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SURFACE LAYER SEEING AT SAN PEDRO MÁRTIR REVISITED

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RESUMEN

Reportamos medidas de la contribución de la capa superficial (2.3 a 15 m) al *seeing* óptico en el Observatorio Astronómico Nacional de San Pedro Mártir (OAN-SPM). Utilizamos un mástil con sensores de temperatura microdiferenciales localizados a 7 diferentes alturas, para medir la constante de estructura del índice de refracción $C_{\rm n}^2$ en los primeros 15 m. El parámetro de distorsión de la imagen (llamado comúnmente *seeing*) integrado se determinó utilizando un Monitor Diferencial de Movimiento de Imagen (DIMM) durante 23 noches, encontrándose una estadística log-normal con una mediana de 0.″84. El *seeing* promedio debido a la capa superficial fue de 0.″16. La turbulencia óptica de esta capa tiene una contribución promedio de 5.2% del $C_{\rm n}^2$ total, lo cual corresponde a una degradación promedio de 3.2% del *seeing* total. Estos valores son similares a los encontrados en otros observatorios en el mundo, lo que sugiere que la presencia de árboles en el sitio del OAN-SPM no influye de manera considerable en el *seeing* debido a la capa superficial.

ABSTRACT

Results from experiments measuring the contribution of the surface layer (2.3 to 15 m) to the optical *seeing* at the Observatorio Astronómico Nacional at San Pedro Mártir (OAN-SPM) are reported. Microthermal sensors placed at 7 heights on a 15-m-high instrumented mast were used to measure the structure constant of the refractive index $C_{\rm n}^2$. The integrated *seeing* parameter was measured with a Differential Image Motion Monitor (DIMM) during 23 nights. Log-normal statistics were found for the DIMM *seeing* with a median value of 0.″84. The surface layer average *seeing* was found to be 0.″16. The measured optical turbulence of this layer has a mean contribution of 5.2% to the total $C_{\rm n}^2$, which corresponds to a mean degradation of 3.2% of the total *seeing*. These values are similar to those found in other observatories around the world, suggesting that the presence of trees in the OAN-SPM does not have a significant effect on the surface layer *seeing*.

Key Words: **ATMOSPHERIC EFFECTS — METHODS: DATA ANALYSIS — SITE TESTING — TURBULENCE**

1. INTRODUCTION

Important constraints on astronomical site selection and the design of telescopes and instruments are imposed by the, so called, astroclimatical parameters. On-site measurements are essential for the determination of these parameters. One of these parameters is called the *seeing*.

Astronomical *seeing* is known as the blur of a stellar image generated by the propagation of light in turbulent nonisothermal air. It arises in the free atmosphere, the boundary layer above the site, the air layer near the ground, and the air around and inside the telescope enclosure (local *seeing*).

The surface layer (SL) can be defined as the turbulent layer which extends a few meters above the ground and produces optical turbulence.

In this communication we report the SL contribution to the *seeing* at the Observatorio Astronómico Nacional at San Pedro Mártir (OAN-SPM), Baja California, México, operated by the Instituto de Astronomía of the Universidad Nacional Autónoma de México (IA-UNAM).

The main purpose of this communication is to revise the analysis of measurements already reported by Sánchez et al. (2003).

During two different seasons a Differential Image Motion Monitor (DIMM) was used to measure the integrated optical turbulence over the whole atmosphere (open-air *seeing*) and simultaneously we used microthermal sensors mounted on a dedicated 15-m

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mast to measure the optical turbulence strength C_n^2 vertical distribution in the first 15 m.

Similar studies on surface layer (SL) *seeing* contribution (Gur'yanov et al. 1992; Vernin & Muñoz-Tuñón 1992, 1994; Marks et al. 1996; Pant, Stalin, & Sagar 1999; Martin et al. 2000; Aristidi et al. 2005) carried out in several observatories gave contributions to the total *seeing* ranging from a few tenths of arcseconds to $\sim 1.''2$ (Racine 2005).

In § 2 a brief description of the intensive site testing campaign and the experimental methods is presented. *Seeing* measurements and statistics are presented in § 3. In § 4 the results on the optical turbulence at the surface layer are discussed. The summary and final remarks are given in § 5.

