Turbulence characterization at the Nasmyth focal plane of the VLT Melipal

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ABSTRACT

The Multi-conjugate Adaptive optics Demonstrator (MAD) has been developed by ESO, and installed at the Nasmyth focal plane of the Very Large Telescope Melipal at Cerro Paranal in Chile. Thanks to the multi-dimensional sensing and correction of MAD, the measurements recorded while the system is performing MCAO can be analyzed to retrieve the instantaneous characteristics of the turbulence seen from the focal plane of the telescope: seeing and turbulence profile. In this paper those measurements will be compared to the ones given by other tools at disposition at the focal plane: the guide probe and the active optics sensor, and at another location on the Paranal platform: DIMM and MASS.

Keywords: Seeing, Turbulence profile, Paranal, MCAO

1. INTRODUCTION

Seeing monitoring on a site like Paranal is a very important activity to know in real time what the conditions of observation are. It also allows on the longer term drawing statistics on the atmospheric conditions above the observatory, and predicting, to a limited extend, what the general conditions are going to be the next night as a function of some parameters.

Knowing the characteristics of the turbulence above Paranal is also critical to design and operate the Adaptive Optics (AO) instruments that are mounted on the telescopes. In addition to the integrated seeing that has now been measured for decades, the profile of the turbulence has also become of great interest in the past years, with the development of new instruments and the organization of observation campaigns to determine the repartition of the turbulent layers, its evolution with time, and the correlation with the integrated seeing. The knowledge of the turbulence profile is vital in particular to the future AO instruments that make use of tomography, i.e. correct the turbulence in selected layers. It is the case of the Multi-conjugate Adaptive optics Demonstrator (MAD) [1], the future Ground Layer AO (GLAO) modules GRAAL and GALACSI for the AO Facility [2], and the instrument concepts that are being developed for the E-ELT [3][4][5][6].

In order to understand better the evolution of the seeing at Paranal over the years, turbulence profiling has been coordinated with years of image quality data and with meteorological conditions [7], and part of the result is that the turbulence monitors at Paranal, located below the UT primary mirror level and outside of its enclosure, overestimate the integrated seeing value, and in particular see a Surface turbulent layer party hidden to the telescopes. This conclusion pushed us towards making direct comparison of seeing and turbulence profile measurements between instruments located on the Paranal plateform and one located at the Nasmyth focal plane of the UT itself.

The section 2 of this paper describes the different sources for turbulence measurement that we have used and how the data is reduced. We took the opportunity to have the MAD instrument during a campaign of Science Demonstration in November 2007 to record real-time data in AO closed loop, which are described together with their analysis in the section 3. Finally the section 4 gives some examples of comparison between all measurements before we conclude and present future work that will be done on the subject.

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2. TURBULENCE MONITORS AT PARANAL

2.1 DIMM

The Differential Image Motion Monitor (DIMM) started its observations in Paranal in 1988. It measures wavefront slope differences over two small pupils some distance apart, caused by the atmospheric turbulence [8]. This measurement of distortion is then converted into an estimate of the image size (seeing FWHM) it would correspond to on a large telescope, using the Kolmogorov-Fried model.

It was the main element of the instrument package developed for the VLT site evaluation campaign. It uses a 35 cm diameter telescope in the open air on a 6 m high tower. The DIMM makes an estimation of the seeing in its line of sight at a frequency of about 1 measurement per minute, which is then scaled to a wavelength of 500 nm and to an airmass of 1 in order to provide the user with the seeing value at zenith. The values can be retrieved from the ESO Observatories Ambient Conditions Database [9].

The main advantages of this measurement for our study is that it is independent of tracking errors being a differential measurement, and that it is not sensitive to the outer scale of turbulence. Some drawbacks are that the DIMM is located outside of the VLT enclosure, at a lower height, and that it doesn't point in the same direction. An example of DIMM measurement over a night can be seen on Figure 1.

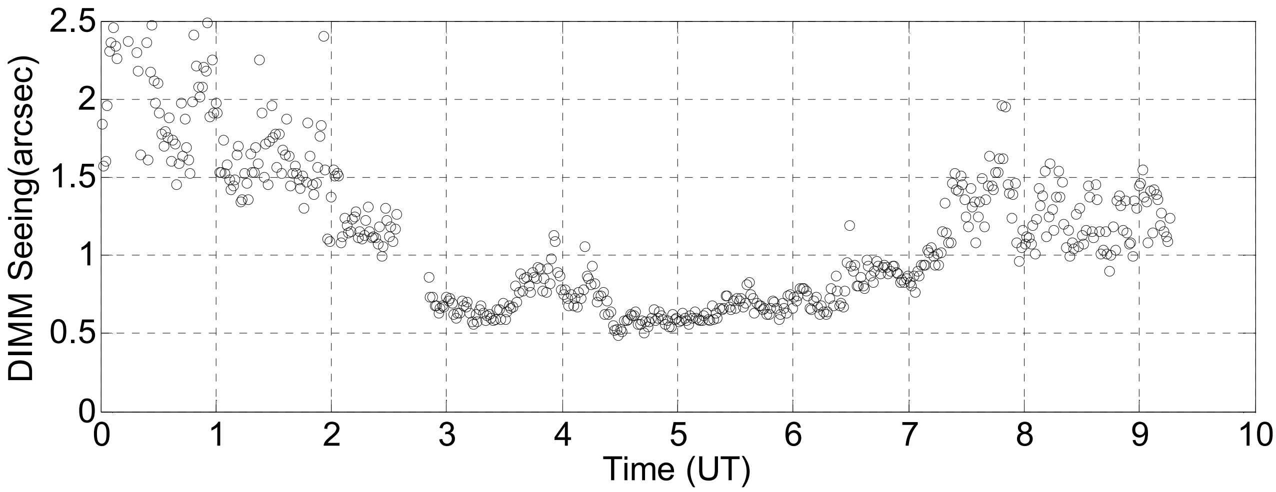

Figure 1 Evolution of the seeing measured by the DIMM during the night of the 29/11/07

2.2 VLT guide probe

The VLT focal planes are equipped with an arm used for acquisition of a Natural Guide Star. The light from this star is then split between a guide probe for an accurate tracking of the sky, and a Shack-Hartmann Wavefront Sensor (SHWFS) used to control the active optics that shapes the primary mirror.

