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# 3D OPTICAL TURBULENCE CHARACTERIZATION AT SAN PEDRO MÁRTIR

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## RESUMEN

Muchos instrumentos son capaces de proporcionar estimaciones locales (en espacio y tiempo) de todos los parámetros astroclimáticos que dependen de la turbulencia óptica. Actualmente, la técnica numérica es el único método que puede proporcionar una caracterización en 3D de la turbulencia óptica. Desde hace algunos años, grandes esfuerzos han sido dedicados a incrementar la confiabilidad del modelo atmosférico de meso-escala llamado Meso-Nh para simular perfiles de $C_{\rm N}^2$ arriba de sitios astronómicos. Los resultados más recientes y más prometedores han sido obtenidos en el sitio de San Pedro Mártir. En este artículo, se presenta un resumen de dichos resultados.

## ABSTRACT

Many instruments are able to provide local (in space and time) estimations of all the astroclimatic parameters that depend on the optical turbulence. The numerical technique is, at the present time, the only approach that can provide 3D characterization of the optical turbulence. Since a few years, many efforts have been dedicated to increase the reliability of the atmospherical meso-scale model called Meso-Nh in simulating $C_{\rm N}^2$ profiles above astronomical sites. The most recent and promising results have been obtained above the San Pedro Mártir site. In this paper these results are summarized.

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

## 1. INTRODUCTION

Since many years the characterization of the optical turbulence (OT) has been shown to be fundamental for the ground-based astronomy for several reasons: (a) the selection of the astronomical sites, (b) the optimization of the flexible-scheduling of the instruments placed at the focus of the telescopes and of the scientific programs and finally (c) the applicability of the most recent AO techniques as like as the Multi-conjugated Adaptive Optics. Many instruments exist today able to provide local measurements (along a single line of sight or *in situ*) of the OT but the numerical technique is the only one that can characterize the OT during a long period in a 3D region around a telescope. Nevertheless this task is not easy because an intrinsical difficulty in relating the microscopic spatio-temporal fluctuations of the OT with the macroscopic fluctuations of the atmospherical flow at synoptic scales (Masciadri 2002a). Which kind of atmospherical model is useful for this kind of exercise? How to initialize this model? How to describe in a an analytical way the OT strength ($C_{\rm N}^2$) in the model? Can we hope to resolve the $C_{\rm N}^2$ explicitly or we have to parameterize it in the code? In this last option, how to do it? In the next section we will try to give a few answers to these questions.

Here we simply underline that we started a research in this field a few years ago in the Departe-

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ment d'Astrophysique de l'Université de Nice-Sophie Antipolis, France (DAUNSA) under the impulse of a couple of studies (Coulman 1986; Bougeault et al. 1995). The meso-scale atmospherical model Meso-Nh, developed at the Centre National de Recherche Météorologique (CNRM)-Meteo France, Toulouse (France) was adapted to simulate the optical turbulence and was tested above different astronomical sites (Paranal, Chile: Masciadri, Vernin & Bougeault 1999a; 1999b; Roque de los Muchachos, Canaries Islands: Bougeault & Masciadri 1998; Masciadri, Vernin & Bougeault 2001). We tried to improve the reliability of the results during these last years. The most important difficulty in testing the performances of this model is to dispose of an orographic model (horizontal resolution $\sim$ 500 m) of the site extended over a surface of around 60 km×60 km and a set of $C_{\rm N}^2$ measurements, sufficiently rich from a statistical point of view to be compared to the simulations. The typical duration of a site testing campaign made with a Generalized Scidar (GS) or balloons is of not more than 7 nights and we have to consider a percentage of lost data due to many and different reasons.

In 1999 the Instituto de Astronomía of the Universidad Nacional Autónoma de México (IA-UNAM) engaged itself in providing part of the financial support for a site testing campaign on the San Pedro Mártir observatory (15 nights). One of the principal tasks of this study was the validation of the Meso-Nh model. The campaign was done on May 2000 (more details relating to the instruments that were employed in the campaign will be given in Sect. 3.2).

