Optical turbulence forecasting and comparisons with daytime and nighttime measurements

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ABSTRACT

Forecasting the optical turbulence has become a necessary information to plan astronomical observations in the best possible way and to avoid scientific and pecuniary losses. This planification, called the "flexible scheduling", has been studied from different viewpoints in the past. Our choice is to use the Weather Research and Forecasting model coupled with different turbulence models to compare and analyse a set of possible options. At this point, the model mainly used in our group has been developed empirically from a large amount of balloons sounding. We present, in this paper, a study of a forecasting above the Calern observatory and comparisons with daytime and nighttime optical measurements obtained by the Calern Atmospheric Turbulence Station (CATS). We will show that we can reach a good precision above the Calern site, mainly above an altitude of a few hundreds meter, by binding the model with measurements.

Keywords: Turbulence - Atmospheric effects - Forecasting - Flexible Scheduling - Modeling

1. INTRODUCTION

It is well known that atmospherical and optical turbulence reduce the resolution reached by large telescopes. Indeed, even with a pupil as large as the future E-ELT one (39m), the theoretical resolution, given by $\frac{\lambda}{D}$, is limited by the Fried parameter r_0 to become $\frac{\lambda}{r_0}$. The adaptive optics (AO) is able to well compensate this effect but its performances depends also of the optical turbulence strength. Indeed the design and the dimensioning of AO systems are, among other things, constrained by the intensity and the profile of the turbulence. Also in case of strong turbulence, the correction bring by the AO system will be limited and the loop could not be close.

Moreover, in each observatories, astronomers have different observation programs, different modes of observations and the success of these programs strongly depends on the reachable performances. Having a forecasting about the nighttime evolution of the turbulence strength would allow to schedule the night and to adapt observations modes considering these informations, this is called the **flexible scheduling**. This aspect has become essential for the current generation of 8-10m class telescope and will be even more important for the next generation of 30-40m telescopes. The two main reasons are financial and scientific: by optimizing the scientific efficiency of each night using forecasting of optical turbulence, we optimize the cost of each observing night. For exemple, the expected cost of one night of observation with the E-ELT would be around 500,000 euros, and then increasing its efficiency will reduce the financial losses due to a wrong observations scheduling.

Our approach is based on the use of the Weather Research and Forecasting model (WRF)[1] coupled with a model initially deduced from an empirical analysis of a large amount of radiosounding balloons launched around the world.[2,3] The novelty presented in this proceeding is the availability of a large database acquired on the Plateau de Calern (in South of France) thanks to the Calern Atmospheric Turbulence Station (CATS)[4] which measured both meteorological and optical parameters such as the ground temperature and wind speed, the seeing, the vertical profile of the C_n^2, ... This database will be used as a calibration tool for forecasts, and as a constraint for the optical turbulence model. We will briefly present in the following section the CATS station and its instruments. Section 3 will be dedicated to the use of CATS measurements to constrain the turbulence

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model. Section 4 will presents the configuration used for prediction above Calern observatory and section 5 will presents our first 24h prediction results and the comparison with local measurements.

2. CALERN ATMOSPHERIC TURBULENCE STATION - CATS

The CATS station (see figure 1) is a fully autonomous station installed in 2015 on the Plateau de Calern close to Nice in South of France. It's composed of a set of complementary instruments allowing the measurements of both optical and meteorological parameters:

- A weather station measures the ground parameters such as the temperature, the relative humidity or the wind speed and direction, and gives informations for the aperture of the domes.
- An all-sky camera coupled with a pyranometer to measure the cloud cover, and command, with the weather station, the aperture of the domes.
- A Generalized DIMM (G-DIMM)[5] (figure 1, left) measures the nighttime integrated optical parameters such as the seeing, the isoplanatic angle and the coherence time.
- A Profiler of Moon Limb (PML)[6] (figure 1, right) measures during daytime (on the sun limb) and nighttime (on the moon limb) the vertical profile of the C_n^2 with a high resolution ($\Delta h = 100m$ near the ground) and the integrated parameters (seeing, isoplanatic angle, outer scale, scintillation, and, in the future, the coherence time)

Figure 1. CATS station installed on the Calern Observatory. The left instrument is the G-DIMM, and the right one is the PML.

