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SAMPLING AND CHARACTERIZATION OF THE TURBULENCE VERTICAL DISTRIBUTION. STATISTICS OF SCIDAR PROFILING

J. J. Fuensalida,[1] B. García-Lorenzo,[1] J. M. Delgado,[1] M. A. C. Rodríguez-Hernández,[1] and J. Vernin[2]

RESUMEN

A diferencia de los procedimientos de sondeo, una caracterización fiable de la distribución vertical de la turbulencia en un lugar debería basarse en criterios de muestreo sin sesgo estadístico. El tamaño de la muestra es tan importante como los criterios bajo los cuales se llevan a cabo. Presentamos aquí los resultados estadísticos de los perfiles de turbulencia ópticos en el Observatorio del Roque de los Muchachos (La Palma, Islas Canarias) en periodos anuales (2004 y 2005), así como la instrumentación desarrollada para satisfacer los criterios establecidos. Los datos se obtuvieron usando la técnica generalized-SCIDAR en el telescopio "Jacobus Kapteyn" y las campanãs se llevaron a cabo mensualmente. Para extender la estadística de los perfiles a otros parámetros importantes para los sistemas de Óptica Adaptativa, mostramos el comportamiento promedio mensual, estudiando la variación estacional de la distribución vertical de la turbulencia.

ABSTRACT

Unlike the trial procedures, a reliable characterization of the vertical turbulence distribution on a site should be based in unbiased statistical sample criteria. The sample size is as important as the criteria under which it is taken. We present here the statistical results of the optical turbulence profiles at the Roque de los Muchachos Observatory (La Palma, Canary Islands) over annual periods (2004 and 2005), as well as the developed instrumentation to fulfil the established criteria. The data were obtained using the generalized-SCIDAR technique at the Jacobus Kapteyn Telescope, and the campaigns were done monthly. In order to extend the statistics of the profiles to other important parameters for Adaptive Optics systems, we show the monthly average behavior of the profiles, studying the seasonal variation of the vertical distribution of the turbulence.

Key Words: **INSTRUMENTATION: ADAPTIVE OPTICS — SITE TESTING — TURBULENCE**

1. INTRODUCTION

Although the importance of the experimental knowledge of the vertical structure of the turbulence with good statistical coverage is obvious, there has been little effort for their continued and systematic measurement at the observatories, as it has happened to the seeing size. The common monitoring parameters for the turbulence characterization are insufficient for forthcoming MCAO (Multi-Conjugate Adaptive Optics) systems and large telescopes. Site quality traditionally has been characterized by seeing size (zero moment of C_N^2), the stability of weather conditions, and useful observing time. Numerous publications give statistical results for sites (e.g. Vernin & Muñoz-Tuñón 1994, 1995) such as the Roque de los Muchachos Observatory (ORM, La Palma, Spain). On the other hand, generalized-SCIDAR is perhaps the most contrasted, extended and reliable technique for turbulence profiling. Probably the reason for the absence of systematic studies is the need for a common-user instrument providing profiles of turbulence and wind with good height resolution.

Vernin & Roddier (1973) proposed the classical SCIDAR (Scintillation Detection And Ranging) technique, which was developed over a period of several years (Rocca, Roddier, & Vernin 1974). But this did not allow measuring the turbulence in the lower atmospheric layers above the telescope dome. In order to overcome this shortcoming, Funchs, Tallon, & Vernin (1994, 1998) proposed the generalized-SCIDAR technique, which has been successfully tested and exploited over the last decade (Ávila, Vernin, & Masciadri 1997; Ávila, Vernin, & Cuevas 1998; Kluckers et al. 1998). We have developed a new instrument (Fuensalida et al. 2004; Hoegemann et al. 2004) based on the original generalized-SCIDAR used by the Vernin's group of Laboratoire

[1]Instituto de Astrofísica de Canarias, Vía Láctea S/N, 38200, La Laguna, Tenerife, Spain (jjf, bgarcia, jdelgado, ahernan@iac.es).

[2]Laboratoire Universitaire d'Astrophysique de Nice, France.

Universitaire d'Astrophysique de Nice (LUAN), with the goal to be used systematically.

After describing the most relevant characteristics of the generalized-SCIDAR instrument in § 2, we present in § 3, the criteria of the observations, the campaigns and its statistical coverage throughout the years 2004 and 2005. In § 4, we study the annual behavior of the vertical distribution of the turbulence. Firstly, we discuss the seasonal variation of the seeing in the boundary layer and the free atmosphere. Afterwards, the monthly average profiles allow us to consider several scenarios of evolution of the turbulence distribution throughout the year. Finally, in § 5, we summarize the results.

