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Tommaso Mazzoni, Lorenzo Busoni, Marco Bonaglia, Simone Esposito, "Atmospheric turbulence profiling using the SLODAR technique with ARGOS at LBT," Proc. SPIE 9909, Adaptive Optics Systems V, 99093R (27 July 2016); doi: 10.1117/12.2234268

Event: SPIE Astronomical Telescopes + Instrumentation, 2016, Edinburgh, United Kingdom

Atmospheric turbulence profiling using the SLODAR technique with ARGOS at LBT

Tommaso Mazzoni[a, b], Lorenzo Busoni[a], Marco Bonaglia[a], and Simone Esposito[a]

[a]INAF Osservatorio Arcetri, L. Enrico Fermi 5, 50125 Firenze, Italy
[b]Università degli studi di Firenze, P.zza S.Marco 4, 50121 Firenze, Italy

ABSTRACT

ARGOS is the Ground Layer Adaptive Optics system of the Large Binocular Telescope, it uses three Laser Guide Stars, generated by Rayleigh backscattered light of pulsed lasers. Three Shack-Hartmann WFS measure the wavefront distortion in the Ground Layer. The SLOpe Detection And Ranging (SLODAR) is a method used to measure the turbulence profiles. Cross correlation of wavefronts gradient from multiple stars is used to estimate the relative strengths of turbulent layers at different altitudes. We present here the results on sky of the SLODAR profile on ARGOS.

Keywords: Adaptive Optics, atmospheric profiling

1. ARGOS

ARGOS[1] is the laser guide star adaptive optics facility of the Large Binocular Telescope (Arizona, USA). The aim of the ARGOS system is to improve the scientific throughput of the LUCI instrument, an imaging and Multi-Object Spectrograph, in the "seeing" limited configuration. The "seeing" limited configuration has a wide field of view ($4'$) and a $0.125''$/px pixel scale. ARGOS implements a Ground Layer Adaptive Optics (GLAO) with three Rayleigh Laser Guide Stars (LGSs), three Shack-Hartmann (SH) WaveFront Sensors (WFSs) and a Natural Guide Star WFS for the Tip-Tilt correction.

The LGSs are generated by three pulsed laser, launched from the back of the secondary mirror and focalized at z= 12 km. The asterism is an equilateral triangle inscribed in a $2'$ radius circle. The gating units (Pockel Cells) allow to observe the LGSs in a range of 150 m centered on the nominal altitude. The SH WFSs sens the pupil, one WFS for each LGS, with 15×15 subaperuters and they are arranged in single pnCCD (248×256 pixels).[2] The TT WFS is Quad Cell that feed an Avalanche Photo Diode (APD). The Pyramid WFS of the FLAO[3] system is used as Truth Sensor and can be also used as Tip-Tilt WFS alternatively to the APD. The wavefront reconstructions performed by the three SH are combined to obtain the estimation of the aberration introduced by the ground layer of the turbulence. The Adaptive Secondary Mirror[4] (ASM) performs the wavefront correction.

The ARGOS telemetry stores the individual signals of the 3 SH sensors at 1 kHz rate and we make use of these data to reconstruct the turbulence profiling using the SLODAR technique. During the GLAO operation the ARGOS system works in Closed Loop and it is possible to compute the Pseudo Open Loop (POL) signals that are the total turbulence felt by the WFSs. The POL slopes are evaluated as the sum of the residual measured by the WFSs (s_t^{RES}) and the projection of the ASM position (P_{t-3}^{DM}) on the WFSs. The projection is performed by the AO Interaction Matrix ($\mathcal{I}_M^{\mathrm{AO}}$).

$$s_t^{\mathrm{POL}} = s_t^{\mathrm{RES}} + \mathcal{I}_M^{\mathrm{AO}} \times P_{t-3}^{\mathrm{DM}} \tag{1}$$

where t is an integer multiple of the integration time d_t= 1.03 ms.

