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List of Abbreviations

EST	European Solar Telescope
INAF-OAA	INAF Osservatorio Astrofisico di Arcetri
LOS	Line Of Sight
ORM	Roque de los Muchachos Observatory
OT	Optical Turbulence
TO	Teide Observatory
WFWFS	Wide Field Wave Front Sensor

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1. Introduction

The H2020 SOLARNET project includes a study to investigate the possibility to set-up systems for the forecast of the optical turbulence in the day-time regimes at the two sites of Roque de los Muchachos Observatory (ORM, La Palma) and Teide Observatory (TO, Tenerife), with a particular attention to the site that will be selected for the European Solar Telescope (EST) [RF1]. More precisely the study (hereafter referred to as the proposed study) aims to upgrade to day-time conditions the method to forecast the optical turbulence (C_N^2 profiles and integrated astroclimatic parameters) that was developed by the INAF partner for night-time ground-based astronomy.

The technique implies the use of a mesoscale model (Meso-Nh) developed by the Centre National des Recherches Meteorologiques (CNRM) and Laboratoire d'Aerologie (LA) in Toulouse (France), and a dedicated code (Astro-Meso-NH) created by Elena Masciadri of INAF-Osservatorio Astrofisico di Arcetri (INAF-OAA), to forecast the optical turbulence [RF2]. The Astro-Meso-Nh code is in continuous evolution since more than a decade. It is now managed by the Optical Turbulence team of INAF-OAA and the applications of this code evolved in the time. The most recent version of the code is described in [RF3]. The application to day-time conditions implies new challenges, because the turbulence in day-time presents different features with respect to those developed in night-time, and it is characterised by different typical values for C_N^2 and derived astroclimatic parameters. This study can lead to the development and implementation of an operational and automatic system for the optical turbulence forecast for EST and other solar telescopes operated at the ORM and TO sites.

INAF-OAA has already developed an equivalent system for the Large Binocular Telescope (ALTA Center project – alta.arcetri.astro.it) that runs nightly providing a complete description of the atmosphere conditions (including the optical turbulence). The system is used for the science operations of LBT and in particular to optimize the use of instrumentation supported by the adaptive optics. Such a tool can be considered as a reference with respect to a potential similar tool to be conceived for the EST. The final and ultimate goal of this activity is to develop and implement an operational and automatic system for the optical turbulence forecast for EST and other solar telescopes operated at the ORM and TO sites.

This report deals with the availability of optical turbulence measurements above the ORM and TO sites. Actually, data on the vertical stratification of the quantities monitored and on their integrated values are required to calibrate the Astro-Meso-Nh model and to validate it for day-time conditions, i.e. to quantify the performances of the model.

2. Optical Turbulence Measurements at the ORM and TO sites

Part of measurements of the atmospheric parameters and the optical turbulence above the ORM and TO sites have been taken in a few site testing campaigns performed over the last years. In particular, in the framework of the FP7 SOLARNET, the IAC partner led the acquisition and analysis of data acquired with short and long SHABAR instruments operated at the ORM and TO sites. Results derived from analysis of those measurements were published in the deliverables [RF4, RF5] of the FP7 SOLARNET project. Part of OT measurements are on the contrary more recent, or they are planned to be acquired soon. They consist on a vertical stratification obtained with the wide field-wavefront sensor (WFWFS) technique. To carry out our study we need both kind of information: vertical distribution (C_N^2) as well as integrated values (r_0) provided by the WFWFS.

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(a) SHABAR measurements.

Following discussions started at the beginning of the H2020 SOLARNET project, the IAC partner provided to the INAF partner measurements from the SHABAR instruments right after the KOM of the project.

SHABAR measurements consist on vertical distribution of the optical turbulence in the first hundreds of meters above the ground. These measurements can be useful to control the Astro-Meso-Nh model behaviour close to the ground. We remember that in the first kilometre above the ground (the so called boundary layer) is normally concentrated the most part of the turbulence developed in the whole atmosphere.
Several tens of days have been monitored at both sites. Therefore, the statistics of those measurements should be consistently rich and suitable for the proposed study.

(b) WFWFS measurements

This technique implies the implementation of an instrument on in-situ telescopes. Measurements are obtained thanks to a SDIMM+ technique [RF6]. In principle this kind of measurements will be available on both sites ORM and TO.