2. INSTRUMENTATION

The Generalized-SCIDAR technique is based in the measurement of the spatial and temporal correlations of the scintillation produced by the light from the two components of a determined binary system. The detection is made in a conjugated plane equivalent to a specific distance below the entrance pupil. The high cost of resources that entails the monitoring of the turbulence with high height resolution, using G- SCIDAR technique, justifies the development of an instrument that diminishes these constraints. Long campaigns of measurements of the vertical structure of the turbulence in the Roque de los Muchachos observatory (ORM) has encouraged us to build an instrument with high performances and minimal operational efforts, which we call "Cute-SCIDAR" (Fuensalida et al. 2004; Hoegemann et al. 2004).

Cute-SCIDAR is a full automatically controlled instrument. This means a complete automation of both displacement of optical elements and rotation of the instrument itself. These movements are controlled by a user-friendly interface. Moreover, this custom-made software package performs both fast data acquisition and processing. As a consequence, alignment and observation procedures reduce to easy handling without the effort of operating in the dome. These lead to a high temporal profit during the observation campaign. In Figure 1, we show the instrument installed in the telescope (on the left), and one of the windows of the user interface (on the right), which illustrates the partial processing on real time of the data, such as the frames, its autocorrelation function, and the cross-correlation functions. The Cute-SCIDAR instrument is permanently installed in the 1m Jacobus Kapteyn telescope (JKT) of the Isaac Newton Group of Telescopes at the Roque de los Muchachos Observatory, so that, all measurements presented here have been taken at this location. A copy of this instrument will be installed in Paranal Observatory (ESO). It will be adapted to one of the Auxiliary Telescopes of the VLTI and will be used for the "site characterization" workpackage within of the ELT-FP6 project of the European Union.

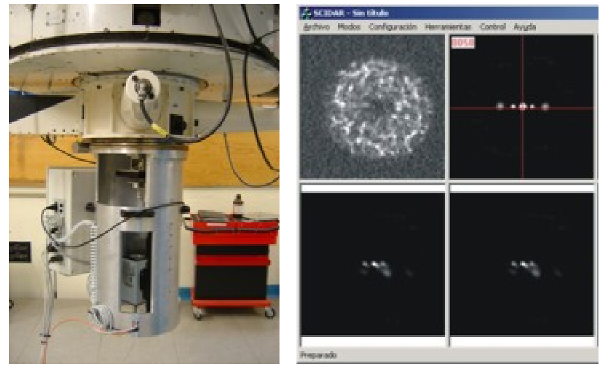

Fig. 1. Cute-SCIDAR instrument installed in the Jacobus Kapteyn Telescope (on the left). On the right, one of the windows of the user interface.

3. STATISTICAL CRITERIA AND OBSERVATIONS

In order to avoid biased statistical data, we have established to obtain the measurements in the period of dark nights (around new moon nights) each month. This way, besides fixing the statistical sample criterion, we facilitated the SCIDAR observations reducing the background emission. The programming for 2004 was the monitoring throughout one week (dark nights) every month, however technical troubles, bad weather (extreme climatologic conditions), or overload of work of the team have made the sample to fluctuate. Due to a decrease of human resources in the course of 2005, we were reduced to doing less observing nights each month. All resulting profiles were involved in the statistical calculations, this is, no profile was rejected after data processing.

In Table 1, we summarize the statistical coverage of the observations with the number of nights and the profiles obtained each month during 2004 and 2005. We started the measurements with the Cute-SCIDAR instrument in the JKT on February, 2004. During 2004, the average number of profiles per month was 5529 corresponding to more than 997 profiles per night each month (see last row). The total number of nights with measurements was 61 distributed throughout 11 months (5.55 nights/month). In the case of 2005, the average number of profiles per night was 903 in 43 nights throughout 12 months

TABLE 1

MONTHLY STATISTICAL COVERAGE OF THE OBSERVATIONS DURING 2004 AND 2005

	2004			2005		
	Nights	Profiles	Prof/night	Nights	Profiles	Prof/night
Jan				7	10345	1477.86
Feb	3	2322	774.00	1	380	380.00
Mar	6	5942	990.30	3	1029	343.00
Apr	8	9586	1198.25	4	4450	1112.50
May	6	5343	890.50	4	4029	1007.25
Jun	5	5045	1009.00	7	5116	730.86
Jul	7	7530	1075.71	4	4313	1078.25
Aug	7	8264	1180.57	3	1337	445.67
Sep	9	8867	985.22	3	1723	574.33
Oct	2	1260	630.00	3	2715	905.00
Nov	4	3847	961.75	2	1270	635.00
Dec	4	2813	703.25	2	2123	1061.50
TOTAL	61	60819	997.03	43	38830	903.02
Average	5.55	5529.00	997.03	3.58	3235.83	903.02

(3.58 nights/month). We also present in Table 1 the total number of nights and profiles obtained, as well as annual averages.

