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ANAtOLIA : First light to first results



## ANAtOLIA : First light to first results

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### ABSTRACT

ANAtOLIA (Atmospheric moNitoring to Assess the availability of Optical Links through the Atmosphere) is a project funded by the European Space Agency and aims to ground sites selection and assess their availabilities for optical links through the atmosphere. Astronomical observations and space-to-ground optical communications are limited by clouds, aerosols and atmospheric turbulence. Therefore, we developed in the framework of the ANAtOLIA project, an innovative and efficient instrumentation and methods to accurately measure, analyze, characterize, and ultimately predict critical atmospheric parameters for the purposes of the selection of the astronomical and OGS (Optical Ground Station) sites and the evaluation of their availability. ANAtOLIA is a compact mobile station consisting of the GMT monitor (Generalized Monitor of Turbulence), Reuniwatt Sky Insight camera and Cimel CE318-T photometer, which is operational 24h a day, 7 days a week in any site around the world with minimal infrastructure. The ANAtOLIA station, being installed in Calern Observatory (France), Cebreros (Spain) and in Catania (Italy) in the beginning of 2023, we present in this communication the first light and first statistical analysis above the three sites.

**Keywords:** Site-testing, atmospheric optics, atmospheric turbulence, turbulence monitoring, cloud monitoring, aerosol characterization

### 1. INTRODUCTION

The motivation for optical space communication systems stems from the expectation that substantially higher (10 times) data rates than RF-based solutions. But optical space communication through the Earth atmosphere is nearly impossible in the presence of most types of clouds. In addition to cloud cover, space-to-ground optical communications are limited by the presence of dust, aerosols and atmospheric turbulence. Therefore, it is important to specify, accurately measure, analyze, characterize, and ultimately predict critical atmospheric parameters for the purposes of the selection of the OGS sites and the evaluation of their availability. The limited availability of OGS due to clouds and other atmospheric impacts need to be considered to give a reliable estimate of the optical link system performance. An OGS network is required for increasing the availability to acceptable figures.<sup>1</sup> In this case, a site diversity concept needs to be implemented in order to boost the low availability of an individual OGS to an acceptable availability of a network of OGS. Ultimately, the decision and frequency of

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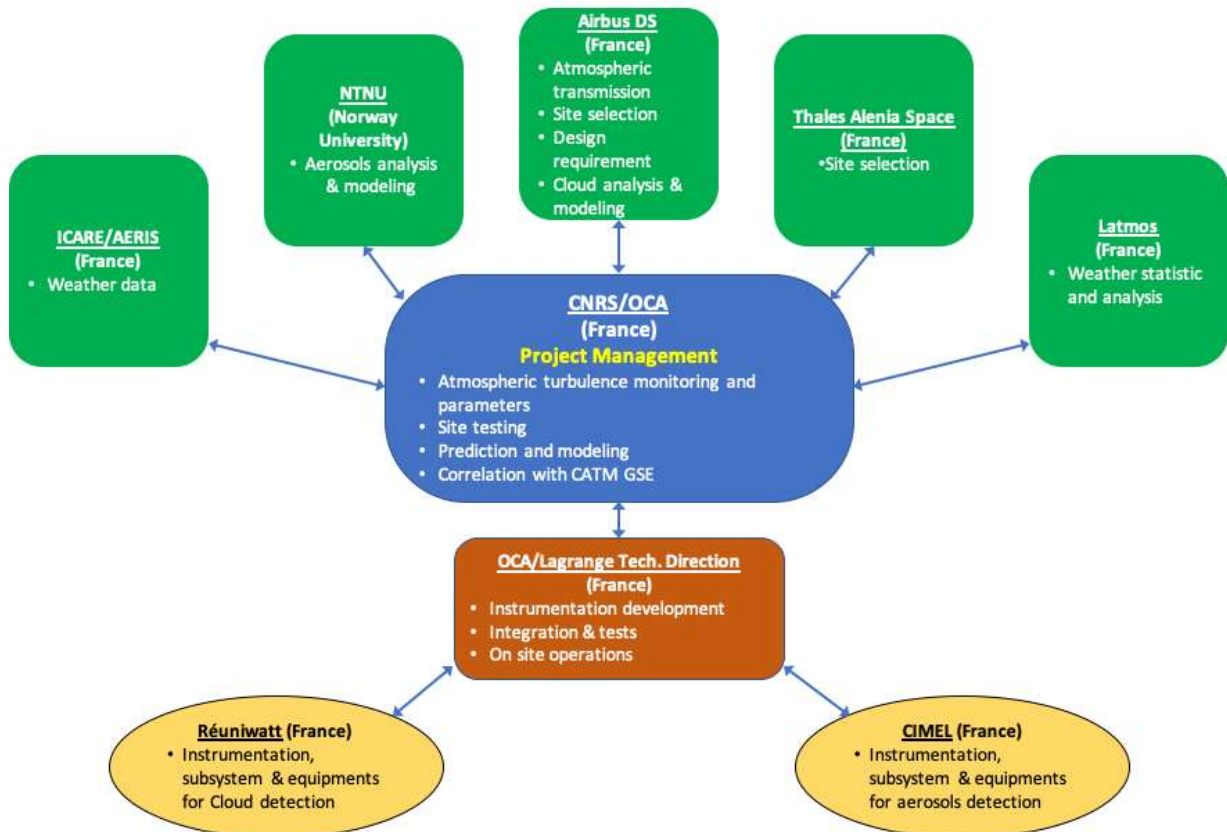


