International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

CATS: upgrade of the atmospheric characterization station for both optical telecommunication and astronomical support

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 12777, 1277777 · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2691381

CATS: upgrade of the atmospheric characterization station for both optical telecommunication and astronomical support

C. Giordano[a], A. Ziad[a], E. Aristidi[a], J. Chabé[b], Y. Fanteï-Caujolle[a], A. Rafalimanana[a], A. Gillioën[a], T. Charbonnel[a], and C. Bailet[a]

[a]Laboratoire J.L. Lagrange, OCA, UCA, CNRS, UMR 7293, Parc Valrose 06108 Nice Cedex 2, France
[b]Université Côte d'Azur, OCA, CNRS, IRD, Géoazur, 2130 route de l'Observatoire, 06460 Caussols, France

ABSTRACT

The atmospheric turbulence measurement and characterization is an essential information for optical link (telecommunication, telemetry, time transfer, ...) and for high-angular resolution imaging in astronomy. Indeed, its impact on the light propagation degrades the bit error rate of optical communication signals and decreases the resolution of astronomical images. In this framework, since 2015, the Calern Atmospheric Turbulence Station (CATS) monitors optical turbulence conditions at the Calern observatory, from the ground to the top of the atmosphere during both daytime and nighttime. This instrumental platform is completely autonomous and is equipped with a set of complementary instruments using original techniques for monitoring optical turbulence during both daytime and nighttime. The Profiler of Moon Limb (PML) measures, from Sun or Moon observations, the vertical profiles of the refractive index structure constant C_n^2 with a high vertical resolution ($\sim 100m$ at ground level). The Generalized Differential Image Motion Monitor (GDIMM) monitors the wavefront coherence parameters (seeing, isoplanatic angle, coherence time, scintillation, outer scale) from bright stars observations. To control the monitors, a weather station provides the ground meteorological conditions (pressure, temperature, relative humidity, wind speed, wind direction and irradiance), and the nighttime cloud fraction is given by an all-sky camera. In addition, a turbulence forecasting system has been developed and integrated in the CATS station to daily predict daytime and nighttime meteorological and optical turbulence conditions for the next 48h. In this paper we present the CATS station and its last upgrades, and in particular the forecasting tool developed and test either on Cerro Pachon (Chile) and on Calern Observatory (France).

Keywords: Turbulence - Atmospheric effects - Instrumentation - Monitoring - Forecasting - Optical telecommunications

1. INTRODUCTION

With the advent of the optical telecommunications, and the free space optical links in general, the atmospheric turbulence is become a key phenomenon because of its impact on the signal quality, the bit error rate and the link budget. Such a phenomenon is well known for astronomical observations. Indeed, atmospheric turbulence disturbs the light propagation through the atmosphere, resulting in deformations and fluctuations of images acquired with telescopes.

Currently, to overcome these problems, adaptive optics (AO) systems are used to correct wavefront deformation and improve image/signal quality or fiber injection. However, AO systems are dimensioned considering turbulence conditions, and are limited in case of too strong turbulence. Therefore, the astronomical/telecoms communities need turbulence characterization to select interesting sites, to dimension AO systems and to give real-time information to astronomers/researchers and on-site technicians.

In addition, both communities have important issues link to the lack of information in advance. Astronomical observatory need to plan the observations with respect to atmospheric conditions in order to optimize the scientific

E-mail: cgiordano@oca.eu

efficiency of the programs, and to reduce the cost due to time losses. For telecommunications, it is mandatory to have information in advance to define, for exemple, 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, 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[1–4] (CATS) came out from a long and recognized expertise of the Lagrange Laboratory (OCA) in Atmospheric Optics. The CATS station is a support of other project on the Calern Observatory, mainly to improve the link budget of Laser Telemetry from MeO station and generally free space optical links. CATS is also supporting projects on MéO (Métrologie Optique) station and C2PU (Centre Pédagogique Planète Univers) telescopes to test and validate new concepts and components in order to overcome the current limitations of existing Adaptive Optics (AO) systems. The idea is to offer to community a fully operational on-sky test platform. The ultimate goal being the optimization of the scientific returns of the AO assisted instrumentations.

Since 2019, we have added into the CATS station a forecasting tool[5–8] allowing to predict 48h in advance 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. 8.