2. SITE TESTING CAMPAIGN AND EXPERIMENTAL METHODS

2.1. *Site Testing Campaign at San Pedro Mártir*

The San Pedro Mártir (SPM) Sierra, site of the Mexican Observatorio Astronómico Nacional operated by IA-UNAM, is situated on the northern part of the Baja California peninsula. A complete description of the site characteristics can be found in previous papers (Tapia 1992; Alvarez 1969; Cruz-González, Avila, & Tapia 2003; Cruz-González, et al. 2004; Tapia, Cruz-González & Avila 2007). Concerning optical turbulence studies, Avila, Vernin, & Cuevas (1998) monitored the vertical distribution of C_n^2, using the Generalized Scidar of the Départment d'Astrophysique of the Nice-Sophia Antipolis University, France (DA-UNSA). They report that in the first kilometer the median seeing value is $0.''56$, in the free atmosphere its value is $0.''44$ and for the whole atmosphere it results in a median value of $0.''77$. These values were found when the Generalized Scidar was installed at the 2.1-m telescope and include dome seeing. Echevarría et al. (1998) reported a median open-air seeing of $0.''61$, obtained during an extensive (3-years) seeing campaign, using non-differential seeing monitors. Masciadri, Avila & Sánchez (2002) presented evidence of a finite horizontal extension of turbulence layers at the site, and Conan et al. (2002) reported log-normal statistics for the seeing and for the outer scale, with median values of $0.''77$ and 27 m, respectively. Finally, Michel et al. (2003), using the same DIMM we used in our experiment, measured the seeing during 123 nights and found a median seeing of $0.''61$.

During May and December 2000, intensive site testing campaigns took place at SPM. The campaigns were developed by a collaboration between the IA-UNAM and the DA-UNSA. A full description of the campaigns can be found in Avila et al. (2002) and Conan et al. (2002).

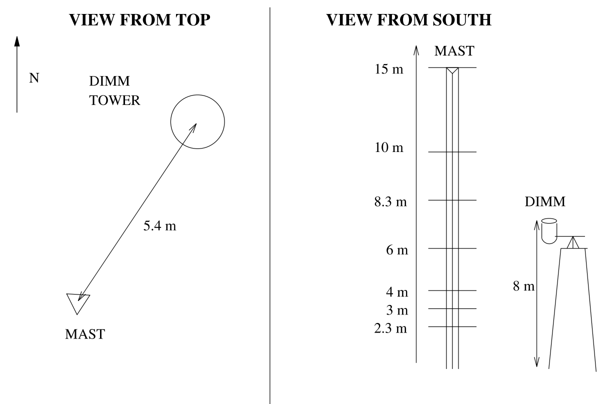

Fig. 1. Layout of the location of the DIMM and the instrumented mast during the December 2000 campaign.

Among the several instruments deployed, a 15-m mast, equipped with sensors measuring temperature microfluctuations, was used to sample the vertical distribution of C_n^2 in the surface layer. Simultaneously we used a DIMM to measure the total open-air seeing.

All atmospheric-turbulence parameters given here are calculated for a wavelength of $\lambda = 0.5$ μm and for observations at the zenith. The seeing angle ε (expressed in arcseconds) corresponds to the full width at half maximum intensity (FWHM) of a long-exposure image of a point source in a large telescope.

We analyzed DIMM data obtained in two different epochs: 7–22 May, and 1–14 December 2000. During May, the DIMM was installed on a low-altitude platform, that brought the entrance pupil $\sim$2 m above the ground, whereas in the December 2000 campaign, the DIMM was installed on a dedicated tower, so that the pupil was $\sim$8 m above the ground. The position of the DIMM relative to the mast during the December 2000 campaign is shown in Figure 1.