Figure 1. The structure of the ANAtOLIA consortium

the handover operation will be determined by the accuracy of the local monitoring of clouds, turbulence, and aerosols.

In this paper we present the updates of Ref.<sup>2</sup> related to a new compact station for site-testing in terms of clouds, turbulence and aerosols. The ANAtOLIA station<sup>2</sup> has been developed in the framework of a european consortium (see Figure 1) and a contract with the European Space Agency (ESA). The ANAtOLIA is a compact mobile high performance station operational 24h a day, 7 days a week in any site around the world with minimal infrastructure such as power and internet access. After two year development and on-sky tests campaign at the Calern Observatory, the ANAtOLIA station is now installed and operational at four european sites (Calern, Catania, Cebreros and Sintra). The ANAtOLIA project and objectives are presented in Section 2. The different instruments of the ANAtOLIA station are described in Section 3, and the preliminary statistics are presented and discussed in Section 4.

## 2. THE ANATOLIA PROJECT

The optical communication system solution for a particular mission uses OGS that are geographically dispersed. The goal is to increase probability of a cloud-free line of sight (CFLOS) to a ground station from spacecraft at any time and position. The Optical Link Study Group (OLSG)<sup>1</sup> analyzed the space-Earth mission scenarios for CFLOS and expressed the results in a common metric across the scenarios-percent data transferred (PDT). The analysis indicates ground segment solutions are possible for all scenarios, but require multiple, geographically diverse ground stations in view of the spacecraft.

ANAtOLIA aims to ground-sites selection and assess their availabilities for optical links through the atmosphere. Therefore, we propose an innovative and efficiency instrumentation and studies to specify, accurately

measure, analyze, characterize, and ultimately predict critical atmospheric parameters for the purposes of the selection of the OGS sites and the evaluation of their availability.

ANAtOLIA's goal is to identify ground sites and evaluate their availability for atmospheric optical links. To achieve this, we propose innovative and efficient tools and studies that will specify, accurately measure, analyze, and characterize critical atmospheric parameters to assess the availability of OGS sites. Ultimately we will predict these parameters to improve in real time the choice of OGS for the handover.

ANAtOLIA project is divided in three objectives:

1. The main objective is to design, manufacture, procure and assembly a self-standing and autonomous ground support equipment, comprising cloud, aerosol and turbulence monitoring to deliver precise measurements of the atmosphere transmission.
2. The second objective is to install and commission these atmosphere monitors at selected ground locations in ESA member states or in their vicinity and to record continuously local cloud, aerosol information and atmospheric turbulence conditions for a sufficiently long temporal period (24 months).
3. The last objective is to correlate these local ground measurements from monitors with data available from other sources of cloud coverage and atmospheric conditions (e.g., MSG, MODIS, local meteorological sites). The main goal of these correlations is to improve knowledge of the optical link availability for selected optical ground station locations and to carry out a long-term validation of the optical link availability prediction methods.

To fulfill these objectives, the CNRS-OCA's consortium proposal consists to design and manufacture a mobile station with high performance equipment. Before starting instrumental development, a specific attention has been dedicated to the definition of the list of critical atmospheric parameters and the selection of optical ground stations. Based on numerical simulations and on the atmosphere data, impacts of atmospheric transmission on link performances has been studied to finalize the list of the pertinent parameters in terms of clouds, aerosols and turbulence. This list is then visible in table 1.

In front of this final list of critical parameters we provided a finalized list of instrumental solutions to perform the measurements with the required precision and the adequate sampling. The chosen instrumentation is composed of (Fig. 2):

- a unique atmospheric turbulence monitor GMT capable of extracting, the whole atmospheric turbulence parameters required by ESA (Table 1) during both daytime and nighttime,
- the Reunivatt Sky Insight which is a wide field IR sky imager as a monitoring equipment 24h/day for a precise characterization of clouds
- the Cimel CE318-T photometer which is a multispectral atmospheric photometer for aerosols precise characterization.

This compact mobile station is operational 24h a day, 7 days a week in any site around the world with minimal infrastructure such as power access.

