IDEA 2026 Workshop
Opportunities for R&D

Measurements of Optical Turbulence in Astronomy

Angel Otarola – Atmosphere Scientist

12 August 2025

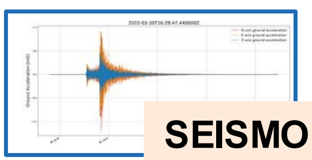
The Astronomical Site Monitoring (ASM) System - INSTRUMENTS

METEO

LHATPRO WVRs

ALPACA & NINOX

MASS DIMM



SEISMOMETER

S-SCIDAR

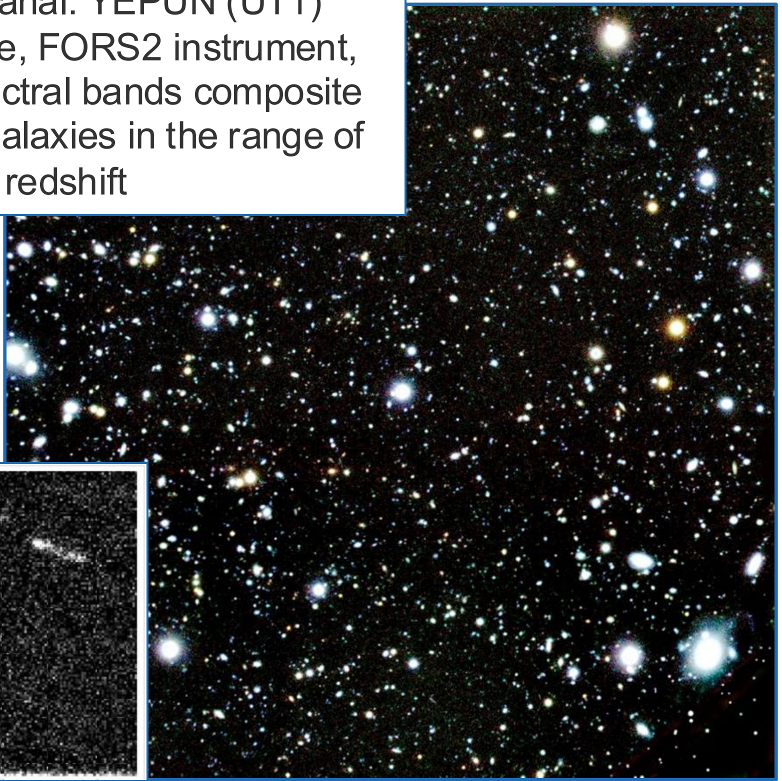
SLODAR

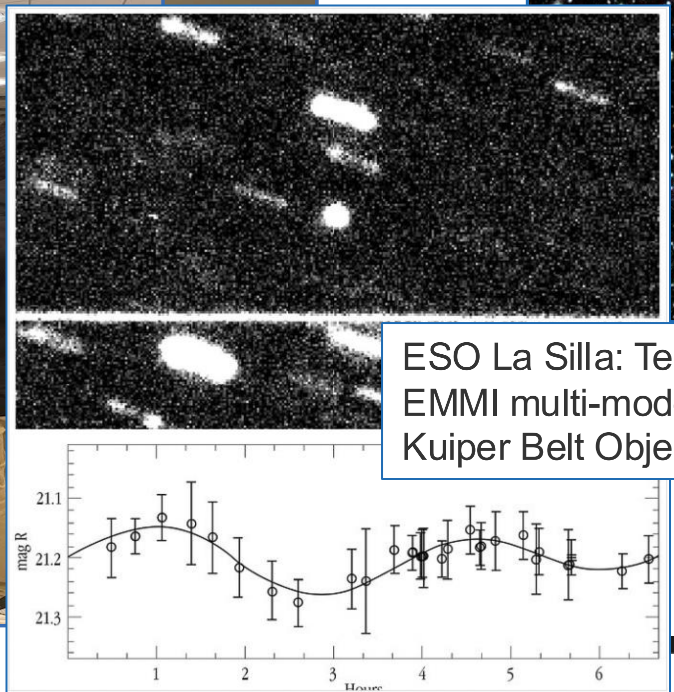
Continuous flow of meteorological and atmospheric condition data

Support the Filtering, Ranking and Scheduling of Science Observations

View of ESO's VLT Control Room

ESO Paranal: YEPUN (UT1) Telescope, FORS2 instrument, R,I,Z spectral bands composite image. Galaxies in the range of 4.8 – 5.8 redshift

