PML/PBL: A new generalized monitor of atmospheric turbulence profiles

Aziz Ziad1,a, Flavien Blary1, Julien Borgnino1, Yan Fanteï-Caujolle1, Eric Aristidi1, François Martin1, Henri Lantéri1, Richard Douet1, Erick Bondoux1, and Djamel Mekarnia1

Laboratoire J.L. Lagrange-UMR 7293, Université de Nice-Sophia Antipolis/CNRS/OCA, Parc Valrose F-06108 Nice Cedex 2, France

Abstract. The optimization of the performances of the next generation of Adaptive Optics (AO) systems dedicated to future generation of extremely large telescopes (ELT), requires a precise specification of their different components. Technical specifications of these Wide-Field AO systems are related to the atmospheric turbulence parameters, particularly, the profile of the structure constant of the refractive index $C_n^2(h)$, the outer scale profile $L_0(h)$, the coherence time $\tau_0$ and the isoplanatic domain $\theta_i$. Most of these parameters are now provided by a new generalized monitor called Moon Limb Profiler (PML) but known initially as Profileur Bord Lunaire (PBL). The PML/PBL technique is based on the Moon limb observation through two small subapertures (6cm) separated by a baseline of $\sim 27\text{cm}$ as in a DIMM (Differential Image Motion Monitor) configuration. The Moon limb offers a continuum of double stars at different angular separations allowing the scan the atmosphere with a very high vertical resolution. The PML/PBL instrument has been installed at Dome C in Antarctica and a second copy of this instrument has been developed for mid-latitude sites. The first results of the PML/PBL monitor lead to $C_n^2(h)$ profile with 33 layers well distributed over the whole atmosphere with a high resolution particularly, in the ground layer ($h \leq 1\text{km}$) with a resolution of $\Delta h = 100m$. Other parameters of turbulence are also accessible from this instrument such as the profile of outer scale, the seeing, isoplanatic and isopistonic domains.

1 Introduction

With the current interest in the design of extremely large ground-based optical and infrared telescopes (ELT), precise estimates of whole atmospheric turbulence parameters are required. Wide-Field AO (WFAO) systems have been proposed for the equipment of these ELTs [1-2]. The performance optimization of the WFAO techniques requires a precise specification of the different components of these systems. Atmospheric turbulence parameters play a huge role in the WFAO specifications, particularly the $C_n^2(h)$ profile. Moreover, recent studies [3] show that $C_n^2(h)$ profiles have to be measured with high vertical resolution for a better evaluation of the performance of a WFAO system.

All existing instruments for the $C_n^2(h)$ measurement do not respond fully to the requirements of the WFAO systems. Indeed, for the radio-sounding balloon technique [4], if the $C_n^2(h)$ profiles are provided with high vertical resolution, the measurements are sequential (balloon’s ascent time $\sim 2h$) in addition to their expensive cost. The SCIDAR [5] technique is demanding in term of telescope’s size ($\sim 2m$) and the resolution is low in the ground layer (GL). The other instruments such as SLODAR [6], MASS [7] and MOSP [8] lead to a low altitude resolution and/or are restricted to a part of the atmosphere (GL or free atmosphere (FA)). A new technique CO-SLIDAR combining scintillation and Angle-of-Arrival measurements by use of a Shack-Hartmann leads to on-sky promising results [9].

A new generalized monitor called Moon Limb Profiler (PML) but originally known under its french name Profileur Bord Lunaire (PBL), allows the extraction of the $C_n^2(h)$ profile with high vertical resolution. This instrument combines the DIMM [10] and MOSP [8] techniques by observation of the Moon limb. In addition to the $C_n^2(h)$ profile obtained with high resolution in altitude, the PML/PBL instrument provides other atmospheric turbulence parameters such as the profile of outer scale [8], the seeing, isoplanatic and isopistonic angles [11].

The PML/PBL instrument has been installed at Dome C in Antarctica since January 2011. In addition to this winterized PML/PBL for Dome C, a second copy of this instrument has been developed for mid-latitude sites. A first campaign with this light version of PML/PBL, was carried out at the...
South African Large Telescope (SALT) Observatory in August 2011. In this paper, the PML/PBL is presented after a recall of the theoretical background. The first results obtained with the PML/PBL monitor are presented and compared to other instruments. A particular focus is done along this paper to emphasize the generalized role of the PML/PBL instrument. Thus, all other turbulence parameters provided by PML/PBL monitor such as outer scale profile, daytime $C_N^2(h)$ profiles via the solar limb and isoplanatic and isopistonic angles, are presented.