The station has been installed and is now operational on four selected sites for measurement campaign during a period of 24 months. Then, data extraction and analysis, including correlations with data from other data sources (MODIS, MSG, etc...) will be performed. Finally, we propose to carry out long-term characterization of the selected sites by means of predictive methods and models.<sup>3</sup>

Table 1. List of atmospheric parameters measured by the ANAtOLIA station.

Cloud parameters	Cloud coverage
	Cloud base height
	Cloud type
	Cloud Optical Depth
Aerosol parameters	Aerosol Optical Depth
	Angstrom Exponent
	Single Scattering Albedo
Turbulence parameters	Fried's parameter
	Atmospheric seeing $\varepsilon_0$
	Isoplanatic angle $\theta_0$
	Isokinetic angle $\theta_k$
	Angle of Arrival fluctuations
	Greenwood frequency
	Scintillation
	Refractive index structure constant $C_n^2(h)$
	Outer scale $L_0$
	Effective wind speed $v_e$
Coherence time $\tau_0$	
Standard ground weather parameters	Temperature
	Relative humidity
	Pressure

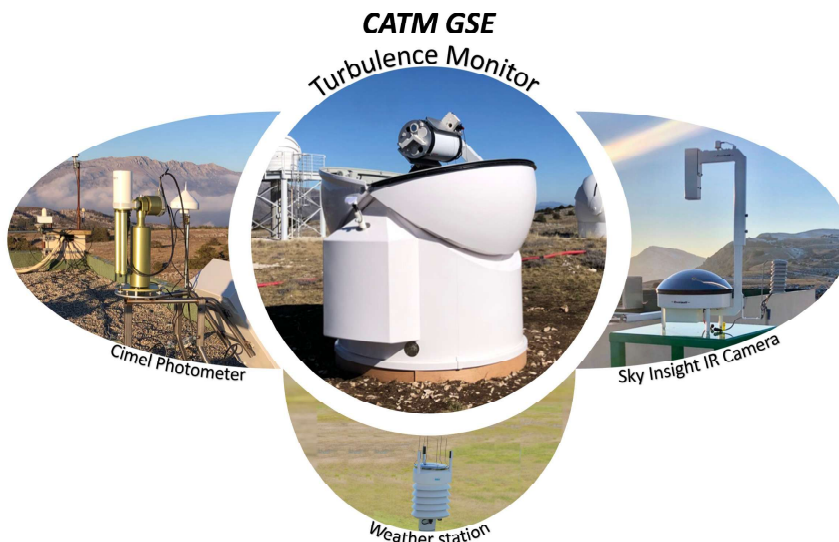


Figure 2. The high performance ANAtOLIA station

### 3. THE ANATOLIA INSTRUMENTS

To achieve the requirements of the ANAtOLIA project in terms of scientific goals, the station Calern Atmospheric Turbulence Station<sup>4,5</sup> (CATS) is the best set of instrument to meet the requirements afor optical turbulence measurements. However, to respect the budget of this project we needed to compact CATS. Thus, we proposed

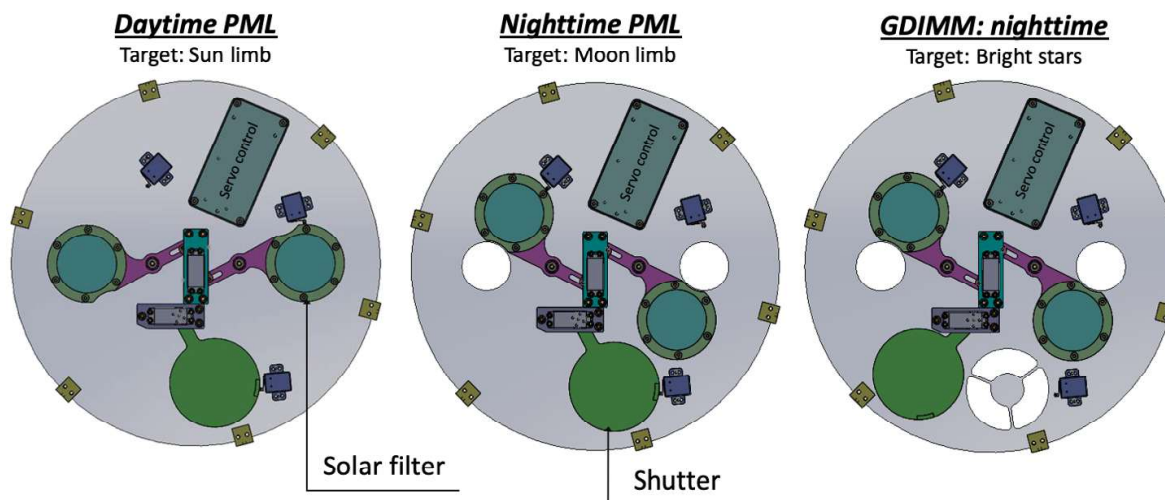


Figure 3. Different GMT's mask configurations for 24h atmospheric turbulence monitoring passing from PML to GDIMM mode.