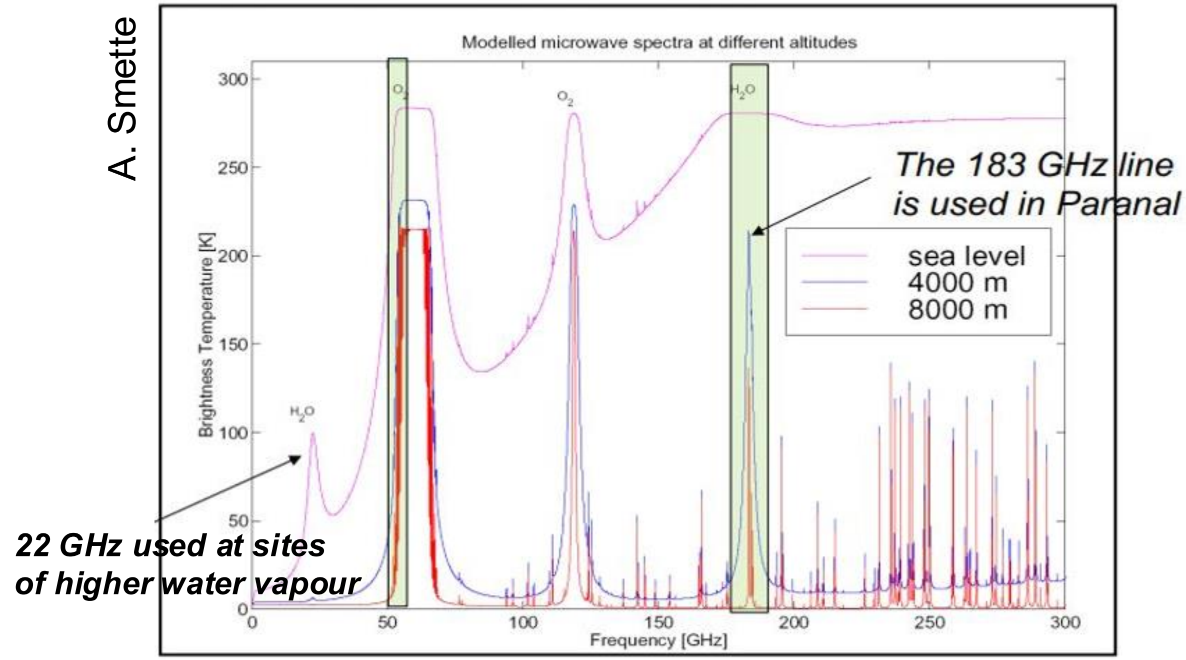


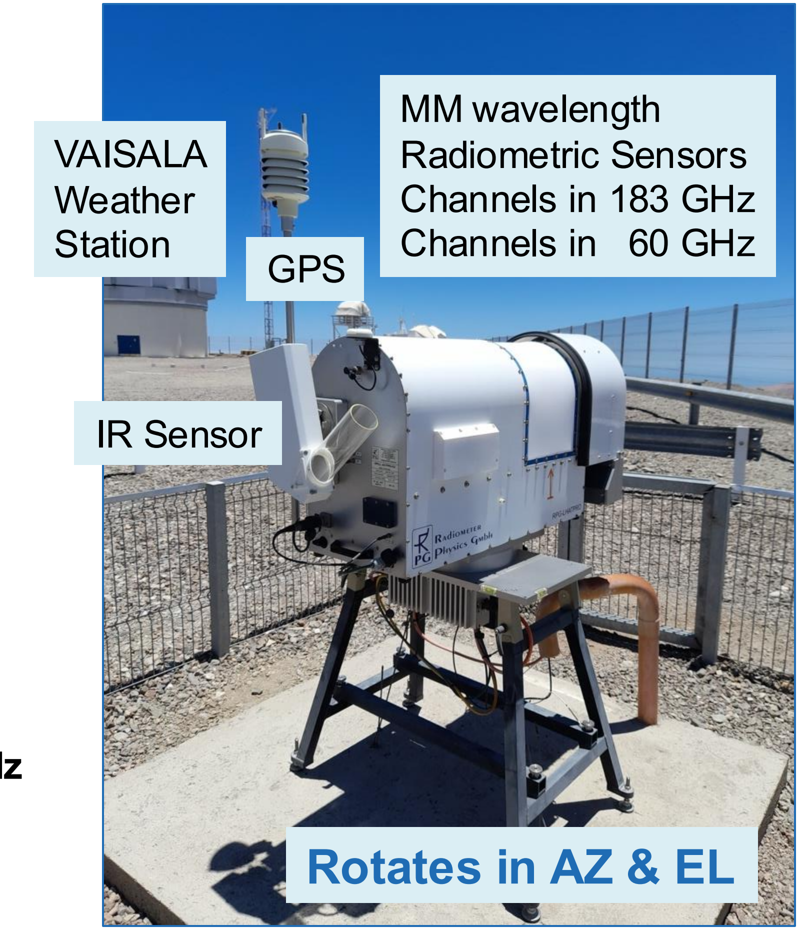


ESO La Silla: Telescope 3.6-m, EMMI multi-mode instrument: Kuiper Belt Object 1996 TO66.

