SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Optical turbulence modelling for Extremely Large Telescopes (ELTs).
Computer Project Account:	SPITFOT
Start Year - End Year :	2014 - 2016
Principal Investigator(s)	Elena Masciadri
Affiliation/Address:	INAF-Osservatorio Astrofisico di Arcetri Largo E. Fermi 5, 50125, Firenze, Italy
Other Researchers (Name/Affiliation):	Dr. Alessio Turchi INAF-Osservatorio Astrofisico di Arcetri Largo E. Fermi 5, 50125, Firenze, Italy Dr. Franck Lascaux INAF-Osservatorio Astrofisico di Arcetri Largo E. Fermi 5, 50125, Firenze, Italy

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The project is centred on the employment of a numerical mesoscale model (Meso-NH) for the forecast of the optical turbulence in astronomical applications. Optical turbulence is the main source of deterioration of the image quality for ground-based telescopes. We are, at present, mainly involved in two projects:
(1) We have been in charge of a feasibility study (MOSE) for the European Southern Observatory (ESO) focused on the optical turbulence forecast at the two main ESO sites for ground-based facilities that are conceived to work in the near infrared and infrared wavelengths: Cerro Paranal (site of the Very Large Telescope) and Cerro Armazones (the selected site for the European Extremely Large Telescope E-ELT). Both sites are located in the north part of Chile.
(2) The second project (ALTA), supported by the Large Binocular Telescope (LBT) Consortium, aims to set-up an automatic and operational forecast system of the optical turbulence at Mt. Graham (Arizona) to support astronomical observations and scheduling of instrumentations to be placed at the focus of the telescope.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

No major problems encountered

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

No problems with the user support team (very efficient and competent).
Concerning the progress and final reports I am wondering if it is not possible to keep the progress report a little bit lighter with just a description of problems (if any) and to deserve to the final report a more auto-consistent analysis of the results of the project including the list of papers. I understand the necessity of the ECMWF Committee to judge the outputs of the individual projects. However, I think that it should be easier and more efficient to collect published papers on a time scale of three years. This might in part replace the writing of a report. May be this solution would get simpler the life of the PI and provide a satisfactory and exhaustive feedback for the ECMWF Committee who is supposed to monitor the projects.

Summary of results

(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

We summarized here the main conclusions we obtained at conclusion of the project. We refer to the main goals described in the project submitted on 2014 listed in 6 points.

(1) The most important goal of our project was to improve the model performances in reconstructing a more realistic spatio-temporal variability of the optical turbulence in the free atmosphere. This goal has been achieved with the development of a new algorithm for the C_N^2 described in the paper (18) Masciadri et al., 2017, MNRAS. The Astro-Meso-Nh model has been calibrated and then validated above the site of Cerro Paranal on a rich statistical sample of 89 nights uniformly distributed on 2010 and 2011 and totally independent from the sample used to calibrate the model. A detailed analysis focused on the three most relevant astroclimatic parameters (seeing, isoplanatic angle and wavefront coherence time) has been carried out to quantify the efficiency of the model in predicting those parameters. The method we followed implied the analysis of standard statistical operators such as bias, RMSE and sigma that put in evidence statistical and systematic errors. Besides we calculated the contingency tables of seeing, isoplanatic angle and wavefront coherence time with the associated statistical operators (percent of correct detection, probability of detection in different ranges identified by the tertiles of the climatological distribution) that haps in quantifying the model performance in a post-processing approach. Results of this analysis performed on the site of the Very Large Telescope have been published on paper (18). We obtained a probability of detection of the wavefront coherence time larger than the third tertile that is in the [65-78] %. A probability of detection of the detection of the isoplanatic angle larger than the third tertile that is of the order of 58-60% and the probability of detection of the seeing weaker than 1" (critical value from an astronomical point of view) of the order of [62-72] %.

