Optical turbulence forecast with non-hydrostatic atmospherical meso-scale models

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Abstract. All observing operations for the astronomy of the third millennium are planned to be done in Service Mode at the new generation ground-based facilities (ELTs). This will permit to select, in a dynamic queue (called *flexible-scheduling*), the most suitable observing program and instrumentation for a particular temporal window as a function of the status of the optical turbulence that mainly affects the wavefront perturbations. It follows that, to optimize the flexible-scheduling of scientific observations, the optical turbulence forecast is mandatory, particularly when observations concern adaptive optics (AO) facilities. Without such a tool the risk is that all potential advantage provided by an AO facility can be neutralized. In this contribution we review the principle of the technique of the optical turbulence prediction with non-hydrostatic atmospherical meso-scale models as well as its most important challenges. Besides we present the progress we recently obtained applying these models to top class astronomical sites.

1 Introduction

It is known that most of the scientific programs, associated to the most challenging scientific goals, require frequently excellent optical turbulence (OT) conditions to be carried out. The traditional queue system, that is based on the quality of the scientific program but that does not take into account the OT conditions, leads necessarily to a paradox: the higher is the scientific challenge of a scientific program, the lower is the probability to complete the program itself. From this we derive that the Service Mode, that takes into account the status of the OT, is mandatory to optimize the exploitation of the ELTs. However, to implement a Service Mode we need to forecast the OT and to know its status at different delayed times ΔT with respect to time in which the prediction is performed. The optimization of the *use* of a ground-based facility has therefore serious implications on the final scientific impact of the facility itself. We note, moreover, that the cost of a night of observation is of the order of hundreds of KDollars. The implementation of an OT forecast system leads therefore to a not negligible rationalization of costs versus scientific feedbacks. We remind also that, for evident statistical reasons, the advantage of the Service Mode can be fully achieved only if most of the available observing time is scheduled in this mode. For all these reasons ELTs plan to have, in their baseline configuration, permanent instruments located at different focal stations. It has been estimated that, at the E-ELT, the typical time required to switch the beam from an instrument to another is of the order of 10-20 minutes [1]. This is therefore the final minimal time-scale in terms of OT prediction that we can take as a reference. All these premises lead to a twofold main conclusion: **(1)** The success and the feasibility of the ELTs relies on our ability in forecasting the OT. **(2)** The fact that the meso-scale models are the unique tool of investigation that can achieve such a scientific tool, gets these studies very timing.

The goal of this contribution is to try to condensate and get more easily understandable by the adaptive optics community the most important concepts related to this topic and report the most recent and advanced results we obtained in the field. A more extended review can be found in [2].

A meso-scale model can reconstruct 3D maps of the C_N^2 in a region of a few kilometers around the telescope. The C_N^2 is the constant of the structure function of the refractive index valid an the interior of the inertial regime of the Kolmogorov model. The parameters that can be simulated by 3 dimensional maps are all the classical atmospherical parameters (the wind intensity, the pressure, the temperature, the relative humidity, the dynamic outer scale, ...) and the C_N^2 that depends on all of the parameters previously cited. The parameters that can be reconstructed and characterized with 2 dimensional maps derive all from the integration of the optical turbulence over the whole atmosphere (~20 km) times a function depending on (the height from the ground h, the dynamic outer scale L_0 and the wind speed

V) with different power laws ([2]-Eq.(3)). These parameters are all the main astroclimatic parameters i.e. the seeing ε, the wavefront coherence time τ_0, the isoplanatic angle θ_0, the scintillation rate σ_I^2, the spatial coherence outer scale $\mathcal{L}_0$, the optimal heights at which to conjugate the deformable mirrors, the isoplanatic angle θ_M for the MCAO.

