



HAL
open science

Metrology of atmospheric turbulence for Astronomical Observations and Optical Communications

A Ziad

► **To cite this version:**

A Ziad. Metrology of atmospheric turbulence for Astronomical Observations and Optical Communications. COAT2023, Mar 2023, Durham, United Kingdom. hal-04605097

HAL Id: hal-04605097

<https://hal.science/hal-04605097>

Submitted on 7 Jun 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Metrology of atmospheric turbulence for Astronomical Observations and Optical Communications.

A. Ziad

Université Côte d'Azur, OCA, CNRS, Lagrange, Parc Valrose 06108 Nice Cedex 2, France

ABSTRACT

Beyond Site-Testing and Site-Selection for Astronomical Observations or Optical Ground Stations for Optical Communications, precise nocturnal and diurnal knowledge of atmospheric turbulence parameters is of interest for the technical specifications of the Adaptive Optics (AO) systems dedicated to real-time correction of the atmospheric turbulence. In addition, the $C_N^2(h)$ profiles (as well as wind and outer scale profiles) with high vertical resolution is necessary for a better evaluation of the performance of AO systems. A large number of monitors have been developed for this purpose, particularly with the emergence of ELT projects, but very few meet the required need. Indeed, a minority of these instruments are profilers, the majority of which are limited by the vertical resolution and/or confined to part of the atmosphere (Ground Layer or Free Atmosphere). When these limitations are lifted, some profilers require telescopes larger than 1m in diameter. On the other hand, there is a strong imbalance in favor of night monitors, whereas there is an insistent need for daytime conditions, especially for optical telecommunications. Generally, the majority of existing monitors are dedicated to the measurement of integrated turbulence parameters and not necessarily whole of them, only partially meeting the need and without any guarantee on the relevance and reliability of their results.

Keywords: Optical Communications, 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. Future optical communications and telemetry stations will be forced to meet the same requirements.¹ 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 τ_0 and the isoplanatic domain θ_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.

This paper aims to give a review of existing techniques and instruments for the measurement of atmospheric turbulence. A list of required criteria for turbulence monitors selection is provided and discussed. The list of the most pertinent atmospheric parameters is provided and discussed. Comparisons with HAR techniques measurements will be presented and discussed to conclude on the relevance of measurements and the associated observable quantities. Finally, a recent station developed in the framework of a european consortium and a

Further author information: (Send correspondence to A. Z.): E-mail: ziad@unice.fr, Telephone: (33) (0)4 89 15 03 92

contract with the European Space Agency (ESA) is presented. This ANAtOLIA station is a compact mobile high performance station, equipped with the Generalized Monitor of Turbulence (GMT) for turbulence characterization which is operational 24h a day, 7 days a week in any site around the world. The GMT monitor is one of the most performing instrument leading to the whole atmospheric turbulence parameters.

2. PERTINENT ATMOSPHERIC PARAMETERS FOR SITE-SELECTION

Astronomical observations and optical links for optical communications are severely affected by the atmospheric perturbations leading to the loss of the telescopes resolution and the information of the communication signal. In addition to the clouds and aerosols in a less level, the atmospheric turbulence plays an important role since it potentially implies a non-negligible distortion of the light and the transmitted signal. In particular, atmospheric turbulence can cause both amplitude and phase distortion due to the local variation of the refractive. If in astronomical observations wavefront amplitude distortion are considered negligible but this shall be considered in the optical link budget and it implies the necessity of a greater transmitting power. In other words, very high-power booster shall be used in order to compensate for these signal losses. On the other hand, phase distortion is potentially compensated by adaptive optics techniques that allow to recover the signal thanks to the use of a deformable mirror and a wave-front sensor. The most critical and relevant atmospheric turbulence parameters useful for astronomical observations and optical communications purposes are (Table 1): the Fried parameter r_0 or the seeing ϵ_0 ; the isoplanatic angle θ_0 ; the Greenwood frequency f_g ; the scintillation index σ_I ; the refractive index structure constant profile $C_N^2(h)$; the wavefront coherence outer scale \mathcal{L}_0 ; the coherence time τ_0 and the effective wind speed v_e

Turbulent parameters are mostly measured in the visible range ($\lambda = 500\text{nm}$) on astronomical sources (stars, Moon, Sun). They are wavelength dependent and are function of the airmass provided by the zenithal distance z . Table 1 hereafter summarizes this wavelength dependence and airmass correction for each atmospheric turbulence parameter.

