Pseudo-infinite guide stars for multi-conjugated adaptive optics on extremely large telescopes

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Accepted 2006 February 24. Received 2006 February 23; in original form 2005 May 19

ABSTRACT
We introduce a novel concept to sense the wavefront for adaptive optics purposes in astronomy using a conventional laser beacon. The concept we describe involves treating the light scattered in the mesospheric sodium layer as if it comes from multiple rings located at infinity. Such a concept resembles an inverse Bessel beam and is particularly suitable for multi-conjugated adaptive optics on extremely large telescopes. In fact, as the sensing process uses light apparently coming from infinity, some problems linked to the finite distance and vertical extent of the guide source are solved. Since such a technique is able to sense a wavefront solely in the radial direction, we propose furthermore a novel wavefront sensor by combining the inverse Bessel beam approach with the recently introduced z-invariant technique for a pseudo-infinite guide star sensor.

Key words: instrumentation: adaptive optics – telescopes.

1 INTRODUCTION

Adaptive optics (AO hereafter) allows almost diffraction-limited imaging, provided that a suitable reference source is close enough to the scientific target (Beckers 1993). Such a dependence leads to the well-known problem of limited sky coverage. Creating artificial beacons in the atmosphere (Happer et al. 1994) is at the moment one of the most favoured options to overcome this problem. These so-called laser guide stars (LGSs hereafter) are excited as a result of Rayleigh or resonant backscattered laser light and supposed to be created near the science target at a distance of a few arcseconds. The use of resonant backscattered light goes back to Foy & Labeyrie who proposed to generate an LGS by exciting sodium atoms in the Earth’s atmosphere (Foy & Labeyrie 1985). Since the sodium is concentrated in a high atmospheric layer from roughly 90 to 100 km, a large part of the atmosphere is probed by the light of the artificial reference source. Nevertheless, several problems limit the easy adoption of this technique at astronomical telescopes: unlike a natural guide star (NGS hereafter), an artificial guide star forms at a finite distance from the telescope aperture. Therefore the backscattered beam samples a cone rather than a cylinder of the atmospheric turbulent layers, leading to an error in the wavefront estimation known as conical anisoplanatism (Fried 1982). This error strongly depends on the ratio of telescope diameter $D$ and height $H$ of the artificial source. Thus it becomes most problematic in the framework of extremely large telescopes (ELTs hereafter) (Gilmozzi, Dierickx & Monnet 2001; Andersen, Owner-Pettersen & Gontcharov 2001). Furthermore, one has to consider the absolute tip–tilt indetermination problem (Pilkington Thompson & Gardner 1987).

Because of the technical difficulties in producing a reliable laser beam of proper characteristics, LGSs are not widely yet used as facility instruments. To achieve a diffraction-limited correction over a big field of view (FoV hereafter) (Beckers 1989) this becomes even more complex, since several LGSs have to be projected simultaneously. Nevertheless, different efforts have been made to build facilities for LGSs at several 8–10 m class telescopes in order to prove the efficiency and reliability of such systems (Rabien et al. 2002; Contos et al. 2003), and the first scientific results from applying such guide stars have been obtained (Gates & al. 2004). Recently it has been pointed out that besides the adoption of LGSs, an interesting sky coverage in terms of multi-conjugated adaptive optics (MCAO hereafter) can be achieved by using several NGSs, especially at the longer wavelengths (Ragazzoni et al. 2002). However, it is questionable what performance in terms of achieved Strehl and sky coverage is considered acceptable, and hence to what extent it will be advantageous to utilize solely NGSs. Moreover, one should consider that by pushing the limits in terms of Strehl and sky coverage to higher values and shorter wavelengths, the exclusive sensing of NGSs is not sufficient. While we do not know exactly where such a limit is placed, LGSs seem to be a realistic option, especially for ELTs. It is noticeable that some recent findings have shown

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unexpected possibilities for NGS-based approaches within the ELT framework (Ghedina et al. 2003), while most of the conventional techniques used for LGSs scale badly to ELTs.