WFWFS measurements acquired by the SU partner at the ORM (at Swedish Solar Telescope – SST) since May 2018 are not yet available for the proposed study. It has been recently understood that measurements of the temporal evolution of r_0 are in principle already available, while C_N^2 data will be available later on as the SU partner requires more time to reduce data.
At present, the lack of r_0 data and information on when the C_N^2 data can be made available to the INAF partner prevents any analysis and planning for application of the WFWFS data in the proposed study.

The same kind of WFWFS measurements are foreseen (as described in the H2020 SOLARNET project [RF1] to be taken at the VTT at the TO site by KIS. The final goal of the activity performed by SU and KIS partners is to compare the sets of measurements taken above the two sites to gain insights on the vertical distribution of turbulence on the first 12 km above the ground (a.g.l.) and in particular on the highest layers. This analysis is certainly critical for the design of the MCAO system and site selection of the EST. Simultaneous measurements at the two sites were expected to be performed during 2019, following the schedule for the decision of the EST site in the H2020 PRE-EST project. However, since the simultaneous measurements still have to be acquired, they are not available for the proposed study yet.

As a general statement it is worth emphasizing that the proposed study aims to investigate the possibility to set-up systems for the forecast of the optical turbulence at the ORM and TO sites. Characterization of these sites do not pertain to the proposed study, which will consider the available measurements only in relation to their use for the turbulence prediction.

2.1 SHABAR Measurements

Measurements related to ORM were provided in ASCII format, containing the measured C_N^2 profiles only. Measurements for TO were provided in IDL format, containing, among other things, also the measured C_N^2 profiles.

The measurements have passed a cleaning process to eliminate measurements affected by clouds or guiding misalignments, and have been inverted to get the C_N^2 profiles. The results presented in the following concern all the measurements as received from the IAC partner, without any removal of outliers affecting the series.

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ORM: Roque de los Michachos Observatory

For ORM we received measurements for a total of 476 days, from 2010 to 2014. Document [RF4] states that, after the cleaning procedure, the final data-set consisted on 461 days of measurements. Therefore, the results in the following include 15 days of measurements that were discarded in the data reported in [RF4]. Table 1 summarizes the statistics of the days with measurements. The seasonal distribution is definitely not uniform as we have much more days in summer time than in winter time. This element has to be taken into account in the phase of identification of the sample of reference.

Dates with observations	Number of dates	Summer	Winter
ALL	476/**341**	418/**298**	58/**43**
2010	7	0	7
2011	161	139	22
2012	153	129	24
2013	134	129	5
214	21	21	0

***Table 1**: ORM observations statistics. Values in bold style indicate the residual days after discarding a number of measurments not reliable (see text).*

TO: Teide Observatory

For TO we received measurements for a total of 215 days, from 2010 to 2013. Document [RF4] states that there should be also measurements related to 2014 year that, however, were not provided to the INAF partner. [RF4] also states that, after the cleaning procedure, a total of 214 days of measurements have been preserved in the years 2010-2013. In this case, it seems that we have at least 1 day of measurements that was discarded in the cleaning and was nevertheless provided to us. We observe the same unbalanced seasonal distribution observed above ORM: much more days in summer time than in winter time.

Dates with observations	Number of dates	Summer	Winter
ALL	215/**130**	182/**111**	33/**19**
2010	9	9	0
2011	113	92	21
2012	35	23	12
2013	58	58	0

***Table 2**: TO observations statistics. Values in bold style indicate the residual days after discarding a number of measurments not reliable (see text).*

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Correction by the air-mass

SHABAR measurements are distributed on 64 levels on the LOS, for each profile the angle with respect to zenith (γ) is provided. Measurements have been corrected by the air-mass that means to multiply the height by the cos(γ). This means that C_N^2 have been projected along the vertical axis (zenith), by resulting in a data sampling that is more or less dense depending on the LOS. The larger is the angle γ, the denser is the vertical sampling along zenith. To homogenise the sampling for all the profiles, we interpolated all the profiles on the vertical grid characterized by the densest sampling, i.e. that corresponding to the largest angle γ.

Fig.1 shows a schematic view of the variation of the maximum height (H_{max}) of the vertical profile depending on the LOS. The larger is γ, the lower is H_{max}.

