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Letter to the Editor

Robust tilt determination from Laser Guide Stars using a combination of different techniques

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Abstract

The techniques proposed in the literature for the Laser Guide Star absolute tilt determination suffer from some limitations, due to fundamental reasons and/or to practical aspects. A combination of two techniques is proposed here: the tri–static (Belen'kii 1995; Ragazzoni 1996a) and the auxiliary telescope (Ragazzoni, Esposito & Marchetti, 1995) configurations leading to a solution where two auxiliary laser projectors are located in the neighborhood of the main observatory. The laser stripes are used to link the scientific target to two natural guide stars (with no constraints on their location) allowing a complete recovery of tip–tilt information. In this way a robust, whole sky coverage, approach is obtained. Moreover, a combination with the Double Adaptive Optic technique (Rigaut & Gendron, 1992) can further reduce the required displacements of the auxiliary projectors.

1. Introduction

In the forthcoming years the solution of the absolute tip–tilt problem of a Laser Guide Star (LGS hereafter) will play a central role in the development of Adaptive Optics for high angular resolution ground based astronomy. After the multicolour LGS technique proposed by Foy *et al.* (1992, 1995), in the last couple of years a number of different solutions have been proposed, giving the feeling that the field is still rather unexplored and that some robust and practicable solution could be obtained in the near term.

None of the proposed method is flawless. It might be useful to recall here which are the main drawbacks of the proposed techniques:

– The multicolour LGS requires a large amount of power for the transmitting laser beam and suffers from some inability to rule out effects due to the jitter of the telescope and to the C_n^2 distribution (Ragazzoni, Marchetti & Brusa, 1996);
– The Double Adaptive Optics (DAO) technique, proposed by Rigaut & Gendron (1992), increases the sky coverage by performing adaptive optics compensation also on the Natural Guide Star (NGS hereafter) to be adopted for the tilt determination. This technique appears to increase substantially the sky coverage, although it is not at all able to guarantee a full coverage of any scientific target in the sky.
– The tristatic solution, first proposed by Belen'kii (1995) and independently figured out by Ragazzoni (1996a) requires two auxiliary telescope projectors. Their distance and power depend upon the size of the isoplanatic patch. The robustness of the technique will depend upon the seeing conditions. Moreover it is to be pointed out that such an approach is not able to rule out tilt displacements with a very large coherence size, induced to the observed field of view, as, for instance, the one produced by jitter, ground layers and dome seeing.
– The auxiliary telescope technique(Ragazzoni, Esposito & Marchetti, 1995) relies on some NGS to be located in the neighborhood of the scientific target, even if they are found at distances much larger than the isoplanatic patch. Full sky coverage, however, is obtained assuming the auxiliary telescopes can move on a large area around the main observatory. Moreover such an area, which depends upon the limiting magnitude of the NGS for the auxiliary telescope, will depend in an inverse manner upon the diameter of the auxiliary telescopes. Small auxiliary telescopes lead to the requirement of an available region around the main observatory of the order of several hundreds of meters in size (Marchetti & Ragazzoni, 1996). As a further problem (if only of technological nature) one should cite the requirement to transmit the data from the two auxiliary telescopes to the main observatory over a distance of a few hundred meters, typically, and with a bandwidth of the order of 100Kbps to assure a proper tilt sampling.
– The propagation delay technique (Ragazzoni, 1996b) introduces the approach to relax the characteristic evolution time of the LGS, via some short term evaluation of the LGS absolute tilt. While this approach is probably of some general interest (it can be applied, for example, at the predictive

technique as shown in Ragazzoni & Marchetti, 1996; an option, however, still too speculative at the current knowledge of the matter) it is specifically applied to the estimation of the derivative of the tilt. This estimation requires the adoption of a large projector in order to be effective, leading to the temptation of using the main scientific telescope as projector; such an approach introduces a number of practical problems that could cancel out most of the improvements introduced by the adaptive optics system. Moreover it can be shown that it has some fundamental limitations.(Ragazzoni & Brusa, 1996).
– The perspective technique (Ragazzoni & Marchetti, 1996) requires a pulsed Sodium laser. This fact translates into a great care in the projecting optical train because of the very large instantaneous power transmitted. It can be easily argued that problems depending upon the C_n^2 distribution along the altitude can be a serious drawback; a clear analysis of this option, however, is still missing.

Another strong limitation of a fundamental nature is conical anisoplanatism (Esposito, Riccardi & Ragazzoni, 1996; Neymann, 1996). Conical anisoplanatism is a well known problem for adaptive optics imaging using LGS as a reference beacon. The effect is due to the finite height of the artificial reference and by consequence to the conical shape of the light beam from the beacon to the entrance aperture of the telescope, as compared to the cylindrical shape of the light beam from a celestial object. In the following the tilt component of the conical anisoplanatism, namely the conical anisokinetism, is explicitely figured out in the calculation. Conical anisokinetism affects all the techniques that rely on LGS for tilt recovery (for istance DAO is not affected by such a limitation).