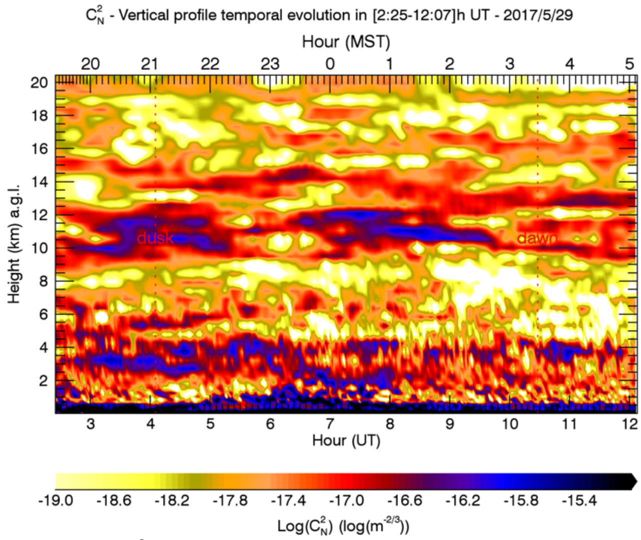

Fig.1: temporal evolution of the C_N^2 during the night of 29/5/2017 above Mt.Graham. The profile is extended on 20 km above the ground.

The same algorithm has been applied to the study we performed above Mt.Graham in the study we performed for LBT. Fig.1 shows the example of the temporal evolution during one night of the C_N^2 extended on the whole 20 km above the ground above Mt.Graham. Fig.2 show the temporal evolution of the isoplanatic angle all along the same night in which it is well visible the realistic temporal variability. The isoplanatic angle is the parameter that is more sensitive to the turbulence in the high part of the atmosphere. For Mt.Graham we were forced to develop a different method to calibrate the model because of the different nature of measurements we disposed as a reference. We do not enter in details of this issue because was not part of the main goals we had indicated in the project but it is worth to mention that this method takes advantage of measurements coming not only from a vertical profiler such a Generalized Scidar (GS) but also from a monitor such a DIMM. This fact would highly probable get more efficient the calibration of model also in other sites because it is easier to collect a large number of measurements from a monitor such a DIMM than from an instrument such as a GS that requires a telescope of 1m-1.5m at least.

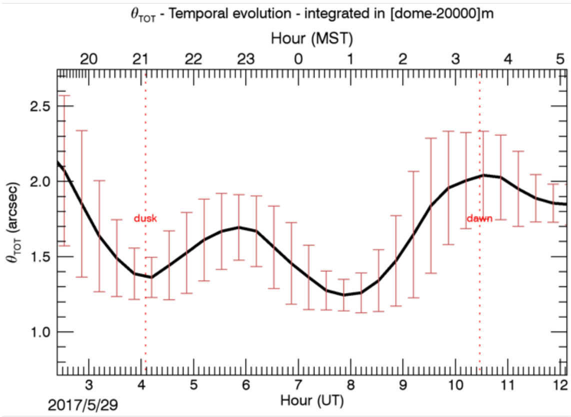

Fig.2: Temporal evolution of the isoplanatic angle during the night of 29/5/2017 above Mt.Graham.

(3) For what concerns the atmospheric parameters (temperature, wind speed and direction and relative humidity) we finally performed an extended study on very rich statistical samples of nights above three sites: Cerro Paranal (Chile, site of the VLT) with 129 nights, Cerro Armazones (Chile, site of the European Extremely Large Telescope) with 42 nights plus 53 nights with different instrumentation and Mt. Graham (Arziona, site of the Large Binocular Telescope) with 144 nights. For the case of Paranal and Mt.Graham we published two peer-reviewed papers (Lascaux et al., 2015 (17) and Turchi et al. 2017 (20)). For Cerro Armazones we refer to a report of the feasibility study we performed for ESO. The model provided in general excellent results with performances definitely within the accuracy and precision required. At the same time, we observe some difference above the sites as indicated in the progress report (2016).
Among these differences we observed that the wind direction RMSE and sigma above Mt.Graham was substantially better than above Cerro Paranal (even if the performances above these last two sites were already very good). We note, however, that we cannot say at present which is the cause of this result: it might be the different quality of initialization data, the different topography or also the fact that the model grids distribution was a little different in the three cases. We used a vertical grid having a first grid point of 5 m above ground at Paranal and Armazones and 20 m above ground Mt.Graham. The atmospheric flow is therefore subjected to a different stress/friction with the ground and the the Mt. Graham case with a 20m grid size presents certainly less stresses. We were forced to use 5 m at Paranal because this is the height of the GS measurements used in this site.
Another difference was observed on the relative humidity (RH). In all the three sites, we found that the model can well discriminate the high and low relative humidity (RH). However, the correlation is definitely better above Mt.Graham. This is due to the fact that Paranal is a an extremely dry site with a median value of only 12 %. The model easily detects high RH but it showed more difficulties in detecting the tight RH when the values are larger than 70 %. This is translated in a more modets value of POD_3 when the threshold is equal to the third tertile of the climatologic distribution (72 %). Results are in any case very satisfactory as shown in Turchi et al. 2017 – Fig.7.

