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Optical parameters relevant for High Angular Resolution at Paranal from GSM instrument and surface layer contribution

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Abstract. Main atmospheric parameters characterizing the turbulence were measured at the Paranal ESO Observatory (Chile) with the Generalized Seeing Monitor (GSM) during 19 nights in November–December 1998. The median seeing for this period was 0.88″, a little worse than average , the spatial coherence outer scale of the wavefront $\mathcal{L}_0$ = 22.0 m and the median isoplanatic angle θ_0= 1.90″. A very good agreement with seeing values given by ESO DIMM was found. Effects of ground layer turbulence were estimated from measurements of temperature micro–fluctuations at several altitudes. These measurements revealed that the first 21 meters above ground account for 12.5% of the total turbulent energy. Comparison between GSM and ESO DIMM values have permitted to highlight a local phenomenon which occurs sometimes at the site in the middle of the night. Statistics of the refractive index structure constant C_n^2 in the surface layer is also studied.

Key words: turbulence – atmospheric effects – site testing – high angular resolution – outer scale

1. Introduction

It is well known that performances of high angular resolution techniques (HAR) are severely limited by the random optical effects induced by the turbulent atmosphere on the light propagation. A quantitative spatial and temporal characterization of the corrugated wavefront at the ground is necessary to optimize the operation of adaptive optics (AO) and long baseline interferometry (LBI) instruments and to guide the future development of these techniques.

The parameters which characterize the wavefront statistics from an optical point of view are the well known Fried's parameter $r_0(\lambda)$, the spatial coherence outer scale of the wavefront $\mathcal{L}_0$ (called outer scale hereafter), which becomes of importance when comparable to the telescope aperture, the isoplanatic angle $\theta_0(\lambda)$, and the characteristic time which determines the response time for the deformable mirror in AO or for the fringe tracking in LBI.

A specific instrument named GSM (Generalized Seeing Monitor)dedicated to the monitoring of these parameters has been built. It has been essentially developed (Martin et al. 1994) to evaluate the outer scale statistics because no systematic measurements existed for it. The scattered values available in the literature were deduced from various techniques and were somewhat controversial (Mariotti et al. 1984, Colavita et al.1987, Rigaut et al. 1991, Ziad et al. 1994, Buscher et al. 1995, Takato et al. 1995, Davis et al. 1995, Beriot et al. 1997)

The VLT system with its four 8 m apertures is a set of optical telescopes. It is located at the ESO Cerro Paranal observatory in Chile which is among the major world astronomical sites. The properties of the atmospheric turbulence at this site are of the utmost importance for the operation of this unique system.

A statistics of seeing and cloud coverage at Paranal over several years was obtained from the Differential Image Motion Monitor of ESO (Sarazin & Roddier 1990) and shows it to be one of the lowest among those measured at several astronomical sites, with the long–term median seeing of 0.70″. However, the information on some other properties of atmosphere at Paranal was missing. The aim of our measurement campaign with GSM in December 1998 was to provide statistics of the outer scale $\mathcal{L}_0$ and of the isoplanatic angle θ_0. The corresponding results are presented in section 3.

Previously, the GSM worked successfully at the ESO La Silla observatory (Martin et al. 1998b), and in some other observatories over the world (Oukaïmeden in Morocco, Maydanak in Uzbekistan, and Cerro Pachon in Chile, the southern site for the Gemini project).

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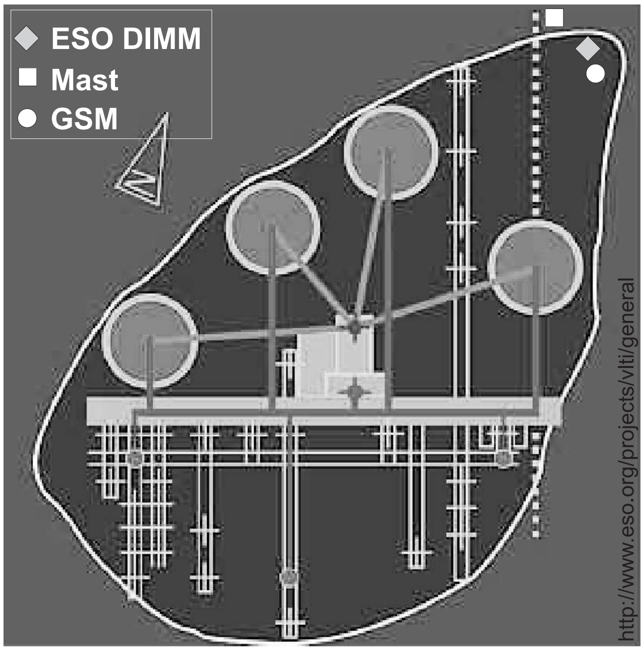

Fig. 1. The plan of Paranal site and the location of the equipment.

