

# Statistics of turbulence profile at Cerro Tololo

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## ABSTRACT

Results of 3-month continuous monitoring of turbulence profile and seeing at Cerro Tololo (Chile) in May–July 2002 are presented. Some 28000 low-resolution profiles were measured by a new MASS single-star turbulence monitor, accompanied by seeing data from DIMM. The median seeing was 0.95 arcseconds. The first 500 m contribute 60% to the total seeing, the free-atmosphere median seeing was 0.55 arcseconds. Free-atmosphere seeing is almost never better than 0.15 arcseconds because there is always some turbulence above 12 km. A 4-day period of calm upper atmosphere with a stable free-atmosphere seeing of 0.2–0.3 arcseconds was noted. A gain in resolution from adaptive compensation of ground layer will be 1.7 times typically and 2–3 times during such calm periods. Correlations of the free-atmosphere turbulence with the wind speed at tropopause and of the ground-layer turbulence with ground wind are studied. Temporal evolution of turbulence is characterized by recurrent bursts, their typical duration increases from 15 minutes in low layers to 1–2 hours in high layers. The large data base of turbulence profiles can be used to test meso-scale modeling of astronomical seeing.

**Key words:** atmospheric effects – site testing – instrumentation: adaptive optics.

## 1 INTRODUCTION

A crucial role of ‘seeing’ in ground-based astronomy was recognized long time ago. Nowadays it is possible to improve the seeing with adaptive optics (AO), but this technology is itself so dependent on the properties of turbulence that it generated a new and important driver for detailed atmospheric studies. AO requires a knowledge of the temporal time constant and of the vertical turbulence profile, in addition to the overall (integrated) seeing. It is desirable to have a reliable statistics of these parameters for a given site in order to predict the performance of AO systems. A real-time monitoring of optical turbulence would help in optimizing the AO operation. For example, the scintillometer of Ochs. et al. was regularly operated at the AMOS station for this reason (Chonasky & Deuel 1988).

The vertical distribution of the optical turbulence strength (characterized by the altitude dependence of the refractive index structure constant  $C_n^2$ ) is notoriously difficult to monitor. Balloon-born micro-thermal probes are expensive and sample the turbulence profile (TP) only once per flight, without any statistical averaging. Optical remote sounding by SCIDAR (Fuchs et al. 1998) is free from this drawback, but it requires moderately large telescopes, sensitive detectors, and powerful signal processing. For these reasons SCIDAR was only used in a campaign mode at existing observatories.

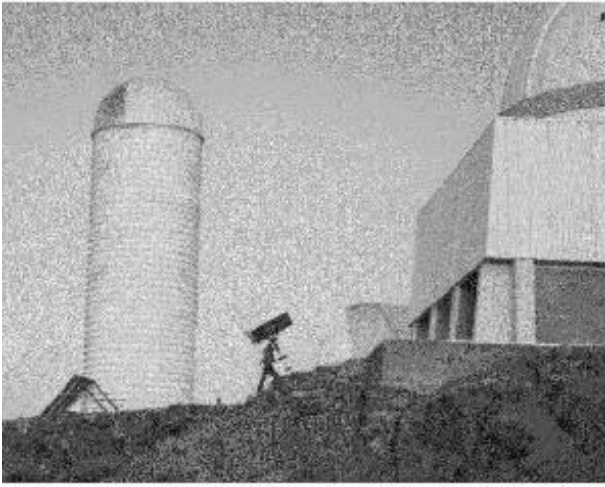
A limited number of TPs measured world-wide revealed that

turbulence is typically concentrated in few thin layers. The physical mechanism generating such distribution was studied by Coulman et al. (1995). It inspired designers of AO systems to add more deformable mirrors, each conjugated to its own layer, and thus to compensate seeing over a much wider field with such multi-conjugate AO (MCAO) (Rigaut et al. 2000). The promising potential and wide popularity of MCAO added even more pressure to measure turbulence profiles; the Gemini site testing campaign at Cerro Pachón (Vernin et al. 2000; Avila et al. 2000) is an example of such MCAO-driven study.

Ground-based telescopes of next generation with apertures of 20–100 m will include turbulence compensation already in their designs (Andersen et al. 2000). Sites for these telescopes are being selected with a strong weight given to AO-related turbulence parameters; site surveys based on seeing measurements alone, as was the case for the previous generation of telescopes, are no longer sufficient. Seeing is very much dominated by local and orographic effects that diminish predictive power of seeing data. With modern computers, a modeling of optical turbulence becomes feasible, giving new insights into the physics of seeing and new guidance to the choice of sites, e.g. (Masciadri et al. 2001). But computer models still need real TPs for their calibration.

A low-resolution turbulence profile monitor, Multi-Aperture Scintillation Sensor (MASS), was developed in response to the needs of AO and MCAO, as well as a portable instrument for site testing (Tokovinin & Kornilov 2001; Kornilov et al. 2002). MASS was operated in 2002 for several months at the Cerro Tololo Inter-American Observatory (CTIO) jointly with the Differential Image

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**Figure 1.** The DIMM instrument is installed in a 6 m high tower at the edge of Cerro Tololo summit. MASS was initially located on the ground, as shown; it was moved into the USNO dome (on the right) on May 19 2002.

Motion Monitor (DIMM) (Boccas 2001). This paper presents the results of this campaign. It appears to be the most extensive data base of turbulence profiles existing to date worldwide.

