Diffraction limited operation with ARGOS: a hybrid AO system

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Diffraction limited operation with ARGOS: an hybrid AO system

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ABSTRACT

ARGOS, the Laser Guide Star (LGS) facility of the Large Binocular Telescope (LBT), implements a Ground Layer Adaptive Optics (GLAO) system, using 3 low-altitude beacons, to improve the resolution over the 4'x4' FoV of the imager and Multi Object Spectrograph (MOS) LUCIFER. In this paper we discuss the performance and the reconstruction scheme of an hybrid AO system using the ARGOS Rayleigh beacons complemented with a single faint high-altitude star (NGS or sodium beacon) to sense the turbulence of the upper atmosphere allowing an high degree of on-axis correction.

With the ARGOS system, the NGS-upgrade can be immediately implemented at LBT using the already existing Pyramid WFS offering performance similar to the NGS AO system with the advantage of a larger sky coverage.

Keywords: Adaptive optics, ARGOS, Pyramid wavefront sensor, hybrid AO, ground layer AO, laser guide star.

1. INTRODUCTION

The Large Binocular Telescope (LBT) is an adaptive optical/infrared telescope. It is equipped with two 8.4m primary mirrors mounted on a common elevation structure (see Figure 1). The adaptive optics correctors are the Gregorian secondary mirrors (ASM):[1] made by a 1.2mm thick shell of 911mm diameter deformed by 672 voice-coil actuators. The wavefront sensor of the First Light AO (FLAO) system is a Pyramid WFS[2] with adjustable sampling. It uses a natural star taken from the science field to provide single conjugate AO correction to LUCIFER, a $4 \times 4'$ infrared imager and MOS. Recently a first eye of LBT has been equipped with the FLAO, providing the first diffraction limited images.[3]

The ARGOS[4] system will make use of three 15x15 subapertures Shack-Hartman (SH) WFS to sense the lower layers of the atmospheric turbulence using three Rayleigh laser beacons focused at 12km altitude.[5] This system will provide a GLAO correction for the LUCIFER instrument using as corrector the ground-conjugated ASM already installed at the telescope. The ARGOS project has recently passed the final design review and it is now in the procurement and integration phase. This system is scheduled to be operative at LBT in early 2012.

This paper presents the result of a study aimed at investigate the performance of an hybrid NGS-LGS AO system that can be implemented at the BT complementing the full atmosphere measurements done by the Pyramid WFS using a NGS with the ground layer turbulence informations obtained by ARGOS using the Rayleigh beacons. In the case of a faint NGS the optimal sampling of the full atmospheric turbulence requires large subapertures, hence the reconstructed wavefront is fitted on a limited number of modes. For low altitude atmospheric layers, modes not sensed by the NGS WFS can be reconstructed using the information of the Rayleigh beacons obtaining a better on-axis reconstruction for a given NGS magnitude. It is important to note that once ARGOS will be installed no additional hardware is required to test this operation mode. The performance of the hybrid NGS-LGS AO system has been estimated with numerical simulations using the code developed to estimate the FLAO performance.[6] For FLAO the agreement between the simulations and the solar tower test campaign,[3] carried out in Arcetri in December 2009, is excellent.

In section 2 of this paper the AO system model is described: we summarize the parameters and the modeling of the system. In section 3 are analyzed the performance of the hybrid NGS-Rayleigh AO system: the parameters of the Pyramid WFS are optimized to account for the best correction on-axis and the gain in reference star magnitude and sky coverage is discussed.

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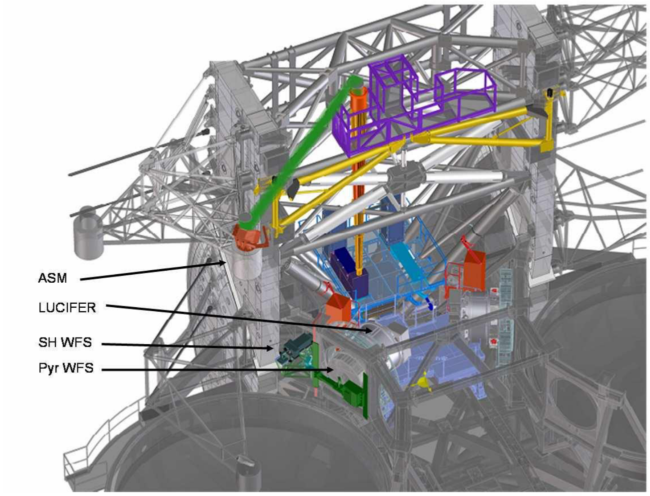

