MOSE: a feasibility study for the prediction of the optical turbulence and meteorological parameters at Cerro Paranal and Cerro Armazones.

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Abstract. The optical turbulence (OT) forecast is definitely mandatory for ground-based astronomy supported by AO to schedule scientific programs, instrumentation and instrumentation mode (ex: narrow or wide field) to exploit the AO potentialities and optimize the telescope management and scientific feedbacks. A status report of the on-going MOSE project aiming at assess the feasibility of the prediction of the (1) OT and (2) all the classical atmospheric parameters from which the OT depends on at the two major ESO sites for ground-based astronomy in the visible and infrared regimes (Cerro Paranal and Cerro Armazones) is presented. The study employed a wide variety of measurements obtained with different instruments running simultaneously to constrain and validate the model. Results obtained so far are very promising showing that the hydrodynamic technique is already mature for an operational implementation in present and forthcoming observatories. In this contribution we will present a summary of the most important achieved results and forthcoming plans to overcome the observed limitations. The analysis of procedures required to quantify the models score of success for the OT revealed us that an improved strategy for automatic systematic monitoring of turbulence is necessary in modern Observatories.

1 Introduction

In this contribution we present the status progress of an on-going project called MOSE (MOd-eling ESO Sites). It is a feasibility study that aims at evaluating the opportunity for the set-up of an automatic system for the forecast of: (1) all the classical atmospherical parameters (absolute temperature, wind speed and direction, relative humidity, ...) and (2) the optical turbulence (OT) that is the $C_n^2$ profiles and the integrated astroclimatic parameters that derive from the $C_n^2$: the seeing $\varepsilon$, the isoplanatic angle $\theta_0$ and the wavefront coherence time $\tau_0$. The project is co-funded by INAF and ESO and started on April 2011. Phase A has concluded on April 2013. Phase B has been defining in these weeks. The most relevant parameters we intend to predict are:

(a) the surface temperature that is fundamental to thermalize the dome of the telescopes and to eliminate the dome seeing i.e. the most important contribution in the total turbulent energetic budget that affects the images at the focus of the telescopes;
(b) the surface wind speed that is the main source of vibrations of structure such as the adaptive secondaries and primary mirrors;
(c) the surface wind direction that is the atmospherical parameter that is more easily correlated to the seeing conditions. It is frequently possible to associate bad or good seeing conditions to particular wind directions in the the low part of the atmosphere;
(d) the vertical stratification on the whole 20 km of all the classical atmospherical parameters.

We are particularly interested on the wind speed that is one of the main ingredient necessary to calculate the $\tau_0$. There does not exist a monitor that is able to provide systematic measurements

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of the wind speed vertical stratification on the whole 20 km, particularly above mountain regions. For this reason this method might reveal particularly interesting in this respect not only for the prediction but also for the real time calculation of $\tau_0$ (see [1]);

(e) the optical turbulence. It is known that the meso-scale model represents the unique method that is able to provide 3D maps of the $C_n^2$ from which we can retrieve all the astrometric parameters integrated along whatever line of sight. For the first time we undertook a study with a systematic approach looking at the model performances in reconstructing these parameters all together.

The MOSE project aims at overcoming two major limitations that are typically encountered in studies focused on the optical turbulence forecast with atmospheric models: (1) the difficulty in having independent samples of measurements for the model calibration and model validation to estimate if and how the correlation between measurements and predictions on the validation sample changes with the increasing of the number of nights and to estimate if and how the statistical richness of the calibration sample affects the calibration itself; (2) the difficulty in having a large number of simultaneous measurements done with different and independent instruments for the OT estimates (in particular vertical profilers). This project is performed with the non-hydrostatic mesoscale atmospheric model Meso-NH [2] joined with the Astro-Meso-NH package for the calculation of the optical turbulence [3,4] to perform the OT forecasts. An extended data-set of observations (meteorological parameters and optical turbulence) have been considered in the project as a reference for the model validation. We took advantage of measurements obtained in the context of the site selection for the TMT ([5]) at Cerro Armazones and on measurements taken routinely during the last decade and/or in a dedicated site testing campaign (PAR2007 [6]) at Cerro Paranal.