The principal results obtained applying the Meso-Nh model to the San Pedro Mártir site are the following:

- a new calibration technique of the Meso-Nh model was proposed (Masciadri & Jabouille, 2001)
- a study of the statistical reliability of the model was completed (Masciadri, Avila & Sánchez 2003)
- a first evidence of the finite horizontal extent of the optical turbulence layers was shown (Masciadri et al. 2000; Masciadri 2002b)

One of the most important benefits obtained with the validation of the Meso-Nh model and the estimation of its statistical reliability is the possibility to use Meso-Nh in an *independent* way. This means that it is now possible to simulate the $C_{\rm N}^2$ for long periods to provide OT estimations on temporal scales larger than tens days. A study aiming to provide (simulate) $C_{\rm N}^2$ profiles above San Pedro Mártir extended over a *whole year* started a few months ago. With this study we will be able to characterize the seasonal variation of the turbulence at different altitudes and the seasonal variations of the principal integrated astroclimatic parameters: seeing, isoplanatic angle, wavefront coherence time, spatial coherence outer scale. A first attempt aiming to estimate the seasonal variation of the wavefront coherence time was done by Masciadri & Garfias (2001).

## 2. 3D OT CHARACTERIZATION

The fundamental parameter that can be characterized with 3D maps by an atmospherical model is the $C_{\rm N}^2 = C_{\rm N}^2$(x,y,z), that is the intensity of the OT. The $C_{\rm N}^2$ depends on ALL the classical atmospherical parameters such as the wind intensity $\mathbf{V}$, the pressure $p$, the temperature $T$, and the mixing ratio $r$ (i.e. the concentration of the water vapor in the atmosphere). It is possible so to calculate it using hydrodinamical simulations describing the spatio-temporal evolution of these basic parameters. All the integrated astroclimatic parameters (the seeing $\varepsilon$, the isoplanatic angle $\theta_{\rm AO}$, the isoplanatic angle for the MCAO $\theta_{\rm M}$, the isoplanatic angle at partial correction $\theta_{\rm PCAO}$ [Roddier et al. 1993], the wavefront coherence time $\tau_{\rm AO}$, the spatial coherence outer scale $\mathcal{L}_0$) depend on the integral of the $C_{\rm N}^2$ made along the line of sight. 2D maps of those astroclimatic parameters can be so retrieved.

From a general point of view, one would like to have at the same time a model with a sufficiently high resolution to resolve the fluctuations of the OT, and also a model able to be initialized by 3D ($\mathbf{V}$, $p$ and $T$) fields that are representative of the atmospherical flow above the site at the instant at which the simulation starts. In the atmospherical simulations applied to the meteorology (and in particular in the cases in which one would like to forecast the atmospherical changes in time) it is well known that this cannot be done with the DNS (direct numerical simulation) technique. The principle of this technique is to resolve explicitly the OT, which requires the use of very high resolutions, i.e. mesh sizes smaller or equal to the typical OT fluctuations scale $\Delta(S)$. The typical value of $\Delta(S)$ is not constant in the atmosphere and near the ground, where the friction of the atmospherical flow is strong, it can reach values of the order of a few meters. It is in principle possible to use the DNS above regions extended over just few hundreds meters for evident reasons of computational resource limitations. The real drawback is another one. Unfortunately, with the DNS it

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is not possible to initialize the models with external 3D fields ($\mathbf{V}$, $p$ and $T$) sampled with such a high resolution.