2 LIMITATIONS OF LGSs IN THE ELT CASE

Already at 8–10 m class telescopes it is a technical challenge to realize LGS facilities because of several limitations. We want to focus in this section especially on the problems, which will have an even higher impact in the case of ELTs.

(i) Perspective elongation. A sodium LGS takes shape in the mesospheric sodium layer at an altitude \( H \sim 100 \) km, having a non-negligible thickness \( \Delta h \sim 10 \) km. Therefore the LGS appears elongated, even assuming an on-axis launch of the LGS from the centre of the telescope. The maximum size \( \Omega \) of the elongation can be deduced by geometric considerations and is given by

\[
\Omega \approx \frac{D \Delta h}{2 H^2}.
\]

For a \( D = 100 \) m telescope this would lead to \( \theta \approx 10 \) arcsec. Firing the laser off-axis will create an even larger elongation. The result of this estimation translates into hard requirements on the FoV and detector size of a wavefront sensor. In any case, however, the elongation impacts any centroiding technique, as the spot has a different width depending on the direction (Viard et al. 2000), not to mention that under several circumstances the elongation length could be larger than the isoplanatic patch itself. This raises, in general, the issue of performing temporal gating, by using a pulsed LGS, as is usually performed with Rayleigh beacons.

(ii) Pulse format. Temporal gating cannot be made arbitrarily small, and the fact that a pulse cannot be infinitesimally short will make the elongation of the projected guide star never smaller than a certain amount. Take equation (1) with \( \Delta h \) substituted by \( c r \), where \( r \) is the duration of the pulse and \( c \) is the speed of light. Constraining the expression with the isoplanatic angle defined as the ratio of the Fried parameter to the average height of the turbulence \( r_0 / (h) \), we obtain an upper limit to the macro-pulse duration given by

\[
\tau < \frac{2r_0 H^2}{(h) D c}.
\]

Today, as has been pointed out (Thompson 2002), no sodium laser facility exists that could reach such requirements for an ELT of the considered diameters doing correction in the visible. A further point to be mentioned is the problem of saturation which becomes stronger when the pulse is shorter, as the instantaneous power should scale accordingly. Moreover, this technique is connected with a huge loss of light.

(iii) Differential aberrations. A telescope optimized for objects at infinity takes lower quality images of a source at a finite distance. As calculated for a simple single mirror (Ragazzoni et al. 2001a), the spherical aberration for a \( D = 100 \) m telescope on-axis will be \( \approx 9 \) \( \mu \)m. However, this is strongly dependent upon the optical configuration and changes from case to case. The optical system has to compensate for such distortion with a precision better than one part in \( 10^3 \) to get AO running in a closed loop with negligible Strehl degradation in the red end of the visible band. Alternatively, one could conceive of a wavefront sensor with an equivalent dynamic range, i.e. through blurring the spot for a Shack–Hartmann sensor or huge vibration of the pyramid prism for a pyramid sensor but any wavefront sensor would pay for such a dynamic range in loss of sensitivity (a decrease to an accuracy of 1 part in 100 will nearly halve the achievable Strehl ratio). Furthermore, such aberrations are inversely proportional to the average height of the sodium layer from where the light returns. With any variation, introduced through changes in sodium density distribution or zenith distance during tracking, the optic has to be corrected for these intrinsic aberrations all the time with the same level of accuracy.

(iv) FoV requirements. A detailed treatment of the required FoV for MCAO with LGSs was discussed recently (Farinato & Ragazzoni, in preparation). One can easily see that the LGSs will cover a field of \( D/H \approx 200 \) arcsec or more to be able to compensate for a scientific FoV of the order of 1 arcmin. Detailed calculations for a larger number of LGSs placed in a circular ring, which is a more likely requirement for an MCAO system at an ELT, show that the required field will exceed 6 arcmin for the multiple field of view (MFOV hereafter) NGS MCAO in a layer-oriented fashion (Ragazzoni et al. 2002). It is noticeable that the requirement in FoV for a conventional LGS-based system can easily overcome that imposed by an NGS-based system (although with limited sky coverage).

