European Organisation for Astronomical Research in the Southern Hemisphere

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# Astronomical Site Monitor Data User Manual

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# Change Record from previous Version

| Affected Section(s) | Changes / Reason / Remarks |
|---|---|
| | First issue |
| 3<br>3.5 | Removed ambiguity between Cn2(h) and integrated Cn2<br>Corrected SLODAR range |
| 7 | Corrected errors in meteo sensor height |
| 8.2 | Corrected error in Kolmogorov criterium limit<br>Corrected error in noise fraction unit |
| 12.2 | Added comparison DIMM-1998 and DIMM-2016 |
| | Version 2 |
| 3.3, 6.1, 6.2 | Clarify methodology of joint MASS-DIMM processing |

# Contents

# 1. Introduction

## 1.1 Scope

The ASM Upgrade Project aims at replacing the current Paranal ASM (since 1998) by an upgraded and extended version resolving the obsolescence of the ASM and fulfilling AOF requirements. The new seeing measurements are conducted on a new location more representative of the observatory conditions. To insure the consistency of the seeing database for studying the long term evolution of Paranal observing conditions, the two ASM should be operated in parallel during a transition phase of at least 6 months.

## 1.2 Definitions, Acronyms and Abbreviations

This document employs several abbreviations and acronyms to refer concisely to an item, after it has been introduced. The following list is aimed to help the reader in recalling the extended meaning of each short expression:

| | |
|---|---|
| TBC | To Be Clarified |
| TBD | To Be Defined |
| UT | VLT Unit Telescope |
| DIMM | Differential Image Motion Monitor |
| MASS | Multi-aperture Scintillation Sensor |
| SLODAR | SLOpe Detection And Ranging |
| PWV | Precipitable Water Vapour |
| wrt. | with respect to |
| rms | root mean square |

# 2. Related Documents

## 2.1 Applicable Documents

The following documents, of the exact version shown, form part of this document to the extent specified herein. In the event of conflict between the documents referenced herein and the content of this document, the content of this document shall be considered as superseding.

AD references shall be specific about which part of the target document is the subject of the reference.

| AD | Document Nr. | Version | Document Title |
|---|---|---|---|
| AD1 | ESO-041653 | 2, 2009.03.31 | VLT ASM Data User Manual VLT-MAN-ESO-17440-1773 |

## 2.2 Reference Documents

The following documents, of the exact version shown herein, are listed as background references only. They are not to be construed as a binding complement to the present document.

| RD Nr. | Document Nr. | Version | Document Title |
|---|---|---|---|
| RD1 | ESO-252204 | 1 | SLODAR User/Maintenance Manual |
| RD2 | ESO-239666 | 1 | Paranal ASM Upgrade Statement of Work, Technical Specifications and Management Plan |

# 3. ASM Upgrade Instrumentation

## 3.1 DIMM

The DIMM (**D**ifferential **I**mage **M**otion **M**onitor) channel of the MASS-DIMM instrument (developed by Sternberg Observatory (Moscow) for the TMT and E-ELT site surveys) is imaging a single star through two sub-apertures on a CCD. The MASS-DIMM instrument is attached to an 11" Celestron telescope on an ASTELCO NTM500 direct drive mount. It operates in robotic mode on top of a 7m high tower located 100m to the North of UT4 (Figure 1). The DIMM measures the differential motion of the two stellar images with a frame rate of 100Hz during a base time of 1s. A statistical analysis of these signals during the 1mn averaging period allows to compute the integral of the turbulence along the path responsible for the seeing. The seeing is defined as the Full Width at Half Maximum (FWHM) of a long exposure stellar image at the focus of a telescope observing at 500nm wavelength and at zenith, limited by an atmospheric turbulence with infinite outer scale. The finite nature of the outer scale of the atmospheric turbulence results in an image quality of large telescope actually better than the seeing due to the reduction of the share of atmospheric image motion in the final image size. The ASM upgrade DIMM-2016 replaces the DIMM-1998 (AD1). Cn2 values produced by the ASM are integral along the path in m+1/3 (also called "J" by some authors). This is not to be confused with local Cn2(h) in m-2/3, only defined at a given altitude and not relevant in this case.

## 3.2 LHATPRO

A **L**ow **H**umidity **A**nd **T**emperature **PRO**filing microwave radiometer, manufactured by Radiometer Physics GmbH (RPG), is used to monitor sky conditions over ESO's Paranal observatory in support of VLT science operations. The unit measures several channels across the strong water vapour emission line at 183 GHz, necessary for resolving the low levels of precipitable water vapour (PWV) that are prevalent on Paranal (median ~2.4 mm). The instrument consists of a humidity profiler (183-191 GHz), a temperature profiler (51-58 GHz), and an infrared camera (~10 micrometers) for cloud detection.

## 3.3 MASS

MASS (**M**ulti-**A**perture **S**cintillation **S**ensor), developed at Sternberg Institute (Moscow) with ESO support, consists of an off-axis reflecting telescope and a detector unit which measures the scintillations of single stars in four concentric zones of the telescope pupil using photo-multipliers at a frequency of 1kHz [RD2]. Measurements of the scintillation indices from the 4 apertures (A,B,C,D) plus the differentials (AB,AC,AD,BC,BD,CD) are taken during a base time of 1s. A statistical analysis of these signals during the 1mn averaging period yields information on the vertical profile of the turbulence Cn2(h). It is performed by piping MASS and DIMM raw files into ATMOS, a software module which looks for the most probable profile which could have produced this given set of scintillation indices. ATMOS has been considerably modified in 2011 (V. Kornilov et al.; PASP126:482–495). The main change is that the newer versions of ATMOS (2.9 and above) allow to include DIMM raw measurements (slopes) into the reconstruction process. MASS-DIMM products are expected to be more accurate because MASS is corrected for scintillation saturation and DIMM is corrected for propagation effects. ATMOS delivers, under the MASS-DIMM label, the integrated Cn2 in 6 layers (J1:J6) placed at 0.5, 1, 2, 4, 8 and 16 km above the telescope pupil with a resolution of about half their altitude, plus the ground layer (J0) as the complement of the sum of the 6 layers to the total MASS-DIMM seeing. The combination of a DIMM and a MASS gives the possibility not only to measure both seeing and turbulence profiles, but also coherence time (using local wind velocity for the ground layer) and isoplanatic angle for the whole atmosphere.

## 3.4 METEO

The VAISALA **METEO**rological station was installed in Paranal in October 1984 and upgraded in June 1998 (AD1). It includes, on a 30 m high mast, a number of sensors at 2m, 10 and 30m and below ground. The following measurements are provided: Wind speed and direction, temperature, humidity and particle count. The meteorological station computes and stores average, root mean square and extrema of each parameter during a preset averaging period (20 minutes). The sampling intervals are 2 seconds for digital sensors (wind speed and direction) and one minute for analog sensors (Temperature, Humidity).

## 3.5 SLODAR

SLODAR (**SLO**pe **D**etection **A**nd **R**anging) is an optical crossed-beams method for turbulence ranging, based on the Shack-Hartmann wavefront sensor. The instrument, developed by Durham University (UK) and ESO, has been operating in robotic mode at Paranal since March 2011 and was upgraded to Paranal standards in 2014. It uses an optical triangulation method for the measurement of the atmospheric turbulence profile. The profile is determined from the spatial covariance of the slope of the wavefront phase aberration at the ground for the two different paths through the atmosphere defined by a double star target. It gives the Cn2(h) for 8 layers starting from the ground with a resolution that varies between 12m and 107m depending on the separation of the observed binary system and its zenith distance. The instrument is optimised to measure the vertical profile of the turbulence in the first 500m above the site. The data is relevant to modelling and understanding the imaging performance of the VLT, both with and without adaptive optical correction.

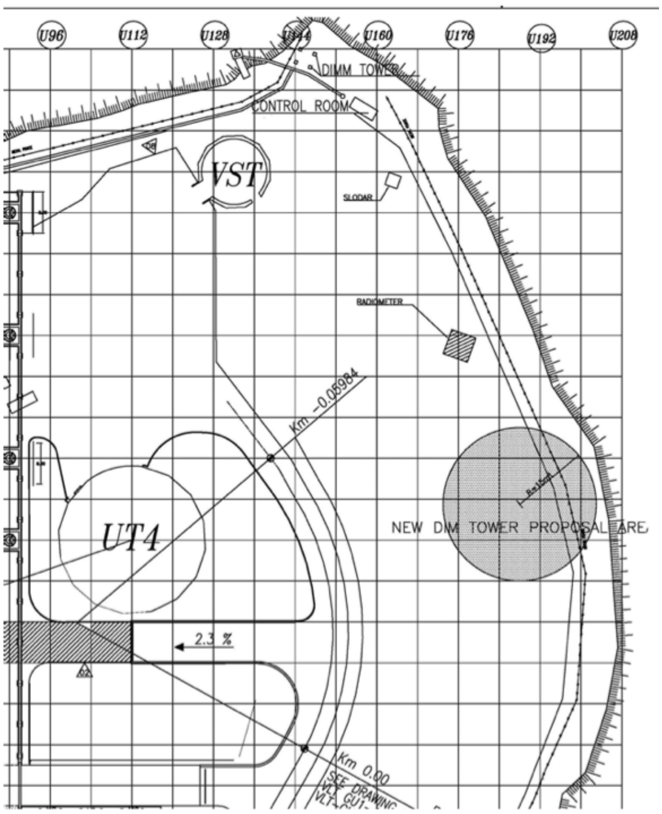



**Figure 1: Layout of the ASM Upgrade instrumentation on the VLT platform**

## 3.6 Operational Limits

| | Max. Sun Elevation (degree) | Max. Airmass | Min. Moon Distance (degree) | Max. Wind Speed (m/s) | Max. Relative Humidity (%) |
|---|---|---|---|---|---|
| DIMM | -6 | 1.4 | 15 | 18 | 70 |
| MASS | -12 | 1.4 | 30 | 18 | 70 |
| SLODAR | -10 | 1.4 | 15 | 13 | 70 |
| LHATPRO | n/a | n/a | n/a | n/a | n/a |
| METEO | n/a | n/a | n/a | n/a | n/a |

**Table 1: ASM Operational Limits**

## 3.7 ECMWF Forecasts

Since 1998 the European Center for Medium range Forecasts (ECMWF, Reading UK) has been supporting astronomical research at ESO by providing meteorological products for its observatories located in Northern Chile. Thanks to a recent decision by its Council, ECMWF is now able to provide products from the Boundary Conditions Programme to research projects and international organisations like ESO. ESO was the first international organisation to benefit from this decision and is now receiving hourly forecasts four times a day divided into in three data streams:

- ESS stream is made of: ES (name of the stream), S (Boundary Conditions data, i.e.: hourly data from base time 00/06/12/18h, which are considered separate from the normal operational data). Hourly data are only available up to 90 hours.
- ESD stream is made of: ES (name of the stream), D (Operational Data, i.e.: 3hourly data from base time 00/12h) from 90 to 192 hours
- ESE stream is made of: ES (name of the stream), E (Ensemble Forecast Data, i.e. 3-hourly data from base time 00/12h) from 0 to 144h