In the following it is asumed, as usual, that wavefront and tilt distortions introduced by the atmosphere layers higher than the mesospheric Sodium height, are negligible.

2. A combination of some techniques

The combination of two techniques (the tristatic configuration and the auxiliary telescope) and possibly of a third one (the DAO) translate into a solution that overcomes most of the difficulties explained in the introductive section. Let us assume the main observatory is pointing at the zenith. In the Field of View (FoV hereafter) of the main telescope the scientific target and a pair of NGSs bright enough to be used as tilt reference are located. With the exception of a tiny fraction of the sky the two NGSs will be located at a distance of some isoplanatic patches from the scientific target. An LGS projector is located in the neighborood of the main observatory in such a way that the elongation perspective effect, as seen from the main observatory, will translate into a bright strip *linking* the isoplanatic patches of the scientific target and of one of the NGS (see Fig.1 where for simplicity only one NGS has been taken into account). A second LGS will provide the same feature for the second NGS; the position angles of the two NGSs with respect to the scientific target are such that through proper cosine projections one is able to retrieve the bidimensional tilt from the knowledge of

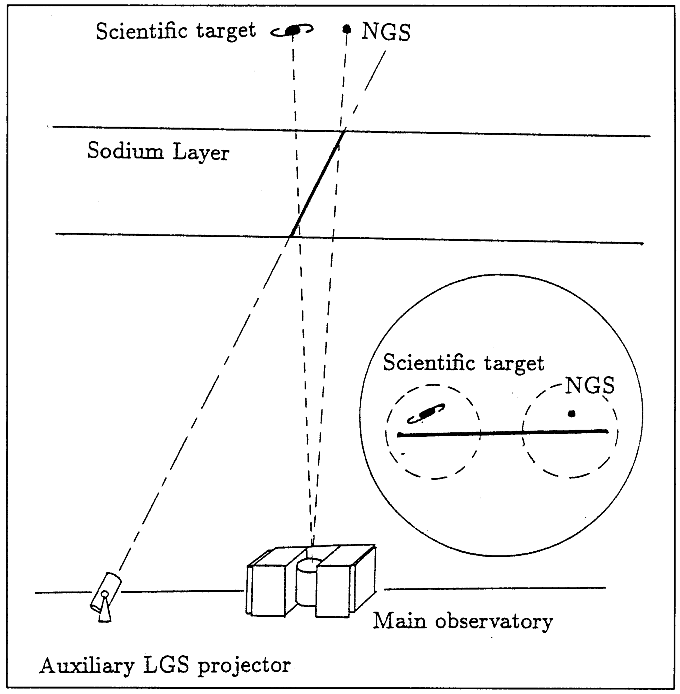

Fig. 1. A section of the method described in the text. In the circular inset the objects, as seen in the FoV of the main observatory, are sketched; the dashed circles represent the isoplanatic patch size.

the one–axis tilt from the two NGSs. The absolute tip–tilt in the object direction can be measured by combining the tip–tilt measurements in the direction of the NGS and the differential tip–tilt between the NGS and the object derived using the deviation of the laser strip.

Now we analyze the differential tilt of the portion of the strip within the isoplanatic patch of the NGS with the tilt of the NGS itself. This tilt is to be compared with the corresponding tilts on the scientific target area (taking into account that the tilt of the scientific target is unknown). All these tilts are measured along the perpendicular to the apparent elongation of the strip. We consider also the effects of *jitter* of the auxiliary laser projectors and of the main observatory. It is worthwhile to point out that here we refer to *jitter* as any tilt coherent over an angular scale of the order of the distance between the scientific target and the NGSs or more.

Moreover we make a distinction between the tilt of the portion of the LGS strip and the natural object within the related isoplanatic patch. We use the notation $T_{l(obj)}$ to identify the tilt of the laser strip with respect to the *true* tilt T_{obj}. Their difference will be denoted by Δ_{obj} and its nature is related to the conical anisokinetism problem.

