Third AO4ELT Conference - Adaptive Optics for Extremely Large Telescopes
Florence, Italy. May 2013
ISBN: 978-88-908876-0-4
DOI: 10.12839/AO4ELT3.13383

DEFINING REFERENCE TURBULENCE PROFILES FOR E-ELT AO PERFORMANCE SIMULATIONS

M. Sarazin[1,a], M. Le Louarn[1], J. Ascenso[1], G. Lombardi[2] and J. Navarrete[2]

[1]European Southern Observatory, Garching, Germany
[2] European Southern Observatory, Santiago, Chile

Abstract. ELT sites have been chosen after many years of site evaluation with various atmospheric turbulence profilers. ELT instrument planners are expecting reference profiles as input to the adaptive optics (AO) instrument performance estimators. It appears however that, for some AO modes like laser tomography (LTAO), the requirements exceed the available products in terms of altitude resolution. We explore the possibility of mixing long term statistics at low altitude resolution with high resolution data collected during short term campaigns to produce representative profiles

1. Introduction

The paper describes the method for generating high resolution turbulence and wind profiles representative of the expected observing conditions at Cerro Armazones and the corresponding simulation results for laser tomography (LTAO) and wide field natural guide star (NGS) multi-conjugate adaptive optics (MCAO).

An adaptive optics (AO) instrument performance simulation model assumes that the turbulence is distributed in infinitely thin layers. The input atmospheric parameters thus consist of

- A set of integrated C_n^2integral values (J_i, m1/3) located at arbitrarily chosen heights (h_i, m) above the observatory platform.
- The corresponding values of wind velocity (V_i, m/s)

This means that the knowledge of the actual monotonous profile is not needed, but only a realistic digital representation of it. This paper aims at assessing the degree of complexity (number of layer) and the accuracy (in amplitude and in position) required for performing the simulations, depending on the AO mode considered. The reference profiles used in the simulations are described in section 2.3.

2. Available atmospheric data

The atmospheric turbulence has been monitored at Cerro Armazones (3064m) during the site surveys for TMT (2004-2009) and ESO E-ELT (2010-2013) using MASS-DIMM profilers. These highly

a e-mail : msarazin@eso.org

portable instruments are well adapted to site testing campaigns but have a low vertical resolution at high altitude. We use here the MASS measurements performed by ESO at Armazones from 2010 to 2012 after reprocessing by ATMOS 2.97.3 [1] with the standard 6-layer configuration. The turbulence in the surface layer (h<250m) has been monitored at Armazones and Paranal with a dedicated profiler LuSci [1].

On the other hand, the atmospheric turbulence above Paranal, only 22km away to the West, has been studied at high resolution on several occasions. Because of the short distance and of mostly westward wind flow at higher altitude, the free atmosphere (i.e. above the boundary layer, typically h>1km) is assumed to be similar at both sites.

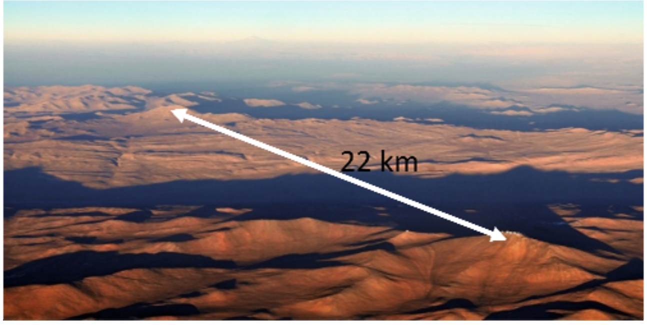

Fig. 1. Aerial view of Armazones (left, 3064m) and Paranal (right, 2630m). The white line is along the E-W direction

The goal is to combine all the available data to generate realistic sets of (h_i, J_i, V_i) in agreement with the long term statistics of the Armazones database.

