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## CATS: turbulence measurement and forecasting

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### ABSTRACT

Abstract: The atmospheric turbulence measurement is an essential information for high-angular resolution imaging in astronomy, and for optical link. Since 2015, the Calern Atmospheric Turbulence Station (CATS) monitors atmospheric conditions at the Calern observatory, during both daytime and nighttime from the ground to the top of the atmosphere. The station is fully autonomous and is equipped with a set of complementary instruments to continuously monitor optical turbulence. The Profiler of Moon Limb (PML) measures, from Sun or Moon limbs observation, the vertical profiles of the refractive index structure constant  $C_n^2$  with a high vertical resolution. The Generalized DIMM monitors the integrated turbulence parameters by observing bright stars. More recently, knowing the need of turbulence forecasting, we developed a system integrated in the CATS station to daily predict daytime and nighttime meteorological and optical turbulence conditions for the next 48h. We also have designed an instrumental platform attached to a drone and allowing to measure, with a high resolution, the weather conditions between the ground and an altitude of around 500m.

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

### 1. INTRODUCTION

It is well known that atmospheric turbulence disturbs the light propagation through the atmosphere, resulting in deformations and fluctuations of images acquired with telescopes. However, with the new generation of extremely large telescope, this topic remains of a major importance to dimension instruments and to control the observations conditions in real time. Recently, with the emergence of optical telecommunications, particularly free space optical links, atmospheric turbulence has gained significant importance in these applications due to its influence on signal quality, bit error rate, and link budget.

To overcome these problems, and to correct wavefront deformations, adaptive optics (AO) systems are used, and improve image/signal quality or fiber injection. However, AO systems are dimensioned considering both turbulence conditions and the application field. They can therefore be limited when turbulence conditions are far from those used to design them. Consequently, the astronomy and telecommunications communities

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need turbulence characterization to select interesting sites, to dimension AO systems and to provide real-time information to astronomers/researchers and on-site technicians.

In addition, both astronomy and telecom applications must carefully strategize and coordinate their operations. Observatories need to plan the observations with respect to atmospheric conditions in order to optimize the scientific efficiency of the programs, and to reduce the cost due to time losses. Telecommunications need to have information in advance to select, for example, the most favorable optical ground station location to receive/send the telecom signal from/to satellites. Moreover, such a prediction tool could be able to characterize several sites in the same time, and to complete on site measurements.

Regarding, all these points, having an instrumentation able to measure, during both daytime and nighttime, the optical turbulence conditions, and having a prediction tool are of real interest for both astronomical and optical communications communities.

Since 2015, the Observatoire de la Côte d’Azur (OCA) has designed, manufactured, and installed a new generation station for atmospheric turbulence characterization on the Calern Observatory. The Calern Atmospheric Turbulence Station [8, 24, 22, 14] (CATS) came out from a long and recognized expertise of the Lagrange Laboratory (OCA) in Atmospheric Optics. The idea is to offer to community a fully operational on-sky test platform.

Since 2019, we have added into the CATS station a forecasting tool [10, 13, 9, 11] allowing to predict the atmospheric and optical conditions above the Calern Observatory. This tool has been tested and improved both in Cerro Pachon and on Calern Observatory. It is continuously improved thanks to the CATS station which allows to:

- compare the prediction with local measurements and local turbulence profiles for long period during both daytime and nighttime.
- improve the efficiency of the forecasting thanks to site learning processes presented in Ref. [11].

For any enhancements in weather forecasting, it is essential to have access to local measurements of vertical profiles of weather parameters. In this scope, we have started in 2020 to develop an instrumented drone flying vertically above Calern Observatory from the ground up to an altitude of 450m. Thanks to this new database, we will be able to improve the turbulence and weather forecasting by injecting local measured profiles in models.

Since 2021, the CATS station became the reference station of the ANAtOLIA project (Atmospheric moNitoring to Assess the AvailabiliTY of Optical LInks through the Atmosphere). This project, ordered by the European Space Agency (ESA) is ensured by a European consortium led by our laboratory, through a contract between the CNRS (Centre National de la Recherche Scientifique) and ESA. A detailed presentation is given in Ref. [23].

