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## **ANAtOLIA : a high-performance mobile station for atmospheric characterization for Astronomical Observations and Optical Communications**

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### **ABSTRACT**

ANAtOLIA (Atmospheric moNitoring to Assess the availability of Optical LIinks 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,

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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. The main mission objectives of ANAtOLIA are 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. ANAtOLIA is a compact mobile station consisting of the GMT monitor (Generalized Monitor of Turbulence), Reunivatt 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. After two years of instrumental specifications, design, development and on sky tests, we started recently installation of the ANAtOLIA station on selected ground sites in ESA member states to record continuously local clouds, aerosol information and atmospheric turbulence conditions during a 24 month campaign. The data collected with these ANAtOLIA monitors will be correlated 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 OGS sites and to carry out a long-term validation of the optical link availability prediction methods.

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

## 1. INTRODUCTION

The atmospheric parameters have a strong impact on the image formation through the atmosphere. Indeed, the effect of atmospheric turbulence on wavefronts reduces severely the resolution of ground-based astronomical observations. Thus, in the context of astronomical observations, the site-selection has now become essential with the advent of the next generation of Extremely Large Telescopes (ELT). Indeed, it is important to choose sites with reduced cloud coverage, weak turbulence and low aerosol distribution in order to enhance observations time and to improve their scientific performance. It is also important to remember that the choice of sites hosting astronomical projects must meet very strict criteria in terms of optical quality.

In addition, design, performance and optimization of HAR techniques require a well-knowledge of atmospheric turbulence parameters, notably the  $C_N^2$  profile, the seeing, the outer scale  $\mathcal{L}_0$ , the coherence time  $\tau_0$  and the isoplanatic domain  $\theta_0$ . Knowledge of these parameters is also important for future ELTs specifications. Indeed, the Fried parameter  $r_0$  and  $\mathcal{L}_0$  are critical for the deformable mirror in terms of the number of actuators and the required stroke. The knowledge of the wavefront coherence time is of interest to optimize the HAR technique detector exposure time and the correction frequency of the AO system. In addition, the choice of the AO reference star must take into account the constraints related to the isoplanatic angle. On the other hand, the same requirements are necessary for Ground Optical Communication stations, particularly for their AO systems technical specifications.

Future optical communications and telemetry stations will be forced to meet the same requirements than astronomical sites [3]. 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 (Optical Ground Station) 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 [3]. 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 virtual optical gateway (i.e., a network of OGS implementing handover procedure). Ultimately, the decision and frequency of the handover operation will be determined by the accuracy of the local monitoring of clouds, turbulence, and aerosols.

In this paper we present a new compact station for site-testing in terms of clouds, turbulence and aerosols. The ANAtOLIA station is has been developed in the framework of a european consortium (see Fig. 1) and a

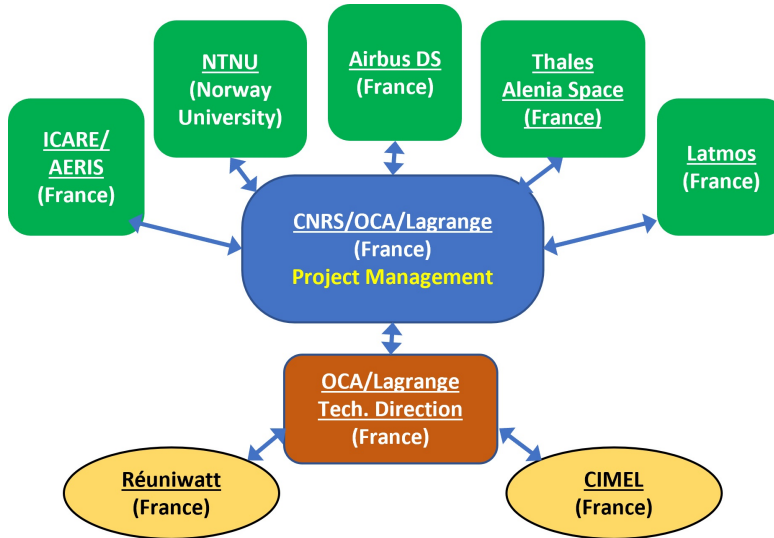


Figure 1. The structure of the ANAtOLIA consortium.

