



HAL
open science

Astronomical Site Monitoring for the joint Paranal-Armazones Observatories: high-priority measurements and instruments

Angel Otarola, Joseph Anderson, Pablo Barriga, Natalie Behara, Fuyan Bian,
Aleksandar Cikota, Pedro Fluxa, Miska Le Louarn, Steffen Mieske, Elyar
Sedaghati, et al.

► **To cite this version:**

Angel Otarola, Joseph Anderson, Pablo Barriga, Natalie Behara, Fuyan Bian, et al.. Astronomical Site Monitoring for the joint Paranal-Armazones Observatories: high-priority measurements and instruments. COAT2023, Mar 2023, Durham, United Kingdom. hal-04605058

HAL Id: hal-04605058

<https://hal.science/hal-04605058v1>

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.

Astronomical Site Monitoring for the joint Paranal-Armazones Observatories: high-priority measurements and instruments

Angel Otarola^{*a}, Joseph Anderson^a, Pablo Barriga^a, Natalie Behara^a, Fuyan Bian^a, Aleksandar Cikota^b, Pedro Fluxa^a, Miska le Louarn^a, Steffen Mieske^a, Elyar Sedaghati^a, Alain Smette^a, Rodrigo Romero^a, Julien Milli^c

^aEuropean Southern Observatory, Alonso de Córdova 3107, Vitacura, Región Metropolitana, Chile;

^bGemini Observatory, NSF's NOIRLab, Casilla 603, La Serena, Chile;

^cGrenoble Alpes University, CNRS, IPAG, 621 avenue Centrale, 38400 Saint-Martin-d'Hères, France

ABSTRACT

The European Southern Observatory strategy is supporting an integrated operations programme of the Paranal-Armazones Observatories. This plan arises from the need to create an operations model that is more economic and efficient than operating individual separated observatories. The plan is based on three main principles (so-called pillars): Lean Operations (i.e. optimized level of synergies), Remote Operations (allowing automatic and continuous monitoring of key parameters for the safe and efficient operations of telescopes and instruments); and, High-Performance Operations (on the science operations aspects this implies maximizing the scientific productivity by improving the scheduling of science observing blocks to best match the current atmospheric conditions).

Following the guiding principles shared above, the ESO science operations team is working towards the design and implementation of an astronomical site monitoring effort that: a) shall provide information to optimally assist all the observatory processes for which weather and atmospheric turbulence information is required, including health & safety of operations, technical & engineering processes, science operations; b) accurate forecasting of critical weather conditions to enable safe operations and c) provide information (measurements and forecast) for an optimal exploitation of the seeing limited and adaptive optics nature of existing and future astronomical instrumentation, at the Paranal and Armazones observatory sites. Accurate forecast, in short- and mid-timescales shall help us exploit the best atmospheric conditions of the site maximizing the on-sky science time.

This paper summarizes the status of our existing work and plans, for the ESO's astronomical site monitoring system, to fulfil the needs and requirement for the safe and optimum engineering and science operations of the VLT and ELT telescopes.

Keywords: Site monitoring, atmosphere

*angel.otarola@eso.org ; website: www.angel.otarola.org

1. INTRODUCTION

At the European Southern Observatory (ESO), the Astronomical Site Monitor (ASM) system comprises a set of instruments to monitor meteorological and atmospheric conditions to provide the observatory with timely information to support various processes, such as observatory science operations; but also importantly, to support the safety of the site operations and all engineering processes where accurate and timely meteorological information is needed. A detailed system overview of the Very Large Telescope (VLT) ASM system is given in [1], [2]. Figure 1 shows the location of ASM instruments at Paranal and views of some of the instruments comprising the ASM system.

The set of instruments, typically included in the ESO ASM system includes the following:

- Weather stations: A set of weather stations, at various heights above the ground level, to monitor meteorological variables such as: wind speed and wind direction, air temperature, air dewpoint temperature and/or relative humidity as well as barometric pressure. The data gets store in a database including the following metrics: averages in one-minute intervals, minimum and maximum values in the said time interval, root mean square and an instantaneous value. The brand of choice at ESO has been traditionally VAISALA.
- Differential Image Motion Monitor (DIMM) [3]: This instrument was designed to monitor the integrated turbulence along the observation atmospheric column, a variable called *seeing*. The DIMM itself is an instrument consisting of a telescope located on a 5 to 7 meters high tower. The instrument has been designed to produce, in the image plane, two images of a single star. The two images are produced by either adding a specially designed aperture mask with two smaller apertures and an optical wedge prism, or via a more sophisticated optical arrangement including two spherical mirrors located in the pupil plane [4]. The point is to create two images of the same observed single star onto the CCD and compute the integrated turbulence (seeing) from the temporal variances of the measured centroid changes of each of the star components [3].
- A Multi-Aperture Scintillation Sensor (MASS): This instrument allows to obtain a vertical profile of the strength of the atmospheric turbulence from the statistical analysis of scintillation of light, from a single star, detected in four concentric ring-apertures [5]. Note: The DIMM and MASS have been combined in a single turbulence monitor system, as described in [4], and the output data is also combined in a MASS-DIMM dataset.
- Water Vapour Radiometers (WVR): This kind of instrument are intended to monitor the integrated amount of water vapor along the observation atmospheric column. At the ESO Paranal Observatory, the WVR instrument of preference is the Low Humidity and Temperature Profiling (LHATPRO) microwave radiometer, manufactured by Radiometer Physics GmbH (RPG) [6]. This instrument monitors the sky brightness temperature at various radiometric channels around the 183.3 GHz H₂O molecules rotational emission line, as well as in the 51-58 GHz O₂ molecules emission band. The channels around 183 GHz allow the determination of the integrated and vertical profile of water vapor in the atmosphere, and the channels in the O₂ oxygen band allow the determination of the vertical profile of atmospheric temperature. This instrument also includes an infrared sensor to obtain the sky temperature from thermal emission in the 9.6 to 10.4 micrometers wavelength range. This makes this instrument quite complete and powerful to obtain not inly integrated water vapor, but the vertical profiles and using the IR sensor data information on sky condition (detection of clouds, or clear air condition).
- All-Sky Paranal-APICAL Camera (ALPACA): This is a camera designed, built and deployed by APICAL Technologies (France). This, camera images the whole hemisphere of the visible sky in the optical wavelengths range. This helps to monitor the sky condition, whether is clear or cloudy and track the clouds evolution [7]. The camera system includes a software (ESKYMO, also designed and programmed by APICAL) to produce: differences between consecutive all-sky images, movies using the sky images obtained in a given time interval (10-min for instance), and a map of sky transparency.

In addition to the basic set of instruments listed above, the VLT's ASM system also includes other turbulence profiler instruments. One of them to monitor the vertical profile of the strength of the turbulence, in the whole atmospheric column to high vertical resolution; this is the Stereo-SCintillation Detection And Ranging (S-SCIDAR) instrument [8], [9]. An another one intended to monitor the vertical strength of the turbulence, in the optical wavelengths in the surface layer (first few hundred meters above the ground level) with a medium to high vertical resolution. This is the Slope Detection and Ranging (SLODAR) instrument [10].

Besides the instrumentation to conduct measurement of the key meteorological and atmospheric parameters, the ASM system also includes a database for the permanent storage of all data and tools for the prompt and continuous display of the information at the users end; for instance the observatory control room when supporting science operations, or via web-based applications to help with the support of the safety and engineering operations at the observatory.

A centralized website to access the ESO ASM data, including statistics of various key variables as well as weather forecast information is found at: www.eso.org/scatmo (current as 11 May 2023). Access to this website requires ESO Portal user credentials, follow the link to create a new account if necessary.