(v) Conical anisoplanatism. Conical anisoplanatism issues are supposed to be solved automatically owing to the nature of an MCAO system. This statement is certainly true when noise considerations are not taken into account. With a huge conical anisoplanatism, however, as is the case for ELTs, a tomographic solution with LGSs is more noisy than a solely NGS solution. One should, for instance, think about the coverage of high-altitude layers which are less sampled with LGSs than in the NGS case, as the related footprint is smaller. Moreover, even in a closed loop, the difference between the correction of a single LGS and an NGS will be relevant, because of the different correction of the turbulence located away from the deformable mirror (DM) themselves.

(vi) Ray skewness. The skewness of rays can amount to several arcminutes. With any linear approach of MCAO the loss of spatial resolution for turbulence located away from the DM will be severe.

(vii) Absolute tilt. This effect is caused by the ground-to-beacon propagation and it is generally believed to be small for an ELT, taking into account the most recent outer scale measurements. Although the tilt effect on such apertures is probably tiny, it should not be overlooked at all. Although it is a technical issue, it will no longer be considered here as it is not a problem the fundamental nature of which will inhibit the realization of an effective MCAO on ELTs.

All of the listed effects can be reduced within a certain error budget by different approaches, but for the extreme diameters of ELTs this will in some cases be a really difficult task. However, we want to emphasize that all the problems, except for the absolute tilt determination, depend upon the finite range of the laser beacon and its elongation in the sodium layer. Some of the techniques to counteract the effects of LGSs do not only need a big technical effort, but also minimize the light efficiency and reliability of the complete system. A typical example is temporal gating, which imposes technical constraints on the detectors – fast readout electronics and shutter – and reduces the use of light by throwing away all the light outside the measurement period. Putting all the energy into the pulse translates into higher power requirements with more technical effort to reach a similar signal-to-noise ratio to the case without temporal gating.

We want now to introduce a novel concept of wavefront sensing using an LGS which can solve most of the above-mentioned problems. Similar attempts have already appeared in the literature and in fact, as usual, we can only say that this is one approach and maybe many others exist but are still to be unveiled, with features that can be much more interesting in the ELT framework.
3 THE BESSEL BEAM CONCEPT

Any beam with the intensity maximum along the axis of propagation is undergoing diffractive spreading proportional to the ratio of the wavelength $\lambda$ over the beam size $r$. The spreading is given initially by the nature of electromagnetic waves and gets increasingly noticeable at the distance $r^2/\lambda$, which is called the Rayleigh range. In Durnin (1987) it is shown that there exist solutions to the wave equation in free space that are non-diffractive over a finite distance without violating the Rayleigh law of diffraction. These solutions have an amplitude distribution described by the zero-order Bessel function, giving such a type of beam the name ‘Bessel beam’. The theory is experimentally verified (Durnin et al. 1987) using a circular slit in the focal plane of a lens and illuminating the slit with collimated light of wavelength $\lambda$ from behind. Fig. 1 shows the experimental arrangement. The lens transforms a point in the focal plane to plane waves in a certain direction as in the inverse case parallel light coming from infinity will be imaged on a distinct point in the focal plane, like a telescope does with star light. All points of the circular slit in the focal plane will create plane waves which are superimposed until $z_{\text{max}}$ and then separate again into an annulus to infinity. Along the optical axis these plane waves interfere constructively, building a non-diffractive beam. Bessel beams can be produced not only with annular masks in the focal plane but also with conical lenses or through spherical aberration as described in Hermann & Wiggins (1991). For the proposed wavefront sensor we will take advantage of such a setup in an inverse way using an LGS as a quasi-non-diffractive beam. However, this is not strictly an exact realization of the inverse Bessel beam, as we are not going to use any coherence between different portions of light in the LGS. Inverse Bessel beams translate a set of directions from infinity to a beam of light localized along the $z$-axis (a feature that is not affected by most of the problems described in the previous section). This kind of beam attracted our attention because of the similarity to the type of source represented by an LGS.