contract with the European Space Agency (ESA). The ANAtOLIA is a compact mobile high performance station consisting of the Generalized Monitor of Turbulence (GMT) for turbulence characterization, the Reuniwatt Sky Insight camera for the estimation of clouds parameters and the Cimel CE318-T photometer for aerosols detection and characterization. The ANAtOLIA station is operational 24h a day, 7 days a week in any site around the world with minimal infrastructure such as power access. After one year campaign at the Calern Observatory for on-sky tests and also for cross-calibration with the Calern Atmospheric Turbulence Station (CATS), the ANAtOLIA station is now installed and operational at three european sites (Calern, Cebreros and Catania). The ANAtOLIA project and objectives are presented in Sect. 2. The different instruments of the ANAtOLIA station are described in Sect. 3. The sites to be tested in the frame of the ANAtOLIA project are the results of a specific climate study. Since last spring, a 2 year campaign of measurement on the three sites has started and the preliminary obtained results are presented and discussed in Sect. 4.

## 2. THE ANATOLIA PROJECT

The optical communication system solution for a particular mission has to utilize optical ground stations that are geographically dispersed, such that there is a high probability of a cloud-free line of site (CFLOS) to a ground station from spacecraft at any given point in time (e.g., at the same longitude, or at a sufficient number of stations at different longitudes to allow the stored onboard data to be transmitted within the allocated time). The Optical Link Study Group (OLSG) [3] 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. 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.

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. The main mission objectives of ANAtOLIA are 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. Secondary study goals are to install and commission of 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). 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. This study proposes to use existing instrumentation within the consortium partners and adapt them in an optimal or simplified configuration to retrieve the ESA objectives. A full high performance instrumentation is proposed allowing a fine characterization of the whole atmospheric parameters required by ESA. Based on years of knowledge and experience, the CNRS-OCA's consortium proposal consists to design and manufacture a mobile station with high performance equipment composed by (Fig. 2):

- A unique atmospheric turbulence monitor GMT capable of extracting 24h/day, the whole atmospheric turbulence parameters required by ESA (Fried parameter, seeing, Isoplanatic angle, Angle of Arrival fluctuations, Greenwood frequency, Scintillation, Refractive index structure profile  $C_N^2(h)$  with high vertical resolution, Outer scale, Coherence time, Wind speed). This GMT monitor is a compact version of the completely automated CATS station installed since 7 years at the Calern Observatory.
- The Reuniwatt Sky Insight which is a wide field IR sky imager as a monitoring equipment 24h/day for a precise characterization of clouds (coverage, height, type/phase, optical thickness and attenuation). The Sky Insight imager is a confirmed and validated instrument. In addition, several weather sensors are also embedded into the Sky Insight: a solar reference cell, a thermometer, and a humidity sensor.
- The Cimel CE318-T photometer. This is a multispectral atmospheric photometer which is the reference for automatic aerosols monitoring for day and night conditions. The CE318-T performs Sun, sky and lunar light measurements, for the retrieval of aerosol transmittance, visual Range, sky radiance and cloud optical thickness.

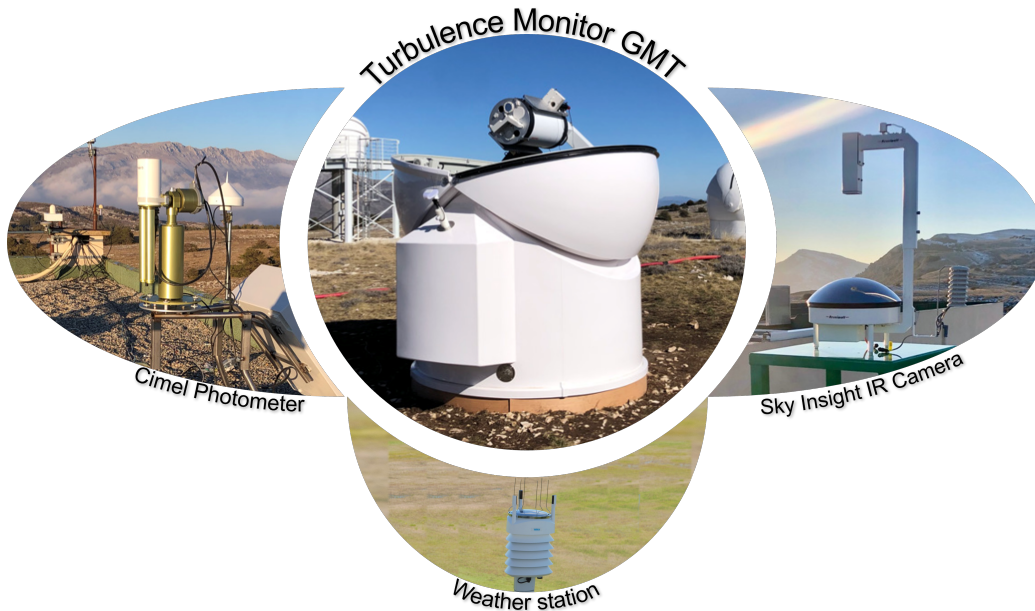


Figure 2. The high performance ANAtOLIA station.