Our aim was to gain some understanding of the turbulence localization above CTIO. We were specifically interested in the fraction of turbulence in the first few hundred meters over the ground and in the seeing that can be attained if these low layers were compensated by AO. *Ground-layer compensation* offers improved seeing in a much wider field than does classical AO (Rigaut 2001). This option is being studied for the 4.2-m SOAR telescope located close to CTIO on Cerro Pachón (Tokovinin et al. 2002), as well as for extremely large telescopes of next generation. Our work quantifies the gain expected from ground-layer compensation at a specific good astronomical site, CTIO.

In Sect. 2 we briefly describe the instrumentation used in this study and give typical examples of the data. The statistics of the vertical turbulence distribution is explored in Sect. 3. Sect. 4 contains summary and conclusions.

## 2 SITE, INSTRUMENTS AND DATA

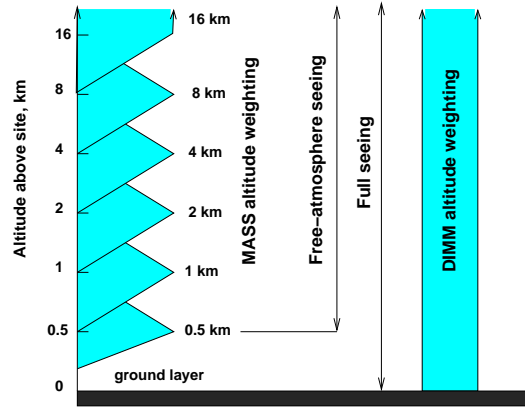
### 2.1 Site

Cerro Tololo is located in Chile some 500 km to the north of Santiago ( $70^{\circ}48'52''.7$  W,  $30^{\circ}09'55''.5$  S). Altitude is 2200 m above sea level (a.s.l.). Among other Chilean sites, Cerro Tololo is known for its low ground wind speed.

The two instruments used in this campaign, Multi-Aperture Scintillation Sensor (MASS) and Differential Image Motion Monitor (DIMM), were placed at the northern edge of the summit, facing the direction of prevailing wind (Fig. 1). DIMM is placed in a small tower at some 6 m above the ground. The MASS feeding telescope was installed on the Losmandy equatorial mount, initially on the ground and later in a small dome.

### 2.2 MASS

MASS (Tokovinin & Kornilov 2001; Kornilov et al. 2002) measures low-resolution turbulence profiles from the scintillation of



**Figure 2.** Scheme of the sub-division of atmospheric path into 0.5-km, 1-km, etc. layers measured by MASS and the total path measured by DIMM. Turbulence in the ground layer is inferred from the difference between DIMM and MASS.

single stars. Light flux is received by four concentric-ring apertures with diameters of 2, 3.7, 7.0, and 13 cm and detected by photo-multipliers in photon counting mode with 1 ms time sampling. Statistical analysis of the fluxes with 1 minute accumulation time produces 10 scintillation indices that correspond to 4 individual apertures and 6 pair-wise aperture combinations. MASS is fed by a 14-cm off-axis reflecting telescope specially designed for this purpose.

At the beginning of a night, MASS is pointed to a bright ( $V < 2^m$ ) blue single star close to zenith. After background measurement and star centering, a series of continuous 1-minute integrations is started, with either manual or automatic guiding of the telescope. When zenith distance of the star increases above  $45^{\circ}$ , the telescope is re-pointed to another object (a total of 3-4 stars per night).

A model of turbulence distribution with 6 layers at fixed altitudes of 0.5, 1, 2, 4, 8, and 16 km above ground is fitted to the data. Each ‘layer’ represents in fact an integral of turbulence  $J_l$

$$J_l = \int_{\text{layer}} C_n^2(h)W(h)dh \quad (1)$$

measured in  $\text{m}^{1/3}$ , where  $C_n^2(h)$  is the refractive-index structure constant in  $\text{m}^{-2/3}$  and  $W(h)$  is the dimensionless response function of the instrument. MASS response functions are nearly triangular, going to zero at the altitudes of adjacent layers (Fig. 2). Thus, the 8-km layer measures, roughly, integrated turbulence strength from 6 to 12 km, while 16-km layer measures everything above 12 km. Turbulence at 6 km will show up in 4-km and 8-km ‘layers’ with equal intensity. The sum of all response functions is constant (within 10%) at altitudes above 0.5 km.

Atmospheric seeing  $\epsilon_l$  (full width at half maximum of a long-exposure image in a large telescope) produced by a turbulent layer can be computed from the intensity  $J_l$ . For  $\epsilon_l$  in arcseconds at  $\lambda = 500$  nm and  $J_l$  in  $\text{m}^{1/3}$ ,

$$\epsilon_l = (J_l/6.8 \cdot 10^{13})^{3/5}. \quad (2)$$

The sum of all layer intensities measured by MASS gives a good estimate of the ‘free-atmosphere seeing’  $\epsilon_f$  – the seeing that would be obtained without contribution of the turbulence in the first 500 m above ground. The free-atmosphere seeing is also estimated by MASS directly from a combination of 3 scintillation indices. There is a very good agreement between  $\epsilon_f$  computed from the integrated profiles and directly. More details on the restoration pro-

cedure are given in (Tokovinin et al. 2002). It is shown in this study that noise in MASS is signal-dependent, becoming smaller under low-turbulence conditions. The strength of dominating layers is always measured with a typical relative error of 10% which may be as low as  $4 \cdot 10^{-15} \text{ m}^{1/3}$  under calm conditions.