The guide probe makes an image of the selected star on a technical CCD with a plate scale of 0.18 arcseconds per pixel, and the active re-centering of this image is done by telescope tracking compensation at a frequency from 5 to 50 Hz, depending on the magnitude of the guide star. The FWHM of this image (in two fixed orthogonal axes X and Y) can be saved at about 1 Hz thanks to the VLT sampling tool and retrieved at the end of the night. Those values can also be an indication of the seeing, but several facts have to be taken into consideration to convert the FWHM into a seeing value that can be compared to the DIMM one:

- The measurement of the FWHM is too fast to average the turbulence. This averaging is done on the measured data over periods of 30 seconds. Even by doing this, one cannot correct the fact that the guide probe images are residuals of the tip-tilt correction which is the tracking. The tracking corrects for the slow tip-tilt variations in the atmosphere, so using the FWHM of the residual image might lead to a slight underestimation of the seeing.

An opposite effect comes from the automatic routine that computes the FHWM of the spots and that is known to be overestimating this value.

- For telescope apertures that are not much smaller that the outer scale, it has been shown that this one has the effect of reducing the FWHM of long-exposure images [10]. An approximation of the analytical law that links the FWHM and the seeing with a finite outer scale (Van Karman law) is [11]:

$$\left(\frac{\varepsilon_{VK}}{\varepsilon_{Kolmo}}\right)^2 \approx 1 - 2.183 \times \left(\frac{r_0}{L_0}\right)^{0.356}$$

where ε_{VK} is the FWHM of the spot, ε_{Kolmo} the seeing, r_0 the Fried parameter of the turbulence and L_0 the outer scale. The seeing and r_0 are in addition linked through:

$$\varepsilon_{Kolmo} = 0.9759 \times \frac{\lambda}{r_0}$$

The effect of the outer scale on the difference between seeing and spot size is illustrated on Figure 2. If we choose for the outer scale the value L_0 = 22 m (measured median at Paranal [12]) and combined the two previous equations, we come to the following approximation, valid at 650 nm (central sensing wavelength of the guide probe) and for seeing values between 0.5 and 2 arcsec:

$$\text{seeing}('') \approx 1.12 \times \text{FWHM}('') + 0.09$$

- The central wavelength of the guide probe path is 650 nm, so one has to scale the seeing to 500 nm with a law in $\lambda^{-1/5}$
- Finally the estimated seeing value has to be reported from the observation angle to the zenith (airmass AM = 1):

$$\text{seeing(zenith)} = \frac{\text{seeing(AM)}}{\text{AM}^{3/5}}$$

Figure 3 shows how those scaling modify the measured FWHM in order to reach an estimated seeing value comparable to the one provided by the DIMM.

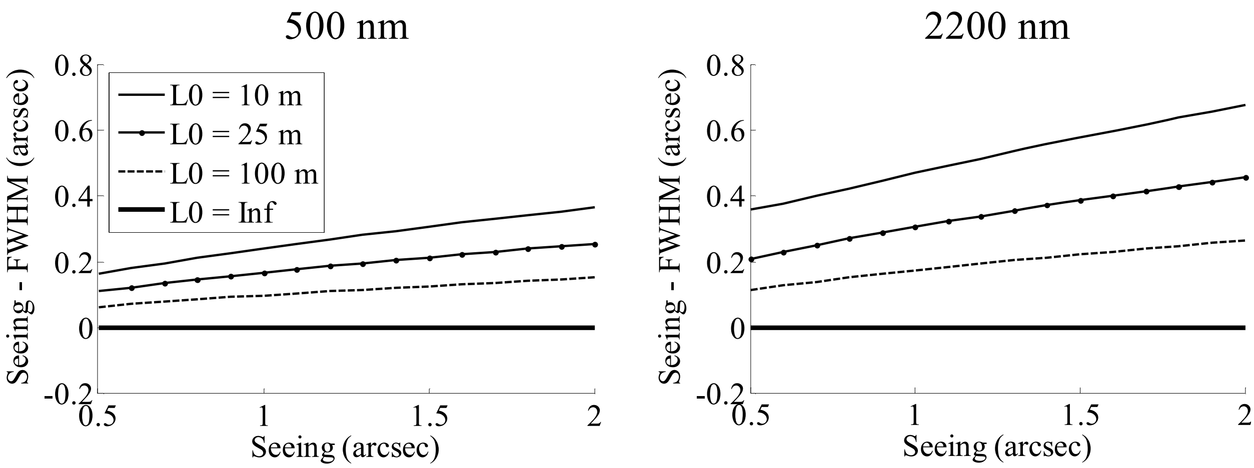

Figure 2 Effect of the outer scale on the spot size reduction. Spot size reduction vs. seeing and outer scale at 500 nm (left) and 2200 nm (right)