Figure 1. Overview of the LBT structure. In color are the elements that compose the ARGOS system. The ASM is the adaptive optics corrector for both the FLAO and ARGOS systems. The Pyramid WFS is placed in the rotator structure in the bent Gregorian station, in front of the LUCIFER imager and MOS. The 3 SH WFS of the ARGOS system are hosted in a separate enclosure aside the LUCIFER focal station.

2. SYSTEM MODEL

This work is based on numerical simulations carried out in IDL code. The system include a realistic modeling of the atmosphere, laser and natural guide stars, Shack-Hartman and Pyramid wavefront sensors, the deformable mirror and the closed-loop control with temporal evolution. The corrected point spread function is evaluated at each simulation step. The telescope is supposed to be paraxial, pointing to the zenith, where performance of the system are evaluated by averaging the short-exposure PSF. Table 1 resumes the main parameters of the system.

2.1 Atmospheric model

The atmosphere is modeled with 12 infinitely thin phase screens of 4096x512 pixels sampled at 0.053m/pix. The outer scale parameter is $L_0 = 30m$. The height distribution, wind speed and equivalent Fried parameter of the layers are reported in Table 2. The total Fried parameter is $0.135m$ at $0.5\mu m$. The equivalent seeing is $0.75arcsec$. This atmospheric model has been retrieved as "typical" turbulence distribution from a site test campaign done at Mt. Graham[7] and it was employed to evaluate the performance of the ARGOS system.[8]

The temporal evolution of the turbulence is simulated by shifting each phase screen with the associated wind speed. The propagation of the phase to the wavefront sensors is simulated adding the contribution of each phase screen. In case of a laser reference source the footprint on each layer is resized to account for the cone factor. The resizing factor is given by: $k_{cf} = 1 - h_{lgs}/h_{lay}$, where h_{lay} and h_{lgs} are respectively the distances of the turbulent layer and laser guide star from the telescope pupil.

2.2 Guide star constellation

In this work the natural guide star is always sensed by the Pyramid WFS and it is used to measure at least the five lowest modes (tip-tilt, defocus and astigmatisms) in case of very faint guide stars. The NGS is modeled as point-like source and it is located at the center of the FoV. The 3 Rayleigh LGS are located at the vertex of an equilateral triangle inscribed in a circle of $120arcsec$ radius. The Rayleigh LGS are sensed by SH WFS. The LGS spot size is simulated by convolving the image of each SH subaperture with a Gaussian distribution of $2arcsec$ FWHM before adding photon, background and read-out noise. No spot elongation due to the gating height is considered. The power of the 3 Rayleigh lasers is fixed to $18W$ and the gating thickness is set to $300m$ centered on a distance of $12km$ from the telescope pupil. This setup ensures a flux of $1655\gamma\ sa^{-1}ms^{-1}$ for a 15×15 SH WFS.

Telescope	
Effective diameter (D)	8.22m
Central Obstruction	0.11D
Optics transmission	0.36
Altitude	3600m
Deformable mirror	
Conjugation height [m]	0
Number of actuators	672
Controlled modes	Karhunen-Loève fitted
Loop parameters	
Loop frequency	1kHz
Total integration time	2s
AO controller	simple integrator: $C(z) = g/1 - z^{-1}$
Pyramid WFS	
Sensing wavelength	750nm
Tilt modulation	$\pm 6.0\lambda/D$
Number of subapertures	30×30
Field of view [$arcsec$]	2.1
CCD quantum efficiency	0.8
CCD readout noise	3.5
Shack-Hartman WFS	
Sensing wavelength	532nm
Number of subapertures	15×15
Number of pixels for sa side	8
Field of view [$arcsec$]	4.9
CCD quantum efficiency	0.9
CCD readout noise	3.6

Table 1. Summary of simulation parameters.