First C_N^2 vertical profiles obtained with a non-hydrostatic atmospherical meso-scale (Meso-NH) in application to the astronomy have been provided by Masciadri et al. [3],[4]. The optical turbulence has been introduced in the Meso-Nh model with a dedicated parameterization for the C_N^2 ([3]) (Astro-Meso-Nh code). In those papers, we proved the possibility to reconstruct the C_N^2 profiles above astronomical sites from a qualitative point of view (the model could reconstruct an OT vertical distribution that well matched the observed one) and from a quantitative point of view (the integral of the OT along the 20 km from the ground estimated by the model could well match the observed one). At the same time we indicate the road-map for further progresses on the numerical technique. On 2001 we proposed a method to calibrate the model ([5]) to eliminate systematic errors of the model and to improve its reliability and a few years later we provided a statistic validation of the model ([6]) (using such a calibration procedure) comparing numerical calculations with measurements provided by a Generalized Scidar. The most relevant result to be retained obtained in that paper is that the discrepancy between measurements and numerical calculations revealed to be comparable to the discrepancies between observations done with different techniques and instruments and it was of the order of 20-30 %. This permitted us to perform the first seasonal variation study of the vertical distribution of the OT ([7]) on 20 km from the ground ever done so far using the model in autonomous way. Interesting a few years later ([8],[9]), similar studies done with measurements confirmed conclusions we achieved in 2006 ([7]) showing the incredible great potentiality of the numerical technique.

2 Why do we need non-hydrostatic atmospheric meso-scale models ?

The typologies of models that can be used to study thermodynamic evolution of the earth's atmosphere are: the General Circulation Models (GCM), the non-hydrostatic meso-scale models, the models for Large Eddy Simulations (LES) and the models for Direct Numerical Simulations (DNS). They differ in their resolution and, as a consequence, also in the extent of the typical domain of the atmosphere that can be reconstructed by these models. We deduce that each of these typologies of model is dedicated to resolve phenomena of different nature and that the numerical approach as well as the physics described inside each of these models is done following completely different approaches.

The OT can not be resolved by the GCMs because its spatio-temporal fluctuation of the OT is much smaller (order of centimeter/meter) than the typical resolution of the GCM (~16 km). With the DNS the OT can be completely resolved but we can not forecast it because we definitely miss the link with initialization data i.e. with the evolution of the atmospheric flow at large spatial scales. The meso-scale models represent the right trade-off that permits to reconstruct the OT maintaining the link with the external spatio-temporal evolution of the atmospheric flow. The OT is completely parameterized in the meso-scale models. With the LES the OT is partially resolved and partially parameterized. In principle it is possible in perspective to use the LES to improve the resolution of the simulations if initialized with outputs coming from meso-scale models.

3 Parameterization

The basic idea of the parameterization is to provide a solution to the problem of the numerical representation in a model characterized by a finite resolution of all the parameters, such as the dynamic and optical turbulence, that evolve at spatial and temporal scales that are much smaller than the resolution of the model itself. Considering the whole set of models typologies we can say that, in terms of resolution in space, we pass by the order of centimeter (for the DNS) up to a maximum resolution of 16 km (for the GCMs). In time we have a jump from the millisecond to a scale of the order of minutes/hours.

The meso-scale models technique consists on reconstructing the atmospheric evolution on a region around a telescope of a few tens of kilometers; the atmospheric model is linked with an digital elevation

model (DEM) with a horizontal resolution of at least 500m (in any case sub-kilometric resolution) and the parameters that we intend to study, the OT in our case, is parameterized. This means that the fluctuations of the microscopic quantity of the parameter ξ is expressed as a function of the gradient of the same parameter but space averaged over a greater region:

$$\overline{w'\xi'} = K_\xi \frac{\partial \overline{\xi}}{\partial z} \tag{1}$$

K_ξ is the exchange coefficient, a constant expressing the properties of the turbulent flux in the whole turbulent layer. A detailed description of the optical turbulence parameterization for the Astro-Meso-Nh code is reported in [3]). The important thing to retain is the law that relates the C_N^2 to three macroscopic quantities:

$$C_N^2(h) \sim \phi_3(h) \cdot L_0(h)^{4/3} \cdot \left(\frac{\partial \overline{\theta(h)}}{\partial h} \right)^2 \tag{2}$$

where θ is the potential temperature, L_0 is the dynamic outer scale and ϕ_3 is the a thermo-stability term proportional to the inverse of the Prandtl number. The mixing length ([10]) is a key parameter for the numerical representation of the C_N^2 and it corresponds basically to the dynamic outer scale. It is defined in the following way in the model: at each height h, a particle having a fixed kinetic energy E can move upward and downward being stopped by the buoyancy forces produced by the atmospheric stability. The size of such a path represents the mixing length. When there is just dynamic turbulence we have a neutral regime i.e. the gradient of the potential temperature is equal to zero. To have optical turbulence we need a simultaneous gradient of the wind speed and the potential temperature different from zero.