# 4. DIMM

## 4.1 DIMM Scientific parameters

| | |
|---|---|
| **DIMM-Seeing** | This is the total seeing calculated with DIMM telescope (arcsec). The value is calculated using the following formulae: FWHM = 2E07 $J^{0.6}$ where J is the integral of the turbulence along the vertical path. |
| **Relative Flux** | Relative Flux RMS variations as measure along the line of sight normalized by the average flux. |
| **Relative Flux Variance integration time** | Time range of measurements (start of first interval to end of last interval) used to calculate the relative Flux RMS variations as measure along the line of sight [s]. |

## 4.2 DIMM Engineering parameters

| | |
|---|---|
| **Number of frames** | Total number of processed frames. |

| | |
|---|---|
| **Airmass** | Airmass at which the ASM-DIMM telescope measures the site seeing. |
| **Target Dec** | Declination of observed star |
| **Target RA** | Right Ascension of observed star |
| **Telescope Az** | Telescope azimuth position |
| **Telescope El** | Telescope elevation position |
| **Cn2** | Turbulence intensity integrated along the vertical path, calculated with both motions [$10^{-15}m^{1/3}$]. |
| **Cn2 Residual** | Turbulence intensity calculated with both motions averaged over base time. |
| **Left Mean Flux** | Mean total flux in the left image [ADU]. |
| **Left Mean Flux RMS** | Relative RMS error of total flux in the left image. |
| **Left Scintillation Index** | Mean scintillation index in the DIMM aperture for the left image. |
| **Left Strehl Number** | Strehl number corrected for seeing for the left image. |
| **Longitudinal Cn2** | Turbulence intensity integrated along the vertical path calculated with longitudinal motion [$10^{-15}m^{1/3}$]. |
| **Longitudinal Cn2 Residual** | Turbulence intensity integrated along the vertical path calculated with longitudinal motion averaged over basetime [$10^{-15}m^{1/3}$]. |
| **Longitudinal Correlation** | Average of the longitudinal basetime correlation coefficient. |
| **Longitudinal Separation** | Mean longitudinal separation of right and left images [pixel]. |
| **Longitudinal Variance** | Average of the longitudinal motion basetime variance [$pixel^2$]. |
| **Longitudinal Variance Averaged** | Low frequency longitudinal motion variance [$pixel^2$]. |
| **Longitudinal Variance rms** | Variance of the longitudinal motion averaged over basetime. |
| **Right Mean Flux** | Mean total flux in the right image [ADU]. |
| **Right Mean Flux rms** | Relative RMS error of total flux in the right image. |
| **Right Scintillation Index** | Mean scintillation index in the DIMM aperture for the right image. |
| **Right Strehl Number** | Strehl number corrected for seeing for the right image. |
| **Scintillation Index** | Mean scintillation index in the DIMM aperture for both images. The value is the average between lsci and rsci. |
| **Transverse Cn2** | Turbulence intensity integrated along the vertical path calculated with transverse motion [$10^{-15}m^{1/3}$]. |

| | |
|---|---|
| **Transverse Cn2 Residual** | Turbulence intensity calculated with transverse motion averaged over base time [$10^{-15}m^{1/3}$]. |
| **Transverse Correlation** | Average of the transverse base time correlation coefficient. |
| **Transverse Separation** | Mean transverse separation of right and left images [pixel]. |
| **Transverse Variance** | Average of the transverse motion base time variance [$pixel^2$]. |
| **Transverse Variance Average** | Low frequency transversal motion variance [$pixel^2$]. |
| **Transverse Variance rms** | RMS of the transverse motion base time variance [pixel]. |

# 5. LHATPRO

| | |
|---|---|
| **IR temperature** | Measured infrared sky brightness temperature in Kelvin at Zenith. |
| **Liquid water path** | Measured liquid water path in $g/m^2$ at Zenith. |
| **Water vapour** | Measured Precipitable Water Vapor at Zenith (mm). |

# 6. MASS

## 6.1 MASS Scientific parameters

| | |
|---|---|
| **Free Atmosphere Seeing** | Free atmosphere seeing at 500nm/zenith from MASS stand-alone integrated profile [arcsec]. MASS-DIMM free atmosphere seeing should be computed from $FWHM_{FA}$=2E+7($J_{FA}$)^0.6 with $J_{FA}$=SUM(J1:J6) |
| **Free Atmosphere Seeing RMS** | Relative rms of free atmosphere seeing at 500nm/zenith from MASS stand-alone integrated profile. |
| **MASS Tau0** | Coherence time (weights method) from MASS stand-alone [s]. |
| **MASS Tau0 RMS** | Relative rms on the coherence time (weights method) from MASS stand-alone |
| **MASS Theta0** | Isoplanatic angle from MASS-DIMM integrated profile [J1:J6] in arcsec. |
| **MASS Theta0 RMS** | Relative rms on the isoplanatic angle from MASS-DIMM integrated profile [J1:J6]. |
| **MASS Turb Altitude** | Characteristic altitude of the free atmosphere turbulence from MASS-DIMM integrated profile [J1:J6] [meter]. |
| **MASS Turb Altitude RMS** | Relative rms on the characteristic altitude of the turbulence in MASS-DIMM integrated profile [J1:J6]. |

**MASS-DIMM Cn2 fraction at ground** Fraction of turbulence in the ground layer (GL defined as J0, or DIMM minus MASS):

FracGL = J0/sum(J0:J6);

**MASS-DIMM seeing** Whole atmosphere seeing at 500nm/zenith from MASS-DIMM combined profile [J0:J6] [arcsec].

**MASS-DIMM Tau0** Coherence time of the turbulence in the whole atmosphere from MASS-DIMM combined profile [J0:J6] [s].

$\tau_0 = (\tau_{0GL}{}^{-5/3} + \tau_{0MASS}{}^{-5/3})^{-3/5}$; $\tau_{0GL} = 0.0324 / FWHM_{GL} / V_{30m}$;

FWHMGL=2E+7(JGL)^0.6 ; JGL= J0

**MASS-DIMM Theta0** Isoplanatic angle of the turbulence in the whole atmosphere in arcsec.

$\theta_0 = (\theta_{0GL}{}^{-5/3} + \theta_{0MASS}{}^{-5/3})^{-3/5}$; $\theta_{0GL}(rd) = 0.0324 / FWHM_{GL} / H_{GL}$

$H_{GL}$ = ¾ MASS-DIMM Layer 1 height (cdg of layer 0 weighting function)

**MASS-DIMM Turb Altitude** Characteristic altitude of the turbulence in the whole atmosphere from MASS-DIMM combined profile [m].

$$\overline{H}_{TURB} = \left( \frac{J_{GL} H_{GL}^{5/3} + J_{MASS} H_{MASS}^{5/3}}{J_{TOT}} \right)^{3/5};$$

**MASS-DIMM Turb Velocity** Characteristic velocity of the turbulence in the whole atmosphere from MASS-DIMM combined profile [m/s].

$$\overline{V}_{MASSDIMM} = \left( \frac{J_{GL} V_{30m}^2 + J_{MASS} \overline{V}_{MASS}^2}{J_{DIMM}} \right)^{1/2};$$

$$\overline{V}_{MASS}^2 = (0.0324/FWHM_{MASS}/\tau_{0MASS})^2$$

## 6.2 MASS engineering parameters

**Airmass** Airmass of observed star.

**Average Flux** Average flux in aperture A,B,C and D respectively [counts/ms].

**Average Flux rms** Relative rms on the average flux in aperture A,B,C and D respectively.

**Averaged norm of residual** Value of averaged norm of residual.

| | |
|---|---|
| **Cn2** | Turbulence intensity from MASS stand-alone integrated profile [$10^{-15}m^{1/3}$]. MASS-DIMM free atmosphere turbulence intensity should be computed from $J_{FA}$=SUM(J1:J6) |
| **Cn2 rms** | Relative rms on the turbulence intensity from MASS stand-alone integrated profile. |
| **DESI Tau0** | Coherence time (DESI method) from MASS integrated profile [s]. |
| **DESI Tau0 rms** | Relative rms on the coherence time (DESI method) from MASS integrated profile. |
| **MASS-DIMM Layer Cn2** | Turbulence intensity J1:J6 in MASS-DIMM layers 1-2-3-4-5-6 respectively [$10^{-15}m^{1/3}$]. |
| **MASS-DIMM Layer Cn2 rms** | Rms on the turbulence intensity in MASS-DIMM layer 1-2-3-4-5-6 respectively [$10^{-15}m^{1/3}$]. |
| **MASS-DIMM Layer Height** | Position above ground of the maximum sensitivity in MASS-DIMM layer 1-2-3-4-5-6 respectively [m]. |
| **MASS-DIMM Layer 0 Cn2** | Turbulence intensity $J_0$ in MASS-DIMM layer 0 (Ground layer: DIMM minus MASS) [$10^{-15}m^{1/3}$]. |
| **MASS-DIMM Layer 0 Cn2 rms** | Rms on the turbulence intensity $J_0$ in MASS-DIMM layer 0 [$10^{-15}m^{1/3}$]. |
| **MASS-DIMM Layer 0 height** | Altitude for layer provided by DIMM. The value is only present if the MASS data have been processed together with DIMM data. If present the value is always 0 (m). |
| **Number of layers** | Number of nodes of the grid of altitudes, in ESO configuration the number of nodes is set to 6. Additional node on the grid at altitude of 0 km is added when dimm data are used. |
| **Scintillation index** | Index of scintillation in aperture A,B,C,D,AB,AC,AD,BC,BD,CD. |
| **Scintillation index rms** | Relative rms on the index of scintillation in aperture A,B,C,D,AB,AC,AD,BC,BD and CD. |
| **Second altitude moment** | Second altitude moment from MASS integrated profile [$m^{7/3}$]. |
| **Second altitude moment rms** | Relative rms on the second altitude moment from MASS integrated profile. |

