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MOSE: operational optical turbulence forecasts for the E-ELT flexible scheduling

E. Masciadri, F. Lascaux, A. Turchi, and L. Fini

Istituto Nazionale di Astrofisica – Osservatorio Astrofisico di Firenze, L.go E. Fermi 5, 50125 Firenze, Italy, e-mail: masciadri@arcetri.astro.it

Abstract. In this contribution the most relevant results obtained in the context of a feasibility study (MOSE) undertaken for ESO are presented. The project lasted three years and its principal aim has been to define the performances of an atmospherical non-hydrostatical mesoscale model (Meso-NH) in forecasting all the main atmospherical parameters relevant for astronomical applications and the optical turbulence with the associated integrated astroclimatic parameters above Cerro Paranal (site of the VLT) and Cerro Armazones (site of the E-ELT). Considering the promising results obtained so far, this study sets-up the bases for the implementation on these sites of an automatic system to be run nightly in an operational configuration to support the scheduling of scientific programs as well as of instrumentation of the VLT and the E-ELT.

Key words. turbulence – atmospheric effects – Methods: data analysis – Methods: numerical – site testing

1. Introduction

MOSE is a feasibility study (Masciadri et al. 2013) whose main aims is evaluating the opportunity for the set-up of an automatic system for the forecast of: **(1)** all the classical atmospherical parameters (absolute temperature, potential temperature, wind speed and direction, relative humidity) that have some relevance in the astronomical context and **(2)** the optical turbulence i.e. the C_N^2 and the integrated astroclimatic parameters that derive from the C_N^2: seeing ε, isoplanatic angle θ_0 and wavefront coherence time τ_0.

The project has been applied above two major sites of the European Southern Observatory: Cerro Paranal (site of the VLT) and Cerro Armazones (site of the E-ELT). The method used by our approach is the modeling with a non-hydrostatical mesoscale atmospherical model called Meso-Nh (Lafore et al. 1998) for the atmospherical parameters and the Astro-Meso-Nh code for the optical turbulence and astroclimatic parameters (Masciadri et al. 1999).

We used the grid-nesting technique that permits to perform simulations with a set of imbricated domains achieving the highest resolution in the innermost domain on a limited surface around the point of interest. We selected two main model configurations: the so called 'standard configuration' having three domains and the horizontal resolution of the innermost domain equal to 500 m; the 'high-resolution configuration' made by five domains having the innermost domain with the horizontal resolution equal to 100 m (see Masciadri et al. 2013; Lascaux et al. 2013). Simulations are initialized and forced with atmospherical forecast and analyses coming from the General Circulations Models of the European Center for Medium Range Weather Forecasts (ECMWF) (see Masciadri et al. 2013, for details).

2. Feedbacks in terms of efficiency of observations

The predictions of the previously cited parameters can produce a not negligible number of beneficial feedbacks in terms of efficiency of observations and of management of the instrumentation.

Knowing in advance the value of the **surface temperature** is fundamental to eliminate the thermal gradient between the air in the dome and the primary mirror and therefore eliminate the 'mirror seeing' that is by far the most important contribution in the total turbulent energetic budget that affects the images quality at the focus of telescopes. Results of our analyses, done on a sample of 129 nights uniformly distributed along three solar years, indicate a median value of both BIAS and RMSE below 1 degree Celsius.

The **surface wind speed** is the main source of vibration of structures such as the primary mirror and even more of the adaptive secondary. When the wind speed is above a specific threshold the AO can not work at all. Results of our estimates, done on the same sample of 129 nights, indicate a median BIAS value below 0.93 ms^{-1} and a median RMSE value below 2.3 ms^{-1}.