It is meaningless also to use General Circulation Models in which the resolution is too low (∼100 km). The meso-scale models have an intermediate resolution and they are useful for our aims. They are usually used with a horizontal resolution in the range [50 m–10 km]. The $C_{\rm N}^2$ cannot be resolved explicitly but it has to be parameterized, that is the microscopic fluctuations of the $C_{\rm N}^2$ are expressed as function of the gradient of macroscopic atmospherical parameters ($\mathbf{V}$, $p$, $T$) space averaged over the region of a mesh (see Masciadri, Avila & Sánchez 2002a for more details and quantitative informations). We underline that the *parameterization* technique for the turbulence and gravity waves is largely applied in the meteorological and atmospherical models, and it is used for the French regional model Aladin.

## 3. 3D OT CHARACTERIZATION: SAN PEDRO MÁRTIR

The application of the Meso-Nh model to the San Pedro Mártir site represents a milestone in the history of the progress done in this field of research. In terms of scientific results a new calibration technique permitting to reduce systematic errors was proposed (Masciadri & Jabouille 2001) and a study aiming to estimate the statistical reliability of the Meso-Nh model was completed above this site (Masciadri et al. 2003). In the following sections we will summarize the principal results. More details can be found in the two papers just cited.

### 3.1. *Calibration Technique*

The studies done applying Meso-Nh above the Paranal and Roque de los Muchachos sites showed that one of the principal limitation of the model was the statistical reliability that, at that time, was not too high. A few modifications in the parameterization of the optical turbulence were introduced in the code and a new calibration technique was proposed by Masciadri & Jabouille (2001). This new calibration technique is based on *a posteriori* comparison of measurements with simulations. This is necessary because the model has a free parameter: the minimum kinetic energy $E_{\rm min}$. This is a sort of seed necessary to start a simulation. We refer the reader to the Masciadri & Jabouille (2001) paper for more details related to the physical meaning of the $E_{\rm min}$. Here we simply underline that the $C_{\rm N}^2$ depends on the $E_{\rm min}$ as:

$$C_{\rm N}^2 \propto {E_{\rm min}}^{2/3} \qquad (1)$$

The aim of the calibration is to estimate the $E_{\rm min}$ value. In Masciadri & Jabouille (2001) the authors propose a method, they calculate the $E_{\rm min}$ and they also proved that better results are obtained if different values of $E_{\rm min}$ are defined in different vertical slabs of the atmosphere. The new calibration technique was tested with measurements obtained with the GS during the site testing campaign on March-April 1997 (Avila, Vernin & Cuevas 1998). The most interesting results obtained are summarized in the following. Table 1 shows, for the three nights April 19, 20 and 21, 1997, the seeing measured by the GS (third column) and the seeing simulated by Meso-Nh (fourth column) obtained in the boundary layer ($\varepsilon_{\rm BL}$), in the free atmosphere ($\varepsilon_{\rm FA}$) and in the whole troposphere ($\varepsilon_{\rm TOT}$). The simulated $C_{\rm N}^2$ profiles are calibrated using the new technique and they are averaged over 3 simulation hours. We define a relative error as the following:

$$\varepsilon_{\rm rel} = \frac{(\varepsilon_{\rm TOT,SCI} - \varepsilon_{\rm TOT,MNH})}{\varepsilon_{\rm TOT,SCI}} \qquad (2)$$

where the values of the seeing are in the first line of each night in Table 1. For each night we calculate, $\varepsilon_{\rm rel}$ and then we calculate the average over all the nights. The relative error between the measured and simulated $C_{\rm N}^2$ profiles over the whole troposphere is estimated equal to about 8%. Figure 1 shows, as an example, the $C_{\rm N}^2$ profile simulated by the model in the night of 19/4/1997 before and after the calibration. The bold line is the $C_{\rm N}^2$ profile measured by the GS, the dotted line is the simulated $C_{\rm N}^2$ profile before the calibration and the thin line is the simulated $C_{\rm N}^2$ profile obtained after the calibration. It is clear how the shape of the profile is changed in a suitable way: over the 15 km and near the ground the turbulence is reduced and in the range of [6–10] km is increased. The conclusions of this study are that preliminary results, obtained comparing the simulations with the GS measurements taken at the San Pedro Mártir site in March-April 1997 show that we can obtain a better qualitative and quantitative estimate of the $C_{\rm N}^2$ profiles (with respect to previous ones) using the new calibration technique proposed.