# 7. METEO

## 7.1 METEO Scientific parameters

| | |
|---|---|
| **Air Pressure** | Temporal (1 minute) mean of observatory site ambient barometric air pressure measured at ground during measurement period [hPa]. |
| **Ambient Temperature** | Temporal (1 minute) mean of site ambient temperature in degree Celsius measured at 30m, 2m, 0m and -20m wrt. VLT platform [Celsius]. |

| | |
|---|---|
| **Dew Temperature** | Temporal (1 minute) mean of observatory site ambient dew temperature measured at sensor position 30m, 2m, and -20m wrt. VLT platform during measurement period [Celsius]. |
| **Large (5 micron) dust Particles** | Temporal (20 minutes) mean of observatory site ambient large (5 micron size) dust particle count per cubic meter measured at sensor position 20 m and 10 during measurement period [$m^{-3}$]. |
| **Normalised Air Pressure** | 1 minute average pressure normalized to sea level [hPa]. |
| **Rain intensity** | 1 minute rain percentage measured at 20m below VLT platform. |
| **Relative Humidity** | Temporal (1 minute) mean of observatory site ambient relative humidity measured at sensor position 30m, 2m and -20m wrt. VLT platform during measurement period (percentage). |
| **Small (0.5 micron) dust Particles** | Temporal (20 minutes) mean of observatory site small (0.5 micron) dust Particle count per cube meter measured at sensor position 20m and 10m during measurement period. |
| **Wind Direction (0/360)** | 1 minute average wind direction at 30m and 10m above ground counted clockwise from North (standard). |
| **Wind Direction (180/-180)** | 1 minute average wind direction at 30m and 10m above ground counted clockwise from North (with 180 degree negative offset for display purposes) |
| **Wind Speed** | 1 minute average wind speed at sensor position 30m and 10m [m/s]. |
| **Wind Speed component U** | Temporal (1 minute) mean of observatory site ambient wind speed U vector component, where U is horizontal and points to 330 degree measured at sensor position 20m during measurement period [m/s]. |
| **Wind Speed component V** | Temporal (1 minute) mean of observatory site ambient wind speed V vector component, where V is horizontal and points to 240 degree measured at sensor position 20m during measurement period [m/s]. |
| **Wind Speed component W** | Temporal (1 minute) mean of observatory site ambient wind speed W vector component, where W is vertically pointing upwards, measured at sensor position 20m during measurement period [m/s]. |

## 7.2 METEO Engineering parameters

| | |
|---|---|
| **0.5 um Particle Count instantaneous** | Small (0.5 micron) dust particle count at 20m and 10m above ground at the end of the averaging period [$m^{-3}$]. |
| **0.5 um Particle Count max** | 20 minute maximum small (0.5 micron) dust particle count at 20m and 10m above ground [$m^{-3}$]. |
| **0.5 um Particle Count min** | 20 minute minimum small (0.5 micron) dust particle count at 20m and 10m above ground [$m^{-3}$]. |

| | |
|---|---|
| **0.5 um Particle Count rms** | 20 minute RMS small (0.5 micron) dust particle count at 20m and 10m above ground [$m^{-3}$]. |
| **5 um Particle Count instantaneous** | Large (5 micron) dust particle count at 20m and 10m above ground at the end of the averaging period [$m^{-3}$]. |
| **5 um Particle Count max** | 20 minute maximum large (5 micron) dust particle count at 20m and 10m above ground [$m^{-3}$]. |
| **5 um Particle Count min** | 20 minute minimum large (5 micron) dust particle count at 20m and 10m above ground [$m^{-3}$]. |
| **5 um Particle Count rms** | 20 minute RMS large (5 micron) dust particle count at 20m and 10m above ground [$m^{-3}$]]. |
| **Air Pressure 3h trend** | Surface pressure trend over 3 hours [hPa]. |
| **Air Pressure instantaneous** | Surface pressure at the end of the averaging period [hPa]. |
| **Air Pressure max** | 1 minute and 20 minute maximum surface pressure [hPa]. |
| **Air Pressure min** | 1 minute and 20 minute minimum surface pressure [hPa]. |
| **Air Pressure normalized instantaneous** | Pressure normalized to sea level at the end of the averaging period [hPa]. |
| **Air Pressure normalized max** | 1 minute and 20 minute maximum pressure normalized to sea level [hPa]. |
| **Air Pressure normalized min** | 1 minute and 20 minute minimum pressure normalized to sea level [hPa]. |
| **Air Pressure normalized rms** | 1 minute and 20 minute RMS pressure normalized to sea level [hPa]. |
| **Air Pressure rms** | 1 minute and 20 minute rms surface pressure variation. |
| **Air Temperature instantaneous** | 1 minute and 20 minute air temperature at 30m, 2m, 0m and -20m wrt. VLT platform measured at the end of the averaging period [Celsius]. |
| **Air Temperature max** | 1 minute and 20 minute maximum air temperature at 30m,2m, 0m and -20m below VLT platform [Celsius]. |
| **Air Temperature min** | 1 minute and 20 minute minimum air temperature at 30m,2m, 0m and -20m wrt. VLT platform [Celsius]. |
| **Air Temperature rms** | 1 minute and 20 minute rms air temperature variation at 30m, 2m, 0m and -20m wrt. VLT platform below VLT platform [Celsius]. |
| **Dew Temperature instantaneous** | 1 minute and 20 minute dew temperature at 30m, 2m and -20m wrt. VLT platform measured at the end of the averaging period [Celsius]. |
| **Dew Temperature max** | 1 minute and 20 minute maximum dew temperature at 30m, 2m and -20m wrt. VLT platform [Celsius]. |

| | |
|---|---|
| **Dew Temperature min** | 1 minute and 20 minute minimum dew temperature at 30m, 2m and -20m wrt. VLT platform [Celsius]. |
| **Dew Temperature rms** | 1 minute and 20 minute RMS dew temperature at 30m, 2m and -20m wrt. VLT platform [Celsius]. |
| **Humidity instantaneous** | 1 minute and 20 minute relative humidity measured at 30m, 2m and -20m wrt. VLT platform at the end of the averaging period [%]. |
| **Humidity max** | 1 minute and 20 minute maximum relative humidity measured at 30m, 2m and -20m wrt. VLT platform [%]. |
| **Humidity min** | 1 minute and 20 minute minimum relative humidity measured at 30m, 2m and -20m wrt VLT platform [%]. |
| **Humidity rms** | 1 minute and 20 minute RMS relative humidity measured at 30m, 2m and -20m wrt. VLT platform [%]. |
| **Rain Intensity instantaneous** | Rain percentage 20m below VLT platform at the end of the averaging period. |
| **Rain Intensity max** | 1 minute maximum rain percentage 20m below VLT platform. |
| **Rain Intensity min** | 1 minute minimum rain percentage 20m below VLT platform. |
| **Rain Intensity rms** | 1 minute RMS rain percentage 20m below VLT platform. |
| **Wind Direction instantaneous** | Wind direction at 30m and 10m above ground at the end of the averaging period. |
| **Wind Direction max** | 1 minute and 20 minute maximum wind direction at 30m and 10m above ground. |
| **Wind Direction min** | 1 minute and 20 minute minimum wind direction at 30m and 10m above ground. |
| **Wind Direction rms** | 1 minute and 20 minute rms air wind direction at 30m and 10m above ground. |
| **Wind Speed component U instantaneous** | Horizontal wind speed U component (into 330 degree) at 20m above ground at the end of the averaging period (in m/s). |
| **Wind Speed component U max** | 1 minute and 20 minute maximum horizontal wind speed U component (into 330 degree) at 20m above ground. |
| **Wind Speed component U min** | 1 minute and 20 minute minimum horizontal wind speed U component (into 330 degree) at 20m above ground. |
| **Wind Speed component U rms** | 1 minute and 20 minute RMS horizontal wind speed U component (into 330 degree) at 20m above ground. |
| **Wind Speed component V instantaneous** | Horizontal wind speed V component (into 240 degree) at 20m above ground at the end of the averaging period (in m/s). |
| **Wind Speed component V instantaneous** | Vertical wind speed W component at 20m above ground at the end of the averaging period (in m/s). |

| | |
|---|---|
| **Wind Speed component V max** | 1 minute and 20 minute maximum horizontal wind speed V component (into 240 degree) at 20m above ground. |
| **Wind Speed component V min** | 1 minute and 20 minute minimum horizontal wind speed V component (into 240 degree) at 20m above ground. |
| **Wind Speed component V rms** | 1 minute and 20 minute RMS horizontal wind speed V component (into 240 degree) at 20m above ground. |
| **Wind Speed component W max** | 1 minute and 20 minute maximum vertical wind speed W component at 20m above ground. |
| **Wind Speed component W min** | 1 minute and 20 minute minimum vertical wind speed W component at 20m above ground. |
| **Wind Speed component W rms** | 1 minute and 20 minute RMS vertical wind speed W component at 20m above ground. |
| **Wind Speed instantaneous** | Wind speed at 30m and 10m above ground at the end of the averaging period (in m/s). |
| **Wind Speed max** | 1 minute and 20 minute maximum wind speed at 30m and 10m above ground. |
| **Wind Speed min** | 1 minute and 20 minute minimum wind speed at 30m and 10m above ground. |
| **Wind Speed rms** | 1 minute and 20 minute RMS wind speed at 30m and 10m above ground. |

# 8. SLODAR

## 8.1 SLODAR Scientific parameters

| | |
|---|---|
| **Cn2 above Uts** | Integrated Cn2 above the equivalent UT (VLT Unit Telescope) height [$10^{-15}$ $m^{1/3}$].<br><br>*The equivalent UT height is the lower limit of the surface layer which is seen from a UT: currently set at 10m, it will be adjusted to AOF results in the future* |
| **Cn2 fractions** | Cn2 fraction below 300m and 500m respectively.<br><br>*Ratio of the Cn2 integrated from the UT height up to 300m (resp. 500) to <Cn2 above UTs>* |
| **Surface layer profile** | High resolution surface layer fit strength [$10^{-15}$ $m^{1/3}$].<br><br>*The result of an exponential model fit with 5m scale height and scaled in strength according to the value of the first SLODAR bin. The integration range is from the SLODAR aperture (2m above ground) up to infinity -in practice the exponential model drops to zero after a few tens of meters.* |

## 8.2 SLODAR Engineering parameters

| | |
|---|---|
| **Airmass** | SLODAR Airmass. |
| **Cn2 layer thickness** | Vertical distance between profiled layers [m]. |
| **Cn2 Max Height** | Maximum height profiled by this measurement [m]. |
| **Cn2 profile in each layer** | Turbulence profile Cn2 in layer 1,2,3,4,5,6,7 and 8 respectively [$10^{-15}$ $m^{1/3}$]. |
| **Cn2 Unresolved** | Unresolved turbulence profile Cn2 [$10^{-15}$ $m^{1/3}$]. |
| **Flux** | Flux for star 1 and star 2 respectively [ADU] |
| **Flux Variance** | Flux variance for star 1 and star 2 respectively [$ADU^2$]. |
| **Kolmogorov criterium** | Power law exponent of power spectrum density (11/3 = Kolmogorov turbulence).<br><br>*Data taken in clearly non-Kolmogorov conditions (<3.4) are not validated* |
| **Noise fraction** | Fraction of the centroid variance that is due to noise for star 1 and star 2 respectively [dimensionless]. |
| **Seeing** | SLODAR Seeing at zenith in arcsec. |
| **Target name** | SLODAR target name. |
| **Telescope azimuth and elevation** | Telescope azimuth and elevation in degrees. |

# 9. Forecasts

## 9.1 ECMWF Weather Forecasts

### 9.1.1 Domain and Parameters

#### 9.1.1.1 Deterministic Forecasts

Low Resolution data cube: (10-43 South, 110-65 West, 3 degree, GH-U-V-T, levels 1000-925-850-700-500-400-300-200-100)

High Resolution data cubes (*Grid: 0.125 x 0.125 (Lat-Lon)*):

- *Area1: 21S to 26.5S,72.5W to 66W (+/- 2 degrees around Paranal/Armazones 24.5S,70.5W & Chajnantor 23S, 67.75W)*
- *Area2: 27S to 31.5S,72.5W to 68.5W (+/- 2 degrees around La Silla 70.75, -29.25)*

