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MODEL AND SETUP OF THE PROTOTYPE OF THE POLYCHROMATIC LASER GUIDE STAR AT OBSERVATOIRE DE HAUTE-PROVENCE

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Abstract. We discuss our Polychromatic Laser Guide Star (PLGS) end-to-end model and describe the the status of demonstrator at OHP. PLGS aims at measuring the tilt from the LGS without any NGS. Two dye pulsed laser chains locked at 589 and 569nm are required. Beams will deliver 34 W each, so that 22 W will be deposited into the mesosphere. These lasers are being settled in the building of the OHP 1.52m telescope. Beams will propagate from there to the launch device attached to the 1.52 m telescope through a train of mirrors with constant incident angles. The coudé focus of the 1.52m telescope will be equipped with an adaptive optics device, closely derived from the ONERA's BOA one. The Strehl ratio at 330nm is expected to be 30-40% for $r_0 = 8 - 10$cm. The full demonstrator is planned to run in 2010.

1 Introduction

Diffraction limited long exposure images at large telescopes is possible thanks to adaptive optics (AO) if there is at least one source of reference bright enough within the isoplanatic patch of the source of interest, in order to measure the wavefront phase. If there is no such a source, the phase reference can be provided by a laser guide star (Foy & Labeyrie, 1985) (LGS), generally relying on the mesospheric NaI D_2 line. But with a LGS the wavefront tilt remains undetermined, because the location of the laser spot in the mesosphere is not known (Pilkington, 1987; Séchaud, 1988).

At large telescopes equipped with LGSs the tilt is measured from a natural guide star (NGS), whereas higher orders of the wavefront are measured from the LGS. It results in limited sky coverage performances, dramatically at visible wavelengths. Nevertheless, AO at visible wavelengths is still in its infancy, although it has been proved it works (Fugate et al, 1994; Madec et al, 1997). With or without LGS, coronographic observations of the environment of cool stars, or of AGN seems to be very promising targets such devices. Interesting reviews of other programmes of AO + LGS at visible wavelengths are given in the SPIE-7015 conference (Max et al, 2008; Ammons et al, 2008; Gavel et al, 2008; Bouchez et al, 2008; Britton et al, 2008).

A number of different solutions have been proposed to overcome the tilt problem, e.g. Esposito et al (2000), Foy et al (2000), Belenkii et al (1999), Belenkii (2000) & Schöck et al (2000). Currently the only ongoing R& D programme to measure the tilt from the LGS alone is the *Polychromatic LGS (PLGS)* (Foy et al, 1995). It is the *Étoile Laser Polychromatique pour l'Optique Adaptative ELP-OA* project, which we are conducting at Observatoire de Haute-Provence (*OHP*). The overall goal of ELP-OA is the experimental validation that the measurement of the wavefront tilt *without NGS* is possible at an astronomical telescope.

The PLGS concept relies on the chromatism of the air refraction index n, mostly in the ultraviolet. Therefore the tilt θ of the wavefront slightly varies with λ. Foy et al (1995) have shown that: $\theta_{\lambda_3} = \Delta\theta_{\lambda_1,\lambda_2}(n_{\lambda_3} - 1)/\Delta n_{\lambda_1,\lambda_2}$. Thus the tilt at λ_3 can be derived from $\Delta\theta_{\lambda_1,\lambda_2}$ between λ_1 and λ_2 . The larger is the wavelength difference $\Delta\lambda$ and the shorter is the shortest λ, the higher is $\Delta\theta$ and accordingly the sensitivity.

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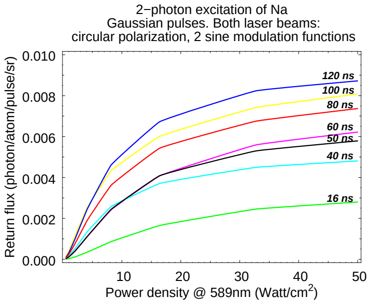

Fig. 1. Curve of growth of the return flux at 330 nm from the resonant two-photon excitation of the $4D_{5/2}$ energy level of sodium, for different pulse durations. BEACON code of CEA (Bellanger et al, 2004).

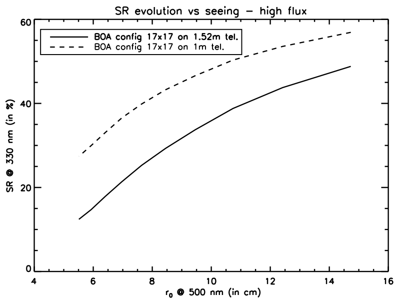

Fig. 2. Expected performances of a 17^2 actuators adaptive optics device at an 1.52m telescope at 330 nm, for two aperture diameters. Case of a bright reference source.