Monitoring of telluric lines (H_2O) ➔ Science Data Processing ➔ Cleaning of Science Spectra

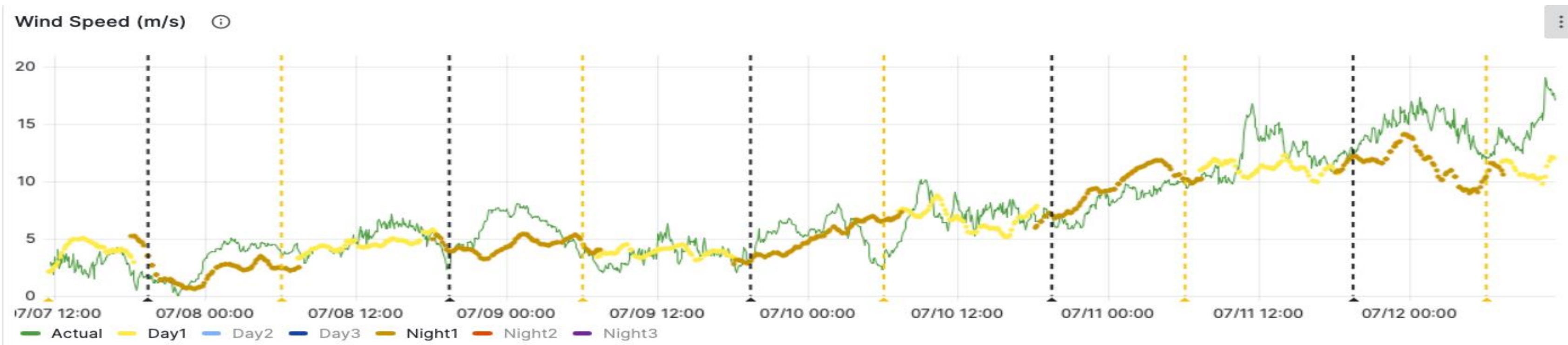
A. Smette

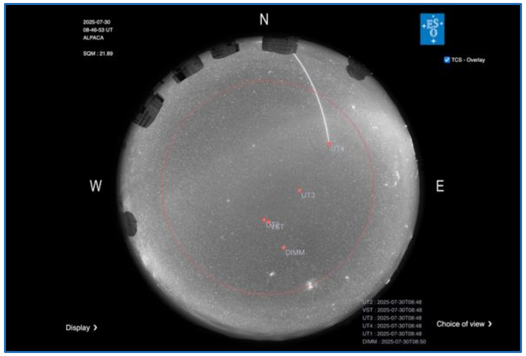


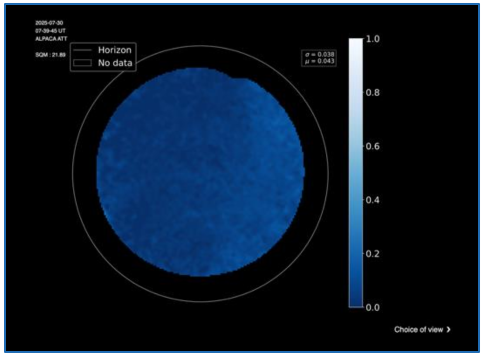


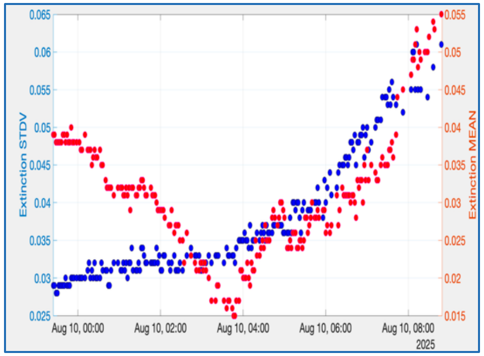
- The radiometer **measures the brightness temperature** of the atmosphere in various non-overlapped channels **around the 183 GHz H2O emission line** and in the **60 GHz O2 emission line**
- The vertical profile of temperature, water vapour as well as the integrated amount of water vapour in the atmosphere are **derived from the main observables with support in an accurate radiative transfer model**

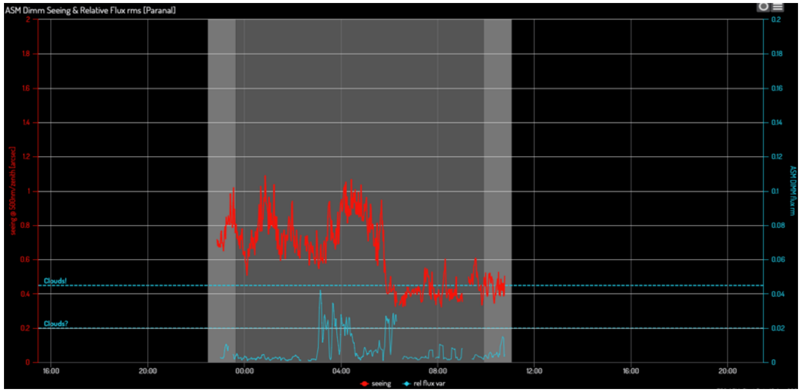
Measurements → Data Processing & Modelling →
Support of Operations → Optimization of Resources →
Maximize Scientific Productivity (Observing Time)