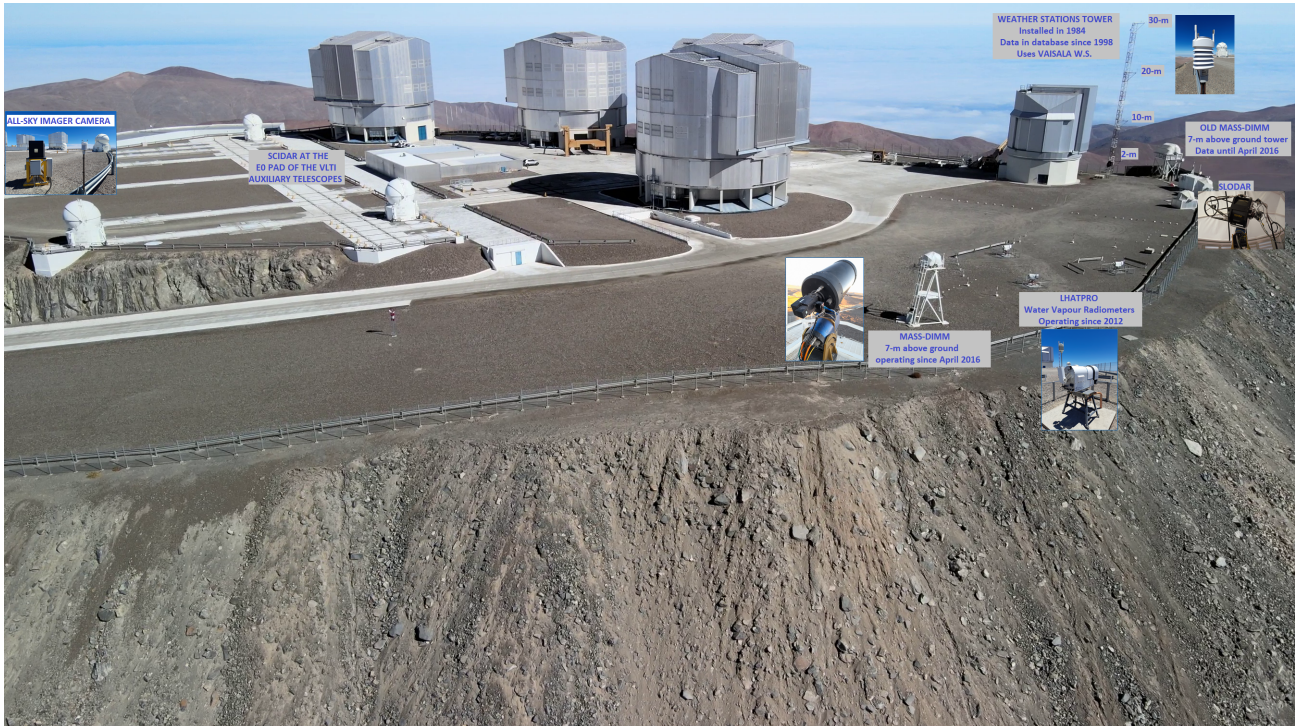


Figure 1 The European Southern Observatory, Very Large Telescope (VLT) site: Distribution of the Astronomical Site Monitor (ASM) system instruments. Drone-view picture by Eng. Juan Beltran @beltran_juan.p

2. KEY APPLICATIONS OF ASM DATA

Some key applications of data from the various ASM instruments are the following:

- Determination of the atmospheric refraction: For the accurate pointing of the telescope to a cosmic source it is required to offset the telescope pointing to accurately account for the refraction angle affecting the wavefront from the cosmic object while crossing the Earth's atmosphere. The atmospheric refraction is a function of increasing density of the atmosphere and of air temperature [11]. Thus, the instantaneous monitoring of surface pressure and of air temperature is used to compute the overall atmospheric refraction angle and apply it as an offset to the Telescope Control System to accurately point to the object outside of the Earth's atmosphere.
- Observations can be performed in either Visitor or Service Modes; VM or SM, respectively. The selection of the next Observing Block (OB) for observation is done using a Short-Term Scheduler (STS). The averages of seeing, precipitable water vapour, and other estimators of the atmospheric turbulence such as the coherence time of the turbulence and the ground-layer-fraction of the turbulence, are used as an input to the Observing Blocks Ranking Engine (ORANG). These variables and other more deterministic constraints such as: the current moon phase and airmass of the science objects are used to filter the observing blocks. The observability, i.e., the probability that the observing blocks can be observed, and project scientific priority help rank the observing blocks still in the observing queue. The top-ranked observing block is the one that has the best matches observability and highest science ranking [12].

- Timely meteorological data helps to assess the overall current weather conditions. This is particularly important to alert of approaching critical weather conditions such as: high wind speed, high relative humidity, low air temperatures. Data from the LHATPRO water vapour radiometers, and images from the All-Sky imager camera monitors the sky condition, whether this is clear, there are thin or thick high-altitude cirrus clouds or thick low level, potentially wet, clouds that could produce precipitation. Proper determination of any of these conditions are not only based on the raw measurements/observations but also the quick statistical analysis of the data. An example of sky assessment, supported on the statistical analysis of the sky temperature measurements done with the infrared sensor, part of the LHATPRO radiometers, is shown in Figure 2. The corresponding All-sky Image associated to the time (indicated by the arrow) is also included.

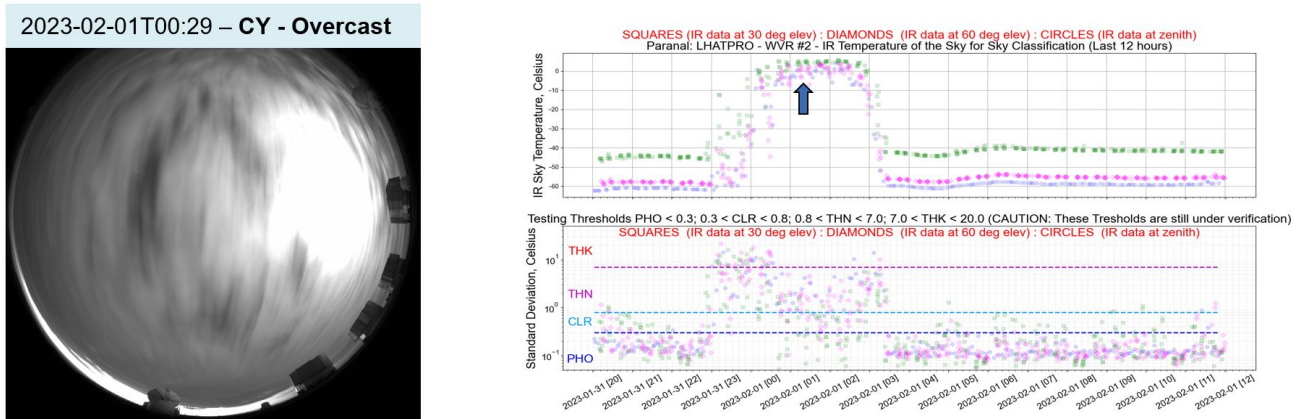


Figure 2 Assessment of sky condition. All-sky (ALPCA) image (left). Statistics (mean and rms) of the infrared sky temperature. The sky temperature measured by the infrared sensor included in the LHATPRO radiometer instrument. The data shows the mean and rms of I IR sky temperature measured at three main elevating angles (30, 60 and 90 degrees) and for various azimuthal directions.