The process to create the polychromatic LGS is the excitation of the $4D_{5/2}$ energy level of sodium atoms in the mesosphere, via the $3P_{3/2}$ level with two laser beams locked at 589 nm and 569 nm respectively. From the $4D_{5/2}$ level, valence electrons decay down to the ground level radiating within spectral lines spanning the 0.330 μm to 2.34 μm interval. Choosing $\lambda_1 = 0.33$ μm and $\lambda_2 = 2.34$ μm leads to $\theta/\Delta\theta = 18$. Thus one needs either 18^2 times more photons, or a spot size 18 times smaller than with a NGS to get the same error in θ if measured with a center of gravity algorithm. The feasibility study of ELP-OA is summarized in Foy et al. (2007).

2 Atomic physics modeling

The PLGS relies on the two-photon incoherent resonant excitation of Na atoms in the mesosphere: $3S_{1/2} \rightarrow 3P_{3/2} \rightarrow 4D_{5/2}$. It provides a spectrum ranging from 330 nm to 2.34μm. We investigated the direct one-photon excitation (Foy et al, 1995) $3S_{1/2} \rightarrow 4P_{3/2}$ at 330 nm: it fails to provide us with enough return flux because the cross section σ_{330} is too low and because the number of velocity classes is much higher than that of the transitions $3S_{1/2} \rightarrow 3P_{3/2} \rightarrow 4D_{5/2}$. High return fluxes modeled by Pique et al (2006) are overoptimistic because they have $\sigma_{330} = 4.0 \times 10^{-14}\mathrm{m}^2$ instead of $1.1 \times 10^{-14}\mathrm{m}^2$ (see e.g. Siegman (1983)), and their rate equation model for a phase modulated laser does not fit with Morris (1994) and Bellanger et al. (2004) models which relies on optical Bloch equations.

Laser parameters have to be optimized to maximize the return flux at 330 nm f_{330}. Figure 1 shows f_{330} as a function of the laser power density d_P at 589 nm. One could conclude that at given d_P the longer is the pulse duration τ, the higher is f_{330}. But d_P being kept constant, increasing τ requires to increase the average power $\overline{P}$ in the same ratio, or to decrease the repetition rate F_R. But these parameters cannot be varied easily because of technological constraints, from NdYAGs and dye lasers. At given $\overline{P}$ and F_R, increasing τ increases F_R but decreases d_p which decreases f_{330}. The balance between these two effects depends on the local slope of the $f_{330} = f(d_p)$ relationship and hence on the spatial energy distribution of the laser beam at the mesosphere.

3 End-to-end model

We have developed a code to simulate the whole ELP process, from the pupil of the launch device lightened by the two lasers up to the measurement of the Strehl ratio $\mathcal{S}$ due to the only tilt at the focus of the master telescope. Our previous, analytical, code (Schöck et al, 2002) was not coupled with the laser-sodium interaction code BEACON. A Kolmogorov phase screen is applied to the pupil function. The power spectrum of the resulting phase map provides us with the spatial d_p map in the mesosphere. It is converted into a photon flux map by interpolating the density power in Fig. 1. The image of this flux map is convolved with the point spread function (PSF) at the output of the master telescope. It is generated from another area of the same Kolmogorov phase screen used for the projector. It includes also an AO device. It is simply modeled by subtracting from the phase screen itself its smoothed map in order to fit an input value $\mathcal{S}$.

The detector is assumed to be an EMCCD, so that the readout noise can be neglected (Basden et al, 2003).

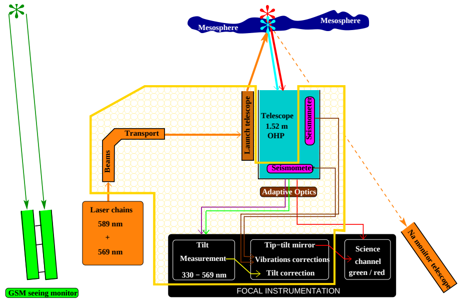

Fig. 3. Layout of the ELP-OA experiment at OHP. In addition to the equipment installed at the master 1.52 m telescope, there will be a seeing monitor and a monitor of the sodium density in the mesosphere installed at another telescope on the OHP site

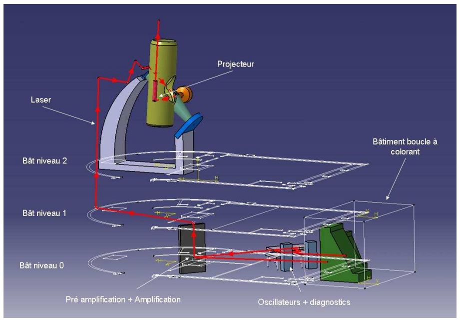

Fig. 4. Layout of the optical path of laser beams from the clean room to the projector through the master telescope mount. All incidence angles are constant.