In this paper, we present these CATS upgrades. Section 2 briefly describes the initial CATS station. Section 3 introduces the forecasting tool and results above Cerro Pachon and Calern Observatory. Finally, section 4 will introduce the aforementioned drone and how it works.

## 2. CALERN ATMOSPHERIC TURBULENCE STATION: CATS

The CATS station [8, 24, 22, 14] (see figure 1a) is a fully autonomous station working during both daytime and nighttime. Initially, CATS was composed of a first set of instruments allowing the measurements of both optical turbulence and meteorological parameters:

- The Generalized DIMM (G-DIMM) [2, 4, 1] (figure 1b) uses a small telescope equipped with a specific pupil mask. It observes bright stars in the zenithal region. From the spot positions and scintillation, it deduces the nighttime integrated optical parameters such as the seeing, the isoplanatic angle and the coherence time.
- The Profiler of Moon Limb (PML) [25, 5, 3, 7] (figure 1c) uses a small telescope equipped with a two sub-aperture mask to observe both solar and lunar limbs. From the limb position fluctuations, it can deduce during daytime (on the Sun limb) and nighttime (on the Moon limb) the vertical profile of the turbulence energy  $C_n^2(h)$  with a high resolution ( $\Delta h = 100m$  near the ground) and the integrated parameters (seeing, isoplanatic angle, scintillation, and, in the future, the coherence time)



(a) CATS station on Calern observatory



(b) GDIMM



(c) PML

Figure 1: CATS station instruments

- A weather station measures the ground meteorological parameters such as the temperature, the relative humidity or the wind speed and direction, and gives information for the control of the domes aperture. It was completed with a nighttime allsky camera used to deduce the cloud coverage by counting stars (see [24, 22, 12])

Recently, in the framework of the ANAtOLIA project, the CATS station has been upgraded by adding a new all-sky camera built by the Reuniwatt company. It works during daytime and nighttime by observing clouds in infrared. Therefore, it continuously deduces the cloud cover by analysing aquired images (see fig. 2). It allows to have a better control of the cloud conditions and the CATS dome apertures. In addition, another instrument (Cimel photometer) measuring aerosol distributions has been also installed and is more discussed in Ref. [23].

The GDIMM is based on a small telescope with an entrance pupil made of 2 small sub-apertures (6cm diameter) and a third one (10cm diameter) having a central obstruction (4cm) (see figure 1b). It observes a bright single star with a short exposure time. From these three apertures, we have three different spots on the camera, as shown on figure 3. From the differential variance of the photocenter coming from the two small sub-apertures, it deduces the Fried parameter  $r_0$  and the seeing  $\varepsilon_0$ . The third sub-aperture allows to calculate the isoplanatic angle  $\theta_0$  from scintillation measurements [1]. By computing the temporal structure constant of the Angle of Arrival (AA) through each sub-aperture, GDIMM deduces the effective wind speed  $\bar{v}$  and then the coherence time  $\tau_0 = 0.31 \frac{r_0}{\bar{v}}$ . Finally, using a combination of one of the small apertures and the third one, we are able to compute the wavefront coherence outer scale  $\mathcal{L}_0$ . More details are presented in Ref. [1]. The main drawback of the G-DIMM is that it cannot retrieve the turbulence vertical profile, it only measures integrated parameters, and it cannot work during daytime because it needs bright stars.