2 Observations

At Cerro Paranal (CP), observations of meteorological parameters near the surface come from an automatic weather station (AWS) and a 30 m high mast including a number of sensors placed at different heights. Absolute temperature are available at 2 and 30 m above the ground level (a.g.l.). Wind speed measurements are available at 10 and 30 m a.g.l.. At Cerro Armazones (CA), observations of the meteorological parameters near the ground surface come from an AWS and a 30 m tower with temperature sensors and sonic anemometers. Absolute temperature and wind speed are available at 2, 11, 20 and 28 m a.g.l. At CP we had access to 50 radiosoundings launched above the site in the context of an intense site testing campaign for the water vapor characterization [7] and covering 23 nights in 2009, 11 nights in summer and 12 in winter time. For what concerns the optical turbulence at CP we used measurements related to the Site Testing Campaign (PAR2007) including a Generalized Scidar (GS), a MASS and a DIMM running simultaneously. At CA we had access to measurements of a MASS and a DIMM related to the TMT site selection activities.

3 Model configuration

The two sites (CP and CA) are located on the Chilean Andes. The distance between them is $\sim 22$ km. We used a grid-nesting technique [8] that permits to perform simulations with a set of imbricated domains selected on the Digital Elevation Models (DEM i.e. orography) extended on smaller and smaller surfaces and achieving the highest resolution in the innermost
domain on a more limited surface around our point of interest. Two different configurations have been chosen. The standard configuration includes three domains and the innermost resolution is $\Delta X = 500$ m. The second configuration is made of five imbricated domains, the first three as the previous configuration, and other two centered at both CP and CA with a horizontal resolution of $\Delta X = 100$ m. The vertical resolution is the same for all domains. We have 62 levels distributed as follows: a first grid point equal to 5 m, a logarithmic stretching of 20% up to 3.5 km above the ground and, above 3.5 km an almost constant vertical grid size of $\sim 600$ m up to 23.8 km.

4 Atmospheric parameters

4.1 Vertical stratification on $[0, 20]$ km range

Vertical stratification of the atmospheric parameters (absolute temperature, wind speed, wind direction and relative humidity) extended on the $[0, 20]$ km range predicted by the model has been compared to that provided by observations related to 50 radiosoundings launched on 23 nights at CP. This topic is treated extensively in the paper [1] and we refer the reader to that source for an exhaustive description of the analysis. Here we summarize the main elements of such a study. Data have been analyzed with two statistical operators: the bias and the root mean squared error (RMSE) describing statistical and systematic errors. We find that, for all the atmospheric parameters we have just cited, the model provides excellent levels of correlation in the $[3, 20]$ km a.s.l. range. In the $[3, 5]$ km a.s.l. vertical slab, where the orographic effects are visibly present, the model performances in reconstructing the wind direction is slightly deteriorated (bias is $20^\circ$ and RMSE can reach $60^\circ$). However we put in evidence that the deterioration is not necessarily due to a weakness of the model but, highly probably, to the fact that our reference (balloon) is an in-situ measurement (see discussion in [1]). Considering the good model reliability in reconstructing the wind speed vertical stratification during the time with whatever temporal sampling $V(t)$, the Meso-Nh model appears to be as the most practical and cheap tool, at present, to be used for an estimation of $V(t)$ to be used for the calculation of the temporal evolution of the wavefront coherence time $\tau_0$. Using $V(t)$ from Meso-Nh plus the $C^2_n$ from a vertical profiler (GS, MASS, other...) one can calculate $\tau_0(t)$. This method offers the more advantageous solution in terms of accuracy and temporal coverage with respect to the General Circulation Models that are not so reliable in the low part of the atmosphere and that provide informations only at synoptic hours (00:00, 06:00, 12:00, 18:00) UT. It also provides considerable advantages with respect to other instruments (Generalized SCIDAR and/or Stereo SCIDAR). Both instruments require, indeed, a telescope of at least 1 m size to be run and they can hardly be used as automatic monitors.

4.2 Surface layer on $[0, 30]$ m range

In this section we summarize results obtained in studying the model reliability in reconstructing the atmospheric parameters (temperature and wind speed and direction) in the first 30 m above the ground at CP and CA. This topic is treated extensively in the paper [9] and we refer the reader to that source for an exhaustive description of the analysis. Two different model configuration were used, the first one with three imbricated domains with the innermost high resolution of $\Delta X = 500$ m, the second one with five imbricated domains with the innermost high
resolution $\Delta X = 100$ m. Using a configuration with five domains permitted us to perform simultaneous simulations above CP and CA. We found that absolute temperature and wind direction are reconstructed by the model with a high level of correlation with respect to measurements (see details in [9]). For the wind speed we proved that, using a resolution of $\Delta X = 500$ m the median value of the bias is of the order of $2 \text{ m} \cdot \text{s}^{-1}$. Using a resolution of $\Delta X = 100$ m we achieve in maintaining the medium value of the bias within $1 \text{ m} \cdot \text{s}^{-1}$ and the RMSE within $2 \text{ m} \cdot \text{s}^{-1}$.