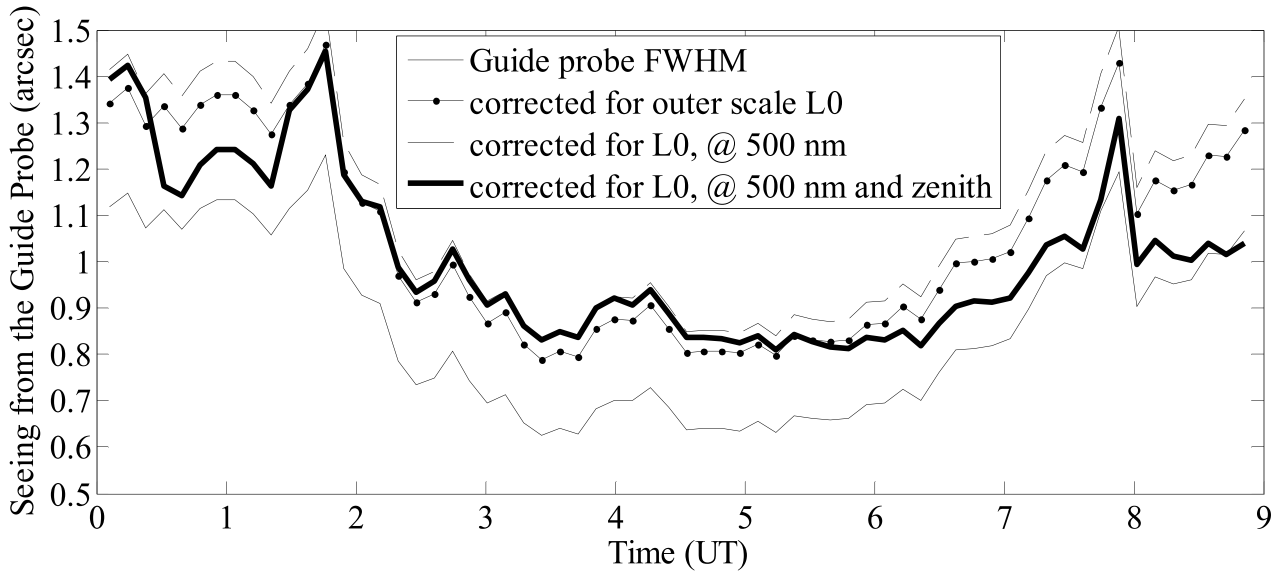

Figure 3 Evolution of the seeing estimated by the Guide Probe during the night of the 29/11/07. In order to have an estimation of the seeing (thick solid line), the measured FWHM (thin solid line) has to be corrected for the effect of the outer scale (increase of ~0.3"), the wavelength (increase of <0.1") and the observation angle (decrease as function of the airmass).

2.3 VLT active optics Shack-Hartmann Wavefront Sensors

As described before, the VLT focal planes are equipped with SHWFSs used to control the active optics that shapes the primary mirror. They sense the WF at a central wavelength of 550 nm thanks to 20x20 sub-apertures, with an integration time between 10 and 45 s. The SHWFS images are not automatically saved but some diagnostic on those images are in the Paranal Automatic Report sever, such as the FWHM of the spots, which is a direct estimation of the seeing [13], this one independent of the outer scale because of the small sub-apertures size. There are however some limitations to the use of this seeing estimator:

- We have only access to the spots FWHM. The different steps of the images reduction are a selection of the useful sub-apertures (fully illuminated and answering to a quality criterion), a Gaussian fit of the spots and a FWHM averaging
- The sampling of the detector (0.26 arcsec/pixel), sufficient for the active optics functions, is rather poor for FWHM estimations
- Only the VLT Cassegrain focus is equipped with an ADC, so the Nasmyth focus images can suffer from a spot elongation at high observation angle, which is not taken into account in the algorithm
- Aberrations of the lenslet array tend to increase artificially the spot size. When those aberrations are known (as for the VLT Cassegrain focii), they can be compensated for (as it is done in [13]
- The central wavelength of the SHWFS path is 550 nm, so one has to scale the seeing to 500 nm with a law in $\lambda^{-1/5}$
- Finally the estimated seeing value has to be reported from the observation angle to the zenith with a law in $AM^{3/5}$ (see §2.2)

The limitations listed above, especially at the Nasmyth focal plane, make the SHWFS spots FWHM an uncertain estimator of the seeing. We will however show its evolution along the other estimators and see that its values are often not so far out. As an example, Figure 4 shows the comparison between the seeing estimated by the Guide Probe and the one from the SHWFS data during one night. Both show very similar evolution, even at high airmass.

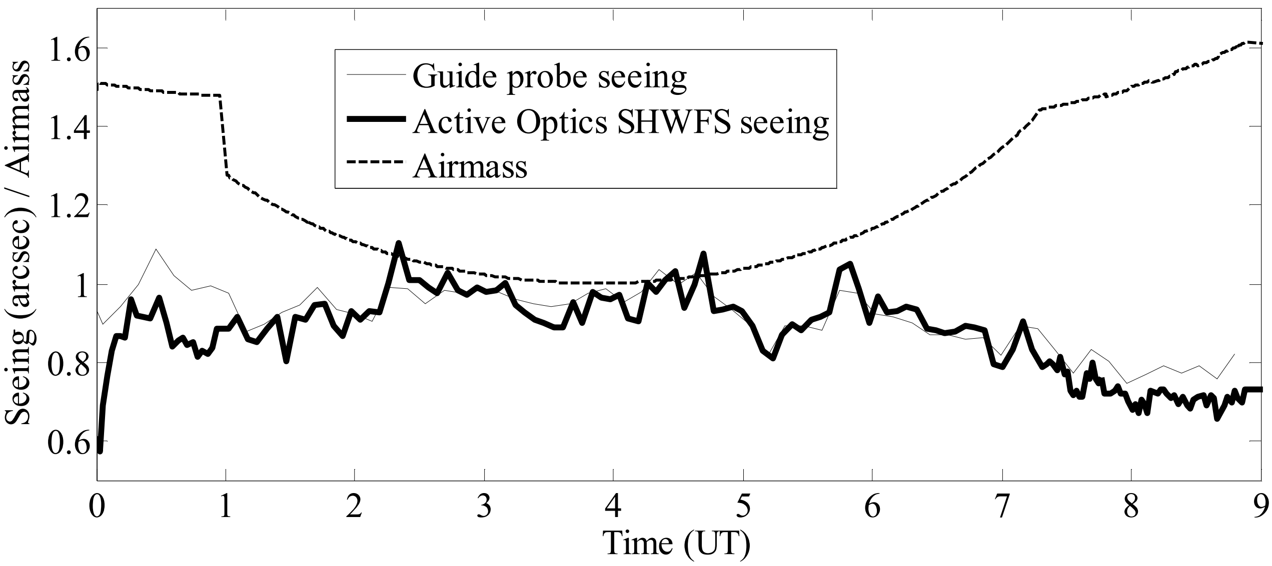

Figure 4 Evolution of the seeing estimated by the Guide Probe and the Active Optics SHWFS during the night of the 27/11/07. The airmass in the line of sight is also shown in order to point an eventual affect on the seeing estimation using SHWFS data. We only notice a slight under-estimation at high airmass.