The schematic plan of the Paranal site is given in Fig. 1. The pillars with GSM telescopes were located near the ESO DIMM seeing monitor. A pre–existing mast was used to install three couples of temperature sensors for temperature micro–fluctuation measurements in the Surface Layer (SL).

All atmospheric parameters given in this report are calculated for a wavelength $\lambda = 500$ nm for observations at zenith. Seeing angle ε is the full width at half maximum (FWHM) of a long-exposure stellar image in a large telescope, $\varepsilon = 0.98\lambda/r_0$. Outer scale $\mathcal{L}_0$ is a C_n^2–weighted average of the local turbulence outer scale $\mathcal{L}_0$(h), as defined by Borgnino (1990). The isoplanatic angle θ_0 is relevant for adaptive optics (Fried 1982).

2. Principle of measurements

Although the Generalized Seeing Monitor was the main instrument used in this campaign, we devote little space to its description, which can be found in our previous works.

2.1. Principle of the GSM

In its initial version GSM is presented in Martin et al. (1994). The actual instrument is described in Martin et al. (1998b) and Tokovinin et al. (1998b). Description and performance analysis are also given in Ziad et al. (1999). We refer the interested readers to the reports on the previous GSM missions (Martin et al. 1998a and Tokovinin et al. 1998a).

The GSM instrument consists of four 10-cm telescopes with their individual image analysis devices to sense the angle of arrival (AA) fluctuations in one direction, called *modules*. The telescopes are installed on three equatorial mounts; two modules share the same mount and are working as the ESO DIMM. At a distance of 1 meter to the south of these modules a third one is installed on a separate mount. The fourth one, with its mount, is located at 0.8 m to the east. The same L–shaped configuration has been used in the previous GSM missions except at Maydanak site.

GSM modules and their mounts were installed on top of 3 concrete pillars, with the height of telescopes 1.7 m above ground. From 3 sides the experiment was surrounded by a wind-protective enclosure consisting of a 2 m high net.

Atmospheric AA fluctuations are measured by each module in the declination direction, with 5 ms time resolution. A typical measurement consists of a 2 mn long data acquisition. It is processed immediately, providing the estimate of the Fried's coherence diameter r_0 (from differential AA fluctuations in modules 1 and 2), outer scale $\mathcal{L}_0$ (inferred from the covariances of AA and computed via the Von Karman model for the phase spectrum of the turbulent atmosphere), and isoplanatic angle θ_0(from scintillation index).

The ESO DIMM seeing monitor (Sarazin & Roddier 1990) which operates at the Paranal site continuously was located at a distance of the order of 10 meters from GSM. It is installed on a 6 m high tower, in order to avoid the near-ground turbulence effects as much as possible.

2.2. Temperature micro-fluctuation measurements in the surface layer

Turbulence sensing in the SL has been undertaken in order to gain a better understanding of the turbulence effects near the ground. For balloon measurements of the vertical turbulence profiles,very sensitive temperature sensors have been developed in our laboratory. Each probe consists of two thin-wire sensors mounted at a separation of 1 m on a rod. The structure constant of temperature fluctuations, C_T^2, is calculated from the dispersion of the temperature difference between the pair of sensors. The time resolution of the micro–thermometers with their electronics and transmitting devices is about 5 ms and an integrated value of the structure constant is transmitted to the ground each 1.5 s. The typical noise level can reach a few 10^{-8} (Celsius degree)^2. The refractive index structure constant C_n^2 is calculated from C_T^2 using the appropriate values of mean temperature and pressure. C_n^2 values are obtained with a precision around 10^{-20} m$^{-2/3}$. Previous results obtained with this equipment can be found in Vernin & Muñoz-Tuñon (1992).

Four pairs of sensors were installed on the meteorological mast at the heights of 3, 7, 21, and 31 m above the base of the mast. The upper sensor, however, was damaged, and only the remaining 3 have provided valid data.

It must be noted that the base of the mast was somewhat lower (by 1 m) than the ground level of GSM/DIMM location. Hence the sensors at 3 and 7 meters are at the same heights as GSM and DIMM, respectively.