to merge GDIMM\*<sup>6</sup> and PML<sup>†7</sup> of the CATS station<sup>4,5</sup> in one unique and compact monitor called GMT (Generalized Monitor of Turbulence) without impacting the list of the measured parameters. In addition, to fill the goal in terms of aerosol and cloud measurements, we need to complete the station with two instruments, for clouds and aerosols detection and characterization corresponding respectively to the Reuniwatt Sky InSight camera and the Cimel CE318-TL9 photometer in addition to a ground weather station (Fig. 2).

This compact mobile station consisting of GMT monitor, Reuniwatt Sky InSight camera and Cimel CE318-TL9 photometer is then a high performance and confirmed set of instruments. This station is operational 24h a day, 7 days a week and is usable in any site around the world with minimal infrastructure such power access or internet connection.

### 3.1 Generalized Monitor of Turbulence

The GMT is a unique instrument to monitor the optical turbulence in any site around the world and during daytime and nighttime. It is a compact and improved version of the CATS station as shown in Fig. 2 and as explained in detail here-after. The GMT instrument is mainly dedicated to the extraction turbulence parameters from lunar, solar or bright star observations and fluctuations.

The GMT instrument consists of a small telescope installed on an precise equatorial mount. A pupil mask (see Fig. 2) is placed at the entrance pupil of the telescope. It is composed of two sub-apertures of diameter  $D = 6\text{cm}$  separated by a baseline  $B = 26.7\text{cm}$  and a third one of 10cm diameter with a 4cm central obstruction (Fig. 3). In addition, the GMT instrument is equipped with automatic solar filter to cover the two small sub-apertures for Sun observations, and a stop filter cover the third aperture for Sun or Moon observations (Fig. 3). This stop filter (in addition to solar filter) is removed to observe bright stars in the GDIMM mode using the three pupils. The third sub-aperture is also covered by a prism to avoid overlapping with the two other spots when observing a bright star.

A small optical bench is installed in the focal plan of the telescope. It allows to separate the three beams coming from the three sub-apertures, and to re-image the Sun, the Moon or the bright star on the scientific CCD

\*Generalized Differential Image Motion Monitor

†Profiler of Moon Limb

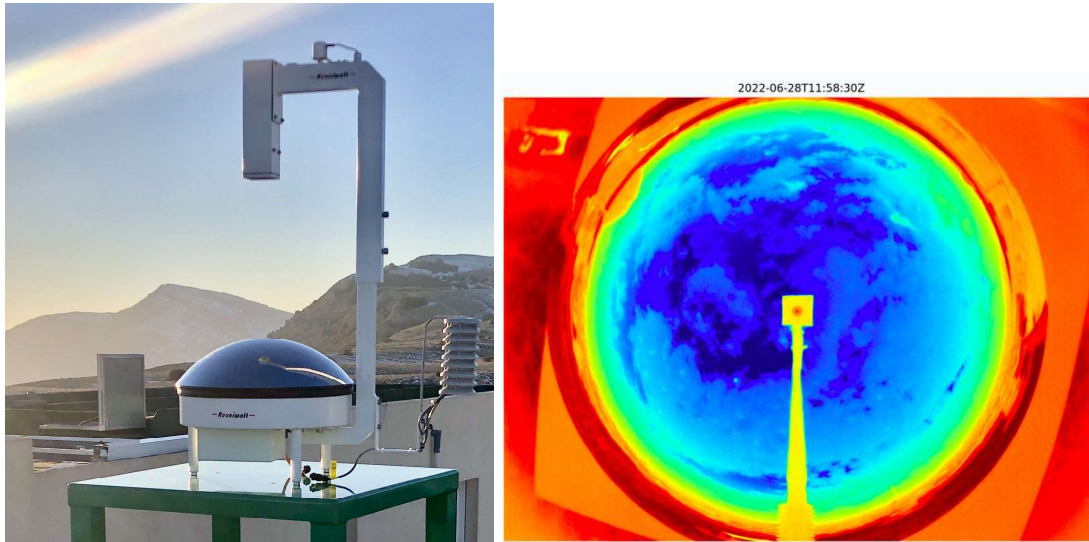


Figure 4. Left: Sky InSight installed on Calern observatory. Right: Example of image acquired with the Sky InSight camera.

camera. In order to freeze atmospheric effects on the motion of the Moon/Sun or bright star and to have enough flux, the exposure time is set to 5-10ms.

