

PBL: A monitor of atmospheric turbulence profile

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Abstract. The future large telescopes will be certainly equipped with Multi-Conjugate Adaptive Optics systems. The optimization of the performances of these techniques requires a precise specification of the different components of these systems. Major of these technical specifications are related to the atmospheric turbulence particularly the structure constant of the refractive index $C_n^2(h)$ and the outer scale $\mathcal{L}_0(h)$. New techniques based on the moon limb observation for the monitoring of the $C_n^2(h)$ and $\mathcal{L}_0(h)$ profiles with high vertical resolution will be presented. A new monitor PBL (Profileur Bord Lunaire) for the extraction of the $C_n^2(h)$ profile with high vertical resolution has been developed. This instrument uses an optical method based on observation of the moon limb with a DIMM configuration (Differential Image Motion Monitor). Indeed, in the PBL the lunar limb is observed through two sub-apertures of 6cm separated by a base of 30cm. The moon limb offers a continuum of stars at different angular separations allowing the scan the atmosphere with a very high resolution. The angular correlation along the lunar limb between of the differential distance between the two images of the lunar edge leads to the $C_n^2(h)$ profile. The other parameters of turbulence are also accessible from this instrument as the profile of outer scale, the seeing and isoplanatic & isopistonc domains. The PBL succeeded to our first moon limb profiler MOSP (Monitor of Outer Scale Profile) which was developed mainly for outer scale profile extraction. Several campaigns have been carried out with MOSP particularly at Mauna Kea Observatory (Hawaii) and Cerro Paranal in Chile. The PBL instrument has been installed at Dome C in Antarctica since January 2011. In addition to this winterized 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 PBL, was carried out at the South African Large Telescope (SALT) Observatory in August 2011.

1 Introduction

For the next generation of the ground-based telescopes, the classical Adaptive Optics (AO) reaches its limitations mainly due to a large field of view. Other AO concepts namely MCAO have been proposed for this large field compensation in the perspective of future ELTs. The optimization of the performances of the MCAO and GLAO technique requires a precise specification of the different components of these systems. Some of these technical specifications are related to the optical parameters of the atmospheric turbulence. Indeed, the wavefront sensor (WFS) subaperture number is directly defined by the Fried parameter and the correction frequency of the AO system is conditioned by the wavefront coherence time. The choice of a reference star requires the knowledge of the isoplanatic angle. In addition, a spatial-coherence outer scale smaller than the telescope diameter reduces strongly the lowest Zernike aberrations modes [1,2]. Consequently, the need of a separate tip/tilt correction is unjustified in this case. In the case of an MCAO system the task is more difficult because of the multiplicity of WFSs and DMs. Therefore, the integrated turbulence parameters are insufficient and their profiles are required, particularly the structure constant of the index-of-refraction $C_n^2(h)$ and the outer scale $\mathcal{L}_0(h)$. Different profilers as SCIDAR, MASS, SLODAR and instrumented balloons have been developed for $C_n^2(h)$ estimation but recently a new instrument PBL is under development for the extraction of $C_n^2(h)$ profile with high resolution. This instrument and the used techniques are presented in this paper.

Wavefront outer scale is also a relevant parameter for the experimental performance evaluation of large aperture telescopes. The actual size of the outer scale has long been controversial, with measured

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values ranging from less than 10 m to more than 2 km. What is not controversial is the conclusion that when the diameter of the telescope approaches or exceeds the size of the outer scale, the optical consequences of atmospheric turbulence are changed dramatically from their traditional Kolmogorov behavior. In particular, power in the lowest Zernike aberration modes, e.g., tip and tilt and the overall stroke required for an adaptive-optics system can be much reduced [1,2]. A finite outer scale has implications for interferometry as well. With the current interest in the design of extremely large ground-based optical and infrared telescopes, reliable estimates of the outer scale profile have assumed considerable importance. A first instrument MOSP (Monitor of Outer Scale Profile) has been developed by our team for outer scale profile extraction. We retrieve the vertical distribution of wavefront outer scale by analyzing angular correlation of wavefront Angle-of-Arrival (AA) fluctuations deduced from Moon's limb images motion. A new monitor PBL (Profileur Bord Lunaire) for the extraction of the $C_n^2(h)$ profile with high vertical resolution has been developed. This instrument combines the DIMM and MOSP techniques. In addition to the $C_n^2(h)$ profile, the PBL instrument provides other atmospheric turbulence parameters as the profile of outer scale, the seeing and isoplanatic & isopistonc angles.