*Pressure levels 1000, 950, 925, 900, 850, 800, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10, 7, 5, 3, 2, 1 hPa*

- GH: 156 Geopotential height (m)

- R: 157 Relative humidity (%)

- T: 130 Temperature (Celsius)

- U: 131 U-velocity (m/s)

- V: 132 V-velocity (m/s)

*Single level*

- TP: 228 Total precipitation

- HCC: 188 High cloud cover (fraction 0->1)

- LCC: 186 Low cloud cover (fraction 0->1)

- MCC: 187 Medium cloud cover (fraction 0->1)

- TCWV: 137 Total column water vapour (mm)

#### 9.1.1.2 Ensemble Forecasts

*Time: 00:00:00, 12:00:00 UTC*

*Steps: T+0h to T+144h at 3-hour intervals*

*Domain (Grid: 0.25 x 0.25 (Lat-Lon)):*

- *Area1: 21S to 26.5S,72.5W to 66W (+/- 2 degrees around Paranal/Armazones 24.5S,70.5W & Chajnantor 23S, 67.75W)*
- *Area2: 27S to 31.5S,72.5W to 68.5W (+/- 2 degrees around La Silla 70.75, -29.25)*

*Model level: 31*

- CC: 248 Cloud Cover

*Single*

- TP: 228 Total precipitation

- HCC: 188 High cloud cover

- LCC: 186 Low cloud cover

- MCC: 187 Medium cloud cover

- SF: 144 Snow fall

### 9.1.2 Forecast accuracy

The forecasts are delivered to ESO about 5 hours after initialisation time. Hence the accuracy should be estimated by comparing to the local data the forecasts issued 24h in advance (24h-casts) which are the ones used to prepare an observing night. The forecasts are not available outside ESO in agreement with the ECMWF dissemination licence.

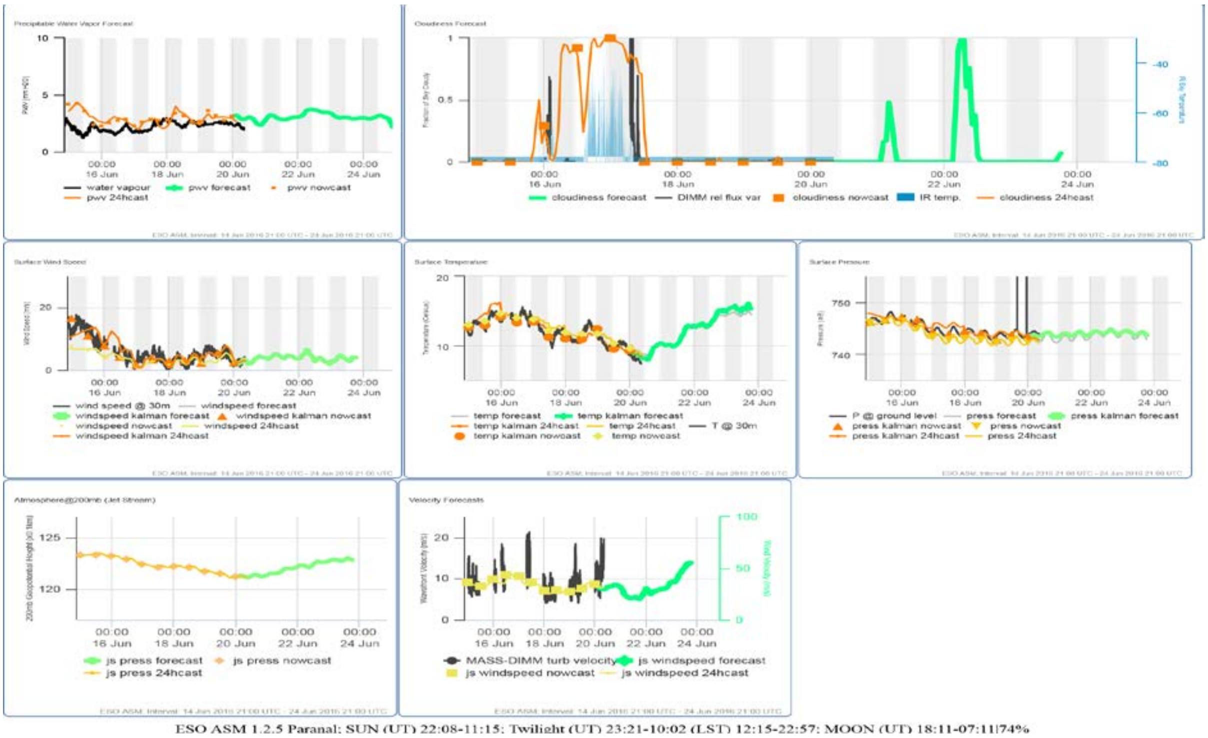



**Figure 2: Current forecasts for the next five days (green) and 24casts of the previous 5 days (orange) compared to local measurements (black) when available**

http://www.eso.org/asm/ui/log?namespace=msarazin&name=forecasts&hoursInterval=240&daysInPast=6

## 9.2 Meso-Scale Model Forecasts

Predictability of observing conditions, including seeing and GL fraction, is an AOF requirement. A feasibility study has been conducted for using Meso-Nh meteorological model to predict meteorological and turbulence profiles over Paranal-Armazones area. Promising results were obtained [RD2], discussion for implementing an operational demonstrator are underway

# 10. ESO Science Archive Data Access

## 10.1 Data Display

Two ASM graphical configurations (presets) have been created for Paranal and La Silla, mimicking the original ambient server (M.Albrecht, 1995):

http://www.eso.org/asm/ui/publicLog?name=Paranal

http://www.eso.org/asm/ui/publicLog?name=LaSilla

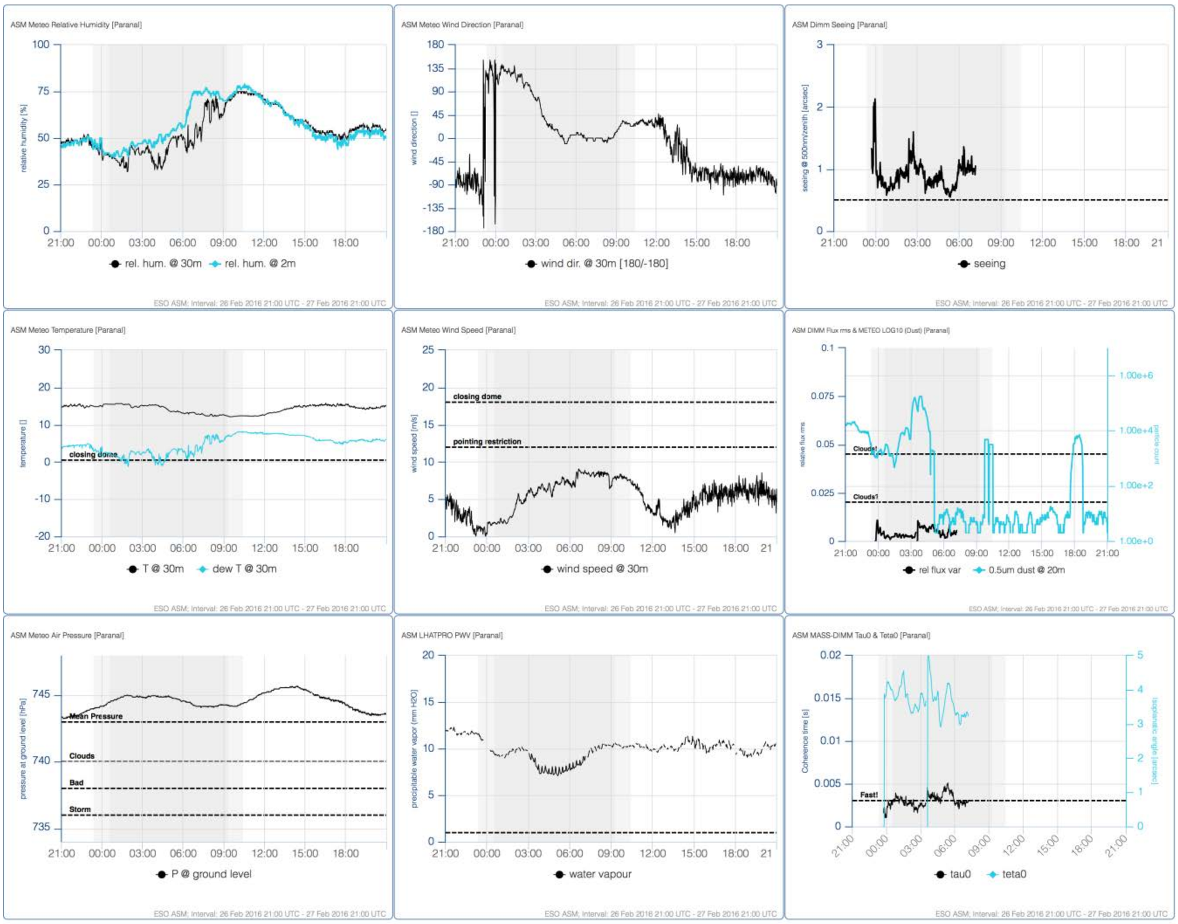
integrated by a similar monitoring system for Chajnantor Apex Weather. The archive query interfaces described in 9.2 (except SLODAR) allow a user to navigate from the (HTML) result page of a query to the graphical representation of the main parameters for the related night. Table 2 lists the types of plot (vs time) available for the three different sites.

**Table 2**

| Measurement | Paranal preset | La Silla preset | Apex Weather |
|---|---|---|---|
| **Relative Humidity** | Yes | Yes | Yes |
| **Air Temperature** | Yes | Yes | Yes |
| **Atmospheric Pressure** | Yes | Yes | Yes |
| **Wind Speed** | Yes | Yes | Yes |
| **Wind Direction** | Yes | Yes | Yes |
| **DIMM Seeing** | Yes | Yes | N/A |
| **Flux Variations normalised by average flux** | Yes | Yes | N/A |
| **Coherence Time (Tau0) & Isoplanatic Angle (Theta0)** | Yes | N/A | N/A |
| **Precipitable Water Vapour** | Yes | N/A | Yes |

Figure 3 shows an example of the ambient plots available for Paranal. On the plot are visible the site, the sun/moon rise and set UT times, while the twilight times are provided in both UT and LST times. The ASM display tool allows the user to export the plots in PNG format by clicking on the PNG button on the top right corner[1].

[1] Figure 3 is actually the PNG exported plot of the indicated night.




ESO ASM 1.2.4 Paranal; SUN (UT) 23:21-10:27; Twilight (UT) 00:32-09:17 (LST) 06:16-15:02; MOON (UT) 01:33-13:50|84%

**Figure 3: Paranal ambient conditions plots**

## 10.2 Data Download

Specific archive query interfaces have been set up to allow users to query and download the measurements of the various ASM instruments. They are accessible via the main page:

http://archive.eso.org/cms/eso-data/ambient-conditions.html

Users of the Science Archive Facility (http://archive.eso.org/) can find their way to that page via the navigation pulldown menu on the left side of the SAF home page (-> ESO Data -> Ambient Conditions Database).