4. STATISTICAL RESULTS

From the individual profiles, we have computed the global statistics of the seeing size. In Figure 2a, we show the monthly median of the whole seeing, while in Figures 2b and 2c are the monthly mean of the seeing in the boundary layer (first km above ground) and the free atmosphere, respectively (the bars are the standard deviation). The black circles are results belonging to 2004, and the white squares to 2005 values.

As it has been mentioned previously, all data reported here have been taken with the JKT, so that, some local effect in the surface seeing could be affecting because the typical global seeing on the ORM is better than the values given here. Global statistics of the seeing on the ORM obtained from long campaigns with DIMMs (Differential Image Motion Monitors), and reported in several publications (e.g. Muñoz-Tuñón, Vernin, & Varela 1997; Wilson et al. 1999; Muñoz-Tuñón 2002; Muñoz-Tuñón, Varela, & Mahoney 1998, and references therein) give the typical overall seeing value for the ORM of $0''.68$ and typical median of $0''.64$ (available to the community in databases `http://www.otri.iac.es/sitesting/principal/`).

Although it makes clear a seasonal behavior, as it is well known from DIMM (Differential Image Motion Monitor) data taken during years (Vernin & Muñoz-Tuñón 1994, 1995), evident differences are shown between the data of 2004 and 2005. The whole seeing gets better in the summer and worse during the winter. The clearer discrepancies between the data of both years are during the spring. Although the tendency of the whole seeing is to have larger values during spring and summer of 2005 (except August), the largest difference is in spring, especially in May (see Figure 2a).

Looking at Figures 2b and 2c, it seems clear that the differences of the whole seeing size come from the turbulence in the boundary layer. Effectively, Figure 2a shows a similar behavior to Figure 2b, which is the variation of the seeing in the boundary layer. On the other hand, the contribution of the seeing in the free atmosphere (Figure 2c) is notably similar, within the error bars, during both years. So that, the seasonal variations and the discrepancies between the two years arises mainly from the turbulence produced in the first km above ground.

In Figures 3 and 4, we present the monthly average profiles of 2004 and 2005, respectively. They have been calculated from all individual profiles in each month. The systematic measurements with the Cute–SCIDAR instrument in JKT began on Febru-

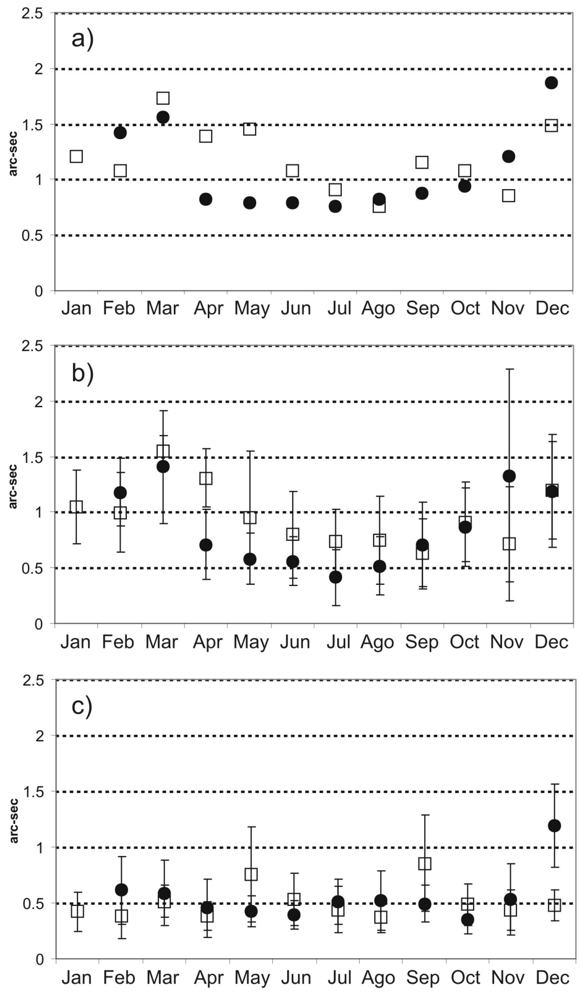

Fig. 2. Global statistics of the seeing size derived from the profiles. The black circles are 2004 and the white squares are 2005. a) The median of the whole seeing. b) The mean of the seeing in the boundary layer (the bars indicate the standard deviation). c) The mean of the seeing in free atmosphere.