To complete this prediction tool, we are studying the use of machine learning algorithm[9] to improve short-terms prediction thanks to last available measurements and to the whole CATS database. A thesis about this subject starts in autumn 2022.

All the improvements of forecasting need to have access to local measurements of weather parameter vertical profiles. In this scope, we have started in 2020 to develop an instrumented drone flying vertically above Calern Observatory from the ground to a 450m height. 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. 10.

In this paper, we present these CATS upgrades. Section 2 briefly presents the initial CATS station. Section 3 present the forecasting tool and results above Cerro Pachon and Calern Observatory. It present also the machine learning used for short term predictions. Finally, section 4 will introduce the aforementioned drone and how it works.

2. INITIAL CALERN ATMOSPHERIC TURBULENCE STATION: CATS

The CATS station[1–4] (see figure 1) 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)[11–13] (figure 1, left) uses a small telescope equipped with a specific mask. It observes bright stars in the zenithal region. From the spot positions and scintillations, it deduces the nighttime integrated optical parameters such as the seeing, the isoplanatic angle and the coherence time.

- The Profiler of Moon Limb (PML)[14–17] (figure 1, right) uses a small telescope equipped with a two sub-aperture mask to observe both solar and lunar limbs. From the limb 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, wavefront coherence outer scale, scintillation, and, in the future, the coherence time)
- A weather station measures the ground parameters such as the temperature, the relative humidity or the wind speed and direction, and gives information for the control of the domes aperture.
- A visible all-sky camera[2,3] works during nighttime. It deduces the cloud cover by counting the number of star visible in different portion of the sky. It allows (with the weather station) the domes aperture.

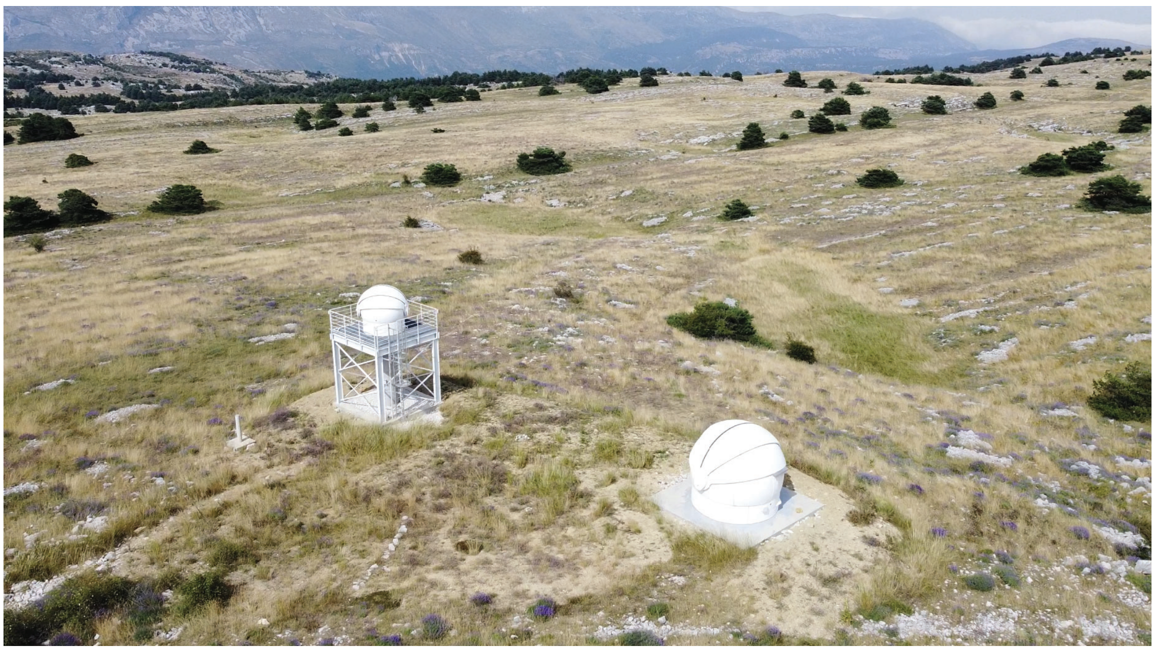

Figure 1. CATS station installed on the Calern Observatory. The left instrument on the platform is the G-DIMM, and the right one is the PML.