2.2. *The Differential Image Motion Monitor*

A Differential Image Motion Monitor (DIMM) is a fairly well known instrument used to measure the seeing (Sarazin & Roddier 1990). We give here only a brief description. A complete presentation can be found in Vernin & Muñoz-Tuñón (1995). The DIMM used here was originally developed in a collaboration between the DA-UNSA and the Instituto de Astrofísica de Canarias (IAC), Spain. It consists of a 20-cm Celestron telescope supported by a very robust equatorial mount. The entrance pupil of the telescope has a diaphragm that creates two 6-cm circular sub-pupils with a 14 cm separation. One of the sub-pupils has an optical wedge, so that on the focal plane two images of the observed point source are formed. An intensified CCD records a focal plane frame every 20 ms, with an exposure time of 10 ms. Using a PC, for each frame, the photo-centers of the two star-images are determined. The position of these photo-centers vary randomly as a consequence of atmospheric turbulence. From a set of 400 frames, the variance of the differential image positions is calculated and related to the seeing using the standard theory of optical turbulence (Roddier 1981). Because it is a differential method the technique is practically insensitive to erratic motions of the telescope introduced by wind or ground vibrations (Sarazin & Roddier 1990). The seeing value is given by

$$\varepsilon_{\rm FWHM} = 0.98 \left[\frac{\lambda}{r_0(\lambda)}\right] \quad , \qquad (1)$$

where $r_0(\lambda)$ is the Fried's parameter (Fried 1982). So, the seeing equals the angular resolution of a telescope with a mirror of diameter $r_0(\lambda)$. The instrument delivers one seeing value, corrected for the air-mass factor, every 30 s with an accuracy better than $0''.1$ for stars brighter than 4th-mag.

Data results obtained with the DIMM during the 13 nights on May and 10 nights December are presented in § 3.

2.3. *Microthermal sensors at the Instrumented Mast*

The microthermal sensors were developed at the DA-UNSA by M. Azouit and J. Vernin for balloon measurements of the vertical turbulence profiles (Azouit & Vernin 2005). Each probe consists of two thin-wire sensors mounted on a horizontal rod and separated from each other by 0.95 m. The structure constant of temperature fluctuations, $C_{\rm T}^2$, is calculated from the dispersion of the temperature difference between the pair of sensors. The time resolution of the microthermal sensors is approximately 5 ms and an integrated value of the structure constant $C_{\rm T}^2$ is transmitted to a computer every 1.5 s. The refractive index structure constant $C_{\rm n}^2$ is calculated from $C_{\rm T}^2$ and the appropriate values of mean temperature T and pressure P via:

$$C_{\rm n}^2 = \left[\frac{8\times10^{-5}P}{T^2}\right]^2 C_{\rm T}^2 \quad . \qquad (2)$$

In our data processing we decided to keep one $C_{\rm n}^2$ data point every 30 seconds.

The typical uncertainty of the $C_{\rm n}^2$ values is 1.5% (Azouit 2001). Previous results obtained with this instrument can be found in Vernin & Muñoz-Tuñón (1992, 1994), Marks et al. (1996), Martin et al. (2000) and Conan et al. (2002).

Seven pairs of sensors were installed on the mast at the heights above the ground of 2.3, 3, 4, 6, 8.3, 10, and 15 m. At the highest level 2 pairs were installed. The setup was done for the May 2000 campaign and reused during the December 2000 campaign with new probes, which were installed on December 6th. Unfortunately, on December 9th, a snow storm destroyed the whole set of sensors installed on the mast. Only four pairs could be replaced, so in the last few days of the campaign, $C_{\rm n}^2$ values were measured only at 2.3, 4, 8.3, and 15 m. So, we obtained $C_{\rm n}^2$ usable data only for 9 nights on May and 4 nights on December.

We also obtained measurements of absolute temperature values for 4 levels: 3, 4, 10, and 15 m.

3. SEEING MEASUREMENTS AND STATISTICS

A statistical analysis of the seeing measurements obtained with the DIMM during the two observational campaigns was developed. A total of 14930 measurements were gathered during 23 nights.

In the whole data set of DIMM measurements there are 3 nights (May 17th and 19th, and December 13th) with strong bursts of optical turbulence that raise significantly the average seeing.