Using the following notation:

- T_{st}
  Downward tilt of the scientific target;
- T_{lp}
  Upward tilt of the laser projector;
- T_{NGS}
  Downward tilt of the NGS;

- $T_{l(st)}$
  Downward tilt of the portion of LGS strip in the scientific target isoplanatic patch;
- $T_{l(NGS)}$
  Downward tilt of the portion of the LGS strip in the NGS isoplanatic patch;
- J_{lp}
  Jitter at the laser projector;
- J_{mo}
  Jitter at the main observatory.

we can form the apparent absolute tilt (AT hereafter) as measured on the focal plane of the main observatory of three objects:

1) the laser strip in the NGS isoplanatic patch:

$$AT_{l(NGS)} = J_{lp} + T_{lp} + T_{l(NGS)} + J_{mo}; \tag{1}$$

2) the laser strip in the scientific target isoplanatic patch:

$$AT_{l(st)} = J_{lp} + T_{lp} + T_{l(st)} + J_{mo}; \tag{2}$$

3) and the NGS itself:

$$AT_{NGS} = T_{NGS} + J_{mo}. \tag{3}$$

It is easy to see that the combination:

$$AT_{l(st)} - AT_{l(NGS)} + AT_{NGS} = T_{l(st)} + J_{mo} + \Delta_{NGS} \tag{4}$$

differs from the wanted quantity $T_{st} + J_{mo}$ by Δ_{st}.

Neglecting the conical anisokinetism (that is assuming $\Delta_{st} = \Delta_{NGS} = 0$) the measurements will give the direct estimation of the tilt of the scientific target.

The measurement and the removal of the conical anisokinetism effect is a matter beyond the limit of this Letter. It has to be pointed out, however, that in the described scheme (as in the auxiliary telescopes technique) four different conical anisokinetisms, related to the two different LGSs, are involved. While only very preliminary work has been published on how to reduce or how to remove this effect (see also Riccardi, Ragazzoni & Esposito, 1996) a detailed study on the subject is currently under development.

2.1. Sky coverage

We use ϕ^2 to denote the area in the sky such that a nearly P = 100% probability of finding an adequate star for tracking purpose is obtained. Such area is centered on the scientific target of adaptive optics observations. We can rewrite this term as:

$$\phi^2 \approx \eta\epsilon^2 \tag{5}$$

where ϵ is the isoplanatic patch size. Using the definition of η given by eq.(5) it is straightforward to figure out that the following relationship holds:

$$\eta = \frac{100}{P\%_\epsilon} \tag{6}$$

where $P\%_\epsilon$ is the propbability to find out a useful reference, expressed in percent units, when an isoplanatic patch of ϵ size is assumed. $P\%_\epsilon$ is usually referred to as sky coverage. In deriving eq.(6) it has been used the fact that the probability to find out an useful NGS is proportional to the area taken into consideration.

Following the analysis of Rigaut & Gendron (1992) one should expect that, in order to reach a nearly 100% sky coverage, one should extend the searchable area for NGS by a factor η = 100 in the visible band (being the expected sky coverage $P\%_\epsilon \approx 1\%$), and by a factor depending upon the telescope diameter when the DAO is to be adopted (see Tab.2 in Rigaut & Gendron, 1992). In our case one should consider that the adaptive optics compensation of the NGS is to be allowed only in the direction perpendicular to the bright strip elongation, the only direction relevant for the tilt measurement related to that particular NGS. Maybe, this could translates into the simplification of the further adaptive optics system required by DAO (*e.g.* the wavefront sensor can be limited to sense the wavefront derivative in only one direction). For a D = 6m telescope, for example, the required increase appears to be only of a factor η = 4, given the expected sky coverage of $P\%_\epsilon = 25\%$. Because of the requirements of two NGSs one should double such numbers. In order to make a numerical estimation of the position of the auxiliary LGSs projectors we assume the requirement of factors η = 200 and η = 8 respectively for non–DAO and DAO supported NGS tilt recovery. It is to be recalled that the DAO here proposed requires to triplicate the focal plane adaptive optics compensation system, while there is no need of any additional LGS (however a total number of three LGS projectors is required). The adoption of DAO allow for a significantly smaller ground area to be exploited by the auxiliary laser projectors. A trade–off study is required to establish the cost–effectiveness of introducting DAO in the proposed scheme.

Moreover the typical isoplanatic patch size (at visible wavelengths and under normal seeing conditions) is assumed here to be of a radius roughly ϵ" = 5", thus, in order to obtain a full–sky coverage, it is required to search for NGS in a region of diameter 2ϕ around the scientific target, where $\phi \approx \sqrt{\eta} \times \epsilon$. It is to be mentioned that there is no assumption here regarding the uncorrelation between the tilts on different isoplanatic patches; a condition, on the other hand, crucial for the effectiveness of the simple tristatic solution.