Besides this we note that the reliability of the model could not be tested from a statistical point of view due to the poverty of the statistical sample (just three nights).

### 3.2. *Statistical reliability of the Meso-Nh model*

An intensive site testing campaign (SPM2000) was planned on May 2000 at San Pedro Mártir. The

TABLE 1

MEASURED AND SIMULATED SEEING (ARCSEC)

| NIGHT | Parameters[a] | $\varepsilon_{SCI}$[b] | $\varepsilon_{MNH}$[c] |
|---|---|---|---|
| 19/4/1997 | $\varepsilon_{TOT}$ | 0.80 | 0.72 |
| ” | $\varepsilon_{BL}$ | 0.59 | 0.58 |
| ” | $\varepsilon_{FA}$ | 0.46 | 0.35 |
| 20/4/1997 | $\varepsilon_{TOT}$ | 0.75 | 0.71 |
| ” | $\varepsilon_{BL}$ | 0.61 | 0.62 |
| ” | $\varepsilon_{FA}$ | 0.36 | 0.26 |
| 21/4/1997 | $\varepsilon_{TOT}$ | 0.73 | 0.66 |
| ” | $\varepsilon_{BL}$ | 0.60 | 0.53 |
| ” | $\varepsilon_{FA}$ | 0.34 | 0.33 |

[a] Seeing in the boundary layer ($\varepsilon_{\rm BL}$), free atmosphere ($\varepsilon_{\rm FA}$) and whole atmosphere ($\varepsilon_{\rm TOT}$)

[b] Seeing measured by the GS

[c] Seeing simulated using the *‘a posteriori’* calibration procedure

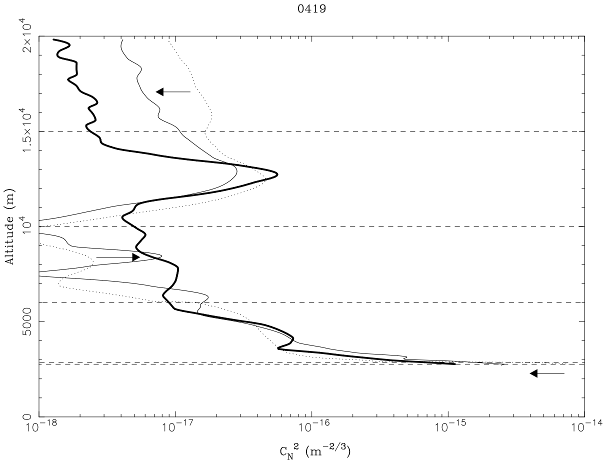

Fig. 1. Simulated and measured $C_{\rm N}^2$ vertical profiles on the 19/4/1997 night. The bold line represents GS measurements. The dotted and thin lines represent simulated values *before* and *after* the calibration, respectively. See Masciadri & Jabouille (2001) for more details.

principal aims were a detailed characterization of the optical turbulence distribution and intensity above the site and the Meso-Nh validation. Here we briefly list the instruments that were used: a GS and balloons (DAUNSA) were used to retrieved vertical $C_{\rm N}^2$ profiles over the whole atmosphere. A DIMM (IA-UNAM) was used to measure the integrated turbulence over the whole atmosphere and an instrumented mast (IA-UNAM) monitored the $C_{\rm N}^2$ vertical distribution in the surface layer (first 15 m). Meteorological radiousoundings (CNRM-Météo France, Toulouse), measuring classical parameters (**V**, $p$, $T$) was launched each night from Pta. Colonet, a locality on the seaside at about 80 km to the west of San Pedro Mártir. These radiosoundings are supposed to be unperturbed by the ground effects because Pta. Colonet is in an upstream position with respect to the principal wind direction. The site testing campaign lasted 15 nights but we selected only 10 nights to calibrate the Meso-Nh model and to study its statistical reliability. The selection was done following this criterium: we selected the nights in which GS measurements were taken at angles below 10 degrees with respect to the zenith. This choice is justified by the fact that we want to eliminate any dependency of our analysis by possible horizontal no-uniform distribution of the $C_{\rm N}^2$.