This compact mobile station consisting of GMT monitor, Reuniwatt Sky Insight camera and Cimel CE318-T photometer will be operational 24h a day, 7 days a week in any site around the world with minimal infrastructure such as power access.

The ANAtOLIA high performance instrumentation has been installed for one year at the Calern Observatory for on-sky tests and cross-calibration under different turbulence conditions by means of CATS station (Fig 2).

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. 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 has been installed and now operational on three 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.

### 3. ANATOLIA STATION

To achieve the requirements of the ANAtOLIA project in terms of scientific goals and budget, we were aware in the consortium that the CATS station deserves to be compacted and completed to reduce its cost while meeting the needs of ESA in terms of turbulence, aerosols and clouds characterization with high performance. Thus, we proposed to merge GDIMM\* [1] and PML† [5, 2] of the CATS station ([4]) in one unique and compact monitor called GMT (Generalized Monitor of Turbulence) without impacting the list of the measured parameters. To this GMT instrument we added two instruments for clouds and aerosols detection and characterization corresponding respectively to the Reuniwatt Sky Insight camera and the Cimel CE318-T 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-T photometer is a high performance and confirmed set of instruments. This station is operational 24h a day, 7 days a week in any site around the world with minimal infrastructure such power access.

#### 3.1 GMT instrument



Figure 3. Left: the GMT instrument inside its 2.3m AllSky Baader dome. Right: The pupil mask and the optical device of the GMT instrument.

The GMT is a unique instrument to monitor the optical turbulence in any site around the world and during daytime and nighttime conditions. The GMT is a compact and improved version of the CATS station as shown in Fig. 2 and as explained in detail here-after.

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\*Generalized Differential Image Motion Monitor

†Profiler of Moon Limb

The GMT instrument is mainly dedicated to the extraction of the  $C_n^2$  profile with high vertical resolution from lunar (or solar) limb fluctuations. The GMT instrument is based on a differential method by observation of the lunar (or solar) limb through two sub-apertures (Fig. 3). The Moon or Sun limb acts as a continuum of double stars with all possible angular separations required between two points to scan the atmosphere with a very fine resolution [5, 2].

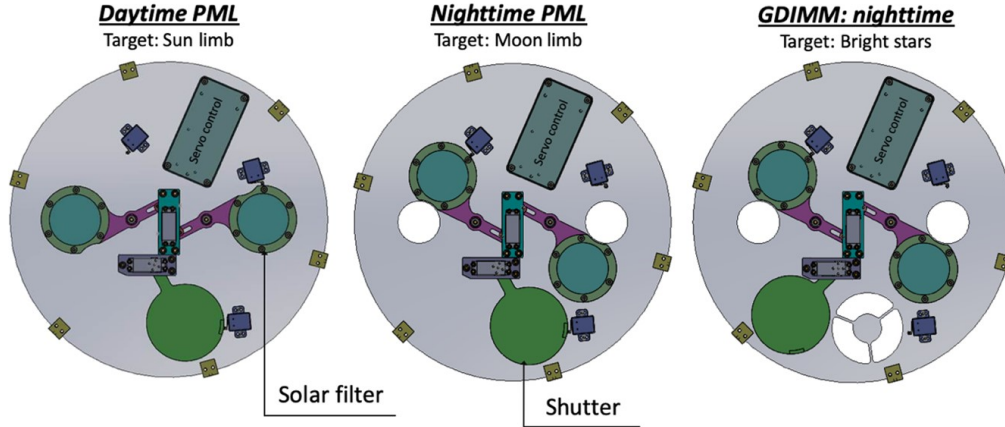


Figure 4. Different GMT's mask configurations for 24h atmospheric turbulence monitoring passing from PML to GDIMM mode.

