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PROPAGATION DELAY OF A LASER BEACON AS A TOOL TO RETRIEVE ABSOLUTE TILT MEASUREMENTS

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ABSTRACT

The knowledge of the temporal evolution of a star wandering for a limited time interval (e.g., a fraction of a second) can be used to increase dramatically the sky coverage of a laser-beacon adaptive optics system. A technique to achieve such short-term tracking is described. The full sky coverage is easily achieved by using the whole telescope as a laser projector.

Subject headings: atmospheric effects — techniques: miscellaneous

1. INTRODUCTION

Laser beacons as reference sources for adaptive optics have been proposed for astronomical purposes by Foy & Labeyrie (1985) and even earlier for military applications. They have been demonstrated to be capable of producing artificial laser stars (Thompson & Gardner 1987), which provide a reference source for a closed-loop adaptive optics correction (Fugate et al. 1991; Primmerman et al. 1991), and these first astronomical results have already been published in the literature (Drummond, Christou, & Fugate 1995; McCullough et al. 1995).

However, laser guide stars (LGSs) are not able to provide a useful signal for tilt correction. This is due to the fact that the upward wandering of the laser beam is generally unknown. A classic example employs the same telescope to project and to sense the laser beacon. Because the light will encounter the same refractive index variations in both upward and downward directions, the LGS will appear motionless, aligned with the optical axis of the telescope. It is curious that Beckers (1993) attributes the authorship of this example to Sechaud (1988), and that several authors (Foy et al. 1995; Ragazzoni, Esposito, & Marchetti 1995) report the same reference. However, there is no trace of this example or similar statement in the Sechaud paper (or in any of Sechaud's papers referenced in Beckers's review). The earliest reference to the apparent fixed position of an LGS can be traced back, to the best of my knowledge, to Pilkington (1987) in the open literature and even earlier in the defense community by Fried (see Fried & Belsher 1994).

Several techniques have been proposed in order to solve the tilt indetermination problem. The adoption of a nearby natural guide star (NGS) is an obvious solution. The required high accuracy of the tilt correction in adaptive optics has been pointed out by Rigaut & Gendron (1992) and later studied in deeper detail by Olivier et al. (1993), confirming the earlier results. Rigaut & Gendron (1992) proposed the double adaptive optic technique (DAO) in their paper in order to relax the requirement on the limiting magnitude for the NGS. Even allowing for such a solution (which, essentially, requires the duplication of the adaptive optics system), the sky coverage in the visible band remains limited. While the preceding solutions rely uniquely on an NGS in order to retrieve the tilt information, the multicolor LGS proposed by Foy et al. (1995), the auxiliary telescopes technique (Ragazzoni et al. 1995), and the tristatic configuration (Ragazzoni 1995) provide information on the LGS position using the telescope as a reference frame. These techniques do not rely on the availability of NGSs within the isoplanatic patch of the observed astronomical object. They represent a second class of solutions to the tilt indetermination problems.

In this Letter a prototype of a new third class of solutions is presented. In the technique that will be shown below the absolute wandering is retrieved from the LGS with an indetermination growing with time. In the technique described in this Letter, the integration time of the tilt sensor for a nearby NGS used for absolute tilt correction can be increased (thus allowing fainter NGSs to be used and thereby increasing the sky coverage) by using a signal obtained from short-term measurements of the apparent position of an LGS. For laser beacons in the mesosphere, there is a propagation delay of the order of 0.5 ms between the time the laser first passes through the most turbulent layers on the upward propagation and the time it returns to the layer on the return propagation. During this small time interval caused by the propagation delay, the turbulent layer will change slightly (Buchheim, Pringle, & Schaefgen 1978), disturbing the reciprocity of the two-way path and creating a slight difference in the apparent tilt of the laser beacon as detected by a sensor at the focus of the telescope used to launch the laser. The thesis of this Letter is that the error signal derived from the apparent tilt on the laser beacon caused by the propagation delay to and from the mesosphere can be used to control a tilt mirror to reduce sufficiently the full aperture tilt on an NGS, thereby allowing a significant increase in the integration time of the NGS tilt sensor. In this way a nearby NGS corrected with such a signal will drift slowly. When the amount of drift exceeds the required precision (typically a fraction of the Airy disk of the telescope used) a correction based upon the NGS is required. However, if the time delay required to fall into such a situation is significantly larger than the typical correlation time of the tilt, a fainter NGS can be used and the sky coverage is correspondingly increased.