The PML (see figure 4) is based on a 40cm diameter telescope equipped with a 2 small sub-aperture mask at the entrance pupil. PML observes Moon or Sun limbs to deduce turbulence parameters during both daytime and nighttime. The Moon/Sun limbs acts as a continuum of double stars with all possible angular separations. By triangulation, each separation is linked to a specific height of the atmosphere. Therefore, using this continuum, PML scans the atmosphere with a high vertical resolution of  $\Delta h = 100m$  for the ground layer to  $\Delta h = 2000m$  for the highest layers. Figure 4 shows an example of images aquired with the control software (left), and the principle of profiling using the double star continuum formed by the two limbs. The vertical profile of the  $C_n^2$  is computed from the angular correlation of the fluctuation differences in the wavefront AA deduced from the

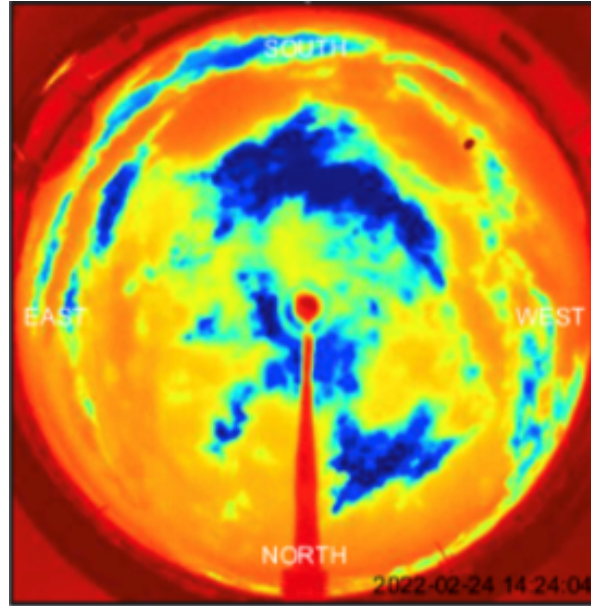


Figure 2: Example of image acquired with the Reuniwatt Sky InSight all-sky camera used to compute the cloud coverage.

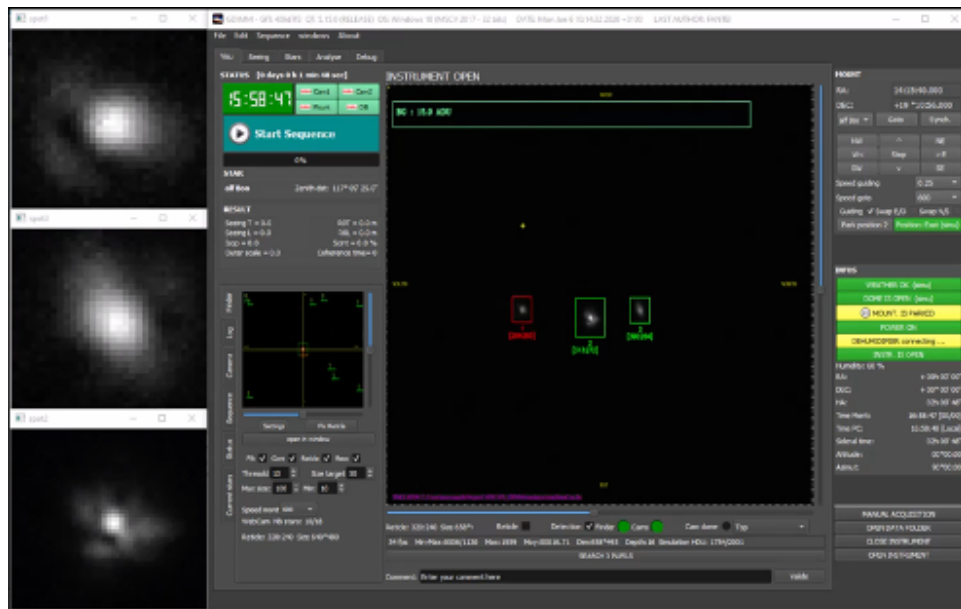


Figure 3: Images acquired with GDIMM instrument, and software controlling it.

motion of the Sun/Moon limbs. The AA fluctuations are measured perpendicularly to the lunar/solar limbs leading to transverse correlations for different angular separations along these limbs. From the  $C_n^2(h)$  profile one can deduce other integrated parameters. For more details about the computation method, see Refs. [22, 7]. The main drawback of the PML instrument is that it needs either Sun or Moon to work. To remain in the framework of the weak perturbation assumption, these targets need to be at least at a 20 degrees elevation above horizon. Therefore, there is a lack of measurements, when the target is low, or when the Moon is not visible (1 week per month).