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 2). It observes a bright single star with a short exposure time. From the differential variance of the photocenter coming from the two small sub-apertures, it deduces the Fried parameter r_0 and the seeing ε_0. The third sub-aperture allows to deduce the isoplanatic angle θ_0 from scintillation measurements.[13] By computing the temporal structure constant of the Angle of Arrival (AA) through each sub-aperture, GDIMM deduces the effective wind speed $\overline{v}$ and then the coherence time $\tau_0 = 0.31\frac{r_0}{\overline{v}}$. Finally, using a combination of one of the small apertures and the third one, we are able to compute the wavefront coherence outer scale $\mathcal{L}_0$. For more details about the GDIMM method, see Ref. 13. 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 3) 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 spatial resolution of $\Delta h = 100m$ for the ground layer to $\Delta h = 2000m$ for

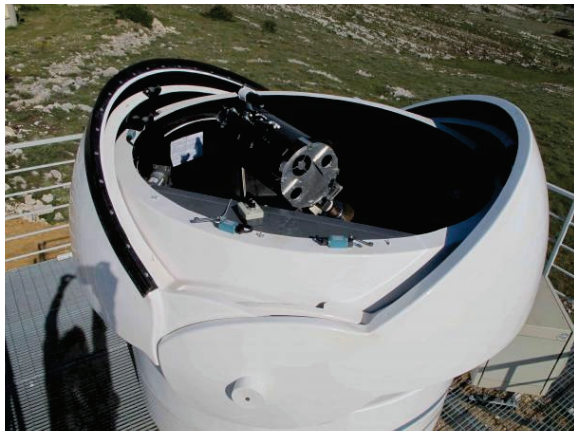

Figure 2. GDIMM instrument installed on the Calern Observatory.

the highest layers (see figure 3, right). 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 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. 3, 17. 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).

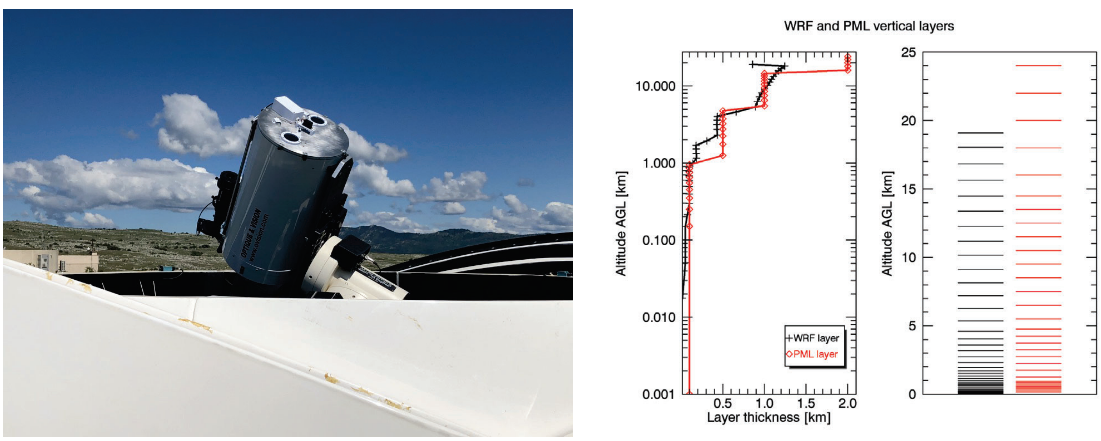

Figure 3. PML instrument installed on the Calern Observatory. On the right panel one can see the vertical levels of the layers measured by PML (in red). One can also see the vertical levels of the prediction tool presented below.

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, and which is presented in 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. 10.

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 during both daytime and nighttime the atmospheric turbulence conditions from the ground level up to the top of atmosphere. However, in astronomical observatories and for optical telecommunications, it is now mandatory to forecast atmospheric conditions and optical turbulence. The goal of such a prediction is multiple:

- Adapt the observation planning regarding the predicted turbulence to improve efficiency of observatories and to avoid pecuniary losses: **flexible scheduling**
- Improve site characterization and site search by using long-terms analysis of predictions
- Search optical ground station sites for optical telecommunications
- Define the best optical ground station, between a network, in function of the turbulence conditions, to transfer the signal from satellite: **smart scheduling**.