MASS data are reduced in real time and stored in an ASCII file, a profile every minute. Many additional parameters (instrumental configuration, stellar fluxes, quality of the model fit) are also written to this file. This permits to identify and reject any wrong data. The reasons for erroneous data are guiding errors, wrong background estimates, and, by far most numerous, clouds. It was found that MASS gives consistent and reproducible results through thin cirrus clouds because slow light variations (below 1 Hz) are filtered out in the data reduction algorithm. We rejected only the data with low stellar fluxes and with flux variance (in 1 minute with 1 s flux averaging) of more than 1% that indicated varying cloud transmission during integration.

### 2.3 DIMM

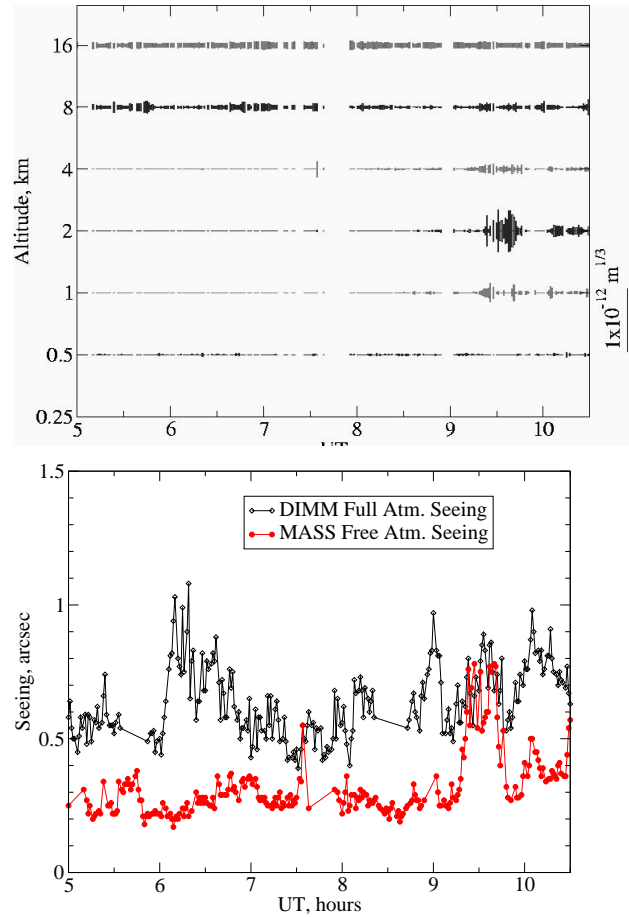
DIMM measures the Fried parameter  $r_0$  related to the full seeing  $\epsilon = 0.98\lambda/r_0$  at wavelength  $\lambda$  (Sarazin & Roddier 1990; Tokovinin 2002). The seeing is deduced from the variance of the angle-of-arrival fluctuations (or image motion) is two small apertures.

The CTIO DIMM (Boccas 2001) uses 25 cm Meade as feeding telescope. The diameter of the apertures is 95 mm (partially obstructed), the distance between their centres is 15.3 cm. Images of a bright star formed by both apertures are separated by a wedge prism placed on one entrance aperture and detected by a CCD camera with pixel size of  $0''.77$ . Frame exposure time is alternating between 5 ms and 10 ms, the integration time for seeing estimate is 1 minute, with acquisition rate about 300 images per minute. Upon background subtraction, the centroids of images are computed in a window of 8 pixel radius. The variance of centroid coordinate differences in two orthogonal directions is corrected for noise variance and converted to seeing. The bias in seeing caused by finite exposure time is corrected by the modified exponential prescription as detailed in (Tokovinin 2002). The DIMM data are stored in an ASCII file and are also available on the Internet in real time.

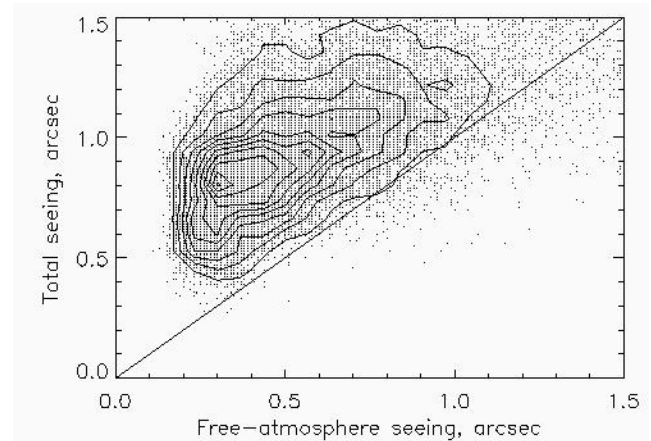
DIMM operates in a robotic mode, opening its dome and pointing suitable stars when the meteorological conditions are adequate. Guiding is done in-between 1-minute data accumulations. Robotic operation was interrupted repeatedly by failures to find a star which called for manual interventions (the Meade mount does not have absolute position sensors to recover its pointing) and by failures of the drive motors, replaced several times. For this reason the time coverage of DIMM is somewhat less than that of MASS for the same period.

