Rayleigh laser guide star wavefront sensing

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ABSTRACT

Rayleigh laser guide stars are an interesting tool to probe the atmospheric turbulence in astronomical adaptive optics. Conventional wavefront sensors can be applied at the expense of a restriction of the beacon range, usually realized by gating techniques, which translates into a very inefficient use of the light. Some alternative solutions to this inconvenient are presented in this paper, leading to the introduction of a new wavefront sensing concept. The idea is to place in the focal plane area an optical element whose section does not change for the conjugation to different ranges from the telescope aperture, hence the z–invariant name of the concept.

Keywords: Adaptive optics, Rayleigh laser guide stars, wavefront sensors, z–invariant

1. INTRODUCTION

Wavefront sensing in current Adaptive Optics (AO) systems for astronomical applications relies on the availability of a star close to the object of interest. The reference source must be sufficiently bright, to fulfill the photon requirements of current Wavefront Sensors (WFS). This constraint translates into a limited sky coverage.[1] A possible solution is represented by Laser Guide Stars (LGSs), i.e. artificial beacons generated by laser–light launched from the ground.[2] A further application of LGSs is related to Multi-Conjugate Adaptive Optics (MCAO), a technique proposed for the first time by Beckers[3] to obtain a more uniform correction over a larger field. While different practical implementations of MCAO have been proposed[4, 5] and the choice between natural and artificial sources is still an open problem, we focus here on LGSs.

Two ways have been conceived so far to generate a LGS, namely the back–scattering resonance in the natural Sodium layer at approximately 92km of altitude[2, 6] and the Rayleigh scattering in the lower portion of the atmosphere. At first glance the Sodium LGSs are superior: they occur at a higher altitude than attainable with a Rayleigh beacon and, because of the limited thickness of the Sodium layer, they can be, as a first approximation and for relatively small telescopes, treated as a thin slab, hence producing a nearly point reference. Most of the disadvantages of LGSs, like the lack of tip–tilt information[7, 8] and light pollution in the launching area, are common to both Sodium and Rayleigh types.

In contrast with a Sodium LGS, a Rayleigh beacon is not localized at a specific altitude. A straightforward approach is to generate the LGS by a pulsed laser and *gate* the returning signal, in order to restrict the useful range of the beacon.[9] Rayleigh LGS in gating mode have also already produced astronomical science.[10, 11]

The other main difference is inherent to the type of physical process involved in order to get a reasonable photon return. Because of the resonant backscattering nature of the Sodium LGS, the artificial beacon has to be generated by a laser exactly tuned to the Sodium doublet wavelengths. Rayleigh LGSs, on the other hand, can be generated by lasers of any wavelength, with some preference for the shorter wavelength because of the larger photon return (proportional to λ^{-4}), to be balanced against the lower transparency of the atmosphere. Unfortunately there are no known lasers that *naturally* emit at the proper Sodium resonance frequency and, moreover, the properties of the Sodium layer are not fully understood yet, especially concerning its saturation characteristics.[12] All these considerations translate into an objective difficulty to easily generate Sodium LGSs.

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Scaling to larger power and larger telescopes is another issue that, if not against Sodium LGSs, is at least able to reconduct the comparison with Rayleigh on a more common ground. For a $D = 100$m class telescope[13,14] in fact, perspective enlargement[15] of a Sodium spot will lead to an apparent angular size of the order of 10 arcsec, at least at the edge of the pupil and in the radial direction. A Shack–Hartmann approach, to sense such a huge spot with a precision of the order of the resolving power in the visible of such a telescope (being of the order of one milli–arcsec), needs a centroiding accuracy with a precision of the order of one part over 10^4, a task to be accomplished with the formidable number of $N \approx 10^8$ photons per subaperture per integration time: this figure is greater than the full–well of currently available fast CCDs. Futhermore saturation effects in the Sodium layer should be taken into account and maybe the required power to get a useful photon return will become unrealistic. Finally, when a pulsed laser is used, it might be worthwhile to use some gating technique very similar to those used with Rayleigh beacons, introducing similar practical difficulties and drawbacks.
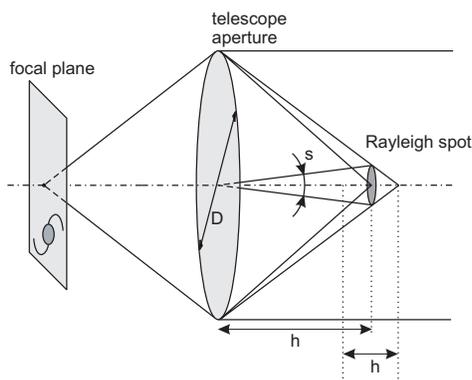