The PBL instrument has been installed at Dome C in Antarctica since January 2011. In addition to this winterized 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 PBL, was carried out at the South African Large Telescope (SALT) Observatory in August 2011.

2 PBL instrument

2.1 Description

The PBL ("Profileur Bord Lunaire") is a new 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 [3]. This later has the advantage of offering all angular separations required between two points of the edge allowing the scan the atmosphere with a very fine resolution. The PBL instrument uses the differential method of a DIMM (Differential Image Motion Monitor) based this time on observation of the lunar limb through two sub-apertures of 6cm separated by a base of $\sim 30cm$ (Fig. 1). The angular correlation along the lunar limb of the differential distance between the two lunar edges leads to the $C_n^2(h)$ profile. The other parameters of turbulence will be also accessible from this instrument as the profile of outer scale, the seeing and isoplanatic & isopistonc domains.

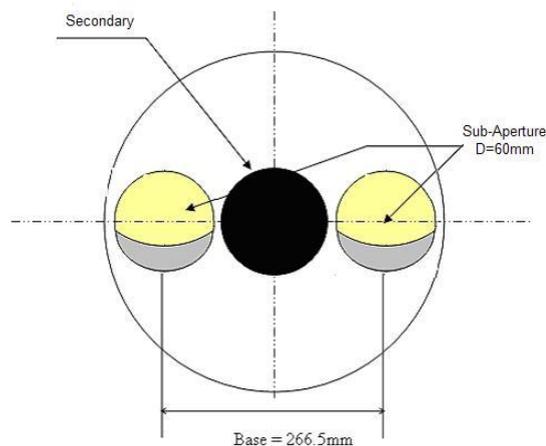


Fig. 1. The PBL instrument configuration on the telescope entrance pupil.

The instrument consists of a 16-inch telescope (Meade M16) which is installed on an Astrophysics AP3600 mount. The choice of this mount was chosen to avoid overload especially in Dome C conditions. The optical device of the 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 adjustments that normally are final after a row in the laboratory. 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 (Fig. 3) controlled by software (Fig. 4).

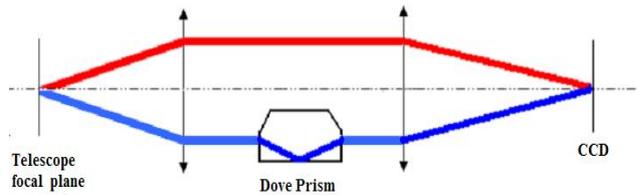


Fig. 2. The optical device of the PBL instrument.

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

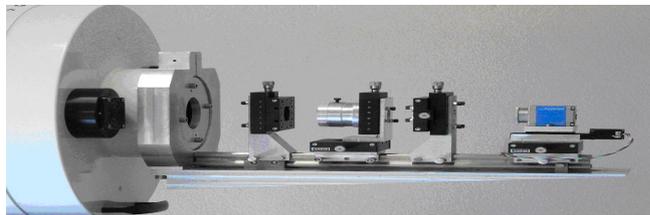


Fig. 3. The focal plane instrument of PBL.

Images at the focal plane are recorded using a PixelFly CCD camera with 640×480 pixel matrix and $(9.9 \times 9.9)\mu\text{m}^2$ pixel size. Its dynamic range of the analogic/digital conversion is 12 bits. The readout noise is 12 e-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 5 or 10ms. The spectral response of the camera is maximal for $\lambda = 0.5\mu\text{m}$ in a $375 - 550\mu\text{m}$ range.

