Combining turbulence profiles from MASS and SLODAR

A statistical study of the evolution of the seeing at Paranal

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Abstract. We have recombined turbulence profiles from MASS and SLODAR at Paranal Observatory using a new grid of atmospheric layers defined on the basis of the comparison between the MASS and SLODAR weighting functions. A statistical analysis of the relation between the total Paranal DIMM C_n^2, the ground layer C_n^2 and the free atmosphere C_n^2 is presented. Taking into account the height of the VLT Unit Telescopes we have recalculated the seeing skipping the atmosphere below that height, obtaining an estimation of the real turbulence affecting science at the Very Large Telescope and its evolution from January 2005 to June 2007.

1. Introduction

The present paper describes the implementation of a new technique applicable to simultaneous atmospheric turbulence profiles measurements from three different instruments: the Differential Image Motion Monitor (DIMM), the Multi-Aperture Scintillation Sensor (MASS) and the Slope Detection and Ranging instrument (SLODAR). This technique allows the restoration of unified profiles from the surface (or platform) of the observatory to the high atmosphere. The application of this technique to large database from ESO Paranal Observatory (Atacama Desert, northern Chile) gives a detailed statistics of the evolution of the turbulence and the seeing at Paranal. The main goal of this study is to understand the differences between the image quality of the Very Large Telescope (VLT) Unit Telescopes (UT) and the DIMM seeing.

2. DIMM, MASS and SLODAR at Paranal

The 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 (Sarazin&Roddier

1990). 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.
The MASS has observed in Paranal between 2004 and June 2007. It 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 (Kornilov et al. 2003). A statistical analysis of these signals yields information of the vertical profile of the turbulence $C_n^2(h)$ as a function of the altitude in the atmosphere h. It gives the $C_n^2(h)$ for 6 layers placed at 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.
The SLODAR instrument has operated in Paranal in 2005, 2006 and 2007. 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 (Butterley et al. 2006). It gives the $C_n^2(h)$ for 8 layers starting from the ground with a resolution that varies between ~50 and ~100 meters depending on the separation of the observed binary system and its zenithal distance.

3. Recombination of the profiles

We made use of long term recombined databases from Paranal DIMM, MASS and SLODAR in the period from January 2005 to June 2007 in order to study the evolution of both the turbulence profile and the seeing at Paranal Observatory.
MASS and SLODAR provide each minute simultaneous profiles of the atmospheric turbulence at different altitudes above the ground. In particular, the MASS senses the atmosphere between 0.5 and 16 km, what we define as *high atmosphere*. The SLODAR measures the turbulence between the ground and ~1 km, so it gives the C_n^2 of the *ground layer* (typically between 0 and ~400 m above the ground) plus several layers that overlap with the lower atmosphere measured by the MASS. The difference between the total C_n^2 sensed by the SLODAR and the sum of the $C_n^2(h)$ of the 8 layers is called *unsensed* C_n^2.
The two instruments use different weighting functions to calculate the integral of the turbulence in each layer. In fact the MASS uses triangular functions distributed on a 2^n logarithmic scale which peaks are centered in the respective layer altitudes (see Figure 1, left), while the SLODAR uses rectangles centered in the sensed layer altitude (see Figure 1, right). The base of the rectangles (Δh), corresponding to the thickness of the layers, is the same for each layer and depends by the angular separation of the observed binary system (θ) and the WFS subaperture (w). The thickness of the layers changes every moment because it depends also by the zenith distance of the observed target (see Figure 2). This generates a continuous variation of the area in which MASS and SLODAR overlap.