Figure 1. In a Rayleigh LGS one can *gate* the returning pulse corresponding to a certain range interval Δh. The larger such a figure, the larger the photon return. However, a large Δh also produces some unacceptable enlargement of the spot as seen from the telescope and a trade–off is required in order to have such a defocus smaller than the beacon angular size s.

2. RAYLEIGH BEACONS EFFICIENCY

Let us consider a telescope of diameter D looking at a pulsed Rayleigh beacon gated to an average range h and extending for a Δh span (Fig.1). Let us also assume that the LGS is launched from a co–axial projector focused at the range h from the telescope aperture. The spot at the minimum waist has an angular size s; other portions of the beacon, along the axis of the column, exhibit a certain angular broadening, because they are defocussed with respect to the h–ranged mid–point. It is reasonable to impose that such a broadening is to be limited to roughly the same angular size s: a larger spot size would result in larger photon demands to achieve the required centroiding accuracy with a Shack–Hartmann WFS. The range of the gated beacon is

$$\Delta h \approx \frac{2sh^2}{D}. \tag{1}$$

In order to avoid adaptive optics compensation in the launching projector it is reasonable that $s \approx \lambda/r_0$, where r_0 is the Fried parameter,[16] and Eq. (1) turns out to become

$$\frac{\Delta h}{h} \approx \frac{2h\lambda}{Dr_0}. \tag{2}$$

Using $D = 10$m, $h = 30$km, $\lambda = 500$nm and $r_0 = 0.2$m one obtains $\Delta h/h \approx 0.015$. In principle the light coming back to the ground is hampered by the same factor, assuming for comparison that a large fraction of the Rayleigh column, corresponding to $\Delta h/h \approx 1$, could be used. While the calculation carried out is a sort of order–of–magnitude estimate, it is clear that with the simple gating approach a large part of the light is

essentially wasted. The attainable gain, just in terms of collected photons, is of the order of $h/\Delta h$, as given by the inverse of Eq. (2). This amounts to a couple of orders of magnitude for a $D = 10$m class telescope and rises to three orders or magnitude for a $D = 100$m class telescope.

3. IS GATING AVOIDABLE?

A possible way to avoid gating the pulse is the *movie*-like approach,[17,18] which however is based on detectors whose performance is beyond the current capabilities. Other approaches, that might be referred to as *continuous gating* and *multiple gating*, have been described in Ragazzoni[19] and will be briefly reviewed in this Section.
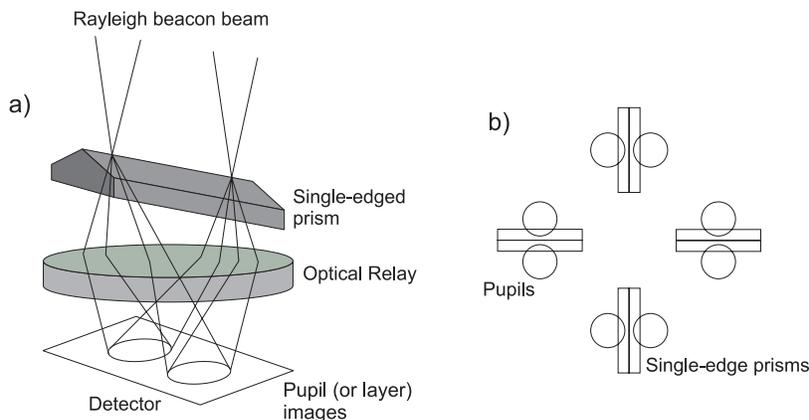