4 How do we forecast the optical turbulence ?

We can use a toy model, that is an extremely simplified schema, to explain the principle for forecasting the OT. Let's take the time axis and let's imagine to be at 12 hour on the day J. We take then the meteorological forecast, calculated at 12 and 18 hours, that is at 0 and 6 hours of the day (J+1). At these two instants we can know the atmospherical state at the boundaries and on the inner part (cube) of the meso-scale model. Passing by a temporal interpolation we can know the state of the atmospheric flow at the boundaries and in the inner part of the model at each time step. If we start our simulation at 0 hours of the day J+1, and we link our simulations with the DEM, the temporal evolution of the optical turbulence is a real forecast of the OT because the atmospheric flow in the inner part of the cube (i.e. the region reconstructed by the model) is in constant thermodynamic balance with the external atmospherical flow. This example represents a OT forecast calculated at 12 hours. The procedure is, from a practical point of view, more complex than this toy model because it takes into account two more main elements: **(1)** the simulations are forced each six hours (the synoptic hours) with successive forecast taken from the ECMWF that are available in the meanwhile. **(2)** the simulations are performed using the grid-nesting technique that permits to increase the resolution on specific portion of the domain using a set of imbricated models (typically three or four models).

5 Main relevant recent results: ForOT

In this contribution we will focus our attention on the most recent results we obtained in the framework of the ForOT project ([11]) that aimed to study two sites: Mt. Graham site of the Large Binocular Telescope (LBT) and the internal Antarctic Plateau (more precisely on South Pole, Dome C and Dome A). The main scientific goals of ForOT were: the forecasting the OT for the implementation of the flexible scheduling at Mt. Graham, and the study of a site independent model calibration for sites searches above the Internal Antarctic Plateau. Basically we tried to attack two different aspects of the modeling: the ability in predicting and the ability in discriminating sites with different characteristics.

Table 1. Median values and standard deviation of the total and free atmosphere seeing measured and reconstructed by the model above Dome C. Statistical sample of 15 nights (see [14]).

	OBS		MODEL	
	ε_{TOT}	ε_{FA}	ε_{TOT}	ε_{FA}
median value	1.6	0.30	1.70	0.30
σ	0.70	0.70	0.77	0.67

5.1 Internal Antarctic Plateau

Above Dome C we could validate the model using, as a reference, the whole set of measurements done in winter time by Trinquet et al. ([12]) that consists on 15 C_N^2 profiles measured in different nights distributed uniformly in the June-September period i.e. the winter time period in the Antarctic continent. The key parameters that define the C_N^2 features above this continent are the typical thickness of the surface layer that we know to be particularly thin in this region, the total seeing (ε_{TOT}) and the seeing in the free atmosphere (ε_{FA}). Using two different horizontal resolution of the model (1km and 100 km) we obtained ([13],[14]) a median value of the surface layer h_{sl} equal to 44 m and 68 m compared to a measured h_{sl} equal to 35 m (see [14], Table 2). We concluded that the high resolution mode (1 km) permitted to achieve a very good correlation between simulations and measurements (an extended discussion can be found on [13]). The median value of simulations was slightly higher than the observed one but the median value was within the typical and natural dispersion of measurements of the order of $\sim$ 20 m. If we look at the results obtained with the total and the free atmosphere seeing (Table 1) we observe that the correlation between the median values (observed and reproduced with the model) are extremely good (see [14]-Fig.3).