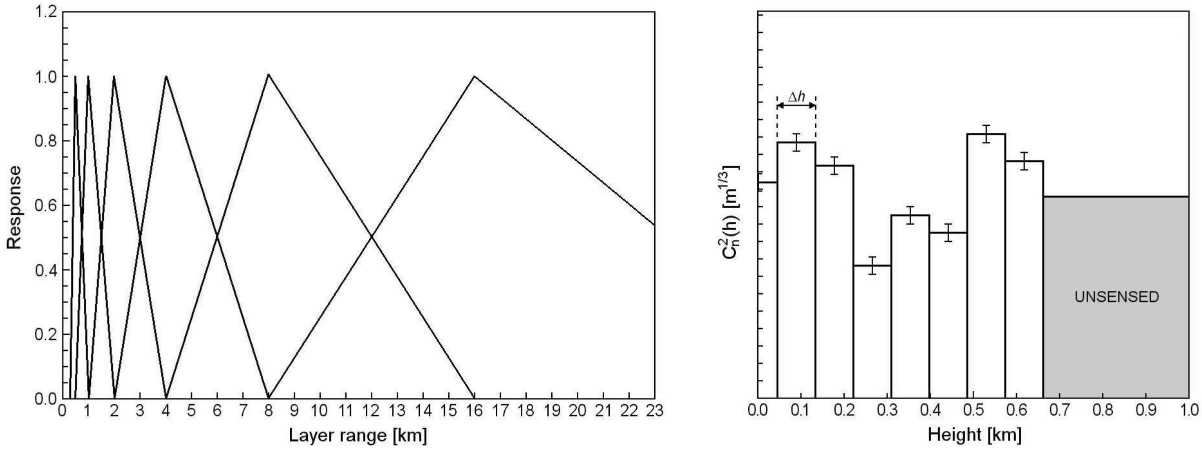

Figure 1. (*left*) MASS weighting functions. (*right*) An example of SLODAR response functions.

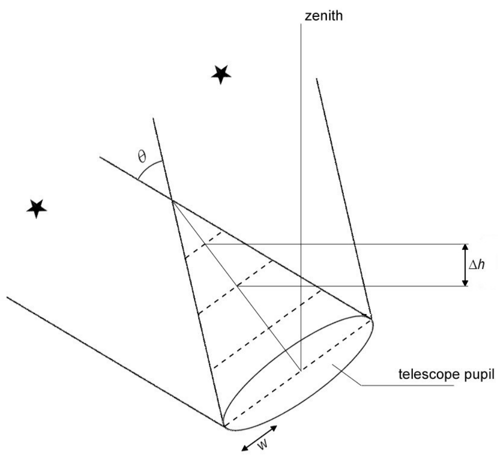

Figure 2. A schematic representation of the SLODAR layer thickness.

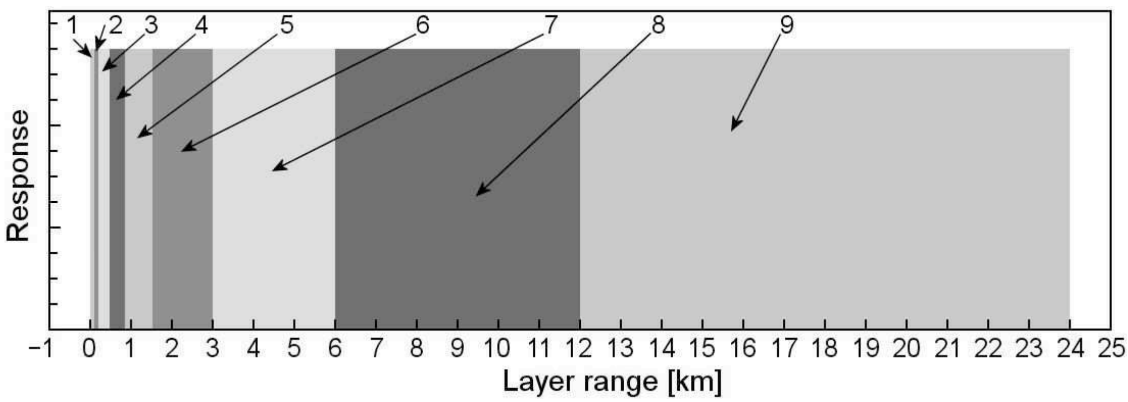

Figure 3. A qualitative scheme of the new grid.

To combine the two profiles we transform the MASS triangular functions into rectangular ones having the same area. The extremes of each rectangle are defined as the contact points of two consecutive triangles and the sensed altitude is assumed to be in the middle. In this way the MASS functions become comparable with the SLODAR layers. The new rectangles define a new grid of layers distributed with a 2^n logarithmic scale starting from the ground. Figure 3 shows a qualitative representation of the new grid of layers, while their extremes are reported in Table 1.
Having the new grid, we assume that in each layer the turbulence is uniformly distributed. We fill the lower new layers using the originals 8 SLODAR $C_n^2(h)$ proportionally to their overlap within those, while the high atmosphere is filled using the MASS layers normalized to the unsensed SLODAR C_n^2.
In this way we have defined a recombined new profile that takes into account the differences between the two instruments. The sum of the layers 1, 2 and 3 represents the *ground layer* (GL) that extent between the ground and 375 m. The sum of the layers 4, 5, 6, 7, 8 and 9 represents the *high* (or *free*) *atmosphere* (FA), that extents between 375 m to 24 km.
In case of missing of SLODAR data we can consider the combination of the layers 1, 2 and 3 as a generalized ground layer 375 m thick and centered at 188 m which integral is simply the difference between the total DIMM C_n^2 and the total MASS C_n^2.

