smaller distances \( d \).

**TABLE 1**

Properties of Lasers used for Laser Guide Star Generation on the Mesospheric Sodium Layer

<table>
<thead>
<tr>
<th>Authors</th>
<th>Pulse Length</th>
<th>Rate</th>
<th>Duty Cycle</th>
<th>Energy per Pulse</th>
<th>Average Power</th>
<th>Power in Pulse</th>
<th>Predicted Stellar Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thompson et al</td>
<td>2.0 ( \mu )s</td>
<td>7.5</td>
<td>.0015</td>
<td>.020</td>
<td>0.15</td>
<td>10 000</td>
<td>14</td>
</tr>
<tr>
<td>Jeys et al</td>
<td>0.1 ( \mu )s</td>
<td>1000</td>
<td>.01</td>
<td>.0003</td>
<td>0.3</td>
<td>3 000</td>
<td>12</td>
</tr>
<tr>
<td>Humphreys et al</td>
<td>4.0 ( \mu )s</td>
<td>20</td>
<td>.008</td>
<td>.120</td>
<td>2.4</td>
<td>30 000</td>
<td>12</td>
</tr>
</tbody>
</table>

**ADAPTIVE OPTICS NEEDS (.67" seeing)**

(I-CCD = intensified CCD; CCD = bare CCD)

- at 2.2 \( \mu \)m (K) I-CCD/CCD 13/15
- 1.62 \( \mu \)m (H) 12/14
- 1.25 \( \mu \)m (J) 11/13
- 0.90 \( \mu \)m (I) 10/12
- 0.70 \( \mu \)m (R) 9/11
- 0.55 \( \mu \)m (V) 8/10

**Ultimate Limit to Laser Guide Stars**

- 100
- 5 000+ 5 000+ 2

1 Assumes \( 2 \times 10^9 \) Na atoms/cm\(^2\) in mesospheric sodium layer which is the minimum value. The actual value varies, and can be as much as a factor of 4 larger. The optical depth at line center equals approximately .05.

3.4 Using CCD Technology for Image Tracking

As suggested in section 3.1 CCD arrays appear to present the most attractive way to track the rapidly moving instantaneous laser guide star image. CCD's are used for television imaging with charge transfer rates in the MHz range. In astronomical applications images are often spatially integrated by adding charges along CCD column segments. It is possible to move charges, and hence images, on the CCD without adding significant noise to the signal. The dominant noise thus originates from the statistics of the photon events and from the read-
out noise resulting from the electronics when the CCD image is ultimately read out. For Shack-Chartmann wavefront sensing the limiting sensitivity for wavefront sensing requires 100 photoelectron events per image, having 10 electron statistical noise. This is of comparable magnitude to the read-out noise, which is why intensified CCD's (I-CCD's) are often used. With the CCD read-out noise gradually improving it might be anticipated that bare CCD's will be used in future astronomical Shack-Hartmann wavefront sensors (thus eliminating the fourth image shifting method suggested in section 3.1).

For the rapid tracking of the electronic image of the laser guide star one would align the columns of the CCD with its anticipated motion direction which is set by the geometry of the telescope-laser transmitter-pointing configuration. The tracking speed varies with time in a known way provided the average height of the mesospheric sodium layer is known (e.g., using LIDAR techniques). For the conditions assumed in this paper (see caption Figure 1) and for d = 71 meters the speed varies between .33 and .25 arcsec/μs, for smaller d it will be less. With 2 x 2 pixels per laser guide star diameter (≈ 1 arcsec) that means a charge transfer rate of about 600 kHz, well within the capabilities of a CCD. In case an intensified CCD is used one has to take care that the intensifier itself has the speed required. A phosphor intermediate stage will probably not have the speed required.

3.5 Compensating the Perspective Elongation Effects at the Mirror Boundaries

After compensation of the perspective elongation effect for the telescope-laser transmitter distance d there still remains an elongation of about 1.25 arcsec of the laser guide star spots in the Hartmann-Shack sensor at the edge of the VLT 8 meter mirrors. This perspective elongation effect is symmetrical around the pupil center, and proportional to the distance to the center of the pupil. One might therefore consider removing it by a rapid variation of the magnification inside the Hartmann-Shack wavefront sensor, for example by incorporating in the intensifier which precedes the CCD detector a short zoom range.

Another way to compensate partly this effect is to make use of the polarization of the laser light. If the laser is polarized, the laser guide star will be. Using a birefringent lens to for the pupil image in the Shack-Hartmann wavefront sensor combined with a way to switch the polarization in front of the lens (e.g., using a Pockels cell) then could half the effect from 1.25 to .62 arcsec which is probably small enough to be negligible with respect to the laser guide star size (about 1 arcsec ?).

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Fig. 4 Present site layout of the VLT 8 meter telescopes (large filled circles) and of the auxiliary telescope stations (small filled circles). The laser transmitter for the presently planned 200 element infrared adaptive optics system could be located near the laser laboratory LL (filled triangle) in the center of the 71 meter circle which encompasses all of the 8 meter telescopes and many of the auxiliary telescope stations. For an eventual 2000 element visible adaptive optics system the laser laboratories have to be within 22.5 meters of the 8 meter telescopes, perhaps at the three locations shown (filled squares).
4. SUGGESTION FOR THE INCORPORATION IN THE VLT

4.1 Location of the Laser Transmitters

The removal of the perspective elongation effect will allow the location of the laser transmitters away from the VLT telescopes themselves, which substantially simplifies their incorporation in the VLT complex. Figure 4 shows the layout of the VLT site, including the four 8 meter telescopes and the stations for the mobile 1.8 meter diameter auxiliary telescopes used solely for interferometry. Also shown is the possible location of a single laser transmitting station which is within the \( d = 71 \) meter range of all 8 meter telescopes (set by the initial \( N = 200 \) adaptive optics complement of the 8 meter telescopes) and of many of the auxiliary telescope stations. It would have to include a number of steering devices to place the desired number of laser guide stars in the light paths of each of the telescopes.

In the future, as \( N \) is increased, it will be necessary to provide for laser transmitters for each of the VLT telescopes, including (mobile?) ones for the auxiliary telescopes. The removal of the perspective elongation effect allows these transmitters to be located outside the \( \approx 30 \) meter diameter 8 meter telescope enclosures, possibly as shown in Figure 4.

4.2 Pointing of the Laser Transmitters

Each of the laser steering devices has to be accurately pointed to place the laser guide star at the correct location near the center of the isoplanatic patch. To place the laser guide star in the center of the 8 meter telescope light beam an offset pointing of \( \alpha \) will be needed (see figure 1). This pointing can be controlled by the "tilt" signal provided by the Hartmann-Shack wavefront sensor. As is well known, this tilt signal does not contain any useful information on the astronomical wavefront itself. It is however very well suited as a signal to be used to point the laser transmitter.

5. CONCLUSION

The implementation of laser guide star technology for astronomical telescopes is still in its infancy. Its promise for vast enhancements in the scientific capabilities of ground-based astronomical telescopes make it likely that this technology will experience rapid development. With it will come the desire to fit and retrofit telescopes with it. The capability to eliminate the perspective elongation effect as proposed here will substantially simplify this.
References:


