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CONTRIBUTION OF THE SURFACE LAYER TO THE SEEING AT SAN PEDRO MÁRTIR: SIMULTANEOUS MICROTHERMAL AND DIMM MEASUREMENTS

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RESUMEN

Reportamos medidas de la contribución de la capa superficial al seeing en el Observatorio Astronómico Nacional de San Pedro Mártir (OAN–SPM). Utilizamos un mástil instrumentado con sensores de temperatura micro-diferenciales localizados en 7 niveles para medir la constante de estructura del indice de refracción C_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 durante 23 noches. Se encontró una estadística log–normal con valores promedio de $0.98''$ y de mediana $0.84''$. La contribución de la capa superficial (2.3 a 15-m) a la turbulencia óptica total tiene un valor promedio de 16%, lo cual corresponde a una degradación de 10% 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 afecta de manera considerable el *seeing* debido a la capa superficial. Se requieren más estudios para confirmar esta tendencia.

ABSTRACT

Results from experiments measuring the contribution of the surface layer to the optical seeing at the Observatorio Astronómico Nacional at San Pedro Mártir (OAN–SPM) are reported. Microthermal sensors placed at 7 levels on a 15-m-high instrumented mast were used to measure the structure constant of the refractive index C_n^2. The integrated seeing parameter was measured with a Differential Image Motion Monitor during 23 nights. Log–normal statistics were found for the seeing with mean of $0.98''$ and median value $0.84''$. The contribution of the surface layer (2.3 to 15 m) to the total optical turbulence has a mean value of 16%, which corresponds to a degradation of 10% 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. Further studies should provide a confirmation of this tendency.

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

1. INTRODUCTION

Observational methods with high angular resolution in optical astronomy have seen recently a fast improvement and deployment. Adaptive Optics, one of the leading techniques, benefits from a better knowledge of the optical effects of atmospheric turbulence. Important constraints on astronomical sites selection and the design of telescopes and instruments are also imposed by the, so called, astroclimatical parameters. On–site measurements are essential for the knowledge of these parameters.

The main purpose here is to report measurements of the surface layer (SL) contribution to the seeing at the Observatorio Astronómico Nacional at San Pedro Mártir (OAN–SPM), Baja California, México, held by the Instituto de Astronomía of the Universidad Nacional Autónoma de México (IA–UNAM).

The SL can be defined as the turbulent layer which extends a few meters above the ground.

A Differential Image Motion Monitor (DIMM) was used to measure the integrated turbulence over the whole atmosphere (open–air seeing) during different epochs and simultaneously we used microthermal sensors mounted on a dedicated 15-m-high 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 (Martin et al. 2000; Pant, Stalin & Sagar 1999; Marks et al. 1996) carried out in several obser-

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vatories gave contributions to the total seeing ranging from a few tenths to $\sim 1.5''$.

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 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*

San Pedro Mártir 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). Concerning optical turbulence studies, Avila, Vernin & Cuevas (1998) monitored the vertical distribution of C_n^2, using the Generalized Scidar of the Département d'Astrophysique of the Nice–Sophia Antipolis University, France (DA–UNSA), finding that the seeing originated in the first kilometer, in the free atmosphere, and in the whole atmosphere, had median values of $0.56''$, $0.44''$ and $0.77''$, respectively. 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 $0.77''$[6] and 27-m, respectively.

During May and December 2000, intensive site testing campaigns took place at SPM. The campaigns were performed under 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).

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 zenith. The seeing angle ε

Fig. 1. The DIMM telescope (in front) and the instrumented mast during the May 2000 campaign.

corresponds to the full width at half maximum 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 about 2-m above the ground, whereas in the December 2000 campaign, the DIMM was installed on a tower, so that the pupil was about 8-m above the ground. The position of the DIMM relative to the mast during the two campaigns is shown in Figs. 2 and 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 in these observations was purchased at the company LHESA Electronique and was originally developed in a collaboration between the (DA–

[6]The median value of the seeing was mistakenly reported as $0.92''$ in the abstract of Conan et al. (2002)

San Pedro Mártir: Astronomical Site Evaluation (México, D. F. and Ensenada, B. C., México, April 3-4, 2003)
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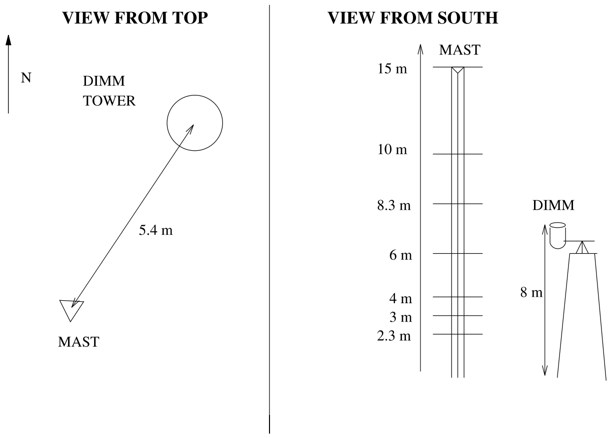

Fig. 2. Layout of the location of the DIMM and the instrumented mast during the December 2000 campaign.

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 separated by a distance of $d = 14$ cm. 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, the photo-center of each of the two star-images is determined for each frame. 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

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

where $r_0(\lambda)$ is the Fried's parameter (Fried 1982). The seeing is corrected for the airmass factor. The instrument delivers one seeing value every 30 s with an accuracy better than $0.1''$ for stars brighter than fourth magnitude.

The distance between the DIMM and the OAN–SPM 2.1 m telescope can be assessed on Fig. 3.

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

Fig. 3. DIMM's telescope on the top of the tower and far behind the OAN–SPM 2.1 m telescope.

2.3. *Microthermal sensors at the Instrumented Mast*

The microthermal sensors were developed at the DAUNSA by M. Azouit and J. F. Manigault for balloon measurements of the vertical turbulence profiles. 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 5 ms approximately 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:

$$C_{\rm n}^2 = \left[\frac{8 \times 10^{-5} P}{T^2} \right]^2 C_{\rm T}^2. \qquad (2)$$

The typical uncertainty of the $C_{\rm n}^2$ values is 1.5% (Azouit 2001). Previous results obtained with this equipment can be found in 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 of 2.3, 3, 4, 6, 8.3, 10 and 15 m above the ground. 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

San Pedro Mártir: Astronomical Site Evaluation (México, D. F. and Ensenada, B. C., México, April 3-4, 2003)
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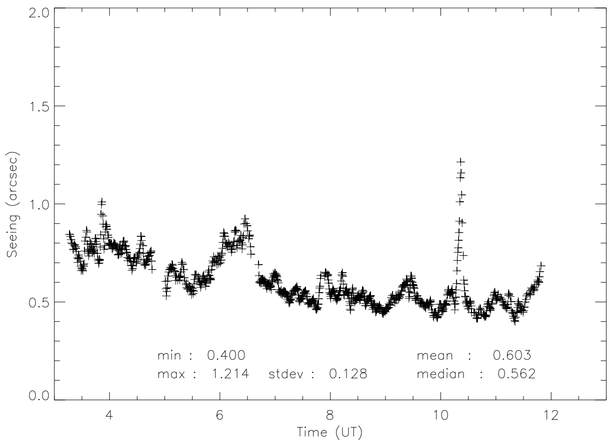

Fig. 4. Example of one night (18-05-2000) of DIMM data and some statistical results for that particular night.

May and 4 nights on December.

Besides, an error in the wiring for levels 4 y 8.3 m led to unusable $C_{\rm n}^2$ values and obliged us to do interpolations in order to have data for this heights.

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

3. SEEING MEASUREMENTS AND STATISTICS

We performed a statistical analysis of the seeing measurements obtained with the DIMM during the two observational campaigns. A total of 14930 measurements where gathered during 23 nights.

In Fig. 5 we show the whole data set of DIMM measurements. As can be seen, there are 3 nights (17, 19 May and 13 December) 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 right formula is:

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

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

TABLE 1

MEAN DIMM SEEING (arcsec)

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

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 $\langle\varepsilon_{\rm DIMM}\rangle$ goes from $0.52''$ to $2.4''$.