In PML mode,<sup>7</sup> the principle of the GMT instrument is based on the measurement of the angular correlation of the fluctuation differences in the wavefront AA deduced from the motion of the Moon's (or Sun) limb image. From these AA fluctuations we can extract the  $C_n^2(h)$  profile with high resolution (see Ref.<sup>7</sup>) in real time and every 2-3 minutes. Other parameters of turbulence are also accessible from this instrument the seeing, the isoplanatic angle or the scintillation.

When the Moon is not observable during nighttime, the GMT switch to GDIMM mode.<sup>6</sup> A bright star is thus observed with the three sub-apertures as shown in Fig. 3 right. The GMT in GDIMM mode is able to measure/deduce in real time all the integrated turbulence parameters<sup>6</sup> every 1-2 minutes. The seeing (or Fried parameter) is computed from DIMM method using the two small sub-apertures. The isoplanatic angle is deduced from scintillation measurement through the third and larger sub-aperture. The coherence time is obtained from the 3 sub-apertures by computing the temporal structure function. Finally, the outer scale is obtained from normalized Angle-of-Arrival variances. All other parameters are deduced from these ones.

### 3.2 Sky Insight IR camera

The SkyInSight IR camera is a patented infrared sky imager developed by Reuniwatt<sup>‡</sup> company for the continuous tracking and forecasting of the cloud cover. The use of the infrared wavelength enables an unprecedented accuracy for day & night cloud detection, while catching additional information on the cloud ceiling. The Sky Insight imager is a confirmed and validated instrument allowing a precise and a complete characterization of clouds (cloud coverage, base height, type, optical thickness and attenuation). In addition, several weather sensors are also embedded into Sky Insight: a solar reference cell, a thermometer, and a humidity sensor to refine the precision of each measurement.

Sky InSight (Figs. 2 & 4) is composed of a long-wave infrared (LWIR) camera with a  $640 \times 480$  pixel spatial resolution. The radiation coming from the sky is reflected on a hemispherical mirror that provides a  $360/180^\circ$  view of the sky. Its chrome-coated surface ensures an optimal reflection of LWIR radiations. This mirror has been chosen for cost-reduction purposes as well as for a better calibration due to a lower curvature of the dome than that of a small germanium upward-looking fish-eye camera. Humidity and temperature sensors, installed in

<sup>‡</sup><https://reuniwatt.com/>

a ventilated casing located near the camera, provide in situ meteorological information improving the estimation of clear atmosphere radiance. An embedded computer is used to acquire and upload the data on a server for measurement processing. The LWIR atmospheric window from  $8\mu\text{m}$  to  $13\mu\text{m}$  is well suited for cloud observation. Cloud emission is high to present a strong contrast with a clear sky radiometric signature. A thermal infrared imager has the advantage of directly detecting cloud emission rather than relying on reflected and scattered sunlight in the case of visible or near-infrared observation systems. Thus, cloud detection performance does not depend on the illumination of the cloud cover by the Sun, enabling continuous night and day observation. Benefits of using a thermal camera are particularly obvious when you look in the Sun's direction. The pixels of visible cameras tend to be saturated, which distorts any relevant information regarding cloud presence. In contrast, Sky InSight shows a very limited saturated region. The accompanying software, provides a cloud image (Fig. 4 right) every 30 seconds (a higher rate is also possible) as well as the result of the automatic and real-time cloud fraction calculation in okta. Other parameters such as cloud optical depth and altitude of clouds are also provided in real time.

### 3.3 Cimel Aerosol photometer

Although the effect of aerosol concentration is not a primary attenuation parameter (fade is typically less than 1 dB) for optical communications, it is still important to characterize them at ground station (GS) and account for aerosols in the system's link budget. Composed of particles and droplets suspended in the atmosphere, the aerosol density in the atmosphere can vary significantly according to location and time of year. For example, an optical ground station located on Tenerife would experience large transmission losses due to the Calima (Saharan dust) events that occur periodically in the spring and summer months.

The Cimel<sup>§</sup> CE318 photometer is a reference for automatic multispectral atmospheric photometry. Developed for NASA in 1992, it was constantly improved to meet the growing requirements of AERONET (Aerosol RObotic NETwork), the worldwide federation of networks dedicated to the measurement of atmospheric aerosols and federated by NASA. Other independent networks such as SKYNET, CARSNET, and SONENT also operate CE318 photometers. The latest version, the CE318-TL9, takes advantage of cutting-edge technologies to improve metrological performance and facilitate operations. AERONET decided in 2015, after full validation, to accept only the CE318-T for new photometers entering the network. The CE318-T performs Sun, sky and lunar light measurements, for the retrieval of essential physico-optical parameters: Aerosol Optical Depth (AOD), Volume Size Distribution (VSD), complex refractive index ( $n$ ), shape factor and water vapor content. The high sensitivity tracking, detection chain and internal data processing result in enhanced measurements. Flexible communication and solar autonomy allow easy operation both on fixed sites and temporary locations.