The GMT instrument consists of a small telescope installed on an precise direct drive mount. The pupil mask, composed of two sub-apertures of diameter  $D = 6\text{cm}$  separated by a baseline  $B = 26.7\text{ cm}$ , is placed at the entrance pupil of the telescope (Fig. 3). In addition, the GMT instrument is equipped with automatic panels to cover the two subapertures with solar filters for a fast and automatic switch from night/Moon observation to day/Sun observation (Fig. 3 & Fig. 4). The GMT is also equipped with a third subaperture of 10cm with a central obstruction of 4cm which is masked with a panel during Moon/Sun observations and removed to observe bright stars in the GDIMM mode. This third subaperture is also covered by a prism to avoid overlapping with the two other spots when observing a bright star in the GDIMM mode.

An optical device is installed in the focal plan of the telescope. It consists of a collimated beam by using a first lens L1 placed at its focal length from the telescope focus (Fig. 5). Then, two parallel beams are formed at the output of L1 corresponding to each sub-aperture. A Dove prism is inserted on one of the two beams to reverse one of two images of the lunar (solar) edge in order to avoid an overlapping of the two images of the Moon/Sun (Fig. 5). This Dove prism is also used to avoid spots overlapping by shifting one spot when observing a bright star in the GDIMM mode. A second lens L2 is used to form the two images of the Moon limb (or Sun edge) on the CCD camera. To compensate for variations in the telescope's focus because of the temperature variations, we installed the CCD camera on an automatic micro-control plate controlled by the acquisition software (Fig. 5). Images at the focal plane are recorded using a CCD camera with  $640 \times 480$  pixel matrix. In order to freeze atmospheric effects on the motion of the Moon's (or Sun) limb image and to have enough flux, the exposure time is set to 5ms.

The principle of the GMT instrument is based in the same way than the PML monitor [5, 2] 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. The AA fluctuations are measured perpendicularly to the lunar (or solar) limb leading to transverse correlations for different angular separations along the Moon (or Sun). The observed Moon or Sun limb is parallel to the sub-apertures baseline. In this case, the transverse covariance of the difference of the AA fluctuations (motion of the Moon or Sun limb)  $\alpha$  between the two images of the lunar (or solar) limb (Fig. 5) are deduced and then used to extract the  $C_N^2(h)$  profile with high resolution by solving an inverse problem [5, 2],

The GMT acquisition software provides a real time computation of the  $C_n^2$  profile with a high resolution vertical every 3 minutes. Other parameters of turbulence are also accessible from this instrument such as the profile of outer scale, the seeing, and the isoplanatic angle.

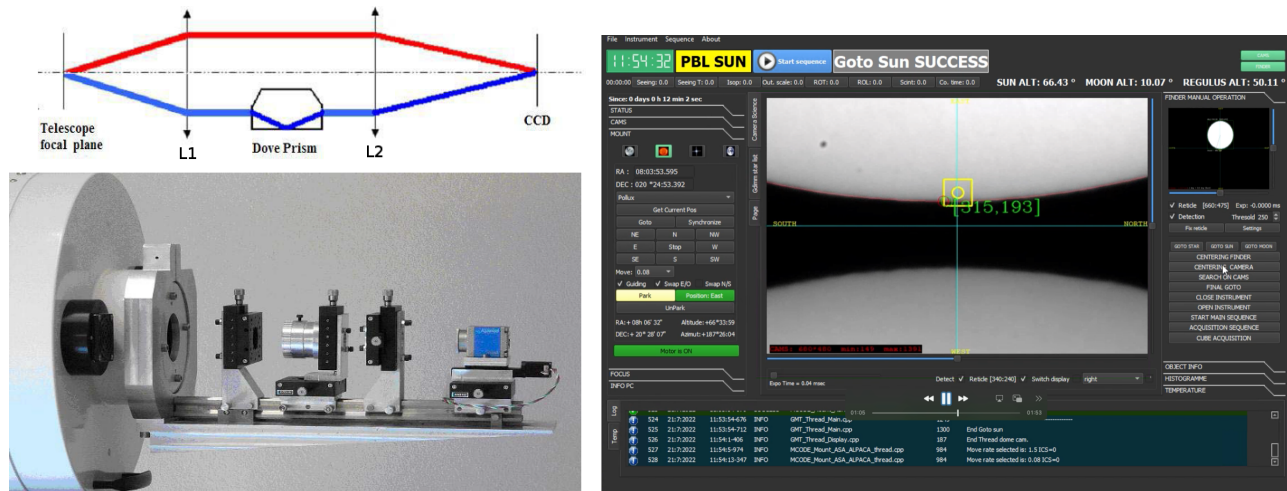


Figure 5. Left: GMT optical device. Right: the graphical user interface of the GMT instrument showing the two Sun limb images.