Layer number	1	2	3	4	5	6	7	8	9	10	11	12
Layer height [m]	125	375	625	875	1125	1375	1675	3000	5000	10000	15000	20000
Layer speed [m/s]	9	9	9	9	11	13	15	25	21	35	20	22
r_0 [m]	0.21	0.44	0.81	1.83	2.18	1.67	1.44	0.61	0.69	0.58	1.09	3.11

Table 2. Summary of the atmospheric parameters used in the simulations.

2.3 The AO loop

The interaction matrices (IM) of the various WFS are recorded independently using a diffraction limited source. The 3 IM of the SH WFS that sense the GL turbulence through the Rayleigh beacons are concatenated forming a single matrix: $\mathbf{M}_{lgs} = [\mathbf{M}_{ray1}, \mathbf{M}_{ray2}, \mathbf{M}_{ray3}]$ that is then inverted using SVD. The IM of the Pyramid WFS ($\mathbf{M}_{ngs}$) is truncated to a certain number of modes (n_{ngs}) and then it is inverted with SVD.

The NGS and LGS WFS are sampling turbulence at different frequencies: the 3 SH run at a fixed frequency of $1kHz$ while the Pyramid WFS sampling frequency is optimized on the flux of the considered reference star and it is always less than $1kHz$ in the considered cases. Assuming to have a reference star of magnitude m_r the Pyramid WFS will sample the overall turbulence at a frequency f_{ngs} correcting for a maximum n_{ngs} number of modes. In this case the phase measured by the Pyramid WFS will be:

$$\Phi_{ngs} = \Phi_{GL}^{n_{ngs}} + \Phi_{HL}^{n_{ngs}},$$

where $\Phi_{GL,n_{ngs}}$ and $\Phi_{HL,n_{ngs}}$ are respectively the contribution of the ground layer and high layer to the overall phase sampled by the NGS WFS with n_{ngs} modes. At the same time step $t^k = (k/f_{ngs})$ with $k = 0, 1, 2, ..$ the lower layers of the turbulence will be sampled also by the LGS WFS with n_{lgs} modes . So the phase measured from the 3 SH WFS will be:

$$\Phi_{lgs} = \Phi_{GL}^{n_{lgs}}$$

The best estimation of the turbulent phase in a time step t^k will be:

$$\Phi' = \Phi_{HL} 0 ... n_{ngs} + \Phi_{GL}^{0...n_{ngs}} + \Phi_{GL}^{n_{ngs}+1...n_{lgs}},$$

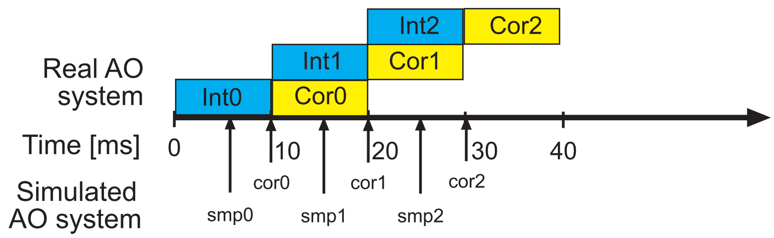

Figure 2. Scheme of the temporal delay implemented in the simulation code. The correction made on the NGS measurements is delayed by an half of the integration time. A real AO control loop is sketched for comparison, the reconstruction time is supposed to be negligible for a system running at $100Hz$.

where the superscripts means the modes from 0 to n_{ngs} and from $n_{ngs}+1$ to n_{lgs} respectively. So, when the NGS measurements are available, the first n_{ngs} modes are sensed by the Pyramid WFS. At these time steps the NGS and LGS measurement vectors are concatenated in a single one: $\mathbf{s}_{hyb} = [\mathbf{s}_{ngs}, \mathbf{s}_{ray1}, \mathbf{s}_{ray2}, \mathbf{s}_{ray3}]$ and the two reconstructors $\mathbf{R}_{ngs}$ and $\mathbf{R}_{lgs}$ are merged:

$$\mathbf{R}_{hyb} = \begin{vmatrix} \mathbf{R}_{ngs} & 0 \\ 0 & \mathbf{R}_{lgs} \end{vmatrix}.$$