### 2.4 Comparison between MASS and DIMM

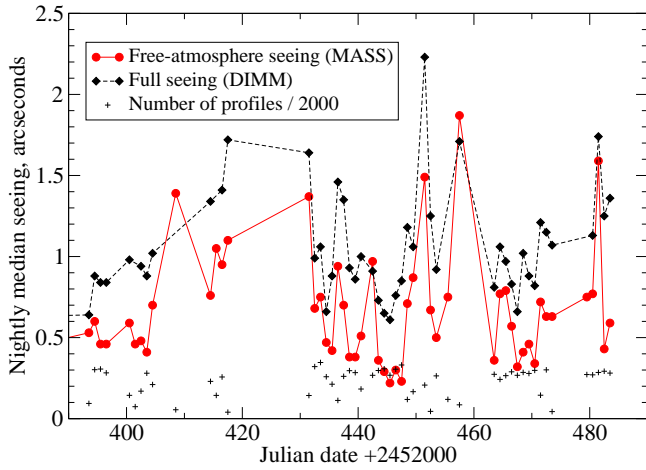
MASS and DIMM measure different ‘seeings’,  $\epsilon_f$  and  $\epsilon$ . Whenever the contribution of the first 500 m above ground to the total seeing is small, we must obtain  $\epsilon_f \approx \epsilon$ , otherwise the inequality  $\epsilon_f < \epsilon$  must hold. This is indeed the case. In Fig. 3 we display a portion of data for the night of June 19-20 2002 with very calm atmospheric conditions. Around 9.5h UT an increased turbulence at 2 km dominated the seeing, with both instruments giving very similar results. For the rest of the night, the full seeing  $\epsilon$  was very good, but still worse than  $\epsilon_f$  because of ground-layer turbulence.



**Figure 3.** Turbulence profiles (top) and seeing (bottom) on a very calm night of June 19-20, 2002. Bars show the intensity of layers in  $\text{m}^{1/3}$  with a scale indicated on the right.



**Figure 4.** Comparison of the free-atmosphere seeing  $\epsilon_f$  measured by MASS (horizontal axis) and the full seeing  $\epsilon$  measured by DIMM (vertical axis) for all data in common. Contour plots are over-layed with 10% intervals to show the density of points. The line shows  $\epsilon_f = \epsilon$ .



**Figure 5.** Nightly median values of total seeing  $\epsilon$  and free-atmosphere seeing  $\epsilon_f$  for the period April 29 to July 28 2002. The crosses show a total number of TPs acquired each night (less than 500 on partially cloudy nights).

The condition  $\epsilon_f \approx \epsilon$  illustrated above was not exceptional, but, on the contrary, was encountered regularly. Dominating high layers were frequently located at 0.5 – 1 km, but could be as high as 8 km. The agreement between the two very different instruments, MASS and DIMM, is better than one could expect; it gives confidence that both produce correct data.

Fig. 4 shows free-atmosphere seeing compared to the full seeing measured simultaneously (interpolated to the moments of MASS measurement from two adjacent DIMM points) for the whole data set. The occasional equality  $\epsilon_f \approx \epsilon$  is clearly seen. A small number of points is located below the diagonal,  $\epsilon_f > \epsilon$ . These points can be explained by noise and by the fact that both instruments used different stars, so small localized patches of turbulence occasionally caused spikes in the MASS seeing not matched by DIMM. The inverse is also happening, of course.

## 2.5 Data overview

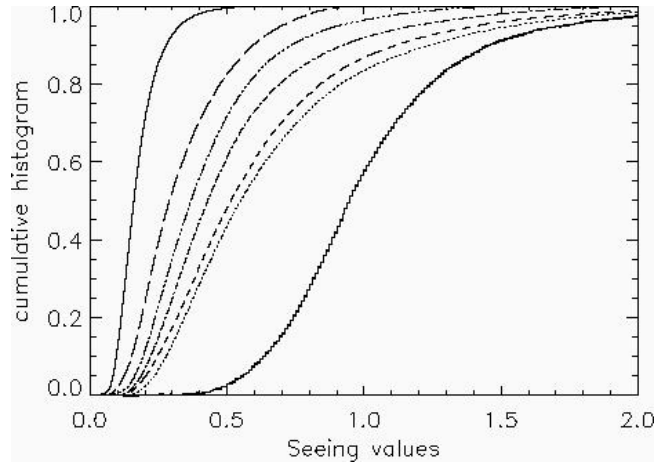
First useful MASS data were obtained on March 21-27 2002 during the commissioning of this instrument. Systematic profile monitoring started on April 29. Here we consider the data obtained to July 28 inclusive, with 3 complete months covered. During this period MASS worked for 58 nights, but some of them were partially cloudy with a reduced number of data. On a clear night MASS measured some 500-600 profiles. The total number of TPs used for the analysis (after the cleaning mentioned above) is 22300, of which 16968 TPs have matching DIMM data.

The periods of bad weather are apparent in Fig. 5 where nightly median values of  $\epsilon$  and  $\epsilon_f$  are plotted. A particularly long cloudy period occurred between May 11 and June 6.

All seeing and TP data in this article refer to the wavelength of 500 nm and to zenith. The following results characterize atmosphere at Cerro Tololo in the period May-July 2002. This corresponds to autumn and winter conditions, typically worse than average.