Figure 4 shows one of the lowest-seeing nights, with minimum seeing value of $0.4''$ and median of $0.56''$.

The histogram and the cumulative distribution of the entire DIMM data set are shown in Fig. 6. The median value is $0.84''$, and the 1st and 3rd quartiles are $0.68''$ and $1.09''$.

The histogram of the logarithm of the seeing values (Fig. 7) 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).

The seeing values measured by the DIMM are comparable to those found by Avila, Vernin & Cuevas (1998) using a Generalized Scidar at the 2.1m telescope, and are somewhat larger than those found by Echevarría et al. (1998) using non-differential seeing monitors.

We have also analyzed the temporal variation of the seeing in order to have a better insight into the atmospheric behavior which gives rise to optical turbulence.

In Fig. 8 the result of calculating the median of all observing nights is shown versus UT and no significant general trend in the seeing evolution is observed. This is an important conclusion which can be opposed to the generally accepted assumption that ε is worst at the beginning of the night. Our mea-

San Pedro Mártir: Astronomical Site Evaluation (México, D. F. and Ensenada, B. C., México, April 3-4, 2003)
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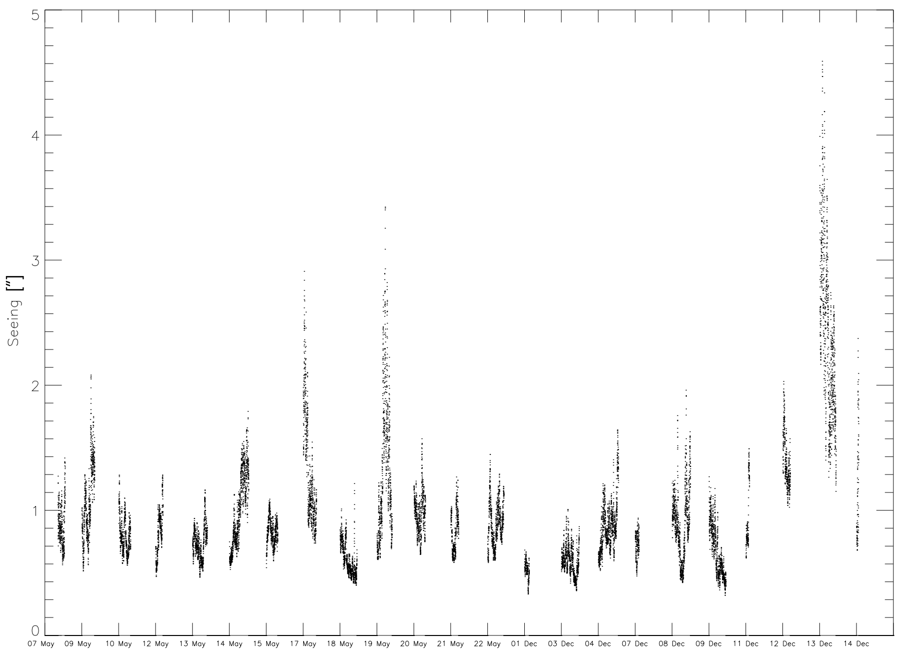

Fig. 5. DIMM measured seeing for the 23 nights of May and December 2000 campaigns.

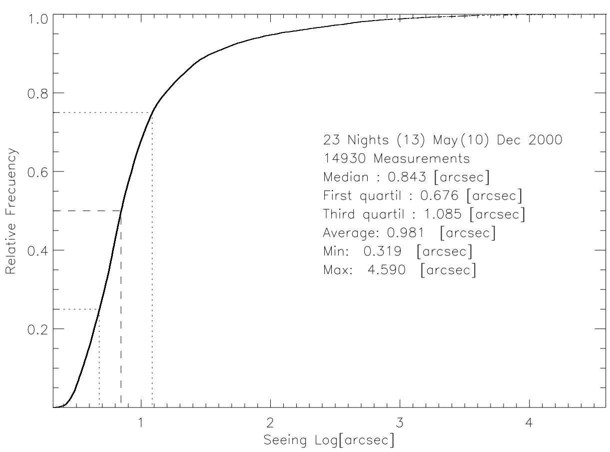

Fig. 6. Cumulative distribution of the DIMM measured seeing and general statistics.

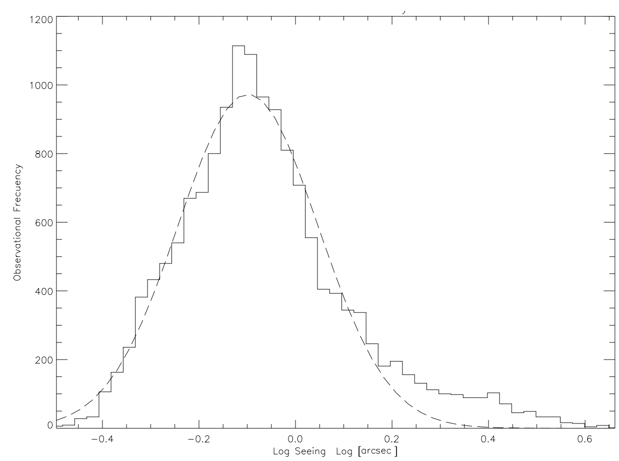

Fig. 7. Histogram of the logarithmic values of seeing with a Gaussian fit showing the log–normal behavior.

surements are free of local disturbances that occur in telescope buildings which, in the best cases, reach thermal equilibrium after several hours.

We are also interested in the possible presence of a universal temporal behavior of seeing to be interpreted in more general theories concerning turbulence phenomena, so in a forthcoming paper, Sánchez et al. (2003), we will discuss some results on the temporal correlation of seeing.

4. OPTICAL TURBULENCE AT THE SURFACE LAYER

Examples of micro-thermal data $C_{\rm n}^2\,(h_i, t)$ for two nights are plotted in Figs. 9 and 10. We show two cases: *normal*, in which the turbulence strength decreases with height, and the so-called *anomalous* case in which it increases with height, showing an inverted tendency. A statistical processing of the temperature micro-fluctuations over a larger data set will permit us to give a general behavior of the $C_{\rm n}^2$ measured at the different heights and we expect to show that the $C_{\rm n}^2$ mean value near the ground (at 2.3-m) is greater than the one at 15-m.

Equivalent seeing contribution of the surface layer is calculated as

San Pedro Mártir: Astronomical Site Evaluation (México, D. F. and Ensenada, B. C., México, April 3-4, 2003)
Editors: Irene Cruz-González, Remy Avila & Mauricio Tapia

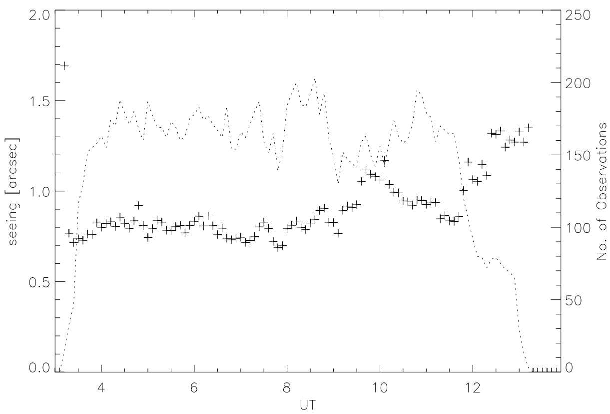

Fig. 8. Median seeing (crosses) versus UT for the entire observing campaign. The dotted line indicates number of data points used (right vertical axis).

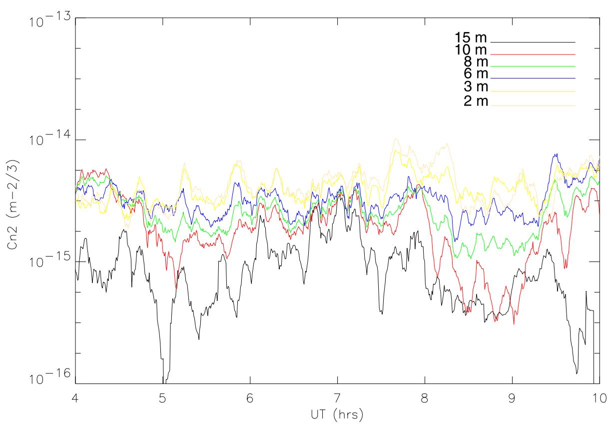

Fig. 9. Temporal evolution of C_n^2 measured with the microthermal sensors at the heights of 2, 3, 6, 8, 10 and 15-m. Example of one night (13-05-2000) of "normal" data.

$$\varepsilon_{SL} = 5.25\,\lambda^{-1/5}\left[\left\langle \int_{2.3\mathrm{m}}^{15\mathrm{m}} C_n^2\,(h,t)\,dh \right\rangle\right]^{3/5}, \quad (4)$$

where the average is taken over the time.

In Table 2 we show for each night the measured average C_n^2 and its corresponding seeing value. Mean values for the May and December data are also shown. The total contribution of the turbulence strength in the surface layer is found to be of $1.63 \times 10^{-14}\,[\mathrm{m}^{-2/3}]$ which is equivalent to a seeing value of 0.11″.

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 define

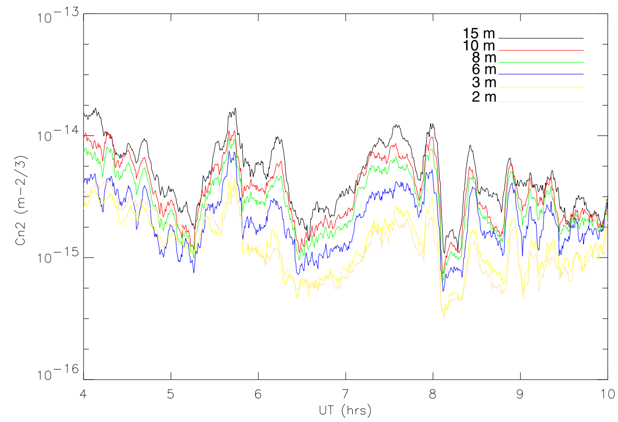

Fig. 10. Temporal evolution of C_n^2 measured with the microthermal sensors at the heights of 2, 3, 6, 8, 10 and 15-m. Example of one night (17-05-2000) of "anomalous" (inverted) data.

TABLE 2

MAST MEASURED C_n^2 AND EQUIVALENT SEEING ε_{SL}

Date (UT)	$\int_{2.3\mathrm{m}}^{15\mathrm{m}} \langle C_n^2\,(h)\rangle dh$ $(\mathrm{m}^{-2/3})$	ε_{SL} (″)
May		
12-5-2000	2.94×10^{-14}	0.15
13-5-2000	1.03×10^{-14}	0.08
14-5-2000	1.13×10^{-14}	0.08
15-5-2000	1.01×10^{-14}	0.08
16-5-2000	3.25×10^{-15}	0.04
17-5-2000	1.35×10^{-14}	0.09
18-5-2000	8.26×10^{-15}	0.07
19-5-2000	2.00×10^{-15}	0.03
20-5-2000	3.05×10^{-15}	0.04
Mean May	1.01×10^{-14}	0.08
December		
7-12-2000	2.43×10^{-14}	0.14
8-12-2000	1.28×10^{-14}	0.09
9-12-2000	4.19×10^{-14}	0.19
10-12-2000	1.09×10^{-14}	0.08
Mean Dec.	2.25×10^{-14}	0.13
Total Mean	1.63×10^{-14}	0.11

the Turbulent Energy Ratio (*TER*) – following 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

San Pedro Mártir: Astronomical Site Evaluation (México, D. F. and Ensenada, B. C., México, April 3-4, 2003)
Editors: Irene Cruz-González, Remy Avila & Mauricio Tapia

TABLE 3

MEAN TURBULENT ENERGY RATIO

Date	TER (%)
12/05/2000	23.9
13/05/2000	14.3
14/05/2000	14.1
15/05/2000	13.5
17/05/2000	19.9
18/05/2000	23.8
19/05/2000	1.4
20/05/2000	4.5
07/12/2000	33.0
08/12/2000	12.4