As explained in § 2.2, in May 2000, the pupil of the DIMM was about 2.3 m above the ground, while in December 2000 its altitude was 8.3 m. In order to analyze the entire DIMM data together as if the instrument would have always been at an altitude of 8.3 m, we estimated the seeing values that would have been measured at 8.3 m ($\varepsilon_{\rm DIMM@8m}$) by subtracting the mean turbulence contribution from 2 to 8.3 m ($\langle\int_{2.3{\rm m}}^{8.3{\rm m}} C_{\rm n}^2(h){\rm d}h\rangle$) to the DIMM data measured at 2 m ($\varepsilon_{\rm DIMM@2.3m}$). The formula used is:

$$\varepsilon_{\rm DIMM@8.3m}^{5/3} = \varepsilon_{\rm DIMM@2.3m}^{5/3} - 15.86\,\lambda^{-1/3}\left\langle \int_{2.3{\rm m}}^{8.3{\rm m}} C_{\rm n}^2(h)\,{\rm d}h \right\rangle \quad , \qquad (3)$$

where the average, represented by the signs $\langle\rangle$, is carried out over the measurements obtained with the instrumented mast during the whole May 2000 campaign.

Table 1 gives the mean DIMM seeing for each night of the May and December 2000 campaigns. We can see that the average integrated seeing $\langle\varepsilon_{\rm DIMM}\rangle$ values range from $0''.52$ to $2''.4$.

TABLE 1

MEAN DIMM SEEING (arcsec)

Date	$\langle \varepsilon_{\rm DIMM} \rangle$	Date	$\langle \varepsilon_{\rm DIMM} \rangle$
05-07-2000	0.88	12-01-2000	0.52
05-09-2000	1.08	12-03-2000	0.59
05-10-2000	0.80	12-04-2000	0.88
05-12-2000	0.83	12-07-2000	0.72
05-13-2000	0.73	12-08-2000	0.89
05-14-2000	1.00	12-09-2000	0.66
05-15-2000	0.83	12-11-2000	0.94
05-17-2000	1.30	12-12-2000	1.38
05-18-2000	0.60	12-13-2000	2.40
05-19-2000	1.34	12-14-2000	1.19
05-20-2000	0.98		
05-21-2000	0.82		
05-22-2000	0.89		

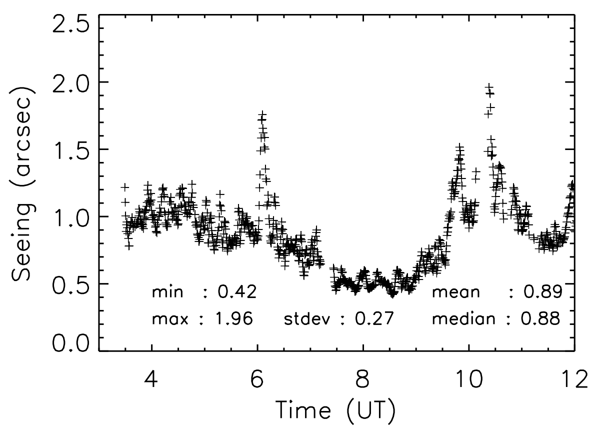

Fig. 2. Example of one night (12-08-2000) of DIMM data and some statistical results for that particular night.

Figure 2 shows an example of DIMM seeing measurements for one night (12-08-2000), with a minimum seeing value of 0.″42 and median of 0.″89.

The cumulative distribution of the entire DIMM data set is shown in Figure 3. The median value is 0.84″, and the 1st and 3rd quartiles are 0.67″ and 1.08″.

The histogram of the logarithm of the seeing values (Figure 4) is well fitted by a Gaussian, which shows that the measured seeing follows nearly a log-normal distribution. The fitted Gaussian is centered at -0.07 log(arcsec) and has a dispersion of 0.15 log(arcsec).