- The long-term observations of meteorological (temperature, humidity, wind) and atmospheric conditions (optical atmospheric turbulence and water vapour) can help with studies intended to understand the effects of atmospheric patterns, such as the El Niño Southern Oscillation phases (positive/warm, or negative/cold), inter-annual, or inter-decadal atmospheric variability on the environmental conditions at the observatory site. A clear example of the ENSO phases is shown in **Figure 4**. This shows the number of days, in each month, when the daily maximum air temperature reaches beyond 16 Celsius degrees. This result is part of an ongoing investigation to uncover the effects of ENSO and other climate trends on the atmospheric conditions at the ESO observatory sites. The results show a remarkable correlation between the ENSO phases (warm, cold) with the number of days in a month when the 30-m level air temperature exceeds 16 Celsius degrees. This threshold is of interest for the ESO engineering crew as they have to plan for the VLT telescopes dome air conditioning power capacity (likely relevant for the ELT as well). This result has predicting power, i.e. we expect a larger number of days when the maximum of air temperature exceeds 16 Celsius degrees during El Niño periods (warm phase of ENSO) than when La Niña (cold phase of ENSO). As of May 2023, ENSO is in a transition from La Niña to El Niño; hence, we expect a larger number of hot days, above the long-term median (10 days), for the austral summer of 2024. El Niño has also been associated to stronger wind speed in altitude, making it harder for the AO system to correct [13].

2.1 Use of ASM data (seeing) to predict future trends (nowcast) and provide input in the ranking and selection of Observing Blocks for observation in the next one hour

At the Paranal Observatory (VLT) the typical Observing Blocks (OB) are of one hour in length. In service mode (SM), the OB to be observed, at a given telescope, in the next one hour is selected based on a short-term-scheduling (STS) tool. The STS's frontend is the ORANG interface. The OBs still in the observing queue are ranked according to estimates of key atmospheric conditions for the next one hour. The atmospheric seeing is one of the input atmospheric variables required for filtering the OBs. The current strategy at the Paranal Observatory, for the estimation of the seeing in the

next one hour, is to assume the average seeing in the last ten minutes will remain the same, plus or minus 10% variability, in the next one hour. This is the so-called persistence, or stationary, model.

A key work, using seeing ASM data, conducted in the course of 2022, has been the development of a seeing predictor supported on a Machine Learning modelling approach. Three independent seeing predictors have been obtained, two based upon Random Forest (RF) modelling and one based on the Long-Short Term Memory (LSTM) approach. The use of the ML technique for predicting of seeing was initiated in the work reported in [14].

Figure 3 shows the success rate in the prediction of seeing, based on the most recent ML work conducted at ESO. The success rate metric is computed as follows: a) For each 0.1 arcsecond seeing bin, the magnitude of the predicted seeing is compared to the real 1-hour average seeing. If the predicted seeing doesn't exceed 1.1 times the real (measured) 1-hour average seeing this is considered a success. If the predicted seeing exceeds 1.1 times the measured 1-hour seeing, then is a failure. The success rate for four different predictors are shown: a) the persistence model (in blue), b) the LSTM ML seeing predictor (in red), c) the RF ML predictor (obtained in March 2022, in green), and d) the RF ML predictor (obtained in September 2022, in black). As possible to see, all of the ML-based seeing predictors show better success rate than persistence model when the seeing is in the better conditions (below 0.7 arcsecs, which is the long-term median seeing at the Paranal site). And the two RF machine learning predictors show better performance than the persistence model below 1.1 arcsecs. In the range 1.2 and higher the RF and persistence models show similar success rates.

This illustrate quite well how ASM data can be used to improve the forecast of relevant atmospheric variables in short time scales. And also illustrate that machine learning algorithms are suitable for this kind of application.

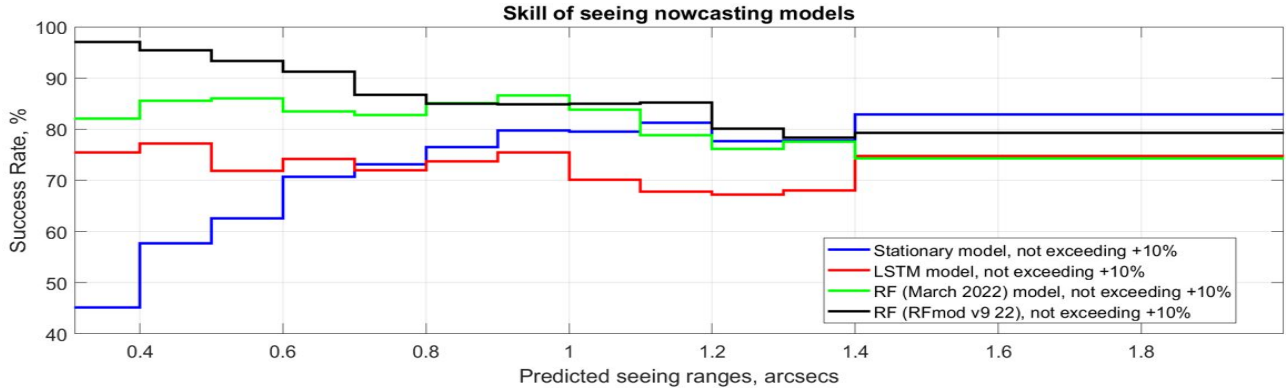


Figure 3 Success rate in the prediction of 1-hour average seeing at the Paranal observatory in the year 2021. This shows: a) the persistence model (in blue), b) the LSTM ML seeing predictor (in red), c) the RF ML predictor (obtained in March 2022, in green), and d) the RF ML predictor (obtained in September 2022, in black).