	Wavelength dependence	Airmass compensation
Seeing ϵ_0	$\epsilon_0(\lambda_1) = \epsilon_0(\lambda_0) \left(\frac{\lambda_1}{\lambda_0}\right)^{-1/5}$	$\epsilon_0(z=0) = \epsilon_0(z) (\cos z)^{3/5}$
Fried parameter r_0	$r_0(\lambda_1) = r_0(\lambda_0) \left(\frac{\lambda_1}{\lambda_0}\right)^{6/5}$	$r_0(z=0) = r_0(z) (\cos z)^{-3/5}$
Isoplanatic angle θ_0	$\theta_0(\lambda_1) = \theta_0(\lambda_0) \left(\frac{\lambda_1}{\lambda_0}\right)^{6/5}$	$\theta_0(z=0) = \theta_0(z) (\cos z)^{-8/5}$
Isokinetic angle θ_k	Achromatic	$\theta_k(z=0) = \theta_k(z) (\cos z)^{-1}$
Coherence time τ_0	$\tau_0(\lambda_1) = \tau_0(\lambda_0) \left(\frac{\lambda_1}{\lambda_0}\right)^{6/5}$	$\tau_0(z=0) = \tau_0(z) (\cos z)^{-3/5}$
Scintillation index σ_I	$\sigma_I(\lambda_1) = \sigma_I(\lambda_0) \left(\frac{\lambda_1}{\lambda_0}\right)^{-7/6}$	$\sigma_I(z=0) = \sigma_I(z) (\cos z)^{8/3}$
Outer scale L_0	Achromatic	-
Angle of Arrival	Achromatic	$(\cos z)^{1/2}$
Greenwood frequency f_g	$f_g(\lambda_1) = f_g(\lambda_0) \left(\frac{\lambda_1}{\lambda_0}\right)^{-6/5}$	$f_g(z=0) = f_g(z) (\cos z)^{3/5}$
Effective wind speed v_e	Achromatic	-
Structure constant $C_n^2(h)$	Achromatic	$C_n^2(z=0) = C_n^2(z) \cos z$

Table 1. List of pertinent of atmospheric turbulence parameters and their dependence on the wavelength and the airmass.

3. METHODS AND TECHNIQUES FOR ATMOSPHERIC TURBULENCE MONITORING

There are different ways to measure turbulence parameters. A short review of turbulence monitors is presented in this section. We also present briefly the most known methods considered to determinate turbulence parameters using different sources (stars, Moon or Sun).

Turbulence monitors can be classified into two categories. The first one gathers instruments which measure integrated turbulence parameters resulting from the propagation of the light through the whole atmosphere.

The most common parameters are the seeing, the Fried diameter, the scintillation, the isoplanatic angle, the coherence time, and the wavefront outer scale (Table 1). A famous example belonging to this group is the DIMM (Differential Image Motion Monitor).² The second category concerns profilers, capable of measuring the vertical distribution of turbulence ($C_N^2(h)$ profile) as a function of altitude. Balloon-borne microthermal probes³ have been used for a long time to make in-situ measurements with very high vertical resolution, but they do not provide a practical solution to continuous monitoring. Hence, a serie of monitors based on the measurements of wavefront slopes (such as the MOSP⁴ and later the PML⁵) or scintillation patterns (SCIDAR family⁶) were developed, mostly in 2000s with the emergence of ELT projects. Table 2 summarizes the technique used by each of the existing monitors considered in this paper, making a classification into 3 categories: monitors based on wavefront-slopes, scintillation measurements, and other observable quantities such as acoustic sounding (SODAR⁷).

In addition, there is a third category of monitors gathering other instruments measuring for example turbulence in confined media such telescope domes.

	DIMM	GDIMM	PML	GMT	G-SCIDAR	LOLAS	Stereo-SCIDAR	MASS-DIMM	GSM	SSS	MOSP	Balloon microth.	SLODAR	SL-SLODAR	LuSci	SODAR	CO-SLIDAR	A-DIMM	H-DIMM	SHIMM	PEPITO	RINGSS	FASS	SHABAR	SDIMM	SDIMM+	MASP/A-MASP	PDSL	MISOLFA	PSM	Sonic	INTENSE/LOTUCE	AIRFLOW
Scint.																																	
Slope																																	
Other																																	

Table 2. List of existing turbulence monitors and the corresponding observable quantities.

Another criterion when dealing with turbulence monitor selection is the ability to provide both of daytime and nighttime turbulence measurements. Indeed, use of methods to measure turbulence during daytime, based on stars even bright, remains very challenging, except very bright stars such as Sirius in the south hemisphere and at very peculiar locations such as Antarctica or high mountain sites, where the sky is coronagraphic to allow sufficient contrast on star images during the day. Therefore, most daytime techniques are based on observations of the Sun (solar limb, solar granulation, or solar scintillation). As shown in figure 1, there is a strong imbalance in favor of nighttime monitors, whereas there is an insistent need for daytime conditions, especially for optical communications.