**Table 1.** Levels of the cumulative distributions of total seeing  $\epsilon$ , free-atmosphere seeing  $\epsilon_f$ , ground-layer seeing  $\epsilon_g$ , fraction of ground layer, and isoplanatic angle  $\theta_0$ .

| Probability                               | 10%  | 25%  | 50%  | 75%  | 90%  |
|---|------|------|------|------|------|
| Total seeing $\epsilon$ , arcsec          | 0.64 | 0.79 | 0.95 | 1.17 | 1.43 |
| Free-atm. seeing $\epsilon_f$ , arcsec    | 0.28 | 0.38 | 0.55 | 0.82 | 1.22 |
| Ground-layer seeing $\epsilon_g$ , arcsec | 0.24 | 0.47 | 0.66 | 0.83 | 1.02 |
| Ground-layer fraction $f_g$               | 0.11 | 0.38 | 0.60 | 0.76 | 0.85 |
| Isoplanatic angle $\theta_0$ , arcsec     | 2.94 | 2.36 | 1.80 | 1.30 | 0.98 |



**Figure 6.** Cumulative distribution of the total seeing (thick line) and (from right to left) of the seeing that would result from correction of the ground layer, first 1 km, first 2 km, etc. to the seeing produced by 16 km layer alone (leftmost curve).

## 3 DATA ANALYSIS

### 3.1 Relative contribution of atmospheric layers to seeing

Table 1 contains the main levels of cumulative distributions of seeing: total  $\epsilon$ , free-atmosphere  $\epsilon_f$ , and ground-layer seeing  $\epsilon_g = (\epsilon^{5/3} - \epsilon_f^{5/3})^{3/5}$ . In 7% of cases with  $\epsilon_f > \epsilon$  we assume that ground layer seeing was close to zero. The data used for this analysis refer only to cases when both MASS and DIMM measurements are available. We also include the distribution of the isoplanatic angle  $\theta_0$  which is readily computed from MASS data.

Supposing that ground-layer turbulence can be measured and corrected by AO, we can estimate the resulting improvement in seeing. Of course, realistic adaptive optics will not correct ground-layer turbulence perfectly, but, on the other hand, it will partially correct higher layers. Still, the analysis presented in Table 2 and in Fig. 6 gives a quantitative idea on the gain in angular resolution

**Table 2.** Levels of the cumulative distributions of seeing in arcseconds for different thickness of corrected layers.

| Probability                       | 10%  | 25%  | 50%  | 75%  | 90%  |
|-----------------------------------|------|------|------|------|------|
| No correction ( $\epsilon$ )      | 0.64 | 0.78 | 0.95 | 1.17 | 1.46 |
| Ground to 0.5 km ( $\epsilon_f$ ) | 0.28 | 0.38 | 0.55 | 0.83 | 1.24 |
| Ground to 2 km                    | 0.22 | 0.30 | 0.43 | 0.62 | 0.92 |
| Ground to 4 km                    | 0.19 | 0.26 | 0.37 | 0.53 | 0.73 |
| Ground to 8 km                    | 0.15 | 0.20 | 0.29 | 0.43 | 0.60 |
| Ground to 16 km                   | 0.10 | 0.12 | 0.16 | 0.21 | 0.28 |

expected from ground-layer correction. The gain increases when a thicker slab of turbulence is corrected, but at the same time the size of corrected field becomes smaller.

Table 1 also contains the distribution of the fraction of  $C_n^2$  integral contained in the first 500 m above the ground,  $f_g = (\epsilon_g/\epsilon)^{5/3}$ . We studied this parameter separately for good ( $< 0''.6$ ) and bad ( $> 1''$ ) seeing and did not find any substantial dependence. For example, median fractions of ground layer for good and bad seeing are 0.57 and 0.53, respectively. The largest median contribution of ground layer – 0.66 – is found for seeing between  $0''.6$  and  $1''$ . Turbulence profiles measured at the nearby mountain Cerro Pachón by Vernin et al. (2000) led to a model where average contribution of ground layer is 65% (Ellerbroek & Rigaut 2000).

Our results should be compared to the extensive monitoring of turbulence profile at Cerro Tololo with Generalized SCIDAR reported by Vernin et al. (2000) and Avila et al. (2000). These authors obtained 6900 TPs over 22 nights distributed in 4 campaigns throughout year 1998. They find median total seeing of  $\epsilon = 1''.06$  ( $0''.85$  when dome contribution is excluded), median free-atmosphere seeing  $\epsilon_f = 0''.56$  and median isoplanatic angle  $\theta_0 = 2''.14$ . The agreement with our data is encouraging. Free atmosphere was more perturbed in April and July compared to January and October 1998. Thus, we expect that somewhat better seeing and larger isoplanatic angles will be measured during summer months.

Barletti et al. (1976) proposed a TP model based on 67 micro-thermal soundings. It predicts an average free-atmosphere seeing (all layers above 1 km) of  $0''.80$ . Their ‘lucky observer’ model assumes the lowest turbulence levels measured at each altitude and predicts  $\epsilon_f = 0''.28$ . We see from Table 1 that such conditions are indeed encountered at Cerro Tololo 10% of time and that the median  $\epsilon_f$  is significantly better than  $0''.80$ . Marks (2002) used 15 soundings in Antarctica to claim that upper atmosphere there is exceptionally calm, with a mean  $\epsilon_f = 0''.37$ . Equivalent or better conditions do occur at Cerro Tololo 25% of time even during unfavorable winter months.