The GMT is also used as a GDIMM [1] when the Moon is not observable during the nighttime. Indeed, in the GDIMM mode a bright star is observed with the three subapertures as shown in Fig. 3 & Fig. 4. The GMT in GDIMM mode provides the whole integrated turbulence parameters [1], the seeing or Fried parameter from DIMM method using the two 6cm subapertures, the isoplanatic angle is deduced from scintillation measurement with the third 10cm subaperture, the coherence time is obtained from the 3 subapertures by means of the temporal structure function and finally the outer scale is obtained from normalized Angle-of-Arrival variances. The GDIMM instrument provides results of turbulence parameters in real time each minute.

### 3.2 Sky Insight IR camera

The Reuniwatt<sup>‡</sup> Sky Insight is a patented infrared sky imager for the continuous tracking and forecasting of the cloud cover. The use of the infrared vision technology 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.

Sky InSight (Fig. 2) is composed of a thermal long-wave infrared (LWIR) camera core with a 640x480 pixel spatial resolution. The radiation coming from the sky is reflected on a hemispherical mirror that provides a 360/180 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 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. 6) every 30 seconds (a higher rate is also possible) as well as the result of the automatic and real-time

<sup>‡</sup><https://reuniwatt.com/>



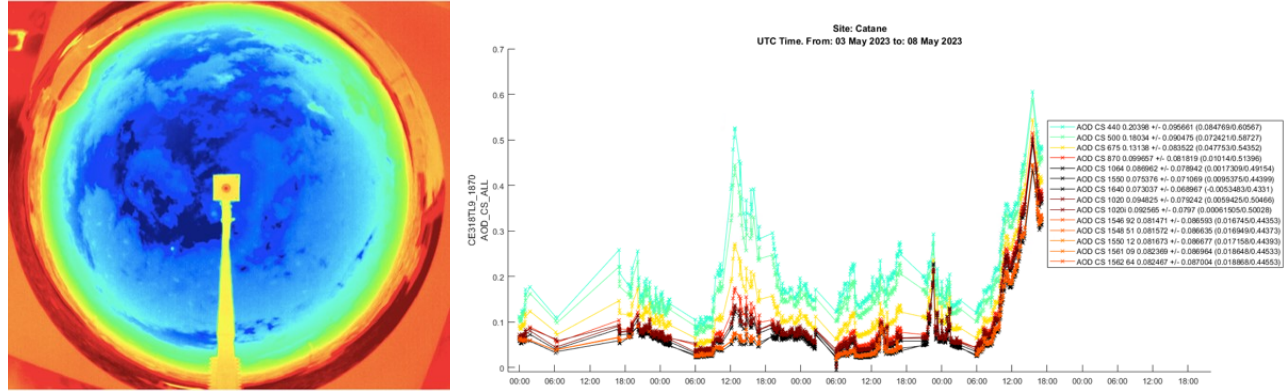


Figure 6. Example of sky image acquired by the Réuniwat Sky Insight IR camera (left panel). Right panel: Example of AOD data measured with the Cimel CE318-TL9 on Catania site at different wavelength channels.

cloud fraction calculation in okta. Other parameters such as cloud optical depth and altitude of clouds are also provided in real time.

### 3.3 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 aerosols 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 loading 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-T, 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) as shown in Fig 6, 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-T 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-T is based on a new control unit and a new four-quadrant system in the sensor head. The CE318-T 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-T performs measurements at an approximate field of view of 1.29° 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) (Fig 6). 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

<sup>§</sup><https://www.cimel.fr>

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.

#### 4. ON-SITE INSTALLATION AND MEASUREMENT CAMPAIGN

Based on a specific climate diversity study, four sites have been selected to be equipped with ANAtOLIA stations. The selected sites are Calern in the South of France, the ESA Cebereros site near Madrid, the Catania Observatory in Sicily and Lisbon's region site with Atlantic influence. The site hosting the instrumentation must be ready before installation. Some requirements are then requested and all these specifications are sent before installation. For example, the platform and the concrete pillar must be built at least one month before the beginning of installation to let time to concrete to dry. The construction must precisely respect the plan send in advance to the site. Figures 2 and 7 show the ANAtOLIA station set up at the three sites of Calern, Cebereros and Catania. Once