5 Optical Turbulence

5.1 Measurements: cross-correlation

A preliminary but fundamental step in this study has been the verification of the correlation of measurements of each astroclimatic parameter provided by different instruments. The comparison of the seeing as provided by the Generalized SCIDAR and the MASS was particularly critical for us because the strategy to be chosen for the model calibration depended on this comparison. We refer the reader to a paper that will be submitted soon [10] for an extended analysis of this comparison treating systematic and statistical errors. In that paper the scattering plots of the seeing as measured by the GS and the MASS in each of the six layers of the MASS as well as the integrated seeing on the all six layers (free atmosphere) as observed by the two instruments are shown. Here we summarize the most important conclusions that state that: (1) the MASS underestimates the turbulence in the free atmosphere with respect to the GS with a relative error of -32% in seeing terms (-48% in J terms). This corresponds to a bias of -0.21 arcsec and a RMSE $=0.25$ arcsec if we consider the contribution of the all six layers; (2) we find important discrepancies between MASS and GS in all individual layers with exception of layers 3 and 6 located respectively at 2 and 16 km. Relative errors reach value as high as -65% in seeing terms (-82% in J terms). Relative error of layers 3 and 6 remains limited within +18% in seeing terms (+20% in J terms); (3) the unique previous study [11] on similar topic (even if it was applied on a poorer statistical sample) found relative errors on individual layers as large as those we found in this paper (see extended discussion in [10]). Evidences of the fact that the problem is an underestimation of the MASS (and not an overestimation of the GS) are also described in the same paper [10].

Fig.1 reports, on the first three columns, all the possible cross-correlation between $\theta_0$ and $\tau_0$ measurements of the PAR2007 campaign from DIMM, GS and MASS. We call this sample A. On the last column, we reported the cross-correlation of the same parameters between MASS and DIMM on a completely independent and richer statistical sample of nights (48 and 44 nights for $\theta_0$ and $\tau_0$ from a sample of 53 nights). We call this sample B. We performed these calculation in order to identify which parameters could be used to validate the model after its calibration. Looking at the GS vs. MASS comparison we note that, in spite of conclusions we achieved for the seeing in the previous paragraph, $\theta_0$ and $\tau_0$ seems well correlated. The agreement of $\theta_0$ can be explained by the fact that it is mainly affected by the turbulence in the high part of the atmosphere and the agreement of the seeing in layer 6 between MASS and GS is good. It is more difficult to explain the good correlation of $\tau_0$ joint with the not negligible discrepancies noted on the individual layers. In [10] we discuss extensively this argument and we provided an explanation to that. The important output of this analysis are that: (1) the distribution of $\theta_0$ and $\tau_0$ between MASS and DIMM is not the same on the two statistical samples (A and B) that we have just described. This means that it would be preferable to repeat cross-correlations between
different instruments on a richer statistical sample to achieve more precise insights on the topic of the absolute value of measurements; (2) we note that DIMM provides smaller values of $\tau_0$ and larger values of $\theta_0$ with respect to MASS and GS.

![Scatter plots of angle ($\theta_0$) and delay ($\tau_0$) measurements for different instrument pairs.](image)

**Fig. 1.** Scattering plot of the $\theta_0$ (top) and the $\tau_0$ (bottom) measurements provided by DIMM, GS and MASS. Simultaneous measurements only are considered. Observations and simulations are resampled on a time scale of 10 minutes. (a) DIMM-GS $\theta_0$ on 20 nights (from sample A); (b) MASS-GS $\theta_0$ on 12 nights (from sample A); (c) DIMM-MASS $\theta_0$ on 12 nights (from sample A); (d) DIMM-MASS $\theta_0$ on 48 nights (from sample B); (e) DIMM-GS $\tau_0$ on 20 nights (from sample A); (f) MASS-GS $\tau_0$ on 14 nights (from sample A); (g) DIMM-MASS $\tau_0$ on 14 nights (from sample A); (h) DIMM-MASS $\tau_0$ on 44 nights (from sample B).