2.1. Balloon borne profiles at Paranal

During the site testing for the VLT, a dedicated profiling campaign (PARSCA, Paranal Seeing Campaign) was conducted, including 20 balloon launches in March 1992 [3]. The payload consisted of standard PTU radiosondes, retrofitted with pairs of microthermal sensors measuring the temperature structure coefficient (C_t^2, $C^2m^{-2/3}$) during the ascent. The balloons were launched from the foot of Paranal and were mostly drifting to the West, thus describing the higher atmosphere of Armazones as well, excluding the surface and ground layers. The records of all the launches are merged into a single composite profile which is then binned at a resolution of 1000m (**Error! Reference source not found.**)

2.2. SCIDAR profiles at Paranal

During the site testing for the E-ELT, a multi-instrument monitoring campaign was conducted at Paranal, funded by the FP6 program [4]. Among other instruments, a SCIDAR built by IAC was operated at the focus of one of the VLTI Auxiliary telescopes. It recorded C_n^2 profiles above Paranal every minute during 20 nights in December 2007 with a vertical resolution of 300m. The database was reprocessed in 2010 with an improved accuracy [5]. The fraction of the total C_n^2 is shown on Fig. 1 for the median profile and for the four quartiles of the total C_n^2 statistics.

2.3. Comparison and merging

Because the balloons and SCIDAR measurements were done at different epochs and cover different periods of the year, a perfect agreement is not expected but rather a demonstration of the consistency of the two methods for representing the atmosphere above Paranal. Indeed Fig. 4 shows that 3 layers out of 4 are clearly detected at high altitude by both instruments, while the lowest one is seen only by the SCIDAR.

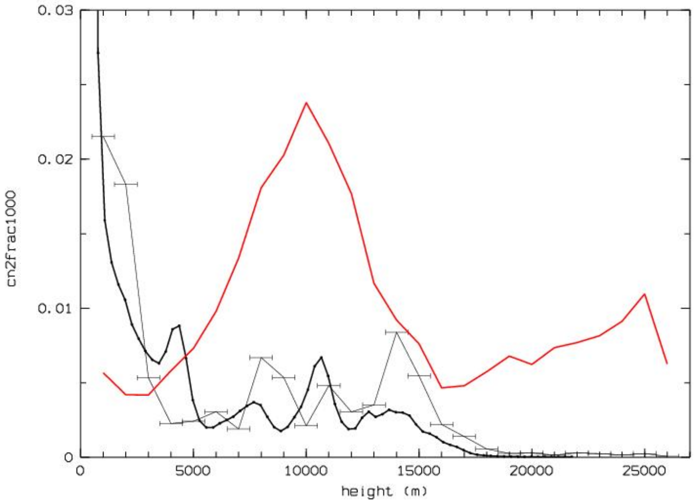

Fig. 2. Comparison of the balloon 20-layer profile (bars) to the median SCIDAR (full black line) at Paranal. The Y axis is the fraction of the total integrated C_n^2. The red curve is the wind profile measured by the balloons in km/s

It has been shown [7] that simultaneous MASS and SCIDAR measurements taken at Mauna Kea present some discrepancies when SCIDAR profiles are merged into MASS triangular weighting functions. As noted in [8], this is also the case for the Paranal 2007 campaign where two MASS units used for the E-ELT site selection were successively operated in the same time as the SCIDAR described in 2.2. For the present application we used the MASS-DIMM seeing quartiles (and corresponding coherence time) representative of long term statistics including the seasonal trends. A set of synthetic reference 35-layer profiles was then generated, breaking the MASS layers into infinitely thin sub-layers at 1km spacing, following the SCIDAR realistic pattern.

The reference profiles used for the simulations are thus synthetic compositions merging the data collected at Paranal and Armazones. The number of layers is degraded while keeping the same seeing (r_0) and coherence time (tau_0) conditions. The fractions of the integrated turbulence in each layer are given for the median seeing and for each four seeing quartiles of the 2010-2012 MASS-DIMM Armazones database. A single common wind profile is provided, based on the balloons records of Fig. 2, which has to be multiplied by the adequate coefficients to fit to the tau_0 measured at the site by MASS-DIMM.