Table 1. Values of the extremes for the definition of the new grid.

Layer	h [m]	Δh [m]	*min* [m]	*max* [m]
1	47	94	0	94
2	140	94	94	188
3	281	188	188	375
4	562	375	375	750
5	1125	750	750	1500
6	2250	1500	1500	3000
7	4500	3000	3000	6000
8	9000	6000	6000	12000
9	18000	12000	12000	24000

4. Results from the recombination

We calculate the 10-minutes averages of the $C_n^2(h)$ of each layer and then proceed with the analysis of the profile. The database from MASS+SLODAR recombination consists of 1807 10-minutes averages in 58 observing nights. The database generated by the MASS+DIMM recombination consists of 28103 10-minutes averages distributed in 719 observing nights.
We calculate the turbulence profile $C_n^2(h)$ for each layer in [$m^{-2/3}$] by dividing the integral of the $C_n^2(h)$ in [$m^{1/3}$] by the thickness of each layer Δh in [m] (see Table 1). Then we derive the percentage of the integral of the $C_n^2(h)$ in each layer and the total percentage of C_n^2 in the ground layer and in the free atmosphere. The Fried parameter (r_0), and thus the total seeing, is calculated using the sum of the integral of the C_n^2 of all the layers.

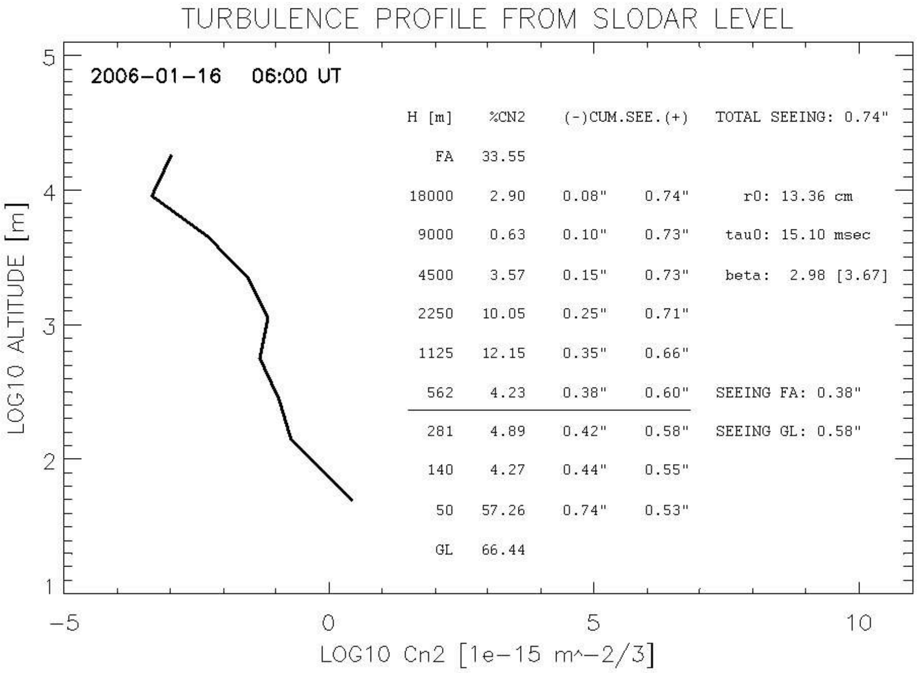

Figure 4. Example of a turbulence profile restored using MASS+SLODAR recombination.