Since many years, to compute such forecasting, we use the Weather Research and Forecasting (WRF)[18] system developed by the National Center for Atmospheric Research (NCAR). This mesoscale model gives access to forecasts of weather conditions (pressure, temperature, wind speed, relative humidity, etc.) within a tridimensional domain defined by the user. To properly work, WRF needs to have access to static data (orography, albedo, land type, etc.), but also to large scale weather conditions to initialize each WRF simulation of the atmospheric evolution.

One of the advantages of WRF is its number of configurations of the microphysical, physical, cloud, etc. schemes to run simulations. All these possibilities are useful, but it is difficult to understand which one is the best for a specific need. In this framework, 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 visible in Ref. 19.

Once the weather conditions predicted, to deduce optical turbulence parameters, we need a model using these conditions. In Ref. 19, we have studied two different turbulence models and we have highlighted their advantages and their drawbacks:

- The theoretical model, based on the Tatarskii equation,[20] is more reliable to compute instantaneous predictions.
- The empirical model was initially deduced from an analysis of radio-sounding balloons.[5,7,21] This model, uses mainly the vertical gradient of the potential temperature and the vertical wind shear to compute the vertical profile of the turbulence energy $C_n^2(h)$. It 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. 8.

Figure 4 shows the difference between the statistical and instantaneous reliability of both models over Cerro Pachon site. As mentioned above, the Tatarskii model gives better instantaneous predictions than the empirical one (call phiModel in this figure 4).

Since 2019, we have developed a forecasting tool[*] in 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 8 to improve the initial empirical model (called BDTM in figure 5) and to better consider site specificities. This new method brings a large improvement on turbulence forecasting, as shown on figure 5. This figure also shows that, in particular during daytime, there are still differences between measurements and predictions. One of the sources of such a difference is due to ground layer conditions which are more instable during the day, and which are very dependent on the site configuration.

[*] https://cats.oca.eu/

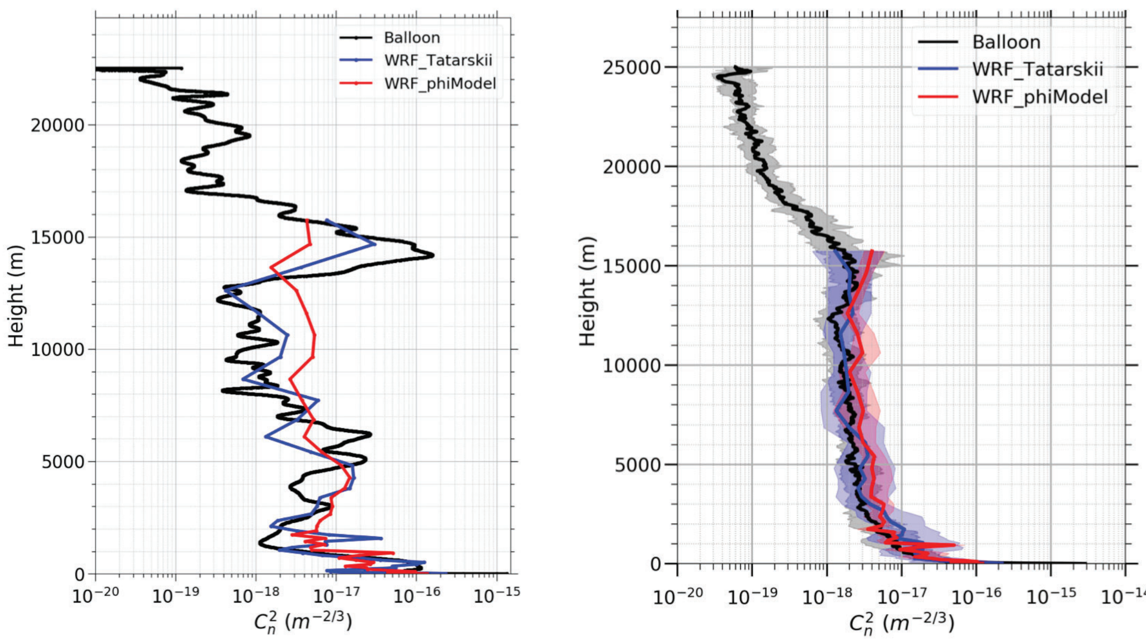

Figure 4. Vertical profile of the C_n^2 above Cerro Pachon site. On the left, the instantaneous C_n^2 measured (black) and predicted (red and blue). On the right the median profile compute over all the campaign. One can see that the Tatarskii model is better than the empirical one (called phiModel) for instantaneous prediction. However, regarding statistics, both model gives comparable predictions, but the empirical model has the lower dispersion. Figure extracted from Ref. 19.