3. THE EXTREMELY LARGE TELESCOPE'S ASM LEVEL 1 REQUIREMENTS

The European Extremely Large Telescope (ELT) is currently under construction at the Armazones peak, about 25 km eastwards from the Paranal Observatory in Northern Chile. The ELT consist of a large (39-m) filled-segmented aperture telescope, equipped with instrumentation for diffraction-limited observations, with emphasis in the infrared [16, 17].

The requirements for the ELT's Astronomical Site Monitor (ASM) system are specified in its Level 1 Requirements Specification Document (internal to the ESO). Some important requirements flowing down to the ASM system are those listed in Table 1.

Table 1: ELT project: ASM system requirements

<i>Requirement</i>	<i>Description</i>
R-L1S-873	The infrastructure services shall provide an Astronomical Site Monitor (ASM) system

R-L1S-875	The ASM shall include a meteorological station providing the local atmospheric conditions (humidity, temperature, wind speed and direction, dust contamination) at three different heights, or more, between 10m and 75m above ground
R-L1S-877	The ASM shall include turbulence monitoring units for measuring seeing (typically to $\pm 10\%$ accuracy), coherence time and turbulence profiles
R-L1S-878	The ASM shall include sky quality monitoring measuring extinction, cloudiness (including cirrus), and infrared properties of the sky (including Precipitable Water Vapour)
R-L1S-880	The E-ELT shall also monitor the seismic activity at Armazones, as a minimum in the range between IFE and NCR earthquakes
R-L1s-874	The ASM shall provide data enabling science operations to decide whether or not to re-program observing sequences on short notice (typically minutes) in order to maximize the quality of scientific data in relation to atmospheric conditions

Additionally, and more recently, the European Southern Observatory is engaged in the preparation of an Integrated Operations Programme (IOP). One main goal of the IOP is to allow the optimum allocation of resources for the joint operations of the VLT and ELT observatories. Two top-level and Level 1 requirements of the IOP plan, that are pertinent to the ASM system, are the IOP-TLR-002 and IOP-L1-041 requirements shown in Table 2.

Table 2: Integrated Operations Programme (selected Requirements)

<i>Requirement</i>	<i>Description</i>
IOP-TLR-002	Integrated Operations shall be ready to transit to remote off-site operations from strategically selected locations in the 2030ies minimizing the overhead of using on-site resources
IOP-L1-041	In IOP losses of observing time due to unforeseen changes in atmospheric conditions shall be minimized while the use of the best atmospheric conditions shall be maximized

Hence, to fulfil the selected IOP requirements shown in Table 2, we could think the ELT's ASM shall provide:

- An accurate forecast of meteorological conditions and of optical turbulence variables → for the safe use of the telescope → as well as to support the Ranking & Selection of the Observing Blocks (i.e. the observations that are a best fit to the existing atmospheric conditions)
- Instrumentation for the accurate assessment of the sky transmission, and tools for the continuous assessment of critical atmospheric conditions → allow timely decision from a remote centralized operations site

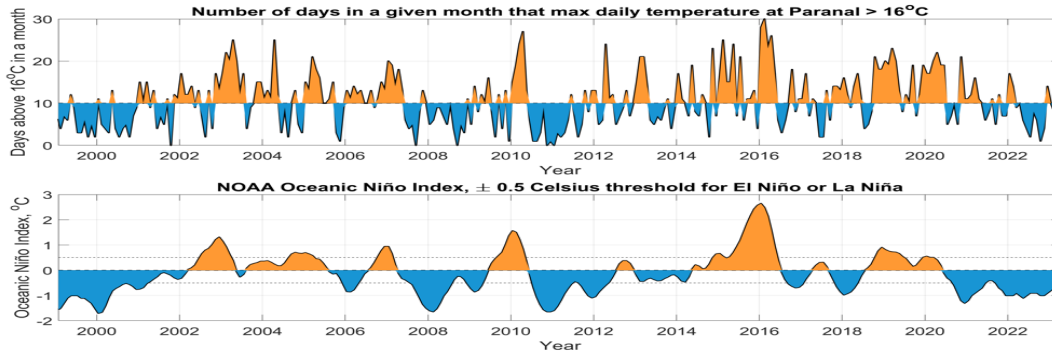


Figure 4 Number of days in a given month when the daily maximum temperatures reached above 16 Celsius degrees (top), the NOAA Oceanic Niño Index [15] (bottom). The data analysis covers the period July 1998 - May 2023. The horizontal line at 10-days (in top plot) shows the long-term median number of days when temperature is above 16 Celsius degrees at Paranal.