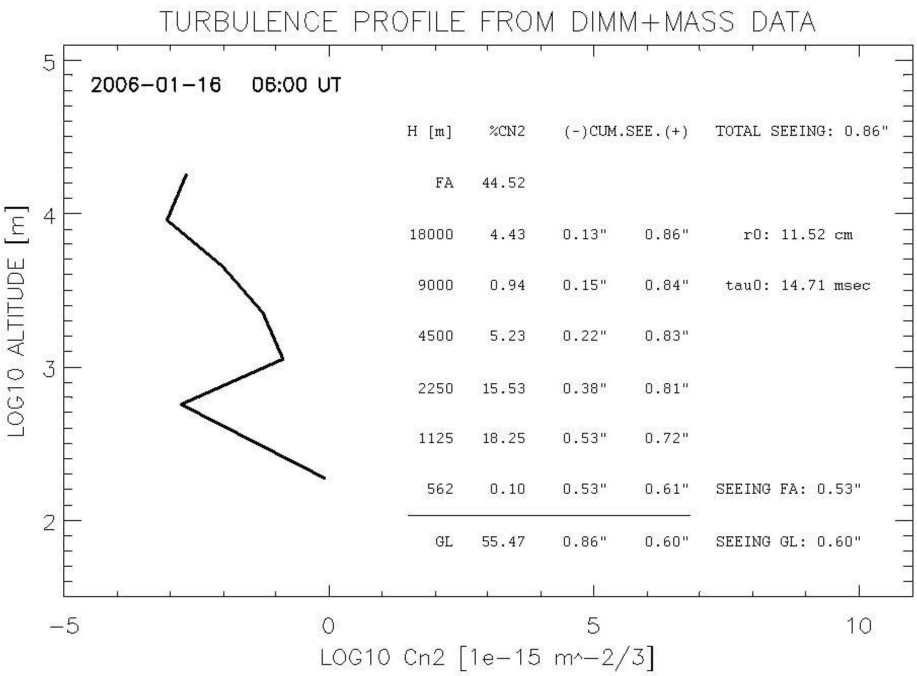

Figure 5. Example of a turbulence profile restored using MASS+DIMM recombination.

We calculate the cumulative seeing starting from both the ground layer (+) and the free atmosphere (−). For a j-th layer (j = 1, 2, …, 9) the considered C_n^2 in [m$^{1/3}$] for the calculation of the seeing is expressed by the following formulas:

$$C_n^2(+) = \sum_{i=1}^{j} C_{n,i}^2 \qquad C_n^2(-) = \sum_{j}^{i=8} C_{n,i}^2$$

The coherence time (τ_0) is taken directly from the MASS data archive, while the slope of the power spectrum in the turbulence law (β) is taken directly from the SLODAR data archive. If β = 3.67 the Kolmogorov's law is perfectly approximated. In case of missing of SLODAR data β is not reported.
In Figure 4 we report an example of a restored turbulence profile plus the calculated parameters for the case of MASS+SLODAR recombination. The same example for the case of MASS+DIMM recombination is reported in Figure 5.

5. Data analysis

In order to both understand the evolution of the seeing at Paranal and if a trend exists in this evolution, we decide to consider the monthly averages of the integral of the turbulence. Starting from the 10-minutes averages we calculate the averaged profile of each night, and from those we proceed to calculate the monthly averages.
Thanks to the new grid we have the possibility to check the differences between the turbulence of the ground layer and the turbulence of the free atmosphere in order to analyze which of the two has the stronger effect on the total seeing.

5.1. MASS+DIMM analysis

We consider the grid obtained using data from the DIMM and MASS, so the ground layer extent from 0 to 375 m and is centered at 188 m (see
Figure 5). We compare the trends of the total C_n^2 measured by the DIMM with the C_n^2 of the GL and the FA. Figure 6 (left) shows an increasing trend in the DIMM C_n^2. This increasing is clearly driven by the increasing of the ground layer, while the evolution of the free atmosphere is almost constant.
This result is confirmed in Figure 6 (right) where we report the monthly percentages of the C_n^2 in the ground layer with respect to the total DIMM C_n^2. As shown in the figure, the trend is increasing of ~7% per year, and this demonstrates that the influence of the ground layer on the total seeing is becoming stronger.

5.2. MASS+SLODAR analysis

Because the seeing is more affected by the ground layer, we decide to consider separately the behaviour of the layers composing the GL in order to look for peculiarities in the evolution of the turbulence of the first 375 m above the Observatory.
To evaluate the contribution of the first layer into the total GL we have used the SLODAR monthly averages in order to compare the C_n^2 of layer 1, $C_n^2(1)$, extended between 0 and 94 m and centered at 47 m, with the sum of the C_n^2 of the layers 1, 2 and 3, that together correspond to the total ground layer (see Figure 4).