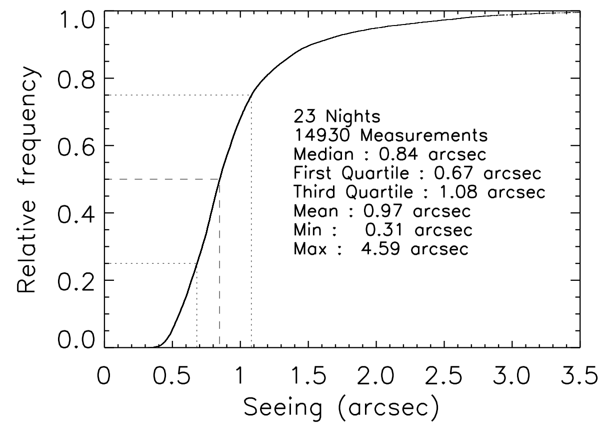

Fig. 3. Cumulative distribution of the DIMM measured seeing and general statistics.

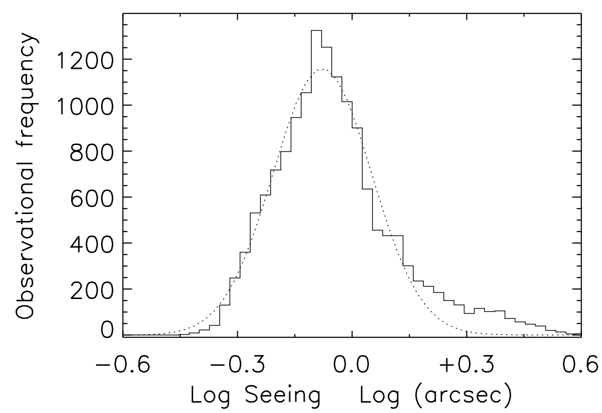

Fig. 4. Histogram of the logarithmic values of seeing with a Gaussian fit showing the log-normal behavior.

The seeing values measured by us, using the DIMM, are comparable to those found by Avila, Vernin, & Cuevas (1998) who used a Generalized Scidar at the 2.1-m telescope, and are somewhat larger than those found by Echevarría et al. (1998) and Michel et al. (2003). The larger seeing values obtained by us can be explained by the reduced number of nights used in our statistics and the bad weather conditions prevailing in some nights during our observations.

4. OPTICAL TURBULENCE AT THE SURFACE LAYER

Examples of micro-thermal data $C_{\rm n}^2(h_i,t)$ for three nights are plotted in Figures 5, 6, and 7. In showing the three possible cases, we want to emphasize that the behavior with altitude of the turbulence strength in the surface layer can show different tendencies: *normal*, in which the turbulence strength

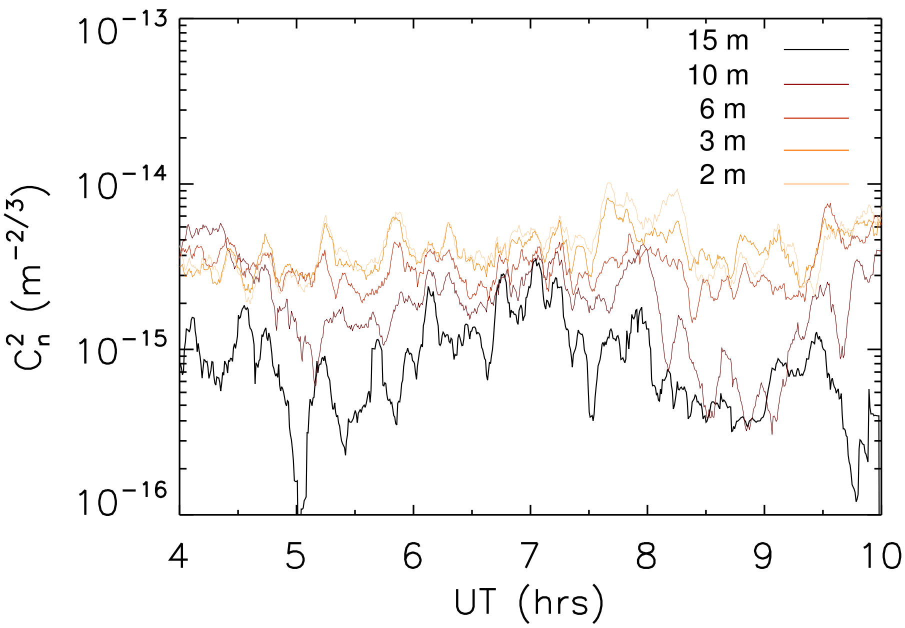

Fig. 5. Temporal evolution of $C_{\rm n}^2$ measured with the microthermal sensors at the heights of 2, 3, 6, 8, 10, and 15 m. Example of one night (05-13-2000) of *normal* behavior of the data.