We intend to study the impact of altitude resolution on wavefront reconstruction so as to set operational requirement for the E-ELT astronomical site monitoring instrumentation. Several levels of vertical resolution are provided, corresponding to hypothetical monitoring configurations:

- 35-layer [30m, 24km]: the highest resolution proposed (Fig. 5), assumes a SL-SLODAR and a SCIDAR on site
- 19-layer in [30m, 24km]: medium resolution, could be achieved with a SL-SLODAR and a HD-MASS (boosted to 13 layers)
- 13-layer in [30m, 18km]: baseline configuration including SL-SLODAR and MASS
- 8-layer in [30m, 12km]: SL-SLODAR alone (only one layer in the free atmosphere)
- 7-layer in [200m,18km]: MASS-DIMM (site testing configuration)

Note that the profiles height scale starts from observatory platform and thus includes the light path within the dome. It is assumed that the outside surface layer turbulence does not enter the dome but that the Cn2 profile inside the dome is flat and equal to the outside value at the top of the slit.

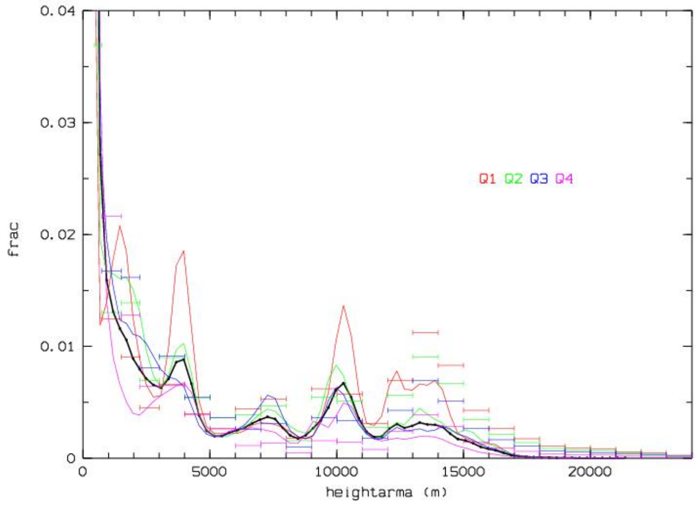

Fig. 3. The four 2010-2012 seeing quartiles of the Armazones 35-layer median reference profile (bars) based on the modified MASS database compared to the four quartiles (colored lines) and median (black line) of the 2007 Paranal SCIDAR profile of 2.2 transferred without deformation to the Armazones altitude. The Y axis is the fraction of the total integrated C_n^2.

3. Simulation results

3.1. LTAO

We simulated a Laser Tomography system for the E-ELT (39m diameter), based on 6 Laser Guide Stars. The LGSs are located in a ring of 1.7' (diameter), and are observed with a Shack Hartmann with 74x74 sub-apertures, with a corresponding 75x75 DM (square geometry), conjugated to the ground. The loop is running at 500Hz. Spot elongation was not simulated. To concentrate on the high order loop aspect, we took an NGS constellation very close to the center of the field of view. We used the Frim3D reconstructor ([8]) for all the simulations.

The simulation actually contains two sets of Cn2 profiles. The first profile is used to simulate the atmosphere. The LGS light is geometrically propagated through it, and that is the profile used to calculate the SH measurements which are then sent to the reconstructor. The DM shape is applied and the Strehl is also calculated using that profile. The other profile is injected into the reconstructor to help better condition the wavefront reconstruction process. This second profile can be the same as the first, or can be another one (usually of lower resolution). How this second profile is obtained is still yet to be defined. Either it is directly estimated from the WFS data (not addressed here), or it is obtained through an independent measurement device. Here we investigate how this device should perform.

In Fig. 4, we reconstruct the same layers as those injected. The goal is to see how the atmospheric profile affects the AO performance, assuming it can be perfectly estimated for the tomographic process. This is therefore an upper limit of the performance. The profiles have two effects embedded into them. First, for each quartile, there is a different r0. Second, each quartile corresponds to a different distribution of the turbulence in the atmosphere. We want to disentangle these two contributions. Therefore, the first curve (solid) represent a profile where the C_n^2 distribution is changed and the r_0 kept fixed (at the median value). We can see that the better the seeing the worst is the AO performance for a given r_0. Looking at the profiles, we see the better the seeing, the more high altitude contribution it has. On the opposite, bad seeing tends to be associated with a beneficial C_n^2 for LTAO.