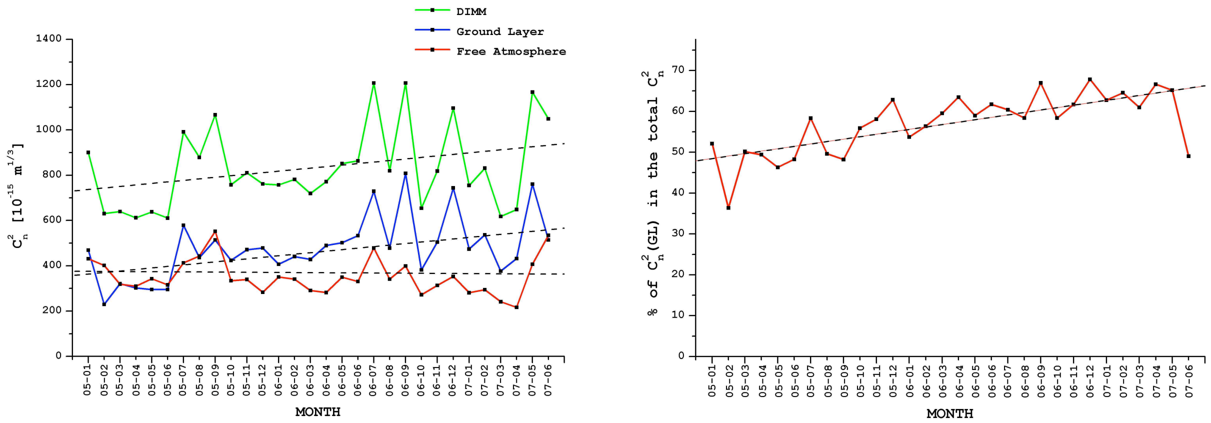

Figure 6. (*left*) Monthly C_n^2 in [10^{-15} $m^{1/3}$] as measured by the DIMM (green) between January 2005 and June 2007. The trend of the free atmosphere (red) is almost constant during the time while the trend of the ground layer (blue) is increasing and is driving the increase of the trend of the total C_n^2. The GL is the sum of the first, the second and the third layer of the new grid. It is centered at 188 m and has a thickness of 375 m. (*right*) Monthly percentages of C_n^2 of the ground layer with respect to the total DIMM C_n^2. The trend is increasing.

Results are reported in Figure 7 where we plot the C_n^2 of the first layer as a function of the total C_n^2(GL). The linear fit is imposed to have the Zero Point at 0 and has a confidence level of 92%. We obtain that typically the 78% of the C_n^2(GL) is concentrated in the first layer. The (very few) points having poor correlation correspond to profiles in which the turbulence was dominated by the free atmosphere.

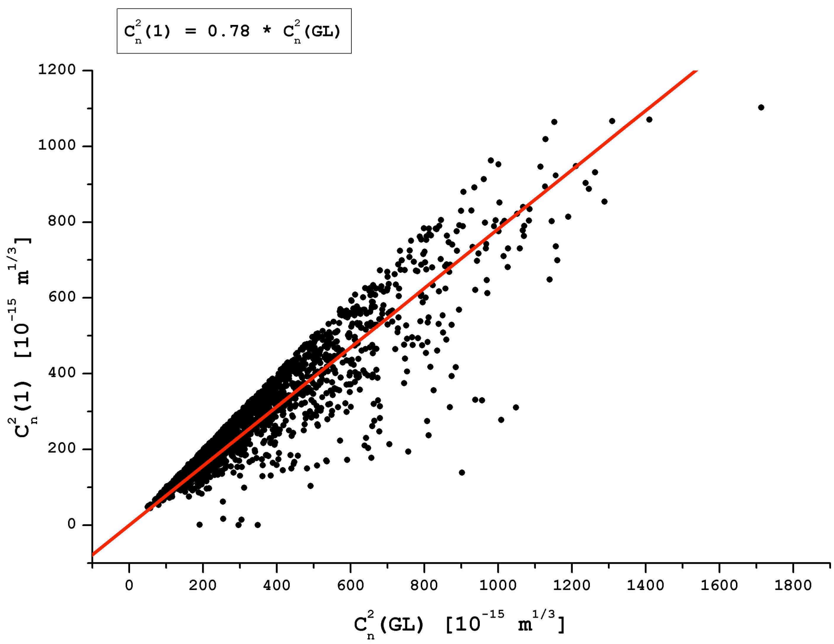

Figure 7. C_n^2 of the first layer as a function of C_n^2(GL). The linear fit has a confidence level of 92%.