2.4 MASS

The Multi-Aperture Scintillation Sensor (MASS) has observed in Paranal between 2004 and June 2007. For the present study we have been using data from another MASS that was being commissioned at Paranal. The MASS 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 photomultipliers [14]. A statistical analysis of these signals yields information of the vertical profile of the turbulence $Cn^2(h)$. It gives the $Cn^2(h)$ for 6 layers placed at h=0.5, 1, 2, 4, 8 and 16 km above the telescope pupil. The combination of a DIMM and a MASS gives the possibility to measure both seeing and low-resolution turbulence profiles with a temporal resolution of about 1 minute. If the total seeing above and including the layer h is seeing(≥h), we can compute the ratio of turbulence present in the upper layers:

$$\mathrm{Alt}_{\mathrm{ratio}}(\geq \mathrm{h}) = \left(\frac{\mathrm{seeing}(\geq \mathrm{h})}{\mathrm{seeing(tot)}} \right)^{5/3}$$

where seeing(tot) is given by the DIMM. When this number gets to 0, it means that most of the turbulence is close to the ground, and when it gets to 1, it means that most of the turbulence is in altitude. For this simple study, we chose to use as an indicator of the location of the turbulence the ratio of it above 2 km: $\mathrm{Alt}_{\mathrm{ratio}}(\geq 2\mathrm{km})$. This choice is driven by the fact that the MAD Deformable Mirrors (DM) are conjugated to 0 and 8.5 km, thus we can give as a rule of thumb that the first one corrects for the turbulence in the first km, and the second one for the rest.

The Figure 6 shows the evolution of the ratio of altitude turbulence during a night, and more detail on the comparison with MAD data is given in the §3.3.

2.5 Wind direction and speed

It has been shown [13] that the wind direction and strength can affect the seeing quality. Monitoring those parameters and correlating them with the seeing estimations is important in the process of understanding seeing evolution during one night, and eventual discrepancies between measurements performed at the VLT focal plane and on the DIMM tower.

Figure 5 shows how the DIMM and guide probe seeing evolved during one night at Paranal. We see that although the wind direction remained NE-NNE the whole night, its speed went from 4 to 11 m/s, causing a burst of the DIMM seeing for values above 8 m/s, which is not seen on the seeing measured at the VLT focal plane. This shows that a stronger wind can increase the overall turbulence (the guide probe does see an increase during the night), but this one especially occurs in the surface layer of the atmosphere, particularly between 6 and 12m altitude, i.e. between the DIMM altitude and the VLT one. This observation during one night is in line with the conclusions presented in [13].

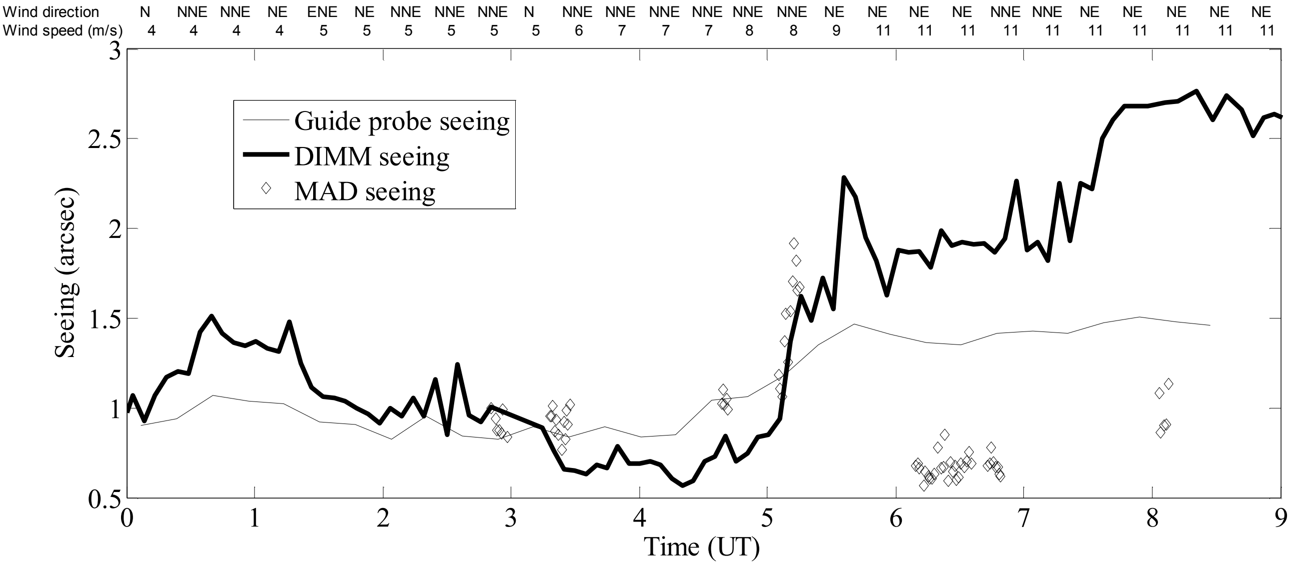

Figure 5 Evolution of the DIMM and guide probe seeing during the night of the 24/11/07, together with wind speed and direction (top of the frame). In this case stronger wind degrades the seeing, especially in the surface layer which is more visible with the DIMM than with the VLT. Measurements of the seeing thanks to MAD are also displayed (see §3.2), and they are consistent with the other ones when the seeing is not too bad (good AO correction).

