# Astronomical site monitoring: current status and ideas for the future

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**ABSTRACT**

Abstract: We present here a summary of current astronomical site monitoring activities related to ESO sites (DIMM, Stereo Scidar, MASS, FASS, turbulence prediction). We also present what parameters we think should be measured in the future, in the era of the next generation of large optical telescopes.
**Keywords:** Site monitoring, Turbulence profiling, Adaptive Optics

## 1. SITE MONITORING MOTIVATIONS

There are several reasons to monitor an astronomical site. A certainly incomplete list of the main customers for such activities is, with a bias towards AO activities due to the nature of this conference:

- Instrument design / simulations (mostly Adaptive Optics) : the goal is to obtain realistic and statistically significant input data to design (AO) instruments and predict their performance as a function of environmental conditions.
- Operations: the goal is to schedule observations in advance and during night ("nowcasting"), to use observing conditions optimally (for example reserve best conditions for highest priority observations, or observe targets where cloud coverage is less). Another aspect is to calibrate observations (using Precipitable Water Vapor monitors or field-variable PSF reconstruction in SCAO are examples of this).
- Site characterization and selection: the goal is to understand our current observation sites better and find new sites for future new projects. Monitoring the site allows for example to find longer term trends and predict how the site characteristics are evolving. Such evolution could for example be due to climate change.

## 2. INTERNAL VS. EXTERNAL MONITORS

We have several means to measure Cn2 profiles (a parameter used here as an example, it is also true for seeing and many other quantities). For example, there is the AOF-LGS based profiler ([3]) and several external dedicated profiling devices, like the Stereo-Scidar ([2]) and the MASS-DIMM ([10]). Both methods (instrument based or dedicated) have pros and cons. For example, the external profiler is well suited for operations, it allows to be able to know conditions even before opening the telescope. It is independent of the functioning of the instrument itself, and statistical gathering of profiles doesn't depend on whether the instrument is used or not. On the other hand, an instrument's internal profiler measures what we want, where we want, when we want it.

Therefore, both approaches are useful. However, cross validation is necessary. Moreover, it can provide insight into the benefits and limitations of each device. For example, in October 2019, we carried out a campaign where both the Stereo-Scidar, and the Muse-NFM tomographic AO system were used at the same time, pointing in the same direction in the sky, gathering Cn2 profiles

simultaneously. An analysis and comparison is going on now. In addition to those two profilers, a prototype of the FASS ([1]) was run on the platform, and may provide additional data to this comparison.
We plan to carry out more of these cross validation campaigns, to both gain trust in the measurements themselves, but also to understand the limitations of each instrument.

## 3. THE CASE OF SEEING MEASUREMENT FOR THE ELT

During commissioning for example, knowing what the seeing outside of the ELT dome is important. Therefore, an external device, like a DIMM seems to be mandatory. However, it is not as simple as just installing the device.
On the ELT, how to does one measure ELT's "seeing" with an external monitor ? Just the height of the ELT pupil is a challenge. It is so high, that it will not see some part of the ground layer turbulence. So one needs to filter out a big part of the boundary layer not seen by ELT. Assuming the turbulence profiler is not built on a huge tower, at the same height as the ELT pupil, we have to find a way to subtract from what the measurement device sees the part that is below the ELT.

Because of the size of the ELT dome, it is likely that very strong local effects will be seen on the ELT site. Like for the different locations of the DIMM on the VLT platform has shown, it is likely that being in the wake of the ELT dome will bias the seeing measurements, perhaps dramatically. To solve this problem, we could use two seeing measurement stations (so that only one is in the wake of the current wind), one DIMM and one SLODAR. In addition to providing another seeing measurement point, a SLODAR would allow to filter out the right fraction of the ground layer turbulence, and accurately reflect the ELT seeing.

## 4. CURRENT AND FUTURE MEASUREMENTS

Currently a full suite of instruments are available at Paranal to monitor environmental conditions.
They can all be visualized in real-time by users, using a customizable interface. An example is given below for the different turbulence profilers.

