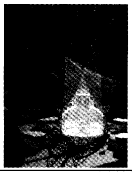
2002ESOC...58..417R

Z-invariant wavefront sensor: sensing a Rayleigh beacon without gating!

Venice 2001
Beyond
Conventional
Adaptive
Optics



Roberto Ragazzoni[a], Emiliano Diolaiti[b], Massimiliano Tordi[a] and David Kirkman[c]

[a]Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, I-35122 Padova, Italy
[b]Dipartimento di Astronomia, Università di Padova, vicolo dell'Osservatorio 2, I-35122 Padova, Italy
[c]Center for Astrophysics and Space Science, UCSD, MS0424 La Jolla, CA 92093-0424, USA

ABSTRACT

We show a novel concept for wavefront sensing, specifically designed for elongated laser beacons. No gating technique is implemented, hence the laser light is used in a very efficient way. An example of the new class of wavefront sensors is described.

1. INTRODUCTION

A possible solution to overcome the sky coverage limitations of Adaptive Optics (Beckers 1993) is the use of artificial reference sources generated by laser light launched from the ground. So far two ways have been conceived: the backscattering of the Sodium layer in the upper atmosphere (Foy & Labeyrie 1985; Happer et al. 1994) and the Rayleigh scattering in the lower portion of the atmosphere. At a first glance Sodium Laser Guide Stars (LGS) look superior, because they occur at a higher altitude and, at least for relatively small telescopes, can be treated as point-like sources. Most of the disadvantages of LGSs, like the lack of tip–tilt information (Pilkington 1987; Rigaut & Gendron 1991) 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 possible solution is to generate the LGS by a pulsed laser and *gate* the returning signal, in order to restrict the useful range of the beacon (Fugate et al. 1991). Rayleigh LGSs in gating mode have also already produced astronomical science (Spinhirne et al. 1998; Drummond, Christou & Fugate 1995). Of course limiting the beacon range translates into a very inefficient use of the scattered light, most of which is essentially wasted out. On the other hand, the practical difficulties inherent to the generation of Sodium LGSs (Milonni, Fugate & Telle 1998) and other issues like scaling to larger power and larger telescopes can reconduct the comparison between Sodium and Rayleigh LGSs on a more common ground. The perspective elongation of a Sodium LGS (Beckers 1992) seen from the aperture of a 100-m class telescope (Gilmozzi et al. 1998; Mountain & Gillet 1998) would produce a huge spot (of the order of 10 arcsec), resulting in formidable photon demands with a Shack-Hartmann WaveFront Sensor, in order to reach the necessary centroiding accuracy. The elongation problem might be overcome using gating techniques also for Sodium LGS, with the related problem of the inefficient use of the scattered light. In this poster, a new wavefront sensing concept is presented, which does not rely on gating techniques and therefore allows, at least in principle, a more efficient use of the photons from an elongated LGS, such as a Rayleigh beacon. The approach is based upon an optical element placed in the focal plane area, whose section does not changes for conjugation to different ranges in the atmosphere, hence the name $z-$invariant. An example of this new class of WaveFront Sensors (WFS) is described.

2. $Z-$INVARIANT WAVEFRONT SENSING

A Rayleigh beacon is characterized by minimum angular size s at a certain range h from the telescope aperture (Fig. 1). Assuming a laser projector with no adaptive optics compensation and with aperture not smaller than r_0, the minimum angular size of the beacon is determined by the seeing at the sensing wavelength, i.e. $s \approx \lambda / r_0$. Other portions of the LGS along the axis of the column are defocused; imposing that such a blurring is not larger than s, one obtains a useful range of

$$\frac{\Delta h}{h} \approx \frac{2h\lambda}{Dr_0} \tag{1}$$

where D is the telescope aperture. Using $D = 10$m, $h = 30$km, $\lambda = 500$nm and $r_0 = 0.2$m one obtains $\Delta h/h \approx 0.015$. This represents the percentage of light coming back to the ground. Assuming for comparison that a large fraction of the Rayleigh column, corresponding to $\Delta h/h \approx 1$, could be used, it is clear that a large gain in terms of collected photons is possible, at least in principle. This gain, given by the inverse of Eq. (1), 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.