4 THE PSEUDO-INFINITE GUIDE STAR SENSING CONCEPT

4.1 Radial wavefront sensing with inverse Bessel beams

The inverse Bessel beam principle can be used to sense a wavefront for radial phase aberrations. Distinct positions in the focal plane of a telescope are directly related to directions of incoming parallel light on the sky. A mask with circular slits placed in the focal plane will select light of an LGS coming from a certain direction $\delta_i$ and project it so virtually to infinity. Let us consider rays originating at the LGS coming from one direction $\delta_i$. Additionally we assume a subaperture $l$ at the telescope pupil located at a distance $x$ from the telescope centre, the radial size of which is smaller than the projected elongation of the LGS at the pupil (Fig. 2). The size of the subaperture is determined by the chosen grid size of the re-imaged pupil on the CCD (see Fig. 5, later). In the non-aberrated case the subaperture will be illuminated by light of the LGS coming from a portion $s$ (Fig. 3). For simplicity we assume in the following that the distances of the circular slits in the focal plane are chosen in such a way that no overlap of the selected directions in the pupil plane occurs and each subaperture is illuminated only by light from one direction $\delta_i$. However, we want to point out that in principle the light throughput can be increased by illuminating each subaperture with rays from several directions, leading to a new gating concept which we call ‘angular gating’ (see Fig. 6 and Section 4.3, later).

Introducing a wavefront distortion close to the telescope pupil, the amount of light of the LGS projected into the subaperture does change with the amplitude of the atmospheric phase aberration at the edges of the subaperture. Fig. 3 illustrates that a wavefront error with a positive curvature at both edges of the subaperture leads to an additional amount of light refracted in. Such rays originate at additional portions $s_j$ $(j = 1, 2)$ of the LGS and therefore come from
different directions from $\delta_i$. Thus the intensity within a subaperture is proportional to the ‘effective’ length $s_1 + s_2$ of the beacon contributing to its illumination. By defining now $I$ and $I'$ as brightnesses within the subaperture in the non-aberrated and aberrated cases, one can write

$$\frac{I' - I}{I} = \Delta \frac{I}{I} \propto \Delta \frac{s}{s} = \frac{s_1 + s_2}{s},$$

(3)

where $\Delta s = s_1 + s_2$ is the change of the beacon length introduced by the radial distortion. Depending on the latter, it may have positive or negative sign and defines the strength of the intensity fluctuation within the subaperture. According to Fig. 3, one can prove that the maximum differential angle of a ray originating at the LGS, which will be refracted because of the distortion into the subaperture, is related to $s_j$ via

$$s_j = \frac{H}{\psi D} \alpha_j, \quad j = 1, 2,$$

(4)

while the portion $s$ in the non-aberrated case is given by

$$s = \frac{2H}{\psi D}.$$  

(5)

Here $\psi$ denotes the normalized radial pupil coordinate and is related to the distance from the centre $x$ as follows:

$$x = \psi D / 2.$$  

(6)

Combining equation (3) with equation (5), and computing the ratio $\Delta s / s$, yields

$$\Delta \frac{I}{I} = \frac{H}{\psi D} (\alpha_1 - \alpha_2).$$

(7)

The difference $\alpha_1 - \alpha_2$ depends on the slope of the wavefront distortion at the edges of the subaperture $l$:

$$\alpha_1 - \alpha_2 = \frac{\partial W}{\partial x} \bigg|_{x=-l/2} - \frac{\partial W}{\partial x} \bigg|_{x=l/2} \approx \frac{\partial^2 W}{\partial x^2} l.$$  