It is interesting that even when all layers except the highest are corrected, the expected seeing is almost *never* better than  $0''.15$ . The same conclusion is strikingly apparent in Fig. 4 where  $\epsilon_f$  has a sharp lower cutoff at  $0''.15$ . There is always some non-negligible turbulence at the upper boundary of the troposphere (see also Fig. 9). Median  $C_n^2$  integral in the 16 km layer is  $3.2 \cdot 10^{-14} \text{ m}^{1/3}$ , some 10 times higher than the instrumental noise of MASS, which means that the effect is real and not related to some instrumental threshold. Vernin et al. (2000) measured the median seeing produced between 15 km and 20 km as  $0''.14$ .

The consequences of this finding are important for adaptive optics. Even when the turbulence profile is completely dominated by few strong and sharp layers, their correction by means of MCAO will not suffice to reach diffraction-limited resolution in a wide field because of the remaining high layers. The numbers in Table 2 indicate median fraction of the 16 km layer as 5%; a similar fraction of high-altitude turbulence is adopted in MCAO simulations for Gemini (Ellerbroek & Rigaut 2000). Another consequence of the upper-troposphere layers is the effective limit on isoplanatic field size  $\theta_0$ : even under very calm conditions it practically never exceeds  $\sim 5''$  as measured at several sites. Median turbulence measured at 16 km layer alone would give isoplanatic angle  $\theta_0 = 13''.4$ .

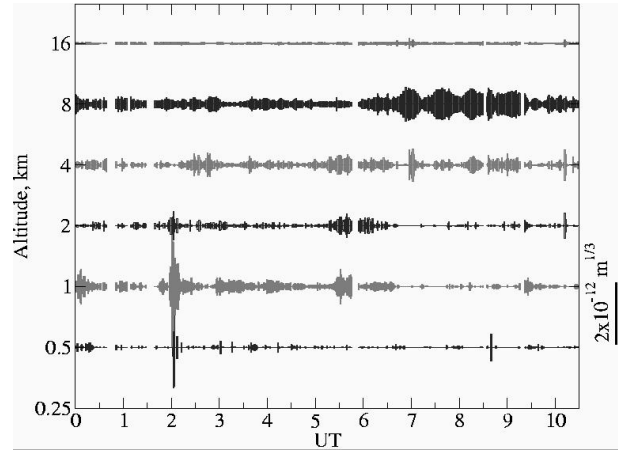


Figure 7. A typical night (July 25-26 2002) with turbulence bursts.

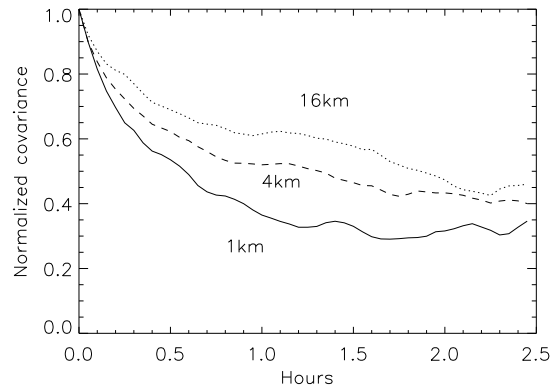


Figure 8. Normalized temporal autocorrelation functions of turbulence strength in three representative layers for the whole TP database.

### 3.2 Temporal variation of turbulence

Strong bursts of turbulence that last typically for less than 0.5 hour were observed repeatedly in almost all layers. An example of a typical night with perturbed atmosphere and bursts is given in Fig. 7 (note the coarser vertical scale compared to Fig. 3).

In Fig. 8 the normalized temporal autocorrelation functions  $A(\Delta t)$  for low, intermediate and high layers are plotted. The data – layer intensities  $J(t)$  – are not evenly spaced in time and have some gaps, making computation of covariance somewhat difficult. For this purpose we re-binned the  $J(t_i)$  on a uniform grid with 3 minute step, padding missing data with zeroes. The covariance  $C(\Delta t)$  was then computed and transformed into autocorrelation  $A(\Delta t)$ :

$$C(\Delta t) = \frac{1}{N} \sum J(t_i)J(t_i + \Delta t), \quad (3)$$

$$A(\Delta t) = \frac{C(\Delta t) - \bar{J}^2}{C(0) - \bar{J}^2}, \quad (4)$$

where  $N$  is the total number of non-zero products for a time lag  $\Delta t$  and  $\bar{J}$  is the average of  $J$ .

It can be seen that the time constant of turbulence variation is longer for high layers and shorter for low layers. At 50% correlation this time is 0.6, 1.3 and 1.9 hours for 1, 4, and 16 km layers



**Table 3.** Nightly median values of the full seeing  $\epsilon$ , free-atmosphere seeing  $\epsilon_f$ , wind speed at 200mb, ground wind speed and direction for a calm period in June 2002 and adjacent dates.

| Date, 2002 | $\epsilon$ , arcsec | $\epsilon_f$ , arcsec | $V_{200\text{mb}}$ , m/s | $V_{\text{ground}}$ , m/s |
|------------|---------------------|-----------------------|--------------------------|---------------------------|
| June 18    | 0.79                | 0.36                  | 21.3                     | 3.4 S                     |
| June 19    | 0.64                | 0.29                  | 22.7                     | 2.3 S                     |
| June 20    | 0.56                | 0.21                  | 26.1                     | 1.5 S                     |
| June 21    | 0.82                | 0.28                  | 29.5                     | 1.8 E                     |
| June 22    | 0.86                | 0.25                  | 27.7                     | 4.6 E                     |
| June 23    | 1.09                | 0.87                  | 29.3                     | 4.7 E                     |