Once the model has been validated above Dome C we repeated the same set of simulations in the same nights used to validate the model above Dome C also above Dome A and South Pole ([15]). In Table 2 are reported the median values obtained for the surface layer h_{sl}, the total and free atmosphere seeing in the case of the high resolution (1 km) mode i.e. the mode providing a good reconstruction of the thickness of the turbulence surface layer. We observe that the median surface layer h_{sl} at Dome A is almost comparable to that at Dome C while at South Pole the median value of h_{sl} is 165 m i.e. much thicker.

Table 2. Median values of the surface layer h_{sl}, seeing in the free atmosphere (ε_{FA}) and total seeing (ε_{TOT}) at Dome C, Dome A and South Pole. The associated standard deviation (σ) and the statistical error ($\sigma/\sqrt{N}$) are also reported. *(Extracted from [15]).*

	h_{sl} (m)	σ	$\sigma/\sqrt{N}$	ε_{FA} (arcsec)	σ	$\sigma/\sqrt{N}$	ε_{TOT} (arcsec)	σ	$\sigma/\sqrt{N}$
Observations - Dome C	35.3	19.9	5.1	0.30	0.70	0.20	1.60	0.70	0.20
Meso-NH - Dome C	44.2	24.6	6.6	0.30	0.67	0.17	1.70	0.77	0.21
Meso-NH - Dome A	37.9	30.2	8.1	0.23	1.08	0.28	2.37	1.03	0.27
Meso-NH - South Pole	165.0	67.3	17.4	0.36	0.43	0.11	1.82	0.90	0.23

From Table 2 we deduce that Dome A presents the best seeing in the free atmosphere. On the other side, Dome A shows the greatest total seeing. In other words, at Dome A, we have the thinner surface layer but inside this layer we obtain the greatest seeing. We note that our estimates are in a very good agreement with previously measurements done at South Pole [16] that estimated a median h_{sl} = 220 m, a total seeing ε_{TOT}=1.86 arcsec and a free atmosphere seeing ε_{FA}=0.37 arcsec. The surface layer was indeed significantly thicker at South Pole than above the two summits (Dome C and Dome A). Fig.1 shows the median C_N^2 profile, with different zooming near the ground, obtained for the 15 nights above the three sites. It is well visible the different shape of the turbulence decay near the ground above the three sites. We remind that these are the first estimates ever done so far of the optical turbulence in the free atmosphere above Dome A. Our results confirm expectations from the whole scientific community concerning this site that appears, visibly, as an excellent site. We derive from our results that Dome A

has two main advantages with respect to Dome C: a thinner surface layer and a weaker wind speed in the high part of the atmosphere [17] that triggers a weaker seeing in the free atmosphere.

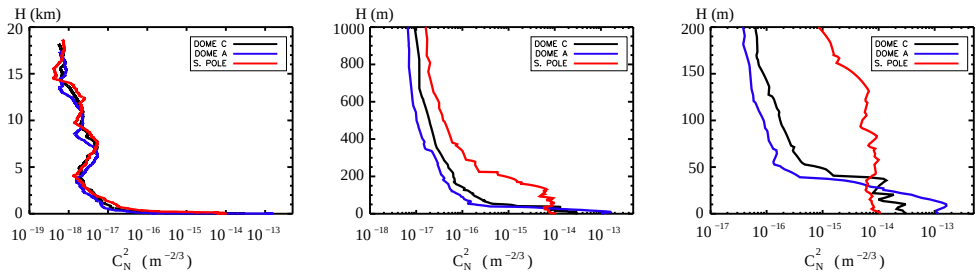

Fig. 1. Median C_N^2 profiles simulated with the Meso-NH meso-scale model at Dome C (black), Dome A (blue) and South Pole (red). Left: from the ground up to 20 km. Middle: from the ground up to 1 km. Right: from the ground up to 200 m. Units are $m^{-2/3}$. *(Extracted from [15]).*

In Fig.2 is shown an example of the temporal evolution of the C_N^2 profiles reconstructed by the model in the first 300 m above the three sites during a night. It is well evident the incredible difference of the feature of the the surface layers associated to the two sites located on the summits of the plateau (Dome A and Dome C) and that of the site located on a slope (South Pole).