(8)

Replacing the differential $\partial^2 x$ by deriving equation (6) and combining with equation (7) gives the intensity fluctuation within the subaperture depending on the second radial derivative of the wavefront distortion:

$$\frac{\Delta I}{I} = \frac{4H}{D^2} \frac{\partial^2 W}{\partial \rho^2}.$$  

(9)

We want to point out that the gain $4H / D^2$ of the radial sensing device is not dependent on the subaperture size $l$. Because of its radial symmetry the mask is a purely radial sensing device not able to sense distortions in azimuthal directions.

### 4.2 Azimuthal wavefront sensing with a z-invariant wavefront sensor

To get information about the deviation of the incoming wavefront in the $\theta$-direction, an additional sensing device is necessary. We adopt here the concept presented by Ragazzoni et al. (2001b), based on a reflective rod placed in the image space conjugated to the laser beacon (see Fig. 5, later). While conventional devices such as the Shack–Hartmann or the pyramid sensors perform the sensing in a single plane in the image space, the reflective rod acts as a three-dimensional wavefront sensor conjugated to the extended source. In the following we give a summary of the reflective rod as an azimuthal sensing device. For simplicity we assume that the exit pupil, seen from the rod, is at infinity. This condition can easily be ensured by using proper imaging optics. It should also be stressed that the pupil image will be rotated by 180$^\circ$ because of the reflection on the rod surface. Rays originating from the LGS at a certain height will converge at the conjugated height slice in the image space and will be reflected by the rod. Let $r$ be the radius of the rod. We consider now a stigmatic ray leaving the exit pupil. It will hit the rod at point $P$ (Fig. 4). Since the projection of the ray trajectory is normal to the rod surface, the reflected ray will not be deviated. Of course this is a consequence of the particular setup shown in the figure, although it is always possible to reproduce this situation by a proper choice of the reference frame on the pupil plane, with no loss of generality. In the case of an aberration associated with a non-zero derivative with respect to the azimuth angle $\theta$, the ray hits the rod at $P'$, displaced from $P$ by an amount $b$, and is deviated at an angle $\beta$ given by

$$\beta \approx \frac{2b}{r},$$  

(10)

where it is assumed that $b \ll r$. Considering that the linear displacement $b$ is proportional to the wavefront aberration and carrying out the details of the calculation as explained in Ragazzoni et al. (2001b), one obtains

$$\beta \approx \frac{4F}{\rho r} \frac{\partial W}{\partial \theta},$$  

(11)

where $F$ is the focal ratio of the telescope. In order to describe the intensity modulation on the image of the exit pupil, we consider two rays coming from the points $(\rho, \theta)$ and $(\rho, \theta + d\theta)$. After reflection on the rod, $\theta$ is mapped to $\theta + \pi + \beta(\theta)$ and $\theta + d\theta$ to $\theta + d\theta + \pi + \beta(\theta + d\theta)$; the angular separation between the reflected rays is therefore

$$d\theta' = d\theta + \beta(\theta + d\theta) - \beta(\theta).$$  

(12)

Expanding $\beta(\theta + d\theta)$ to first order according to equation (11), we obtain

$$d\theta' \approx d\theta + \frac{4F}{\rho r} \frac{\partial^2 W}{\partial \theta^2} d\theta.$$  

(13)

The transformation $d\theta \rightarrow d\theta'$ is associated with a modification of the ray density on the image of the exit pupil. The modulated intensity ratio $\Delta I / I$ can be written as

$$\frac{\Delta I}{I} \approx \frac{4F}{\rho r} \frac{\partial^2 W}{\partial \theta^2}.$$  

(14)
where \( I \) is the illumination at the subaperture in the non-aberrated case and \( \Delta I \) is the change in intensity due to the aberration. It can be concluded that the wavefront sensor, to a first-order approximation, is sensitive to the second derivative of the wavefront with respect to the azimuthal coordinate. The sensitivity is inversely proportional to the radius of the reflective rod: by adjusting the latter it is possible to tune the sensitivity to the azimuthal part of the aberrations and achieve a proper balancing in terms of gain, compared with the radial part.