Further author information:
Tommaso Mazzoni, ✉ tmazzoni@arcetri.astro.it

Adaptive Optics Systems V, edited by Enrico Marchetti, Laird M. Close, Jean-Pierre Véran, Proc. of SPIE Vol. 9909, 99093R

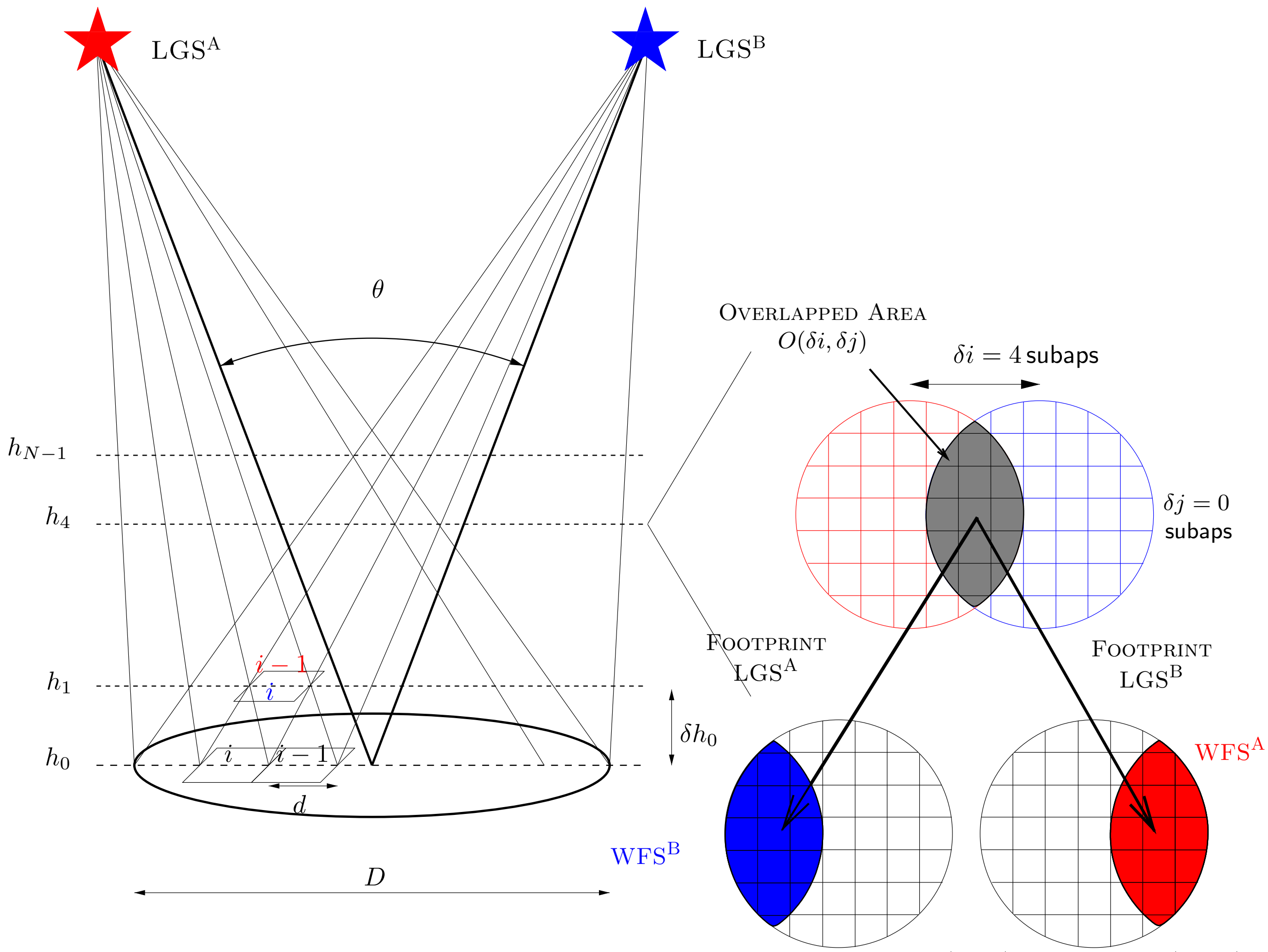


Figure 1: Implementation of the SLODAR technique with two laser guide stars (LGS) and two SH (WFS) with 7 subapertures on the diameter. On the right is showed the footprints at altitude h_4 and lower the projection of the overlapped area on the two sensors.