2 PML/PBL instrument

The PML/PBL is a new generalized instrument for the extraction of the $C_N^2$ profile with high vertical resolution by use of an optical method based on observation of the Moon limb in addition of other atmospheric turbulence parameters. Observing the Moon limb has the advantage of offering a continuum angular separations (2 points of the lunar limb act as a double star) allowing the scan of the atmosphere with a very fine resolution. The PML/PBL instrument uses the differential method of a DIMM (Differential Image Motion Monitor) [10] based this time on observation of the lunar limb through two sub-apertures of 6cm separated by a baseline of $\sim 26.7$cm (Fig. 1). The angular correlation along the lunar limb of the difference between the positions the Moon edge images leads to the $C_N^2(h)$ profile. The other parameters of turbulence will be also accessible from this instrument such as the profile of outer scale [8], the seeing, isoplanatic and isopistonic domains [11].

The instrument consists of a 16-inch telescope (Meade M16) which is installed on an Astrophysics AP3600 mount. This mount was chosen to avoid overload especially in Dome C conditions. The optical device of the PML/PBL consists of a collimated beam by using a first lens placed at its focal length from the telescope focus (Fig. 2). A parallel beam is formed at the output and therefore the image of the entrance pupil of the telescope. A Dove prism is placed on the beam of one of two sub-apertures to reverse one of two images of the Moon edge to avoid overlapping bright parts of the Moon. A second lens is used to form the two images of the Moon limb on a PixelFly CCD camera. Each optical element is placed on a Micro-control plate to facilitate the adjustment of their positions. To
compensate variations in the focus of the telescope because of the temperature variations, we installed the CCD camera on an automatic Micro-control plate controlled by software (Fig. 3).

The principle of the PML/PBL instrument is based on the measurement of the angular correlation of wavefront AA fluctuations difference deduced from the motion Moon’s limb image. The AA fluctuations are measured perpendicularly to the lunar limb leading to transverse correlations for different angular separations along the Moon.

Images at the focal plane are recorded using a PCO PixelFly CCD camera with $640 \times 480$ pixel matrix and $(9.9 \times 9.9)\mu m^2$ pixel size. Its dynamic range of the analog/digital conversion is 12 bits. The readout noise is $12e^{-} \text{rms}$ and the imaging frequency is 33Hz. In order to freeze atmospheric effects on Moon’s limb image motion and enough flux, the exposure time was set to $5ms$. The spectral response of the camera is maximal for $\lambda = 0.5\mu m$ in a $375 - 550\mu m$ range.

The observation of the lunar limb through two sub-apertures of diameter $D = 6cm$ separated by a baseline $B = 26.7cm$ presents two configurations when looking the edge in parallel or perpendicular to the baseline. We use the first configuration as shown in Fig. 1 to extract the $C_2^N$ vertical distribution.

The transverse covariance of the difference of the AA fluctuations (motion of the Moon limb) $\alpha$ between the two images of the lunar limb (Fig. 3) corresponds to,
AO for ELT III

\[ C_{aa}(\theta) = \langle \alpha(r, \theta_0) - \alpha(r + B, \theta_0) \rangle \langle \alpha(r, \theta + \theta_0) - \alpha(r + B, \theta + \theta_0) \rangle \]  

(1)

where \( \alpha(r, \theta_0) \) and \( \alpha(r, \theta + \theta_0) \) represent the fluctuations of the lunar limb image observed through the first subaperture of the PML/PBL and measured at the angular positions \( \theta_0 \) and \( \theta + \theta_0 \), respectively. While, \( \alpha(r + B, \theta_0) \) and \( \alpha(r + B, \theta + \theta_0) \) are the measured fluctuations corresponding to the second subaperture. The arbitrary angular position \( \theta_0 \) is considered equal to zero.