4. ELT ASTROWEATHER WORKING GROUP: RECOMMENDATIONS FOR THE ELT’S ASM SYSTEM

The ELT project includes opportunities for the ESO community and industry to provide inputs to help develop the ESO’s Extremely large telescope [17]. This effort has been organized around thirteen working groups allowing for a wide participation of the academic, research, engineering, industrial communities (see Figure 1, in [21]). One such working group is the ELT Astroweather WG, which was charged with two main goals: firstly, identify the meteorological and atmospheric variables to be monitored considering the ELT first-light instrumentation as well as the expected main operational and observing modes. And secondly, provide some advice on what instruments/sensors that are suitable (or possible) to monitor the key meteorological and atmospheric variables [21]. The result was a document delivered from the ELT Astroweather WG to the ESO’s ELT management listing the high-priority variables to be monitored. Table 3 summarizes the high-priority variables and a succinct description of how the data (for each variable) can help the ESO science operations.

Table 3: ELT AstroWeather Working Group recommendations on high-priority variables to be monitored by the ELT’s ASM system

<i>Variable</i>	<i>Description</i>
Seeing	Required: to help with the short-term scheduling of observing blocks; to predict the IQ (for non AO observations) and the quality of AO correction for all instruments before starting the observations and during the observations; to validate the seeing estimations based on the AO telemetry; and to help improve and validate the skill of seeing forecast/nowcast models
Coherence time of turbulence	Required: to predict and validate/verify the performance of some observing modes and instruments before the start of the observations. Servolag error can be the largest contributor to the budget of error of an AO system at small angular separations, especially for high contrast observations (METIS, MORFEO or HARMONI); to help with the short-term scheduling of observing blocks; to validate the coherence time estimation from the AO telemetry; to help improve and validate the skill of coherence time of the turbulence forecast/nowcast models
Isoplanatic Angle	Required: to predict the isoplanatic error of an AO system (hence the on-target performance) before the start of the observations; to help with the

	short-term scheduling of observing blocks; to help improve and validate the skill of isoplanatic angle forecast/nowcast models
Meteorological parameters	(as a minimum, temperature, pressure, dewpoint temperature/relative humidity, wind speed and wind direction). Required: to help with the safety of the observatory operations; help best planned engineering tasks (especially those taking place outdoors or at elevated platforms, such as telescope domes); to help the scientific observation, avoiding pointing the telescope into high wind, preventing this way jitter and vibrations induced by the wind affecting the telescope and inducing a degradation in image quality
Precipitable water vapour	Required: to help with the scheduling of mid-infrared observations, minimizing atmospheric absorption and atmospheric thermal background emission; in spectroscopic observations: for line of sight telluric lines correction instead of spending additional time in the observation of spectroscopic-featureless standard stars for calibration & subtraction of telluric water lines from the science object spectra.
High-resolution of the surface layer Cn2 profile	Required: to remove the atmospheric turbulence in the layer from the height of the seeing monitors up to the height above ground of the ELT's M1 mirror. → Better estimation of the science observation image quality and help optimize the short-term scheduling
Outer scale of the turbulence	Required: Is required to predict the image quality in seeing-limited observations; during diffraction-limited observations the outer-scale of turbulence can help predict the quality of the adaptive optics correction; information on the magnitude of the outer-scale of the turbulence can help to better predict the sky coverage during multi-conjugated adaptive optics observations. And it can help (via better estimation of image quality) with improving the ranking and selection of observing blocks in the short-term scheduling process

4.1 Instruments for the ELT's ASM

For weather stations, as well as water vapour radiometers and all-sky camera (hardware + software), it is quite likely the ELT's ASM will include the same brand of equipment currently used at Paranal and La Silla observatories.

For what exact turbulence monitor instruments choose for the ELT, there are still ongoing conversation to decide what specific instrumentation to use; for both integrated seeing as well as vertical profile of the strength of the turbulence.

The MASS-DIMM [3,4,5] instruments setup has been the turbulence monitoring setup of choice for the last 20 years at most astronomical observatories. This setup has proved very reliable in the long-term, but spare parts are hard to find, and this represents a reliability issue for long-term operations. This has motivated us at ESO to look for alternative, new generation, turbulence monitors supported on more recent technology (CMOS/CCD cameras).

In the period February 25 – March 5, 2023, a campaign to test new generation turbulence monitors was conducted at the Paranal Observatory. The invited instruments included the following: FASS [18], RINGSS [19] and 24hSHIMM [20], see **Figure 5**. The guests team affiliations are: FASS (Pontificia Universidad Católica de Chile), RINGSS (Cerro Tololo Inter-American Observatory, NOIRLab), and 24SHIMM (Durham University, UK).

These optical turbulence monitors are all able to monitor the integrated turbulence (seeing), and they produce a vertical profile of the strength of the turbulence albeit at varying vertical resolution and number of turbulent layers. Preliminary results from the side-by-side turbulence monitors campaign are presented in this COAT 2023 workshop; see the presentations and corresponding papers of Ryan Griffith, and Andrei Tokovinin, for the 24hSHIMM and RINGSS instruments, respectively. The solutions, integrated seeing and vertical profiles of turbulence from all the guest instruments in this testing campaign, are compared to the ESO VLT's standard turbulence monitors; namely, the SCIDAR and MASS-DIMM setups.