The **surface wind direction** is the atmospheric parameter that is more easily correlated to the values of the seeing. Moreover, when the wind speed is strong, it is extremely important for the adaptive optics (AO) to know the wind direction close to the ground because the wind can have a negligible impact (when the wind flows along a perpendicular direction with respect to the line of sight) or alternatively a destructive impact (when the wind flows in front to the line of sight) depending on the wind direction. Results of our estimates, done on the same sample of 129 nights, indicate a median value of the BIAS $< - 7^{\circ}$, a median value of the RMSE $\sim$ [32-35]° and a relative error of the $RMSE_{REL} \sim$ [17-19] percent. Further details can be found in Lascaux et al. (2015). The vertical stratification on the whole 20 km of all the classical atmospherical parameters can also be predicted.

Among these the **wind speed vertical profile** is particularly critical because **(1)** is one of the main ingredients required to calculate the τ_0 and because **(2)** at present there are no instruments that are able to monitor the wind speed stratification during the night. Comparing model predictions with measurements from 50 radiosoundings (Masciadri et al. 2013) we proved that the reliability of Meso-Nh is so satisfactory that model estimates can be reasonably used as a reference to validate new instrumentation. This means, among other, that such a method is an extremely performant alternative for the wind estimates that can be used for the calculation of the temporal evolution of τ_0 done with whatever temporal sampling. We used at present a 2 minutes sampling equivalent to that of a typical vertical profiler of C_N^2.

Finally the **optical turbulence**, the mesoscale models represent the unique method that is able to provide 3D maps of the C_N^2 from which one can retrieve all the astroclimatic parameters integrated along whatever line of sight.

To show the usefulness of this tool of investigation we report here a few examples: **(1)** it might be possible to identify the temporal windows in which the AO can not work at all (when the seeing is too strong or the τ_0 is too weak); **(2)** it might be possible to identify the temporal windows in which the seeing is particularly good, conditions extremely favorable for high-contrast imaging observations such as search and characterization of extrasolar planets; **(3)** it might be possible to identify the temporal windows in which the seeing in the free atmosphere is extremely weak, conditions extremely favorable for observations with GLAO, MCAO and WFAO systems.

In conclusion, a single tool, can provide a huge amount of informations definitely critical for the astronomical observations.