(5) For what concerned the model performances in reconstructing the atmospheric parameters as a function of different delay time we completed a study on 129 nights at Cerro Paranal using as an initialization data analyses and forecasts calculated at 12:00 of the day (J-2) at 30h with forcing at 36h, 42h and 48h. From a statistic point of view it has been observed a shallow decreasing of the model performances but still acceptable. Fig. 3 and Fig.4 report the results obtained for the temperature at 30 m in which the RMSE passed from 1.02 in the case in which we initialize the model with the analyses to a RMSE=1.09 ms^{-1} when it is initialized with forecasts. The temperature at 2 m passed from a RMSE = 0.99 ms^{-1} to a RMSE = 1.09 ms^{-1}. For the wind speed (Fig.5 and Fig.6) at 10 m we pass from a RMSE=2.47 ms^{-1} to a RMSE =2.73 ms^{-1} and for the wind speed at 30 m we pass from a RMSE = 2.70 ms^{-1} to a RMSE =2.96 ms^{-1}. This tells us that the configuration chosen for the model still provides satisfactory results for an operational application.

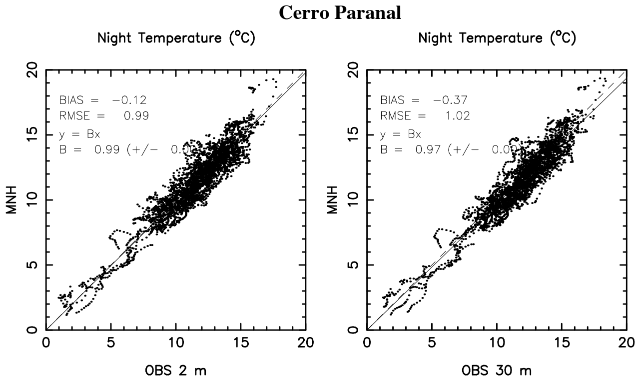

Fig.3: Scattering plot of the temperature observed and reconstructed by the model at 2 m and 30 m above ground at Paranal. The horizontal resolution of the innermost domain is equal to 500 m. Inizialization data: ECMWF analyses.

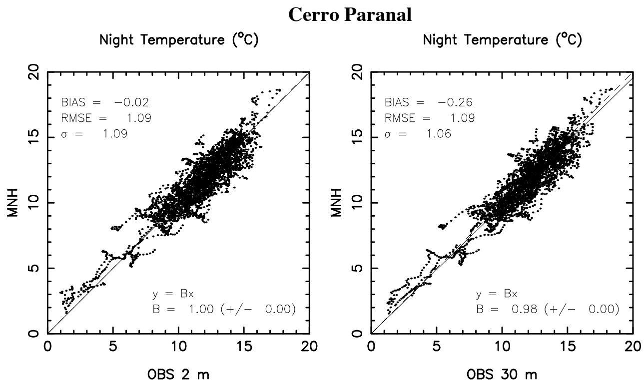

Fig.4: Scattering plot of the temperature observed and reconstructed by the model at 2 m and 30 m above ground at Paranal. The horizontal resolution of the innermost domain is equal to 500 m. Inizialization data: ECMWF forecasts.