3. The GSM campaign at Cerro Paranal Observatory

The GSM instrument has been transported to Paranal after the completion of the previous mission in October 1998 at Cerro Pachon (Chile).

The excellent quality of Paranal site have permitted to collect 1884 acquisitions during 19 nights, more than in any previous GSM campaign.

Micro-thermal data acquisitions have been operational only during 9 nights.

3.1. Results of the campaign

Throughout this report the universal time (UT) is given. A date always refers to the beginning of the night. The data summary for the mission is presented in Table 1. In the first columns we give date, median speed and direction of the wind at 10 m altitude. Next 3 columns contain the nightly median values of main atmospheric parameters measured by GSM, namely seeing ε, outer scale $\mathcal{L}_0$ and isoplanatic angle θ_0. In the last column the seeing values computed by the ESO DIMM are listed.

During our mission the overall median seeing was slightly worse than long–term average for Paranal ($0.70''$), but typical for the whole 1998 year, with its monthly average seeing of $0.9'' - 1''$. We note a very good stability of atmospheric parameters. Notably, in the period of December 1 – 5 surprisingly little variation of all main parameters occurred. Similar values were found again on December 15, 16 and 17.

The graphic representation of the ensemble of GSM data is given in Fig. 2.

3.2. Outer scale statistics

GSM is the first instrument capable to measure the outer scale $\mathcal{L}_0$ continuously and to study the statistics of this important parameter. During its previous missions it was found that $\mathcal{L}_0$ follows a log-normal distribution with a dispersion of $\log(\mathcal{L}_0)$ of about 0.23 , and , rather similar median values, ranging from 24 to 31 m, were obtained in all GSM campaigns (Ziad et al. 1999). Large isolated values of $\mathcal{L}_0$, called “bursts”, were also noted at all sites.

At Paranal we, for the first time, registered during several periods relatively small and stable outer scales. Our overall median $\mathcal{L}_0 = 22.0$ m is smaller than at other sites studied.

In the plot of $\mathcal{L}_0$ given in Fig. 2(a) we note the occurrence of two nights with relatively large median values of $\mathcal{L}_0$ (45 and 48 m).On both these nights the wind of 6 m/s was blowing from South, which is not typical for Paranal.

During any single night there is no obvious systematic correlation of $\mathcal{L}_0$ with seeing, even if a poor correlation appears sometimes.

The bursts of $\mathcal{L}_0$ exist at Paranal, as well as at other sites.

Curiously, a burst occurred at about the same time, 03h30 UT, during several nights. We believe that this effect is not an artefact, but reflects some real changes in the turbulence regime at Paranal site. Persistent local effects occurring in the SL at the same local time during several nights were also found (see below).

Table 1. Data summary

Date	Wind at 10 m m/s		ε $''$	$\mathcal{L}_0$ m	θ_0 $''$	$\varepsilon_{\mathrm{DIMM}}$ $''$
27.11	7.3	E→N	0.81	23.8	1.95	0.79
28.11	0.6	S→W	0.67	15.6	2.45	0.97
29.11	6.9	SE (stable)	0.99	45.3	1.68	1.05
30.11	3.6	S→W	1.02	21.7	1.90	1.00
1.12	4.1	S→NW→NE	0.90	16.7	1.78	0.85
2.12	5.4	N→E→N	0.88	16.9	1.75	0.85
3.12	4.8	E→N	0.79	16.8	1.97	0.76
4.12	4.5	E→N	0.81	17.0	2.17	0.69
5.12	5.2	E→N	0.90	16.5	2.09	0.87
6.12	8.3	N→NE	0.86	24.5	1.74	0.84
7.12	6.5	N→NE	1.03	19.4	1.48	0.95
8.12	3.2	S→N	0.90	16.9	1.51	0.80
14.12	6.3	S (stable)	0.92	48.4	1.95	0.95
15.12	3.4	SE→N	0.95	21.5	2.22	0.80
16.12	3.1	SE→N→NE	0.89	17.5	2.54	0.96
17.12	6.5	E→N	0.89	23.6	1.41	0.99
18.12	8.8	N→NE	1.31	37.0	3.17	1.46
19.12	10.8	N (stable)	0.73	33.9	2.09	0.83
20.12	6.5	E→N	1.29	23.7	1.41	1.30
Average median values			0.88	22.0	1.90	0.87

4. Contribution of the surface layer to the overall seeing

4.1. Surface layer detection from GSM and DIMM measurements

A comparison of seeing values measured simultaneously by ESO DIMM and GSM shows that most of the time both instruments are in excellent mutual agreement. An example of such agreement is given in Fig. 3.