Figure 2. If a LGS is launched aside the main mirror its apparent position on the focal plane will change and, simultaneously the minimum waist position will move along a line. *a)* One can place a roof–prism whose edge is aligned with such a continuous line. Provided the optical relay re–image the pupil of the telescope in this way one can, by the normalized difference of illumination on the two pupils images, retrieve the wavefront derivative along a given direction. *b)* Using four LGSs fired by four equidistant positions around the main telescope and using the proper arrangement of such roof prism one can determine the derivative of the wavefront along two orthogonal direction.
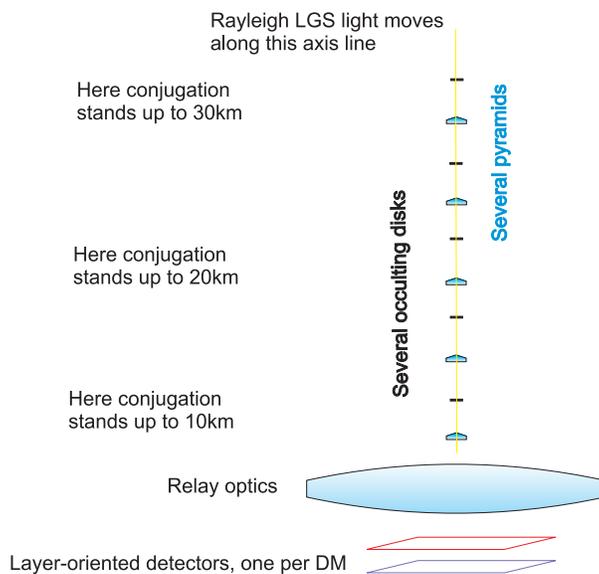

Figure 3. The optomechanical layout for the multi–pyramids WFS concept. The various pyramids are here conjugated to different ranges of the LGS spot.

Let us consider a LGS spot launched in a way that, as seen on the focal plane of the telescope, it moves laterally together with its displacement along the launching line. One can easily see that the waist zone forms a curve that is, under very general conditions, very close to a straight line. In such a situation a roof–like prism may be conceived (Fig. 2). The two faces of the prism, coupled with a relay optics able to form a couple of pupil images onto some specific detector, will lead to a signal proportional to the first wavefront derivative along the direction normal to the roof edge. More than a roof–prism is needed to cover efficiently the sampled atmosphere and to get a bidimensional wavefront map. The major drawback of this system is the opto-mechanical complexity.

A second possibility relies on the pyramid WFS,[20] a sort of quantitative Foucault–like sensor whose signal is given by a pupil plane illumination pattern. The basic idea is to place a sequence of pyramids along the line described by the spot waist in the image space, as the Rayleigh pulse sweeps the atmosphere (Fig. 3). In the time window during which the spot lies sufficiently close to the pin of a pyramid, the WFS produces some useful signal. In the meantime all the other pyramids are in the shadow of the telescope central obstruction. Some occulting disks might be placed between the pyramids to avoid any unwanted light to reach the pupil plane detector. The overall efficiency of such a system is lowered because the useful range is less than Δh, due to the non-continuous character of the wavefront sensing device.

4. Z–INVARIANT WAVEFRONT SENSING

The solutions presented in the previous Section have been a first attempt to collect as much light as possible from the LGS, without any moving part, in order to avoid gating the beacon. The z–invariant concept[21] is an evolution of those ideas. The proposed wavefront sensing device (Fig. 4) consists of a reflecting rod of radius r and a re-imaging optical element. The rod is placed at the focus of the mid-ranged Rayleigh spot; different portions of the rod along the optical axis are conjugated with different ranges, allowing the device to track the motion of the pulsed beacon. In the following, we place no limit on the Δh figure, representing the useful range of the LGS.
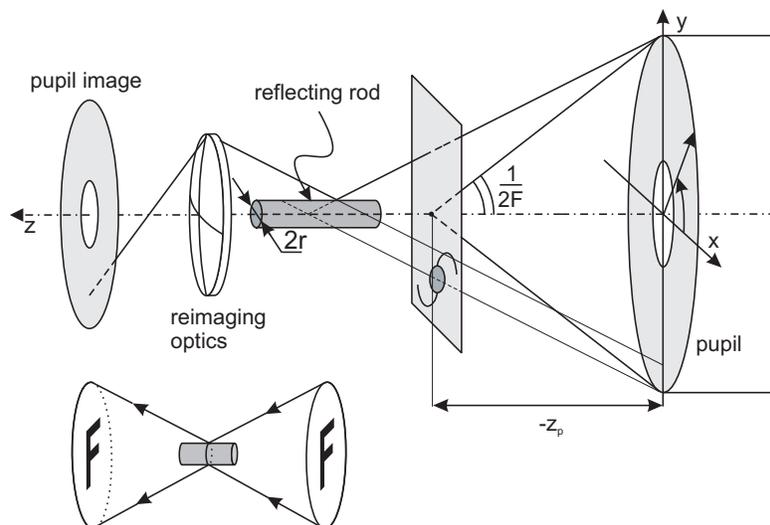