### 4.3 Combined signal

The two techniques can be combined into a pupil-plane wavefront sensor measuring the second derivative of an incoming wavefront. We will call the entire system the pseudo-infinite guide star sensor (hereafter PIGS). Fig. 5 shows a sketch of a practical layout. The optical axis is denoted by \( z \). An LGS excited at height \( H \) in the sodium layer of the mesosphere with thickness \( \Delta h \) is illuminating a telescope with an \( F \)-ratio of \( f_1/D \). The slit-mask is placed at the infinity focus of the telescope performing the radial sensing. The rod is separated from the pupil by a telecentric lens with focal length \( f_2 \) and positioned where the image of the LGS is formed. This setup guarantees conditions for both devices as described in Sections 4.1 and 4.2. The pupil is re-imaged by proper re-imaging optics on a detector.

The entire intensity distribution at the resulting pupil image depends on the curvature of the incoming wavefront. The received signal from both devices can be synthesized by combining both single signals in an additive way:

\[
\frac{\Delta I}{I} \propto \left( A \frac{\partial^2 W}{\partial \rho^2} + B \frac{\partial^3 W}{\partial \rho^3} \right).
\]  

As mentioned in Section 4.2, it is mandatory to adjust the coefficients \( A = 4H/D^2 \) and \( B = 4F/\rho r \) in such a way that the gains of both sensing modes are comparable. This is possible, for instance, by choosing a suitable rod diameter.

### 4.4 Sensor efficiency

#### 4.4.1 Slit width and angular gating

Since the inverted Bessel beam principle involves a selection of the light rays approaching the focal plane, there is no doubt that some light of the LGS is rejected and will not contribute to the formation of the wavefront signal. In the following we want to make an estimate of the real light throughput of such a system and compare it with the temporal gating approach. Let us now consider only a single annular slit in the focal plane and focus our attention on the annular region of the pupil that is illuminated by the light passing through such a slit. Any point in this annular region will receive light coming from a portion of the LGS strip as wide as the slit width. This means that, once such a width is of the same order as the apparent elongation of the temporal gating, the optical throughput will be the same. Since we have considered a slit width of the same size as the seeing disc — which is the usual choice for temporal gating — one can easily see that, for a single circular slit, the throughput is identical. Because of its nature the selection process of the mask can be seen in analogy to the temporal gating technique as angular gating. As soon as one is able to place at least one annular region in the pupil, the throughput of the PIGS will be equal to the temporal gating one.

#### 4.4.2 Multiple angular gating

However, in contrast to temporal gating, multiple gating (Fig. 6) is very easy as this simply translates into placing more and more annular slits illuminating one subaperture. One can argue that the same point on the pupil can be illuminated by a certain multiplicity \( M \) of different annular regions leading to

\[
M \approx \frac{\Delta h \rho D}{2 \mu H}.
\]  

where \( \mu \) is the angular distance between consecutive slits. With some reasonable choices (\( D = 100 \, \text{m}, \mu = 1 \, \text{arcsec} \)) we have \( M \approx 10\rho \).
For an $\varepsilon = 0.3$ telescope (where $\varepsilon$ is the diameter of the central obscuration) this figure is in the range 3 to 10. However, a looser choice for $\mu$ will rapidly make this factor become less dominant. Therefore – using the example considered here – the throughput of a PIGS system can be larger by a factor of $\sim 3$ than in a temporal gating approach. We hereby recall again that, when comparing differences among these techniques, it is imperative to consider that light throughput is not the only factor – the real efficiency should also consider detector efficiency (and on this topic all fast detectors usually exhibit efficiencies much smaller than conventional ones which can integrate for as long as a turbulence coherence time) and wavefront sensor efficiency (for instance, a Shack–Hartmann with huge spots will be less efficient than one with small spots, with the same level of illumination in the two cases). It is interesting to show that in principle a throughput approaching the full usage of the beacon light is possible, by making the blocking part of the mask with the circular slits a reflective one and by arranging a focal plane with a net non-telecentricity angle. In that way the reflected light can be collected by a second and similar system and later recombined with the direct one by numerical or even optical means. This option is merely noted here, as the practical problems involved in such an approach will easily overcome the augmented efficiency.