5.3. Analysis of the evolution of the seeing at Paranal

Due to their height above the ground, the turbulence affecting the VLT Unit Telescopes has to be considered starting from an altitude of 30 m, skipping what is below. Using SLODAR data, the first layer of our grid is centered at 47 m above the ground and has a thickness of 94 m (see Table 1).
Following Tokovinin&Travouillon (2006) we assume that the turbulence in the ground layer has a log-normal distribution, so 80-90% is concentrated in the first 50 meters above the ground, in good approximation with the UT height. In this way we can affirm that the first layer can be considered as representative of the turbulence below the UTs (which we call *surface layer*) with an overestimation of about 10%.
Considering the contribution of the first layer into the total GL we can recalculate the total seeing affecting the VLT Unit Telescopes using as new $C_n^2(\mathrm{GL}_{47\mathrm{M}})$ the 22% of the original $C_n^2(\mathrm{GL})$ as we have calculated in previous Section. So the total integral of the turbulence above surface layer (ASL) affecting the UTs is:

$$C_n^2(\mathrm{ASL}) = 0.22\, C_n^2(\mathrm{GL}) + C_n^2(\mathrm{FA}) = C_n^2(\mathrm{GL}_{47\mathrm{M}}) + C_n^2(\mathrm{FA})$$

In this way we skip the effects of the turbulence of the surface layer. The $C_n^2(\mathrm{ASL})$ can also be considered as the C_n^2 of an imaginary DIMM placed at 47 m above the ground.
We recalculate the 10-minutes averaged profiles applying our formula. After that we calculate the median seeing and the averaged seeing using the entire database composed by the 10-minutes averages (28103 samples). We obtain that the median seeing is 0.63 ± 0.21 arcsec. The uncertainty is calculated as the median of the scatters of the values from the median seeing. The averaged seeing from the same 28103 samples results to be 0.70 arcsec with a standard deviation of 0.33 arcsec.
An independent analysis made by J. Navarrete at ESO Paranal Observatory using 23888 empirical image quality samples from Unit Telescope 1 Shack-Hartmann (SH) at Cassegrain focus (Active Optics) in the period between September 2004 and June 2007 and corrected for lenslet aberration gives median seeing 0.63 ± 0.19 arcsec and average seeing 0.67 ± 0.29 arcsec in very good approximation with results from the theoretical method used in the present paper.
We recalculate the $C_n^2(\mathrm{ASL})$ monthly averages from the 10-mintues ones and the relatives monthly seeing. Figure 8 shows the regression analysis of the monthly image quality at UT1 SH versus the monthly ASL seeing derived from our theoretical calculations. The slope of the fit is imposed to be 1. We obtain a confidence level of 0.9 demonstrating the good reliability of the method when compared to real data.
Figure 9 shows a comparison between the monthly DIMM seeing and the monthly ASL seeing. An increasing trend in the DIMM seeing is evident while the trend of the ASL seeing is clearly constant during the considered 30 months.

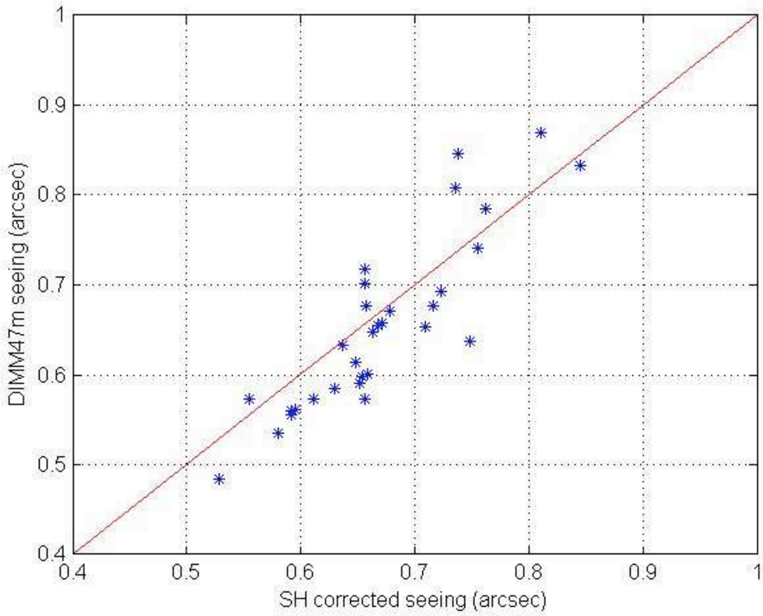

Figure 8. Regression analysis of Unit Telescope 1 Active Optics image quality monthly averages versus the monthly seeing above surface layer. The slope is imposed to be 1. The confidence level is 0.9.