The new Sun-sky-lunar Cimel CE318-TL9 photometer has been developed by the Cimel company improving the tracking precision in order to perform both daytime (Sun) and nighttime (Moon) measurements and providing additional and enhanced operational functionalities. The CE318-TL9 is based on a new control unit and a new four-quadrant system in the sensor head. The CE318-TL9 presents higher signal-to-noise ratios (better than 60 dB) to capture not only the daytime radiation from the Sun but also the limited energy during nighttime reflected by the Moon, and therefore it is able to provide valuable information of aerosols and water vapor 24h a day. The new CE318-TL9 performs measurements at an approximate field of view of  $1.29^\circ$  at ten nominal wavelengths of 1020, 937, 870, 675, 500, 440, 380 and 340 nm, using a silicon photodiode detector, as well as additional measurements at 1020 and 1640 nm using an InGaAs detector. An adjustment has been done to provide measurements at optical communication wavelengths (1064nm and 1550nm). This new instrument performs three different measurement types: spectral direct Sun and direct Moon irradiance measurements to obtain aerosol and water vapor content, and spectral sky radiances to infer aerosol properties from inversion during daytime period. This is the reason for applying the term "triple" to this new Cimel photometer. As in the standard AERONET version, the CE318-T takes a sequence of three measurements (triplet) every 30s at each wavelength. The triplet value is defined as the maximum minus minimum divided by the mean value of these three consecutive measurements. It means that each triplet represents the normalized range of these three consecutive measurements. At this moment, the triplet information is used to detect and remove clouds as well as to check the instrument's stability until a new operative cloud screening is applied.

<sup>§</sup>(<https://www.cimel.fr>)



Figure 5. Cimel CE-318-TL9 photometer installed on Calern Observatory.

#### 4. CAMPAIGN & FIRST RESULTS

##### 4.1 Site installation and selection

Based on a specific climate diversity study, four sites have been selected to be equipped with ANAtOLIA stations. As shown in figure 6, the selected sites are Calern in the South of France, the ESA Cebereros site near Madrid, the Catania Observatory in Sicily and Sintra near Lisbon, with Atlantic influence. Figure 6 shows also pictures of each ANAtOLIA station installed on each site. Once the station installed, different tests and calibrations are performed for each instrument to be ready for campaign measurements.



Figure 6. Selected sites to receive the stations.

ANAtOLIA is a fully autonomous station and for that it is integrated within an internal network allowing to control the whole ANAtOLIA instruments. This internal network allows the control of the GMT thanks to the weather station to control the opening of the dome in function of the real time meteorological conditions, and the cloud cover measured by the Reuniwatt SkyInSight IR camera, also used to decide the dome opening to start observations and measurements. All these automation and control are possible thanks to the software architecture. A Grafana web interface has been developed to check in real time the overall stations in the different sites. With this tool, we are able to have a quick look to the status of all deployed stations. Figure 7 shows this Grafana tool presenting a summary of all the stations already installed (Calern, Cebberos, Catania and Sintra). Moreover, for each site we have an additional Grafana page showing more details about the ongoing observations and each instrument functioning. This Grafana tool also allow to have a visualization of measured parameters (seeing, isoplanatic angle, cloud coverage, etc.) in real time. This control allows to detect and solve possible issues in data acquisition and processing.