3.2 Forecasting with machine learning algorithm

To complete the aforementioned tool which uses mesoscale model, and to improve the short-term forecasting, we are currently developing another forecasting method based on machine learning (ML) algorithm. Indeed, mesoscale model are reliable to have mid-term predictions (3 to 48h in advance), but the computational time could be long, and for short term forecasting, the precision could be better. Therefore, machine learning could act as a complementary tool to improve it forecasting in this time range. The principle is to inject an important amount of local measurements scenarii within a ML algorithm to have a model allowing us to predict the next one or two hours with a better accuracy, because of its dependance to the current measurement. The main difficulties in this context are about the volume and the preparation of the training data used to deduce the relationship between input and output. One of the important point is the temporal aspect of the model. Indeed, we are doing a prediction in the future therefore the scenarii used must integer a temporal effect which must be cyclic to consider diurnal or seasonal effects.

Ref. 9 shows in detail the first step of our work to prepare data and deduce the ML model. We tested two different algorithms (Ridge Regression and Random Forest) to predict the seeing in the next two hours. Figure 6 shows the first encouraging results on seeing prediction by plotting scatter plot and Pearson correlation coefficient evolution between the beginning and the end of the prediction (T0+2h).

4. INSTRUMENTED DRONE

We have shown in previous sections that forecasting the turbulence conditions is a very complex topic requiring a lot of study and requiring in situ measurements either to test and improve the models thanks to SL method or to inject them within ML algorithm. In particular, we have shown in Ref 8 that a difference subsists in the first 500m. This is due to the difficulty for mesoscale model to well consider site specificities such as orography, ground type, etc., especially when the location is a complex terrain such as observatories in mountain. Therefore,