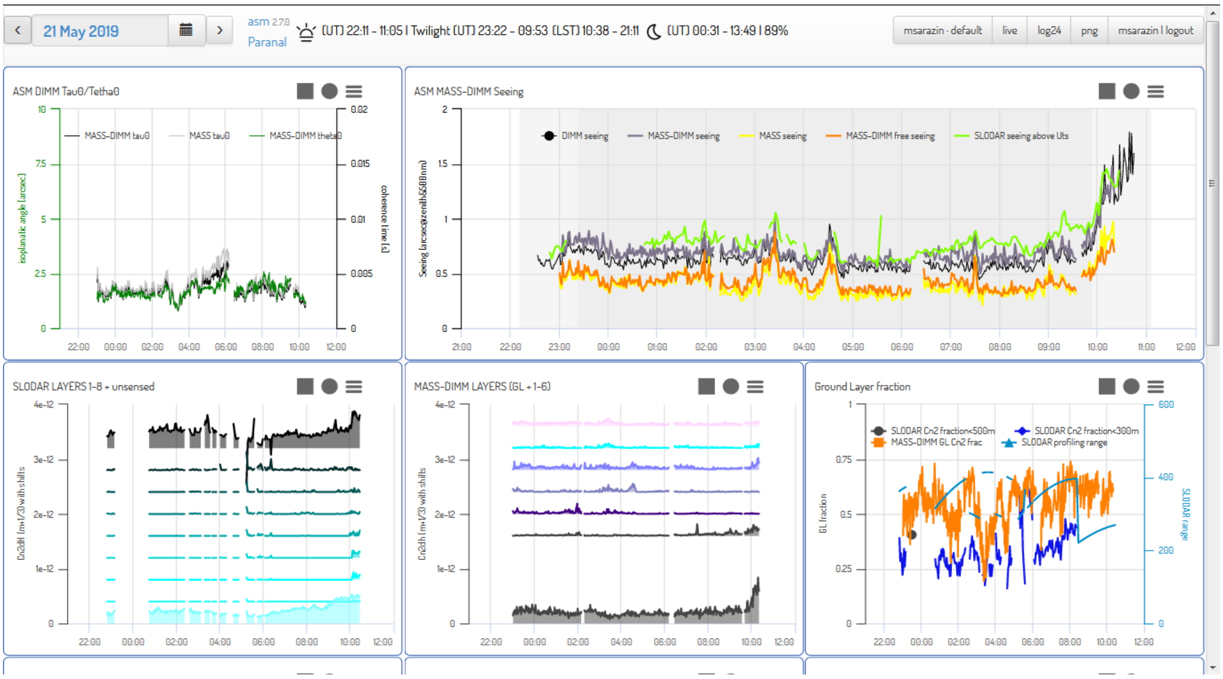

**Figure 1: Example of real time output of some of the turbulence profilers at work in Paranal.**

Here is a non-exhaustive list of parameters regularly monitored in Paranal, that could be also measured at the ELT site.

- “Classical” meteo-parameters (temperature, pressure, wind,…) at several heights. They are critical for operations for example, where some rules are set when the telescope can be operated (wind, humidity restrictions, for example)
- Clouds (but there is currently no automatic detection / monitoring)
- r0, Cn2 (several resolutions), tau0 (indirectly). AO instruments also provide their own measurements, at least of some of these parameters.
- Precipitable Water Vapor ([5]). For this, two devices could potentially be used for the ELT used: one averaging over the sky, one in the line of sight of the ELT.