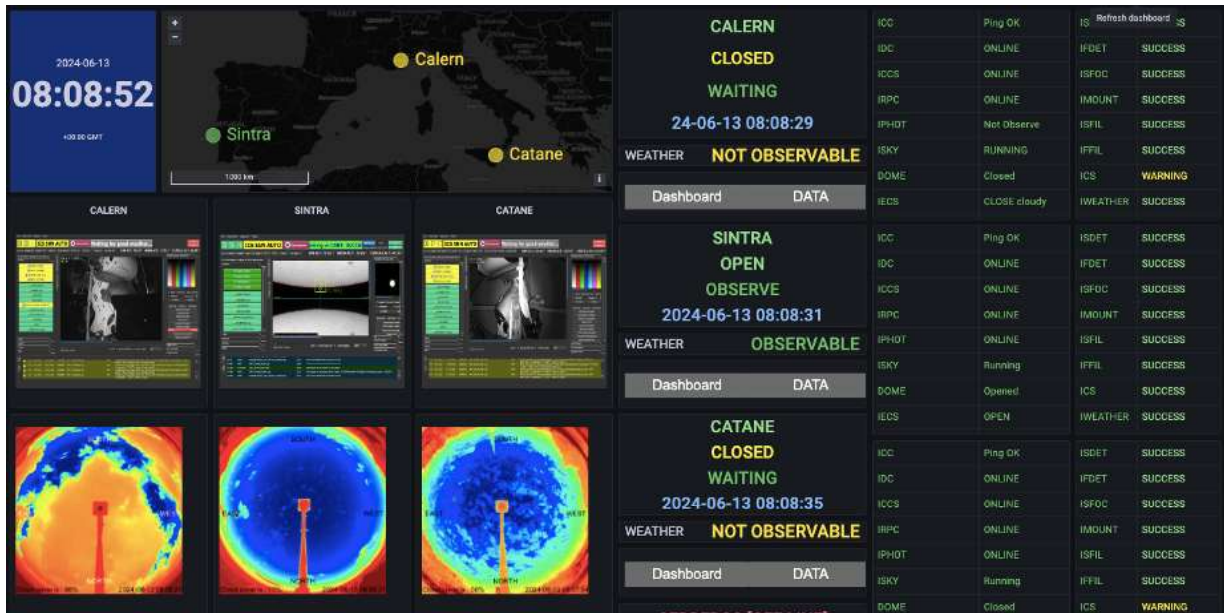


Figure 7. Example of the GRAFANA interface to control the stations.

## 4.2 First results

Figure 8 shows first example of results computed above the Calern observatory. We show the distribution of the seeing measured at  $\lambda = 1550nm$ , separating daytime and nighttime conditions. One can clearly see the differences between the two regimes with a median seeing twice higher during daytime, and a larger dispersion due to the Sun hitting the ground and the atmosphere and producing convection and then optical turbulence. On top right one can see the cloud fraction distribution, showing that the sky is clear for more than 50% of the time on Calern Observatory, and on bottom, we show the distribution of AOD at  $500nm$ . Calern present an  $AOD < 0.1$  within 75% of the measurements, followed by a decreasing tail.

Figure 9 shows first statistics of seeing and isoplanatic angle measured at Calern, Cebberos and Catania sites. In these figure on can see that from almost one-year statistics, the seeing  $\varepsilon_0$  is comparable in Calern and Cebberos, with respectively 78.5% and 72.3% of  $\varepsilon_0$  lower than  $2.5''$ . In Catania, the dominant  $\varepsilon_0$  is between  $2.5''$  and  $5''$  and in 88.7% of the time  $\varepsilon_0$  is lower than  $5''$ . This behavior was expected since Calern and Cebberos are respectively at altitude of 1270m and 850m. When Catania is a urban Observatory at 200m altitude. From almost one-year statistics, the isoplanatic angle  $\theta_0$  behavior is comparable in the 3 sites where  $\theta_0$  is larger than  $1.5''$  in more than 98% of the time. The  $1.5'' - 2.5''$  range is more visible in Catania to the detriment of  $5'' - 10''$  range which is prevailing in Calern and Cebberos. The most prevailing data are between  $2.5''$  and  $10''$  in the 3