The main advantage of this station is that it acquires measurements during daytime and nighttime in an automatic mode thanks to the weather station and the all-sky camera which allow the beginning of observations in function of the meteorological conditions. Therefore a large database is now available and will allow us to have both comparisons and constraints for our optical turbulence model detailed in the following section.

3. USING CATS TO CONSTRAIN OUR TURBULENCE MODEL

The initial model used to compute turbulence intensity from meteorological parameter is based on the paper of Trinquet & Vernin 2007[2] which have analyzed 162 balloons radio sounding launched around the world. In this model we compute the structure constant of the temperature fluctuations $C_T^2(h)$ using the following equation:

$$C_T^2(h) = \phi(h)\chi(h)s^{1/2} \tag{1}$$

$$\chi(h) = \frac{d\theta}{dh} \tag{2}$$

$$s(h) = \sqrt{\left(\frac{dU}{dh}\right)^2 + \left(\frac{dU}{dh}\right)^2} \tag{3}$$

where χ is the vertical gradient of the potential temperature θ, s is the horizontal wind shear, U and V are respectively the wind speed in West-East and South-Nord directions. ϕ is the profile deduce from the balloons analysis following equation 4.

$$\phi(h) = \frac{\langle C_T^2 \rangle_m(h)}{\langle \chi \rangle_m(h) \langle s \rangle_m^{1/2}(h)} \tag{4}$$

$\langle\rangle_m(h)$ defines the median of balloon measurements at each altitude h.

Once we have the C_T^2 we can compute the structure constant of the refractive index fluctuations C_n^2 following the well known Gladstone's formula:

$$C_n^2(h) = \left(\frac{80.10^{-6}P}{T^2}\right)^2 C_T^2(h) \tag{5}$$

where P is the pressure in hPa and T is the absolute temperature in K.

This model works globally well but if we want to reach a better precision in a given site we need to use local informations to better take into account local behavior and ground effects. We have then decided to use the vertical profiles of the C_n^2 measured with the PML instrument, and the ground meteorological parameters measured with the weather station to improve the turbulence model. To do it we have made the assumption than the vertical profiles of temperature, pressure and wind speed are well forecasted with WRF. We can inject all these measured and predicted parameters in the equation 5 and 4 to retrieve a more local ϕ. Of course doing these assumptions brings errors, but we will see in the section 5 that the optical turbulence predicted by using this new ϕ is in a good agreement when compared to local measurements of the CATS station.

4. DOMAIN AND PREDICTION SETTINGS

To run a WRF simulation we need to prepare a grid domain having a given resolution, and nested domain having a higher resolution. We also need to use input meteorological data to gives initial and boundary conditions. Then we need to use terrestrial data such as topography, land type, etc... to have local informations on the ground of the selected domains.

In our case we have chosen to have a coarse domain with a 2700x2700km size gridded in 100x100 grid points. This domain is large enough to consider large scale effect which would cross the finest domain during the simulation duration. The finest resolution reached by our domain is 1x1km and we down to this domain by inserting nested domain with a respective resolution of 9x9km and 3x3km to reduce gradually the resolution.

The meteorological input data used are those delivered by the Global Forecast System (GFS) and have a resolution of 0.25x0.25degrees (111x111km).