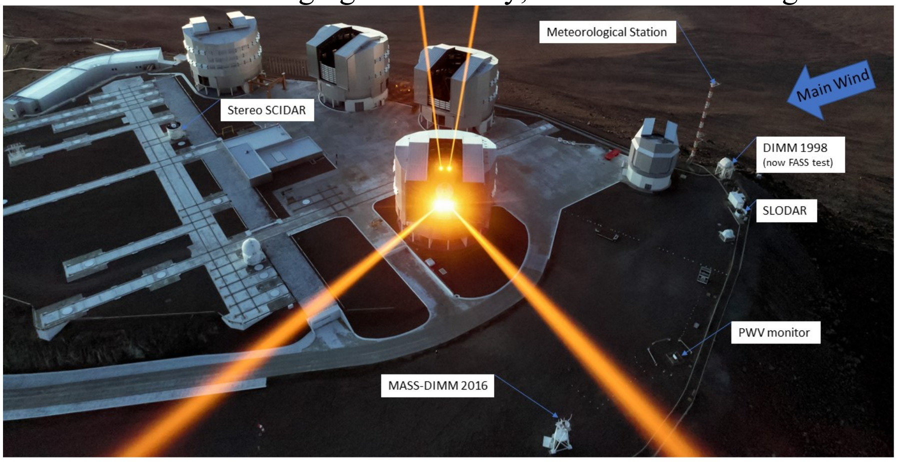


**Figure 2: A picture showing some site monitoring equipment on the summit of Cerro Paranal. It is getting crowded !**

Prediction of future observations on the short and long term are important for operation planning. This goes from “standard” weather predictions (clouds, wind, PWV,…) which impact observations, and a new goal is to predict, for operations, the seeing conditions for the next few nights.
Although seeing predictions have shown encouraging results (see an example of predicted Cn2 profiles above a model of Paranal), it is not yet clear how well these predictions can be used operationally at Paranal.
Currently, a SLODAR ([7]) is operating in Paranal, to provide very high-resolution measurements of the turbulence close to the ground. However, some problems have been observed with it, and they need to be solved to be able to use it efficiently in the context if the ELT. The following should be improved:

- The current SLODAR is very sensitive to wind. This should be solved by improving the telescope mount.
- Sometimes, measurements are being rejected because there is a lot of turbulence in the first layer above the ground. The source of these measurements is being investigated. One cause could be local heat sources (due to the cameras for example) in the SLODAR enclosure. Another possibility is the fact that the SLODAR is not on a tower, and so it see a lot of ground layer turbulence.
- Some software solution could also be applied, to try to estimate the power spectrum of the ground layer turbulence, allowing to provide better measurements.

Thanks to its very high resolution in the ground layer, SLODAR still looks like a very useful device in the context of the ELT, especially to be able to filter out the turbulence the ELT is not seeing thanks to its height. And in addition, it can be used to measure the integrated seeing (like a DIMM), providing another location for seeing measurement than the already planned DIMM.

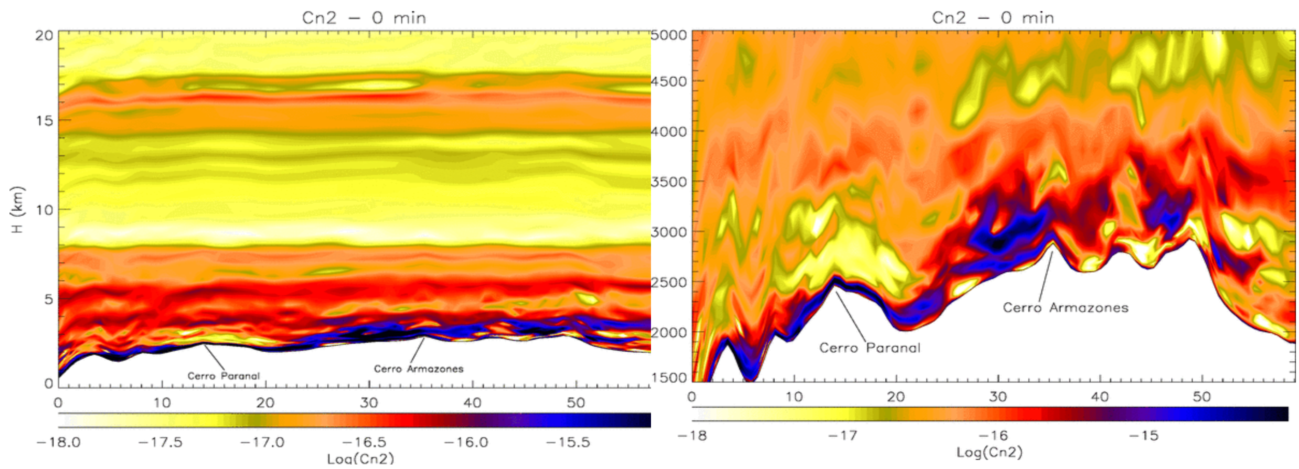

**Figure 3: Example of Cn2 predictions by the MOSE study, E. Masciadri et al. ([4]).**

## 5. VALIDATION AND COMPARISONS OF MEASUREMENTS

We have multiple devices (for example r0 measurements from various AO instruments and different site monitoring devices, Cn2 profilers,…) the same parameter with slight differences, like a different locations on the platform, different heights of the measuring device, time sampling, observation direction, resolution, or even using a different physical principle. It is then not surprising that also the measurement result is *slightly) different. But is it also reflecting what we actually want ?