3. MAD AS SEEING MONITOR AND TURBULENCE PROFILER

3.1 Instrument and measurements description

Multi-Conjugate Adaptive Optics (MCAO) aims at performing wide field of view atmospheric turbulence correction using many Guide Stars (GSs) surrounding the observed target. The light coming from the GSs is analyzed through wave front sensors whose signals are used to reconstruct the atmospheric turbulence at the different heights which some deformable mirrors are conjugated to.

The European Southern Observatory in collaboration with external research institutes has built an instrument prototype, the MCAO demonstrator (MAD) [1], to prove on the sky the feasibility of the MCAO technique in the view of the future 2nd generation of the VLT instrumentation and the European Extremely Large Telescope (E-ELT). MAD has been installed at the VLT early in 2007 and performed on-sky test runs starting from March 2007. It was then used to perform Science Demonstration runs later in the same year.

MAD is equipped with three 8 x 8 SHWFS than can be deployed in the 2 arcmin FoV of the instrument, and the maximum loop speed of the instrument is 400Hz. During a scientific observation in MCAO closed loop, it is possible to record a real-time file containing the system measurements at 400Hz, i.e. residual slopes from the SHWFS and voltages applied to the DMs and Tip-Tilt Mount (TTM) on which is mounted the ground DM, and this for long periods of time (we choose to record 2000 measurements). Although MAD is a low order AO instrument, those data can be used to retrieve information about the atmospheric turbulence being corrected. Note that it is slightly more complex to analyze closed loop data than open loop data, but the former can be recorded without using observation time, and the WFSs behavior is linear only in closed loop. The operation that permits using the closed loop data is a simple projection of all the measurements into the same space, thanks to the interaction matrices (IM) of the system: (primary) IM between the SHWFS and the DMs, and secondary IM between the ground DM and the TTM.

3.2 Seeing determination

The MCAO capabilities of MAD are of no special use to make an estimation of the seeing (a simple AO loop on one star would suffice) so in the case of MAD we choose to project all measurements into the WFS space, and then to use the data of the WFS looking at the brightest star among the three. The detailed work performed on the data is then:

- Project the 2000 measurement into the WFS space:

  SH_data = SH_residuals + [DM_voltages + TTM_voltages x TTM2DM] x IM

  where IM is the (primary) interaction matrix and TTM2DM is the secondary IM
- Select the WFS data of the brightest star
- Project the slopes on the space of the Zernike polynomials, thanks to a projection matrix given by a SHWFS model
- Compute the variance of the Zernike polynomials over the 2000 measurements
- Fit the Zernike decomposition to a Kolmogorov spectrum on the high orders in order to get an r_0 value
- Convert r_0 into seeing (see §2.2), and correct it for the observation airmass

The Figure 5 shows how the seeing evolved during one night at Paranal, as measured by the DIMM, the guide probe, and MAD. When the measurement conditions are good, the 3 values agree very well. As explained in the §2.5, the DIMM sees more of the degrading surface layer when the wind gets stronger. We also notice that in that case, the quality of the measurements taken with MAD gets worse; this is due to less turbulence measured and a poorer correction, plus the eventual change to a fainter observation asterism. The resulting effect is that the seeing is strongly under-estimated.

3.3 Turbulence profiling

By its nature of AO instrument correcting the turbulence in different layers, MAD can be used to retrieve information on the location of the turbulence above the telescope. In the framework of this study we have decided to proceed with a simple analysis of the MAD data in order to obtain a crude turbulence profiling, but we plan in the near future to apply the SLODAR analysis techniques [15] to the MAD data in order to retrieve a profile of the turbulence with a resolution of about 2 km. The detailed work performed on the data is then:

- Project the 2000 measurement into the DM space:

  DM_data = DM_voltages + SH_residuals x CM + TTM_voltages x TTM2DM

  where CM is the control matrix of the system obtained after inversion of the IM
- Project the DM voltages on the influence functions of the mirrors (converting voltages to surface deformations)
- Compute the variance of the DM shape for each of the 2000 iterations.
- Average the 2000 variances for each DM
- Compute r_0 for each DM, the total r0, and the altitude turbulence ratio with the formula:

$$\mathrm{Alt}_{\mathrm{ratio}}(8.5\,\mathrm{km}) = \left(\frac{r_0(8.5\,\mathrm{km})}{r_0(\mathrm{tot})}\right)^{-5/3}$$

On Figure 6 one can see the study of the ratio of turbulence in the altitude layers during one night of observation. This night is the one among the whole Science Demonstration which contains the most simultaneous MASS and MAD measurements. We see that the MASS measurements oscillate around the median value of 0.13 while the MAD ones oscillate around 0.30. The bottom-left plot shows that there is a correlation between the measurements in spite of the offset. Possible error sources when doing this comparison are the actual definition of the estimated quantity (turbulence corrected at 8.5 km for MAD vs. turbulence above 2 km for MASS), an uncertainty in the knowledge of the influence functions of the DMs, and a bias in the repartition of the correction on the DMs due to AO loop properties. However, the difference could also confirm that the surface layer of the turbulence between the MASS and MAD heights is unseen by the latter. In conclusion, the MAD data could be used to get a rough profile of turbulence but this requires a more detailed analysis, less biased with error sources.