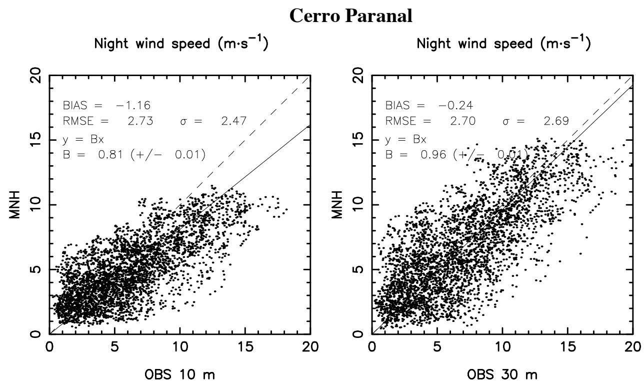

Fig.5: Scattering plot of the wind speed observed and reconstructed by the model at 10 m and 30 m above ground at Paranal. The horizontal resolution of the innermost domain is equal to 100 m. Inizialization data: ECMWF analyses.

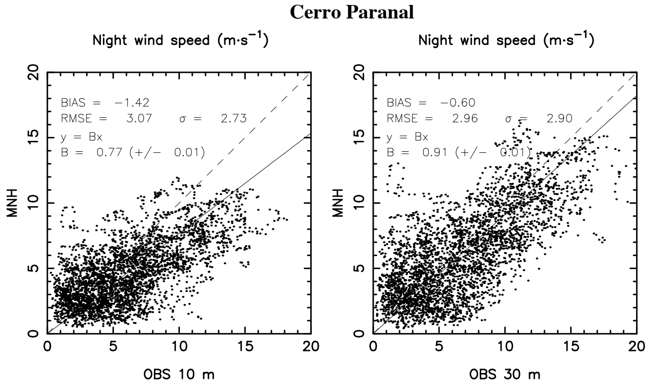

Fig.6: Scattering plot of the wind speed observed and reconstructed by the model at 10 m and 30 m above ground at Paranal. The horizontal resolution of the innermost domain is equal to 100 m. Initialization data: ECMWF forecasts.

We had not the time to well develop points (2) and (4) that we had indicated in the project. The overestimation of the turbulence close to the ground (2) when the horizontal resolution of the innermost domain is higher than 500m has been temporarily shifted to a minor priority issue because we think that this is highly probable related to the fact that the turbulence scheme is at the limit of its validity. The topic is definitely interesting but the other points had a higher level of priority. Point (4) dealt about the possibility to identify the origin of the "bad forecast". This is certainly an important item. As for point (2) we had simply shifted to a minor priority with respect to other items. We highlight that we used in general all the SBU we had asked for at the beginning of the year. In some cases we asked for supplementary computational resources. We intend therefore simply take care about these two items in successive projects.

On the other side, we tackled a few other elements that arose up in the meanwhile and revealed more timely considering the new arrival of the Large Binocular Telescope Interferometry (LBTI) technique that is particularly sensitive to the presence of water vapour in the atmosphere. From one side, we studied the model performances in reconstructing the precipitable water vapour (PWV) and the stratification of the mixing ratio comparing model predictions with measurements obtained with a very precise radiometer (LHATPRO) installed at the VLT and validated by the European Southern Observatory (Kerber at al. 2012, SPIE, vol. 8446, 84463N-1). The study is still on-going but we presented recently to the Conference AO4ELT 5th Edit. (26-30 June), Tenerife, Canary Islands, promising results obtained on a sample of 60 nights. The PWV provided by the model is definitely well correlated for such a dry site and results are definitely satisfactory for applications to ground-based astronomy. In Fig.7 is shown the scattering plots of observed and simulated PWV for values within 6 mm and the RMSE is equal to 0.66 m that is definitely promising.