The query interfaces are presented subdivided by geographical location: La Silla, Paranal, Chajnantor.

La Silla query interfaces:

- DIMM La Silla: http://archive.eso.org/wdb/wdb/asm/ambient_lasilla/form (seeing and airmass)
- METEO La Silla: http://archive.eso.org/wdb/wdb/asm/meteo_lasilla/form (air temperature and pressure, rel. humidity, wind speed and direction at 10m and 30m)

Paranal query interfaces:

- Historical ambient data (DIMM 1998): http://archive.eso.org/wdb/wdb/asm/historical_ambient_paranal/form (seeing, airmass, relative flux rms, coherence time, isoplanatic angle, for DIMM-1998 measurements before April 2016)

- DIMM Seeing 2016: http://archive.eso.org/wdb/wdb/asm/dimm_paranal/form (seeing, relative flux rms, for DIMM-2016 measurements after April 2016)
- MASS: http://archive.eso.org/wdb/wdb/asm/mass_paranal/form (high-atmosphere seeing, isoplanatic angle, coherence time, and turbulence parameters, measured by MASS)
- SLODAR: http://archive.eso.org/wdb/wdb/asm/slodar_paranal/form (Cn2 fraction below 300m, below 500m, and above Unit Telescopes, measured by SLODAR)
- LHATPRO: http://archive.eso.org/wdb/wdb/asm/lhatpro_paranal/form (Water vapour, IR temperature measured by LHATPRO)
- METEO Paranal: http://archive.eso.org/wdb/wdb/asm/meteo_paranal/form (Ambient and dew temperatures, relative humidity, air pressure, wind speed and directions, particle counts measured by the Vaisala meteorological station)

Chajnantor APEX weather query interface:

- METEO APEX: http://archive.eso.org/wdb/wdb/asm/meteo_apex/form (Dew point, temperature, wind speed and direction, radiometer brightness temperature)

One help page describing all the parameters of the various query interfaces is available for each of the three sites:

- http://archive.eso.org/wdb/help/asm/ambient_paranal.html
- http://archive.eso.org/wdb/help/asm/ambient_lasilla.html
- http://archive.eso.org/wdb/help/asm/meteo_apex.html

### 10.2.1 Query constraints

The query interfaces can be used to display or to download data according to the query constraints that a user can set on any field. On all query forms, the button “Syntax Help” brings the user to the documentation describing how a query constraint can be formulated.

Most typically the user will want to retrieve measurements related to a specific time range; to achieve this, the user must type an interval in the Date field, using the range operator “..”. For example: 2016-04-01..2016-05-01 can be used to retrieve the data for the entire month of April 2016.

### 10.2.2 Output preferences

At the top of any query form the Output preferences panel can be used to set the following properties:

- Output format, one of:
  - html table (default)
  - ascii fixed length/display
  - ascii fixed length/download
  - ascii csv/download (comma separated values)

When a download option is chosen, the browser will not show the results on screen, and instead it will prompt the user to either save the results in a file, or to use an helper application to open the results into.

- Return max rows:

The query interface limits to a maximum of 15,000 the number of records returned when the user chooses to display the results within the browser (and not to download the data); if instead the user specifies a download mode (e.g. csv/download), or the query is executed programmatically (e.g. using curl or wget) then the maximum number of returned records is set to ten million. The user can change the default behaviour by setting the “Return max rows” to a lower number.

### 10.2.3 Query results

For all output modes, the result of a query is a document that provides the header information including field names and units, followed by the records matching the user’s constraints.

The values of some selected fields might have been normalised. This is the case of the turbulence intensity (Cn2) parameters, which are presented in units of $[10^{-15}m^{1/3}]$. Please refer to the related help page to get the full description of every field including its units.

To be noted that:

- in “ASCII fixed length” output mode the null values are replaced by the string N/A;
- in “html” output mode, the output table provides, in addition to the requested parameters:
    - o a link (More) that can be followed to display all the measurements of the pertaining record;
    - o a link (Monitor) to the graphical monitor of the relevant site for the night of interest.

### 10.2.4 Programmatic interface

To programmatically interact with the ASM query interfaces, please read a FAQ at:

- http://archive.eso.org/cms/faq/how-do-i-query-the-archive-programmatically.html

The recipe described therein can be used for all the ASM query interfaces. In programmatic mode, all the query interfaces can return a maximum of 10 million records.

# 11. ASM Data Display Tool

The ASM display is reached from the url: www.eso.org/asm with the following characteristics:

| **ASM Display URLs** | **Parameters** |
|---|---|
| **(Default Landing page when anonymous:** http://www.eso.org/asm/ui/publicLog **when logged in:** http://www.eso.org/asm/ui/live) | |

| | |
|---|---|
| http://www.eso.org/asm/ui/publicLog<br><br>*anonymous*<br><br>*log view, default configuration* | **name**=<ConfigName> [: 'Paranal']<br>**hoursInterval**=<displayed time interval starting at 21:00> [: 15, maxValue: 240], but forecast date is not loaded<br>// three ways of specifying start date, first one is chosen<br>// note that the time is ignored, charts always start at 21:00<br>**t**=<starcat date:number of seconds from 1980><br>**daysInPast**=<number><br>**night**=<dd+mmm+yyyy>, e.g. 10+MAR+2014<br>**startDate**=<ISO string>, e.g. 2015-10-09T21:00:00.000Z |
| http://www.eso.org/asm/ui/publicLogFullScreen<br><br>*anonymous*<br><br>*single chart full screen, default configuration* | **name**=<ConfigName> [default: 'Paranal']<br>**chartId**=<number> *required<br>**chartTyp**e=<AsmTimeChart\|AsmPolarChart\|AsmDataPanel><br>**startDate**=<ISO string><br>**hoursInterval**=<displayed time interval starting at 21:00><br>**t**=<starcat date:number of seconds from 1980><br>**daysInPast**=<number><br>**night**=<dd+mmm+yyyy>, e.g. 10+MAR+2014<br>**startDate**=<ISO string>, e.g. 2015-10-09T21:00:00.000Z |
| http://www.eso.org/asm/ui/log<br><br>*login required*<br><br>*log view private configuration* | **namespace**=<ConfigNamespace> [default: 'Presets']<br>**name**=<ConfigName> [default: 'Paranal']<br>**hoursInterval**=<displayed time interval starting at 21:00> [default: 15, maxValue: 240]<br>// three ways of specifying start date, first one is chosen<br>// note that the time is ignored, charts always start at 21:00<br>**t**=<starcat date:number of seconds from 1980><br>**daysInPast**=<number><br>**night**=<dd+mmm+yyyy>, e.g. 10+MAR+2014<br>**startDate**=<ISO string>, e.g. 2015-10-09T21:00:00.000Z |
| http://www.eso.org/asm/ui/live<br><br>*login required*<br><br>*live view, private configuration* | **namespace**=<ConfigNamespace> [default: 'Presets']<br>**name**=<ConfigName> [default: 'Paranal'] |

http://www.eso.org/asm/api/ambientServer

*anonymous*

*log view, export to png of default configuration*

http://www.eso.org/asm/api/ambientServer [default: 'Prints/Paranal']
**site**=<lasilla|paranal> // mapped to config names Prints/Paranal and Prints/LaSilla
**print**=<starcat date:number of seconds from 1980> [default: now]
**name** = <ConfigName> [default: 'Paranal']
**hoursInterval**=<displayed time interval starting at 21:00> [default: 15, maxValue: 240]
**pageWidth** = <pixel width>: [default: 1200]
**pageHeight** =<pixel height>: [default 800]
**noCache** =true|false [default: false] if true regenerates the graph otherwise loads a cached graph previously generated.
**footer**=true|false [default: false] adds general night information in the footer.
If end interval is in the future, the figure is reloaded.
It will generate a file (called asmpage_Prints_<name>_H_<hoursInterval>_D_ <yyyy_MM_dd_hh_mm>_w_<pageWidth>_h_<pageHeight>.png

The ASM display replaces the Ambient Server to be decommissioned:

**Mapping of Ambient Server URLs to ASM Display**

**Ambient Server**

http://archive.eso.org/asm/ambient-server
**site**=<lasilla|paranal>
**night**=<dd+mmm+yyyy>

**ASM Display**

_http://www.eso.org/asm/ui/publicLog
**site**=<lasilla|paranal> // mapped to config names LaSilla, Paranal
**night**=<dd+mmm+yyyy>

**Ambient Server**

http://archive.eso.org/asm/ambient-server
**site**=<lasilla|paranal>
**t**=<starcat date:number of seconds from 1980>

**ASM Display**

http://www.eso.org/asm/ui/publicLog
**site**=<lasilla|paranal> // mapped to config names LaSilla, Paranal
**t**=<starcat date:number of seconds from 1980>

**Ambient Server**

http://archive.eso.org/asm/ambient-server
**site**=<lasilla|paranal>
**print**=<starcat date:number of seconds from 1980>

**ASM Display**

http://www.eso.org/asm/api/ambientServer [default: 'Prints/Paranal']
**site**=<lasilla|paranal> // mapped to config names Prints/Paranal and Prints/LaSilla
**print**=<starcat date:number of seconds from 1980> [default: now]

*To be implemented later: potential mapping of archive search result link to ASM Web Display*

**Ambient Server**

http://archive.eso.org/asm/ambient-server
**site**=<lasilla|paranal>
**mjd**=<jullian date>
**exptime**=80.000
**mark**=VCAM.2014-11-10T08:06:20.727

**ASM Display**

http://www.eso.org/asm/ui/publicLogFullScreen
**site**=<lasilla|paranal>
**startDate**=<ISO string>
exposureStartTime=<ISO string>
exposureEndTime=<ISO string>

# 12. Data Verification

## 12.1 Data Quality Control

### 12.1.1 DIMM

DIMM seeing is measuring image motion produced by the turbulence integrated over the line of sight. DIMM has an internal quality control so that only data with sufficient S/N ratio is used for this calculation.

### 12.1.2 MASS

Because MASS and DIMM are jointly operated, MASS data is produced and archived even when MASS operating conditions recommended by the vendor are not respected, e.g. airmass and cloudiness. It is up to the user to filter data which were taken out of the operating range: note that there is little known about the errors generated by clouds and high airmass in the MASS turbulence profiles. The coherence time tau0 is probably not affected.

MASS data quality is guaranteed when all conditions below are fulfilled:
-airmass<1.4
-line of sight void from clouds: MASS relative rms of flux (computed over 1mn) in ring D<3% or DIMM relative rms of flux (computed over 5mn)<2%)
-moon minimum angular distance to MASS star=30 degree
-sun more than 12 degree below horizon
-sky background measured at each new preset and then every 60 iterations. Measurement is performed after moving target out of the field (field size in largest dimension = 435 arcsec or 7.25 arcmin)

### 12.1.3 SLODAR

SLODAR has an internal quality control of the status of the atmospheric turbulence: the slope beta of the power spectrum is estimated at each measurement. If a profile is generated that does not meet the data quality requirements (beta>3.45, corresponding mostly to low wind conditions wind speed>3m/s), a result file will nevertheless be published but without the following surface layers profiling entries:

FWHM, STEP, MAXHEIGHT, CNSQ*, CNSQ.UNS, FITSCH, HRSFIT

Beta, centroid variances, fluxes and noise estimates are still valid when beta is low (on some level at least).