2. THE SLODAR TECHNIQUE

The SLOpe Detection And Ranging (SLODAR[5]) is a method to calculate the atmospheric turbulence profile $C_n^2(h)$ using the spatial covariance of the cross-correlation of the measured slopes between WFSs. We implemented a system based on SLODAR method with ARGOS. The SLODAR technique must be modified to be applied to AO system based on multiple laser guide stars and independent WFSs as described in Cortes et al.[6] and in Guesalaga et al.[7]

Figure 1 shows the principle of operation of a SLODAR system with two LGSs and two WFSs with 7 subapertures on the pupil diameter. The SLODAR technique operates in the altitude range where the footprints of the LGSs are totally or partially overlapped. The identification of the turbulent layers is based on the research of the correlation signals of the SH slopes between the different WFSs. If we consider a single turbulent layer on the pupil, (at altitude h_0) the i-th subapertures of the two sensors will measure the same signals. The cross correlation between the two WFS is localized at null distance between the subapertures. It exists an altitude (h_1) at which the projection of the i-th subaperture of the WFS2 (in blue) and the $(i-1)$-th subaperture of the WFS1 (in red) are perfectly overlapped; a turbulent layer at altitude h_1 will generate the same signals on the two (different) subapertures. This produce a cross correlation signal localized at a distance equal to the distance between the subapertures, in that case $\delta i = 1$ subaperture. In general we can say that a turbulent layer a altitude h_m produce in subapertures, away from each other $\delta i = m$, signals that correlate between them. So the altitude over the telescope is divided in bins, as many as are the subapertures on the diameter. Going up in altitude fewer subapertures are overlapping, so the correlation signal decrease. With LGSs the projection of the subapertures are conic. Figure 1 shows also the footprints at altitude h_4 where the subapertures are overlapped at distance $\delta i = 4$ subapertures. In the bottom are highlighted the region of the two SH WFSs overlapped at altitude h_4.

The cross correlation between two sensors (A and B) in the x direction is given by:

$$\mathcal{C}_{sx}(\delta i, \delta j) = \frac{\langle \sum_{i,j} s_x^{\mathrm{A}}(i,j)\, s_x^{\mathrm{B}}(i+\delta i, j+\delta j) \rangle}{O(\delta i, \delta j)} \tag{2}$$

where s_x is the slopes signal in the x direction, (i, j) are the (x, y) position expressed in subapertures and $O(\delta i, \delta j)$ is the number of overlapped subapertures as function of the distances $(\delta i, \delta j)$. "$\langle\rangle$" is the temporal average in a data set. A time-delayed cross correlation between different sensor give us a time evolution of the turbulent layers and can be used to profile the wind.[7,8]

The autocorrelation of the two sensors is given by the mean of the two autocorrelation signals:

$$\mathcal{A}_{sx}(\delta i, \delta j) = \frac{1}{2}\frac{\langle \sum_{i,j} s^{\mathrm{A}}(i,j)\, s^{\mathrm{A}}(i+\delta i, j+\delta j) \rangle}{O(\delta i, \delta j)} + \tag{3}$$

$$\frac{1}{2}\frac{\langle \sum_{i,j} s^{\mathrm{B}}(i,j)\, s^{\mathrm{B}}(i+\delta i, j+\delta j) \rangle}{O(\delta i, \delta j)} \tag{4}$$

The autocorrelation signal is used for a two dimensional deconvolution of the cross correlation signals, like:

$$\mathcal{C}_{\mathcal{D}} = \mathcal{F}^{-1}\left[\frac{\mathcal{F}[\mathcal{C}]}{\mathcal{F}[\mathcal{A}/\max(\mathcal{A})]}\right] \tag{5}$$

The autocorrelation is normalized to the maximum because we want preserve the dimensionality.