After development, this expression is a function of the spatial covariance which for the whole atmosphere is given by,

\[ C_{aa}(\theta) = \int dh \ C_N^2(h) \ K_0(B, h, \theta) \]  

(2)

where

\[ K_0(B, h, \theta) = 2 \ C_0(\theta h) - C_0(B - \theta h) - C_0(B + \theta h) \]  

(3)

In this equation \( C_0 \) is the normalized spatial covariance which in the case of the von Kármán model for a baseline \( \varrho \), a sub-aperture diameter \( D \) (here 6cm), and a single layer at altitude \( h \) is given by [12] as

\[ C_0(\varrho z) = 1.19 \sec(z) \int df f^3 (f^2 + \frac{1}{L_0(h)^2})^{-11/6} \left[ J_0(2\pi f \varrho) + J_2(2\pi f \varrho) \right] \frac{2J_1(\pi D f)}{\pi D f} \]  

(4)

where \( f \) is the modulus of the spatial frequency, \( z \) is the zenithal distance and \( L_0(h) \) is the outer scale profile.

Eq. 3 represents for a single layer a spatial covariance triplet similar to the Scidar one [5]. The location of the lateral peak defines the altitude of the layer so that its energy is given by the height of it. For the whole atmosphere we have the superposition of different triplets corresponding to different turbulent layers.

3 Data processing

The first step of PML data processing is to accurately retrieve the AA fluctuations from the Moon’s limb motion (transverse AA fluctuations). After processing a flat and dark field correction, each image \( I(x, y) \) is slightly blurred with a median filter on \( 3 \times 3 \) pixel blocks. This removes the possibility that outliers due to Poisson noise or to small features of the Moon with relative high intensity differences can affect the detection of the limb. This type of filtering is more effective than convolution when the goal is to simultaneously reduce noise and preserve edges ([13]).

Then, the image with the two lunar limbs is separated on two images with top and bottom edges (Fig. 3). On each half-image, a spatial gradient \( G(x, y) \) is processed by convolution with a \( 3 \times 3 \) Prewitt edge detector ([13]) defined as \( P = \begin{bmatrix} -1 & -1 & -1 \\ 0 & 0 & 0 \\ 1 & 1 & 1 \end{bmatrix} \) or \(-P\) if the y-axis points to the Moon center.

Detection of the limb position in absolute value of the image gradient is determined by a centroid calculation over each column.

We process data cubes containing \( N = 1000 \) images (acquisition time of \( \sim 1 \text{min} \)) that give two sets of Moon limb angular positions corresponding to the top and bottom of the lunar edge in Fig. 3.

4 First results

The PML/PBL instrument has been first installed at the Dome C site in Antarctica for a long campaign measurement for the whole austral winter 2011. A very important volume of data has been collected at Dome C with PML/PBL. But due to a very limited Internet connection of Concordia station, we did not have access to the PML/PBL database. We had to wait for the summer campaign to recover it (May 2012). Since this time, the data processing of this campaign has been continuously in progress and the first results are presented hereafter.
4.1 $C_N^2(h)$ profile

Each acquisition (∼ 1 min) of the PML/PBL instrument, leads to two sets of Moon limb angular positions corresponding to the top and bottom of the lunar edge in Fig. 3. Then, a transverse covariance of the difference of the AA fluctuations $C_{\Delta \alpha}(\theta)$ between these two Moon limbs as given in Eq. 1 is deduced. This differential covariance calculated for each image has the practical advantage of being insensitive to vibration effects of the telescope, wind shaking and tracking errors. On the other hand, from top and bottom limbs, we deduce separately two estimations of the central covariance $C_\alpha(\theta h)$ integrated over the whole atmosphere. Twice of the mean of these central covariances is then subtracted from $C_{\Delta \alpha}(\theta)$ leading to the lateral covariance estimator $Y$ defined as,

$$Y(\theta) = C_{\Delta \alpha}(\theta) - 2 \times \int d\theta C_N^2(h) C_\alpha(\theta h) .$$  \hspace{1cm} (5)

The extraction of the $C_N^2(h)$ profile from the PML/PBL is obtained from this estimator $Y$ of the lateral peaks of the whole atmosphere. In a matrix form, one can write,

$$Y = M \times c ,$$  \hspace{1cm} (6)

where $c$ is a vector of the sampled $C_N^2(h_i)$ profile and $M$ is a matrix obtained from the difference $[K_{{\alpha}}(B, h_i, \theta_j) - 2 C_\alpha(\theta_j h_i)]$ for different altitudes $h_i$ and angular separations $\theta_j$.

This estimator and all the covariances are obtained for each pixel along ∼ 620 pixels of the CCD camera (∼ 20 pixels are lost when recentering Moon limbs on the CCD owing to the mount drift). Each pixel corresponds to ≈ 0.57″ leading to a total field of more than 350″.