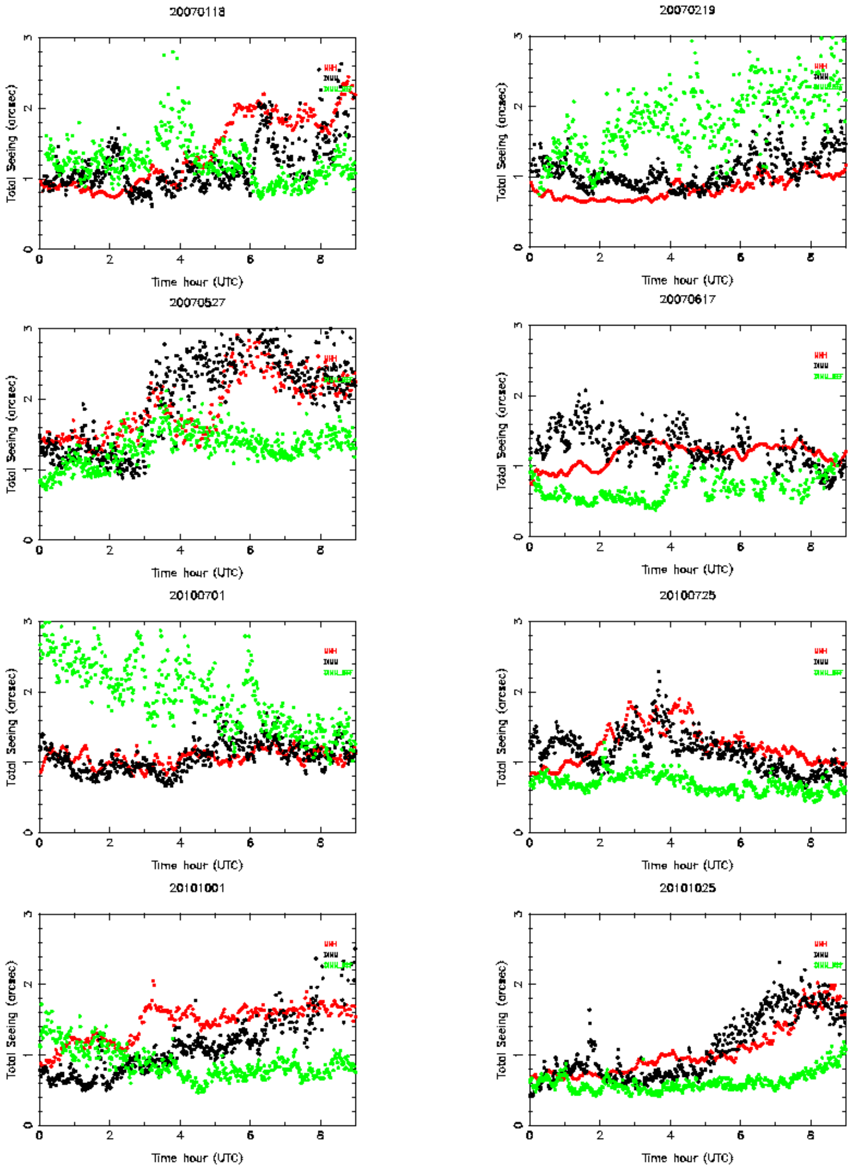

Fig. 1. Temporal evolution of the seeing during 8 nights at Paranal. Black points: DIMM measurements; green points: DIMM measurements of the previous night; red points: Astro-Meso-Nh model. The model estimates are well correlated to the measurements provided by the DIMM during the night that are significantly different from the DIMM measurements of the previous night. The DIMM of the previous night is shown to better appreciate the model reliability and the utility of the information provided by the latter.

3. Model performances in predicting the atmospherical parameters close to the ground

Detailed informations can be found in Lascaux et al. (2013, 2015). We remind here the important fact that the necessity of an horizontal resolution of 100 m for the innermost domain is necessary to guarantee a reliable predictions of the wind speed close to the ground. We proved indeed that a resolution of 500 m was not enough high and the smoothing of the orography was too much important.

4. Model performances in predicting the optical turbulence

Figure 1 shows the temporal evolution of the seeing as measured by a DIMM and estimated by the model during six different nights. In the same figures is shown also the DIMM measurements of the previous nights. It is evident the efficiency of the model in reconstructing the right trend of the optical turbulence. In a forthcoming papers we will publish the statistical results obtained for the seeing, the isoplanatic angle and the wavefront coherence time. A detailed study on the optical turbulence measurements used as a reference has been already published (Masciadri et al. 2014).

5. Conclusions

The most relevant results obtained in this feasibility study can be summarized in the following way: **(1)** We proved that we are able to forecast the atmospherical parameters and the optical turbulence with score of success that is already sufficiently high to definitely guarantee a beneficial impact on the service mode of top-class telescopes and the E-ELT. Results on the model performances in predicting atmospherical parameters close to the ground (Lascaux et al. 2013, 2015) and as well as their vertical stratification on the whole 20 km has been already published in Masciadri et al. (2013). Results on the OT will be published in a forthcoming paper. The model reliability in reconstructing the vertical wind speed profiles on 20 km was so performant that the model has been used as a reference to validate the estimate of the same parameter by GeMS, the first MCAO system that is routinely running. In a preliminary study (Neichel et al. 2014) we proposed to use simultaneously GeMS and Meso-Nh to improve the efficiency of the AO system in reconstructing the speed of the turbulent layers. **(2)** The MOSE final review is planned for autumn 2015. A negotiation with ESO is planned afterward for the implementation on Paranal and Armazones of the automatic operational system to be used for the service mode. **(3)** Besides to MOSE, we are also involved in a similar project for LBT (called ALTA). The milestones of this project are summarized in the following: **(a)** within June 2016 nightly automatic forecasts of the atmospherical parameters are planned; **(b)** within December 2016 nightly automatic forecasts the optical turbulence forecasts are planned.

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