If the two first criteria to consider for monitor selection is the ability to measure whole parameters of interest listed in Table 1 and during both daytime and nighttime conditions, the third criterion is the instrument size for implementation constraints. Indeed, several profilers require telescopes larger than one meter diameter. The last and not the least criterion is the need of a robotic monitor without requiring human intervention except during breakdowns. When combining all these criteria, there is a very limited list of monitors satisfying these conditions. Thus, the only instrument able to measure the whole set of parameters is the GMT.⁸ The PML^{5,9} could also allow to deduce the C_N^2 , the scintillation, the isoplanatic angle and the coherence time. The only instruments able to works 24h a day are the PML, the GMT and the SODAR.⁷ However, the PML does not work when the Moon is not available, and the SODAR suffers from calibration issues and is only able to measure a reduced number of parameters within the boundary layer only ($< 800m$). The profilers allowing to cover the altitudes between 0 and 20 km (where the major part of the optical turbulence is concentrated) are the balloons, the PML, the GMT, the G-SCIDAR,⁶ the Stereo-Scidar,¹⁰ the MASS/DIMM (up to 16km),¹¹ the SSS,¹² the MOSP (16km),⁴ the SLODAR,¹³ the CO-SLIDAR,¹⁴ the SDIMM+,¹⁵ the MASP¹⁶ and the PDSL.¹⁷ However, the PML and GMT are those having the highest vertical resolution and the highest number of available layers

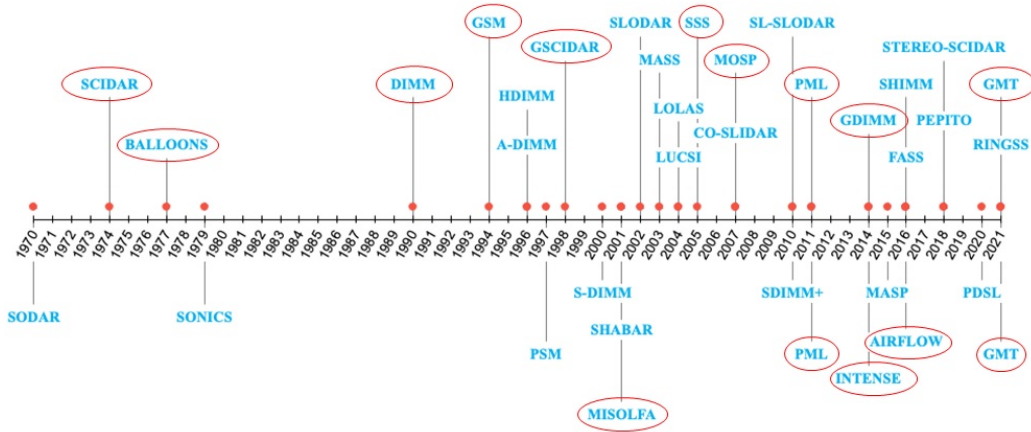


Figure 1. List of existing daytime and nighttime turbulence monitors. The instruments whose names are surrounded by a red circle were developed by the Lagrange Laboratory of the Côte d’Azûr Observatory

(33 layers). The GMT instrument has been then chosen to equip the ESA ANAtOLIA station described in the next section.

4. 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)¹ 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 the OGS 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):



Figure 2. The high performance ANAtOLIA station.

- 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.

This compact mobile station consisting of GMT monitor, Réuniwatt 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 is now installed on different european sites (Calern Observatory in south of France, ESA Cebreros site near Madrid and Catania Observatory in Sicily) for a 24 month campaign starting from February 2023.

Before starting instrumental development, a specific attention has been dedicated to the definition of the list of critical atmospheric parameters (Sec. 2) and the pre-selection of sites for 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 of the atmospheric conditions with the required precision and the adequate sampling. The chosen instrumentation has been installed during one year for on-sky tests on Calern Observatory and then have been moved to the selected sites for measurement operations during a period of 24 months (Sec. 4.1). 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.

4.1 ANAtOLIA station

To achieve the requirements of the ANAtOLIA 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 performances. Thus, we proposed to merge GDIMM*¹⁸ and PML†^{5,9} of the CATS station¹⁹ 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, Réuniwatt Sky Insight camera and Cimel CE318-T photometer is a high performance and confirmed instrument. This station is operational 24h a day, 7 days a week in any site around the world with minimal infrastructure such power access.