The other (dashed) curve shows the combined effect of C_n^2 profile and r_0. There we can see that the r_0 dominates, and the good seeing provides the best performance, despite having an unfavorable profile. Note that the diamond represents the previous 40 layer profile (used by ONERA) – which is quite well representative, in terms of LTAO performance, of a median profile.

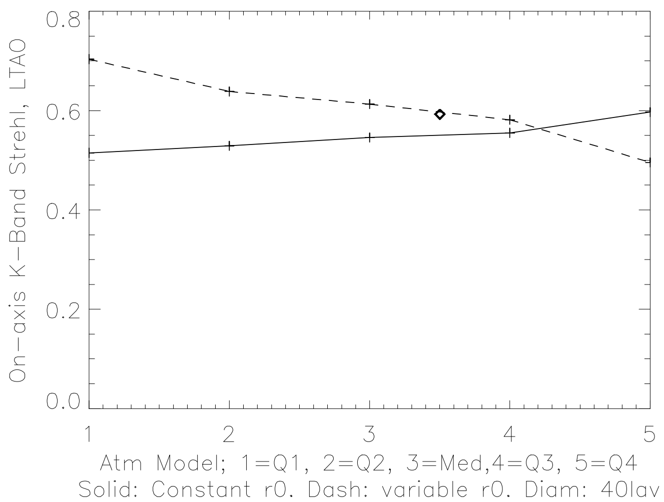

Fig. 4. On-axis LTAO Strehl with for median and quartile profiles and r0 (dashes) and at constant median r_0 (full line)

The second aspect of our study concerns the importance of entering the right kind of profile to the reconstructor. Here, the atmospheric (input simulation) profile stays always the same – it is the median profile. What changes, is what we tell the reconstructor. Since the Real Time Computer complexity depends on the number of estimated layers, there is an incentive to estimate as few layers as possible. Also, how should these layers be estimated ?

We simulated the measurements for several potential monitoring configuration of 2.3, the results can be seen on Fig. 5. Giving the Strehl in K-Band of the LTAO system a function of the number of measured layers. We can see that the more layers are estimated, the better the performance is – in general. There is an exception, as we see that the 7-layer model distributed at high altitude provides a better performance than the 8-layer model concentrated close to the ground. So it is not only the number of layers that matter, it is also their distribution. Entering high altitude layers is determining for the algorithm. The dotted curve of Fig. 5 represents a degradation of the measurement provided by the profilers: we removed completely the information on the intensity in each layer, and replaced the Cn2 profile by a flat profile (but with layers at the same altitudes as previously). The results are remarkably close to the full information. We then degraded the input C_n^2 profiles even further: the dashed curve of Fig. 5 correspond to an equal distribution of the layer heights between 0 and 18km and the dot-dash between 0 and 24km, both with a flat C_n^2 profile. We can see that here, performance is significantly reduced, and estimating more "fake" layers does not help at all. So Cn2 profile information is needed by the algorithm, and this information should concentrate where the layers are, and not so much what is their relative strength. But, adding layers at wrong heights does not help, on the contrary.

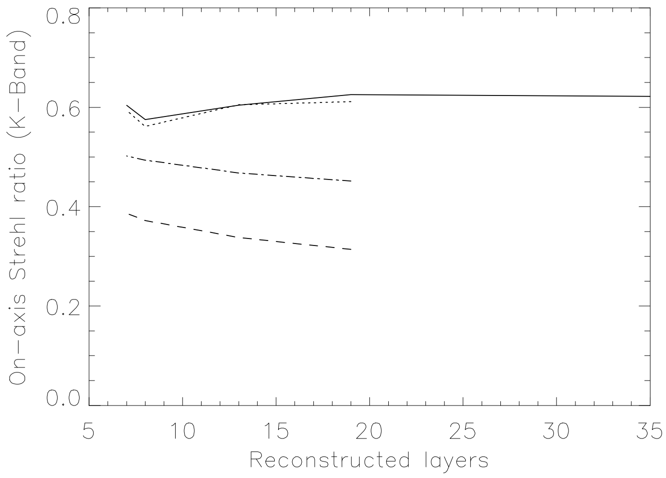

Fig. 5. LTAO system performance as a function of number of reconstructed layers. Solid: “measured profiles”, Dots: Measured heights, but flat Cn2 profile, Dash: Equi-distributed heights with a max height at 18km, flat Cn2 profile, Dot-dash: Equi-distributed heights with a max height at 24km, flat Cn2 profile.