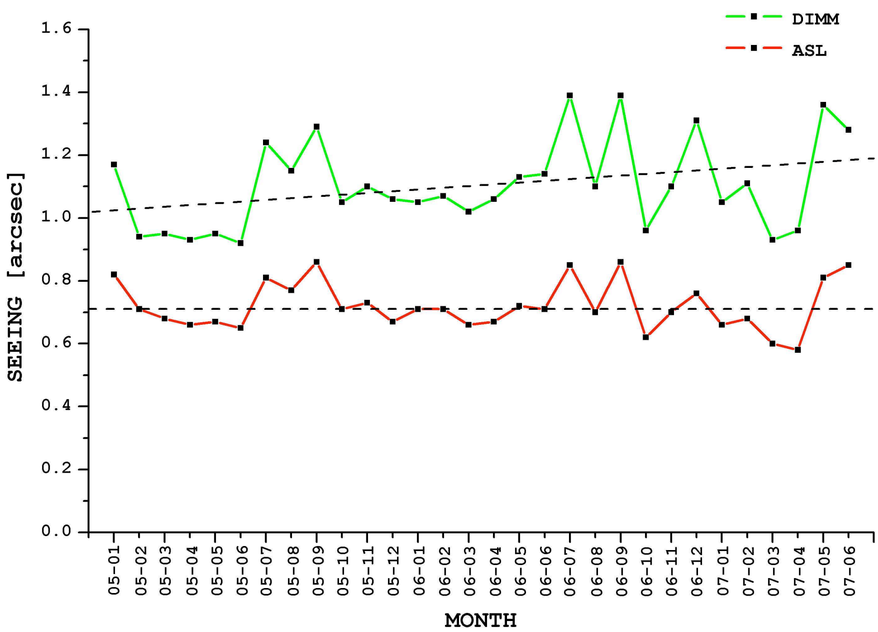

Figure 9. Comparison between the monthly DIMM seeing and the monthly ASL seeing. The trend of the seeing as measured by the DIMM is increasing, while the ASL seeing is constant during the time.

Table 2. MASS+DIMM. Typical profiles for good (33%), median and bad (66%) seeing above surface layer at Paranal. The statistics is made on the basis of 719 observing nights (28103 10-minutes averages) in the period between 2 January 2005 and 30 June 2007.

Layer	h [m] (above platform)	Δh [m]	C_n^2(h) [10^{-15} m$^{-2/3}$] (*above surface layer*) GOOD	MEDIAN	BAD
GL	235	280	0.26841 (87%)	0.42700 (77%)	0.60859 (49%)
4	562	375	0.01934 (6%)	0.07471 (13%)	0.46383 (37%)
5	1125	750	0.00149	0.00863	0.05476
6	2250	1500	0.00392	0.01718	0.06470
7	4500	3000	0.00851	0.01781	0.03415
8	9000	6000	0.00352	0.00583	0.00820
9	18000	12000	0.00303	0.00422	0.00526
ASL SEEING [arcsec]			0.43	0.63	1.00
DIMM SEEING [arcsec]			0.67	0.92	1.39