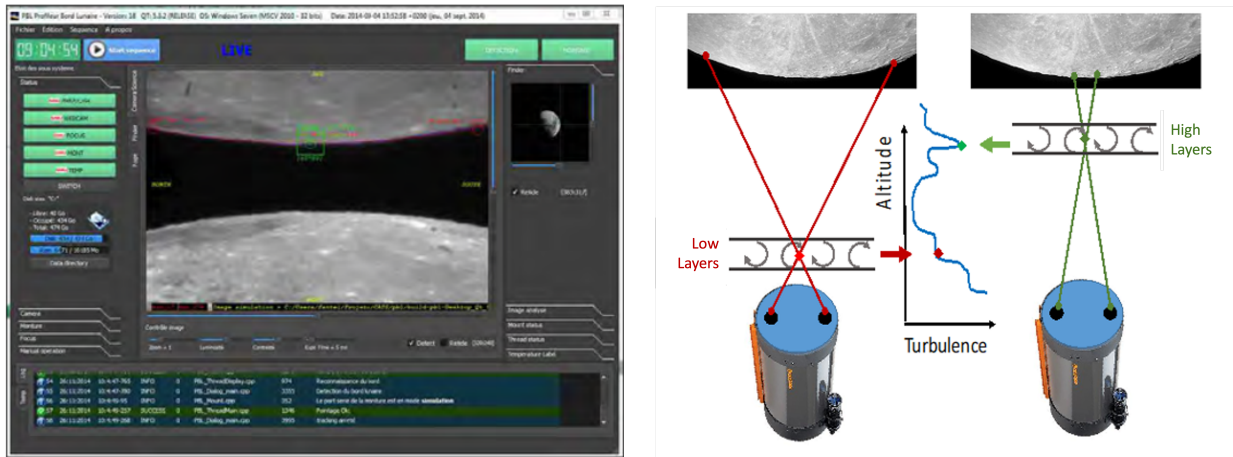


Figure 4: Left: PML software and images. Right: principle of the profiling through different observing angle.

The CATS is fully autonomous and controlled thanks to a GRAFANA\* interface showing the status of the instruments, and the data acquired in real time. Figure 5 shows an example of such a control interface.

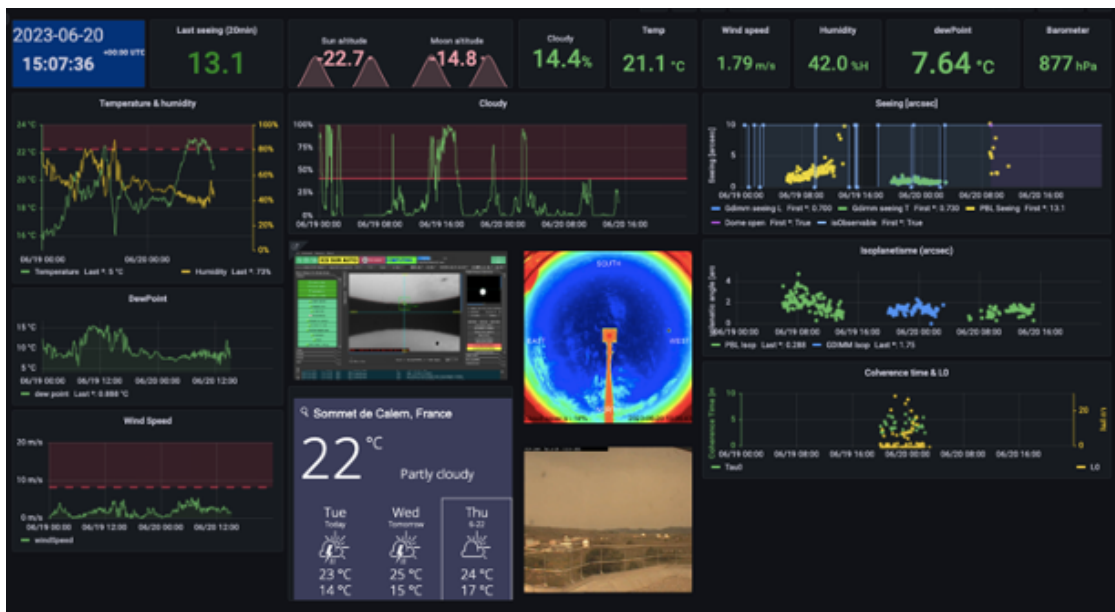


Figure 5: Example of GRAFANA interface used to control the CATS station.