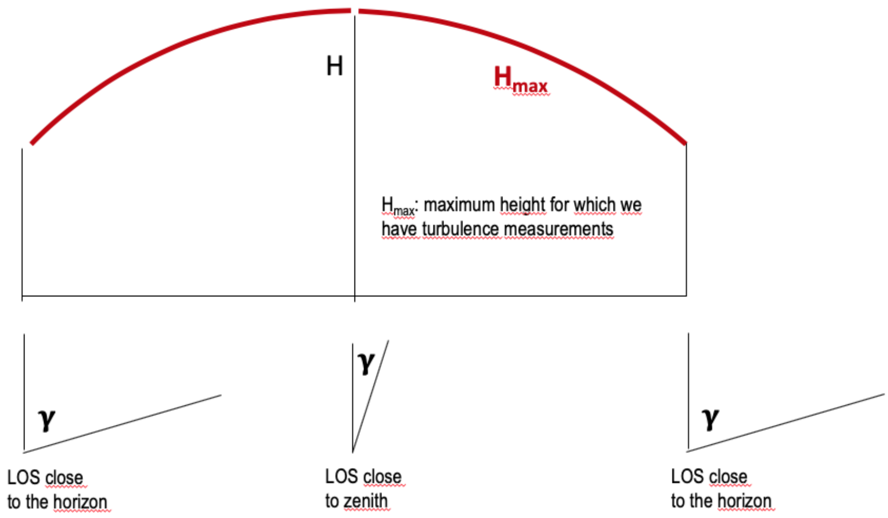

***Fig.1**: Schematic view of the maximum height of the C_N^2 profiles dependent on the LOS.*

Fig.2 displays an example of the temporal evolution of the C_N^2 during one day (14/4/2011) above the ORM. As can been seen in Fig.2, if data are not corrected by the air-mass the strength of the turbulence even close to the ground is consistently different from what we would see if instead of looking at turbulence along the LOS we look at along the zenith. On left side panels, the C_N^2 is plotted taking on the y-axis the LOS. On right side panels, we can appreciate the real extension on the vertical axis of the C_N^2 measurements. The correction by the air-mass is important because if one calculate the r_0 through an integration of the C_N^2 along the LOS, this can hardly be compared to others r_0 that are not taken along the same LOS. The normalization with respect to the zenith permits the comparison between observations and numerical calculations obtained with an atmospheric model. The procedure we used is the following: we first corrected the C_N^2 by the air-mass and then we integrate it along the vertical direction to obtain a consistent value of the integrated turbulence on the whole atmosphere to be compared with independent estimates.

We note that the C_N^2 values (vertical distribution) are extended up to the top of the atmosphere even if in principle values of the stratification above 3 km are unreliable as indicated in [RF5]. Based on discussions occurred with the IAC partner, we assume that above the 3 km threshold, only the integral of the turbulence is reliable.

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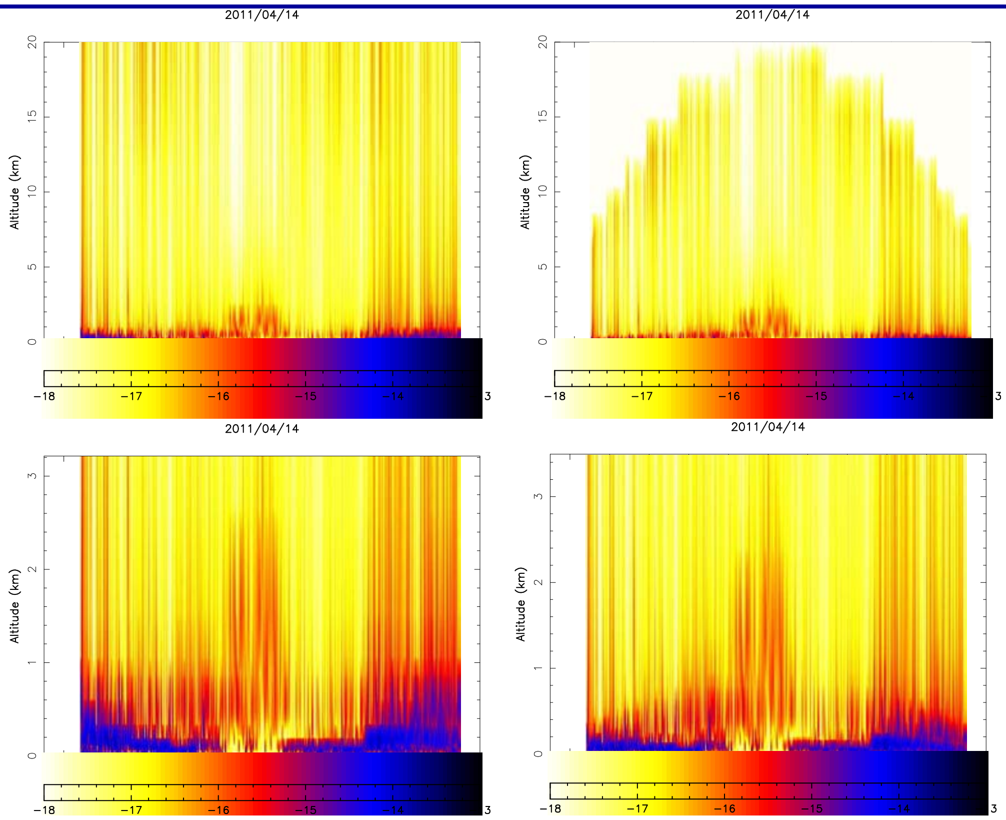