During SLODAR prototype operation before the ASM upgrade (Figure 4), such low beta conditions appeared about 30% of the time.

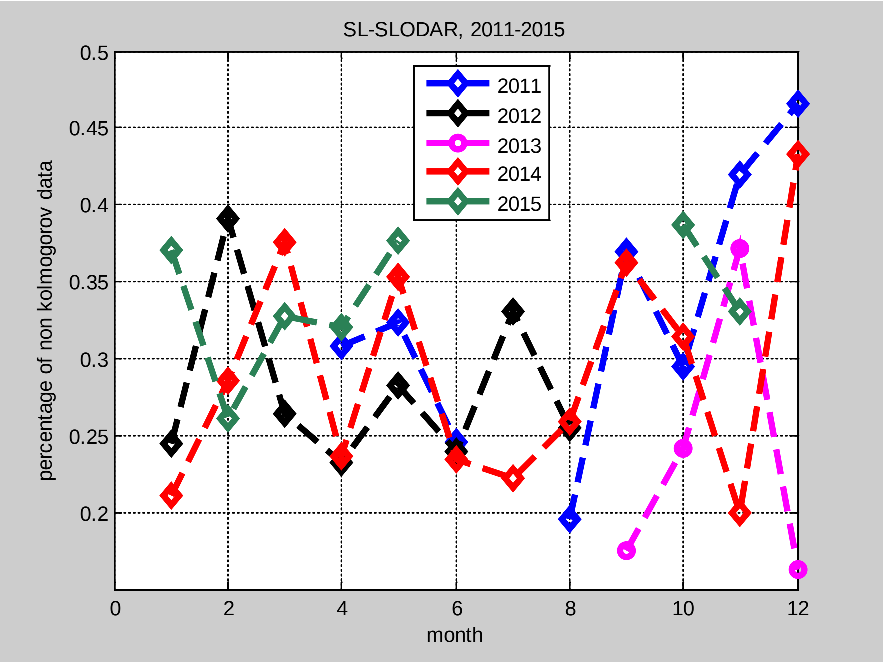



Figure 4: Fraction of the observed time when the SLODAR measurements were not usable (beta<3.45) before the ASM upgrade

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2011 | NaN | NaN | NaN | 31% | 32% | 24% | NaN | 20% | 37% | 30% | 42% | 46% |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2012 | 24% | 39% | 26% | 23% | 28% | 24% | 33% | 25% | NaN | NaN | NaN | NaN |
| 2013 | NaN | NaN | NaN | NaN | NaN | NaN | NaN | NaN | 17% | 24% | 37% | 16% |
| 2014 | 21% | 28% | 37% | 24% | 35% | 23% | 22% | 26% | 36% | 31% | 20% | 40% |
| 2015 | 37% | 26% | 33% | 32% | 38% | NaN | NaN | NaN | NaN | 39% | 33% | NaN |

**Table 3: statistics for the plots of Figure 4**

During the ASM upgrade a Monte-Carlo simulation of the temporal averaging effect was conducted at Durham. The results presented in Figure 5 show that Beta should drop below the threshold of 3.45 (red line) at a wind speed of 0.03 m/s compared to ~3 m/s at Paranal. There is no clear explanation for this difference, the frozen flow assumption may not be valid in low wind conditions. In practice Data taken in clearly non-Kolmogorov conditions (<3.4) are not validated.

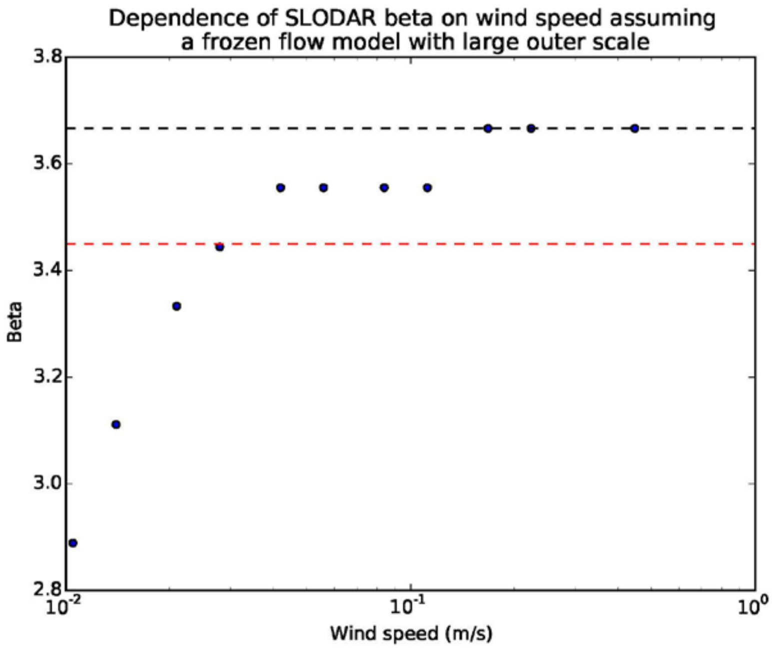



**Figure 5: Result of a Monte-Carlo simulation of the departure from Kolmogorov model at low wind speed**

Suggested during a progress meeting at ESO to increase the SLODAR averaging period to reduce the relative frequency of occurrence of these perturbations: the SLODAR packet size was increased from 500 frames to 1000. Each packet is now therefore 23.2s long instead of 11.6s. Each profile is produced by averaging over 6 packets so each measurement is now based on ~140s of data. Figure 6 shows that this change has considerably reduced the dependency of beta on low wind speed, Figure 7 shows that the frequency of data rejection for low beta has decreased to less than 20% in the period considered (Oct. 2015 – May 2016), the yearly value is expected to be even lower as low wind conditions do not occur so often in wintertime.

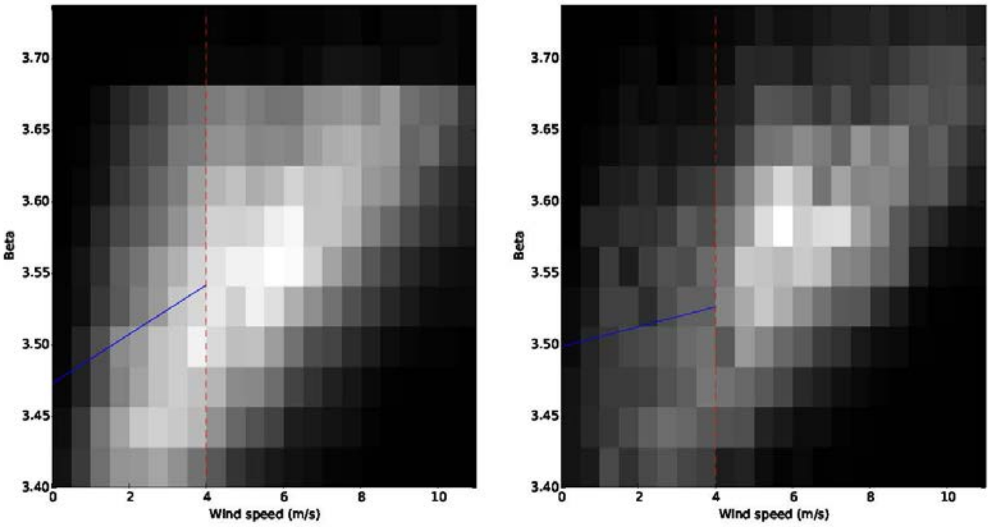



**Figure 6: The left hand panel is a density plot showing measured beta values as a function of wind speed before we increased the integration time (Jan. 2014 to Apr. 2015). The right hand panel shows the same after the increased the integration time by a factor of 2. The blue lines on the plots come from a linear fit to the data points where v < 4m/s**

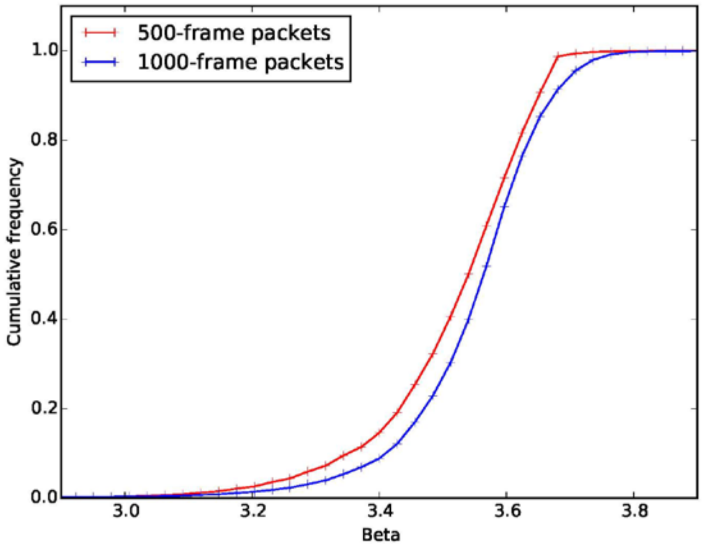



**Figure 7: Improvement of the SLODAR coverage after increasing the measurement averaging period**

## 12.2 Observatory Seeing

The “new” DIMM (DIMM-2016) seeing is to be considered as the Observatory seeing. The new DIMM tower is in a more favourable location, less affected by local constructions than the “old” DIMM (DIMM-1998) which was too close to the VST. The two DIMMs have run in parallel during two years showing about 0.3 arcsec offset of DIMM-1998 (Figure 8) due to local amplification of the turbulence in the surface layer by the backflow in the windwards surface (Figure 9)