The PBL has been developed at the H. Fizeau Laboratory. Two copies of this instrument are now available. One copy has been installed at Dome C in Antarctica and it is operational since January 2011 (Fig. 5). The second copy is used for the characterization of the temperate sites. A first campaign has been carried out with this PBL second copy at the SALT telescope observatory in South Africa in August 2011 (Fig. 5). A second campaign is expected at the VLT Observatory at Paranal during next austral winter.

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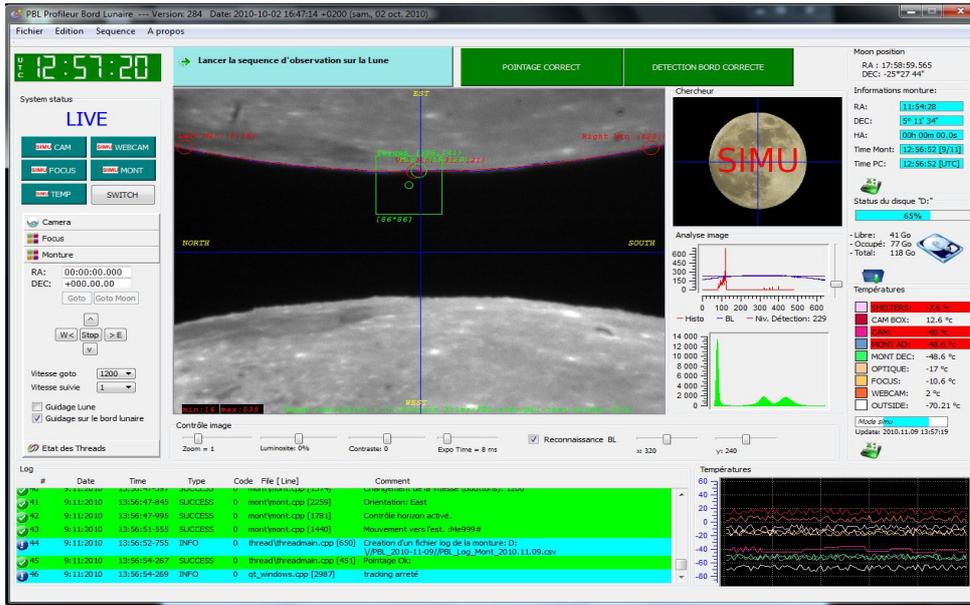


Fig. 4. PBL data acquisition and instrument control.

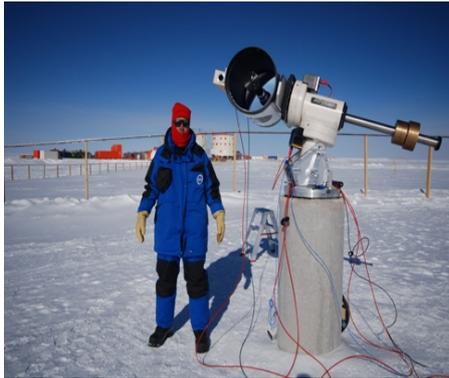


Fig. 5. The PBL instrument at Dome C, Antarctica in January 2011 (left) and at Sutherland Observatory (South Africa) in August 2011.

2.2 Theoretical background

The observation of the lunar limb through two sub-apertures 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_n^2 vertical distribution.

The transverse covariance of the difference of the AA fluctuations α between the two images of the moon limb (Fig. 4) corresponds to,

$$C_{\Delta\alpha}(\theta) = \langle [\alpha(r, 0) - \alpha(r + B, 0)][\alpha(r, \theta) - \alpha(r + B, \theta)] \rangle \quad (1)$$

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

$$C_{\Delta\alpha}(\theta) = \int dh K_{\alpha}(B, h, \theta) \quad (2)$$

where

$$K_{\alpha}(B, h, \theta) = 2 C_{\alpha}(\theta h) - C_{\alpha}(B - \theta h) - C_{\alpha}(B + \theta h) \quad (3)$$

D is the sub-aperture diameter, B the baseline, θ indicates the angular distance along the moon limb and h is the turbulent layer altitude. C_{α} is the spatial covariance which in the case of von Kàrmàn model and for a single layer localized at an altitude h is given by [4],

$$C_{\alpha}(B) = 1.19 \sec(z) C_n^2(h) \int df f^3 \left(f^2 + \frac{1}{L_0(h)^2} \right)^{-11/6} [J_0(2\pi f B) + J_2(2\pi f B)] \left[2 \frac{J_1(\pi D f)}{\pi D f} \right]^2 \quad (4)$$

where f is the modulus of the spatial frequency and z is the zenithal distance.