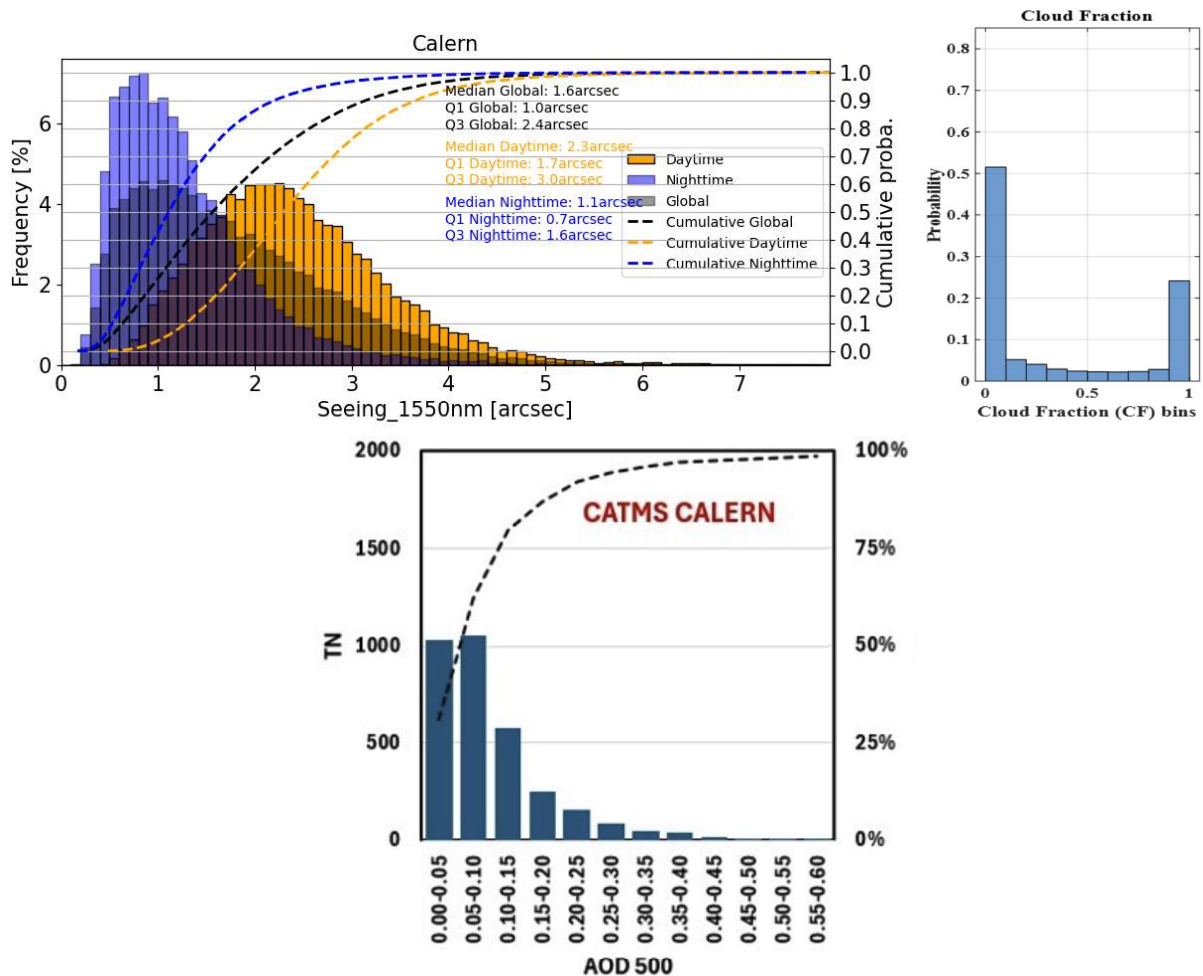


Figure 8. Preliminary results on Calern Observatory. Top left: Distribution of the seeing at  $\lambda = 500nm$ . Top right: Histogram of the cloud fraction measured with the Sky InSight. Bottom: AOD distribution at  $\lambda = 500nm$ .

sites with 84.6% in Calern, 81.5% in Cebrreros and 67.7% in Catania. In Calern and Cebrreros , the  $\theta_0$  is larger than  $5''$  in almost 50% of the time. The isoplanatic angle is mostly impacted by high turbulence layers that why the 3 sites have similar behaviors in terms of  $\theta_0$ . But, due to the ground convection which is stronger in Catania (urban site) and diffuses gradually to the upper layers, and reducing therefore the isoplanatic domain.

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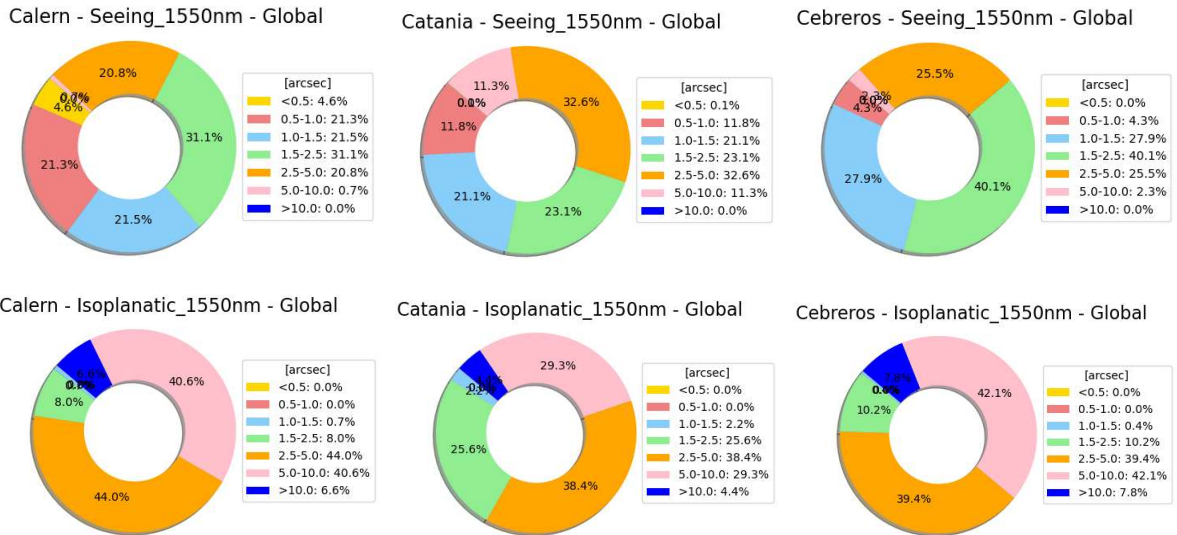


Figure 9. Statistics of Seeing (Top) and Isoplanatic angle (Bottom) measured at Calern, Catania and Cebreros at  $\lambda = 1500nm$ .

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