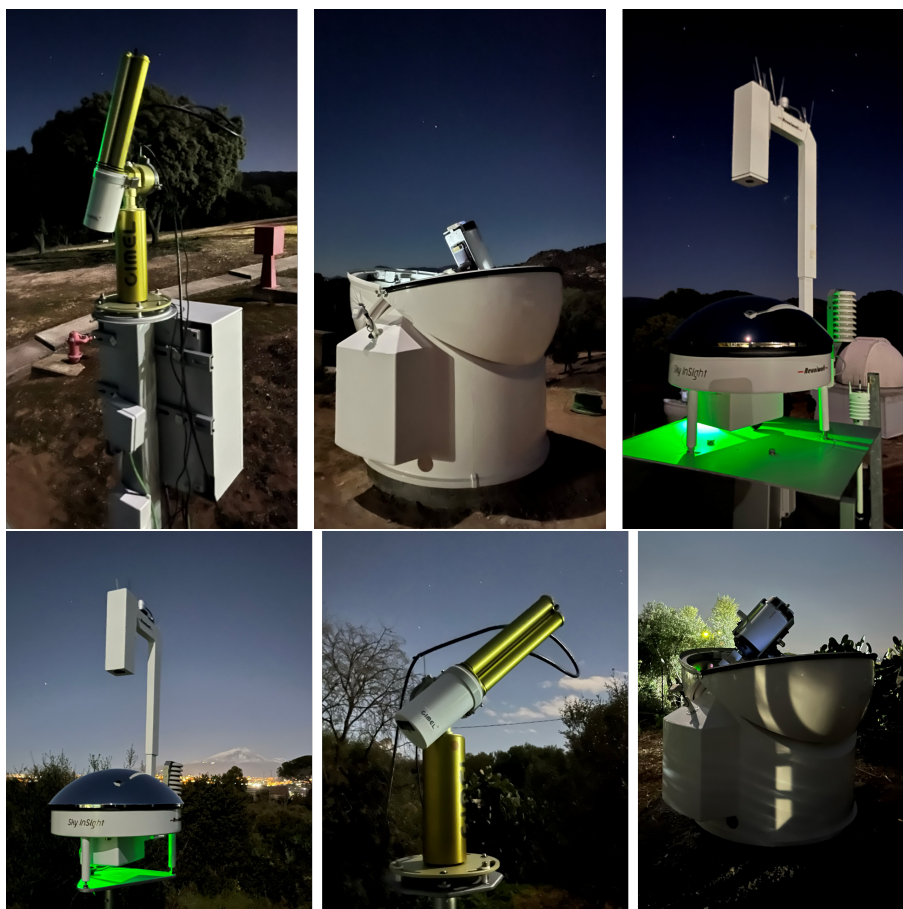


Figure 7. The ANAtOLIA station set up at the Cebereros site (Top) and on the Catania Observatory (Bottom).

the station installed, different tests and calibrations are performed for each instrument to be ready for campaign measurements. The SkyInsight needs time to calibrate itself to well define its position, to well identified the Sun position and to give precise measurements. This calibration is automatic and when it is finished the first results should be collected. The CE318-TL9 doesn't need software calibration. Indeed, it is already factory calibrated on a Cimel reference site before shipment. However, during the installation process, we must follow different

mechanical calibration procedures to setup correctly the instrument. For the GMT monitor, once all mechanical aspect tested, we need to test the focal length of the telescope which is correlated to the sampling on the scientific camera. Indeed, the pixel size is an important parameter in the computation of the turbulence parameters. To proceed to this calibration, one needs to observe a well-known double star and to measure its separation in pixel on the scientific camera. From this separation and knowing the real one in arcseconds we can compute the pixel size and the focal length of the instrument. This value is then passed into software parameters to be used in data processing for the extraction of turbulence parameters. 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. In addition, we have the possibility to remotely control manually the GMT instrument and the dome thanks to the internet connexion. 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 8 shows this Grafana tool presenting a summary of all the stations already installed (Calern, Cebreros, Catania). 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.

