Dealing with the forecast of the optical turbulence as a tool to support astronomy assisted by AO facilities

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Abstract. In the context of the research activities related to the forecast of the optical turbulence and the atmospherical parameters being relevant for ground-based astronomy we focus here our attention on two specific topics: **1.** pros and cons of different solutions to supply wind speed and direction stratification on the whole atmosphere all along a night to support AO facilities; **2.** the necessity of instrumentation for optical turbulence monitoring (vertical profiles on the whole atmosphere) to be used operationally. In the last two decades the development and the use of different vertical profilers covering the whole atmosphere or part of it in application to the astronomy took place. Several instruments based on different principles (with associated pros and cons) have been applied in different contexts in astronomy with a main use in the site characterization and site selection. Time changed and the necessity of the astronomy supported by AO facilities is much more demanding with a diversification of applications. Recently, motivated by a precise necessity related to the identification of an absolute reference to carry out studies on optical turbulence forecasts (MOSE project), we carried out a verification of the reliability of a few instruments that lead us to put in evidence some limitations for a few of them. At the same time such a detailed analysis permitted us to clarify the nature of some astroclimatic parameters. The main conclusion at which we arrived is two-fold. From one side we could trace a list of warnings related to different uses of such instruments. On the other side we could identify open problems that indicate that there is still space for research in the field of turbulence monitoring in application to the astronomy. Some suggestions are proposed.

1. Introduction

In this contribution we concentrate our attention on two specific topics both related to the forecast of the atmospheric parameters and optical turbulence with atmospherical models. From one side we present a method for the estimate of the wind speed stratification on the whole atmosphere and its performances; the advantage of this method with respect to other techniques; the usefulness in using such a method to validate wind speed measurements estimate obtained with the MCAO system GeMS [1] and in general with whatever other wide field AO system; the perspectives for an optimized method of wind speed stratification estimation based on the simultaneous use of the atmospherical model Meso-Nh and the MCAO system GeMS. Besides we present the state of art of optical turbulence vertical profilers to be used operationally to support AO systems and useful to be able to monitor the performances of atmospherical models for the turbulence forecasts. This study permitted us to achieve a better understanding of some atmospherical parameters such as the wavefront coherence time.


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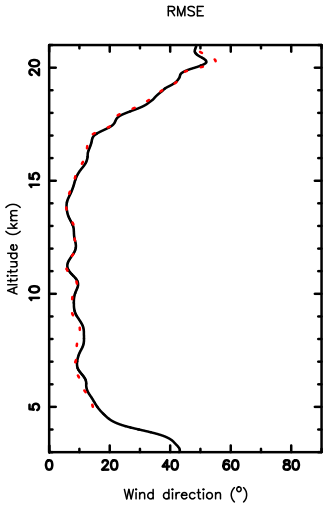

Figure 1. RMSE of the wind direction between radio-soundings and Meso-Nh (full black line) and radio-soundings and analyses from the ECMWF (red dots).

2. Wind speed vertical stratification on 20 km

The method we propose consists of a non-hydrostatic atmospherical model at mesoscale called Meso-Nh [2] that, used with the Astro-Meso-Nh packages [3], permits to calculate all the atmospheric parameters relevant for the ground-based astronomy and the optical turbulence (OT). The most solid validation of this model in terms of wind speed stratification [4]-Fig.2 is supported by the fact that we proved that the model is very well correlated to measurements related to 50 radiosoundings launched on 23 different nights in summer and winter periods. Results indicate that the correlation is good in statistical terms as well as on individual launches. In statistical terms simulations and measurements of wind speed (WS) and direction (WD) have been analyzed giving a bias for WS typically of the order of 1 ms^{-1} and not larger than 2 ms^{-1} along the whole 20 km; the RMSE of WS is typically of the order of 3 ms^{-1}. For the wind direction in the central part of the atmosphere the bias is just a few degrees. In the low part of the atmosphere and the top the bias is not larger than -/+ 10 degrees. The RMSE of WD in the central part of the atmosphere is as small as 10 degrees. Its value increases in the range 3-5 km above sea level and for h $>$ 16km achieving a maximum value of 40 degrees. In this new calculation with respect to [4] we filtered out all data associated to a wind speed $\leq$ 3 ms^{-1} (Fig.1).

