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LETTER

Letter to the Editor

Fixing the LGS tilt problem using tomography

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Abstract. We propose a simple scheme to solve the tilt indetermination problem in adaptive optics compensation with laser guide stars. This technique, providing tomographic turbulence analysis works, increases the area into which a tip-tilt guide star has to be found by approximately two orders of magnitude, boosting the sky coverage close to 100% at visible wavelengths. In addition, the proposed scheme provides a tilt measurement free of anisoplanatism error. It has numerous engineering advantages compared to other tilt retrieval techniques, as it does not require special auxiliary equipment nor an increased laser power.

Key words: adaptive optics – atmospheric effects – telescopes

1. Introduction

Adaptive Optics (AO) is able to boost angular resolution of astronomical telescopes up to the diffraction limit, provided a bright enough source is located within the isoplanatic patch of the observed object. Because of this limitation, sky coverage is severely limited, especially at visible wavelengths, when natural stars are used as reference. In order to overcome this limitation the concept of artificial beacon has been introduced (Foy & Labeyrie, 1985) and proven to be effective (Thompson & Gardner, 1987). However, these artificial references, called Laser Guide Stars (LGSs) do not provide full sky coverage because of both the focus anisoplanatism (Fried & Belsher, 1994; Parenti & Sasiela, 1994) and the absolute tip tilt indetermination problem (Pilkington, 1987; Rigaut and Gendron 1992).

Focal anisoplanatism is due to the finite height of the LGS that translates into a conical shape of the atmospherical volume sampled by the LGS light in contrast with the cilindrical shape of the starlight beam. This difference produce a wavefront measurement error that can be in principle solved through the techniques of butting, stitching (Sasiela, 1994) or three–dimensional tomography (Tallon & Foy, 1990). Fried (1995) pointed out that butting is affected by some fundamental limitations, while stitching is a non–efficient way to use the laser light (because the photons from a single LGS are collected only from a limited portion of the telescope entrance pupil). Tomography, on the other hand, does not appear to suffer from fundamental limitation, needs few LGSs and uses the laser light in the most efficient manner.

We assume in the following that focal anisoplanatism is solved through the use of tomographic techniques and we show how the tip tilt problem can be solved as a by product of tomography.

In the following, we present the concept of Tomographic Tilt Recovery (TTR). We also briefly present the geometry of the problem, evaluate the gain in sky coverage brought by this new method, and detail the case of TTR with 4 and 5 LGSs. We then discuss the merits of the method.

2. Tomographic tilt recovery

Tomography provides a way to obtain a three dimensional map of the atmospheric turbulence, therefore to know the phase distortions in any directions within the field of view probed by the laser beams. It has been shown (Ragazzoni, Esposito & Riccardi, 1998) that focal anisokinetism was potentially solved when using tomography, provided that the absolute tip tilt component was known for at least one of the LGSs. This has very important consequences. Indeed, as the problem is completely isotropic, the LGS constellation can be rotated arbitrarily so that the domain where a Tip-Tilt Guide Star (TTGS) can be found is in fact a large annulus of mean radius equals to the distance between the science object and the LGSs. As we show hereafter, this enlarge by a large factor the probability to find a suitable TTGS. Adding a further LGS provides the capability to find the TTGS within the full disk of the same radius, further enlarging the sky coverage, and zeroing the tilt anisoplanatic error, if the fourth LGS is chosen to be superimposed with the TTGS.

2.1. Geometry of the problem

Fig. 1 presents the geometry of the problem. In this figure and in the following, we present the particular case where four LGSs are used, and placed in the optimal configuration for tomography, as presented in Tallon & Foy (1990). Furthermore in the following D is the telescope aperture diameter and $\tilde{h}$ is the effective turbulence height as given by Roddier et al., 1993.

Tallon & Foy present a full analysis of the LGSs configuration. In the four LGSs case, they find an optimal off–axis distance of the LGSs, $\theta_{\rm lgs}$:

$$\theta_{\rm lgs} = \frac{D}{2h_{\rm max}} \tag{1}$$

where $h_{\rm max}$ is the altitude of the highest turbulence layer considered in the tomography.

In the regular tomographic approach, a TTGS has to be found in the vicinity of the science object, i.e. within an angle $\theta_{\rm t}$. The solid angle or sky area (simply *area* in the following) where such a guide star has to be found is:

$$S_0 = \pi\theta_{\rm t}^2 \tag{2}$$

It is well known that, because the high order phase distortions are compensated by the LGS AO, the tip tilt error has to be contained, imposing severe constraints on θ_t (Rigaut & Gendron, 1992; Olivier et al, 1993). Here, we have adopted

$$\theta_{\rm t} = \frac{r_0}{\tilde{h}} \tag{3}$$

which leads to tip tilt errors of the order of 1 rd^2 (Roddier et al, 1993). Note that this criteria is quite loose and actual constraints on θ_t may be more severe, which would make TTR even more effective.

A necessary condition being $0 < \tilde{h} < h_{\rm max}$, a safe approximation is $\tilde{h} = \eta h_{\rm max}/2$, with $\eta \approx 1$, which leads to:

$$\theta_t = \frac{2r_0}{\eta h_{\rm max}} \tag{4}$$

We adopt this approach in order to trace out a suitable set of relationships depending upon the dimensionless quantity η.