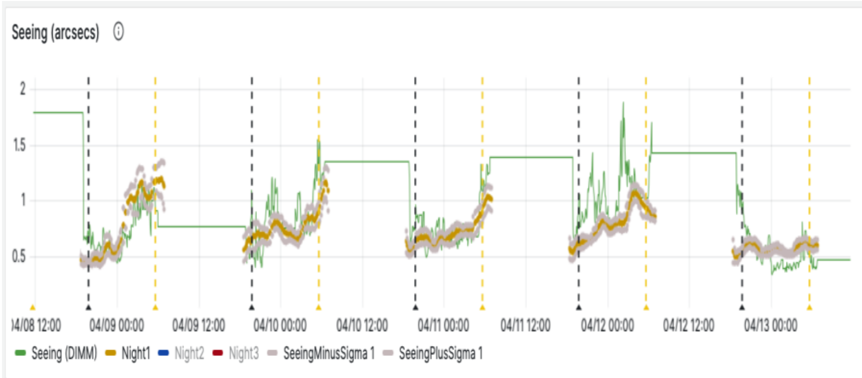












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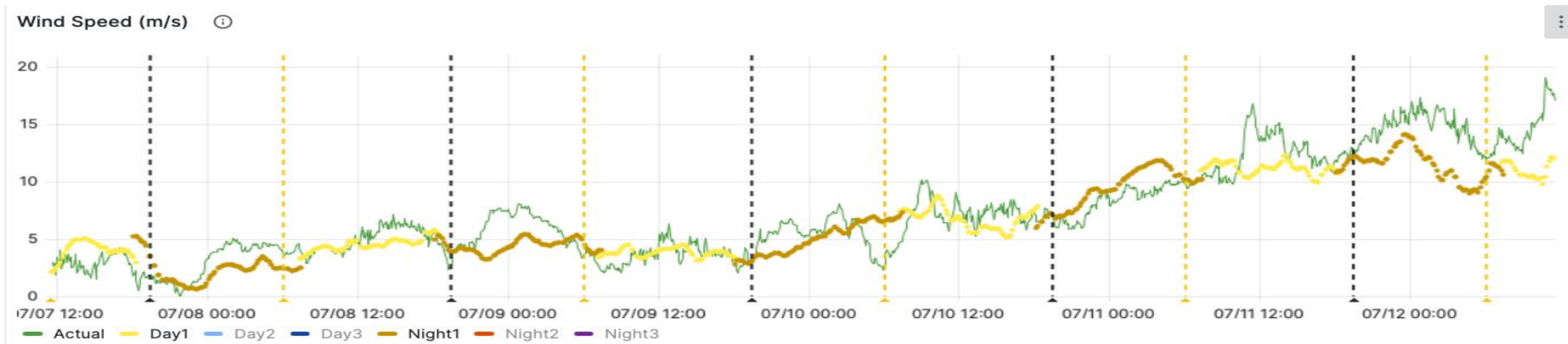
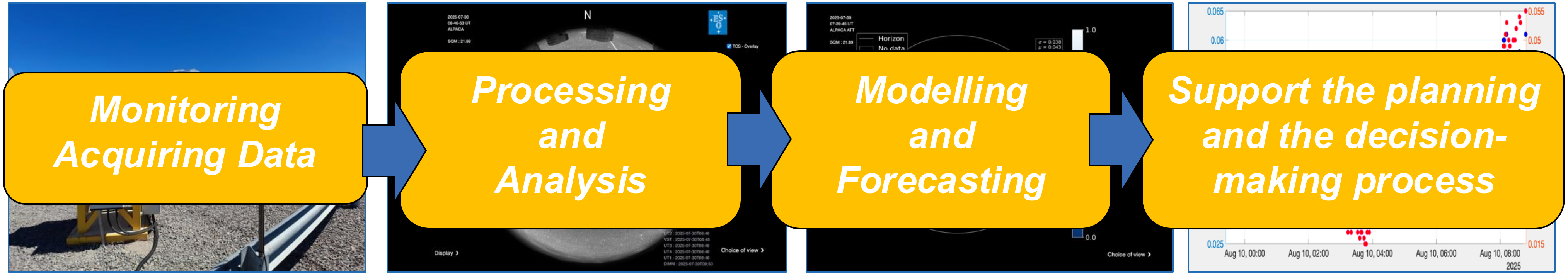
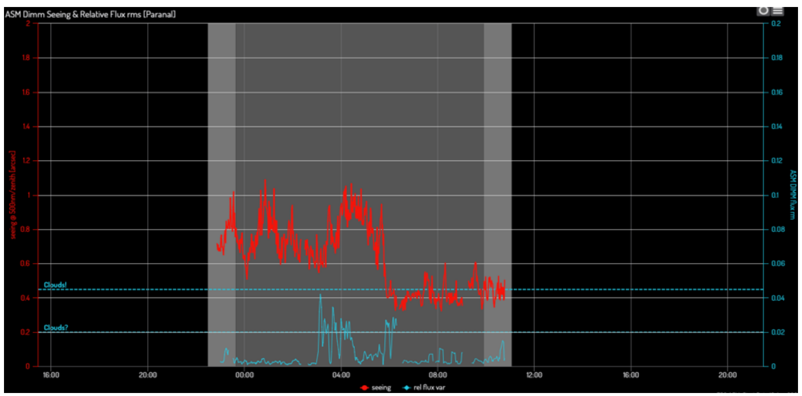
Maximize Scientific Productivity (Observing Time)