2.2. Dislocation of the auxiliary LGS projectors

Under these assumptions and using the Sodium altitude $H \approx$ 90Km and the thickness $\tau \approx$ 10Km (Happer *et al.*, 1994), and noting that one can double the coverage of the bright strip by allowing it to be located on the two sides with respect to the scientific target (see Fig.2) one obtains:

$$l \approx \frac{\sqrt{\eta}\epsilon H^2}{\tau} \tag{7}$$

that leads to some $l \approx$ 275m and $l \approx$ 55m for a non–DAO and a DAO combination (with a D = 6m main observatory) of techniques. Both configurations requires some ground–movement

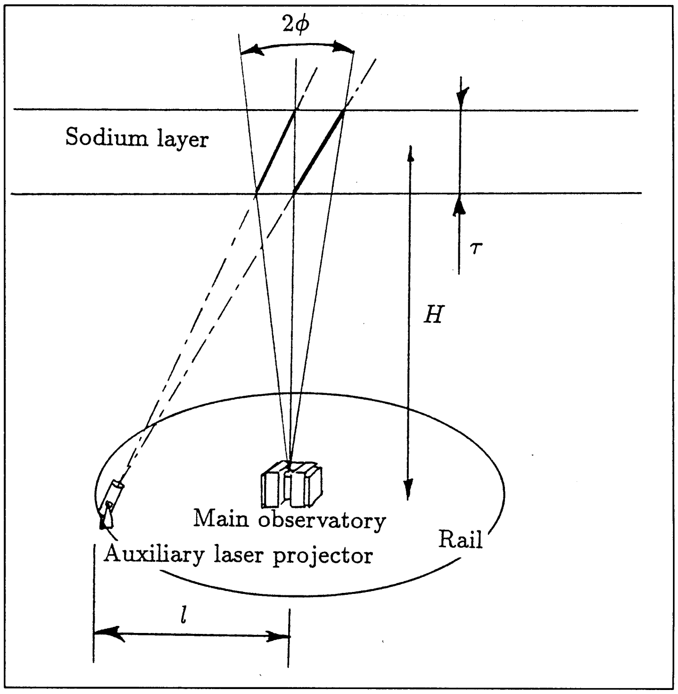

Fig. 2. The two auxiliary LGSs projectors should be movable in a circular track around the main observatory, with a radius l and spanning an angle of the order of 180deg.

of the LGS projectors around the main observatory even during the observations.

This could be accomplished, for example, installing the LGS auxiliary projectors on two carriage holders sliding on a track.

The estimated dimension of such a facility, and the unidimensional development of such a track around the main observatory covering something like a 180deg circle around it does not seem an unsolvable problem, especially taking into account the efforts that are currently spent for large, 8m class telescopes. It is to be recalled that such a realization (one time its effectiveness has been proven) leads to the whole sky, diffraction–limited imaging capability. The altitude of the laser projectors, and by consequence the altitude of the track, does not matter at all: there is no need to have a circular flat area around the main observatory. Moreover the laser projectors could be located much lower than the main observatory altitude leaving enough space to deal with the local orography of the observatory.

It is easy to see that the power requirement P for the auxiliary laser projector is roughly

$$P \approx \frac{P_0 \sqrt{\eta}}{(D/r_0)^2} \tag{8}$$

where P_0 is the power required for the LGS to be fired at the main observatory, to close the higher order adaptive optics loop for a full compensation assuming certain D/r_0 conditions. In usual conditions for visible wavelengths P is only a fraction of P_0.

3. Conclusions

It has been shown that the combination of two to three techniques already published in the literature can give a solution to the LGS tilt indetermination problem, regardless of jitter problems, both on the main observatory and on the auxiliary devices. The technique rely on some NGSs and does not require any special assumption on the correlation of tilt at different points in the sky. The system seems to be particularly adaptable to efficiently deal with the conical anisokinetism problem. While this approach seems able to solve most of the problems related with other techniques, there is no evidence that the described technique is the only one that permits such a result; a detailed and systematic approach to the LGS tilt problem is still missing and urgently required.

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References

Belen'kii M.S. (1995) SPIE proc. **2471**, 289
Esposito S., Riccardi A., Ragazzoni R. (1996) JOSA–A **13**, 1916
Foy R., Boucher Y., Fleury B., Grynberg G., McCullough P.R., Migus A., Tallon M. (1992) ESO proc. conf. **42**, 437
Foy R., Migus A., Biraben F., Grynberg G., McCullough P.R., Tallon M. (1995) A&AS **111**, 569
Happer W., MacDonald G.J., Max C.E., Dyson F.J. (1994) JOSA–A **11**, 263
Marchetti E., Ragazzoni R. (1996) A&AS *in press*
Neymann C.R. (1996) Opt. Lett. **21**, 1806
Ragazzoni R. (1996a) A&A **305**, L13
Ragazzoni R. (1996b) ApJ **465**, L73
Ragazzoni R., Brusa G. (1997) *in preparation*
Ragazzoni R., Esposito S., Marchetti E. (1995) MNRAS **276**, L76
Ragazzoni R., Marchetti E. (1996) SPIE proc. **2871** *in press*
Ragazzoni R., Marchetti E., Brusa G. (1997) A&AS *in press*
Riccardi A., Ragazzoni R., Esposito S. (1996) OSA Technical Digest **13**, 84
Rigaut F., Gendron E. (1992) A&A **261**, 677
Tallon M., Foy R. (1990) A&A **235**, 549

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