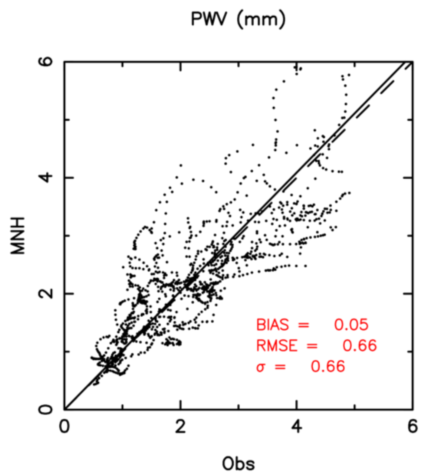

Fig.7: Scattering plot of the PWV measured by a radiometer (LHATPRO) and simulated by the Meso-nh model on a sample of 60 nights above Cerro Paranal.
The good model performances in reconstructing the vertical stratification on the whole 20km i.e. also in the low part of the atmosphere where predictions from GCMs are less reliable due to the limited horizontal resolution pushed us in developing a study aiming to validate a technique of measurement of the wind speed realized with optical instruments and set-up by colleagues of the LAM (Labroatoire d'Astrophysique de Marseille) and Universidad Pontificia, Chile using our simulations as a reference. Considering the difficulty in getting automatic these measurements and considering the excellent model performances, we are envisaging to use the prediction of the model not only for an application to the operational forecast but also as an input of an optical instrument. This is the first multi-conjugated adaptive optics system running on sky at present on a 8-10 m class telescope. A paper is in progress on this topic (Masciadri et al. 2017). We finally proved with a very preliminary test that we should be able to detect turbulence layers in the 20 km above the ground with a higher vertical resolution than that obtained with the current model configuration (~600km in the free atmosphere). This is a very crucial topic for the ground-based astronomy of the next decades (see Future Plans).

List of publications/reports from the project with complete references

MNRAS: Monthly Notices of the Royal Astronomical Society

Peer-reviewed Journals

20) Masciadri, E., Neichel., B., Guesalaga, A., Turchi, A., Sivo, G., - Towards an automatic system for wind speed and direction profiling with GeMS, 2017, **MNRAS**, in preparation
19) Turchi, A., Masciadri, E., Fini, L. - Forecasting surface layer atmospheric parameters at the LBT site, 2017, **MNRA**S, 466, 1925
18) Masciadri, E., Lascaux, F., Turchi, A., Fini, L. - Optical turbulence forecast: ready for an operational application, 2017, **MNRAS**, 466, 520
17) Lascaux, F., Masciadri, E. Fini, L., Forecast of the surface layer meteorological parameters at Cerro Paranal with a mesoscale atmospherical model; **MNRAS**, 2015, 449, 1664
16) Masciadri, E., Lombardi, G., Lascaux, F., *On the comparison between MASS and generalized SCIDAR techniques*, **MNRAS**, 2014, 438, 983
15) Masciadri, E., Lascaux, F., Fini, L., *MOSE: operational forecast of the optical turbulence and atmospherical parameters at European Southern Observatory ground-based sites – I. Overview and vertical stratification of atmospheric parameters at 0-20km*; **MNRAS**, 2013, 436, 1968
14) Lascaux, F., Masciadri, E., Fini, L., *MOSE: operational forecast of the optical turbulence and atmospherical parameters at European Southern Observatory ground-based sites – II. Atmospheric parameters in the surface layer 0-30m;* **MNRAS**, 2013, 436, 3147
13) Masciadri, E., Lascaux, F., Fuensalida, J., Lombardi, G., Vazquez-Ramio, H, *Recalibrated generalized SCIDAR measurements at Cerro Paranal (the site of the Very Large Telescope);* **MNRAS**, 2012, 420, 2399

No-peer reviewed Journals
We indicated with xx) conferences we attended but for which we have not yet written papers for Proceedings.

xx) Turchi, A., Masciadri, E., Fini, L., Kerber, F. **-** Water vapor Forecast for LBTI (LBTO) and VISIR (VLT), Conference AO4ELT 5th Edit., 26-30 June, 2017, Tenerife, Canary Islands