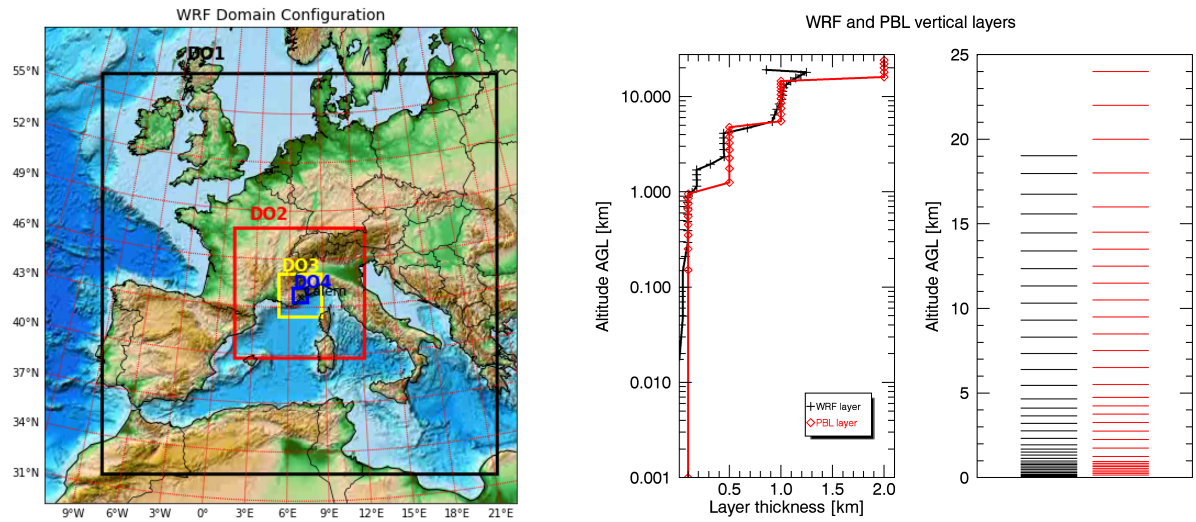
The topographic data used come from the Schuttle Radar Topography Mission (SRTM) * and has a resolution of 0.09x0.09km which is better to take into account the roughness of the relief.

Table 1 summarized the configuration of our domains, and the figure 2 shows the corresponding domains over-plotted on a map and the vertical layers used in the simulation. We can notice that the vertical resolution is higher near the ground ($\Delta h = 0.015m$) and gradually decreases up to $\Delta h = 1.246km$ for the highest layer.

*http://srtm.csi.cgiar.org/

Table 1. Configuration of the predicted domains used in WRF simulations.

	Domains			
	D01	D02	D03	D04
Latitude in the center	43.755			
Longitude in the center	6.922			
Horizontal resolution [km]	27x27	9x9	3x3	1x1
Number of horizontal grid points	100x100	100x100	100x100	70x70
Vertical resolution [km]	from 0.015 to 1.246			
Number of vertical level	42	42	42	42



(a) (b)

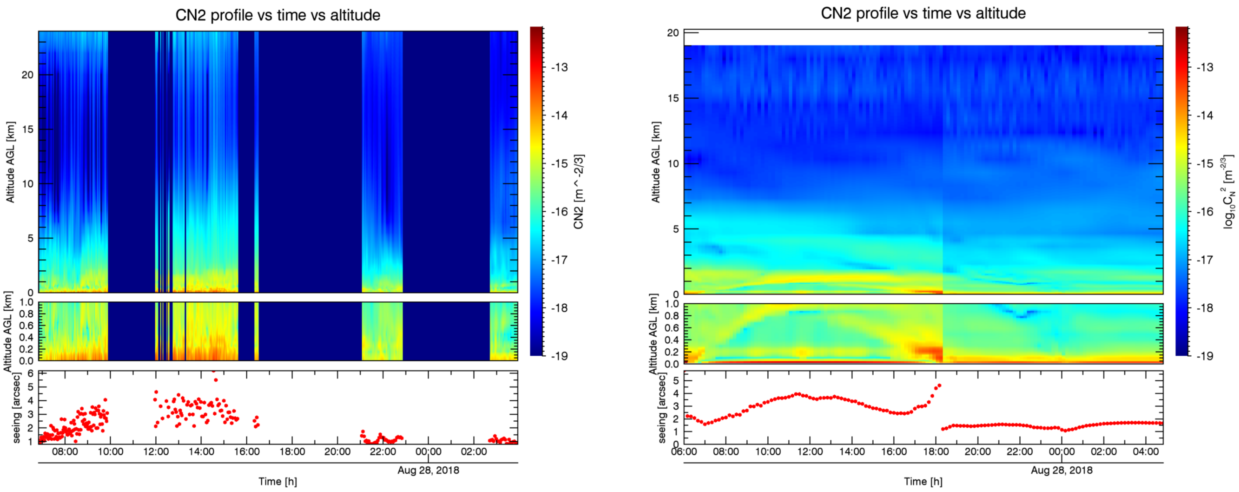
Figure 2. Configuration of the predicted domains. (a) projection of the main domain (D01) and nested domains (D02-D04) on the map. (b) PML vertical levels (red) and WRF vertical levels used for prediction (black).