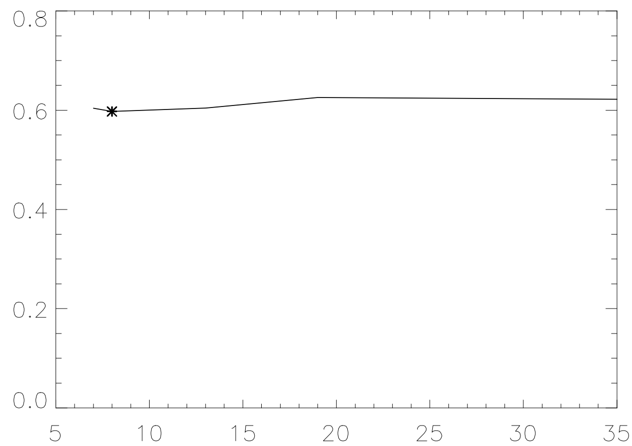

Fig. 6. LTAO system performance as a function of the number of reconstructed layers. The point at 8 has a “guessed” layer added. So at 7 layers, 8 layers are actually estimated, but without any extra measurement.

Now, is it possible to improve the 8 layer estimation in order to get as good a performance as the 7 layer measurement? We investigate this possibility by taking the 8 measurements, and adding two “fake” layers, at 18km and 24km heights, with only ~1% of turbulence in each. We can see that this procedure helps, as the performance is improved. So this underlines again the necessity to estimate layers at the right heights, rather than with the proper intensities.

Finally, another experiment was carried out to estimate the sensitivity of the results to possible errors in the Cn2 profiles (due for example to measurement noise). It appears on Table 1 that an error of 20%, either on the height or on the Cn2 fraction does not change the performance in the case of the estimated 13 layers.

Table 1. LTAO Strehl performance when introducing amplitude or position distortions into the 13-layer profile

Nominal	**FA-minus20%**	**FA-plus20%**	**H-minus20%**	**H-plus20%**
0.604	0.592	0.609	0.609	0.606

3.2. Wide field NGS

In the following section, we investigate a Multi-Conjugate AO system (see [9]), with 3 deformable mirrors (conjugated at 0, 4km, 12.5km) and 6 natural guide stars in a 4 arcmin diameter circular configuration. The WFSs are still 74x74, and the actuator density is the same on the ground DM, but two times less on the high altitude DMs (spacing of 0.5, 1m, 1m). Otherwise, system parameters are similar to the LTAO case.

We compare the results with two different input profiles shown on Fig. 7: the 40-layer “average” profile used previously by ONERA at 30 degrees off zenith and the median 35-layer profile described in this paper.

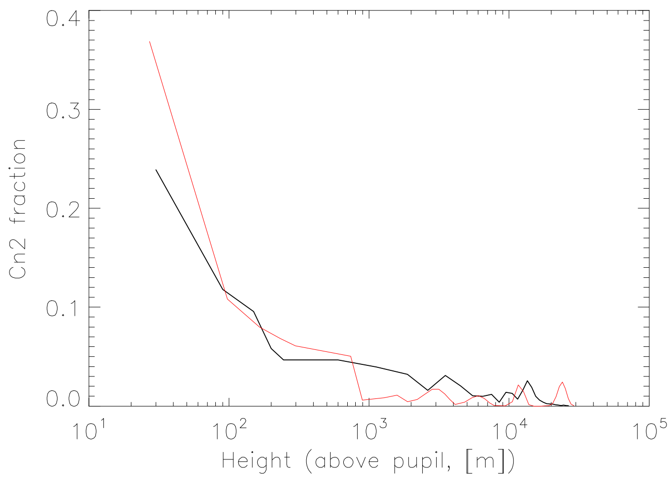

Fig. 7. Comparison of the median 35 layer profile (black) to the 40 layer profile (red) used in previous studies