At time steps when the NGS WFS is not measuring, because the optimal exposure time is less than $1kHz$, the measurement vector $\mathbf{s}_{ngs}$ is 0 and the best estimation of the turbulence is given by the GLAO measurements. In this case the reconstructor $\mathbf{R}_{hyb}$ will be:

$$\mathbf{R}_{hyb} = \begin{vmatrix} 0 & 0 \\ 0 & \mathbf{R}_{lgs} \end{vmatrix}.$$

Note that in these time steps only the GL turbulence is sensed and corrected, while the correction on HL degrades.

The calculated command vector is sent to the DM using a pure integrator with optimal gains for each WFS. Because the simulation time step is $1ms$ we have assumed that the total delay for the LGS measurements running at $1kHz$ frequency is $2ms$. For simplicity the NGS measurements are executed in a single time step, using the equivalent photon flux, and are then delayed by half of the sampling time, as Figure 2 shows.

3. PERFORMANCE OF THE HYBRID NGS-RAYLEIGH SYSTEM

In this section are analyzed the performance of the hybrid NGS-Rayleigh AO system. This system is presented in Figure 3, it will use a natural reference star to sample at low frequencies the whole cylinder of atmospheric turbulence above the telescope with the Pyramid WFS of the FLAO system. The correction available from these measurements will be limited to a certain number of modes and will be complemented by the ground layer correction on 153 modes available through the Rayleigh beacons sampled at $1kHz$ frequency by 3 SH WFS.

The simulations presented here are made of 2000 iterations at $1ms$ time steps. The performance of the system in function of the NGS magnitude are evaluated by computing the SR in the H band from the long-exposure PSF. The long-exposure PSF are obtained by adding all the short exposure images of a run. The Pyramid WFS configurable parameters (mainly the sampling frequency and the maximum number of modes corrected) have been optimized for each flux level, Table 3 resumes the results of this analysis.

M_r	binning	f_{ngs} $[Hz]$	n_{ngs}	SR [% H band]	SR [% K band]
13.5	3	500	74	47.8	73.9
14.5	3	330	58	36.8	66.4
15.5	4	200	36	24.2	55.9
16.5	4	160	36	11.5	41.2
17.5	4	125	12	5.4	30.2
18.5	4	100	12	2.8	23.8

Table 3. Optimized parameters for the Pyramid WFS in function of the reference star magnitude.

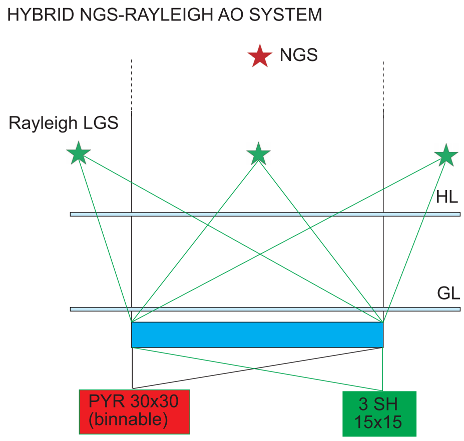

Figure 3. Scheme of the hybrid AO system using a NGS sensed by the Pyramid WFS and 3 Rayleigh beacons sensed by a set of 15×15 SH WFS.

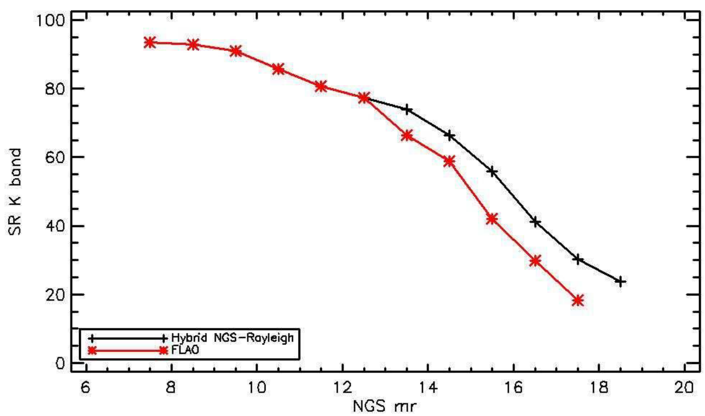

Figure 4. Comparison between the performance of the FLAO and an hybrid NGS-Rayleigh AO system. The gain in reference star magnitude is in about $1mag$.