However, for some periods GSM measured a worse seeing than DIMM because of the lower height of GSM, which makes it more sensitive to the SL turbulence. This situation appeared soon after the beginning of our mission as an enigmatic effect: for several consecutive nights, starting from December 1 and until December 5, GSM registered a much worse seeing than DIMM for a period of about one

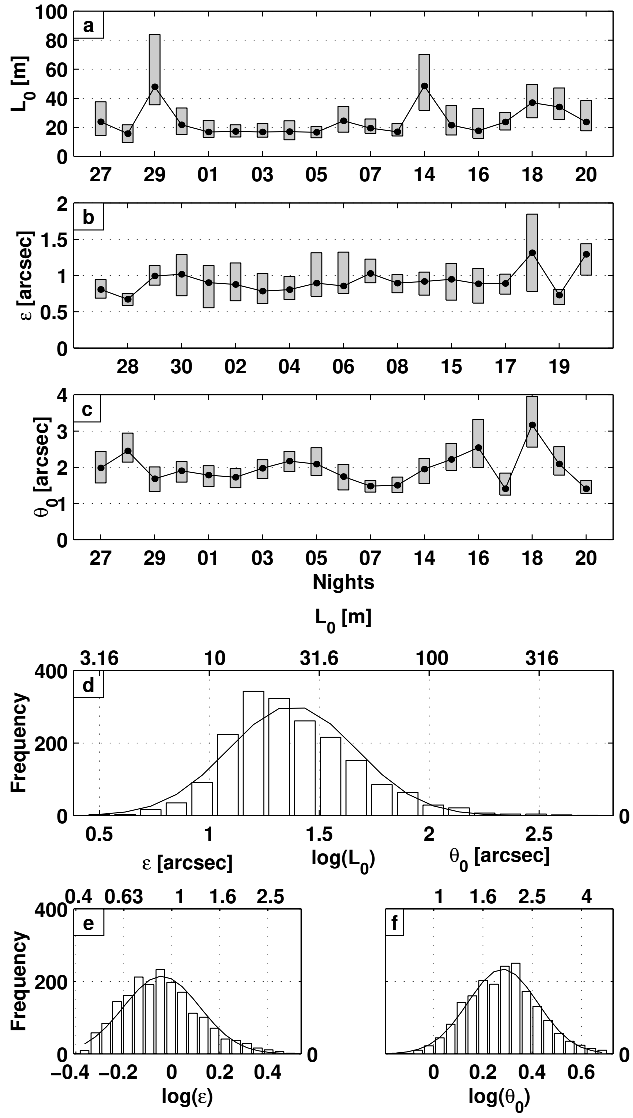

Fig. 2. Summary of the GSM data at Paranal: evolution of (a): wavefront outer scale $\mathcal{L}_0$, (b): seeing ε and (c): isoplanatic angle θ_0 during the 19 nights of the mission. For each night the median value of the considered parameter is plotted as a dot and the rectangle indicates the range in which 50% of the values are included. The histograms of these 3 parameters ((d) , (e) and (f)) correspond closely to a log–normal distribution.

hour, around local midnight. For the rest of the time, the agreement was good. A most clear example of this phenomenon (which we call here midnight local turbulence, or MLT) is given in Fig. 4. On December 2, starting from 03h00 UT, GSM gave a seeing systematically worse than that given by DIMM. This particular local phenomenon (MLT) is explained in the next subsection.

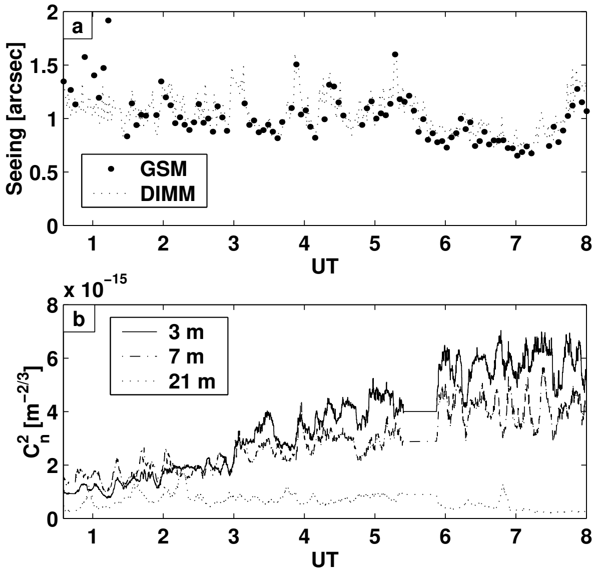

Fig. 3. The seeing measured by GSM (full circles) and ESO DIMM (dotted line) on the night of November 29 is plotted in the upper panel, showing an excellent agreement between both instruments. Simultaneous recordings of the C_n^2 with temperature sensors at the heights of 3, 7 and 21 m are plotted in the lower panel.