The CATS station, working during both daytime and nighttime since 2015, is now used as a reference for the new instrumentations of the Calern Observatory. It integrates also the forecasting tool we have developed (see section 3 below). In addition, CATS is used as a reference within the ANAtOLIA project led by our Laboratory, and presented in another paper of this conference: Ref. [23].

\*<https://grafana.com>

### 3. TURBULENCE FORECASTING TOOL USING WRF AND MACHINE LEARNING

#### 3.1 Forecasting with mesoscale model

As defined above, the CATS station is able to measure almost continuously during both daytime and nighttime the atmospheric turbulence conditions from the ground level up to the top of atmosphere. Forecasting is now a key tool for observations and telecommunications, in order to:

- use the **flexible scheduling**: Adapt the observation planning regarding the predicted turbulence to improve efficiency of observatories and to avoid financial losses.
- Improve site characterization and site prospection by using long-terms analysis of predictions. This could also be useful for system dimensioning.
- Search optical ground station sites for optical telecommunications
- Define the best optical ground station, inside a network, as a function of turbulence conditions, to transfer the signal from and to satellite: **smart scheduling**.

To forecast atmospheric conditions, we use the Weather Research and Forecasting (WRF) [19] system developed by the National Center for Atmospheric Research (NCAR). This mesoscale model gives access to the main atmospheric parameters (pressure, temperature, wind speed, relative humidity, etc.) within a tridimensional domain defined by the user. To work, WRF needs both static data (orography, albedo, land type, etc.) and large scale weather conditions to initialize each simulation/prediction.

One of the specificities of WRF is its number of possible configurations (microphysical, physical, cloud, etc.) to run simulations. In the last years, we did an important study about the optimization of this configuration above the site of Cerro Pachon (Chile) for which we have done a large radio-sounding campaign in the past. More details are given in Ref. [16].

Once we have predicted weather parameters, the derivation of optical turbulence characteristics requires the use of models. In Ref. [16], we have studied two different turbulence models and highlighted their advantages and their drawbacks:

- The theoretical model, based on the Tatarskii equation [20], is more reliable to compute instantaneous predictions.

$$C_n^2(z) = 2.8M(z)^2L_0(z)^{4/3}; M(z) = -80.10^{-6} \frac{P(z)}{T(z)} \frac{1}{\theta(z)} \frac{\delta\theta}{\delta z} \quad (1)$$

with,  $z$  the altitude,  $L_0$  the turbulence outer scale,  $P$  the atmospheric pressure,  $T$  the absolute temperature and  $\theta$  the potential temperature.

- The empirical model was initially deduced from an analysis of radio-sounding balloons [21, 10, 9].

$$C_T^2(z) = \phi(z)\chi(z)s(z)^{1/2}; C_n^2(z) = \left( \frac{80.10^{-6}P(z)}{T(z)^2} \right)^2 C_T^2(z) \quad (2)$$

with  $z$  the altitude,  $\chi(z)$  the vertical gradient of potential temperature,  $s(z)$  the wind shear,  $C_T^2(z)$  the structure constant of temperature fluctuations,  $P(z)$  the atmospheric pressure and  $T(z)$  the absolute temperature.  $\phi(z)$  is the empirical profile depending on  $\chi$ ,  $s$  and  $C_T^2$  analysis.

This model is reliable for long-term statistical analysis and it can be largely improved by injecting local measurements into it, this is called "Site Learning". For more details about this method, see Ref. [11].