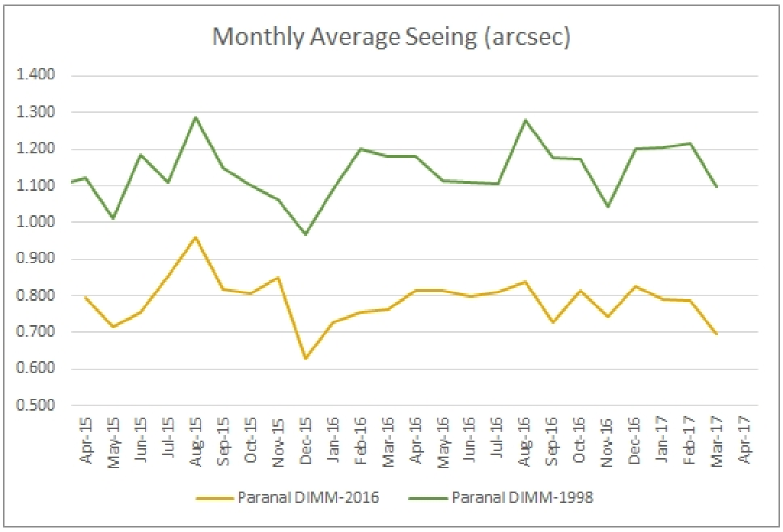



**Figure 8: Monthly average seeing measured by DIMM-1998 and DIMM-2016 during the acceptance phase**

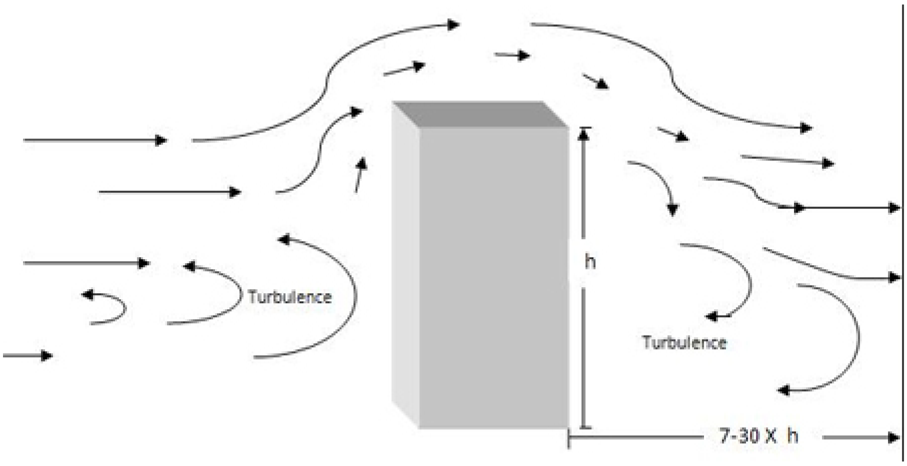
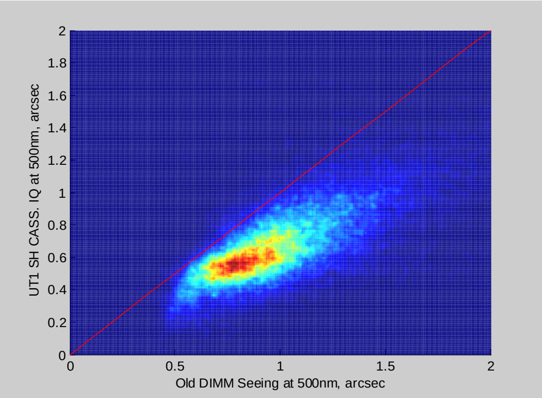



**Figure 9: Flow over a building, a DIMM placed in the recirculation area upwind (left) sees additional turbulence**

The DIMM seeing was compared to the FWHM-LIN-OBS computed by the VLT software from the average FWHM of the spots in the active optics Shack-Hartmann (S-H) images of UT1 Cassegrain focus, which is equipped with an atmospheric dispersion compensator. The S-H images have a combined central wavelength of about 700nm (dichroic + CCD + guide star colour) and the exposure time is on average 20s. The diffraction of a 360mm diameter aperture (diameter of the S-H lenslets projected on to the UT pupil) at this wavelength is quadratically removed from the FWHM measured in the line of sight. Then the value is corrected for zenith and at 500nm to be compared to the DIMM seeing (Figure 10).

A more elaborate processing could be implemented by taking into account the finite outer scale of the turbulence as well as the under-sampling due to the finite (0.3") pixel size of the S-H TCCD camera. It appears that these two effects tend to compensate one-another, but little is known about the exact value of the outer scale of the turbulence at the time the exposure was taken.



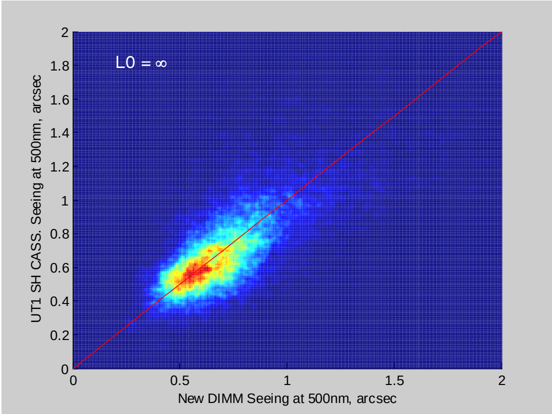




**Figure 10: Comparison of the seeing delivered by DIMM-1998 (left) and DIMM-2016 (right) to the FWHM of active optics spots of UT1 Cassegrain in Jan-December 2015 after removing diffraction. No correction for finite outer scale, nor for TCCD under-sampling were implemented.**

| | 10% | 25% | 50% | 75% | 90% | samples |
|---|---|---|---|---|---|---|
| DIMM-2016 seeing | 0.47 | 0.56 | 0.69 | 0.85 | 1.07 | 17772 |
| SH-FWHM@500nm, zenith diffraction removed | 0.45 | 0.55 | 0.68 | 0.89 | 1.11 | 17772 |
| SH-FWHM @500nm, zenith diffraction removed | 0.44 | 0.53 | 0.66 | 0.86 | 1.01 | 38554 |
| DIMM-1998 seeing | 0.67 | 0.80 | 0.99 | 1.25 | 1.54 | 38554 |

**Table 4: Statistics for the plots of Figure 10. Note that the number of common samples is different in each case.**

The finite outer scale correction $\varepsilon_{VK}/\varepsilon_{Kolmo}$ is computed in the line of sight, after correction for diffraction and under-sampling, using the following formulae (A. Tokovinin modified by J. Kolb for smaller pupils).

$$\varepsilon_{VK} = \varepsilon_{Kolmo} \sqrt{1 + \left( \frac{1}{1 + 300 \times D/L_0} - 1 \right) \times 2.183 \times \left( \frac{r_0}{L_0} \right)^{0.356}}$$

The results on Figure 11 were obtained taking a median outer scale $L_0$ of 30m, a pupil $D =$ 0.36m and assuming that the detector under-sampling has the effect of a quadratic addition of 0.75 times the pixel angular size to the FWHM. This tends to show that DIMM-2016 could be slightly optimistic compared to actual conditions inside an UT.

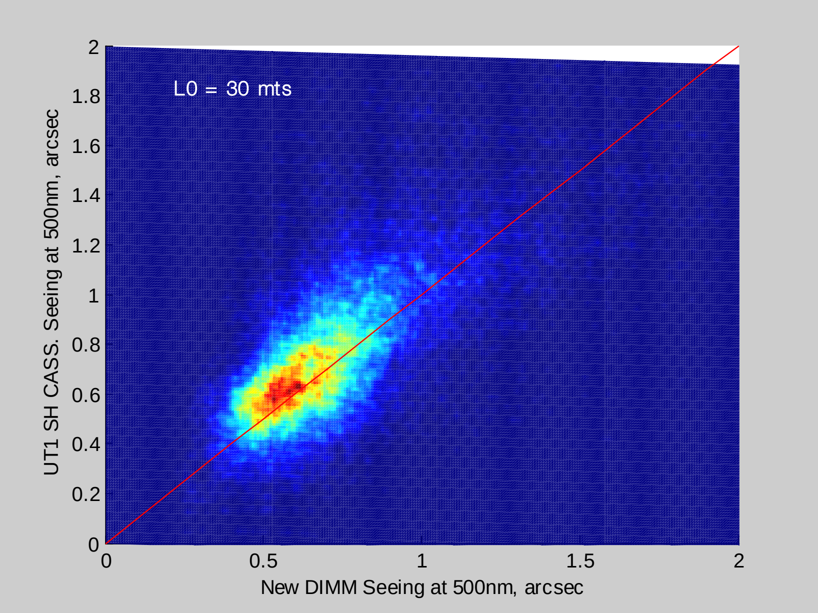



**Figure 11: Comparison of the seeing delivered by DIMM-2016 to the FWHM of active optics spots of UT1 Cassegrain in Jan-December 2015 after removing diffraction, correcting for finite outer scale and for TCCD under-sampling.**

| | 10% | 25% | 50% | 75% | 90% | samples |
|---|---|---|---|---|---|---|
| SH-FWHM @500nm, zenith diffraction removed, corrected for L0 and under-sampling | 0.49 | 0.60 | 0.76 | 0.99 | 1.24 | 17767 |
| DIMM-2016 Seeing | 0.47 | 0.56 | 0.69 | 0.85 | 1.07 | 17767 |

**Table 5: Statistics for the plots of Figure 11**

# 12.3 Observatory Coherence time

## 12.3.1 Comparison to NAOS

An on-line estimation of turbulence parameters is available as a dedicated tool implemented in the real time computer of the NAOS system. To compute atmospheric parameters in closed loop, pseudo open loop slopes are computed by adding the residual SHWFS slopes to the mirror command slopes. The turbulence parameters ($r_0$ and $L_0$) are retrieved from the fit of the variances of the theoretical Zernike coefficients to the variances over time of the estimated Zernike coefficients. The wind speed estimation is derived from the Zernike coefficient temporal autocorrelation. 1/*e* width ($\tau_i$) is computed for each Zernike autocorrelation function. For each radial order (*n*) an average $\tau_n$, of $\tau_i$ is obtained. From $\tau_n$ a temporal cut-off frequency $f_n$ is estimated and using Taylor hypothesis an average wind is obtained using all the $f_n$ values:

$$\overline{V}_{NAOS} = \left( \frac{1.15\pi D \sum (n+1)\tau_n^{-1}}{0.3\sum (n+1)^2} \right)$$

The NAOS database at Paranal was filtered according to (N. Ageorge et al, Symposium on Seeing, Kona 2007) so as to keep only the instrument modes which are less contaminated by instrumental noise: modes 1-1 to 1-9 (except 1-7) & 2-1 to 2-3 were used and the total integration time >12s.

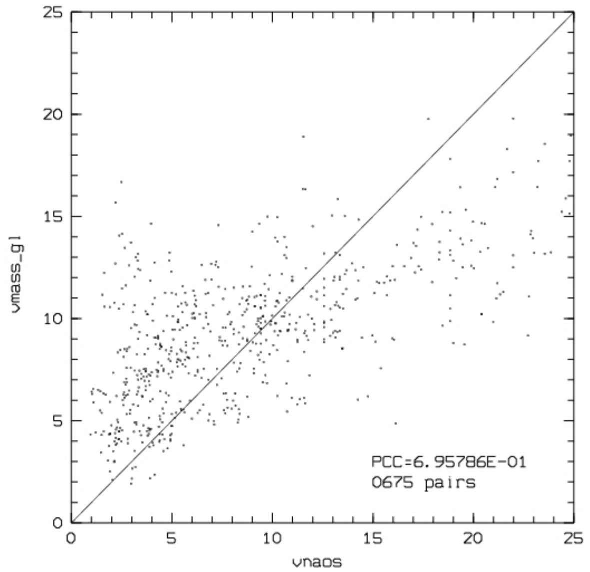



**Figure 12: Comparison of simultaneous measurements of wavefront velocity at Paranal by NAOS (x axis) and by MASS-DIMM (y axis) in 2005-2008. Pearson's correlation coefficient=0.69**

### 12.3.2 Comparison to SPHERE

Adaptive Optics Systems V. Proceedings of the SPIE, 9909-122 (2016)

**Analysis and comparison of the atmospheric parameters retrieved from an Ex-AO instrument with the astroclimatic monitoring system.**

Juan Carlos Guerra, Julio Navarete, J.Valenzuela, J-F.Sauvage, T.Fusco, K.Dohlen

Abstract. Paranal Observatory has a set of astroclimate monitoring instruments; such as DIMM, MASS-DIMM and SLODAR which are delivering information about the sky quality in terms of; seeing, coherence time, high altitude wind speed (200mb) and Cn2 profiles to support the observations. SPHERE instrument is an Extreme Adaptive Optics that uses a Shack-Hartmann wavefront sensor running at close loop frequency of 1.3KHz. The instrument saves close loop snapshot every minute and from the data saved the system retrieves the r0 and the cross wind speed. The wind speed is calculated using a cross-correlation based on the peak identification. The knowledge of this parameter is essential to understand the performances of the AO system, and to optimize its control laws every minutes. The data from the astroclimatic system monitor will help to correlate the turbulence events with the transverse wind speed retrieved from SPHERE close loop data. The goal of this work is also to compare the different atmospheric monitors with the effective turbulence estimation from the focal plane itself (Differential Tip-Tilt Sensor).