***Fig.2**: Temporal evolution of the C_N^2 during one day extended on 20km a.g.l. (top) and on the first 3km a.g.l. (bottom). On the left is shown the C_N^2 as a function of the line of LOS (reported on the y-axis). On the right side, the C_N^2 is corrected by the air-mass and it is shown as a function of the zenith direction (reported on the y-axis). On the bottom is shown a zoom of the first 3 km above the ground. X-axis is the temporal axis. It reports UT=LT.*

Visual analysis of the data clearly shows that these are not cleaned measurements. There are visibly outliers or other artefacts that need to be removed from the series for consistent analysis of the measurements in the proposed study and in compliance with the findings reported from the FP7 SOLARNET project. In the following we provide a few examples of the main features of the available data.

We considered the full time evolution of the C_N^2 profile, the time evolution of the integrated seeing, median and average C_N^2 profile for each day. We selected few criteria for flagging a specific day of measurements as "good" or "bad", based on following features evidenced in the data plots:

1) Values of the average seeing unrealistically high, e.g. seeing > 10 arcsec. (seeing values are frequently above 100 arcsec). Fig.3 shows an example of such a kind of problem. The averaged seeing in each day is of the order of thousands or hundreds of arcsec because of evident spurious data. We considered as a threshold 20 arcsec that corresponds to a r_0 = 0.5 cm in the visible.

2) Line bands in the C_N^2 profile evolution showing evident unrealistic high values of C_N^2 (well above: 10^{-13} $m^{-2/3}$) or manifesting a high contrast with the adjacent lines. Typically, these lines appear in rapid succession; however, they may also appear as isolated black lines. A common feature is the fact that they extend in the high part of the atmosphere with extremely unrealistic C_N^2 values (sometimes around 10^{-8} $m^{-2/3}$). The appearance of those lines, if noticeable from the plot, forces us to discard the whole day. Fig. 4 show examples of the features discussed before. We show C_N^2 time evolution plots up to 20km of altitude because

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sometimes the unusual features develop at high elevations in the atmosphere. Not clear even why there are values above 3 km for the reasons described above.

We point out that the above selection criteria are obviously subjective and based on the manifest, visual evidence of some unrealistic behaviour of the corresponding parameter. It is a poor substitute of a proper data cleaning strategy that was not made clear before the writing of this report, forcing us to discard the whole day even if probably only a portion of the data is "problematic". Using such drastic criteria of data selection, we counted a final discarded days equal to 85 above TO and 135 above ORM. With respect to Table 1 and Table 2 the number of residual days, after the elimination of discarded days is of 341 days at ORM and 130 days at TO. We have simultaneous measurements above the two sites on 93 days (80 days in summer time and 13 days in winter time). Points (1) and (2) are just examples of problems related to the fact that we are analysing all the available measurements ("raw" C_N^2). Of course the absence of evident visual unrealistic features does not mean that the measurement is realistic. That means that also the residual sample of measurements are hardly usable. As it has been communicated to us very recently the criterium used to clean the raw C_N^2 data-set, this should not be any more a problem.