TABLE 4

MEAN SEEING DEGRADATION

Date	SD (%)
12/05/2000	15.1
13/05/2000	8.8
14/05/2000	8.7
15/05/2000	8.3
17/05/2000	12.5
18/05/2000	15.1
19/05/2000	0.8
20/05/2000	2.7
07/12/2000	21.4
08/12/2000	7.6

infinity.

$$TER = \frac{\int_{2.3\mathrm{m}}^{15\mathrm{m}} C_\mathrm{n}^2\,(h)\,\mathrm{d}h}{\int_{2.3\mathrm{m}}^{+\infty} C_\mathrm{n}^2\,(h)\,\mathrm{d}h}. \qquad (5)$$

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: 12–15,17–20 (May) and 7–8 (December). The calculated average TER for the data set is 16%, which means that the surface layer up to 15-m contributes with 16% of the total atmospheric seeing. In Table 3, we show night by night mean values of the TER.

Night–by–night mean TER values vary from 1.4% to 33.0%, which represents a big span in the surface layer seeing contribution.

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 the so-called *seeing degradation (SD)*, which we can define by the relation:

$$SD = \left[1 - (1 - TER)^{0.6}\right]. \qquad (6)$$

SD indicates the relative decrease of the seeing that would be obtained by placing a telescope at an altitude of 15 m. Developing Eq. 6, it is easy to show that

$$SD = \frac{\varepsilon_{2.3\mathrm{m};\infty} - \varepsilon_{15\mathrm{m};\infty}}{\varepsilon_{2.3\mathrm{m};\infty}}, \qquad (7)$$

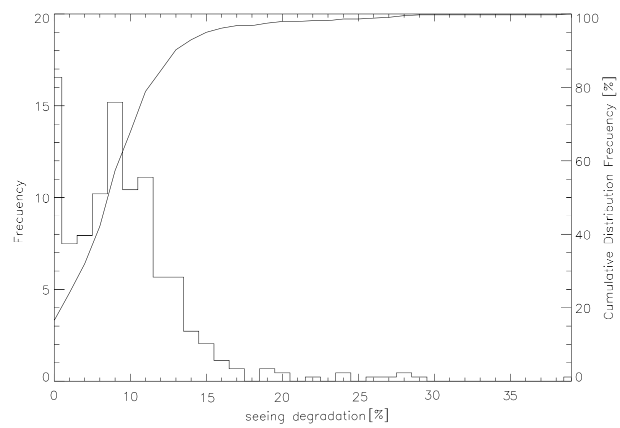

Fig. 11. Histogram of the seeing degradation SD values and corresponding cumulative distribution (CDF).

where $\varepsilon_{2.3\mathrm{m};\infty}$ and $\varepsilon_{15\mathrm{m};\infty}$ 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 0.8 to 21.4%.

The mean seeing degradation due to the surface layer up to 15-m and obtained for the whole campaign is about 10%. This result implies that the contribution of the surface layer to the total seeing is rather small, if we only consider the mean value.

The histogram of the seeing degradation values and its cumulative distribution are plotted in Fig. 11. The median value is about 8.0%. Fifty percent of the values are between 5.0% and 12.0%. It is thus evident that the contribution of the surface layer (SL) to the global seeing cannot always be considered as negligible and DIMM is not always entirely free of its effects.

5. CONCLUSION

An intensive site testing campaign of 23 nights has been carried out at the site of the OAN–SPM to characterize the optical atmospheric turbulence. In this paper we reported results on the surface layer contribution to the seeing. The integrated seeing was measured with a Differential Image Motion Monitor finding log–normal statistics for the total seeing with a mean value of 0.98″ and a median value 0.84″. We equipped with microthermal sensors an instrumented mast in order to measure C_n^2 in the first 15-m (surface layer). The effects of surface layer turbulence were estimated from measurements of temperature micro–fluctuations at several altitudes. These measurements revealed that the first 15-m above the ground account for 16% of the total turbulent energy. For the seeing degradation we obtained a mean value of 10%. These results 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. More micro-thermal and simultaneous DIMM monitoring appears to be desirable to study the local effects in detail and to evaluate their importance for the site seeing.

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