4.2 GMT instrument

The Generalized Monitor of Turbulence (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.

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.^{5,9}



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 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

*Generalized Differential Image Motion Monitor

†Profiler of Moon Limb

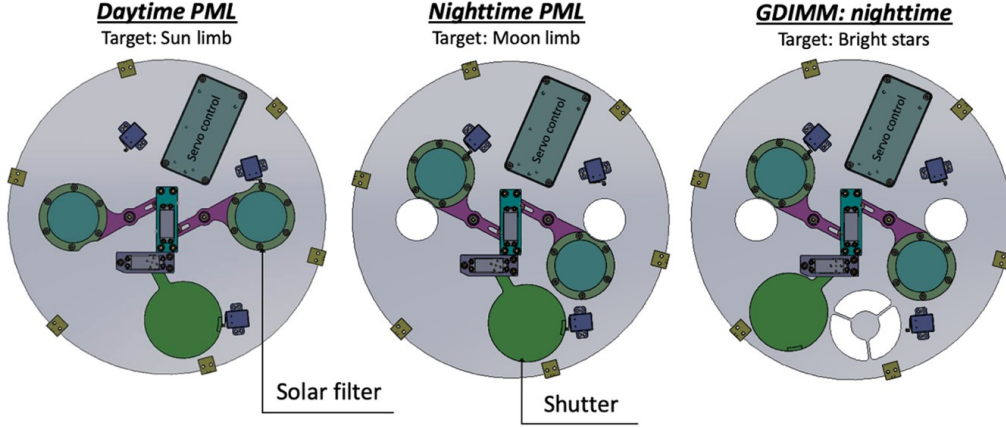


Figure 4. Different GMT's mask configurations for 24h atmospheric turbulence monitoring passing from PML to GDIMM mode.

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 640×480 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^{5,9} 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) α 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,^{5,9}

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.

The GMT is also used as a GDIMM¹⁸ 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,¹⁸ 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

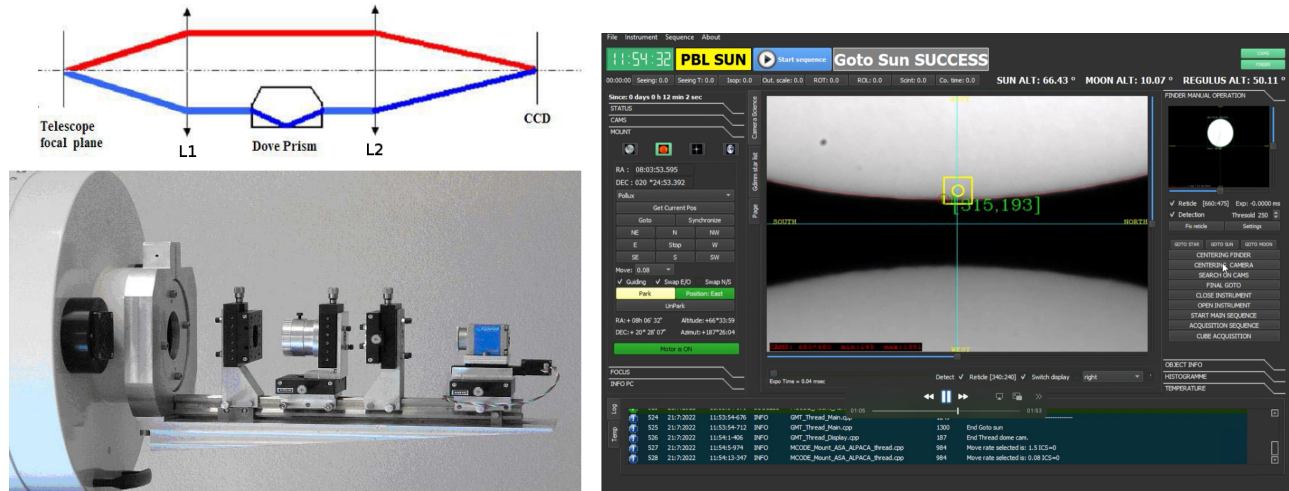


Figure 5. Left: GMT optical device. Right: the graphical user interface of the GMT instrument showing the two Sun limb images.

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.