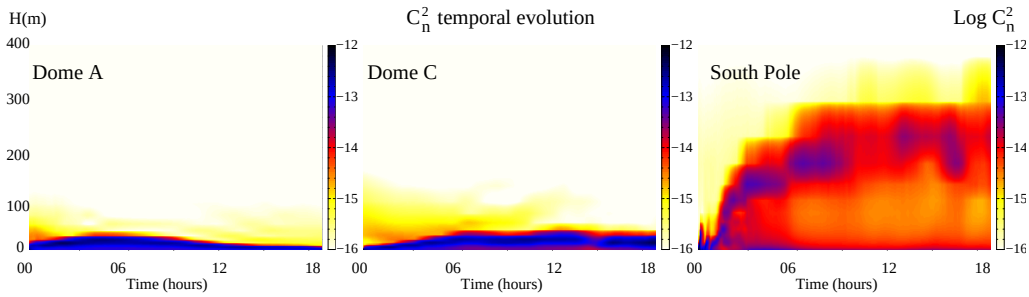

Fig. 2. Temporal evolution of the C_N^2 profiles in the first 400 m calculated in a single night above the three sites: Dome A (left), Dome C (middle) and South Pole (right).

5.2 Mt. Graham

For this study we used, as a reference for the model validation, a set of measurements we performed with a Generalized Scidar (GS) located at the focus of Vatican Advanced Technological Telescope (VATT) on 41 nights uniformly distributed in the solar year [8]. The GS is the most accurate vertical profiler available at present. It was therefore the perfect instrument to be used to collect a sample of C_N^2 profiles to be used, as a reference, to study the ability of the model in reconstructing the OT vertical distribution. A detailed summary of the Meso-Nh model performances obtained at conclusion of this study is reported in [18]. This model validation has been performed with the richest statistical sample of measurements ever used so far. In this study we used two calibration approaches: the first one, is the classical one, proposed by Masciadri & Jabouille ([5]), hereafter MJ01 method, the second method is based on a variant of the MJ01 method that we called MJ01*. In this contribution we present results obtained with both methods. A detailed discussion about the comparison among the two methods can be found in [18]. We anticipate the conclusion obtained in [18] that stated that

Table 3. Total sample (41 nights): average seeing in the total atmosphere, boundary layer and free atmosphere.

	Generalized Scidar			Model MJ01			Model MJ01*		
	ε_{tot}	ε_{BL}	ε_{FA}	ε_{tot}	ε_{BL}	ε_{FA}	ε_{tot}	ε_{BL}	ε_{FA}
Total (41 nights)	0.71	0.51	0.43	0.76	0.56	0.41	0.84	0.59	0.48
Summer (15 nights)	0.45	0.26	0.34	0.51	0.28	0.38	0.60	0.31	0.46
Winter (26 nights)	0.87	0.67	0.48	0.91	0.73	0.43	0.98	0.76	0.49

the classical MJ01 appears as a preferable solution. On Fig.3-left is reported the average C_N^2 profiles obtained with measurements and with the model calibrated using the two different methods. We can observe that the model can reconstruct the OT vertical distribution very well correlated to the observed one. On Fig.3-right are reported the correspondent seeing values, measured and simulated, for each night. To discuss how good/bad is the model prediction we calculated different statistical indicators. The coefficient of correlation CC is equal to 0.81 and 0.82 on the sample of nights used to calibrate the model (34 nights). The CC decreases to 0.61 if we consider the whole sample of 41 nights. We note that the order of magnitude of the CC is similar to that obtained comparing different instruments running simultaneously on the same site. We calculated, for example, that DIMM and GS measurements associated to 20 nights taken at Paranal during the site testing campaign of 2007 provide a CC is equal to 0.71. We calculated also the relative error RR of the seeing ([18]-Table 3) associated to the averaged absolute values reported in Table 3. The RR reveals to be extremely good: for the total seeing is 3.6%, for the boundary layer 9.2% and for the free atmosphere 0.4% for the sample of calibration (34 nights). It becomes 7.2% for the total seeing, 9.0% for the boundary layer and 3.2% for the free atmosphere for the total sample of 41 nights. If we look at different seasons the results remain below 15% therefore still very encouraging.