Eq.3 represents for a single layer a spatial covariance triplet as shown schematically in Fig. 6 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.

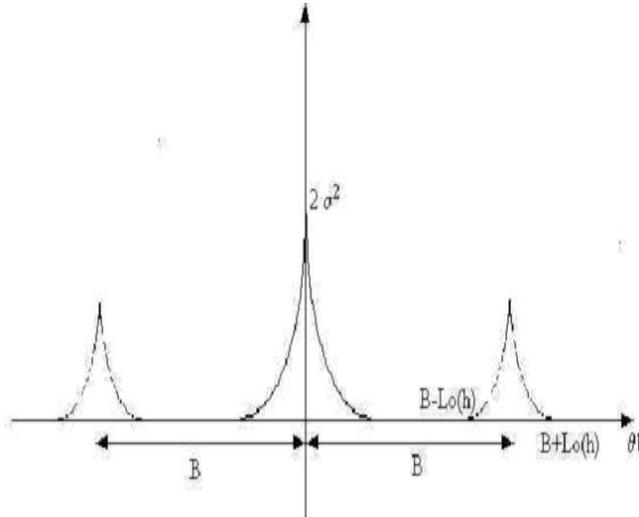


Fig. 6. Schematic triplet of spatial covariance for one turbulent layer.

2.3 Data processing

The first step of data processing is to retrieve accurately AA fluctuations from Moon's limb motion. After processing on each image a flat and dark field correction, each image $I(x, y)$ is slightly blurred with a median filter M on 3×3 pixel blocks. It avoids possible outliers due to Poisson noise or Moon's small features with relative high intensity differences that 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 [6]. Each output pixel with coordinates (x, y) contains the median value in the 3-by-3 neighborhood around the corresponding pixel in the input image. Then, an image gradient $G(x, y)$

is processed by convolution with a 3×3 Prewitt edge detector [6] defined as $P = \begin{pmatrix} -1 & -1 & -1 \\ 0 & 0 & 0 \\ 1 & 1 & 1 \end{pmatrix}$, or $-P$ if

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 $N = 1000$ images (about one minute of acquisition) that gives two sets of limb angular positions obtained at a time t . The transverse covariance of the difference of the AA fluctuations $C_{\Delta\alpha}(\theta)$ between the two moon limbs as given in Eq. 1. This differential variance calculated for each image has the practical advantage of being insensitive to vibration effects of the telescope and tracking errors. This covariance $C_{\Delta\alpha}(\theta)$ is obtained for each pixel along the 640 pixels of the CCD camera. Each pixel corresponds to $\approx 0.7arcsec$ leading to a total large moon field of more than $400arcsecs$.

Retrieving $C_N^2(h)$ profile from this transverse covariance of the difference of the AA fluctuations $C_{\Delta\alpha}(\theta)$ is a non-linear inverse problem. We use 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 covariance of the difference of the AA fluctuations $E = \sum_{\theta}(C_{\Delta\alpha_m}(\theta) - C_{\Delta\alpha_t}(\theta))^2$. This algorithm was developed to statistically find the best global fit of a nonlinear non-convex cost-function [7].

3 First results

The PBL instrument has been installed first 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 PBL. But due to a very limited Internet connection of Concordia station, we didn't have access to this database. We had to wait the summer campaign to recover it. Now the data are available and we started working on them. On the other hand, a mid-latitude version of PBL has been developed and used for the first time in August 2011 at the Sutherland Observatory which is the site of 10m telescope of South-Africa (SALT). Simultaneous observations with the SALT MASS-DIMM were carried out for direct comparisons. The data processing of this campaign is now in progress and the results will be published as soon as possible.