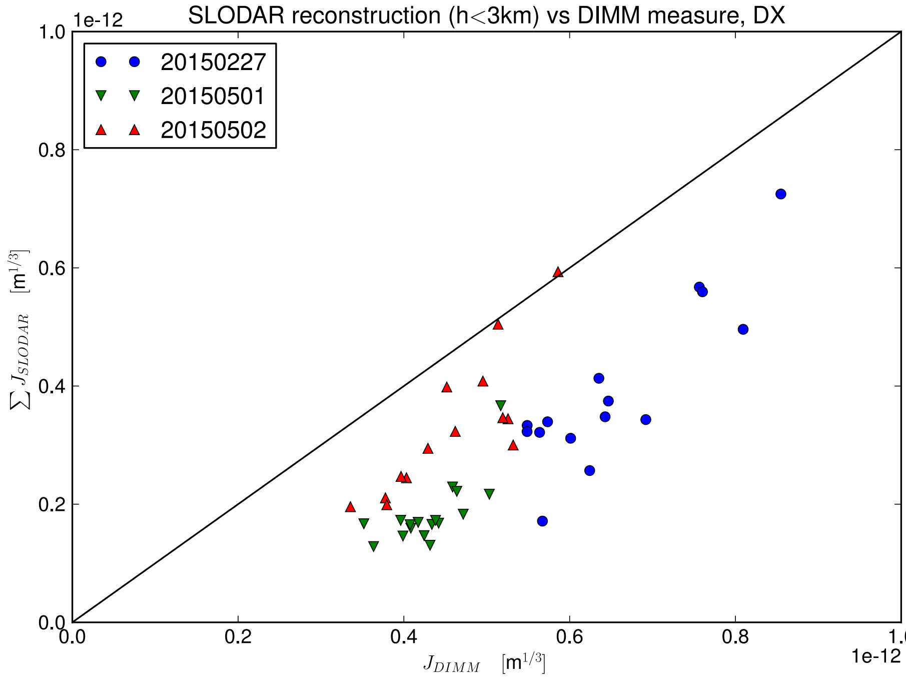
A covariance map can be express as the sum of a series of maps product by different single turbulent layer. The series of maps is a linear operator called "Interaction Matrix" ($\mathcal{I}_{\mathcal{M}}$). We can express the our covariance map as the product of a vector of weight by the $\mathcal{I}_{\mathcal{M}}$:

$$\mathcal{I}_{\mathcal{M}} \boldsymbol{w} = \mathcal{C}_{\mathcal{D}} \tag{6}$$

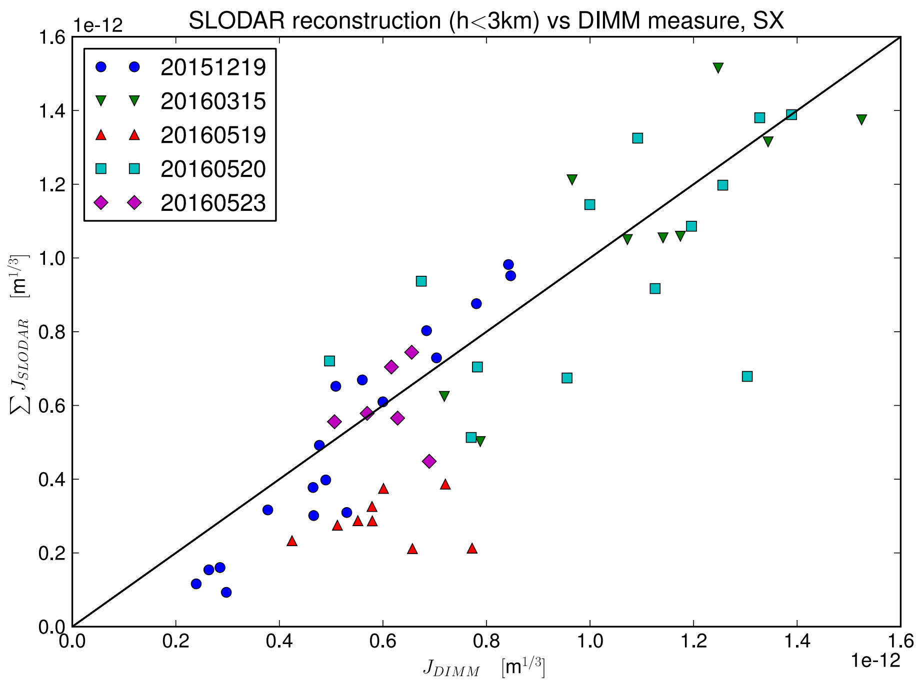
where $\boldsymbol{w}$ are the weights of the turbulence vertical profile at the altitudes $h_0, h_1, \ldots, h_{N-1}$ where we calibrate the system. The "Interaction Matrix" is synthetic: we simulate the respose of the ARGOS system with a series of single layer turbulence distributions and we stack the obtained covariance maps. Our aim is to solve the linear system and obtain the vector $\boldsymbol{w}$ from a covariance map measured on sky. The reconstructor matrix $\mathcal{R} = \mathcal{I}_{\mathcal{M}}^{+}$ is the pseudo inverse of the interaction matrix and we can calculate the weights as $\boldsymbol{w} = \mathcal{C}_{\mathcal{D}}\mathcal{R}$. The weights represent the amount of turbulence measured with the SLODAR technique. Using the parameter of calibration we can express the strength of the turbulence in the selected range of altitude as:

$$J^{\mathrm{SLO}}(h_m) = C_n^2(h_m)\delta h_m = \frac{w_m \hat{r}_0^{-5/3}}{0.423(2\pi/\lambda)^2} \tag{7}$$

where m is the number of the bin and λ is the wavelength relative to the Fried parameter ($\hat{r}_0$ =0.14 m) used for the calibration, that is $\lambda = 500$ nm. We calibrate the system assuming a turbulence spectrum of Von Kármán with an outer scale $L_0 = 20$ m. At the moment we don't have a system to estimate the outer scale and this produce an uncertainty. In the range of value from $L_0^{\mathrm{MIN}} = 10$ m to $L_0^{\mathrm{MAX}} = \infty$ m (Kolmogorov spectrum) the maximum error expected is around 15% in terms of the total strength of the turbulence, J.



(a) Measure on the DX side in the first runs.



(b) Measure on the SX side.

Figure 2: Turbulence strength ($h<$ 3 km) measured with the SLODAR technique as function of the DIMM measure.

3. RESULTS ON SKY

In this section we present the results obtained analyzing the data collected by the two systems (DX and SX) in four commissioning campaign. The binocular operation is not commissioned, so the data of the systems are acquired in different campaign. The data are blocks of 4000 slopes (acquired in ~ 4 s) and then collected in sets of 2-3 blocks. In the nights classified as 20150227, 20150501 and 20150502 we acquired the data with the DX (right) ARGOS system. In the nights 20151219, 20160315, 20160519, 20160520 and 20160523 we used the SX (left) system.

Figures 2 show the total of the turbulence profiles as function of the measure of the "seeing" performed by the DIMM. J_{DIMM} is total strength of the turbulence calculated as:

$$J_{\mathrm{DIMM}} = \frac{(r_0^{\mathrm{DIMM}})^{-5/3}}{0.423(2\pi/\lambda)^2}; \qquad r_0^{\mathrm{DIMM}} = 0.98\frac{\lambda}{\varepsilon^{\mathrm{DIMM}}} \tag{8}$$

where ε is the measure of the "seeing", r_0^{DIMM} is the corresponding Fried parameter. The plots show the coherence of the two measures. The absolute comparison can be biased by the reconstructor. The trend of SLODAR reconstruction follow the DIMM measures but with dispersion that is still under investigation.

We reconstruct only the turbulence under 3 km but we can estimate the contribution of the turbulence between 3 km and 12 km from the difference between the autocorrelation signals and the correlation signals. The autocorrelation signals contains the information of the turbulence under 12 km but integrate in this range. We cannot reconstruct the vertical profile over 3 km so the contribution between 3 km and 12 km has a big uncertainty due to the cone effect. This implementation of the SLODAR method is also insensitive to the turbulence above 12 km.