xx) Masciadri, E., Turchi, A., Milli, J., Sauvage, J.-F., Fusco, T., Neichel, B., Mouillet, D. - Towards forecasts of atmospheric parameters and optical turbulence for ground-based telescopes operation Conference AO4ELT 5th Edit., 26-30 June, 2017, Tenerife, Canary Islands
12) Veillet, C., Ashby, D.S., Christou, J., Hill, J., Little, J., Summers, D., Wagner, R.M., Masciadri, E., Turchi, A., - LBTO's long march to full operation: step 2, 2016, Proc. SPIE 9910, Observatory Operations: Strategies, Processes, and Systems VI, 99100S, doi: 10.1117/12.2234570
11) Masciadri, E., Lascaux, F., Turchi, A., Fini, L. - Operational optical turbulence forecast for the service mode of top-class ground based telescopes, 2016, Proc. SPIE 9909, Adaptive Optics Systems V, 99090I, doi: 10.1117/12.2231196
10) Masciadri, E., Neichel, B., Guesalaga, A., Turchi, A. - Towards an automatic system for monitoring of C_N^2 and wind speed profiles with GeMS, 2016, Proc. SPIE 9909, Adaptive Optics Systems V, 99093B, doi: 10.1117/12.2231887
9) Turchi, A., Masciadri, E., Fini, L. - Forecasts of the atmospherical parameters close to the ground at the LBT site in the context of the ALTA project, 2016, Proc. SPIE 9909, Adaptive Optics Systems V, 990938, doi: 10.1117/12.2231273
8) Masciadri, E., Lascaux, F., Fini, L., *Dealing with the forecast of the optical turbulence as a tool to support astronomy assisted by AO facilities*; Journal of Physics, Conferences Series, 2015, 595, DOI: 10.1088/1742-6596/595/1/012020
7) Lascaux, F., Masciadri, E., Fini, L., *MOSE: verification of the Meso-Nh forecasts of the atmospheric surface parameters at Cerro Paranal and Cerro Armazones using contingency tables*; SPIE, 2014, id. 914865
6) Neichel, B., Masciadri, E., Guesalaga, A., Lascaux, F., Bechet, C., *Towards a reliability assessment of the C_N^2 and wind speed vertical profiles retrieved from GeMS*; SPIE, 2014, id.914863
5) Masciadri, E., Lascaux, F., Fini, L., *MOSE: a feasibility study for the prediction of the optical turbulence and meteorological parameters at Cerro Paranal and Cerro Armazones*; AO4ELT3, 2013, DOI: 10.12839/AO4ELT3.13219
4) Lascaux, F., Masciadri, E., Fini, L., *MOSE: meso-scale prediction of near-ground meteorological parameters at ESO sites (Cerro Paranal and Cerro Armazones);* AO4ELT3, 2013, DOI: 10.12839/AO4ELT3.13217
3) Masciadri, E., Rousset, G., Fusco, T., Basden, A., Bonifacio, P., Fuensalida, J., Robert, C., Sarazin, M., Wilson, R., Ziad, A., *A roadmap for the new era turbulence studies program applied to the gorund-based astronomy supported by AO*; AO4ELT3, 2013, DOI: 10.12839/AO4ELT3.13542
2) Masciadri, E., Lascaux, F., MOSE: a feasibility study for optical turbulence forecast with the Meso-Nh model to support AO facilities at ESO sites (Paranal and Armazones); 2012, SPIE, 8447, id. 84475A
1) Lascaux, F., Masciadri, E., 2012, *MOSE: zooming on the Meso-Nh mesoscale model performances at the surface layer at ESO sites (Paranal and Armazones);* SPIE, 8447, id. 84475B

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

We intend to continue on this research line pushing on a few new aspects:
- We intend to evaluate the possibility to use higher vertical resolution to arrive to discern turbulent layers as thin as 150m in the whole 20 km above the ground. This implies probably new calibration procedures for th e model. The possibility to use that in an operation configuration should be very important for application to the most sophisticated techniques of adaptive optics i.e. the wide field AO. The most complex instruments conceived for the new generation instruments of the Extremely Large Telescopes will be sensitive to distribution of the turbulence in the atmosphere and not only to the total integral value of the turbulence.

Besides a pretty high level of accuracy in detecting position and thickness of thin turbulence layers will be necessary.

- We are also interested in evaluating technique of Kalman filter to improve the model performances taking advantage of measurements available in situ.
- It should be our intention to test the model on day time. We are collecting measurements done in day time in astrophysical context that can be used as a reference and this would get possible a model validation. Day time turbulence condition are expected to be different from those in night time, particularly in the boundary layer. A model that is able to predict optical turbulence in night as well as day conditions might definitely enlarge the fields of application of this technique.
- In perspective, we are interested in evaluating the possibility to use the Ensemble Predictive Systems (EPS).