4.2. Statistical contribution of the surface layer to the global seeing

The micro-thermal data, also plotted in Fig. 3 and Fig. 4, confirm the idea that the divergence between GSM and DIMM seeing values is caused by the strong turbulence in the first few meters above the ground. Indeed, the period of disagreement exactly matches the turbulence increase at 3 m. Similar behavior was observed on the nights of December 1–5 corresponding to the period of stable atmospheric conditions, already noted in Sect. 3. Ground wind of 5 m/s was prevailing during this period, with a direction slowly changing from East to North during the night, and with moderate velocity variations.

A simple statistical processing of the temperature micro-fluctuation data permits to give a global behavior of the C_n^2 measured at the three heights during 9 nights. For each height, about 45000 values of the structure constant have been recorded and processed. The results can be seen in Fig. 5 which shows clearly that statistically the C_n^2 mean value near the ground (at 3 m) is greater than the one at 21 m. The ratio of the corresponding values of C_n^2 is approximately 16. Conversely, the dispersion grows with height.

To estimate the relative contribution of the SL to the total seeing degradation, a turbulent energy ratio (TER) can be defined as the ratio of the turbulent energies in the

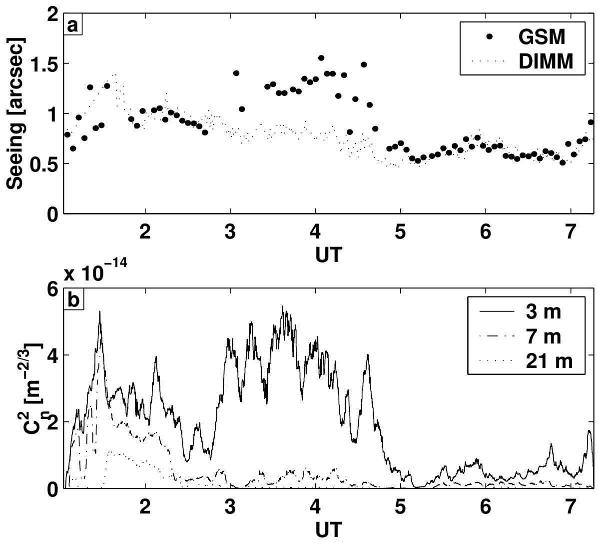

Fig. 4. Same as Fig. 3 for the night of December 2. The local turbulence around midnight caused the difference of the seeing measured by GSM and DIMM. It matches the increase of C_n^2 at the height of 3 m.

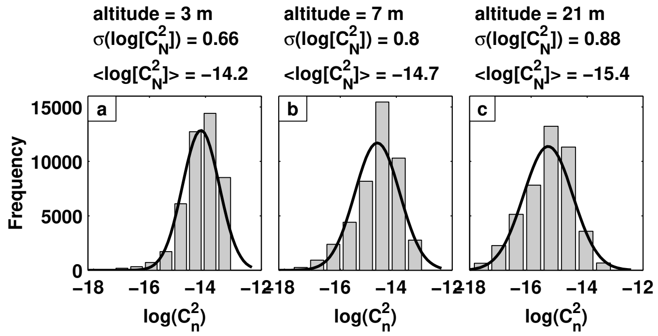

Fig. 5. Histograms of the C_n^2 values computed from the temperature sensors at 3 altitudes , (a): 3m , (b):7m and (c):21m

(3m–21m) and (3m – infinity) layers:

$$TER = \frac{\int_{3m}^{21m} C_n^2 dh}{\int_{3m}^{+\infty} C_n^2 dh} \tag{1}$$

For all the nights during which temperature data where available, this ratio has been computed each four minutes in order to match the sampling rate of the GSM which provides the turbulent energy from 3 m to infinity. Numerator of the above expression is deduced from the integration of rough C_n^2 profile given by the temperature sensors between 3 m and 21 m. Night by night mean values of the TER can be found in Fig. 6. From the table one can see that nightly values are in a ratio of 1 to 2.4.