Further author information: Send correspondence to R.R., Email: ragazzoni@pd.astro.it

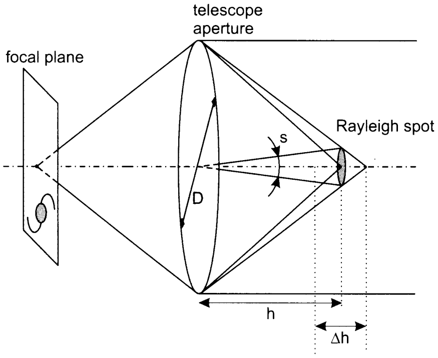


Figure 1. In a Rayleigh LGS one can *gate* the returning pulse corresponding to a certain range interval Δh. The larger such a figure, the larger the photon return. However, a large Δh also produces some unacceptable enlargement of the spot as seen from the telescope and a trade–off is required in order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

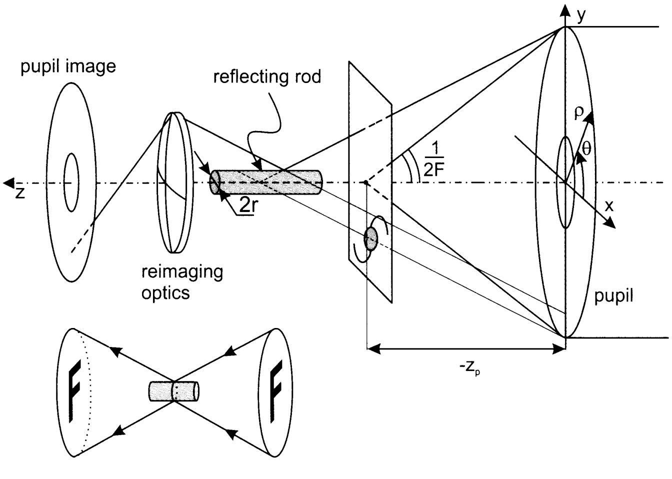


Figure 2. A $z-$invariant WFS, represented by a reflecting rod placed after the focus of an infinitely distant source. Each portion of the rod corresponding to a fixed z is conjugated with a different range from the telescope aperture. The re-imaging optic at the left of the rod forms an image of the 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. $|z_p| \rightarrow \infty$.

Some techniques to collect most of the beacon light have already been described. A possible way is the *movie*-like approach (Angel & Lloyd-Hart 2000, Lloyd-Hart et al. 2000), which however is based on detectors whose performance is beyond the current capabilities. A different approach (Ragazzoni 2000) relies on a static wavefront sensing element in the focal plane area and the $z-$invariant concept that we are going to show here (see also Ragazzoni et al. 2001) is an evolution of this idea. The proposed wavefront sensing device (Fig. 2) 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 along the range span Δh, which, for the present purpose, might represent the whole atmospheric column.

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 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 (Ragazzoni et al. 2001) 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

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

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

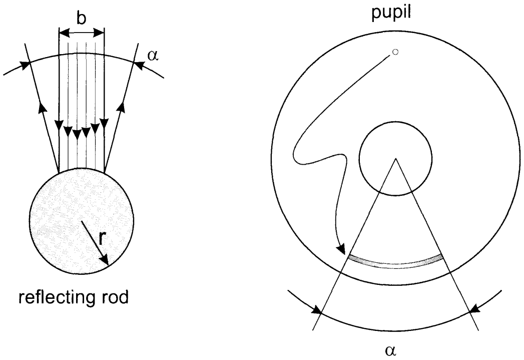


Figure 3. A beam of cross section b at the rod surface (left) is spread over an arc on the pupil image (right).

The LGS has a finite angular size; in the approximation of infinitely distant pupil, the rays incident on the same portion of the telescope aperture appear as a parallel beam of section b on the rod surface (Fig. 3). This translates into a smearing of the pupil image, that must be smaller than the Fried parameter r_0. The net result is a constraint on the minimum radius of the rod, which, according to Eq. (2), limits the sensitivity to the angular part of the aberrations. Imposing the same sensitivity to the angular and radial parts of Eq. (2), a further constraint derives on the constant k, describing the surface reflectivity. Large values of k would limit the overall reflectivity of the rod, defined by

$$\eta = \frac{1}{kl}\left(1 - e^{-kl}\right) \tag{3}$$

where l is the length of the rod. A small reflectivity η translates into a subtle form of gating and should be avoided.