The Meso-Nh model was calibrated with the same technique proposed by Masciadri & Jabouille (2001). The fitting between measurements and simulations was done considering turbulence contributions provided by all the regions of the atmosphere (the boundary layer, the free atmosphere and the surface layer). The need to use surface measurements forced us to introduce a modification in the calibration algorithm (more details in Masciadri et al. 2003). On the other side, the surface measurements, together with the measurements of the dome-seeing allowed us to eliminate, for the first time, all kind of off-sets in the calibration procedure.

A detailed analysis on all the 10 nights was done comparing the measured and simulated seeing, calculated in different region of the atmosphere: the boundary layer $\varepsilon_{\rm BL}$, the free atmosphere $\varepsilon_{\rm FA}$ and the whole atmosphere $\varepsilon_{\rm TOT}$ (see Table 4 of Masciadri et al. 2003). All these values are retrieved by the integration of $C_{\rm N}^2$ profiles simulated by Meso-Nh or measured by the GS and the balloons. Table 2 lists the values of $\varepsilon_{\rm BL}$, $\varepsilon_{\rm FA}$ and $\varepsilon_{\rm TOT}$ averaged over the whole campaign and related to measurements and simulations. We underline that the average is made on the $C_{\rm N}^2$ profiles and then the seeing in the different regions of the atmosphere is calculated. We note that the seeing measured by the GS without the dome contribution ($0\farcs79$) and the seeing simulated by Meso-Nh without the surface contribution ($0\farcs93$) are well correlated. Moreover, the seeing simulated by Meso-Nh over the whole atmosphere differs from the seeing measured by the GS less than the difference between the seeing measured by the GS and the balloons. In other words, the dispersion between the measurements and the simulations is comparable to the dispersion obtained between measurements provided by different instruments.