Date	TER [%]
29.11	7.18
30.11	7.69
01.12	13.41
02.12	17.06
03.12	14.11
04.12	9.90
05.12	16.76
06.12	16.50
07.12	10.26
Mean	12.5

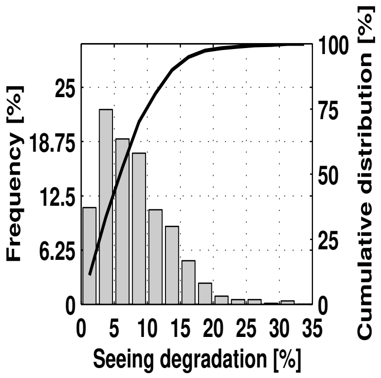

Fig. 6. Values of the turbulent energy ratio for the 9 nights for which temperature data are available. Histogram of the seeing degradation values and corresponding cumulative distribution.

In comparison with the seeing produced by turbulence layers above 21 m, a degradation would occur if the turbulent effects in the SL were added. The value of the seeing degradation (%) is given by $(1 - [1 - TER]^{0.6})$.

Histogram of the seeing degradation values and its cumulative distribution are plotted in Fig. 6. The median value is 7.2%. Fifty percent of the values centered on the median are between 4.0% and 11.0%.

It is thus evident that the contribution of the SL to the global seeing cannot always be considered as negligible and, although GSM is more affected by SL turbulence, DIMM is not always entirely free of it either. Ground turbulence, a part of which appears above DIMM but below VLT, may partially explain the difference sometimes detected between UT telescopes and DIMM seeings.

5. Conclusions

The GSM mission to Paranal was highly successful and for the first time provided statistical data on the outer scale at this site. Our main results consist in the following:

- The distribution of the outer scale $\mathcal{L}_0$ at Paranal is close to log-normal, with a median value of 22.0 m. It means that because $\mathcal{L}_0$ is comparable to the telescope aperture size the effects of the finite outer scale on the operation of VLT are significant and result in reduction of image motion.
- The correlation of $\mathcal{L}_0$ with local meteorological conditions was noted. For typical conditions of NE wind, stable nightly median values of $\mathcal{L}_0$ around 16 m are found, whereas for the southern wind (associated with the wind shear in the boundary layer) they are over 45 m.
- Excellent agreement of the seeing measured by the GSM and by the ESO DIMM is found. Median seeing for our campaign was 0.88″ for GSM and 0.87″ for DIMM.
- The median value of the isoplanatic angle θ_0 was 1.90″ during our mission. This appears as an intermediate

value in comparison with our estimations during previous measurement campaigns at other observatories (1.26″ at La Silla, 2.48″ at Maidanak and 2.73″ at Cerro Pachon). Thus, the high-altitude turbulence over Paranal appears to be not substantially different from other observatories.

– The strong local turbulence in the first few meters of the surface layer exists at Paranal for some periods of time, as evidenced by DIMM-GSM comparison and micro-thermal mast measurements.
  Turbulent energy in the SL contributes an average amount of only 12.5% to the total turbulent energy detected by GSM along the line of sight. This corresponds to an average seeing degradation around 8% if turbulence effects in the SL are added to the turbulence above 21 m. While unit telescopes of the VLT are not affected by these layers, the situation will not be the same for auxiliary telescopes (ATs) of the VLTI which have been designed closer to the ground (4.5–6.5 meters). Hence, continuous micro-thermal monitoring at Paranal appears to be desirable to study the local effects in detail and to evaluate their importance for the site seeing and particularly for the ATs.
– The temporal evolution of atmospheric parameters at Paranal seems to be rather specific (prolonged periods of stable conditions; dependence on the wind speed and its fluctuations; repeatable increases of surface layer turbulence) compared to other sites, and warrants further investigation. A better understanding of the mechanisms of Paranal seeing will eventually lead to forecast observing conditions.

The analysis of the spatio–temporal cross–correlations of the AA fluctuations can lead to the detection of the atmospheric layers (Avila et al. 1997). From the AA cross–correlations one can estimate the number of predominant turbulent layers, their respective strengths, the velocity and direction of the wind which carries the turbulent eddies. The principle of the wind measurement with GSM is given in Conan et al. (1998). The full wind analysis and cross-correlation interpretation must include simultaneous comparisons with other parameters, $\mathcal{L}_0$, ε and θ_0. The methods of such complete analysis are still under development.

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