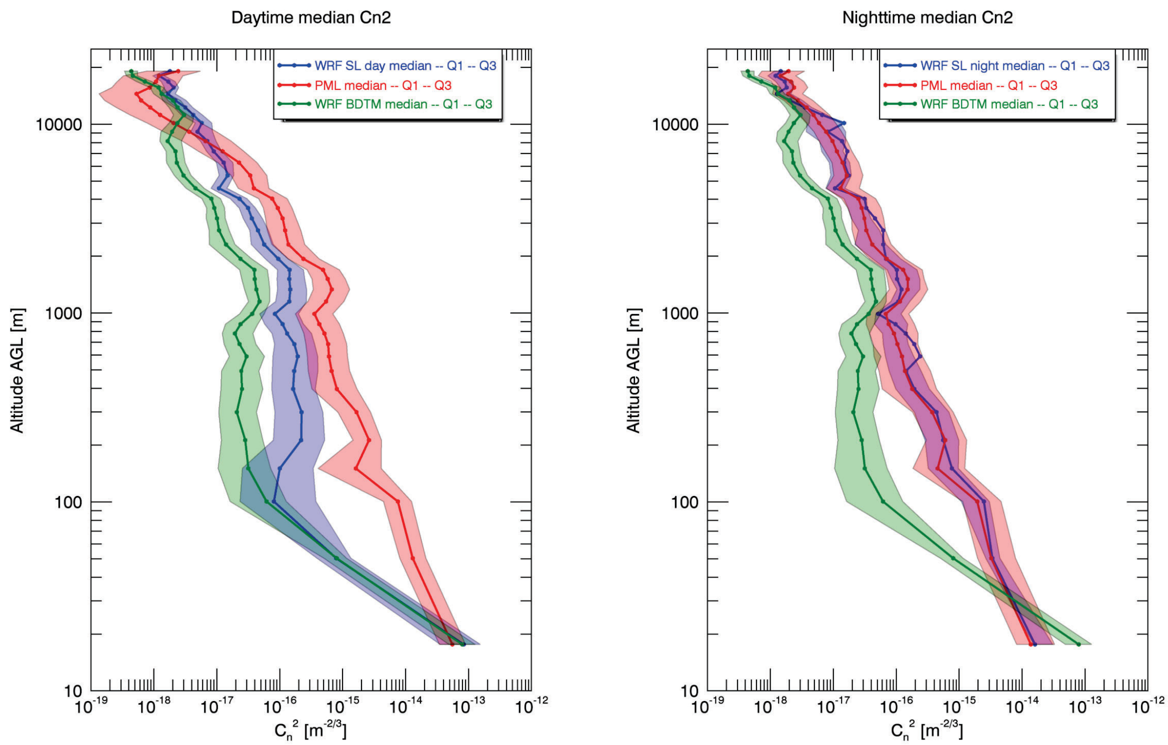

Figure 5. Median vertical profiles of the C_n^2 measured by PML (red) and predicted by WRF using either the initial empirical model (called BTDM) (green) and SL (blue) method. The site learning method considers daytime (left) and nighttime (right) conditions separately. The shaded surfaces show the interval 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. 8.

the models have not enough information to simulate atmospheric conditions near the ground and errors occur and propagate.

In order to investigate about these errors, we need to have an instrument measuring vertical profiles of weather conditions and not only turbulence conditions. Until now, on Calern observatory CATS gives access only to ground weather conditions, and to vertical profiles of turbulence energy $C_n^2(h)$. To complete these measurements, we have then developed a new instrumentation based on the concept of balloon but removing their drawbacks by using a drone. To this drone, we attach an instrumented nacelle measuring weather conditions: pressure, temperature, humidity, wind speed and direction. The main advantages of this instrumented drone are:

- The balloon derives up to hundreds of kilometers from the starting point. Therefore, measured profile does not correspond to the site anymore after a while. With drone we are able to remain stable above a specific location during the ascent and the descent.
- With 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 drone, the nacelle is reusable as much as possible.

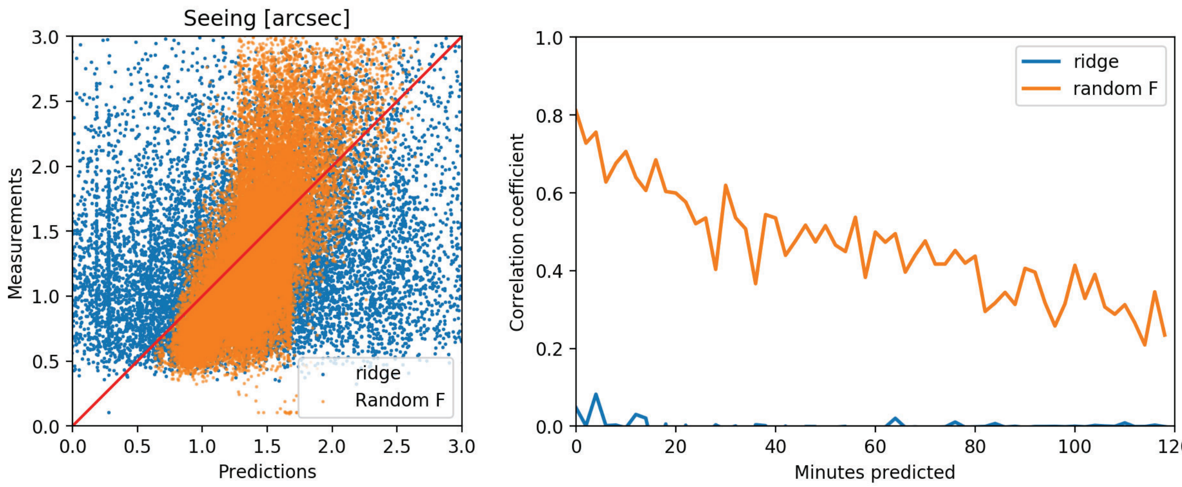

Figure 6. Scatter plot (left) and evolution of the Pearson correlation coefficient (right) during the 2 hours predicted for both algorithms (blue: ridge regression, orange: random forest regression) used in our study.

- 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.

A picture of the drone and the nacelle is visible in figure 7. 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 visible in Ref.22. In the future, these measurements will be used as a constraint to the mesoscale model and as input to turbulence and ML models.