5. DISCUSSION

A review of existing methods and monitors for atmospheric turbulence evaluation has been presented. Turbulence monitors can be classified into two categories. The first one gathers instruments which measure integrated turbulence parameters and the second category concerns turbulence profilers, capable of measuring the vertical distribution of $C_N^2(h)$. Turbulence monitors are based on methods using different observable quantities such as wavefront slopes, scintillation or others (temperature or acoustic sounding). In addition, there is a third category of monitors gathering other instruments measuring for example turbulence in confined media such as telescope domes. Major part of these existing turbulence monitors are not full-filling the criteria required in site evaluation in Astronomy and Optical Communications. Among these criteria, the most important is the possibility to measure or deduce the whole set of the pertinent turbulence parameters, particularly the C_N^2 profile of the whole atmosphere, during both daytime and nighttime conditions. In addition, the turbulence monitor has to be completely autonomous, possibly mobile avoiding for example the need for an imposing telescope. Finally, the last criteria we must consider is the rate of measurement and real-time data processing to gather the maximum of statistics.

The ANAtOLIA project developed in the framework of a European consortium under a contract with ESA, aims to evaluate the availability of OGS stations in terms of clouds, aerosols and atmospheric turbulence for Optical Communications. A specific study within the ANAtOLIA project has been performed for the selection of the turbulence monitor. This study based on the above criteria, concluded and conducted to the selection of the GMT turbulence monitor which is now part of the ANAtOLIA now installed on three different sites in Southern Europe. 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 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, Cebreros (Madrid) and Lisbon in addition to the Calern Observatory. Calern, Catania and Cebreros

are already equipped with ANAtOLIA stations since February 2023 and started gathering data. The Lisbon's site will benefit of the Cebreros or Catania's station which will be moved in February 2024.

ACKNOWLEDGMENTS

Authors would thank the European Space Agency (ESA), the Centre National d'Etudes Spatiales (CNES) and the Norwegian Space Agency for funding the ANAtOLIA project. The ANAtOLIA project is the developed under the ESA Contract 4000131710/21/UK/ND.

REFERENCES

- [1] O., L., S. G., [*Optical Link Study Group Final Report*], Interagency Operations Advisory Group (2012).
- [2] Sarazin, M. and Roddier, F., "The eso differential image motion monitor," *Astronomy and Astrophysics*, vol. 227, no. 1, Jan. 1990, p. 294-300. (1990).
- [3] Azouit, M. and Vernin, J., "Optical turbulence profiling with balloons relevant to astronomy and atmospheric physics," *Publications of the Astronomical Society of the Pacific* **117**(831), pp. 536–543 (2005).
- [4] Maire, J., Ziad, A., Borgnino, J., and Martin, F. *MNRAS* **377**, 232 (2007).
- [5] Ziad, A., Blary, F., Borgnino, J., Fantei-Caujolle, Y., Aristidi, E., Martin, F., Lanteri, H., Douet, R., Bondoux, E., and Merkarnia, D., "First results of the pml monitor of atmospheric turbulence profile with high vertical resolution," *A&A* **559**, L6 (2013).
- [6] Fuchs, A., Tallon, M., and Vernin, J. *PASP* **110**, 86 (1998).
- [7] Crescenti, G. *Boundary Layer Meteorology* **78**, 651 (1997).
- [8] Ziad, A., "et al., anatolia: a new mobile site-testing station for astronomy and optical communications," *Proceedings of the SPIE* Vol. **12185**, id. **121855Z**, 11 (2022).
- [9] Chabé, J., Aristidi, E., Ziad, A., Lantéri, H., Fantei-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 (2020).
- [10] Shepherd, H. W. *et al.*, *MNRAS* **437**, 3568 (2014).
- [11] Kornilov, V. *et al.*, *MNRAS* **382**, 1268 (2007).
- [12] Habib, A. *et al.*, *MNRAS* **368**, 1456 (2006).
- [13] Wilson, R. *et al.*, *MNRAS* **337**, 103 (2002).
- [14] Voyez, J. *et al.*, *Opt. Express* **22**, 10948 (2014).
- [15] Zhong, L. & Beckers, J. M. *Sol. Phys.* **198**, 197 (2000).
- [16] Ren, D. *et al.*, *PASP* **127**, 870 (2015).
- [17] Song, T. *et al.*, *MNRAS* **499**, 1909 (2020).
- [18] Aristidi, E., Ziad, A., Chabé, J., Fantei-Caujolle, Y., Renaud, C., and Giordano, C., "The generalised differential image motion monitor," *MNRAS* **486**, 915 (2019).
- [19] Ziad, A., Chabé, J., Fantei-Caujolle, Y., Aristidi, E., Renaud, C., and Ben Rahhal, M., "Cats: an autonomous station for atmospheric turbulence characterization," *Astronomical Telescopes+ Instrumentation, Proc. SPIE 10703, 107036L* (2018).