5. FIRST RESULTS ON CALERN OBSERVATORY

In this section we present the first results obtained with the WRF model coupled with the turbulence model detailed in the section 3 and including the constraints of the CATS station. We have run a 24h simulations on August 28, 2018 which is a date presenting a large amount of comparative measurements. The figure 3 shows the 2D vertical profils of the $C_n^2(h)$ along the 24h forecasting and the profiles measured by the PML instrument. The WRF forecasting is configured do give one prediction every 10 minutes while PML gives one profile every 2-3 minutes. From these figures we can notice that:

- the planetary boundary layer of the turbulence measured by PML pass from 2-4km during the day, to around 1km during the night. This phenomena is well retrieved by WRF predictions.
- the forecasted surface layer seems thiner than the measured one. This effect could be due to the lower resolution of the PML in the first vertical level ($\Delta h_{PML} = 100m; \Delta h_{WRF}$). Integrate the first levels of the WRF profils up to 100m, could gives a results more similar to the measurements.
- the transitions between day and night and night and day seems to follow a different behavior not well modeled with our approach.

Figure 4 shows a 24h averaged profile of the C_n^2 predicted by WRF in blue and measured by PML in red. The red and blue colored surfaces correspond to the first and third quartiles of both predicted and measured profiles. It appears that the C_n^2 profile seems well predicted above 500m (above ground level) and less well predicted below



(a) (b)

Figure 3. C_n^2 profiles measured versus time for the PML measurements (left) and for the WRF predictions (right). The pixel colors represent the C_n^2 intensity. For each figure, the middle 2D plot corresponds to a zoom within the first kilometer and the bottom plot shows the seeing versus time.

these 500m (within the surface layer). Here again, if we integrate the $C_n^2(h).dh$ within the first 500m, we obtain closest values for both measurements and forecasting. The most likely reason for this discrepancy could be the difficulty to well modeled the ground effects during daytime and nighttime, with respect to the free atmosphere effects, less dependent of the local configuration.

Figure 5 shows the seeing evolution during the 24h predicted. The measurements are plotted in red (PML) and black (GDIMM). The other colors are predictions using different turbulence models:

- Magenta dots: classical balloon analysis turbulence model (see section **??**),
- Blue dots: turbulence model upgraded using both daytime and nighttime local PML measurements,
- Blue crosses: turbulence model upgraded isolating local nighttime PML measurements.

The red colored surface corresponds to the standard deviation resulting from a 10minutes moving average of the PBL and GDIMM measurements to reach the same sample as that of WRF. From this figure we can notice that the turbulence model upgraded gives, for this particular date, better predictions during the day. However this turbulence model is really not adapted for nighttime conditions. Consider only nighttime measurements to constrain the turbulence model gives better results in the predictions, but fluctuations are not well forecasted.

6. DISCUSSION AND CONCLUSION

In this paper we have presented a first result of forecasting above the Calern observatory, and a comparison with instruments of the CATS station: the PML for the vertical profiles of the C_n^2 and the seeing and the G-DIMM only for the seeing. We have presented a way to constrain the turbulence model by using local measurements and we present the results on a 24h forecasting.

From these comparisons, we can assume that our turbulence forecasting model gives encouraging predictions with a rather good accuracy with respect to in-situ measurements. We have shown our ability to retrieve daily effects such as the increase of the planetary boundary layer thickness and the increase of the turbulence intensity due to the ground heating during the day. We have shown the ability to well retrieve the C_n^2 profiles within the free atmosphere (above 500m a.g.l.) and the importance to constrain the turbulence model by local measurement. However, all this results are just for one day, and we need to confirm them by increasing the number of forecast to make a robust statistical analysis of our prediction tool.