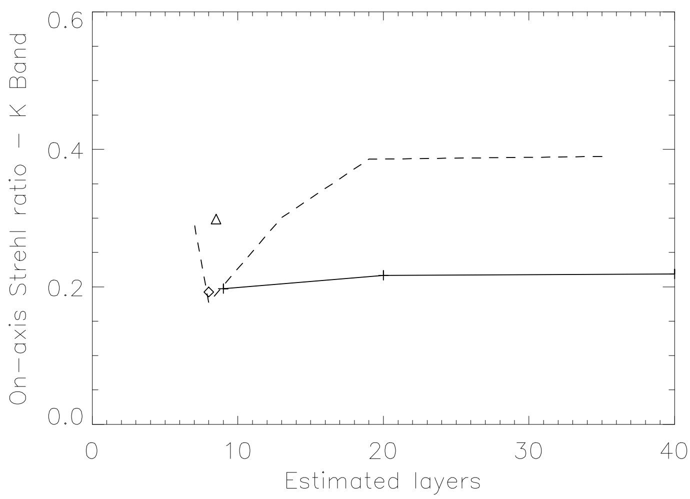

Fig. 8. On-axis performance of the wide field NGS-MCAO mode as a function of the number of estimated layers in the earlier 40-layer model (full line) and the present 35-layer model (dashed line)

The performance is estimated on-axis, with the projection operator described in [8] to allow the best uniformity over the field of view. represents the central Strehl, in the case when the reconstructor is optimized to maximize the uniformity of the performance over the whole field of view. We can see a significant difference in the estimated performance between the two input profiles, even when all the input layers are estimated, and while the Cn2 profiles do not seem too different. This shows the increased importance of the Cn2 simulation for a very wide field MCAO system compared to the LTAO system where the field of view was significantly smaller. It also underlines need for a higher number of estimated layers (notice the decrease in performance for the dashed line, as the number of estimated layers is reduced). We tried to improve the 7 and 8-layer estimates, by adding one layer to the 7-layer model (layer at 24km, 1% strength - triangle) or two layers to the 8-layer model (at 18km and 24km, with 1% of turbulence - diamond). Using ~10 layers (8+2) does improve the result significantly, but one does not reach the levels of the ~20 estimated layers.

As a next step, we shall run all the 35 layer profiles for the MCAO system, to check the variability of system performance for different profiles, as we did for LTAO. This will be presented in a subsequent paper.

4. Conclusion

Vertical profiles of the turbulence and of the wind velocity above the E-ELT site have been extrapolated from ancillary high resolution measurements in the Paranal area. Seasonal variations have been applied, based on the long term statistics accumulated during the E-ELT site survey. We have simulated the performance of MCAO and LTAO wave front corrections as a function of the altitude resolution and of the accuracy of the input profiles. Our results show the importance of having a representative C_n^2 profile for the simulation of performance (especially for wide field of view systems), and the importance of giving the right profile (heights of the dominant layers are very important, their relative importance less – especially in LTAO) to the reconstruction algorithm.

5. References

1. V. Kornilov, A&A, **530**, A56 (2011)

2. G. Lombardi et al., *This conference* (2013)

3. A. Fuchs, PHD Thesis, Univ. of Nice, Dept. of Astrophysics, (1995)

4. W. Dali Ali et al., A&A, **524**, A73 (2010)

5. E. Masciadri et al., MNRAS, **420**, pp. 2399 (2012)

6. A. Tokovini et al., PASP, **117**, 830, pp. 395 (2005)

7. E. Masciadri et al., *This conference* (2013)

8. E. Brunner, Cl. Béchet, M. Tallon, *Proc. SPIE. 8447, Adaptive Optics Systems,* eds. B. L. Ellerbroek; E. Marchetti; J-P. Véran (2012)

9. Ragazzoni et al., *Proc. SPIE. 8447-21, Adaptive Optics Systems,* eds. B. L. Ellerbroek; E. Marchetti; J-P. Véran (2012)