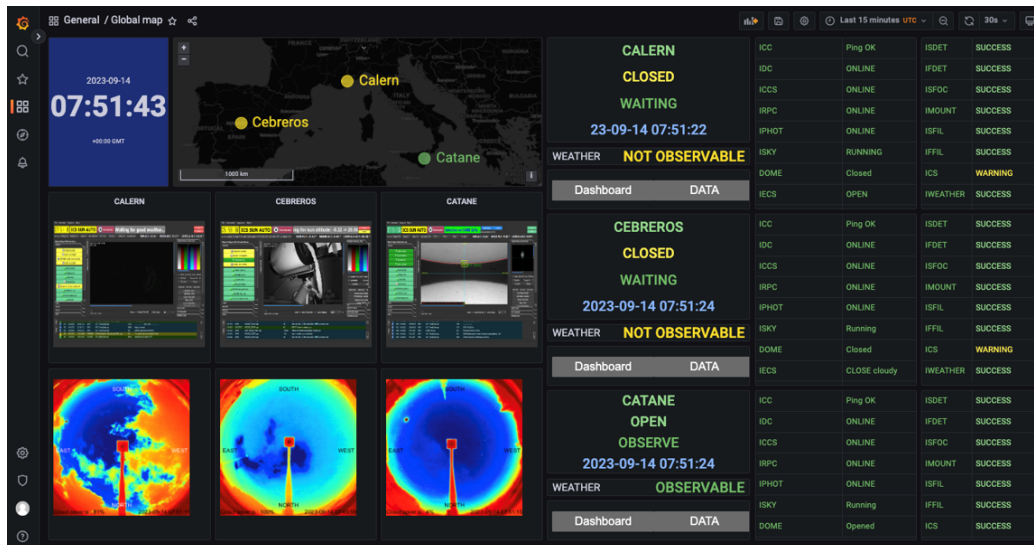


Figure 8. GRAFANA tool summarizing the status of the whole deployed stations.

A central node with double disk is dedicated to the whole data storage and archiving provided by the different instruments. The storage server has also been dimensioned considering the whole data including turbulence centroids, angles of arrival, spots intensities, turbulence parameters. These data are stored and archived in a double disk and it is then still possible to re-process everything from them. In addition, we store also, in a CSV file, the parameters themselves, including the time, the airmass, target, etc. About the SkyInsight IR camera, we store the acquired images of the COD the cloud cover and other provided parameters. We also store the CSV files containing the time, the cloud cover, the cloud type, and the cloud base height. About the CE318-TL9 (Cimel), we store the raw data (K8 format) and processed files (ASCII). The raw data can be reprocessed at each time if needed. Before installing the ANAtOLIA stations on the different selected sites, we proceeded to a cross-calibration with the CATS station on Calern Observatory. Indeed, between October and December 2022, the GMT-ANAtOLIA and PML-CATS ran simultaneously during numerous periods. From these measurements, we extracted 1312 common  $C_N^2$  profiles acquired during both daytime and nighttime using an acceptance time



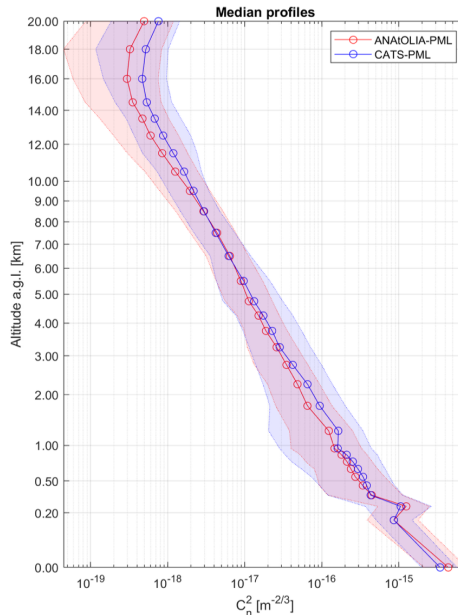


Figure 9. Median vertical profile of the  $C_N^2$  measured with PML from CATS (in blue) and from ANAtOLIA (in red). Colored surfaces represent the first and third quartiles. The median is computed over 1312 simultaneous profiles measurements acquired at  $\lambda = 500nm$ .

interval of 3 minutes. We then computed the median of each layer, as well as their first and third quartiles. Figure 9 displays the obtained median profiles for PML-CATS (in blue) and GMT-ANAtOLIA (in red) when working in PML mode. The colored surfaces represent the interval between first and third quartiles. The median profiles are very similar and coherent, and their differences are well below the dispersion represented by the first and third quartiles. Considering that the CATS-PML has an older camera (less sensitive), a different mount, a different telescope and different optics, results presented in figure 9 show a very good agreement between the reference CATS instrument and the GMT developed in ANAtOLIA project. One can see a small gap above 11km between the two instruments, but the  $C_N^2$  magnitude on this region is around or less than  $10^{-18}m^{-2/3}$ , which is almost noise.