Figure 4 visualizes the data of Table 3. The performance of the FLAO system evaluated in[6] are plotted for comparison. Considering a constant value of the SR the gain in guide star magnitude by using an hybrid NGS-Rayleigh AO system is $1mag$.

Figure 5 shows the evolution on time of the residual phase variance for both the hybrid and FLAO systems. The NGS magnitude is 16.5, the Pyramid WFS is sampling 36 modes respectively at 200 and $100Hz$. The hybrid case shows the decorrelation of the correction of the high turbulent layer when the measurements vector from the Pyramid WFS is not available.

The FLAO limiting magnitude to reach an on-axis SR of 20% in K band is $m_r = 17.5$ while for the hybrid NGS-Rayleigh systems is $m_r = 18.5$. Considering these NGS magnitudes the respective sky coverages are: $1 \div 30\%$ and $1.5 \div 45\%$, where the lower value is obtained considering a $15 \times 15 arcsec$ FoV and a $5 \times 5°$ search field centered on the North Galactic pole while the upper one is obtained around the Galactic center. So the gain in sky coverage by using the hybrid NGS-Rayleigh system is about 50%.

4. CONCLUSIONS

In this paper we analyzed the performance of an hybrid AO system that combines the information on the full atmospheric turbulence obtained from a Pyramid WFS using a NGS and the ground layer information obtained

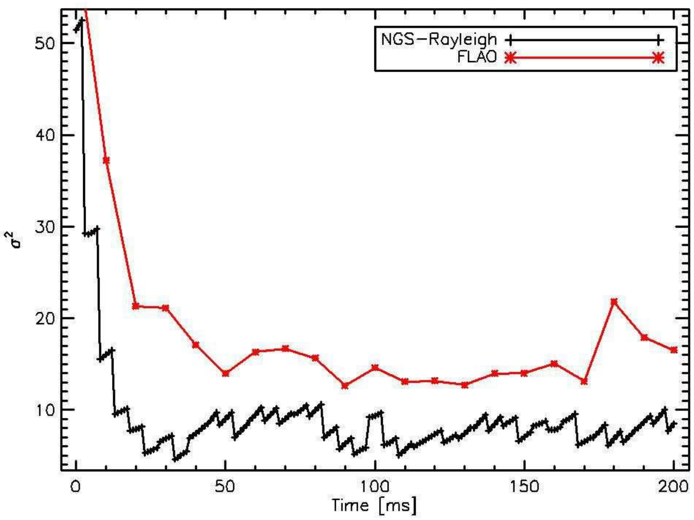

Figure 5. Variance of the residual phase in function of time at $750nm$. The 2 lines refer respectively to the hybrid NGS+Rayleigh (black) and FLAO (red) systems. In the hybrid case it is visible the decorrelation of the correction of the high turbulent layers between two samples of the Pyramid WFS.

through 3 SH WFS using Rayleigh beacons. The wavefront distortions are then corrected using a single ground-conjugated deformable mirror. This operation mode will be available at the LBT once ARGOS system will be installed. The NGS magnitude limits the Pyramid WFS sampling frequency that, in case of faint reference star, is always less than the sampling frequency of the LGS WFS running at $1kHz$. So it is needed an hybrid reconstructor that optimizes the information on the turbulence available at each time step. The optimal setup of the hybrid AO system has been analyzed with numerical simulations and its performance have been evaluated in closed loop, by averaging the short-exposure PSF. The level of on-axis correction achievable from the hybrid system has been compared with the FLAO. This analysis showed that the same level of SR can be obtained with a $1mag$ fainter reference star in case of the hybrid system. This ensures a gain of 50% in sky coverage considering an NGS limiting magnitude $m_r = 18.5$ and a FoV of $15 \times 15arcsec$.

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