3. DISCUSSION

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

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

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

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

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. (1). 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 a traditional one with gating. The gain is essentially due to the extension of the useful range of the beacon, a consequence of the z–invariance property. An advantage of the rod WFS is the remarkable opto-mechanical simplicity, that make it very attractive.

According to the previous discussion, the weak point of the rod WFS 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. 3) and therefore it is constrained by its 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.

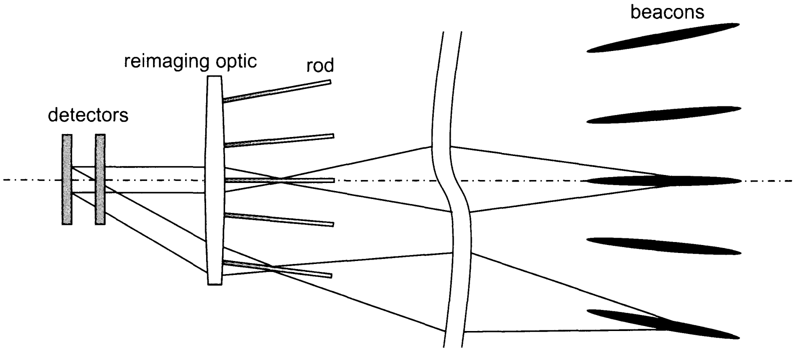


Figure 4. The rod WFS is a pupil–plane one and might be applied in a layer–oriented MCAO configuration. In principle one may conceive a system with a set of Rayleigh beacons and several rods coupled to a single large reimaging optics. The rods could be directly glued to the front surface of the lens. To keep the picture simple, marginal rays are shown here only for a couple of Rayleigh beacons.

An interesting application of the rod WFS is in a layer–oriented MCAO configuration (Ragazzoni, Farinato & Marchetti, 2000), as shown in Fig. 4. 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. Thanks to the large photon return and good signal-to-noise ratio, the wavefront information of each LGS might be read on a separate detector and combined numerically by a wavefront computer, a method that presents some additional degrees of freedom with respect to the optical layer-oriented scheme.

ACKNOWLEDGMENTS

Thanks are due for the useful discussions to Piero Salinari and Simone Esposito.

REFERENCES

Angel J.R.P., Lloyd-Hart M., *Proc. SPIE* **4007**, p. 270, 2000.
Beckers J. M., *Annual review of astronomy and astrophysics* **31**, p. 13, 1993.
Beckers J.M., *Applied Optics* **31**, p. 6592, 1992.
Drummond J.D., Christou J.C., Fugate R.Q., *ApJ* **450**, p. 380, 1995.
Foy R., Labeyrie A., *A&A* **152**, p. L29, 1985.
Fugate R.Q., Wopat L.M., Fried D.L., Ameer G.A., Browne S.L., Roberts P.H., Tyler G.A., Boeke B.R., Ruane R.E., *Nature* **353**, p. 144, 1991.
Gilmozzi R., Delabre B., Dierickx P., Hubin N., Koch F., Monnet G., Quattri M., Rigaut F., Wilson R.N., *Proc. SPIE* **3352**, p. 778, 1998.
Happer W., MacDonald G.J., Max C.E., Dyson F.J., *JOSA A* **11**, p. 263, 1994.
Lloyd-Hart M., Jefferies S.M., Hege E.K., Angel J.R.P., *Proc. SPIE* **4007**, p. 277, 2000.
Milonni P.W., Fugate R.Q., Telle J.M., *JOSA A* **15**, p. 217, 1998.
Mountain M., Gillet F.C., *Nature* **395**, p. A23, 1998.
Pilkington J.D.H., *Nature* **330**, p. 116, 1987.
Ragazzoni R., *Proc. ESO* **57**, p. 175, 2000.
Ragazzoni R., Farinato J., Marchetti E., *Proc. SPIE* **4007**, p. 1076, 2000.
Ragazzoni R., Tordi M., Diolaiti E., Kirkman D., *MNRAS* **327**, p. 949, 2001.
Rigaut F., Gendron E., *A&A* **261**, p. 677, 1991.
Spinhirne J.M. et al., *Proc. SPIE* **3353**, p. 22, 1998.