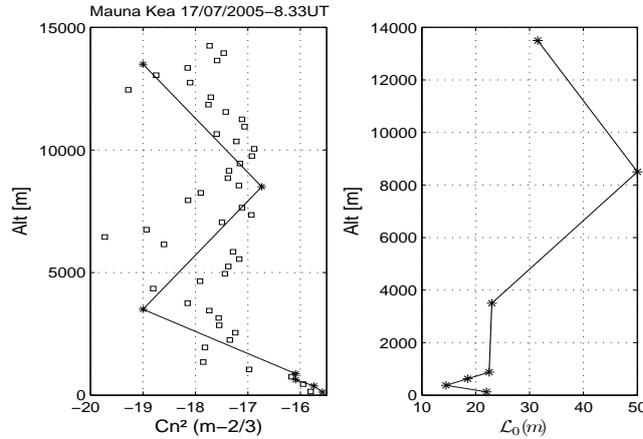


Fig. 7. Example of C_n^2 and outer scale profiles (solid line) that can be retrieved simultaneously by the MOSP instrument. Comparisons with simultaneous SCIDAR profile (square markers) are in close agreement despite different vertical resolutions of these instruments.

Even if the resolution is lower, the first results of the technique based on moon limb measurements have been obtained with the MOSP instrument [8]. Fig. 7 shows an example of profiles obtained during the Mauna Kea campaign with the MOSP and compared to the Scidar simultaneous results. Indeed, this campaign has been carried out at the Mauna Kea Observatory in Hawaii between the 13th and 19th July 2005 with simultaneous observations using the SCIDAR instrument installed at the UH 2.2m telescope, 150m northeast of the UH 60cm telescope used by the MOSP. One can see that there is a good agreement between MOSP and Scidar in terms of C_n^2 profile. However, the vertical resolution

in the free atmosphere is lower in the case of MOSP. This point will be solved by the PBL instrument which will provide a high resolution of C_n^2 profile.

4 Conclusion

For the first time monitoring of the outer scale profile is possible from Moon's limb observations with The MOSP instrument based on a simple device and small telescope aperture. This instrument is also able to extract simultaneously both of C_n^2 and outer scale profiles.

The vertical resolution of the MOSP instrument is low concerning the $C_n^2(h)$ profile that why a new instrument PBL has been developed. The first observations with the PBL have been recently carried out at the Dome C site in Antarctica and at the Sutherland Observatory in South Africa. The data are under processing and the results will be published as soon as possible. The advantage of the PBL is that in addition to the $C_n^2(h)$ profile (extracted with high vertical resolution), it will provide the outer scale profile, the seeing and the isoplanatic angle non model-dependent.

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References

1. D. M. Winker, J. Opt. Soc. Am. A **8**, (1991) 1568
2. R. Conan, *Modélisation des effets de l'échelle externe de cohérence spatiale du front d'onde pour l'observation à Haute Résolution Angulaire en Astronomie* (PhD Thesis of University of Nice, Nice (France) 2000)
3. J. Borgnino, A. Berdja, A. Ziad, J. Maire, Proceedings of the Astronomy Meets Meteorology, Proceedings of the Optical Turbulence Characterization for Astronomical Applications, (2009) 42
4. R. Avila, A. Ziad, J. Borgnino, F. Martin, A. Agabi, A. Tokovinin, J. Opt. Soc. Am. A **14**, (1997) 3070
5. A. Fuchs, M. Tallon, J. Vernin, PASP **110**, (1998) 86
6. W. K. Pratt, *Digital image processing* (A. Wiley-Interscience Publication, New York 1978)
7. S. Kirkpatrick, C. D. Gelatt, M. P. Vecchi, Science **220**, (1983) 671
8. J. Maire, A. Ziad, J. Borgnino, F. Martin, MNRAS **377**, (2007) 232