During the analysis, we also noticed that, at the end of the day, the seeing measurements often tend to diverge, as reported in Fig.5. This corresponds to unusual and unrealistic high turbulence values (often with C_N^2 above 10^{-13}) at high altitudes (up to 18 km) as shown in Fig.6. This was observed specifically on a significant number of days on TO. Since this is highly possibly a measurement problem, we can mitigate this by cutting the last hour of measurement in all days monitored above TO.

In Fig.7 are shown the cumulative distribution and the histogram of the zenithal angle above the two sites of ORM and TO. The two histograms are slightly different in the queues, but the median values and the first and third tertiles are comparable. This indicates that the two samples are statistical representative for the application of the proposed study.

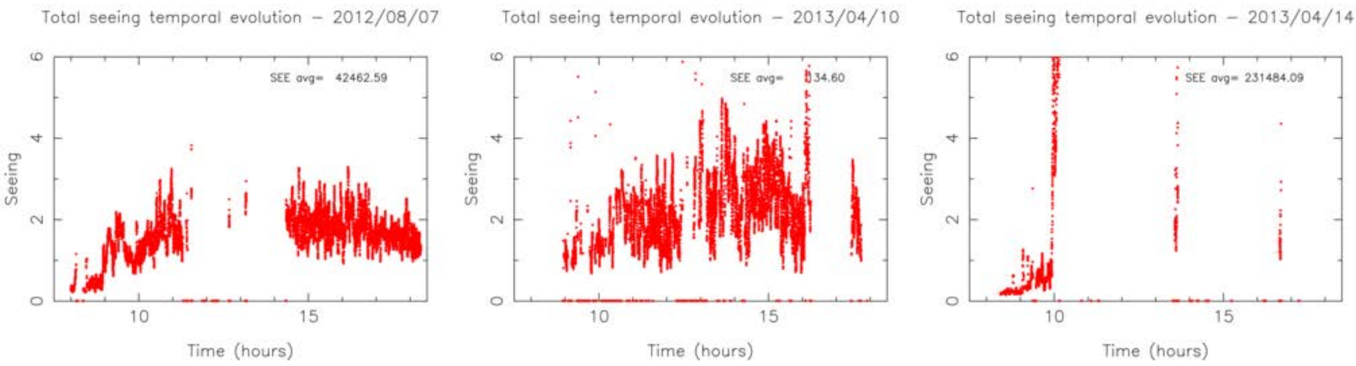

***Fig.3**: Time evolution of integrated seeing from SHABAR measurements. The presence of erroneous profiles is evident from the computation of the average seeing during the day (top right of each figure) that shows overscale values*.