4.5 Calibration issues for PIGS

In this section we want to address several considerations about possible issues relevant to the calibration of this new wavefront sensor. This is not necessarily a complete list and the solutions shown are only a first indication. A detailed study should consider all these and analyse other possible sources of miscalibration.

(i) Sodium density variation. The radial illumination variations on each annulus will resemble the height density variations of the sodium layer in the illuminated column. These will actually be smeared out by an effect similar to the ‘venetian blind effect’ (Ribak & Ragazzoni 2001) and they can be, in principle, tracked by an independent telescope monitor or by averaging one open-loop measurement on a time-scale much larger than $1/f_g$ (where $f_g$ is the Greenwood frequency). This is somehow equivalent to a flat-fielding done on a regular basis on the averaged images collected during the wavefront sensing.

(ii) Beam wandering. A further effect to be considered is related to the wandering experienced by the laser beam in the upward path. As a consequence of this, the position where a ray coming from a virtual point at infinity intersects the beacon changes with time. As long as this variation occurs on time-scales smaller than the integration time, the net effect is equivalent to a smoothing of the sodium layer distribution, which makes the flat-fielding of the pupil plane somewhat easier.

(iii) Beam thickness. A similar effect, although static with respect to time, is due to the finite column of the laser beacon: the rays illuminating a certain portion of the pupil actually come from different depths along the beacon slice and the net effect is a smoothing of the local sodium layer inhomogeneities.

(iv) Static aberrations. Static aberrations of the telescope at the conjugation of the LGSs are an issue in terms of calibration. This is not really a problem for circular symmetric aberrations, as these will translate into a different position where the ray is hitting the reflective rod. The only possible effect could be the need to have a marginally longer reflective rod than is computed without taking account of such an effect. In the case of non-circular symmetric aberrations, however, one has to take care that the diameter of the rod is large enough to ensure that the light beam is within a sufficiently small neighbourhood of the point where a non-aberrated ray would hit the reflective rod. This will place an upper limit on the wavefront sensor sensitivity. As this does not affect the radial wavefront sensing, one could be tempted to have only the latter kind of wavefront sensor for the LGS located far away from the axis of the telescope. Also this will make it more difficult to cover a layer completely in order to recover information on the wavefront. This, in fact, will translate into the need for a larger number of LGSs. A hybrid approach can involve reflective rods of different diameters: small close to the optical axis of the telescope, and larger toward the edges of the FoV. A detailed analysis can only be made as a case study for a specific telescope design.

5 MULTI-CONJUGATION WITH MULTIPLE REFERENCES

We now consider the application of the PIGS concept to MCAO, a technique proposed by Beckers (1993) to overcome the problem of the anisoplanatism inherent to the single-reference AO case. The goal is achieved by measuring the atmospheric turbulence over several angular directions, using the light from different reference sources, in order to reconstruct the three-dimensional structure of the turbulence and then correct it by different deformable mirrors conjugated to the strongest layers. It is interesting to note that, even with a single LGS, the finite distance of the reference source from the telescope aperture, which on the one hand is responsible for the conical anisoplanatism, on the other hand is associated with a finite range of angular directions for the rays coming from the guide star, an effect which, however, does not allow a tomographic reconstruction of the atmospheric turbulence. In order to achieve this goal in a FoV of a few arcminutes, several reference sources are required. A good coverage of the atmospheric column can be achieved by optimizing both the position of the LGS projectors in the aperture plane and the launch direction. The projectors can be reasonably placed in the central obstruction or at the edge of the telescope aperture. The pupil coverage associated with each reference beacon depends on the combination of accepted FoV, vignetting by the telescope aperture and focal plane masks which select specific angular directions depending on their radius. This reasoning can be generalized to the meta-pupil at a certain distance from the telescope.