ary 2004, therefore the graph of January 2004 is not shown. The X axis is the logarithmical scale of the C_N^2 in unit of $m^{-2/3}$ (the range goes from 10^{-20} to 10^{-14} $m^{-2/3}$), and the Y axis is the height in km above the sea level. The horizontal line indicates the observatory height (2400 m).

A consistent layer of turbulence during the summer of 2004 is relevant around the 5 km height (see Figure 3). This characteristic appears in July and goes on until September changing the shape. It contributes to the value of the seeing in the free atmosphere, so that the improvement of the seeing in the boundary layer during the summer can not be attributed to this effect. Furthermore, another lower layer seems to be in winter and spring, which is generally unresolved around 3.5–4 km height. It could indicate a dynamic effect between winter and summer, by which a lower and weaker layer in winter moving upward and strengthening in summer in a range around a height of 5 km. On the other hand, when the characteristic of 5 km is present the average profile reveals a decreasing of the turbulence in a wide interval around 10 km (see July 2004). It produces a relative maximum in the surroundings of 16 km.

In the profiles of 2005 (Figure 4), the characteristics are similar, although with temporal displacements. For example, the characteristic of 5 km, present in the summer of 2004, appears in May in the data of 2005, which is extended until the end of the summer (September shows a strange profile and its error bar in Figure 2c is perceptibly large, what reveals erratic changes among those nights). It is two months ahead of 2004 and produce an increase of the seeing in the free atmosphere on those months (May and June), unlike the remaining months in which the free atmosphere seeing becomes even smaller (Figure 2c). As in 2004, when the 5 km layer comes out, a wide depression around 10 km and a relative maximum roughly 16 km appear: this smooth maximum becomes in a clear layer in July, and August shows a thin and weaker peak at 18 km (this higher altitude could be related to the fact that the 5 km layer is also going upward until 7 km height). Furthermore, October has a high layer quite similar to July, although a little lower and thinner (October, 2004 also shows a small trace in the same altitude). Apparently, this high layer tends to remain in autumn, which should be confirmed with more data. By another part, between April and August, the boundary layer seeing (Figure 2b) is unusually large concerning the same period of 2004. So that, some turbulence layer remained near the ground during this period.

5. CONCLUSIONS

Generalized-SCIDAR is the most efficient and contrasted remote technique capable of giving the vertical distribution of the turbulence and the wind. A systematic monitoring of the turbulence profile on a site requires establishing observing criteria in order to avoid statistical bias. We settled coincident routine campaigns with the periods of dark nights (around the new moon) of every month. It entails a huge observational charge and, therefore, great human resources. For such aim, we developed a G-SCIDAR instrument ("Cute-SCIDAR") which provides performances of easy-use, simplifying the