## 12.4 Observatory Ground Layer Turbulence Fraction

One of the main reason of including SLODAR into the ASM was to fulfil the AOF requirement to monitor the fraction of the turbulence within the first 300m (resp. 500m) above a UT. While nothing was changed in the SLODAR hardware and control software architecture compared to the instrument accepted in April 2014, another layer had to be added to the data processing pipeline to achieve this goal. An analytic profile is fitted for each new SLODAR measurement to the 8 SLODAR layers, as described in [RD1]. The integrated turbulence from the UT height (taken arbitrarily as 10m above ground, to be adjusted when AOF measurements are available) to the top of the AOF correction range (300m, resp. 500m) is compared to the total Cn2 above a UT which includes the “unsensed” turbulence above the maximum range of the SLODAR. The GL turbulence fractions are only available when the SLODAR maximum range is larger than 300m (resp. 500m).

The verification of the SLODAR fitting algorithm is made by comparison to DIMM: the SLODAR seeing integrated from DIMM height (7m) upwards is compared to the DIMM seeing on Figure 13, showing the good agreement of the two instruments. The large scatter is mainly due to the subtraction of the strong and variable first SLODAR layer close to the ground, and secondly to the different observing lines of sight.

It is tempting to compare the ground layer fractions delivered by SLODAR to the GL fraction one can compute from MASS and DIMM. The latter has no well-defined lower boarder because the sensitivity of MASS first layer ramps up linearly from null at 250m to 1 at 500m above ground. However, one would expect comparable values (with high scatter) delivered by the two instruments, while SLODAR GL fraction (300m) is very often 30% lower than MASS-DIM GL fraction as shown on Figure 14. Further analysis by Durham shows that the discrepancy occurs mainly when the high altitude turbulence (MASS layer 6) dominates. It is expected that a comparison of MASS and SLODAR profiles to the profiles to be delivered by the Stereo-SCIDAR recently installed at an AT focus will allow to determine the cause of the discrepancy.

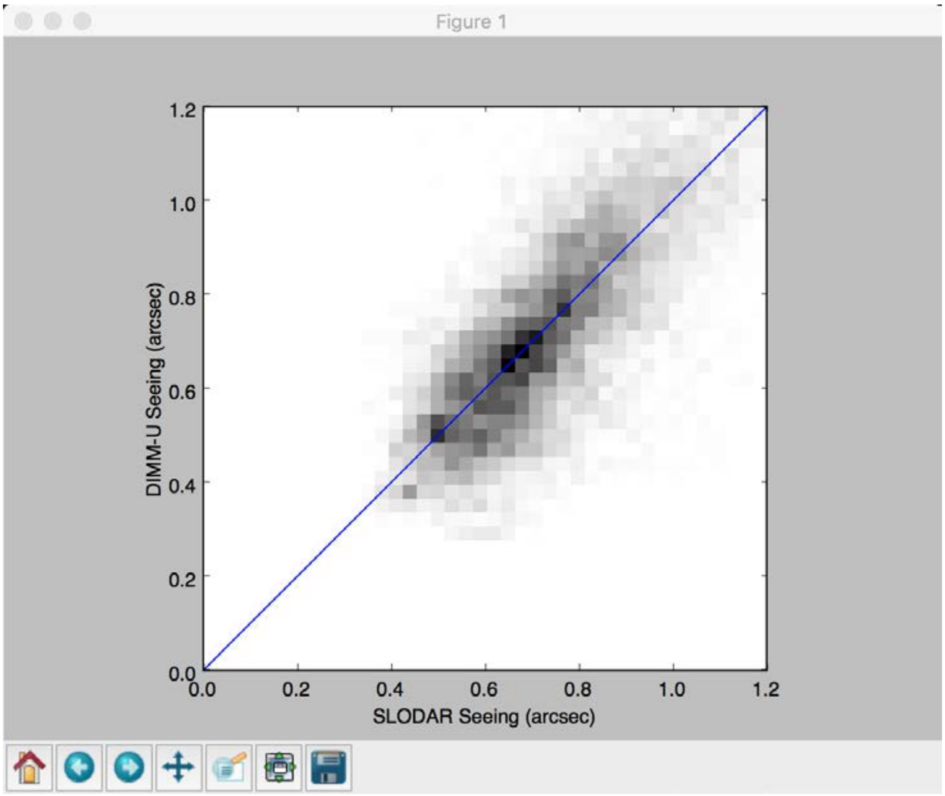



**Figure 13: Comparison of SLODAR and DIMM seeing for Paranal data from October 2015 through Jan 2016 ((SLODAR minimum altitude adjusted to the height of DIMM)**

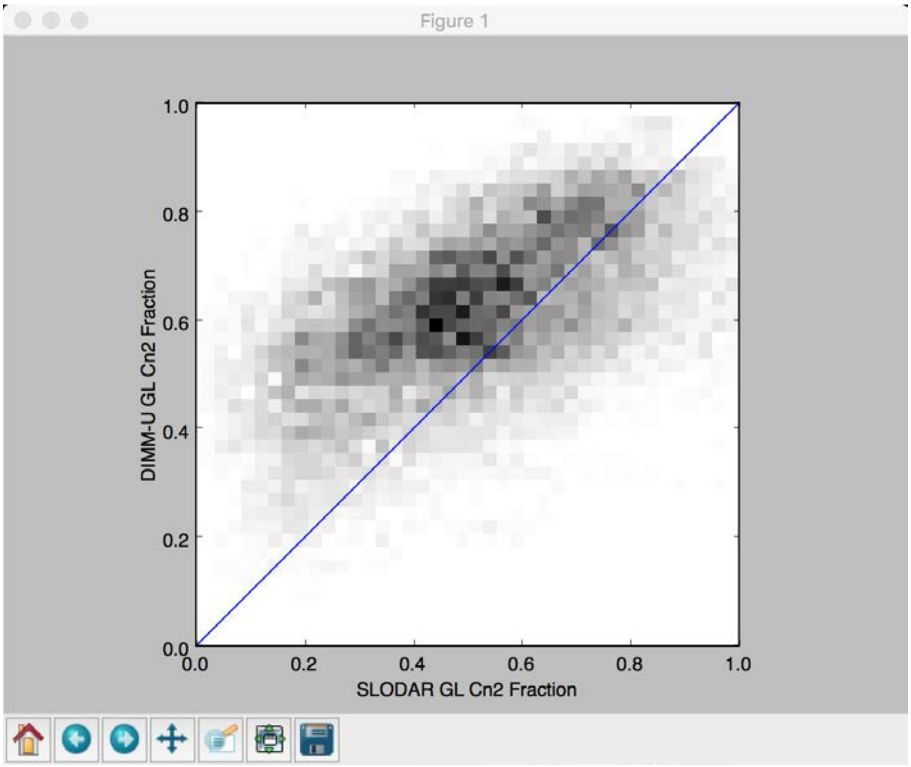



**Figure 14: Ground layer as fractions of the total integrated Cn2, DIMM-MASS versus SLODAR integrated from height of DIMM tower**

## 12.5 Observatory Precipitable Water Vapor (LHATPRO)

### 12.5.1 MNRAS **439,** 247–255 (2014) doi:10.1093/mnras/stt2404

## An episode of extremely low precipitable water vapour over Paranal observatory

F. Kerber et al

**ABSTRACT**

We report on an episode of extremely low precipitable water vapour (PWV) of approximately 0.1mm with a duration of more than 12h at the European Southern Observatory's Paranal observatory [2635m above sea level (asl)]. Such conditions are more commonly expected at sites at much higher altitude such as ALMA on the Chajnantor plateau (5000m asl) or otherwise particularly dry sites such as locations in Antarctica. We provide a full account of the measurements of PWV and other relevant atmospheric parameters. An explanation of the observed conditions is given in terms of the prevailing meteorological pattern. Based on statistical evidence from measurements by VLT spectrographs (UVES and CRIRES) covering more than a decade, we find that PWV <0.2mm can be expected on less than 1 per cent of the nights, while <0.5mm is encountered on 6–7 nights per year (≈2 per cent). The scientific potential of using this small but significant fraction of observing time is illustrated in the context of service mode observing.

### 12.5.2 Ground-based and Airborne Instrumentation for Astronomy IV. Proceedings of the SPIE, Volume 8446, article id. 84463N, 12 pp. (2012)

## A Water Vapour Monitor at Paranal Observatory

F. Kerber et al

**ABSTRACT**
We present the performance characteristics of a water vapour monitor that has been permanently deployed at ESO's Paranal observatory as a part of the VISIR upgrade project. After a careful analysis of the requirements and an open call for tender, the Low Humidity and Temperature Profiling microwave radiometer (LHATPRO), manufactured by Radiometer Physics GmbH (RPG), has been selected. The unit measures several channels across the strong water vapour emission line at 183 GHz, necessary for resolving the low levels of precipitable water vapour (PWV) that are prevalent on Paranal (median ~2.5 mm). The unit comprises the above humidity profiler (183-191 GHz), a temperature profiler (51-58 GHz), and an infrared radiometer (~10 μm) for cloud detection. The instrument has been commissioned during a 2.5 week period in Oct/Nov 2011, by comparing its measurements of PWV and atmospheric profiles with the ones obtained by 22 radiosonde balloons. In parallel an IR radiometer (Univ. Lethbridge) has been operated, and various observations with ESO facility spectrographs have been taken. The RPG radiometer has been validated across the range 0.5 – 9 mm demonstrating an accuracy of better than 0.1 mm. The saturation limit of the radiometer is about 20 mm. Currently, the radiometer is being integrated into the Paranal infrastructure to serve as a high time-resolution monitor in support of VLT science operations. The water vapour radiometer's ability to provide high precision, high time resolution information on this important aspect of the atmosphere will be most useful for conducting

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