### 5.2 Analysis strategy

Being that the MASS turbulence distribution revealed to be not sufficiently reliable for the model calibration, it has been decided to use only GS measurements for the model calibration. $\theta_0$ and $\tau_0$ from MASS and DIMM are used for the model validation. The sequence of actions is: (1) we perform the model calibration with respect to the GS measurements only (sample A); (2) we fix the free parameter i.e. the turbulent kinetic energy ($\text{TKE}_{\min}$); (3) we repeat the whole set of simulations on the 20 nights of the sample A with the same $\text{TKE}_{\min}$; (4) we perform a preliminary validation i.e. we quantify the model performances with respect to the calibration.
sample (GS, DIMM and MASS measurements - sample A); (5) we perform a model validation i.e. we quantify the model performances on a totally independent sample of measurements (sample B).

5.3 Model reliability

For lacking of space we present here only results on the most challenging item that is the model performances in reconstructing all the integrated astroclimatic parameters night by night for the validation sample of 53 nights. A forthcoming paper will treat in a more extensive way, the topic of the model performances in reconstructing the OT. Bias and RMSE of seeing, $\theta_0$ and $\tau_0$ for each night is calculated and then the cumulative distributions of all the parameters are built (Fig.2). After that, it is possible to estimate the preferred percentage, for example, the median and the first and third quartiles. From Fig.2 we retrieve that, for the seeing, the median value of the bias is negligible and the median value of the RMSE is 0.42 arcsec. For the $\tau_0$ and $\theta_0$ we have, in both cases, consistent biases between the two instruments (for the $\tau_0$ a bias of 0.95 ms and for $\theta_0$ a bias of 0.83 arcsec). As a consequence, the model presents a better or a worse bias and RMSE depending on the instruments that we can take as a reference. From a general point of view we can say that the dispersion of measurements vs. model is mostly comparable with the dispersion between observations from different instruments. Let’s consider also that, from bias and RMSE it is possible to retrieve the bias corrected RMSE called $\sigma = \sqrt{RMSE^2 - bias^2}$ that includes just the statistical errors.

An interesting output of this study concerns the model calibration. We could indeed infer that model performances would improve if a separated calibration is done for the summer and winter periods. Fig.3 shows the scattering plot of the $\tau_0$ as reconstructed by the model and measured
by the MASS (top) and by the DIMM (bottom). The same figure reports the scattering plots calculated on the total samples and on the sub-sample of the summer and winter time. Looking at the bias and the regression line, it appears clearly that results from the model are better (smaller bias and more centered regression line) in summer time. We note that the calibration sample belongs to the summer time (Nov./Dec.). We could prove that in winter time the model produces a little bit more turbulence that does that the slope of the regression line of the $\tau_0$ in winter time is more important than in summer. This tells us that a separated calibration performed in summer and winter would probably improve the model performances in winter time.

![Scattering plots](image)

**Fig. 3.** Scattering plot of the $\tau_0$ calculated on the validation sample of 48 nights as simulated by the model and observed by the MASS (top) and the DIMM (bottom). (a) Model/MASS for the total sample of nights; (b) Model/MASS on the subsample of summer time; (c) Model/MASS on the subsample of winter time; (d) Model/DIMM for the total sample of nights; (e) Model/DIMM on the subsample of summer time; (f) Model/DIMM on the subsample of winter time.

### 6 Conclusions

We summarize here the most relevant conclusions:

- We find a very satisfactory model performances in reconstructing the vertical stratification of temperature, wind speed and direction and relative humidity. Meso-Nh appears at present as the most reliable, practical and cheap solution to calculate the temporal evolution of the wind speed vertical stratification, useful, among other things, to predict and calculate the real time temporal evolution of $\tau_0$ (see more details on [1]).
- We find very good model performances in reconstructing temperature, wind speed and direction in the first 30 m at CP and CA. An horizontal resolution of $\Delta X=100$ m for the innermost domain is necessary to maintain the bias of the wind speed within 1 m·s$^{-1}$ (see more details on [9]).
- The original strategic plan for the model calibration has been changed because MASS measurements revealed not sufficiently reliable for a model calibration (see more details on [10]).
- A model validation has been performed for the first time with a totally independent sample of 53 nights. We found a general good agreement between the dispersion of observations and simulations and observations obtained with different instruments.
- We suggest a separated model calibration to be done for the summer and winter time.
- We proved that a richer statistical sample of measurements performed with more than one vertical profiler should be suitable (see [12]).
- We highlight that discrepancies of measurements we put in evidence in this contribution have no major consequences on the conclusions retrieved from the past site testing campaign performed for the ELTs. A dedicated discussion has been done in [10].
- A Phase B of MOSE is being discussed in these weeks and it will start soon. Among issues to be attacked we cite: the model performances using meteorological forecasts as input data; the definition of the architecture on which to run the model for an operational configuration and the automatization of the procedure.

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