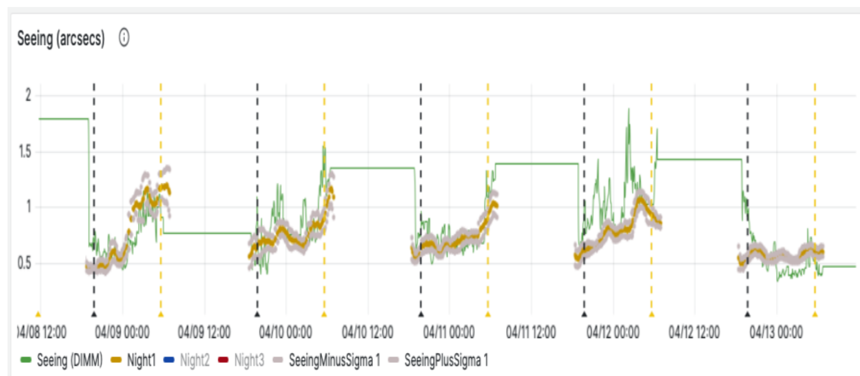
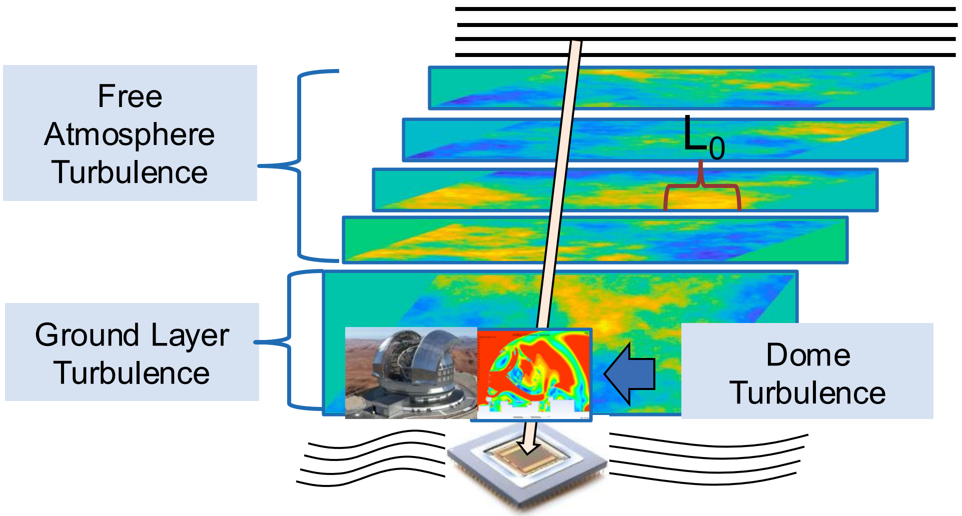
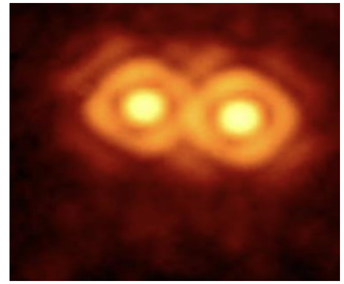


Image Quality (IQ) & Reliability of Adaptive Optics Corrections ➔ Is a function of free atmosphere seeing, ground layer turbulence, dome environment turbulence, outer-scale of the turbulence

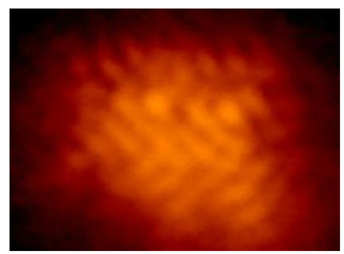
Astronomical object wavefront
(out of atmosphere)



Astronomical object wavefront
(after atm. aberrations)



brown dwarf, Gliese 229B and its companion, *Palomar Observatory / NASA-JPL*



ε_0 Total seeing
ε_{FA} Free atmosphere seeing
ε_{GL} Ground layer seeing
L_0 Outer Scale of turbulence

$$\varepsilon_0 \approx \{ (\varepsilon_{FA})^{5/3} + (\varepsilon_{GL})^{5/3} \}^{3/5}$$

$$\varepsilon_{VK} \approx \varepsilon_0 \sqrt{(1 - 2.183\,(r_0/L_0)^{0.356})}$$

$$IQ \approx \{ (\varepsilon_{VK})^2 + (\varepsilon_{dome})^2 \}^{1/2}$$

Best Image Quality
⬇
Optimized used of our observing time

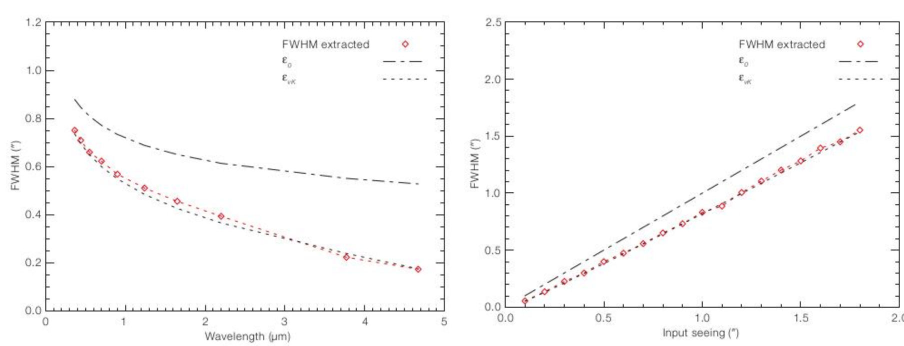


Figure 2. Dependence of the FWHM on wavelength (left, fixed ε_0 = 0.83 arcseconds) and seeing (right, fixed λ = 0.5 μm). Other parameters are L_0 = 22 m, D = 8 m (typical for the VLT).