Figure 6 shows the difference between the statistical and instantaneous reliability of both models over Cerro Pachon site. The statistics has been done over more than 40 balloon flights spread over all a year. As mentioned above, the Tatarskii model gives better instantaneous predictions than the empirical one (call phiModel in figure 6).

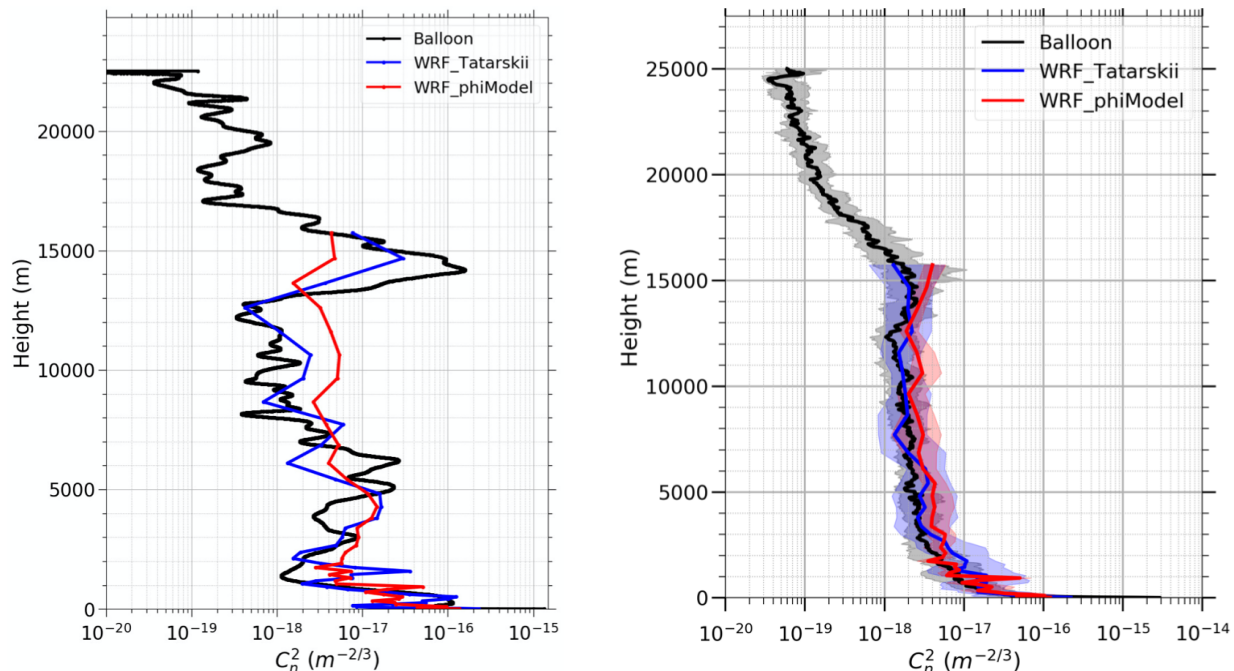


Figure 6: Vertical profile of the  $C_n^2$  above Cerro Pachon site. On the left, the instantaneous  $C_n^2$  measured (black) and predicted (red and blue). On the right the median profile compute over all the campaign. One can see that the Tatarskii model is better than the empirical one (called phiModel) for instantaneous prediction. However, regarding statistics, both model gives comparable predictions, but the empirical model has the lower dispersion. Figure extracted from Ref. [16].

Since 2019, we have developed a forecasting tool<sup>†</sup> for the Calern observatory to predict, daily and 48h in advance the weather and turbulence conditions above the Calern site. Recently, thanks to the CATS station database, we have used the site learning (SL) algorithm [11] to improve the initial empirical model (called BDTM in figure 7) and to better consider site specificities. This new method brings a large improvement on turbulence forecasting, as shown on figure 7. This figure as been computed using data between 2019 July to 2020 January. It also shows that, in particular during daytime, there are still differences between measurements and predictions. One of the factors contributing to these differences is the instability of ground layer conditions, particularly noticeable during the day, and very dependent on the site configuration.