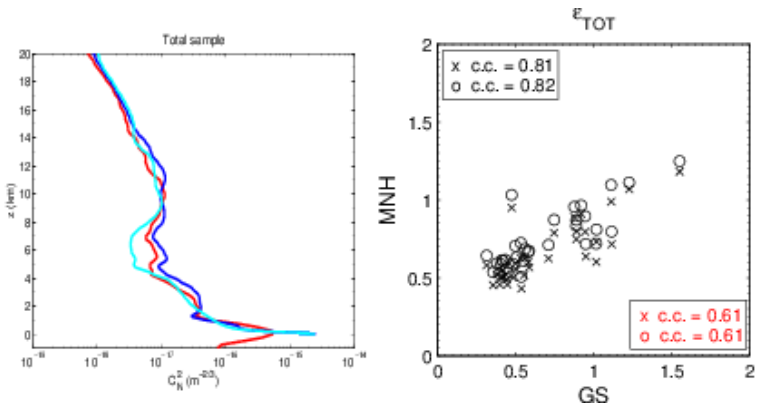

Fig. 3. Left: the average C_N^2-profiles measured by the Generalized Scidar (red line) and the Meso-NH model (light blue line: MJ01; dark blue line: MJ01*) on the total sample of 41 measured nights. Right: the average for the total sample of 41 nights. Values of the seeing from the simulations (MJ01 xs, MJ01* circles) plotted against the measurements in the calibration sample (34 nights). On the top-left box is reported the coefficient of correlation (CC) in the case of the calibration sample of 34 nights; on the bottom-right box (in red) in reported the CC calculated for the total sample of 41 nights. The dome seeing has been removed from the Generalized Scidar data and the seeing in the first 20 m (correspondent to the height of the telescope) has been removed from the Meso-NH simulations. *(Extracted from [18]).*

If we wish to predict the OT is however important to estimate also the model score calculated night by night. We know that is obviously much more difficult and challenging to achieve reasonable good results in this framework. Fig.4 shows the cumulative distribution of the relative error for each single night of the total seeing (left), the seeing in the boundary layer (middle) and the seeing in the free atmosphere (right). We note that the relative error in the three regions of the atmosphere is absolutely

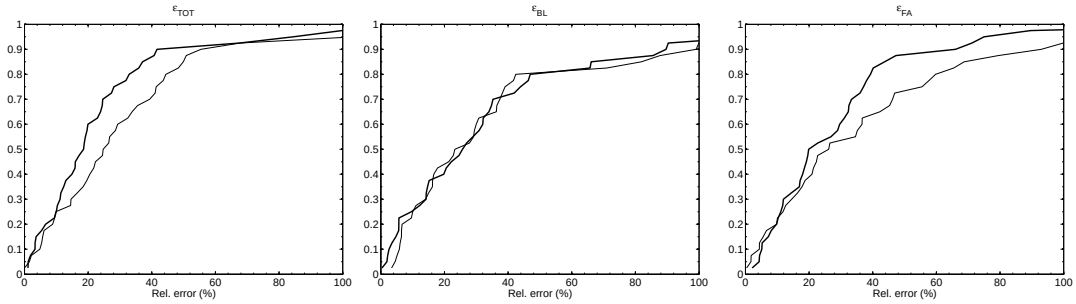

Fig. 4. Cumulative distribution of the relative errors of each single night of the total seeing (ε_{TOT}), the seeing in the boundary layer (ε_{BL}) and the seeing in the free atmosphere (ε_{FA}) for the total sample of 41 nights. Bold line: MJ01 method. Thin line: MJ01* method.