Retrieving the $C_N^2(h)$ profile from the transverse covariance estimator $Y$ is an inverse problem as indicated in Eq. 6. The estimated $C_N^2(h)$ is obtained by minimization of the least squares criterion $J = \|Y - Mc\|^2$ under positivity constraint using an iterative gradient method ([14]). A diagonal weighting matrix with $Y$ variances is used to favor the steadier measurements.

The first $C_N^2(h)$ profiles obtained with the PML/PBL monitor are shown in Fig. 4 compared to median profile of radio-sounding balloons obtained during the 2005 winter campaign ([15]). The left
and right panels in Fig. 4 represent $C^2_N(h)$ profiles obtained respectively from Moon and Sun limbs. This ability of the PML/PBL instrument to monitor turbulence profiles during daytime and nighttime is unique. Direct comparison of these results to radio-sounding balloon profiles is meaningless since these measurements are not simultaneous. But PML/PBL are consistent with the general behavior of the Dome C atmosphere as indicated by the median profile of radio-sounding balloon. Moreover, the Fried parameter deduced from the PML/PBL profile in Fig. 4 is $r_0 = 8.2cm$ from Moon limb and $r_0 = 10cm$ from Sun data, while the median balloon profile from the 2005 campaign leads to $r_0 = 6.7cm$.

The resolution used for the first Dome C results (Fig. 4) is $Δh = 100m$ for the ground layer ($h ≤ 1km$), $Δh = 500m$ for the low free atmosphere ($1km < h < 5km$), $Δh = 1000m$ for the mid-free atmosphere ($5km < h < 15km$), and $Δh = 2000m$ for the high free atmosphere ($h > 15km$). The highest altitude $h_{max}$ measured with the PML/PBL is more than 50km. However, we limited $h_{max}$ to 25km for comparison with balloon profiles reaching only 20km (Fig. 4). On the other hand, because of a limited field of view the PML/PBL instrument has a minimum altitude detectable which is around 100m. The contribution of the lowest layer 0 − 100m is obtained by the difference between the profile deduced from the inversion of the PML/PBL covariances and the total seeing from DIMM method ([10]) using PML data. For the total seeing obtained from PML, we have about 620 estimations (each point of the Moon limb leads to a DIMM measurement) and we keep only the median one.

### 4.2 Outer Scale Profile

The PML/PBL succeeded to the first Moon limb profiler MOSP (Monitor of Outer Scale Profile) which was developed mainly for outer scale profile extraction [8]. Several campaigns have been carried out with MOSP particularly at Mauna Kea Observatory (Hawaii) and Cerro Paranal in Chile. The principle of the MOSP instrument is similar the PML/PBL monitor but using only one subaperture of $D ∼ 20cm$ and measuring always the motion of the Moon limb image. The transverse structure function of AA fluctuations (motion of Moon limb) is obtained along the lunar limb and compared to the theoretical one [8]. The $C^2_N(h)$ profile obtained from PML/PBL (Fig. 4) is injected in the theoretical model of this transverse structure function to retrieve the outer scale profile by inversion. We used simulated annealing (SA) algorithm for minimizing the cost function $E$, defined as the sum over the angular extent of the squared difference between measured and theoretical transverse structure functions of the AA fluctuations[8].

Fig. 5 shows an example of outer scale profile obtained from PML/PBL data at Dome C in Antarctica on January 25, 2011 at 16h45UT. This outer scale profile shows a low value for the first layer of the atmosphere (Surface layer). Since this layer prevails in term of $C^2_N(h)$, the integrated value of the outer scale should be close to the value in the SL. Indeed, the comparison between the outer scale measured by GSM at Dome C ([16]) leads to a median value of 7.8m and the integrated $L_n(h)$ from PML/PBL profiles in Figs 5 and 4 using Eq. A4 of [8] lead to values of 9.1, 9.7 and 10.3m for $n = -1/3$, 5/3 and 11/3, respectively.