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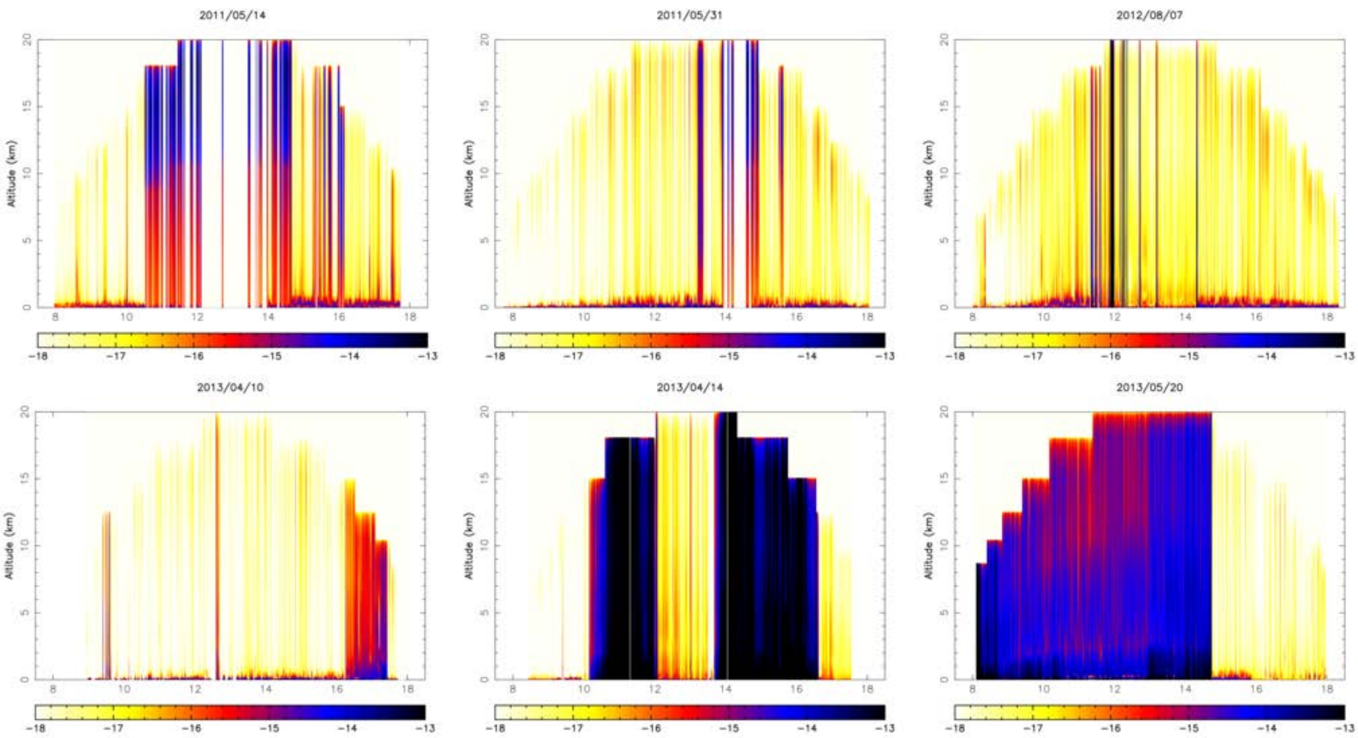

Fig.4: *Time evolution of C_N^2 profiles during different days. Dates were selected based on the presence of problematic features described before.*

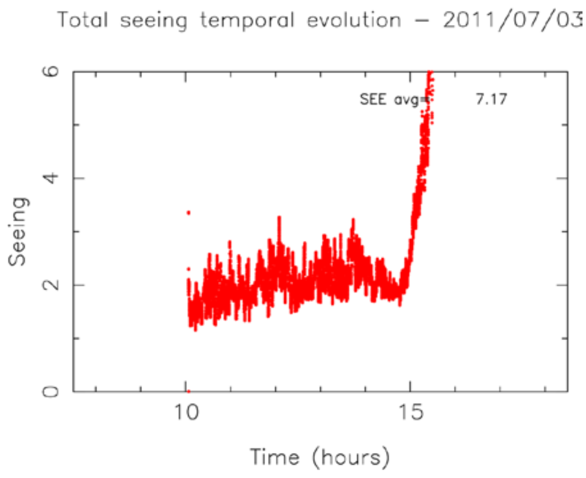

Fig.5: *Example in which the seeing diverges at the end of the observation on TO at the end of the day.*

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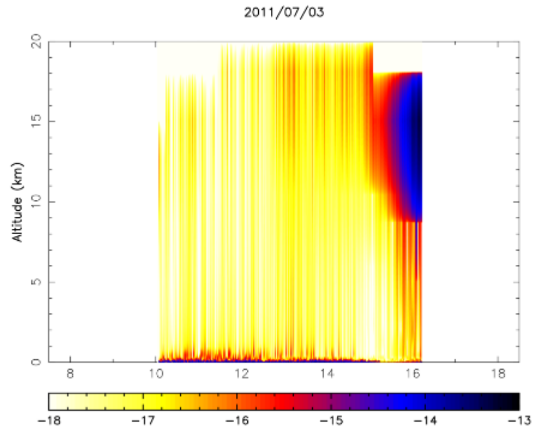

***Fig. 6**: C_N^2 related to Fig.5: high elevation turbulence corresponding to the seeing divergence above TO at the end of the day.*