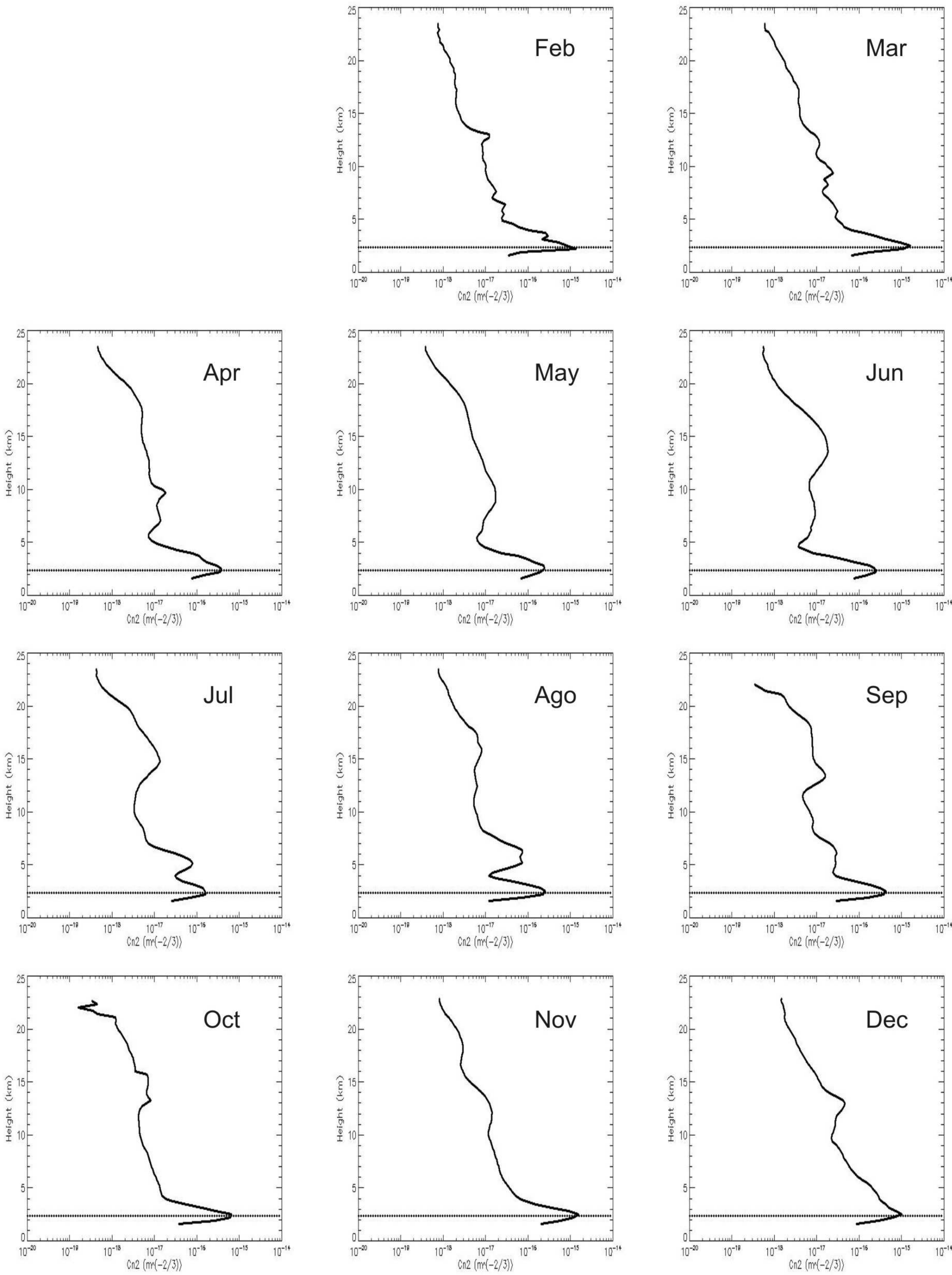

Fig. 3. Average profiles of C_N^2 at each month of 2004. Each value is the mean of all data to its height. The systematic measurements with cute-SCIDAR instrument in JKT began on February 2004. The vertical axis is the height above the sea level in km. The horizontal lines indicate the observatory height (2.4 km). The X axis is the logarithmical scale of the C_N^2 in unit of $m^{-2/3}$ (the range goes from 10^{-20} to 10^{-14} $m^{-2/3}$).