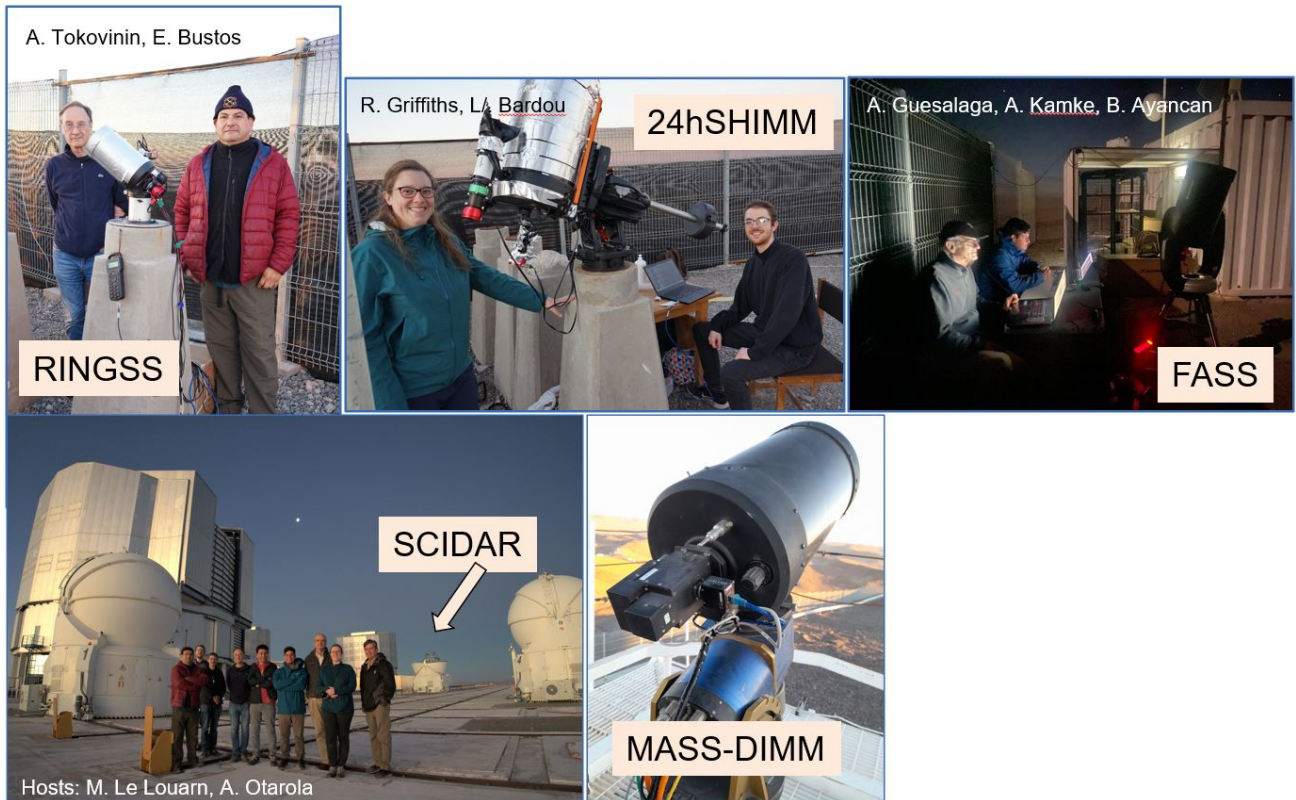


Figure 5 A collage of pictures to show the instruments and participants to the 2023 turbulence instruments side-by-side campaign held at the ESO's VLT Observatory (Paranal site). The guest teams included: FASS (from Pontificia Universidad Católica de Chile), RINGSS (from Cerro Tololo Inter-American Observatory, NOIRLab), and 24SHIMM (from Durham University, UK)

5. SUMMARY

In summary, the astronomical site monitor (ASM) system is an essential suite of instruments providing timely and continuous monitoring of the meteorological and atmospheric conditions at observatory sites. This data is used at various levels and with wide applications, going from observatory safety to help with the ranking and selection of observing blocks in the short-term scheduling of science observations. But importantly, the long-term data sets can help assess any trends in our observing conditions that may be linked to changes in the atmospheric circulation at various time scales from years to decades. The ASM instruments and fast data processing of the data is becoming more and more important to better understand the influence of the atmospheric turbulence in the image quality of astronomical observations, this for various types of observations and observing modes. The ability to accurately forecast the meteorological and atmospheric variables (turbulence and precipitable water vapour) can help making best use of the atmospheric conditions and improving scientific productivity. Here again, the current ASM instruments observations can help correct for biases and differential trends in forecast data as a way to improve the forecast of all relevant parameters in short-time scales.