High-priority variables to be monitored

- **High-resolution Cn2 profile for the surface layer (Hmax=150m, Hres=20m)**
  - 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 IQ on the science observation the night to optimise scheduling.
  - The ELT's M1 is located at ~30m above the platform and the top of the dome is located at 75m.

ARMAZONES: height of surface layer
Measured with a SODAR by the TMT team

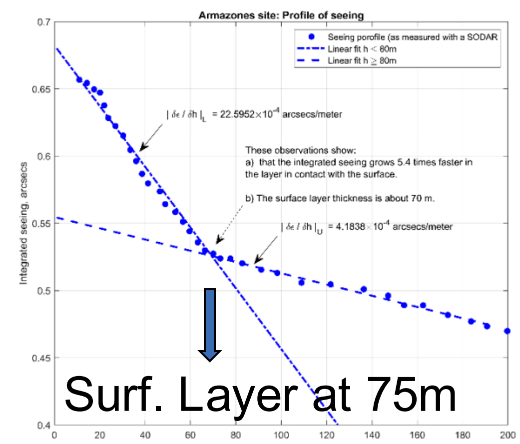
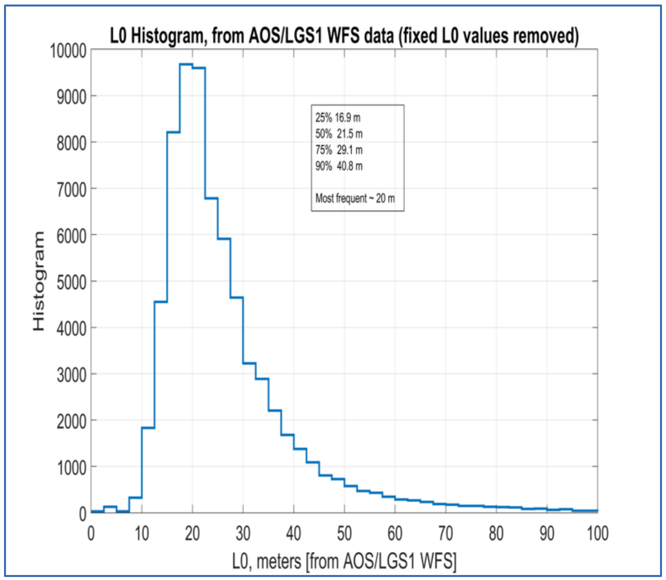


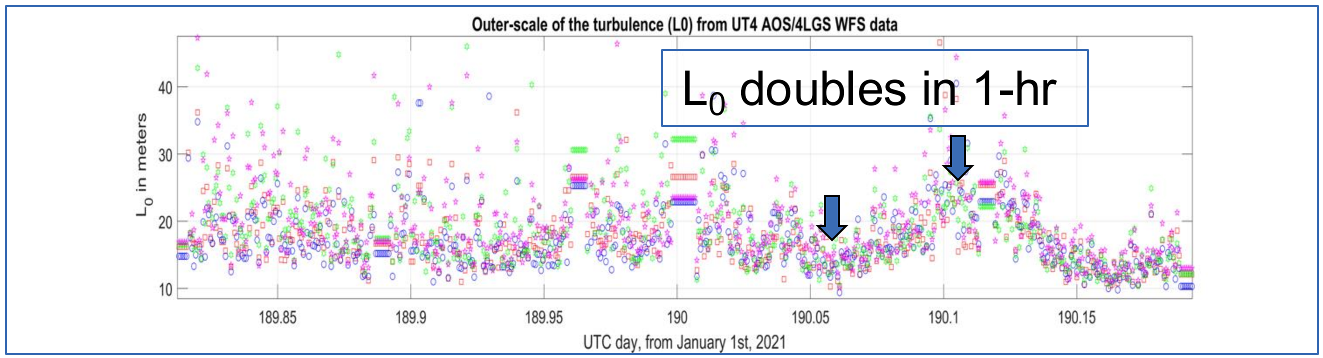
Figure 1 Median seeing an observer would experience, at the Armazones site, at a given altitude above the ground as calculated from the MASS, SODAR and DIMM turbulence measurements (simultaneous data only), from 7 to 200 m above the ground. Data from the TMT Site Testing Campaign (see Schoeck et al., PASP, 121, p. 398-395).