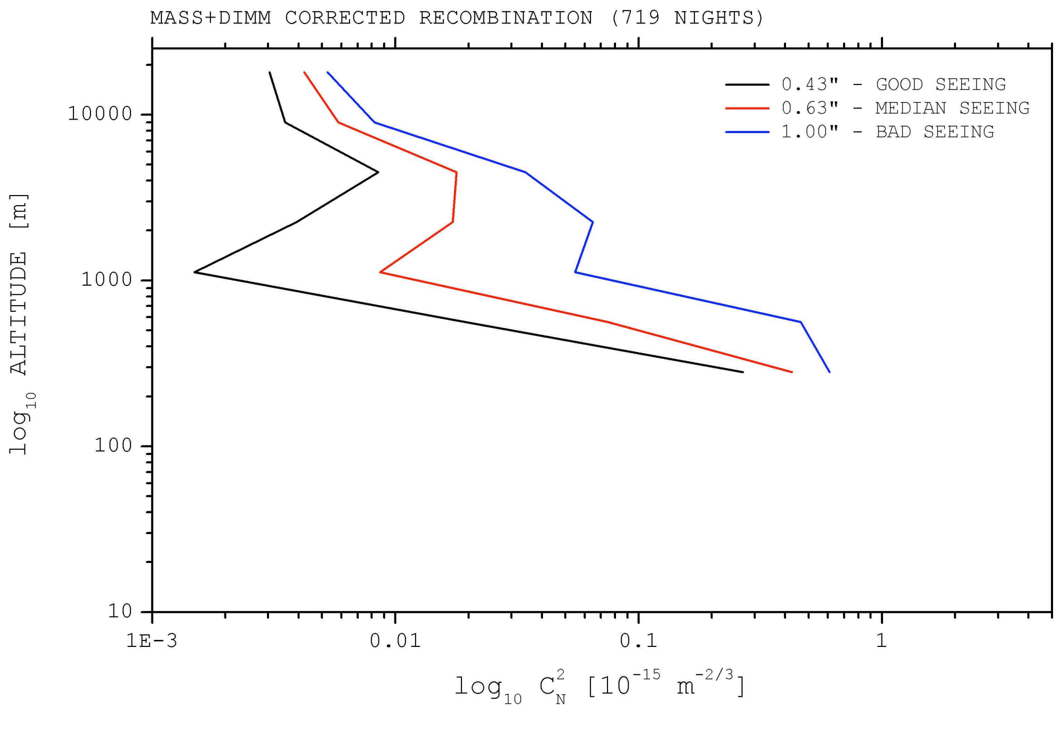

Figure 10. MASS+DIMM. Typical profiles for good (33%, *black*), median (*red*) and bad (66%, *blue*) seeing above surface layer at Paranal. Values are reported in Table 2. The statistics is made on the basis of 719 observing nights (28103 10-minutes averages) in the period between 2 January 2005 and 30 June 2007.

6. The median turbulence profiles for Paranal

To finalize the results we have calculated the typical turbulence profiles for Paranal in case of good (33%), median and bad (66%) seeing using the MASS+DIMM recombination (719 nights). These profiles are computed above surface layer in order to give an exact estimation of the turbulence affecting the UTs. The results are reported in Table 2 and plotted in Figure 10. Although in this case the ground layer is not well resolved with respect to the MASS+SLODAR recombination, we consider these profiles more realistic because of the higher extension of the database.

7. Conclusions

We have recombined turbulence profiles from MASS and SLODAR using a new grid of atmospheric layers defined on the basis of the transformation of the MASS triangular weighting functions into rectangular ones in a way that let them become comparable to the rectangular SLODAR weighting functions.

The new profiles obtained from the recombination permit us to distinguish between several turbulent layers above ground; in particular we can calculate separately the turbulence of the ground layer (between 0 and 375 m) and the turbulence of the free atmosphere (from 375 m to 24 km). Taking into account the properties of the SLODAR layers we can also distinguish in detail three layers composing the ground layer.

A statistical analysis of 30 monthly averages between January 2005 and June 2007 of the relation between the total DIMM C_n^2, the ground layer C_n^2 and the free atmosphere C_n^2 tell us that the DIMM C_n^2 is increasing and this increasing is driven by the worsening of the turbulence in the ground layer, while the free atmosphere does not show a significant evolution. This result is confirmed by the increasing of the percentage of ground layer C_n^2 into the total DIMM C_n^2.

We have obtained that 78% of the total ground layer turbulence is concentrated in the surface layer. Taking into account that the VLT Unit Telescopes are 30 m tall, we have recalculated the integral of the turbulence cutting the 78% of the ground layer. In this way we can calculate with a good approximation the real seeing affecting the UTs. We have obtained that the trend of this seeing is almost constant during the considered 30 months with a median seeing of 0.63 ± 0.21 arcsec and an averaged seeing of 0.70 ± 0.33 arcsec calculated on the basis of the entire database of 10-minutes averages (28103 samples).

In conclusion, there is a worsening of the turbulence of the ground layer at Paranal, but this worsening is almost concentrated in the first 50 m above the ground in a way that is not significantly affecting the image quality of the VLT Unit Telescopes.

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