We do not use a center of gravity algorithm to measure $\Delta\theta$. Indeed in this case the accuracy is ultimately limited by the seeing disc size. We use of the smallest features in the image, following the Cramér-Rao criterion, e.g. the speckle pattern of the laser spot. Phase restoration from the images themselves has now proven to work (Rondeau et al, 2007) up to $D/r_0 \approx 75$. But since it is an iterative algorithm it can be barely used on line. Instead, we use cross correlations, either between the images at the two λs (e.g. at 330 nm and at 569 nm), or between these images and a model. Consequently, the larger is the projector pupil p, the smaller are the spot pattern features in the mesosphere. The master telescope has to resolve this pattern at the longer wavelength used to measure $\Delta\theta$. At an 1.52 m telescope $p < 0.44$ m with IR lines, or $p < 1.5$ m with 569 nm line.

4 Layout of the ELP-OA experiment

Work is in progress to setup the ELP-OA demonstrator at the 1.52 m telescope at OHP. Figure 3 shows the layout of the experimental setup. Phase modulated pulsed dye laser are similar to those which we have used at the LLNL (Foy et al, 2000) and at CEA/Pierrelatte (Schöck et al, 2000) for our previous experiment to check experimentally on the sky the efficiency of the two-photons excitation of sodium atoms in the mesosphere. Pump lasers will be NdYAGs. The laser clean room is being equipped at the ground level of the 1.52 m telescope building. Dye pumps will be installed in an extension of the building, for easier operation and also for safety. The two beams are carried up to the projector telescope through a train of mirrors (Fig. 4). The master telescope has an English equatorial mount. They enter the master telescope English mount through the North tip of its hour angle axis. Then laser beams propagate until the cross of the two telescope axis and through the flat M3 mirror, which has to be drilled. All along their path in the telescope, beams are confined within the M2 central obscuration. In this way, all reflexion angles of the mirror train are constant, which avoid changes in the coating efficiency and of the polarization.

M3 and M4 and possibly M2 mirrors will be coated for improved reflectivity at 330 and 569 nm.

An adapted version of the ONERA's BOA device (Madec et al, 1997) will be implemented at the coudé focus. Modifications are required to improve the throughput at 330nm. The deformable mirror will be an ALPAO's 17^2 actuators one, the Shack-Hartmann wavefront sensor with an EMCCD camera being lent by LAOG. The wavefront sensor will be fed by the backscattered D_2 line. Modeled performances are shown in Fig. 2.

Since θ is derived from $\Delta\theta$, it is insensitive to telescope vibrations. The rms amplitude of resonance vibrations at the OHP 1.52 m telescope is ≈66 mas (Tokovinin, 2000), which is close to the Airy disc FWHM at 550 nm. They will be measured with two pendular seismometers (Tokovinin, 2000) mated to telescope axises.

In parallel to the main ELP-OA setup, two devices will run, to fully characterize the observing conditions. The seeing parameters r_0, τ_0 and the atmospheric transparency will be measured with a Generalized Seeing Monitor (G.S.M.), on loan from Nice University thanks to A. Ziad and J. Borgnino. The GSM will be operated close to the 1.52 m telescope, as far as possible every night to get quantitative measurements of these parameters over the year, which are lacking. For a few runs, a second GSM will be installed inside the dome and it will operated simultaneously with the outer one, in order to get a quantitative estimate of dome seeing. From these campaigns, we hope to be able to improve the telescope environment in terms of image quality.

The second device will be a monitor of the Na column density in the mesosphere at the 1.20 m OHP telescope. Since they are located a few hundred meters away from the 1.52 m telescope, we will get information about the sodium density vertical profile and therefore on the sodium layer average altitude. We will compare our results with measurements at the Grard Mgie Station of aeronomy located 100 m North of the 1.52 m telescope.

5 Conclusion

Models allow us to predict tilt Strehl ratios of $\approx$30 to 40% at 550 nm.

The current status of the setup of ELP-OA is the following. Power water supplies have been increased to match the ELP-OA requirement. The clean room is being installed at the ground level of the building. Negotiations for loans of the laser chains and of AO components are almost completed. We plan to start the installation of these systems by the end of 2008. First launch of laser beams are planned for the end of 2009, and the whole ELP-OA experiment is plan to start first tip-tilt measurement by the end of 2010.

6 Acknowledgments

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