Following the estimations of Rigaut & Gendron (1992), and recalling that the sky coverage roughly increases with the $-3/2$ power of the limiting brightness, the latter being proportional to the exposure time, one can see that in the visible bandwidth an increase in the exposure time of a factor of 20 is enough to provide full sky coverage. The required typical exposure time being $\approx$5 ms, one can see that any technique able to keep the drift below the required threshold for $\approx$0.1 s allows the complete sky coverage. The last statement is strictly true when effects due to the limited extent of our Galaxy and absorption by interstellar matter can be ruled out (this happens for

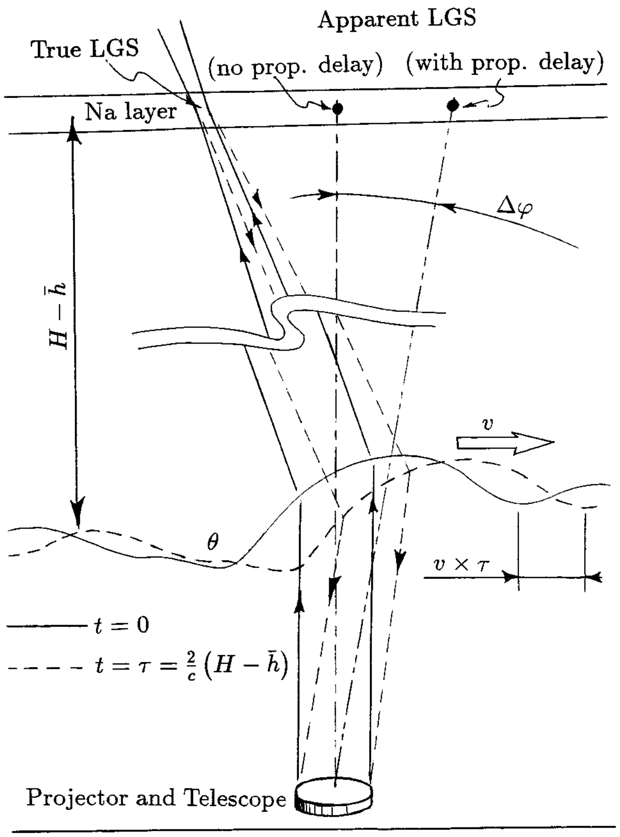

FIG. 1.—Sketch of the technique explained in the text. The tilting effects of the disturbing layers of the atmosphere are here grouped in a single curve θ translating at a speed v. This visualization is to be considered only as a simplification of the true situation, which is much more complex. Without taking into account the propagation delay effects, the LGS is seen on the axis of the telescope. Accounting for the propagation delay, a tiny displacement $\Delta\varphi$ is observed. Such an angle is a measurement of the variation of the tilt induced by the atmosphere. By integration, one can recover the evolution of the absolute tilt experienced by the laser beam.

relatively bright stars). This translates into the requirement of a longer integration time for small telescopes, or the consideration of large telescopes, the limiting magnitude depending upon the collecting area of the telescope.

2. TIME PROPAGATION EFFECTS

Let us suppose that the LGS is produced by a laser projector of diameter D_p, while the telescope diameter is denoted simply by D. The tilt effects on the upward beam will occur in the very first turbulence layers, at an average altitude $\bar{h}$, while the resonant mesospheric scattering takes place at a height $H \gg \bar{h}$. The returning beam will encounter the same perturbing layer only slightly shifted (due to wind and telescope slewing) after a propagation delay τ (see Fig. 1):

$$\tau = \frac{2}{c}(H - \bar{h}). \tag{1}$$

Adopting $\bar{h} \approx 5$ km and $H \approx 90$ km (Happer et al. 1994), one obtains $\tau \approx 5.7 \times 10^{-4}$ s. Assuming that the tilt evolution of the LGS, as seen from the ground if corrected for the upward term (for example, locking a nearby NGS), is given by $\theta(t)$, one discovers that in detecting the tilt of the LGS on the same laser projector, a tiny departure $\Delta\varphi$ from the optical axis of the telescope will be experienced:

$$\Delta\varphi(t) = \theta(t - c/\bar{h}) - \theta(t - c/\bar{h} + \tau). \tag{2}$$

However, $c/\bar{h}$ is much lower than τ, and in the following it is assumed to be negligible. In these approximations one can write

$$\Delta\varphi(t) \approx \tau \frac{\partial\theta(t)}{\partial t}, \tag{3}$$

and the time evolution of $\theta(t)$ can be easily obtained by integration:

$$\theta(t + \Delta t) - \theta(t) = \int_t^{t+\Delta t} \frac{\partial\theta(t)}{\partial t} dt \approx \frac{1}{\tau} \int_t^{t+\Delta t} \Delta\varphi(t)\, dt. \tag{4}$$

In practice, $\Delta\varphi$ will be sampled by the tilt detector with a given time sampling t^*. In these conditions equation (4) has to be discretized:

$$\theta(t + \Delta t) - \theta(t) \approx \frac{t^*}{\tau} \sum \Delta\varphi. \tag{5}$$

Each $\Delta\varphi$ measurement will be performed with an error $\sigma_{\Delta\varphi}$. After an integration time of Δt, a number of measurements of $\Delta\varphi$ given by the ratio $\Delta t / t^*$ will be performed. Assuming that their errors are uncorrelated, the estimation of the sum on the right-hand side of equation (5) will be affected by an error that is larger than the error of a single measurement by a quantity given by the square root of the number of measurements.