One of the main aim of this study is to develop a tool to estimate the GLAO performance according to the reconstructed turbulence profile, and to use it as diagnostic tool during the commissioning of ARGOS at LBT.[9] The performance of GLAO critically depends on the vertical distribution of turbulence. If high altitude turbulence is weak, the gain from GLAO increases. With the terms *gain* we identify a a quantity that represent the perfomance of the system. We can express the *gain* of a GLAO system as the ratio between the Full Width Half Maximum (FWHM) of a seeing limited observation and the FWHM of GLAO corrected image.

$$gain_{\mathrm{FWHM}} = \frac{FWHM^{\mathrm{seeing}}}{FWHM^{\mathrm{GLAO}}} \tag{9}$$

where $FWHM^{\mathrm{seeing}}$ is the PSF dimension in seeing limited observation and $FWHM^{\mathrm{GLAO}}$ is the PSF dimension observed using ARGOS. We expect that usually the 90% of the turbulence strength is located in the first kilometer of altitude, as measured in the site characterization campaign of Mt. Graham.[10] In this condition the expected $gain_{\mathrm{FWHM}}$ is around 2 in K band and lower in H and J band.

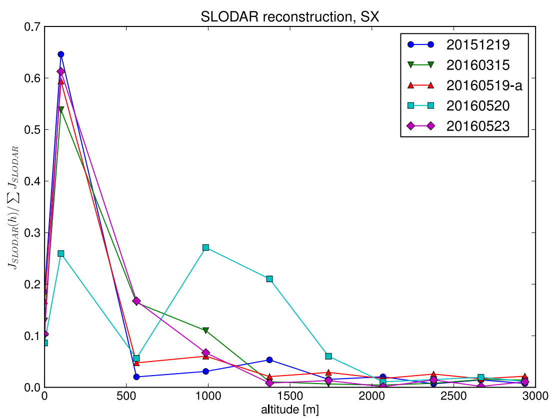
TABLE 1: $gain_{\mathrm{FWHM}}$ measured with LUCI in three IR bands.

side	day	$gain_{\mathrm{FWHM}}$		
		J band	**H band**	**Ks band**
DX	20150227		1.3	
	20150501		1.7	
	20150502	1.6		
SX	20151219	1.6	1.9	2.1
	20160315	1.6	2.0	2.1
	20160519-a			1.6
	20160519-b			1.1
	20160520	1.4	1.5	
	20160523	1.7		2.0

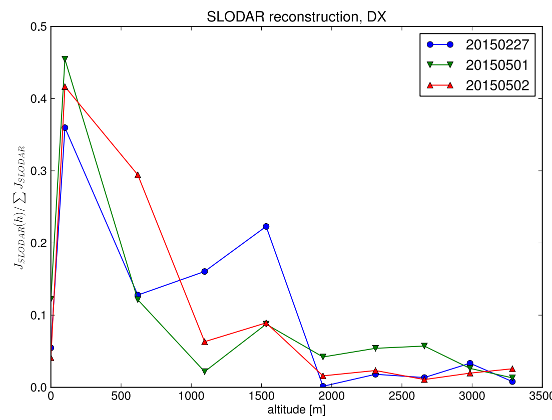
Table 1 reports the $gain_{\text{FWHM}}$ measured with LUCI during the commissioning nights. We compute the ratio (equation 9) using images acquired in Open Loop and in Closed Loop at few minutes of distance. During the Closed Loop acquisition we acquired also the telemetry data for the SLODAR computation. In some cases the gain is significantly different from other; in particular in nights 20150227, 20160519 and 20160520 the gain is lower. We use the SLODAR technique to analyze the turbulence profile to understand this behavior. The results of this analysis are summarized in Figure 3. Altitudes h_m over the telescope are evaluated as:

$$h_m = \left(\frac{mdz}{z\theta + md} + h_p \right) \frac{1}{\sec \zeta} \tag{10}$$