The residual 40 degrees is due to the fact that when the wind speed is weak the direction is much more variable. In the same paper [4] we proved that the residual biases are due to the initialization data and not the mesoscale model. If we look at the model performances in terms of the correlation between measurements and calculation obtained on the individual flights results are even more interesting. In many nights we had radiosoundings launches at different time and this permitted us to investigate the ability of the model in reconstructing the real-time modification of the wind stratification during the same night. We could proved that the model adapts perfectly to the temporal evolution of the wind speed stratification on 20 km ([4]-Fig.3), changing the wind speed values as they are observed at all the heights above the ground. In the same paper (Fig.B1) the model ability in matching the measured wind speed stratification on all the individual 50 radiosoundings is shown indicating excellent model performances. A maximum relative error of just 23% has been observed in the whole sample. This tells us that we can reasonably use the wind speed predicted by the model for the calculation of

the τ_0 (with C_N^2 measured or simulated) with the temporal sampling that we wish. We typically use a sampling of 2 minutes but we could go down to a few seconds. Meso-Nh solves therefore important criticisms in the field of the wind speed characterization. The calculation of τ_0 using wind speed obtained by General Circulation Models (GCMs) can induce to important errors because these models are not reliable in the low part of the atmosphere and, moreover, they provide informations only at synoptic hours that means each six hours (00, 06, 12 and 18) UT.

The wind speed stratification can be very useful in application to the ground-based astronomy. Here are a few of these applications:

1 to manage observational scheduling of scientific program (leading application);
2 to support the use of the AO systems in real time (see for example an operational application to GeMS [1]);
3 to support studies of simulations of AO performances and new AO techniques validation (this is a work to be done offline and not in real time);

How can we use the wind estimates ?

1 the simplest output is the forecast of the temporal evolution of the wind speed at different heights (wind speed stratification).
2 if the wind speed from the model is joint to the C_N^2 predicted by the same model we can calculate the forecasted τ_0.
3 if the wind speed from the model is joint to the C_N^2 measured by an instrument we can have a real time measurement of τ_0. For such a high level of model reliability for the wind speed stratification it is indeed useless to use an instrument even more because, in many cases, uncertainty and limitations for instruments are more severe.

The applications of points 1, 2 and 3 can be obtained with very a high temporal sampling.

2.1. Advantage of the Meso-Nh model with respect to other techniques
The numerical technique, and more precisely the use of the Meso-Nh model presents some advantages with respect to other techniques that are available at present:

1: the atmospheric model is by far the cheapest and fastest technique;
2: there are no logistical constraints;
3: instruments such as the Generalized SCIDAR (GS) [13] and the Stereo SCIDAR [14] need a telescope with a pupil size D of at least of 1 meter. This implies that they can hardly be used for operational applications;
4: Stereo SCIDAR has an automatic procedure for the detection of the wind speed but to cover all the wind spectrum it is necessary a pupil size of the telescope of at least 2 m otherwise the maximum measured wind speed is of the order of 36 ms^{-1}. Wind speed can reach values well above this threshold in the free atmosphere;
5: the model has a better spatial and temporal coverage than instruments based on remote sensing principle. It is enough to compare [4]-Fig.4,top with [5]-Fig.2;
6: the model has basically no constraints on the temporal sampling.

2.2. Meso-Nh and GeMS wind speed estimates
In a recent preliminary study [1], it has been possible to investigate and validate the ability of the MCAO system GeMS [6, 7] in reconstructing reliable wind speed stratification. Vertical wind speed stratification estimates obtained with the Meso-Nh model on 11 nights above Cerro Pachon have been compared to measurements obtained with GeMS during those nights ([1]-Fig.3 and Fig.4). Results of this study indicate that GeMS is able to reconstruct in most cases a good wind speed vertical stratification. Besides that, it has been possible to observe that, in some cases, it might produce not negligible errors. However, in those cases of failure, it has been possible to observe that the Meso-Nh estimates are determinant to correct the GeMS estimates. Results indicate therefore that a simultaneous (and preferably automatic) estimate of the wind speed done simultaneously by Meso-Nh and GeMS might give an exhaustive answer to the necessities of this MCAO system. Of course such a solution might be used for other WFAO systems such as AOF [8] of ESO.

3. Optical turbulence vertical profilers for operational applications
A critical element for the studies on the OT forecast done with atmospherical models is the verification (and quantification) of a good absolute estimate of the OT vertical stratification provided by the vertical profilers (instruments) that have to be used as a reference. In [9]-Fig.3 are shown the scattering plots of the seeing as measured by the Generalized Scidar (GS) and the MASS in all the six layers of the MASS. The C_N^2 profiles of the GS have been therefore projected on the six triangle shape weighting functions of the MASS to perform the comparison. The sample analyzed is part of the data related to the site test campaign of PAR2007 [10, 11] at Cerro Paranal. In [9]-Fig.4 is shown the integral of the seeing in all the 6 layers as seen by the MASS and the GS. The comparison puts in evidence that, in many layers (with exception of the layer 3 and 6), there is an evident discrepancy between the two instruments that is translated in a underestimation of the total seeing in the free atmosphere of the MASS. If we look at the relative errors in each layer ([9]-Table 4) we realize that these discrepancies are not negligible, particularly for the layers 1, 2 and 5 and for the total seeing (order of 50-60%). This in spite of the fact that the difference of the seeing in the free atmosphere is of roughly 0.2 arcsec. In other words, we should not be induced in error by the weak absolute differences. The determinant thing is the relative error. In the same paper we proved that the problem is in the MASS and not in the GS because the correlation between GS and DIMM is consistently good.