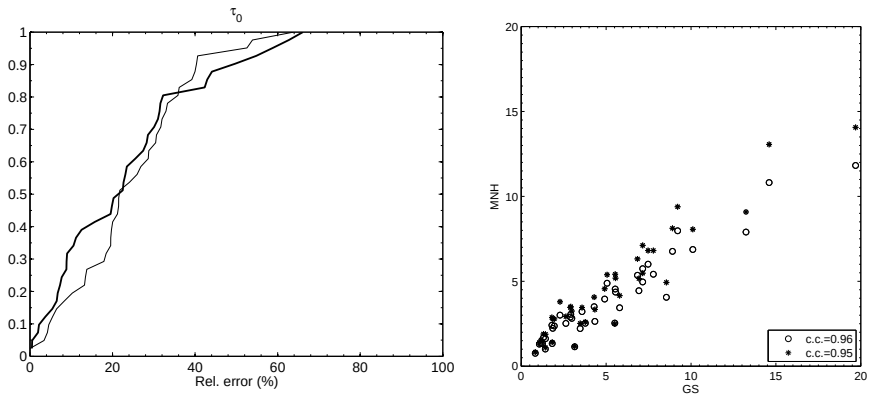

Fig. 5. Left: Cumulative distribution of the relative errors of each single night of the wavefront coherence time ($\tau 0$) for the total sample of 41 nights. Bold line: MJ01 method. Thin line: MJ01* method. Right: wavefront coherence time (stars, MJ01; circles, MJ01*) plotted against the measurements related to the sample of 41 nights. In the bottom-right box is reported the coefficient of correlation obtained using the two methods: MJ01, MJ01*.

remarkably small. The median value of the relative error is 18.7% in the total atmosphere, 26.3% in the boundary layer and 20% in the free atmosphere.

Doing the same calculation for the wavefront coherence time on the same sample of nights we obtained an extremely encouraging result too (Fig.5). The median value of the cumulative distribution is equal to 22.5% and the coefficient of correlation CC is equal to 95%. At the Conference AO4ELT2 we shown an animation[1] to appreciate the coherent results produced by the Astro-Meso-Nh model if compared to measurements. The test case presented in the animation is related to a night on 2008, February and it proves how the model can reconstruct a good vertical distribution of the OT and, at the same time, a good quantitative estimate of the integrated value of the OT on the same vertical slab. The animation of a horizontal cut of the seeing extended on a surface of 20 km $\times$ 20 km calculated integrating the turbulence from 20 m to 20 km along the zenith and centered on the summit of Mt.Graham permits to appreciate the evolution of the seeing in the whole region around the telescope.

6 Perspectives

Besides to the very encouraging results we obtained in the context of ForOT, a more recent project (MOSE) co-funded by ESO and INAF has been undertaken. The main scientific aims of MOSE is

[1] $http://forot.arcetri.astro.it/Press/AO4ELT2\_masciadri\_animation.ppt$

to perform a feasibility study for the OT forecast above the two major sites of ESO in the visible and the near-infrared ranges: Cerro Paranal (VLT's site) and Cerro Armazones (E-ELTs' site). From a scientific point of view we intend, in particular, to overcome the two major limitations encountered so far in this studies: **(1)** the difficulty in having independent samples of measurements for the model calibration and validation to estimate if and how the correlation between measurements and predictions decreases with increasing the number of nights; **(2)** difficulty in having a large number of simultaneous measurements done with different and independent instruments for the OT estimates (in particular vertical profilers). In the framework of MOSE we will take advantage of the large amount of data collected in the site testing campaigns performed in occasion of the site selection for the ELT done mainly by ESO and the TMT.

7 Conclusion

The optical turbulence forecast is definitely an accessible target for the near future. Excellent results have been already obtained on different time scales (months and single nights) particularly for some parameters such as the seeing and the wavefront coherence time. It has been proved that the meso-scale model Meso-Nh can provide an exhaustive reconstruction of the C_N^2 from a qualitative and quantitative point of view. The model prediction scores are comparable with the accuracy of measurements available at present. The most important goal that we need to achieve is, at present, the improvement of the turbulence temporal variability reconstructed by the meso-scale models in the high part of the atmosphere. This will lead to an improvement of the prediction of the isoplanatic angle and the seeing in the free atmosphere.

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