High-priority variables to be monitored

Outer scale of the turbulence

- For no-AO Observations: is required to predict the IQ
- For AO-Observations: to help predict the quality of AO correction
- This variable is also required for short-term scheduling
- To predict the sky coverage in MCAO





$$\left(\frac{\epsilon_{\mathrm{vK}}}{\epsilon_0}\right)^2 \approx 1 - 2.183\left(\frac{r_0}{L_0}\right)^{0.356}$$

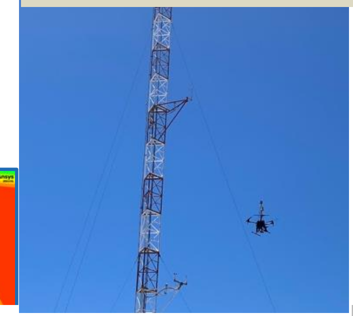
A. Tokovinin, PASP, 114, 2002

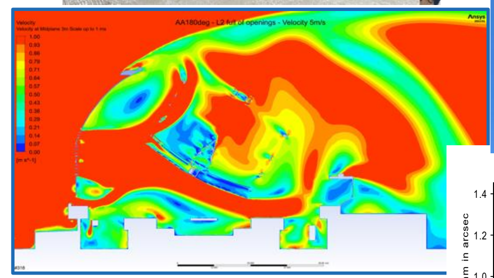
Doubling L_0 ➔ **IQ decreases**
IQ(ratio) = 11% in Z-band
IQ(ratio) = 13% in J-band
IQ(ratio) = 20% in H-band
IQ(ratio) = 26% in K-band

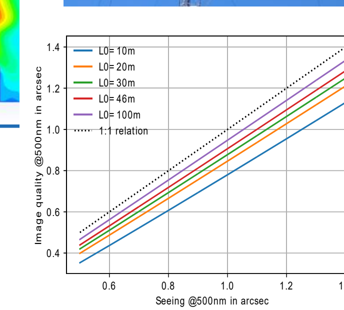
Opportunities for Technical Research and Development for Technical Solutions

- The monitoring of turbulence in **Dome** environments
  - Profiling of atmospheric turbulence via astronomical sources wavefront and/or scintillation effects
  - In-situ measurements of optical aberrations fluctuations
- Accurate monitoring of the **vertical profile of turbulence** within the atmospheric surface layer (10m up to 75m)
  - High sampling rate of air wind and temperature fluctuations using scintillometers
  - Profiling of atmospheric turbulence via astronomical sources wavefront and/or scintillation effects
- **Nowcasting of Atmospheric Turbulence (total seeing)**, to achieve RMSE better than 0.10 arcsecs in the integrated seeing
  - Machine Learning Applications
  - Statistical Methods Applications (AutoRegression, Fourier Techniques, etc…)
- Determination (instruments) / Forecasting (modelling) of the **Outer Scale of Optical Turbulence**
- **Development of a radiometer system for monitoring of stratospheric Ozone column density 231-250 GHz (help with Telluric Lines Correction)**
- Comprehensive (multi-angle) **monitoring of artificial light pollution**
  - Instrumentation
  - Data processing algorithm (for instance to extract relative changes in light pollution from our high-quality All-Sky Images

FONDEF IT2410127
PI. Dr. Galeas, P.
Univ. de La Frontera

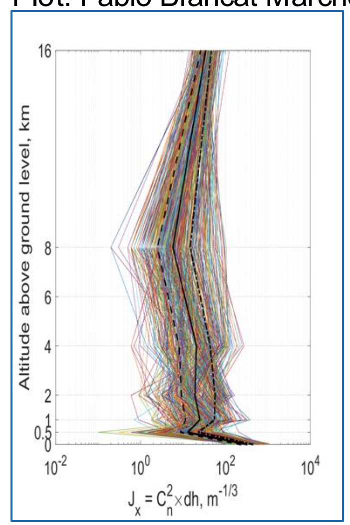


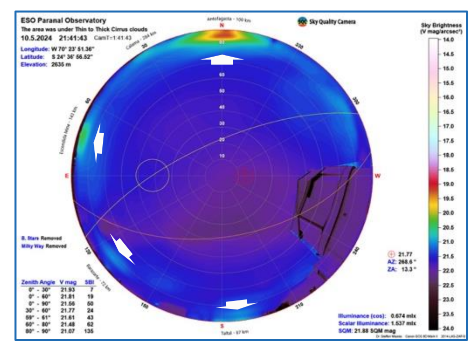




Plot: Pedro Figueira

Plot: Fabio Biancat Marchet





Thank you!

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ESO's Atmospheric Monitoring Data available from:
https://archive.eso.org/cms/eso-data/ambient-conditions.html