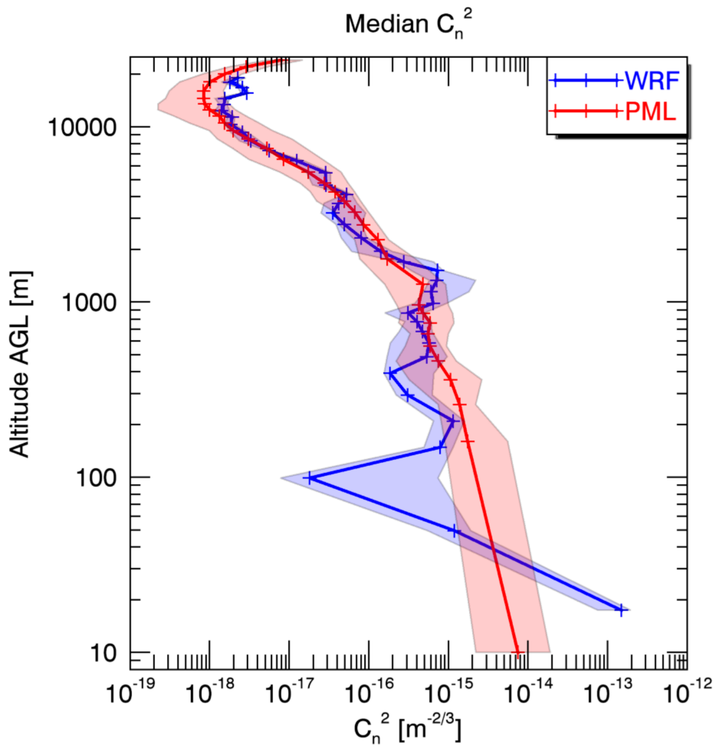


Figure 4. (a) 24h mean profiles of the C_n^2 measured with the PML (in red) and predicted with WRF (in blue) and our turbulence model. The colored surface corresponds to the interval between the first and third quartiles.

We have also identified two some issues in our prediction model: the complexity to forecast the optical turbulence during the day/night and night/day transition phases, the low accuracy in the C_n^2 within the first 500m and the difficulty to follow fluctuations during nighttime conditions. All these issues could be attenuated by increasing our statistics to better constrain the turbulence model. One way to do it is to have a turbulence model which evolves following the hour (day, night, dusk, dawn) and seasons. Indeed the conditions are different in summer, where the sun is very high during the day, and close to the horizon during the night, and in winter where the sun are the opposite behavior. Another possibility is to increase the horizontal resolution of the domain to better take into account the ground effects.

All these possible improvements will be presented in our future papers.

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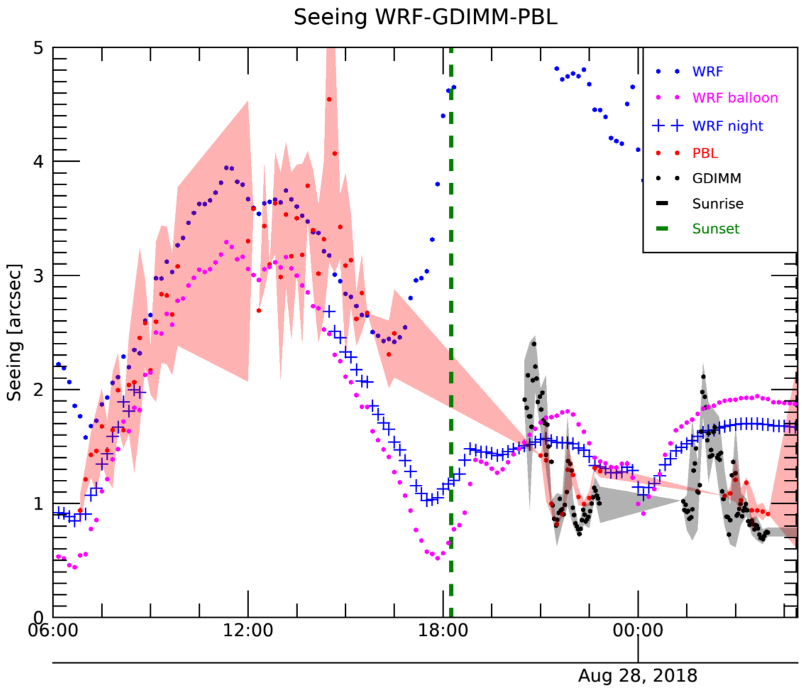

Figure 5. Seeing evolution for the 24h predicted. The magenta dots correspond to the results deduced with the balloon analysis turbulence model. The blue dots correspond to an upgrade of the turbulence model constrained by the local measurement. The blue cross represent again an upgrade with a specific nighttime turbulence model. The red and black dots are respectively the PML and GDIMM measurements. Finally the colored surface correspond to the standard deviation deduced from a 10 minutes moving average of the PML and GDIMM measurements.

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