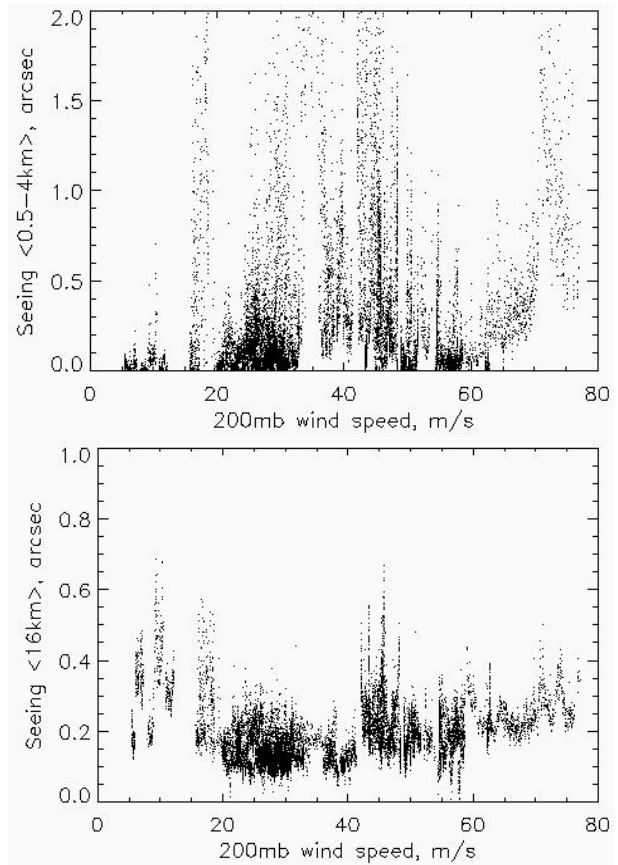
respectively. The autocorrelation functions show a fast decrease at small time lags that correspond to a presence of more rapid variations and are suggestive of power-law temporal spectrum. On the other hand, the ‘tails’ of  $A(\Delta t)$  reflect long-term, night-to-night variations. If we subtract the tail from the 1 km autocorrelation, the 50% correlation time would become 0.25 hour, giving a better idea on the duration of turbulent bursts. Bursts are shorter than periods between them, but  $A(\Delta t)$  cannot reflect this difference.

Rich data on TPs enable a better understanding of the physics of atmospheric seeing. Seeing variations usually observed at good astronomical sites with a time scale of  $\sim 1.2$  h (Sarazin 1997) can now be traced to the appearance turbulence bursts at specific altitudes. These bursts are a local phenomenon. We frequently compared the seeing at Cerro Tololo with the seeing at La Silla, only  $\sim 100$  km away: there is no correlation between seeing variations at these sites. Turbulence at medium altitudes must be related to the orographic disturbances. If at some lucky summit this turbulence could be avoided, it would enjoy a better and more stable seeing. Hydrodynamical modeling of turbulent flows is necessary to understand whether such ‘lucky summits’ indeed exist. On the other hand, it becomes evident that seeing statistics at any specific site is not necessarily representative of other mountains in the same region.

### 3.3 Seeing and weather

A period of calm atmosphere over Cerro Tololo shown in Fig. 3 actually lasted for four consecutive nights, from June 19 to June 22. The free-atmosphere seeing was very stable at  $0''.2-0''.25$ ; the burst shown in Fig. 3 is the worst  $\epsilon_f$  measured during this whole period. The total seeing as measured by DIMM was good but not exceptional. Seeing at the ESO sites La Silla and Paranal was also only moderately good. Based on DIMMs alone, one would never tell that something special was happening in the atmosphere on these dates. We have continuous profile data for the period from June 6 to June 30, with only small gaps due to cirrus clouds, that bracket this special period. Nightly median values of seeing, wind in the high atmosphere and at the ground for this period are listed in Table 3.

Investigation of meteorological conditions that produce extended periods of calm atmosphere is of evident practical interest if it can lead to understanding and prediction of such periods. A similar 3-day calm period was detected by Avila (2002) in May 2000 at San Pedro Mártir in Mexico, with stable values of  $\epsilon_f \approx 0''.2$ . This proves that calm atmosphere is something not very unusual. If all layers were independent of each other, a probability of all being quiet simultaneously would be low, and a probability of extended quiet periods would be vanishingly small. Instead, there must be