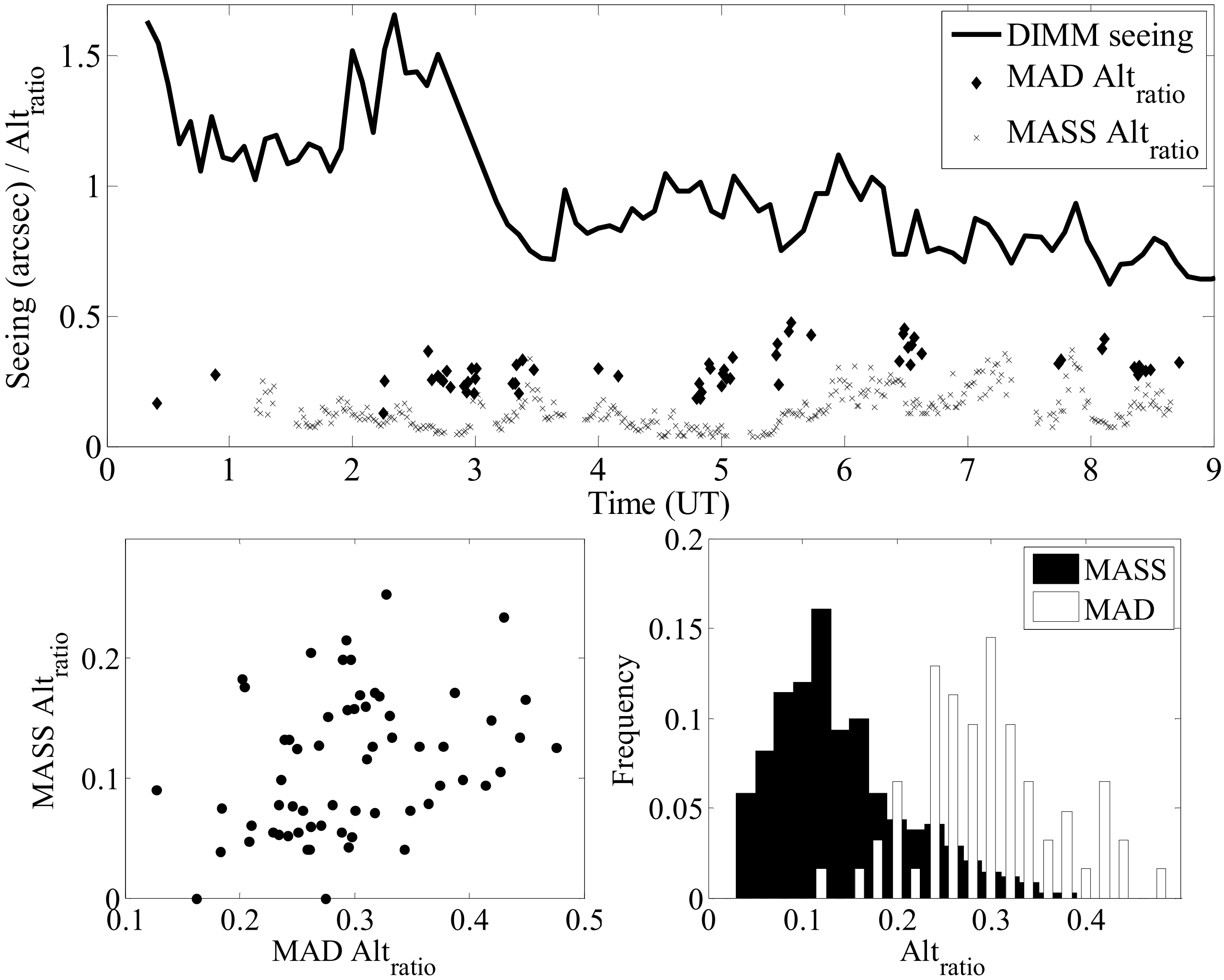

Figure 6 Turbulence profiling with the MASS and MAD. Top: Evolution of the DIMM seeing during the night of the 27/11/07, and ratio of turbulence in the altitude layers estimated by the MASS or MAD during the same night (0 means that all the turbulence is close to the ground, and 1 that all the turbulence is in altitude). Bottom-left: Correlation between the MASS and MAD measurements. Bottom-right: repartition of the measurements during that night.

4. EVOLUTION OF THE TURBULENCE OVER A NIGHT

In previous sections we have compared one by one several estimators of the turbulence strength and profile at Paranal (see Figure 4, Figure 5 and Figure 6). In this chapter we will give a comparison of all the different estimators during several sample nights, and analyze their correlation. The Figure 7 gives the legend for the following figures.

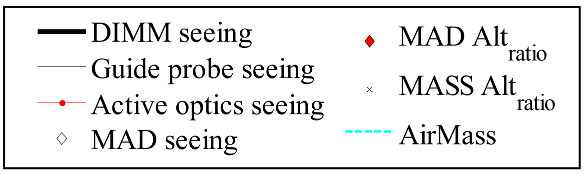

Figure 7 Legend for the figures of the chapter 4

4.1 Night of the 26/11/07

The Figure 8 summarizes the analysis of all the measurements taken on the night of the 26/11/07. The first conclusion is an excellent agreement between the guide probe and active optics seeing over the whole night (as already visible on the Figure 4). The agreement with the DIMM seeing is also remarkable, except between 2:30 and 4:30 UT. The MAD seeing is in line with the others, but seems very dependent on the AO loop conditions. Periods at which the telescope is observing through high airmass don't have an effect on the seeing estimations, which shows that the compensation is properly done. Finally although we don't have many simultaneous turbulence profile estimation, we see a steadily increasing contribution of the ground layer from MAD data, which is consistent at the end of the night with the same conclusion from MASS data, and which could be easily explained by the increasing wind speed over the whole night.