#### 4. INSTRUMENTED DRONE

In previous sections, as well as in Ref [11], it has been demonstrated that predicting turbulence conditions is a highly intricate subject that demands extensive research and relies on in situ measurements for model testing and enhancement, with the assistance of the SL method. In particular, we have shown in [11] that a difference subsists in the first 500m of altitude. Indeed, this atmospheric domain is more impacted by ground effects such as orography, albedo, ground type, heating, etc. Considering, the resolution limit of mesoscale models, it is difficult for them to adequately account for site-specific characteristics, especially when the location is a complex terrain such as observatories in mountain. Hence, models lack sufficient data to simulate atmospheric conditions in the lower atmosphere, leading to errors that can propagate.

To investigate these errors, it is essential to have an instrument that measures vertical profiles of weather parameters. Until now, at Calern observatory CATS gives access only to ground weather parameters, and to vertical profiles of turbulence energy  $C_n^2(h)$ . To complete these measurements, we have then developed a new

<sup>†</sup><https://cats.oca.eu/>



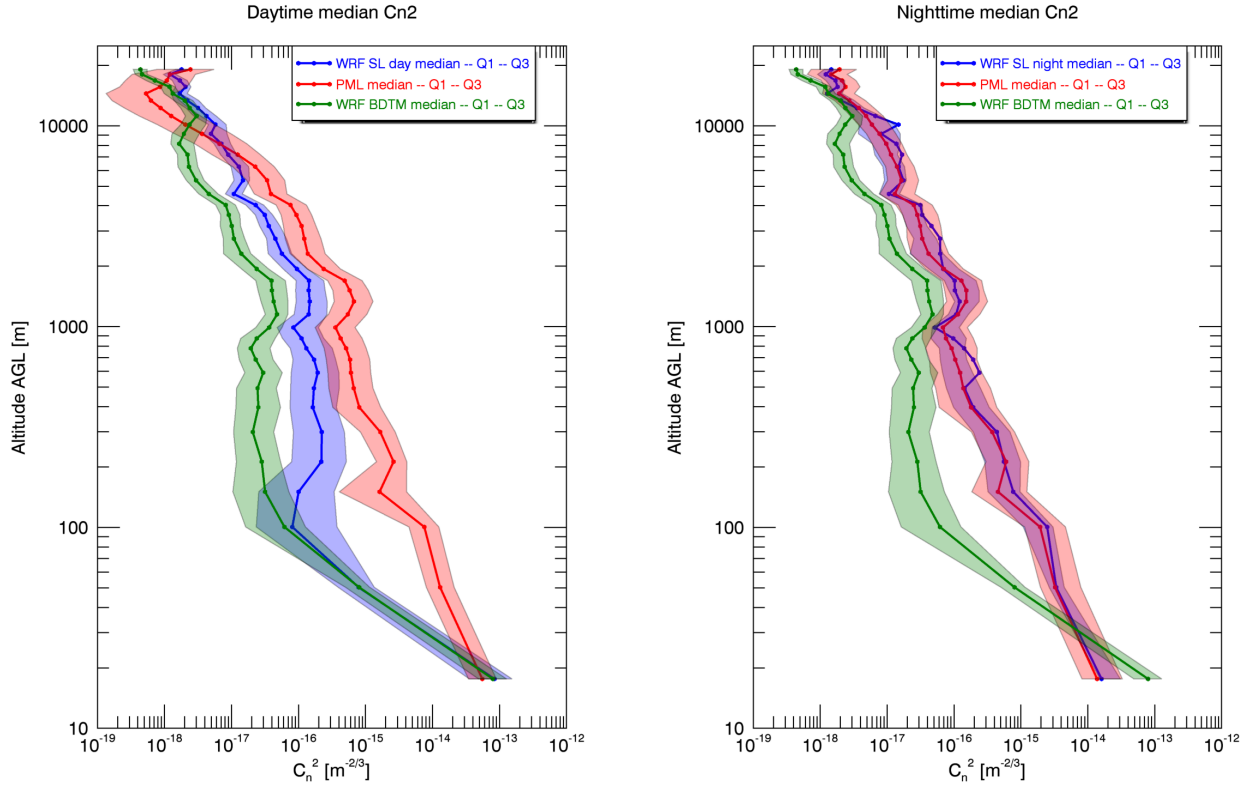


Figure 7: Median vertical profiles of the  $C_n^2$  measured by PML (red) and predicted by WRF using either the initial empirical model (called BTDM) (green) and SL (blue) method. The site learning method considers daytime (left) and nighttime (right) conditions separately. The shaded surfaces show the interval between the first and the third quartiles at each altitude. From left to right are plotted respectively the median for both daytime and nighttime data. Figure extracted from Ref. [11].

instrumentation based on the concept of balloon radiosoundings but without their drawbacks by using a drone. We attach an instrumented nacelle below this drone which hosts instruments able to measure meteorological parameters: pressure, temperature, humidity, wind speed and direction. The main advantages of this instrumented drone over the balloon are:

- The balloon derives horizontally up to hundreds of kilometers from the starting point. Therefore, measured profile does not correspond to the site anymore after some time. With the drone we are able to remain stable above a specific location during the ascent and the descent.
- With a balloon, after its burst, the nacelle with instrumentation is lost. The cost is expensive so we cannot use this kind of instrumentation as much as we want. With a drone, the nacelle is reusable at each flight.
- The manpower requested for a balloon launching is important, therefore we can have only 2-3 flight each day. With drone, the only limit is the batteries capacity.
- With the drone we can control the vertical speed to adapt the vertical resolution of the measured profile.
- With the drone one can adapt the portion of the atmosphere to monitor in function of our needs.