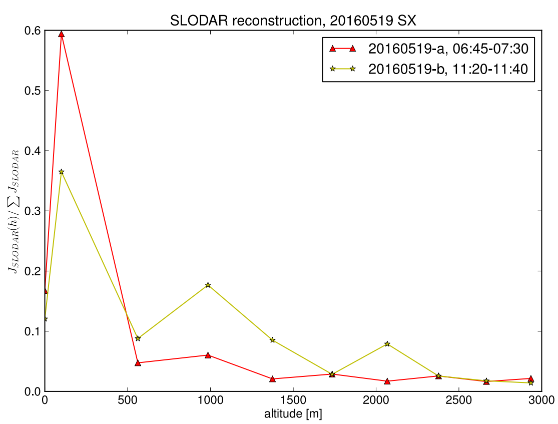
where m is the number of the bin, z =12 km is the distance of the LGSs from the telescope, ζ is the zenith angle and $h_p \approx 150$ m is the altitude at which the pupil is conjugated.



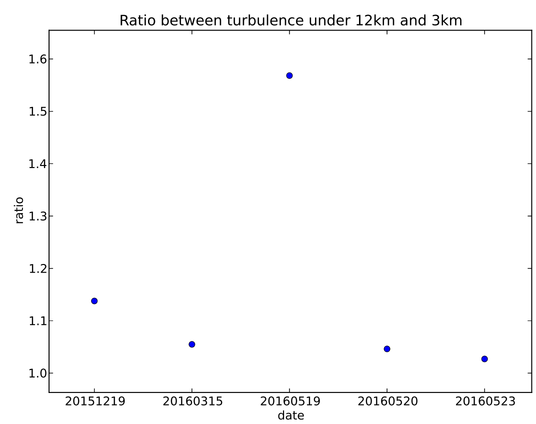
(a) Averaged vertical turbulence profiles measured with the SLODAR technique during five nights with the SX system.



(b) Averaged vertical turbulence profiles measured with the SLODAR technique during three nights with the DX system.



(c) Averaged vertical turbulence profiles measured with the SLODAR technique during the night 20160519 (first part and second part) with the SX system.



(d) Ratio between the turbulence under 12 km (measured with the autocorrelation signals) and 3 km (mesured with the SLODAR techique).

FIGURE 3: Measures with the SLODAR technique.

In the night 20150227 (DX side) the seeing was distributed in two layers (Figure 3(b), blue plot), the ground and an higher one. The presence of a second strong layer around 1 km altitude is probably ralated to the bad performance ($gain_{\text{FWHM}} = 1.3$ in H band). We observe a similar turbulence distribution in the night 20160520 with the SX system (Figure 3(a), cyan plot) and the $gain_{\text{FWHM}}$ was, as before, lower then the other nights. In the first part of the night `20160519` (denotes with the `-a`) we measure a low $gain_{\mathrm{FWHM}}$ (1.6 versus 2 in K band) but, according with SLODAR reconstruction, the turbulence was distributed mainly in the first kilometer. Figure 3(d) shows the ratio between the turbulence below 12 km (measured with the autocorrelation signals) and 3 km (measured with the SLODAR technique). In the night `20160519` this values was higher than 1.5, so there was a strong turbulence between 12 km and 3 km: this is compatible with a lower $gain_{\mathrm{FWHM}}$. In the second part of the night `20160519` (denotes with the `-b`) the contribution of the ARGOS system was negligible ($gain_{\mathrm{FWHM}} \sim 1$) and this is because there were (in addition to the strong turbulent layer above 3 km) strong turbulent layers over 1 km, as Figure 3(c) shows.

4. CONCLUSIONS

As expected, the performance of the ARGOS system depending on the turbulence vertical profile. In good nights (strong turbulence only in the ground layers) $gain_{\mathrm{FWHM}}$ is around 2 in K band, as expected from the simulations. In bad nights (two strong turbulent layers) the $gain_{\mathrm{FWHM}}$ decreases even down to 1.3 and in very bad condition (like `20160519-b` on SX side) the contribution of the ARGOS system can be negligible.

Our goal was to develop a tool to estimate the turbulence profile and use the results to understand the GLAO performance. We can conclude that our implementation of the SLODAR technique can be used during the ARGOS operation to estimate the turbulence profile and can be a useful tool.

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