If the tomography technique is extended to include a TTGS measurement in the vicinity of one of the LGSs, coupled with the tomographic analysis to derive the absolute tilt over the whole volume of atmosphere scanned by the LGS beams, and considering that the LGS constellation can be arbitrarily rotated about the science line of sight, the surface into which a TTGS has to be found is now:

$$S_1 = 4\pi\theta_{\rm t}\theta_{\rm lgs} \tag{5}$$

From this, we deduce the gain in term of searchable area:

$$\frac{S_1}{S_0} = 4\frac{\theta_{\rm lgs}}{\theta_{\rm t}} = \eta\frac{D}{r_0} \tag{6}$$

Under nominal conditions ($D = 8$m, $r_0 = 0.2$m), and assuming $\eta = 1$, the searchable area gain $S_1/S_0 = 40$. The sky coverage imposed by the need to find a TTGS in the case of "regular" LGS compensation has been computed to be approximately 1% for compensation at visible wavelengths (Rigaut & Gendron, 1992), possibly slightly larger (Olivier et al, 1993). The gain in searchable area computed above lead therefore to a sky coverage of 33% for TTR with 4 LGSs (the sky coverage behaves as $1 - \exp(-\mathcal{N})$, expression we used to scale from the quoted figure of 1% being $\mathcal{N}$ the number of useful stars in a unit area). We will now discuss a refinement that will further increase this value.

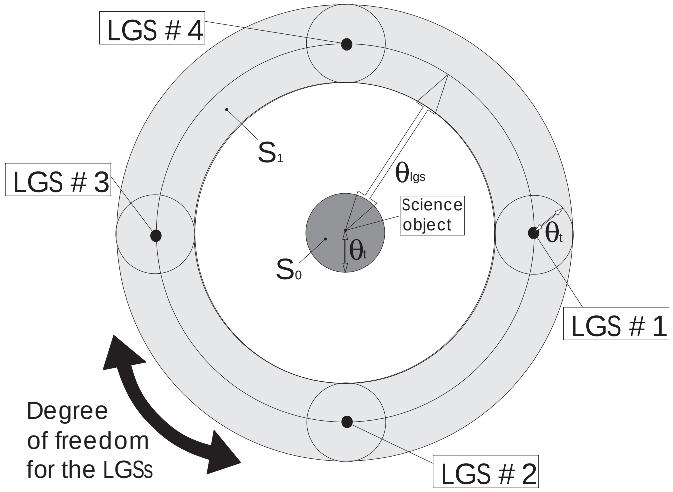

Fig. 1. Schematics of the geometry of the problem, with the various notations used in the text. S_2 is the whole area inside the outest circle.

2.2. Improvement with an additional LGS

By using an additional LGS, one can scan the whole area within the circle defined by $\theta_{\rm lgs}$, leading to an overall searchable area of:

$$S_2 = \pi(\theta_{\rm t} + \theta_{\rm lgs})^2 \tag{7}$$

The comparison with S_0 is even more favorable:

$$\frac{S_2}{S_0} = \left(1 + \frac{\theta_{\rm lgs}}{\theta_{\rm t}}\right)^2 = \left(1 + \frac{\eta}{4}\frac{D}{r_0}\right)^2 \tag{8}$$

with the same numerical values for D and r_0, $S_2/S_0 \approx 120$, leading to a sky coverage of roughly 70%.

Furthermore, the additional LGS can be exactly placed on top of the TTGS, zeroing the tilt anisoplanatism component.

2.3. Extension cases

In this Letter, we have assumed a geometry of the LGSs as presented in Tallon & Foy (1990). In this configuration, whatever the number of LGSs is, they lie on a circle centered on the science line of sight. There may be more efficient configurations, where LGSs may lie at various distances from the line of sight.

Moreover, our original assumption on the LGS positions was derived only from tomographic constraints. A more global approach, taking into account both tomography **and** TTR, may find even more efficient solutions/configurations.

One can also consider a rather more speculative LGS configuration where the additional LGS would be placed outside the $\theta_{\rm lgs}$ circle. In order to have an easy extension of the tomography process (maybe limited to the tilt component), the maximum distance of the additional LGS to the line of sight should be roughly $2\theta_{\rm lgs}$. This would lead to an increase on the searchable area of a factor of four. It is beyond the limits of this Letter to investigate the feasibility and the stability of this variation.

3. Discussion

Let us now examine the pros and cons of TTR. One obvious show stopper is that atmosphere tomography is assumed to work. Although tomography is a very elegant solution to the focal anisoplanatism limitation, and that it shows no fundamental limitation, more theoretical, numerical and experimental work is still missing. Another drawback from TTR is that it does not *entirely* solve the tilt indetermination problem, in the sense that it does not provide a 100% sky coverage. However, the latter is increased by a large factor (two order of magnitude, see Sect. 2.2) and reaches values that we think can be deemed acceptable for most purposes. On the engineering point of view, TTR has also considerable advantages compared to the other methods proposed to solve the tilt indetermination problem: there is no auxiliary equipment (perspective techniques, e.g. Ragazzoni, Esposito & Marchetti, 1995; Ragazzoni, 1997) nor large ground occupation (Marchetti & Ragazzoni, 1997), and laser power requirements are not increased with respect to mere tomography, opposite to polychromatic LGS (Foy et al, 1992 and 1995). Last but not least, not only TTR does not suffer from the isokinetic errors (Esposito, Riccardi & Ragazzoni, 1996; Neymann, 1996; Ragazzoni, Esposito & Riccardi, 1998), but in addition the tilt anisoplanatic error can be zeroed, if one LGS is placed on top of the TTGS.

A global approach to the problem of 8m class whole–sky diffraction limited imaging through LGS–based adaptive optics is missing and urgently required, as this Letter is showing.

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