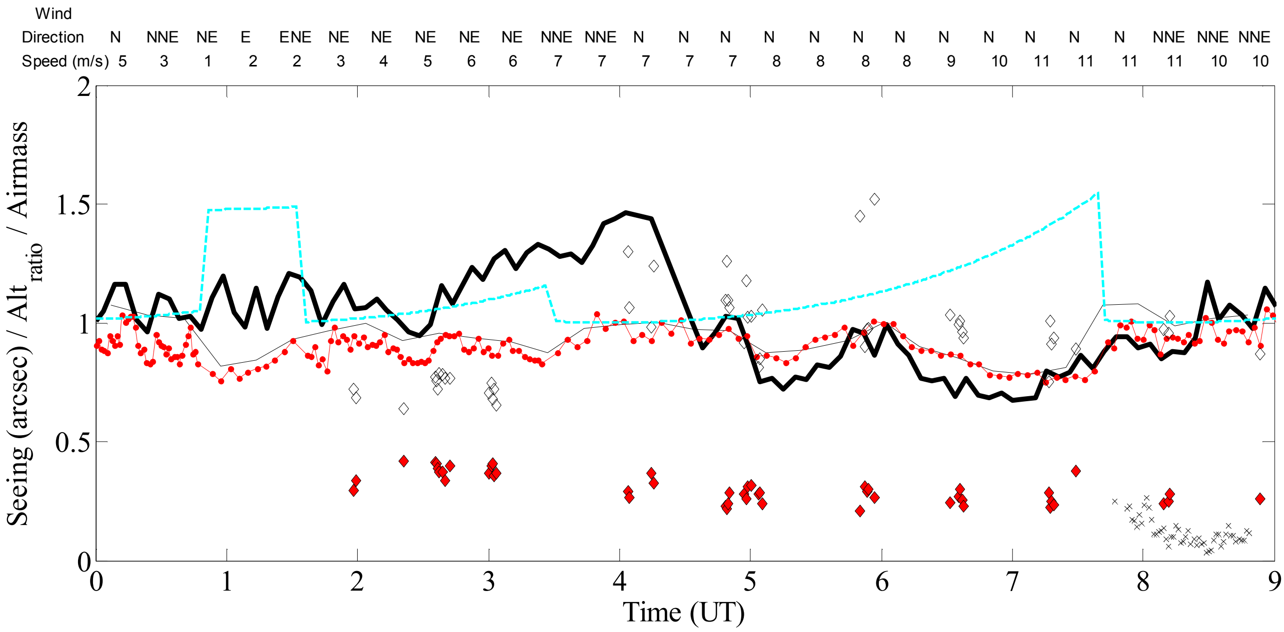

Figure 8 Evolution of the turbulence strength and profile over the night of the 26/11/07. The seeing values are in arcsec, the airmass above 1, and the Alt$_{ratio}$ between 0 meaning that all the turbulence is close to the ground, and 1 that all the turbulence is in altitude.

4.2 Night of the 30/11/07

The Figure 9 summarizes the analysis of all the measurements taken on the night of the 30/11/07. Once again the agreement between the guide probe and Active optics seeing is very good. The MAD seeing is in good agreement too. The DIMM seeing shows strong fluctuations between values similar to the other measurements and values up to 0.5 arcsec higher. Neither the wind direction nor speed can explain this behavior which might be due to occasional increase of the surface layer strength. MASS and MAD data suggest an increase of the altitude layers contribution over the whole night.

4.3 Night of the 25/11/07

The Figure 10 summarizes the analysis of all the measurements taken on the night of the 25/11/07, during which the observation conditions were more difficult than in the two cases presented above. On that day a constant strong wind (>10 m/s) blowing from inland (NNE) causes the DIMM seeing measurements to fluctuate a lot, and be constantly larger than the ones taken at the VLT focus (strong surface layer). The guide probe and active optics data are rather consistent, except between 4:00 and 6:30 UT when a combination of strong seeing and high airmass creates an underestimation of the active optics seeing. The MAD seeing is often underestimated because of a poor AO correction. The turbulence profiling from inside and outside the dome shows a constant strong ground layer.

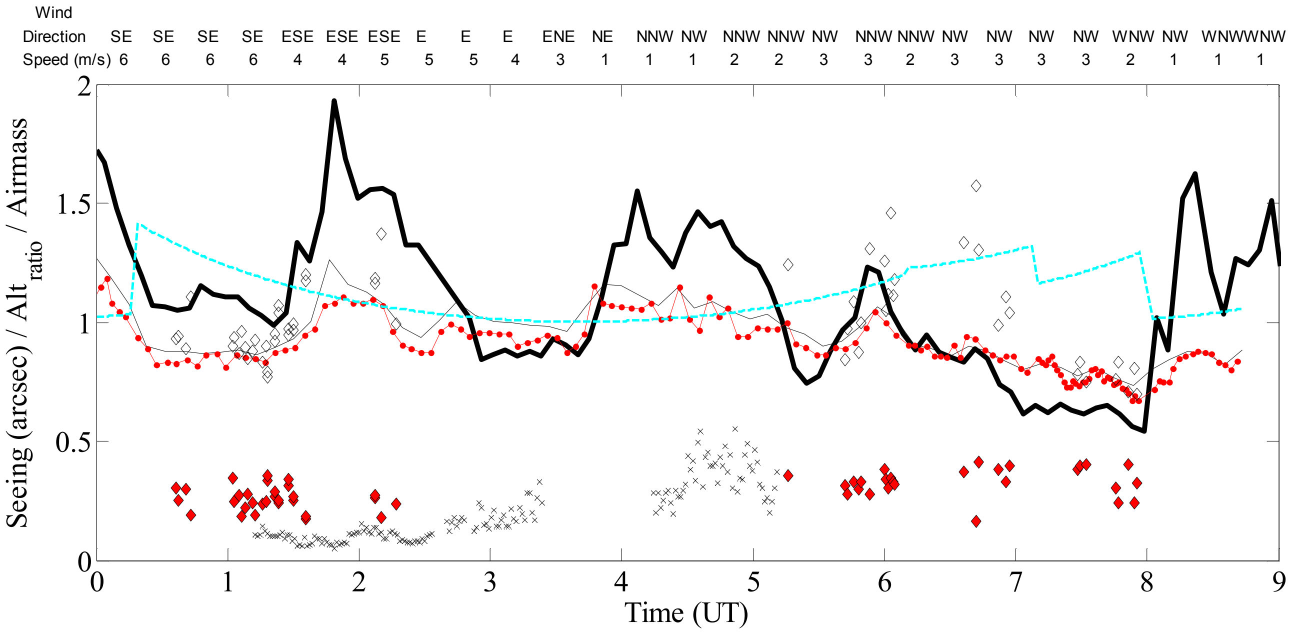

Figure 9 Evolution of the turbulence strength and profile over the night of the 30/11/07. The seeing values are in arcsec, the airmass above 1, and the Alt_{ratio} between 0 meaning that all the turbulence is close to the ground, and 1 that all the turbulence is in altitude.