An example of this is given by the “new” DIMM, which provides more representative seeing measurements than the old one The old DIMM was affected by surrounding telescopes, providing pessimistic measurements of the seeing compared to UT observations, even though the DIMM itself did not have any problems. This demonstrates that local effects are present in an observatory (being in the wake of a large telescope may not be the best idea to measure turbulence) and shows that two well-functioning devices can still provide different measurements. A validation of measurements is therefore key. Below, we show a picture of the “new” DIMM tower, much better suited to measure seeing seen by the UTs than the old one, seen in the background near the VST telescope.

**Figure 4: The "new" DIMM tower.**

How should one then do a meaningful comparison between all those measurements, and be confident that they measure what we want ? Several methods can be explored.

- Different devices (like the DIMM in the example above) at same place, height and time. This approach was used to qualify the DIMM-devices at the beginning of the TMT site testing campaign. This allows to validate that all devices themselves (or their data reduction software) measure the same thing if the conditions are the same. One hopes that what is measured is the sought-after physical parameter (r0 in the example above).
- Validation by simulation and statistics is another approach. Currently a study by University of Durham ([6]) is being carried out to compare MASS and Stereo-Scidar profiles, using statistics. Mostly it is validation by simulation. A further comparison with the AOF profiler took place in October 2019. The goal is to understand strengths and weaknesses of different measurements, using data obtained on the same site at the same time. It will also allow to understand the differences that are seen and answer some questions about local effects on the platform, and the homogeneity of turbulence in different directions.
- Theoretical validation. Here we just assume that the device works. This would be the case for a L0(h) profilers for example, and probably for dome seeing. It is not clear now how they could be validated in standalone mode, without access to ELT and it’s instrument that are sensitive to that parameter.

## 6. TURBULENCE PROFILING

In this section, we give a bit more details about turbulence profiling activities that have been carried out at Paranal recently. Currently the following devices are used for Cn2 profiling:

- MASS / DIMM: every night.
- Stereo-SCIDAR: a few nights a month, on average.
- SLODAR stand alone (ground layer), evry night, if conditions allow.
- AOF profiler, using a SLODAR algo w/ Laser Guide Stars, 10s of nights a month, whenever the instrument performs observations.

Thanks to the Stereo-scidar, we now have a fairly large database of high resolution Cn2 profiles ([11]), covering several years, which has provided valuable information to the ELT instrument building consortia.
In addition to these devices, new profilers are actively investigated, like the Moon Limb Profiler ([8]), FASS ([1]) and others. One key question that is being looked into, is how to compare the measurements of all these profilers and select the best suited for some task. For example, a new application of a Cn2 profiler in the context of the ELT, in addition to the "usual" tomographic AO systems performance prediction, would be SCAO systems, for which one wants to do off-axis PSF reconstruction. In the particular case when the PSF reconstruction has to be "blind" (i.e. there is no other star in the field of view to estimate / fit anisoplanatism effects), it seems that a Cn2 profiler is the only method to derive an off-axis PSF from on-axis WFS measurements ([9]). However, it is not clear for the moment, if a SCIDAR is required, or if a lower resolution profiler (like the MASS-DIMM) would be enough for this task.
One option as a "do it all" profiler is the stereo Scidar (developed by Durham University), which is in routine operation, providing high resolution Cn2 profile measurements during a few nights every month. This provides statistically relevant information to instrument designers (e.g. AO performance estimation and availability). It also provides a reference for other Cn2 profilers, like MASS, and the AOF-turbulence profiling routines based on SLODAR, using the LGSs of the facility. We would like the SCIDAR to be a reference for all Cn2 profilers. It is expensive, so its high resolution must be justified, and further studies are required to do this.
An example of the nightly output of the Stereo-scidar is given below:

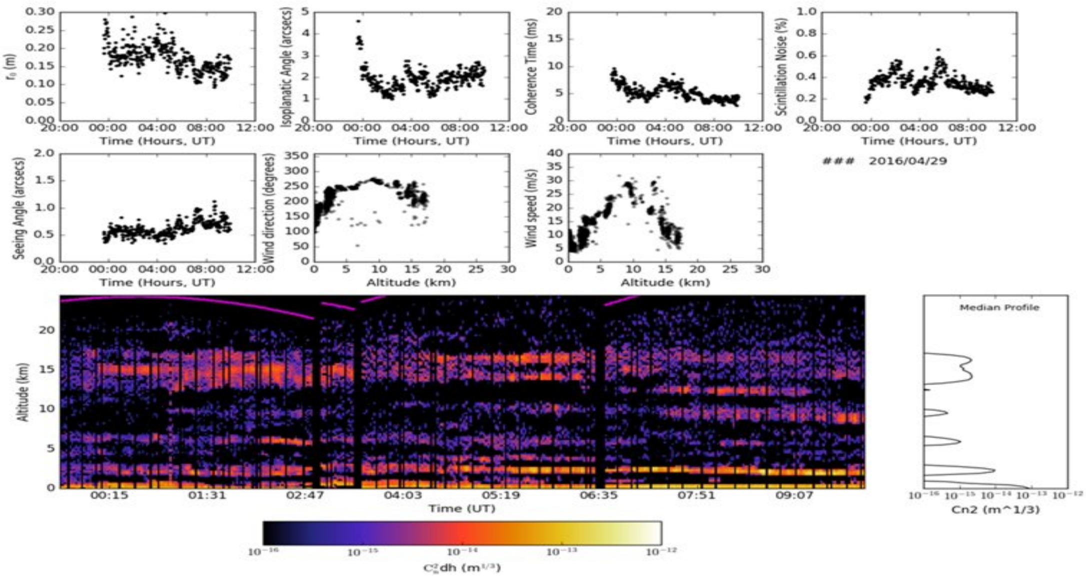


**Figure 5: An example of Stereo Scidar output, during a night of observation.**

## 7. THE FUTURE: QUESTIONS AND CHALLENGES

In this section, we discuss future studies and things that we think should be investigated to improve the understanding of the site.

- Impact of satellite constellations, it is yet unclear if these will have an effect on the observations or not
- Turbulence (Cn2) and v(h) predictions would help scheduling observations. v(h) (turbulence speed per layer), is monitored for example by the Stereo-Scidar, but it's data is not available in real time in the observatory. It is not yet clear if this would be used operationally.
- Outer scale of turbulence $L_0$ and its profile $L_0(h)$. It has been shown in simulations to have a strong impact on (tomographic) AO performance, but there are no plans for the moment to have an external device measuring this parameter. It should come out of the real-time computer of a tomographic AO system, and could be used to diagnose the observations.
- tau0 estimate improvement: currently the estimation is based on the wind at 200mbar, but other measurements (coming from the AO systems) should be also available
- Dome / telescope seeing. Currently the VLT is well behaved in this respect, and it is hope the ELT will be as well. But how could this be verified?
- Complexity of inputs for ELT (it will be sensitive to everything !), and understanding its performance fully will require a lot of inputs from the site, as well as a lot of analysis.
- Photometry along the line of sight. This could reduce the need to observe calibration stars after the observations, but there is currently no specifications for such a device. It may be combined with a dedicated Scidar telescope, but it is not yet clear how the measurements would be done (need for a large number of filters for example). Another possibility would perhaps be to use a dedicated PVW-measurement along the line of sight where the telescope is observing.

Another interesting point of study is that some devices are somewhat **model dependent**. How to deal with that ? For example, Kolmogorov (or von Karman) assumptions are made for SLODAR (and similar techniques), for SCIDAR also. What about L0(h) ? Does it impact also those profilers ? Perhaps getting L0(h) from an AOF-type profiler ([3]) would be sufficient. At least it could be used to gather statistics in view of the ELT. But how to validate such measurements ?

What about climate change ? How does climate change impact our sites? More or less clouds? Seeing? Humidity? Wind? Impact on finding new sites for new telescopes ? Preliminary analysis is inconclusive (too short period). Perhaps climate models could help to investigate this?

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