### 4.3 Isoplanatic domain

Different definitions of the isoplanatic angle $θ_0$ are given in the literature and the most known and used expression is Roddier’s one, which is deduced from the angular correlation of the phase of the complex amplitude [17]. In the case of High Angular Resolution techniques, its expression is given for large telescope as,

$$θ_0 = 0.31 \frac{r_0}{h}$$

(7)

where $h$ indicates an equivalent altitude defined as,

$$\bar{h} = \left[ \frac{\int dh \, h^{5/3} \, C^2_N(h)}{\int dh \, C^2_N(h)} \right]^{3/5}$$

(8)
In this section we want to point out the possibility of a direct measurement of the isoplanatic angle in Eq. 7 from PML/PBL instrument. Indeed, as the PML/PBL provides AA measurements at different angular separations $\theta$ along the Moon limb, one can deduce a structure function of $\theta$ of AA fluctuations. The angular transverse covariance for the AA fluctuations at two positions separated by an angle $\theta$ is related to the spatial covariance $C_\alpha$ of Eq. 4,

$$\Gamma_\alpha(\theta) = \int_0^{\infty} dh C_N(h) C_\alpha(\theta h)$$

Then, the transverse structure function along the Moon limb, is given by,

$$D_\alpha(\theta) = 2 \left[ \Gamma_\alpha(0) - \Gamma_\alpha(\theta) \right]$$

The wavefront isoplanatic angle $\theta_{0,\alpha}$ could be defined as the angle of the drop of a constant $k$ of the structure function of AA fluctuations from the saturation:

$$D_\alpha(\theta_{0,\alpha}) = \frac{2\Gamma_\alpha(0)}{k}$$

Using von Kármán model and the same reasoning than [18] in the case of a small telescope of diameter $D$, we found:

$$\theta_{0,\alpha} = \frac{D}{\bar{h}} \sqrt{2.62k^{-1}[1 - 1.04(\frac{\pi D}{L_0})^{1/3}]} \quad for \quad \theta_{0,\alpha} < \frac{D}{\bar{h}}$$

For large AA isoplanatic angle, we have a simplified expression:

$$\theta_{0,\alpha} \approx \frac{D}{\bar{h}} \left( 1.21 k^{-1} \left( \frac{\pi D}{L_0} \right)^{1/3} + 1.17(1 - k^{-1})^{-3} \right) \quad for \quad \theta_{0,\alpha} > \frac{D}{\bar{h}}$$

Examples of angular structure functions of AA fluctuations $D_\alpha(\theta)$ deduced from Moon limb are shown in Fig. 4 of [8]. The saturation level of $D_\alpha(\theta)$ is given by AA variance in Eq. 10 which is deduced from its theoretical form defined in Eq. 3 of [19] using values of $n_0$ and $L_0$. Thus, for Dome C...
results presented in Fig. 4 on Moon limb, \( r_0 = 8.2\, cm \) and \( L_0 = 9.1\, m \) leading to a saturation of \( D_{\alpha}(\theta) \) equal to 0.45\(^2\). The fold of \( D_{\alpha}(\theta) \) by a constant \( k = e \) lead to \( \theta_{0\alpha} = 9.9'' \). Including this value of \( \theta_{0\alpha} \) in Eq. 12, we obtained an equivalent altitude \( h = 1024\, m \), while the value obtained from balloon data using Eq. 8 is of \( h_{\text{bal}} = 805\, m \). Even if they are not similar for the simple reason that they are not obtained in the same period, these estimations are coherent. Using Eq. 7, these equivalent altitudes lead to isoplanatic angles equal respectively to \( \theta_0 = 5.13'' \) and \( \theta_{0\text{,Bal}} = 5.32'' \) at \( \lambda = 0.5\, \mu m \).

5 Conclusion

For the first time monitoring of the \( C_2^v(h) \) profile extracted with high vertical resolution using an easy and undemanding technique, is now possible by means of the PML/PBL instrument. This monitor is the only instrument providing turbulence profiles for nighttime and daytime conditions by use of Moon and Sun limbs. In addition to the \( C_2^v(h) \) profiles, the PML/PBL monitor is able to provide other parameters of turbulence, particularly the profile of the outer scale and estimations of the isoplanatic and isopistonic domains ([11]).

5.1 Acknowledgments

We would like to thank the Polar Institutes IPEV and PNRA, the National Institute for Earth Sciences and Astronomy INSU, and the French Programme of High Angular Resolution ASHRA for logistical and financial support for the development and the installation of the PML instrument at the site of Dome C in Antarctica. We also wish to thank warmly Alex Robini for his precious help and we are very grateful for his dedication to the success of the PML. We thank the technical team of the Winterover 2011 for their help.

References