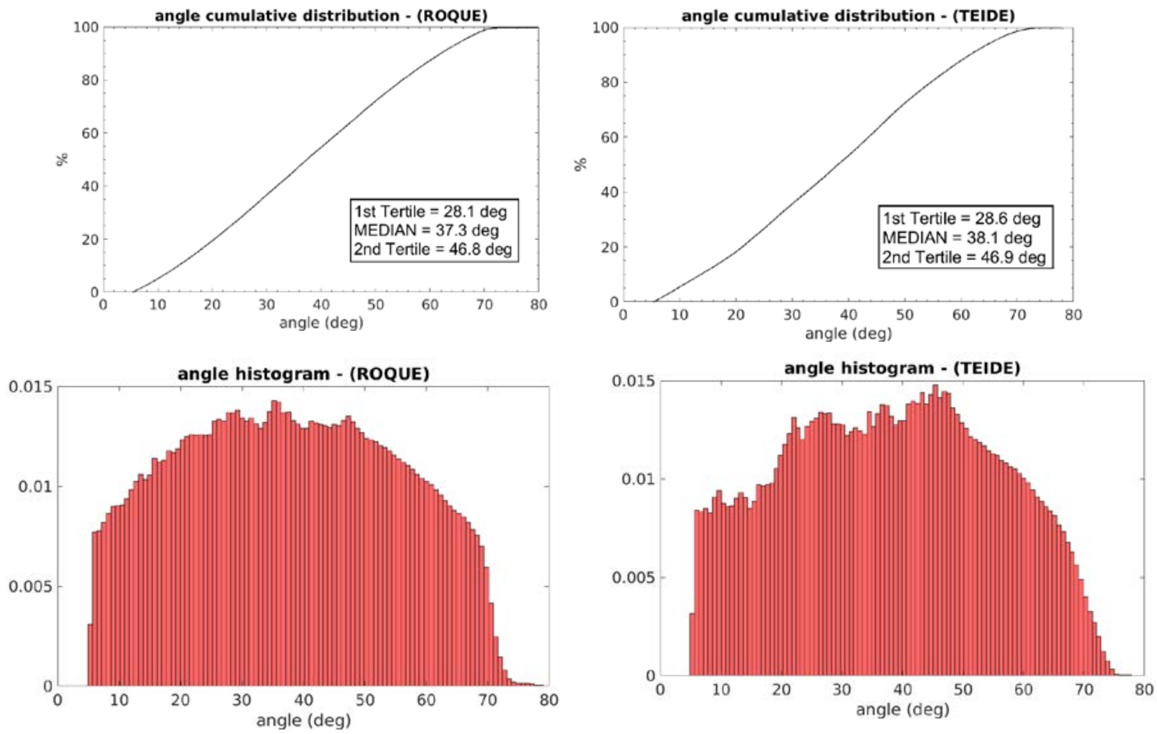

***Fig.7**: Top: cumulative distribution of the zenithal angle related to observations performed above ORM and TO. Bottom: Histograms of the zenithal angles above ORM and TO.*

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3. Conclusions

The proposed study needs to consider SHABAR clean C_N^2 data. Very recently the IAC partner has informed the INAF partner that the C_N^2 data presented in [RF4, RF5] were obtained by applying the following steps:

1. errors due to guiding misalignment and spurious data due to cloud cover have been considered in the inversion process that led to the raw C_N^2 data-set (the one that we analysed so far and presented in this report)
2. the C_N^2 data-set derived from the inversion was filtered out from the database all values in which $r_0 > 1$m and $r_0 < 1$cm. IAC chose therefore to act on the integrated values.

We will take into account this information in the next phases of the proposed study, taking care to check, as a first step, the consistency with results previously published.

We expect that the application of the criterium (2.) will solve part of the data problems reported in this document.

Concerning WFWFS derived from both past site testing campaign at the ORM performed by the SU partner, and new campaigns that will take place at TO, both considered in the H2020 SOLARNET project, the INAF partner is willing to include those data for the proposed study, provided that the plan of the data delivery is clear and compliant with the schedule of the activity, and that the data are made available for the proposed study with complete information on their processing.

References

RD1	Grant Agreement – Number 824135 - SOLARNET
RD2	Masciadri, E., Vernin, J., Bougeault, P., 1999, A&ASS, 137, 185
RD3	Masciadri, E., Martelloni, G., Turchi, A., 2020, MNRAS. (accepted)
RD4	D70.8: Results of the site testing campaign at ORM and OT – May 2017, PR: 312495
RD5	D70.13: Results of the site testing campaign at ORM and OT – May 2017, PR: 312495
RD6	Scharmer, G.B. & van Werkhoven, T.I.M, 2010, A&A, 513, A25

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