High-priority variables to be monitored

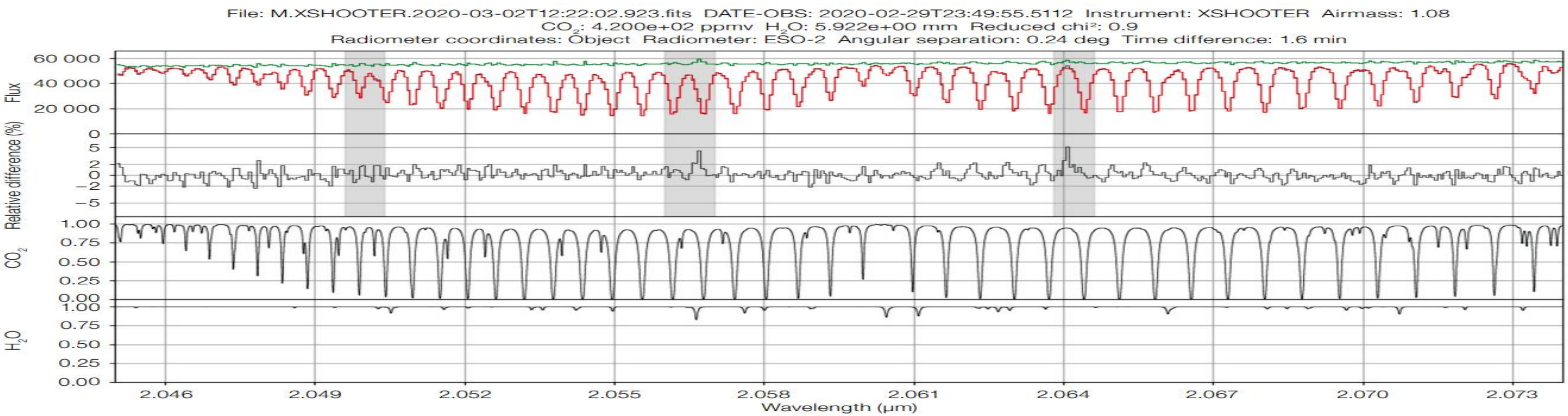
- **Seeing** is required:
  - required for **short-term scheduling**
  - to **predict the IQ** (for non-AO observations) and the quality of AO correction for all instruments before the start and during the observations
  - to **validate the seeing estimations based on the AO telemetry**
  - to help **improve and validate the seeing forecast skill**
- **Coherence time** is 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, MAORY or HARMONI)
  - required **for short-term scheduling**
  - to **validate the coherence time estimation from the AO telemetry**
  - to help **improve and validate the seeing forecast skill**

High-priority variables to be monitored

- **Isoplanatic angle**:
  - **to predict the isoplanatic error of an AO sys**tem (hence the on-target performance) before the start of the observations.
  - required **for short-term scheduling**
  - to help **improve and validate the seeing forecast skill**
- **Monitoring the temperature, pressure, relative humidity, wind speed and wind direction** is required for:
  - The safety of the site operations (engineering, science)
  - Avoid pointing into high wind (prevent wind jitter, avoid vibrations that deteriorates the image quality)

High-priority variables to be monitored

- **Precipitable water vapour**, liquid water path, IR sky temperature
  - **To help better schedule MIR observations** (water vapour in the atmosphere is a source of attenuation but also emission adding to the background noise)
  - Spectroscopic observations: **for line of sight of site telluric correction** instead of observing spectroscopic-featureless standard stars for calibration following the science observation (this saves ~10% of observing time, which can be dedicated to science)



A. Smette (telluric line correction) in Padovani et al., arXiv:2302.14375

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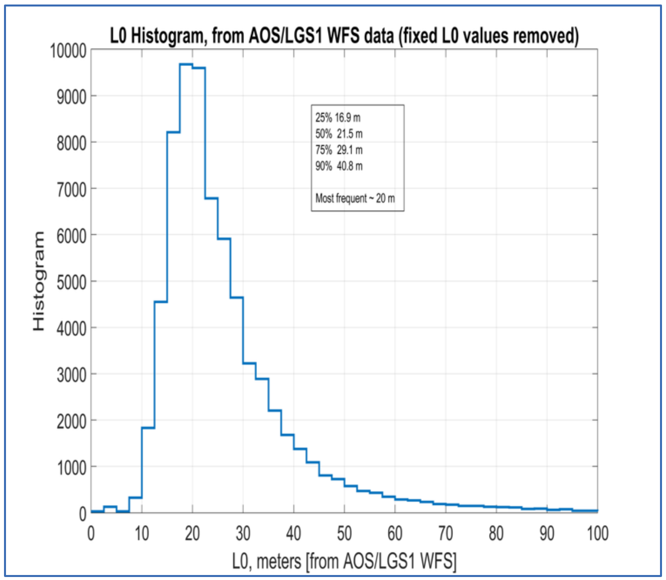

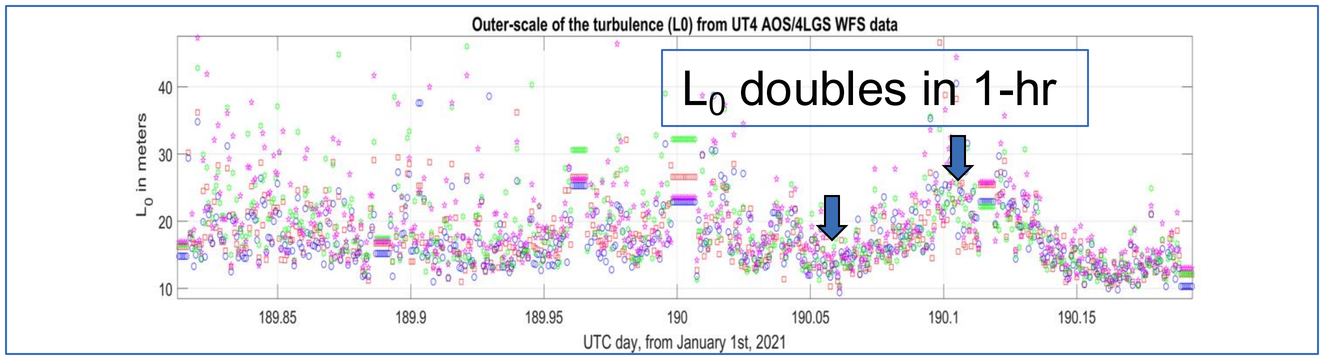

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