Three limiting cases of laser projector position and launch direction are illustrated in Fig. 7. The angular coverage is linked to the focal plane masks, which select specific angular directions depending on their radius. Rays from different LGSs but having the same angular direction are focused by the telescope on to the same mask, as if they were coming from the same source at infinity. It is remarkable that the position of the circular slits depends only on the direction in which the beam is fired, while the position of the annulus on the pupil depends only on from where the beam is fired.

6 CONCLUSIONS

In this paper we have introduced a novel wavefront sensing approach for LGS-based AO facilities on 30–100 m class telescopes. The technique deals with the LGS-induced constraints coming from its finite distance and the non-negligible thickness of the atmosphere. This is done in a somewhat ‘natural’ way and so the approach overcomes some major limitations, like perspective elongation and issues related to the pulse format. The concept is based on the inversion of the Bessel beam concept to create diffractionless beams. Hereby
Figure 7. Three extreme cases of an LGS fired in an MCAO approach for the PIGS concept. A is a beam fired from the centre of the pupil and along the optical axis of the telescope, B is still fired from the pupil centre but with a certain offset angle, and C is fired again along the optical axis of the telescope but from a decentered position with respect to the pupil. It can be noted that these three LGSs are associated in different ways with the pupil and focal planes.

the incoming light is treated as if it originated at an infinitely distant source. A practical implementation has been suggested using a mask, which consists of several concentric circular slits. The device is placed in the focal plane of the telescope and imposes a new gating technique called ‘angular gating’. It has been verified that, although much light is blocked, angular gating is, even under the most conservative assumptions, 3 to 10 times more efficient than temporal gating in terms of light throughput. The mask as a radial sensing device can be upgraded to a fully working pupil-plane wavefront sensor by combining it with a reflective rod (ς-invariant sensor) used as an azimuthal sensing component. Analogous to a curvature wavefront sensor, such a system is able to measure the second derivative of the incoming wavefront in the pupil plane.

Among the effects imposed by the finite distance of the LGS that cannot be solved by the new approach, we mention conical anisoplanatism, which, however, can be solved either by projecting the LGS to a bigger distance or by means of MCAO. A multiple-reference implementation of the new wavefront sensor is possible and has been discussed.

At the time of writing, experimental work is in progress for the validation of the concept in the laboratory. A prototype of the PIGS wavefront sensor has been built and its performance tested on a set of static aberrating screens, previously characterized by a commercial interferometer. The results obtained so far have shown a very good match between the measurements. Furthermore, an on-sky experiment has been performed at the William Herschel Telescope, using a Rayleigh LGS; the experiment was conceived in such a way as to reproduce a scaled-down version of an ELT; the data reduction is still in progress at the time of writing. The outcome of this experimental work, both in the laboratory and on-sky, will be described in a forthcoming paper.

ACKNOWLEDGMENTS

The work described in this paper has been funded through the Wolfgang Paul Prize of the Alexander von Humboldt Foundation. This activity is supported by the European Community (Framework Programme 6, ELT Design Study, contract No. 011863). Thanks are due to Timothy J. Morris, Christopher D. Saunter, R. Meyers, P. Clark (Durham University), R. Rutten and the William Herschel Telescope team for supporting the on-sky experiment.

REFERENCES

Gates E. L., Lacy M., Ridgway S. E., de Vries W. H., 2004, BAAS, 204, 60.09
Thompson, 2002, SPIE, 4839, 1175

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