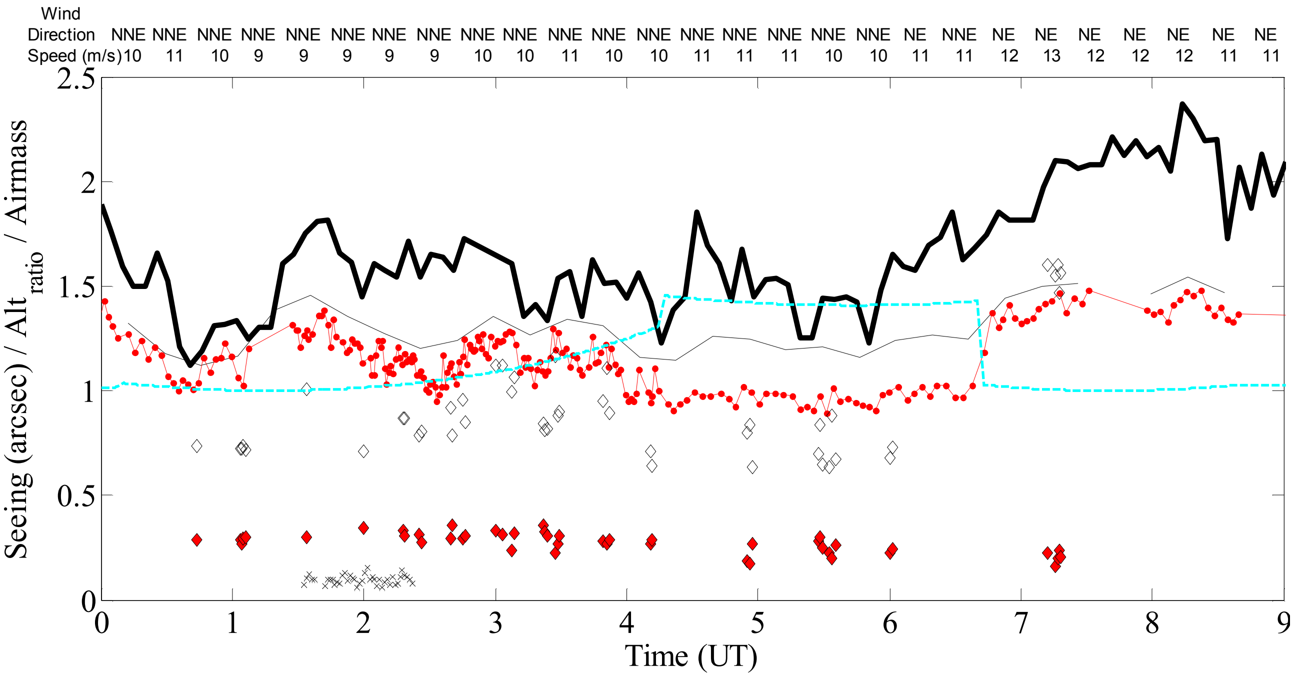

Figure 10 Evolution of the turbulence strength and profile over the night of the 25/11/07. The seeing values are in arcsec, the airmass above 1, and the Alt_{ratio} between 0 meaning that all the turbulence is close to the ground, and 1 that all the turbulence is in altitude.

5. CONCLUSIONS AND FUTURE WORK

The primary objective of the study presented in this paper was to make an analysis of a week of turbulence data recorded at Paranal using various instruments, located at the VLT focal plane and outside of its dome. This analysis would lead to a qualitative comparison of the various measurements, and possibly the understanding of the reason for discrepancies, although the limited amount of data doesn't allow building statistics. In order to make reliable comparisons, we had to analyze the measurements so as to convert them all into to the same parameters of the turbulence: its strength (given by the seeing at zenith and at 500 nm) and profile (given by the ratio of turbulence in the altitude layers).

In the end we have shown that the seeing measurements taken at the VLT focal plane through the guide probe, the active optics SHWFS, and MAD closed loop data are in good agreement (the latter being the less accurate). The three measurements being completely independent, it gives us good confidence in the quality of the data analysis performed.

On the other hand, the comparison with the DIMM seeing often shows a good correlation, within ±0.1 arcsec. When this is not the case, the DIMM values are larger than the ones at the VLT, which is often correlated with wind strengths and directions that are known to bring more turbulence, especially in the surface layer. This one is more seen by the DIMM located in the open air at 6 m height than by the VLT in its enclosure and above 12 m.

We have also tried to use available data to compare turbulence profiles from inside and outside the VLT enclosure. On the Paranal platform the MASS is providing a profile above 500 m, and at the VLT focus the MAD instrument in MCAO close loop provides information on the localization of the corrected turbulence. Unfortunately the first analysis of the MAD data doesn't allow drawing clear conclusions that would tell us how much of the surface layer turbulence is actually unseen by the VLT.

Plans for the future consist in a more detailed analysis of the existing MAD data, allowing building a real turbulence profile above the telescope. At the light of those results, another Science Demonstration run with MAD will be the opportunity to record more data. Finally we also plan to perform more statistical studies of turbulence seen from the VLT focus, a problem which is relevant in the framework of the design of the future AO systems for the VLT.

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