5. DISCUSSION

The CATS station is installed and operational at the Calern Observatory since autumn 2015. CATS is fully autonomous and monitors atmospheric turbulence parameters continuously thanks to a set of new generation instruments. In particular, CATS is equipped with the PML which is a profiler of turbulence measuring the conditions from the first meters above the ground to the borders of the atmosphere with the highest resolution known and during daytime and nighttime. 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 the laser links of the MéO Laser Ranging Station;
- development of Adaptive Optics projects;
- study of laser uplink propagation in the atmosphere thanks to the T2L2 space mission;
- campaign involving optical telecommunications from space to ground with the SOTA satellite and MéO laser ranging station.
- the ANAtOLIA European project with ESA uses the CATS station as a reference station in an optical telecommunications context.

Figure 7. Picture of a drone flight (left) and of the instrumented nacelle (right). For more details see Ref. 22.

In addition, since many years, we are adding to CATS a forecasting tool using different turbulence model to predict the optical turbulence in advance 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 all atmospheric conditions (weather and turbulence) for the next 48h. These predictions have been tested and optimized thanks to a site learning method.[8] Recently, to complete this tool, machine learning algorithm are investigated for short terms prediction using local measurements. For this topic, a thesis will start on next autumn.

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

In a near future, CATS instrumentation will also be upgraded thanks to a new generation of instrument developed within the ANAtOLIA project.[10] In addition, the forecasting of cloud coverage is currently investigated and will be an important point for the community.

6. ACKNOWLEDGMENTS

This CATS project has been done under the financial support of CNES, Observatoire de la Côte d'Azur (OCA), Labex First TF, AS-GRAM, Federation Doblin, Université de Nice-Sophia Antipolis and Region Provence Alpes Côte d'Azur. We would like to thank all the technical and administrative staff of the Observatoire de la Côte d'Azur and our colleagues from the Lagrange and GeoAzur laboratories. We thanks also the NCAR center and the WRF community for giving access and support to this tool.

REFERENCES

[1] Chabé, J., Ziad, A., Fantéï-Caujolle, Y., Aristidi, É., Renaud, C., Blary, F., and Marjani, M., [*The Calern atmospheric turbulence station*], vol. 9906 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 99064Z (2016).

[2] Ziad, A., Chabé, J., Fantei-Caujolle, Y., Aristidi, E., Renaud, C., and Ben Rahhal, M., "CATS: an autonomous station for atmospheric turbulence characterization," in [*Proceedings of the SPIE*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10703**, 107036L (July 2018).

[3] Ziad, A., Chabé, J., Fantei-Caujolle, Y., Aristidi, E., Renaud, C., and Giordano, C., "The Calern Atmospheric Turbulence Station," in [*Proceedings of the sixth AO4ELT Conference*], (2019).

[4] Giordano, C., Ziad, A., Aristidi, E., Chabé, J., Fanteï-Caujolle, Y., Renaud, C., and Rafalimanana, A., "CATS: continuous turbulence characterization station for both optical link and astronomical support," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11852**, 118522D (June 2021).

[5] Giordano, C., Vernin, J., Vázquez Ramió, H., Muñoz-Tuñón, C., Varela, A. M., and Trinquet, H., "Atmospheric and seeing forecast: WRF model validation with in situ measurements at ORM," *Monthly Notices of the Royal Astronomical Society* **430**, 3102–3111 (Apr. 2013).

[6] Giordano, C., Vernin, J., Trinquet, H., and Muñoz-Tuñón, C., "Weather Research and Forecasting prevision model as a tool to search for the best sites for astronomy: application to La Palma, Canary Islands," *Monthly Notices of the Royal Astronomical Society* **440**, 1964–1970 (May 2014).

[7] Giordano, C., *Prédiction et optimisation des techniques pour lâĂŹobservation aÌĂ haute reÌĄsolution angulaire et pour la future génération de très grands télescopes*, PhD thesis, Université de Nice Sophia Antipolis, Nice, France (2014).

[8] Giordano, C., Rafalimanana, A., Ziad, A., Aristidi, E., Chabé, J., Fanteï-Caujole, Y., and Renaud, C., "Contribution of statistical site learning to improve optical turbulence forecasting," *Monthly Notices of the Royal Astronomical Society* **504**, 1927–1938 (June 2021).