Figure 4. A z–invariant WFS, represented by a reflecting rod placed after the focus of an infinitely distant source. Each portion of the rod corresponding to a fixed z is conjugated with a different range from the telescope aperture. The re-imaging optic at the left of the rod forms an image of the exit pupil onto an observation plane. In the absence of wavefront aberrations, the intensity pattern on this plane is just a 1 : 1 re-imaging of the pupil. If the outcoming wavefront is aberrated, the pupil image presents intensity modulations. In all our considerations, the exit pupil is assumed to be at infinite distance, i.e. $|z_p| \to \infty$.

In the absence of aberrations, the system forms an upright image of the exit pupil, whereas if the wavefront is aberrated the pupil image exhibits surface brightness modulations. Given the rotational symmetry, it is
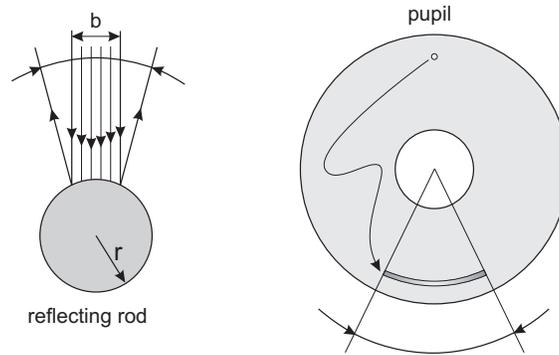
Figure 5. A spot of size b at the rod surface (left) is spread over an arc on the pupil (right). This poses limits on the radius r of the rod, in order to avoid an arc larger than the Fried parameter r_0.

convenient to introduce on the exit pupil a system of normalized polar coordinates (ρ, θ), where $\epsilon \leq \rho \leq 1$ and ϵ is the telescope obstruction ratio. In the approximation of infinitely distant pupil and neglecting the finite spot size, it has been shown that the device is sensitive to the second-order derivative of the wavefront W with respect to the variable θ. However it is insensitive to the derivative $\partial W/\partial \rho$. If the rod surface has a variable reflectivity, for instance proportional to $\exp(-kz)$, then the relative surface brightness variations across the pupil image are given by

$$\left| \frac{\Delta I}{I} \right| \approx \frac{4F}{r\rho} \frac{\partial^2 W}{\partial \theta^2} + k \frac{4F^2}{\rho} \frac{\partial W}{\partial \rho} \tag{3}$$

where F is the focal ratio of the telescope; the higher order terms have been neglected in the above expression.

A finite spot size, of angular size $s = \lambda/r_0$, translates into a smearing of the pupil (Fig. 5) over a certain spatial scale, which must be smaller than the Fried parameter r_0. This leads to a constraint on the minimum radius of the rod, which, according to Eq. (3), limits the sensitivity to the angular part of the aberrations. Imposing the same sensitivity to the angular and radial parts of Eq. (3), a further constraint derives on the constant k, describing the surface reflectivity. Large values of k would limit the overall reflectivity of the rod, translating into a subtle form of gating. It has been found, however, that the rod reflectivity is typically only slightly smaller than unity.