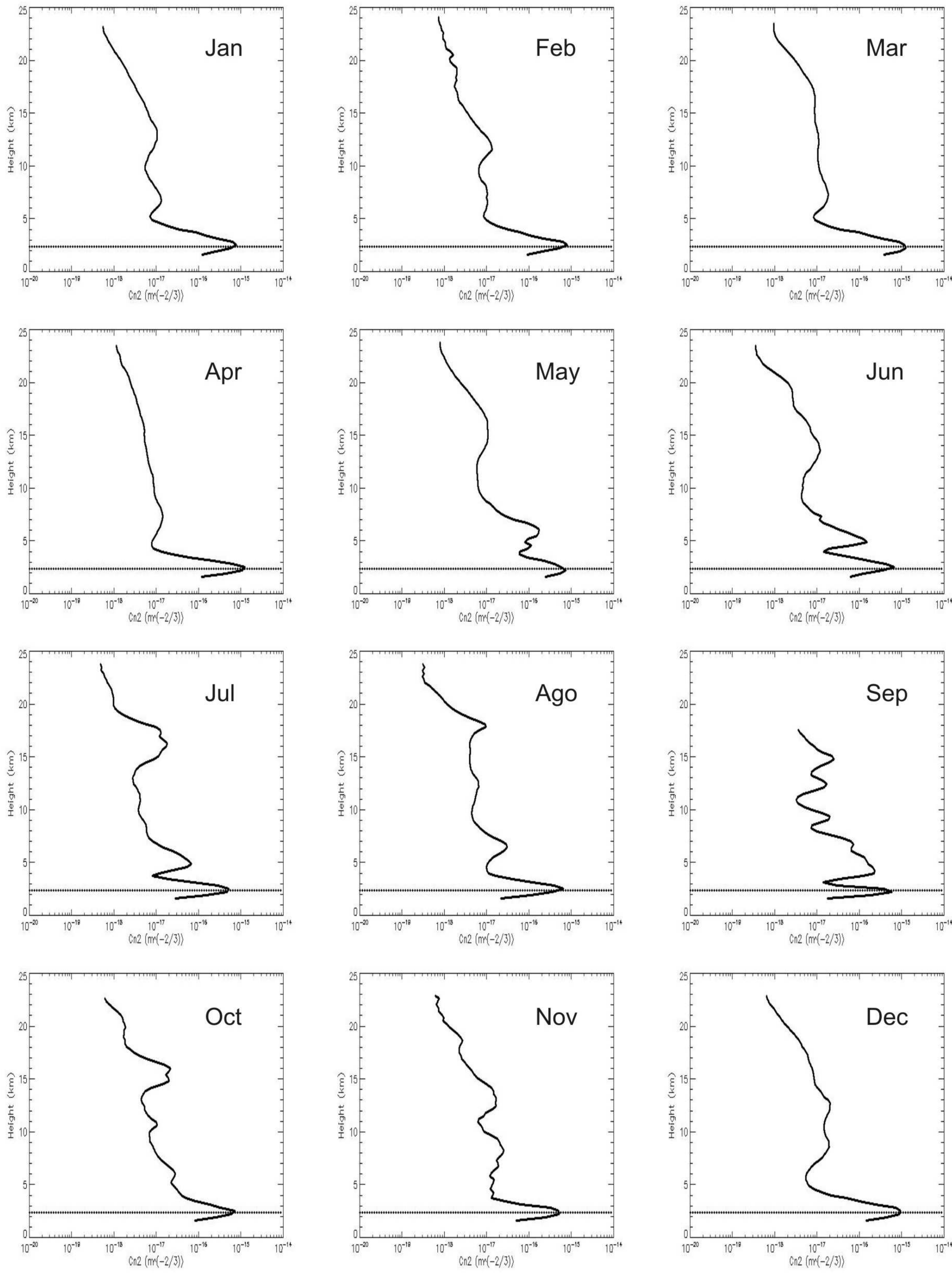

Fig. 4. Average profiles of C_N^2 at each month of 2005. Each value is the mean of all data to its height. The vertical axis is the height above the sea level in km. The horizontal lines indicate the observatory height (2.4 km). The X axis is the logarithmical scale of the C_N^2 in unit of $m^{-2/3}$ (the range goes from 10^{-20} to 10^{-14} $m^{-2/3}$).

operation. It is permanently installed in the 1-m "Jacobus Kapteyn" telescope at the Roque de los Muchachos Observatory (ORM). So that, we have data from February 2004, always using the same instrument and from the same site at the ORM. We have explained here the most relevant characteristics of the instrument and presented results of the measurements taken in 2004 and 2005, of which we summarize:

1. We have treated 60819 profiles acquired in 2004, and 38830 in 2005 (taken every month from February 2004), corresponding to the average rate of 997.03 and 903.02 profiles per night in 2004 and 2005 respectively.
2. The total seeing size follows a seasonal variation (known already in the bibliography using DIMM data): it is better during the summer, getting worse in the winter. This behavior is produced by the turbulence in the first km above the ground level, because the free atmosphere seeing does not show dependency with the months.
3. A consistent layer appears around 2.6 km above ground level during the summer, although it can go upward until 4.5 km, as it is the case in August. This characteristic emerged two months ahead in 2005 with respect to the 2004 data.
4. The existence of the 2.6 km characteristic entails a wide depression around 7.5 km above ground level, producing a relative maximum around 13.5 km. Sometimes, this smooth maximum becomes in a clear layer that extends until the autumn.
5. During the winter, an unresolved small layer comes out in the limit of the boundary layer. It would seem that a dynamic connection exists between winter and summer in the range of the first 3 km, so that the weak and low layer of the winter intensifies and ascends in summer.

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