3.1. Seeing and J
If we look at the temporal evolution of J (related to the seeing by [9]-Eq.8) on all the 12 nights in which simultaneous measurements from the two instruments are available ([9]-Fig.A1), we observe that the trend of the seeing measured by the two instruments is substantially good but the underestimation by the MASS is systematic. If we look at the temporal evolution of J in the first layer the underestimation is quite important ([9]-Fig.A2). If we look at the temporal evolution of J of the highest layer we observe that the correlation is mostly very good ([9]-Fig.A7). The trend remains in general satisfactory.

3.2. Isoplanatic angle
In [9]-Fig.6 is shown the scattering plot of θ_0 as measured by MASS and GS. It is possible to observe a good correlation with a small bias (~ 0.07 arcsec). Looking at the temporal evolution for the different nights ([9]-Fig.A8) also the trend and the correlation seem good. This is not in contradiction with results obtained for the seeing. We know, indeed, that θ_0 is mainly driven by the turbulence in the high part of the atmosphere and the correlation of seeing between the two instruments in the highest layer was satisfactory (see [9]-Fig.A7). In other words, even if there are discrepancies in the spatial distribution of the OT in the middle of the atmosphere these

have negligible impact on θ_0. It is a pity that the statistics in this case is a bit limited. For θ_0 we have only 12 nights with simultaneous measurements and 4 nights with very few values. However it seems that θ_0 estimates from MASS are mainly reliable.

3.3. Wavefront coherence time

In the scattering plot of [9]-Fig.7 it is possible to observe a good correlation between τ_0 estimates obtained from the two instruments with limited BIAS and RMSE. The correlation is better for small values of τ_0, for large values the MASS shows a tendency in providing larger values with respect to the GS. The same can be said for the temporal evolution of τ_0 ([9]-Fig.A9). In the first part of the campaign the correlation is somehow better but it is in general good. It is interesting to investigate the reasons for such a general good behavior. We should expect an overestimation of the τ_0 from the MASS because of the underestimation of the seeing in the free atmosphere. In the same paper we formulated a thesis to explain how it is possible that the τ_0 from MASS is satisfactory also if the seeing is not.

A τ_0 MASS measurement in reality implies the use of three different instruments: a MASS, a DIMM and an automated weather station (AWS) because τ_0 is given by the addition of two contributions. One coming from the MASS (associated to the free atmosphere) and the other coming mainly from the DIMM (associated to the ground layer). The hypothesis is that, if τ_0 is substantially well correlated with the GS that means that the ground layer contribution dominates. We proved this thesis in [9]-Fig.A10 where the three contributions of τ_0 provided by the ground, the free atmosphere and the whole atmosphere are displayed. Details of the demonstration can be found in [9]. We conclude that, differently from what is frequently assumed, the τ_0 is mainly driven by the ground contribution and not by the free atmosphere.

4. Conclusions

The main conclusions of this contribution can be summarized as:

1: Our recent studies [9] permitted us to establish a list of warnings with respect to the use of MASS (the unique monitor used operationally at present): (a) θ_0, τ_0 appear reliable, the seeing in the free atmosphere is underestimated by the MASS. (b) all major conclusions on site selection for TMT and E-ELT are not affected by our results because the analysis in those context is done in relative terms. (c) we proved for MASS the existence of important discrepancies on individual layers with respect to GS estimates. At the same time the GS revealed to be in good agreement with DIMM and the assumption of an overestimation of the GS (in alternative to an underestimation of the MASS) would lead to the absurd result that GS would not be well correlated to DIMM any more. (d) as a consequence it is not suggested to use MASS in applications to the AO and in general in all applications in which is critical the knowledge of the turbulence stratification in individual layers.

2: We put in evidence that the discrepancies on OT absolute estimate obtained with different instruments under conditions of fair comparison can be important and we identified specific limitations in some cases. Also we could identify contexts in which the level of accuracy is acceptable. The problem of the OT absolute estimate is the king topic in the turbulence field in application to the astronomy.

3: We promoted an action (multi-instrument campaign) that goes in the direction to solve this problem [12]. The goal of the site-testing campaign is to quantify the absolute estimate of the OT vertical distribution obtained by independent different instruments.

4: The OT absolute estimate is fundamental to quantify the accuracy. We proved [9] that, when the BIAS in seeing estimates in the free atmosphere between MASS and GS is equal to 0, the bias corrected RMSE $\sigma_{FA} = 0.13$". This tells us that the accuracy in seeing estimates in the free atmosphere is at present of +/- 0.13".

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