The first result of these considerations is that the rod WFS has quite low sensitivity. A one-wavelength wavefront aberration introduces a relative brightness modulation

$$\left(\frac{\Delta I}{I} \right)_{\text{ROD}} = 4\eta \left(\frac{r_0}{D} \right)^2 \tag{4}$$

where η is the overall reflectivity of the rod. The obtained figure is rather low, compared to the relative intensity variation on a quad-cell of a Shack-Hartmann WFS, given by

$$\left(\frac{\Delta I}{I} \right)_{\text{SH}} = \frac{r_0}{D} \tag{5}$$

In the case of the rod WFS, however, the useful range of the beacon is much larger than in the gated approach, according to the inverse of Eq. (2). The effective gain of the non-gated rod WFS over a gated Shack-Hartmann is therefore

$$G = \frac{2\eta r_0^2}{\lambda h} \tag{6}$$

With some reasonable numbers, like $\eta \approx 0.5$, the gain becomes $G \approx 4$. This figure, accepted as it is, shows that, despite the low sensitivity, there is a marginal advantage using such a WFS with respect to the traditional ones. Furthermore the detector side or the optomechanics involved, depending upon how the gating is performed, will become greatly simplified.

5. DISCUSSION

New wavefront sensing solutions, designed explicitly for Rayleigh beacons, have been discussed. A new class of WFSs, named z–invariant, has been introduced with the example of the reflective rod. The proposed device has a very simple optical setup and is slightly superior to conventional wavefront sensing approaches, based on the gating technique. The gain is essentially due to the extension of the useful range of the beacon, a consequence of the z–invariance property. The weak point of the rod WFS is the low sensitivity; the main reason is that on the angular side, related to the $\partial W / \partial \theta$ term, the WFS relies on the spreading of the light pencil on the edge of the pupil (as illustrated in Fig. 5) and therefore it is constrained by the rod radius. One could conceive z–invariant WFSs with other sectional shapes, for instance a square section, which however would suffer from other limitations and would lead to a more complex optomechanical layout. Once the sensitivity problem is overcome, the radial part might become the weak point of this class of WFSs. A possibility might be to slightly relax the z–invariance property, for instance using a device whose sectional shape remains constant along the z axis, while the sectional size changes smoothly.

As a final remark, we notice that the rod WFS is a pupil plane one and therefore can be optically implemented in a layer–oriented MCAO configuration,[5] as shown in Fig. 6. Several Rayleigh beacons may be used to sense the turbulence in a volume of atmosphere. Each beacon has to be coupled to a rod and a single re-imaging optic forms an anamorphic copy of the sensed atmospheric volume, where several detectors may be placed. This optical combination of the light from the reference sources is actually very well suited to natural guide stars, i.e. in a usually low signal-to-ratio regime; in the case of Rayleigh beacons the larger photon return might be exploited in a numerical layer–oriented scheme, reading the signal from each beacon on a separate detector and then combining the information in a layer–oriented fashion by means of a wavefront computer.
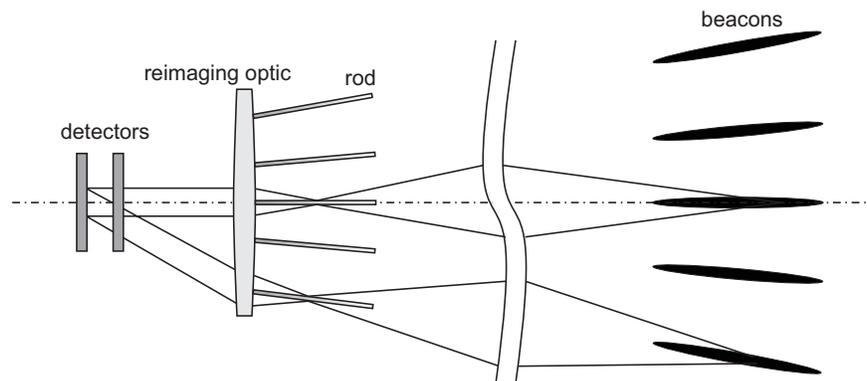

Figure 6. The rod WFS is a pupil–plane one and might be applied in a layer–oriented MCAO configuration. In principle one may conceive a system with a set of Rayleigh beacons and several rods coupled to a single large reimaging optics. The rods could be directly glued to the front surface of the lens. To keep the picture simple, marginal rays are shown here only for a couple of Rayleigh beacons.

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