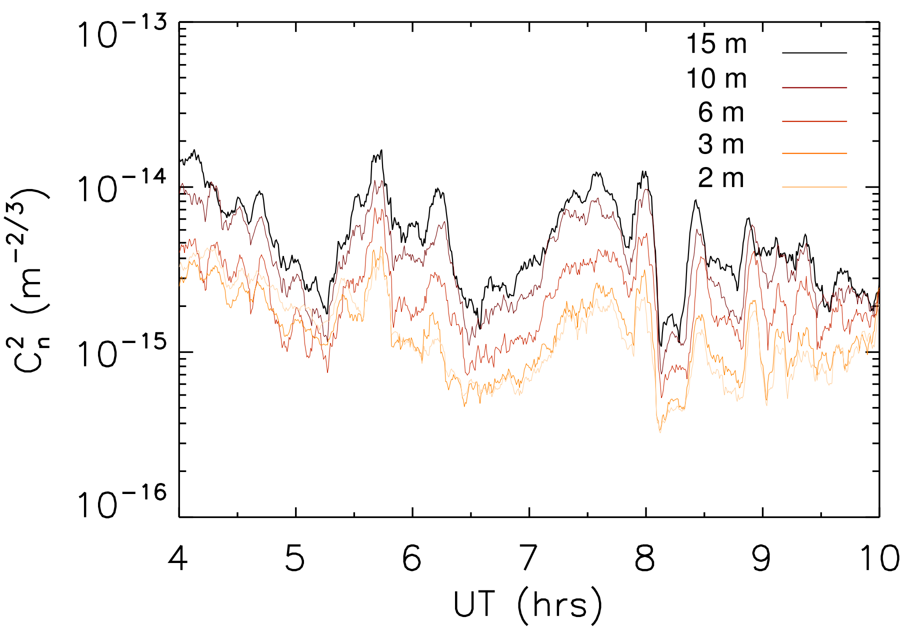

Fig. 6. Temporal evolution of $C_{\rm n}^2$ measured with the microthermal sensors at the heights of 2, 3, 6, 8, 10, and 15 m. Example of one night (05-17-2000) of *anomalous* (inverted) behavior of the data.

decreases with height, the so-called *anomalous* case in which it increases with height, showing an inverted tendency, and finally a *constant* value with height.

We call the first case *normal* following Wyngaard, Izumi, & Collins (1971), who state that the nightly behavior of the refractive-index-structure parameter near the ground follows a decreasing power law with height given by