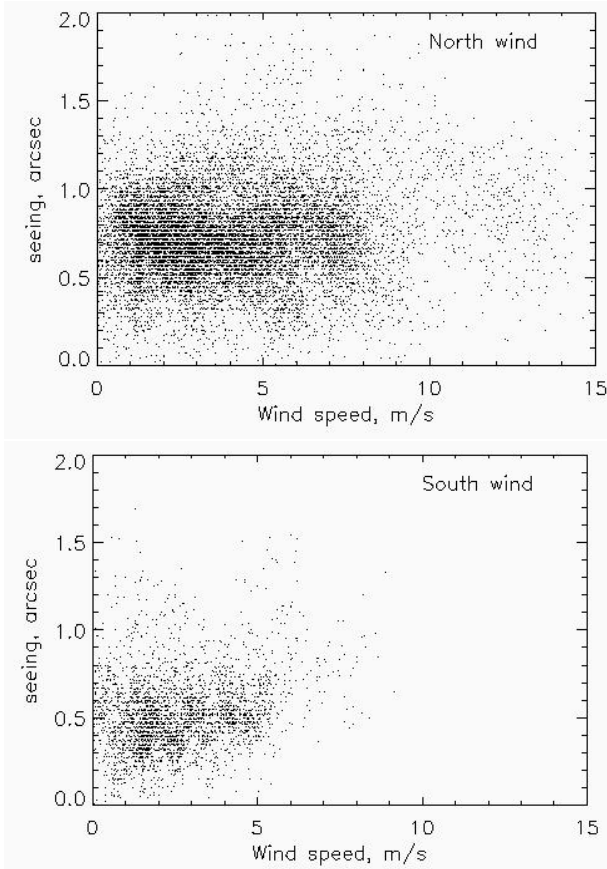
**Figure 9.** Correlation of the seeing generated by the low atmospheric layers (0.5–4 km, top) and by the 16-km layer (upper troposphere, bottom) with the wind speed at 200 mb level (12 km a.s.l.).

a factor common to all layers that produces calm conditions in a systematic way, as noted for the first time by Barletti et al. (1976).

As a first attempt to understand quiet periods, we analyzed the data on the speed of jet stream (wind at 200 mb pressure or 12 km a.s.l.) over La Silla as collected by ESO. Indeed, the wind velocity  $V_{200\text{mb}}$  was low. We have data on  $V_{200\text{mb}}$  only up to July 4, 2002. Seeing produced by low and high layers is compared to  $V_{200\text{mb}}$  for this period in Fig. 9. The period studied is certainly not long enough to cover all representative meteo conditions; the discussion that follows may be affected by a specific combination of weather patterns that occurred during this period.

Looking at Fig. 9, we note that there is no one-to-one correlation between jet stream and turbulence, but some tendencies do emerge. Low layers are generally more quiet when the jet stream speed is low. Of course, this may be related to the fact that wind speed and stability in all layers correlate with the 200 mb wind. The behaviour of the upper tropospheric layer (16 km), however, is noteworthy: it shows a clear minimum of turbulence for jet stream speeds between 20 and 40 m/s, whereas the turbulence increases at both faster and slower winds. Somehow low jet stream is ‘unnatural’ for high atmosphere and causes more turbulence! Note that high layer is never perfectly calm, unlike lower layers.

We also studied the relation between ground-layer seeing and ground wind as measured by the meteorological station on top of Cerro Tololo. Most frequently ground wind blows from North-East, otherwise it is from South-West; the wind-rose clearly shows these two dominating directions. We plot the ground-layer seeing



**Figure 10.** Correlation of the seeing  $\epsilon_g$  generated by the ground layer (below 0.5 km) with the speed of ground wind plotted separately for the north-eastern (top) and south-western (bottom) dominating wind directions.

$\epsilon_g$  against wind speed for these two directions separately in Fig. 10. There is practically no correlation for northern winds and some correlation for southern winds. Southern wind is definitely better for ground-layer seeing.

#### 4 SUMMARY AND CONCLUSIONS

For a period of few months we followed the evolution of optical turbulence over Cerro Tololo, for the first time being able to know where the ‘seeing’ comes from and why it changes. The database of some 28000 low-resolution TPs, most of which are complemented by seeing data, is unique by its volume and time coverage. The insights gained from this data can be summarized as follows:

- (i) Ground layer turbulence (first 500 m) at CTIO contributes 60% of the total turbulence integral in 50% of cases. Thus, a complete compensation of this layer would typically improve the seeing  $0.4^{-3/5} = 1.7$  times.
- (ii) The median free-atmosphere seeing  $\epsilon_f$  (all layers above 500 m) is  $0''.55$ , in 10% of cases it is better than  $0''.28$ , but it is practically never better than  $0''.15$ . The effective lower limit to  $\epsilon_f$  is related to the ever-present weak turbulence in the upper tropospheric layers above 12 km.
- (iii) The periods of stably calm upper atmosphere with  $\epsilon_f < 0''.25$  can be as long as few days. This occurs when the wind velocity at 12 km a.s.l. is around 20-30 m/s. During these periods, a resolution gain from ground layer AO compensation will be 2-3.

(iv) The characteristic time of turbulence variation increases with increasing layer altitudes, from 15 min. (at 50% correlation level) at 1 km to 1-2 hours at 16 km. Often the turbulence at altitudes of 1-8 km has a character of recurrent strong bursts that last for  $\sim 0.5$  hour and repeat every 1-2 hours.

Perhaps the most important impression from the data is the fragility of astronomical seeing. Most of the seeing results from local orographic effects and is significantly influenced by very unstable ground-layer turbulence. A common opinion that all good sites are similar and have a median seeing around  $0''.7$  is in contradiction with the complexity of turbulence phenomena evidenced by this study. We believe that a better understanding and modeling of optical turbulence is possible and will help to choose ‘lucky summits’ that are much less affected by turbulence generated near surrounding mountains. Statistical data on TP will be essential for this work.

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