[9] Giordano, C., Rafalimanana, A., Ziad, A., Aristidi, E., Chabé, J., Fanteï-Caujolle, Y., and Renaud, C., "Statistical learning as a new approach for optical turbulence forecasting," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11448**, 114484E (Dec. 2020).

[10] Ziad, A., Giordano, C., Aresta, A., Aristidi, E., Bailet, C., Cavazzani, S., Bertolin, C., Berto, F., Carbillet, M., Ceus, D., Charbonnel, T., Delanoe, J., Descloitres, J., Fanteï-Caujolle, Y., Gillioen, A., Gonzales-Ramos, Y., Irbah, A., Jacqmart, E., Le Kernec, A., Liandrat, O., Poulenard, S., Riédi, J., Schmutz, N., and Victori, S., "ANAtOLIA : a mobile station for site availability characterization for Optical Communications links," in [*International Conference on Space Optics (ICSO) Conference Series*], *International Conference on Space Optics (ICSO) Conference Series* **11852** (Oct. 2022).

[11] Aristidi, E., Fanteï-Caujolle, Y., Ziad, A., Dimur, C., Chabé, J., and Roland, B., [*A new generalized differential image motion monitor*], vol. 9145 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 91453G (2014).

[12] Aristidi, E., Fantei-Caujolle, Y., Chabé, J., Renaud, C., Ziad, A., and Ben Rahhal, M., "Turbulence monitoring at the Plateau de Calern with the GDIMM instrument," in [*Proceedings of the SPIE*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10703**, 107036U (July 2018).

[13] Aristidi, E., Ziad, A., Chabé, J., Fantéi-Caujolle, Y., Renaud, C., and Giordano, C., "A generalized differential image motion monitor," *Monthly Notices of the Royal Astronomical Society* **486**, 915–925 (Jun 2019).

[14] Ziad, A., Blary, F., Borgnino, J., Fanteï-Caujolle, Y., Aristidi, E., Martin, F., Lantéri, H., Douet, R., Bondoux, E., and Mekarnia, D., "PML/PBL: A new generalized monitor of atmospheric turbulence profiles," in [*Proceedings of the Third AO4ELT Conference*], Esposito, S. and Fini, L., eds., 126 (Dec. 2013).

[15] Blary, F., Ziad, A., Borgnino, J., Fantéï-Caujolle, Y., Aristidi, E., and Lantéri, H., [*Monitoring atmospheric turbulence profiles with high vertical resolution using PML/PBL instrument*], vol. 9145 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 91453H (2014).

[16] Aristidi, E., Ziad, A., Fantéï-Caujolle, Y., Chabé, J., Giordano, C., Renaud, C., and Lantéri, H., "Monitoring daytime and nighttime optical turbulence profiles with the PML instrument," in [*Proceedings of the sixth AO4ELT Conference*], (2019).

[17] Chabé, J., Aristidi, E., Ziad, A., Lantéri, H., Fanteï-Caujolle, Y., Giordano, C., Borgnino, J., Marjani, M., and Renaud, C., "PML: a generalized monitor of atmospheric turbulence profile with high vertical resolution," *Applied Optics* **59**, 7574 (Sept. 2020).

[18] Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D., Liu, Z., Berner, J., Wang, W., Powers, J., Duda, M., Barker, D., and Huang, X.-Y., "A Description of the Advanced Research WRF Version 4," tech. rep., NCAR (2019).

[19] Rafalimanana, A., Giordano, C., Ziad, A., and Aristidi, E., "Optimal Prediction of Atmospheric Turbulence by Means of the Weather Research and Forecasting Model," *Publications of the Astronomical Society of the Pacific* **134**, 055002 (May 2022).

[20] Tatarskii, V. I., [*Wave Propagation in Turbulent Medium*], Dover Publication (1961).

[21] Trinquet, H. and Vernin, J., "A statistical model to forecast the profile of the index structure constant C_N^2," *Environmental Fluid Mechanics* **7**, 397 (Sept. 2007).

[22] Rafalimanana, A., Giordano, C., Ziad, A., Aristidi, E., Fanteï-Caujolle, Y., and Bailet, C., "Towards an optimal prediction of the optical turbulence in the ground layer by means of an instrumented drone," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* (July 2022).