The main disadvantage of the drone is its autonomy, due to the battery charge limit. This means that the drone can only be used for low-atmosphere profiling.

A picture of the drone and the nacelle is visible in figure 8. Currently, we are doing a campaign of measurements between the ground and a 450m height and we are collecting measurements of temperature, wind speed and direction, pressure and relative humidity. First results and more details are given in [15]. In the future, these measurements will be used as a constraint to the mesoscale model and as an input to turbulence and ML models.



Figure 8: Picture of a drone flight (left) and of the instrumented nacelle (right). For more details see Ref. [15].

## 5. DISCUSSION

The CATS station is installed and operational at the Calern Observatory since the autumn 2015. As previously said, it is fully autonomous, monitors atmospheric turbulence parameters continuously and has been upgraded recently by a set of new generation instruments. All these points are the reason why the CATS station is involved in many scientific and educational projects at the Calern Observatory such as:

- study of turbulence impact on laser links of the MéO<sup>‡</sup> Laser Ranging Station;
- development of Adaptive Optics projects (for exemple [6]);
- study of laser uplink propagation in the atmosphere thanks to the T2L2 (Transfert de Temps par Lien Laser) space mission (see [18]);
- campaign involving optical telecommunications from space to ground with the SOTA (Small Optical Terminal) satellite and MéO laser ranging station (see [17]).
- the ANAtOLIA European project with ESA uses the CATS station as a reference station in an optical telecommunications context.

In addition, since many years, we are adding to CATS a forecasting tool using different turbulence models to predict the optical turbulence and to give pertinent information to the community about the sky conditions and site availability in advance. Since 2019 CATS is equipped with this forecasting tool doing daily predictions of

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<sup>‡</sup><https://www.oca.eu/fr/recherche/projets-de-recherches/meo>

all atmospheric conditions (weather and turbulence) for the next 48h. These predictions have been tested and optimized thanks to a site learning method [11].

To improve the atmospheric turbulence model and our understanding about the Calern site conditions, we have developed a new equipment using a drone and an instrumented nacelle measuring within the first 500m the weather parameters, and in the future the turbulence conditions with a high resolution and high precision.

With all these improvement, CATS is becoming one of the best tool to characterize and forecast the atmospheric conditions from the ground to the top of the atmosphere.

CATS instrumentation has recently been upgraded thanks to a new generation of instrument developed within the ANAtOLIA project [23]. In addition, the forecasting of cloud coverage is currently investigated and will be an important point for the community.

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