$$C_{\rm n}^2\,(h) = kh^{-2/3} \quad . \tag{4}$$

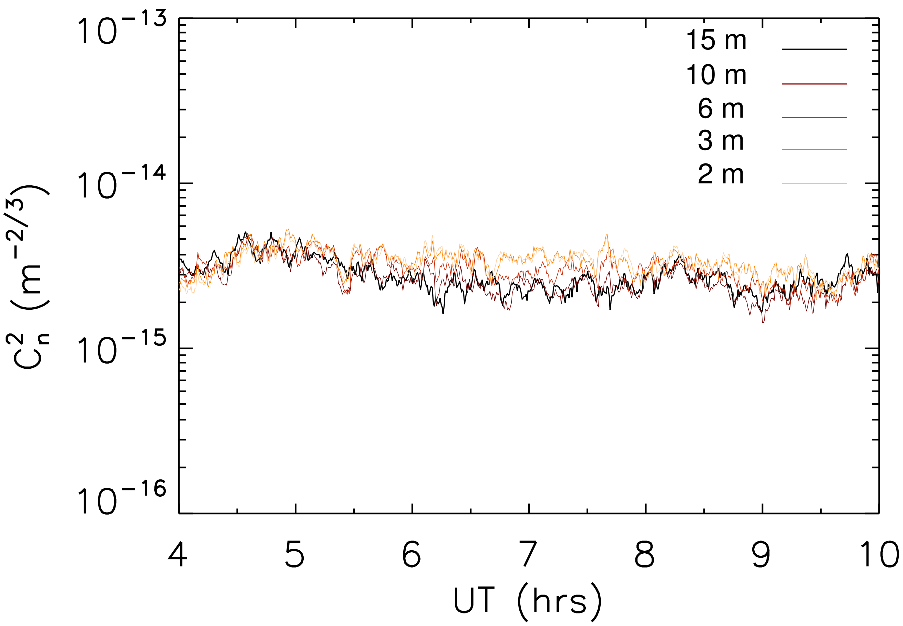

Fig. 7. Temporal evolution of $C_{\rm n}^2$ measured with the microthermal sensors at the heights of 2, 3, 6, 8, 10, and 15 m. Example of one night (05-15-2000) of *constant* behavior of the data.

It is worth mentioning that in our data the *anomalous* case occurred as frequently as the *normal* one.

Equivalent seeing contribution of the surface layer is calculated as

$$\varepsilon_{\rm SL} = 5.25\,\lambda^{-1/5}\left[\left\langle \int_{2.3\rm m}^{15\rm m} C_{\rm n}^2\,(h,t)\,dh \right\rangle\right]^{3/5} \quad , \quad (5)$$

where the average is taken over time. We remark that choosing a $C_{\rm n}^2$ temporal data sampling of 120 data points per hour, gives us reliable statistics with a thousand $C_{\rm n}^2\,(h,t)$ values per night.

In Table 2 we show for each night the measured integrated average of $C_{\rm n}^2$ and its corresponding seeing value. Mean values for the May and December data are also shown. The average total contribution of the turbulence strength in the surface layer is found to be of $3.22 \times 10^{-14}\mathrm{m}^{1/3}$ which is equivalent to a mean seeing value of 0.″16.

4.1. *Contribution of the surface layer to the total seeing*

4.1.1. *Turbulent Energy Ratio (TER)*

In order to calculate the contribution of the surface layer to the total seeing degradation, we make use of the Turbulent Energy Ratio (TER) —introduced by Martin et al. (2000)— as the ratio between the optical turbulent energies obtained for the layers from 2.3 m to 15 m and the average contribution from 2.3 m to infinity.

$$TER = \frac{\int_{2.3\rm m}^{15\rm m} C_{\rm n}^2\,(h)\,\mathrm{d}h}{\int_{2.3\rm m}^{+\infty} C_{\rm n}^2\,(h)\,\mathrm{d}h} = \frac{(\varepsilon_{\rm SL})^{5/3}}{(\varepsilon_{\rm DIMM})^{5/3}} \quad . \quad (6)$$

The denominator is obtained from the average of each night of DIMM data results and re-calculated for a height of 2.3 m, in the case where we have data taken at 8.3 m. The numerator is derived from the microthermal sensor data.

For the TER calculation, we considered 10 nights: May 12–15,17–20 and December 7–8 in which simultaneous DIMM and microthermal measurements were obtained. In Table 3 we show night by night mean values of the TER. They vary from 0.2% to 17.2%, which represents a big span in the surface layer seeing contribution.

The calculated average TER for the data set is 5.2%, which means that the surface layer up to 15-m contributes with 5.2% of the total atmospheric seeing.

4.1.2. *Seeing degradation (SD)*

Another criterion —also introduced by Martin et al. (2000)— that helps to quantify the effects of the optical turbulence produced by the surface layer is