So, an error σ_θ will be accumulated on the θ estimations given by

$$\sigma_\theta \approx \sigma_{\Delta\varphi} \sqrt{\frac{\Delta t}{t^*}} \frac{t^*}{\tau} = \sigma_{\Delta\varphi} \frac{\sqrt{t^* \Delta t}}{\tau}. \tag{6}$$

We shall now assume that a laser system with power P_0 is able to produce enough photons, on a pupil subaperture of size r_0 and in an interval time t^*, to sense the position of the corresponding spot with an accuracy of $0.43\lambda/D$ (Sivaramakrishnan, Weymann, & Beletic 1995). By definition this is the minimum laser power to achieve a full high-order adaptive optics correction using the generated LGS. Recalling that the centroiding precision scales with the inverse square root of the number of photons collected, a general relationship for the centroiding accuracy at the projector telescope can be worked out:

$$\sigma_{\Delta\varphi} \approx 0.43 \frac{\lambda r_0}{D D_p} \sqrt{\frac{P_0}{P}} \tag{7}$$

Combining equations (6) and (7), a maximum time interval Δt, in which the integration process leads to an error within the diffraction limits, is easily obtained:

$$\Delta t \approx \left(\frac{D_p}{r_0}\right)^2 \frac{P}{P_0} \frac{\tau^2}{t^*}, \tag{8}$$

and the corresponding sky coverage is proportionally increased by a factor of η given by

$$\eta \approx \left(\frac{\Delta t}{t^*}\right)^{3/2} = \left(\frac{D_p}{r_0} \frac{\tau}{t^*}\right)^3 \left(\frac{P}{P_0}\right)^{3/2} \tag{9}$$

The sky coverage being without any particular adjustment of the order of 1% both for $D = 4$ m and $D = 8$ m class telescopes (Rigaut & Gendron 1992; Olivier et al. 1993), a full sky coverage is obtained for $\eta \approx 100$. This is difficult to obtain (assuming $r_0 = 0.1$ m) with a coaxial laser projector D_p lying in the 0.5–1 m range. Laser powers of the order of $P \approx 100\ P_0$ should be required. Using the whole telescope as the laser projector, however, it is easy to accomplish the goal: for $D = D_p = 4$ m, the full sky coverage is obtained with the nominal $P \approx P_0$, while one with a Δt even longer than that required is obtained for the $D = D_p = 8$ m class telescopes. In this last case, for example, the integration time for the nearby NGS becomes $\Delta t \approx 400$ ms.

3. CONCLUSIONS

A new class of solutions for the tilt indetermination problem of the LGS has been sketched. It requires some short-term estimation of the tilt evolution. The technique of time propagation delay appears, at the very first rough calculations, to work. It requires only already existing technology, and it could be achieved with hardware already requested for the higher order adaptive optics correction: a faint nearby NGS is fitted with an integration time $\approx\Delta t$, while a faster additional tilt sensor must be implemented on the detected LGS. The solution requires, for all practical purposes, the use of the same telescope used for scientific purposes for the projection of the laser beacon. This could properly take into account the gating, coating fluorescence, and safety concerns. Sharing the same telescope for both the laser projection and the detection, as well as for astronomical purposes, requires great care in order to prevent the scattered light from destroying the gain obtained using the proposed technique. Blocking filters tuned to the laser wavelength and with an extremely good grade of rejection could be developed and could easily perform such a task. A number of details must be studied in deeper detail: the effects of the approximation used in the treatment of the problem, the uncertainty on $\bar{h}$ and H or, possibly, their temporal evolution, could modify the final result. Moreover, the integration time has been assumed to be t^* for both the θ and the $\Delta\varphi$ detection; this is reasonable, but because of the derivative operation between them, it is clear that their spectral content is different. It can be argued that these problems will lead to a shortening of the time interval Δt, a problem that, at least in principle, can be overcome, for example, by a more powerful laser.

As a very final note, it must be pointed out that other techniques may be used to determine the short-term evolution of the star wandering. Speculations about the feasibility of predictive algorithms or the detection of the perspective elongation are beyond the limits of this Letter. The same can be said about the integration of the proposed technique with others, like the DAO.

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