Figure 10 shows examples of seeing and isoplanatic time series measured at Cebreros and Catania sites. In these figure on can see that the seeing is stronger during daytime than during nighttime. It increases until the middle of the day and decreases due to the Sun convection effect. In addition, as expected the turbulence conditions in Catania (200m altitude) seem worst that on Cebreros (850m altitude) during daytime. The isoplanatic conditions are more favorable during nighttime than during daytime. This is due to the fact that the heating of the ground layers gradually spreads to the upper layers (several kilometers), affecting then the isoplanatic angle.

## 5. DISCUSSION

The ANAtOLIA station developed and now installed on three different in Europe. Before these installations and during one year, the ANAtOLIA station has been on-sky tested and cross-calibrated with the CATS station. A dedicated study has been performed during the first year of the project to select sites to be tested with the ANAtOLIA station. The site-selection is based on a preliminary list of sites provided by the partners of the consortium and ESA, a critical analysis has been performed to identify the best suited locations for the deployment of instrumentation, considering the diversity of sampled atmospheric conditions in terms of clear fraction (or availability), frequency of occurrence of thin cirrus and broken cloud cover, expected turbulence diversity (altitude, location, etc) as well as geographical distribution to maximize weather de-correlation among

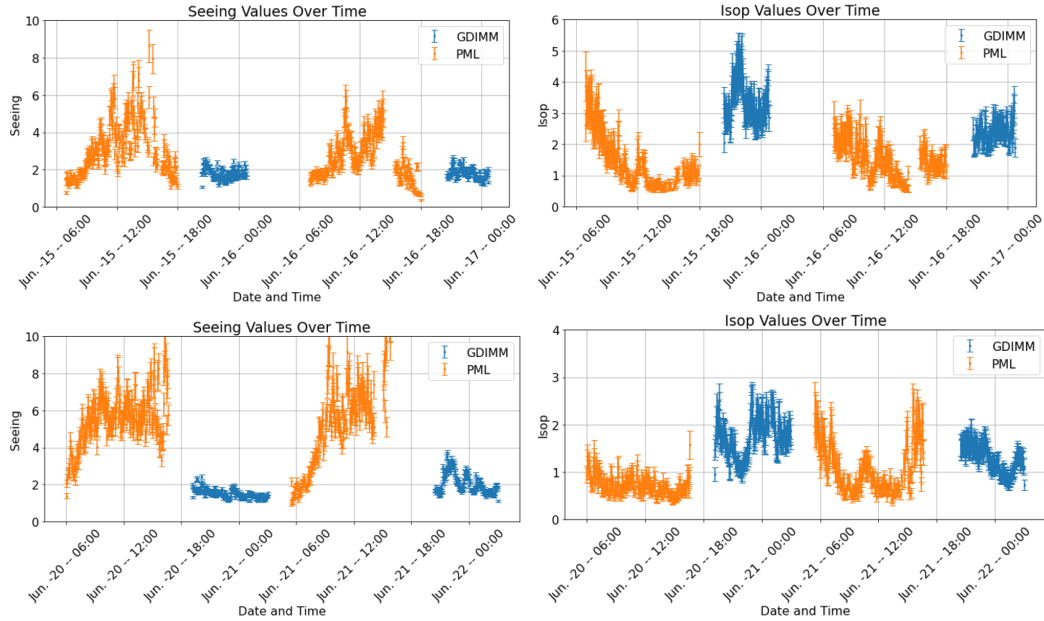


Figure 10. Example of Seeing (left) and Isoplanatic angle (right) measured at Cebreros (top) and Catania (bottom) at  $\lambda = 500nm..$

selected sites. Other practical considerations have been made also to keep travel/transport budget related to site installation and maintenance within the project allocated funding and guarantee site accessibility despite the worldwide Covid-19 crisis. Finally, the four sites selected to be tested with the ANAtOLIA station are, Catania in Sicily, Cebreros near Madrid and Lisbon in addition to the Calern Observatory equipped with the upgraded CATS station. Since spring 2023, three of the four sites (Calern, Catania and Cebreros), have been equipped with ANAtOLIA stations for a 2 year measurement campaign and a statistical study will be then performed to check the availability of these sites in terms of clouds, aerosols and turbulence.

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