TABLE 2

INTEGRATED C_n^2 AND EQUIVALENT SEEING ε_{SL}

Date (UT)	$\left\langle \int_{2.3m}^{15m} C_n^2\,(h,t)dh \right\rangle$ $\left(m^{1/3}\right)$	ε_{SL} ($''$)
May		
05-12-2000	4.62×10^{-14}	0.19
05-13-2000	1.60×10^{-14}	0.10
05-14-2000	1.99×10^{-14}	0.12
05-15-2000	2.24×10^{-14}	0.13
05-16-2000	6.40×10^{-15}	0.06
05-17-2000	2.98×10^{-14}	0.15
05-18-2000	1.62×10^{-14}	0.10
05-19-2000	2.00×10^{-15}	0.03
05-20-2000	4.56×10^{-15}	0.05
Mean May	1.82×10^{-14}	0.11
December		
12-07-2000	7.17×10^{-14}	0.25
12-08-2000	3.60×10^{-14}	0.17
12-09-2000	6.93×10^{-14}	0.25
12-10-2000	8.13×10^{-15}	0.07
Mean Dec.	4.61×10^{-14}	0.20
Total Mean	3.22×10^{-14}	0.16

the so-called *seeing degradation (SD)*, which is defined by the relation:

$$SD = \left[1 - (1 - TER)^{0.6}\right] \quad . \tag{7}$$

SD indicates the relative decrease of the seeing that would be obtained by placing a telescope at an altitude of 15 m. Developing Eq. 7, it is easy to show that

$$SD = \frac{\varepsilon_{2.3m;\infty} - \varepsilon_{15m;\infty}}{\varepsilon_{2.3m;\infty}} \quad , \tag{8}$$

where $\varepsilon_{2.3m;\infty}$ and $\varepsilon_{15m;\infty}$ stand for the seeing produced in the whole atmosphere and that produced above 15 m, respectively.

In Table 4 we show the SD percentage for each night, which varies from 0.1 to 10.7%.

The calculated average SD due to the surface layer up to 15 m obtained for the whole campaign is 3.2%.

From a careful examination of the values shown in Table 4 it is evident that the contribution of the surface layer (SL) to the global seeing cannot always be considered as negligible. For example for the 12-07-2000 night, the SL contributes with more than 10% of the total seeing. On the other hand we can find nights with a large mean seeing value, for example the 05-19-2000 night with an average seeing of 1.″34, and with a measured surface layer contribution to the total seeing of only 0.1%. This means that, for that night, the mean contribution comes from the upper layers of the atmosphere.

TABLE 3

MEAN TURBULENT ENERGY RATIO

Date	TER (%)
05-12-2000	8.6
05-13-2000	3.7
05-14-2000	2.9
05-15-2000	4.6
05-17-2000	2.7
05-18-2000	5.1
05-19-2000	0.2
05-20-2000	0.7
12-07-2000	17.2
12-08-2000	6.3

TABLE 4

MEAN SEEING DEGRADATION

Date	SD (%)
05-12-2000	5.3
05-13-2000	2.2
05-14-2000	1.8
05-15-2000	2.8
05-17-2000	1.6
05-18-2000	3.1
05-19-2000	0.1
05-20-2000	0.4
12-07-2000	10.7
12-08-2000	3.8

5. SUMMARY AND CONCLUSION

An intensive site testing campaign has been carried out at the site of the OAN-SPM to characterize the optical atmospheric turbulence, and in particular the surface layer contribution to the total seeing. The DIMM measurements show log-normal statistics for the total seeing with a median value of 0.″84. The C_n^2 measurements carried out with an instrumented mast revealed that the first 15-m above the ground account for 5.2% of the total turbulent energy. For the seeing degradation we obtained a mean value of 3.2%. The surface layer average seeing was found to be 0.″16. These results are similar to those found for other observatories around the world (Gur'yanov et al. 1992; Vernin & Muñoz-Tuñón 1992, 1994; Marks et al. 1996; Pant, Stalin, & Sagar 1999; Ehgamberdiev et al. 2000; Martin et al. 2000; Racine 2005), suggesting that the presence of trees in the OAN-SPM does not have a significant effect on the surface layer seeing.

We report as an important result that our data present, what we called, *normal*, *anomalous* and *constant* behavior. The study of these different cases will be expanded with the analysis of a set of simultaneous Scidar (Avila et al. 2006) and local meteorological data. These results will be published in a forthcoming paper.

Further simultaneous micro-thermal and DIMM monitoring appears to be desirable to study the local effects in detail and to evaluate their importance for the site seeing. In particular, a statistical processing of the temperature micro-fluctuations over a larger data set will allow to study the general behavior of the optical turbulence measured at different heights.

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