This paper summarizes the high-priority variables, recommended by the ESO community at large via the ELT AstroWeather working group, to be monitored by a suitable set of instruments part of the ELT's ASM system.

REFERENCES

- [1] Sandrock, S., Amestica, R., Duhoux, P., Navarrete, J. and Sarazin, M., “VLT Astronomical Site Monitor: Control, Automation, and Data Flow”, Proc. SPIE 4009, 338-349 (2000)
- [2] Chiozzi, G., Sommer, H., Sarazin, M., Bierwirth, T., Dorigo, D., Vera Sequeiros, I., Navarrete, J., Del Valle, D., “The ESO Astronomical Site Monitor Upgrade”, Proc. SPIE 9913 (2016), doi: [10.1117/12.2232302](https://doi.org/10.1117/12.2232302)
- [3] Sarazin, M. and Roddier, F., “The ESO differential image motion monitor”, Astron. Astrophys, 227, 294-300 (1990)
- [4] Kornilov, V., Tokovinin, A., Shatsky, N., Voziakova, O., Potanin, S and Safonov, B., “Combined MASS-DIMM instruments for atmospheric turbulence studies, Mon. Not. R. Astronom. Soc. 382, 1268-1278 (2007)
- [5] Tokovinin, A., Kornilov, V., Shatsky, N. and Voziakova, O., “Restoration of turbulence profile from scintillation indices”, Mon. Not. R. Astronom. Soc. 343, 891-899 (2003)
- [6] Querel, R. R. and Kerber, F., “All-sky homogeneity of precipitable water vapour over Paranal”, Proc. SPIE 9147, 914792-1 – 914792-11 (2014)
- [7] European Southern Observatory, Paranal Site, <http://archive.eso.org/cms/eso-archive-news/alpaca-all-sky-images-from-paranal-available-in-the-archive.html> (11 May 2023)
- [8] Osborn, J., Wilson, R., Butterley, T., Morris, T., Dubbeldam, M., D erie, F. and Sarazin, M., “E-ELT turbulence profiling with stereo-SCIDAR at Paranal”, Proc. SPIE 9909, 99091N-1 – 99091N-8 (2016).
- [9] D erie, F., Wilson, R., Osborn, J., Dubbeldam, M., Ridings, R., Navarrete, J. and Le Louarn, M., “Stereo-SCIDAR: Instrument and First Commissioning Results”, The Messenger, 166, 41-46 (2016)
- [10] Wilson, R. W., SLODAR: measuring optical turbulence altitude with a Shack-Hartmann wavefront sensor”, Mon. Not. R. Astronom. Soc. 337, 103-108 (2002)
- [11] Nauenberg, M., “Atmospheric refraction based on actual atmospheric pressure and temperature data”, Pub. Of the Astronom. Soc. Of the Pac., 129, 044503 (2017)
- [12] Hainaut, O. R., Bierwirth, T., Brillant, S., Mieske, S., Patat, F., Rejkuba, M., Romaniello, M., Sterzik, M., “End-to-End Operations in the ELT Era”, The Messenger, 171 8-13 (2018)
- [13] Cantalloube, F., Milli, J., Bohm, C., Crewell, S., Navarrete, J., Rehfeld, K., Sarazin, M. and Sommani, A., : The impact of climate on astronomical observations”, Nature Astronomy, 4, 826-829 (2020)
- [14] Milli, J., Gonzalez, R., Fluxa, P.R., Chacon, A., Navarrete, J., Sarazin, M., Pena, E., Carrasco-Davis, R., Solarz, A., Smoker, J., Martayan, C., Melo, C., Sedaghati, E., Mieske, S., Hainaut, O., Tacconi-Garman, L., “Nowcasting the turbulence at the Paranal Observatory”, AO4ELT6 Conference Proceedings (2019), <https://ao4elt6.copl.ulaval.ca/proceedings/401-9pcJ-241.pdf> (as of 16 May 2023)
- [15] National Weather Service, Climate Prediction Center, https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php (11 May 2023)
- [16] European Southern Observatory, Extremely Large Telescope Project Book, https://www.eso.org/public/archives/books/pdf/book_0046.pdf (11 May 2023)
- [17] Ramsay et al., “Instrumentation for ESO’s Extremely Large Telescope”, The Messenger 182, 3-6 (2021)
- [18] Guesalaga, A., Ayanc an, B., Sarazin, M., Wilson, R. W., Perera, S. and M. Le Louarn, “FASS: a turbulence profiler based on a fast, low-noise camera”, Mon. Not. R. Astronom. Soc. 501, 3030-3045 (2021)
- [19] Tokovinin, A., “Measurements of turbulence profile from defocused ring images”, Mon. Not. R. Astronom. Soc. 502, 794-808 (2021)
- [20] Griffiths, R., Osborn, J., Farley, O., Butterley, T., Townson, M. J. and Wilson, R., “Demonstrating 24-hour continuous vertical monitoring of atmospheric optical turbulence”, Optics Express, Vol. 31, No. 4, 6730-6740 (2023)
- [21] Padovani, P. et al., “The ESO’s Extremely Large Telescope Working Groups”, The Messenger 189, 23-30 (2022)