Figure 2 shows $C_{\rm N}^2$ profiles measured by the GS

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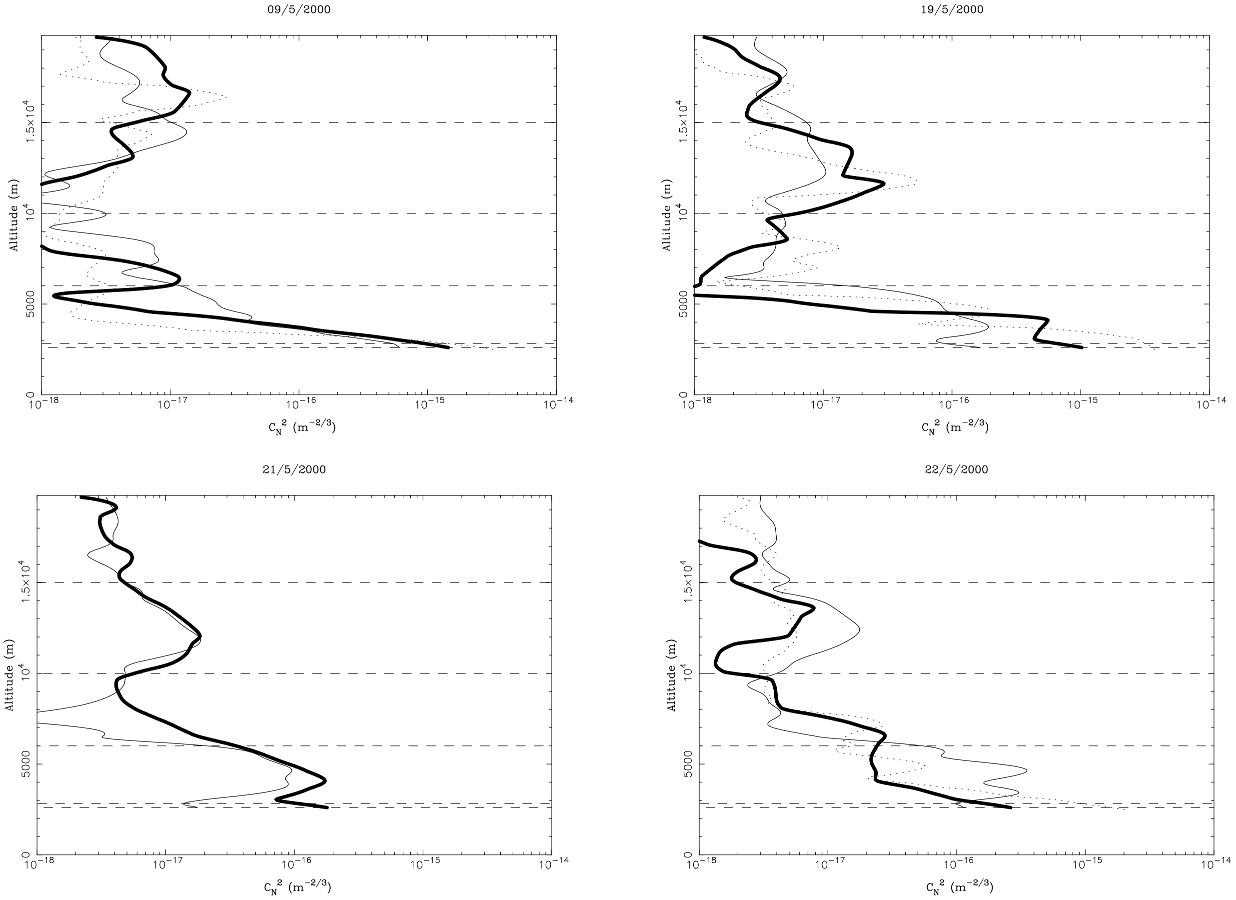

Fig. 2. Vertical $C_{\rm N}^2$ profiles measured and simulated during 4 nights of the SPM2000 campaign: 8–9/5/2000 (up left), 18–19/5/2000 (up right), 20–21/5/2000 (down left) and 21–22/5/2000 (down right). Bold line: GS, thin line: Meso-Nh model, dotted line: balloons.

and radiosoundings, and simulated by the Meso-Nh model related to 4 nights of the SPM2000 campaign. This figure gives a qualitative estimation of the ability of Meso-Nh in reconstructing the shape of the $C_{\rm N}^2$ profiles. One can observe that the simulated $C_{\rm N}^2$ well reproduces the vertical distribution of the turbulent layers over the whole atmosphere during all the 4 nights. No radiosoundings were launched during the May 20–21 night. Figure 3 shows the vertical $C_{\rm N}^2$ profiles averaged over the whole campaign (bold line: GS, thin line: balloons and dotted line: Meso-Nh model). The agreement between the three profiles is good and the turbulence is well reconstructed over the whole troposphere by the model.

A similar good correlation between measured and simulated $C_{\rm N}^2$ profiles was found above different astronomical sites. We cite Paranal as an example (see Masciadri 2002b).

In order to give an estimation of the model reliability over a long temporal scale, we calculate the absolute and relative errors of the seeing calculated over the whole atmosphere between measurements obtained with different instruments (a) and between measurements and simulations (b). We found that in both cases (a) and (b) the relative error is not larger than 30%.

We would like to note that *ALL* the integrated astroclimatic parameters cited in the Sect. 2 are, at the present time, coded in Meso-Nh. Just to give an example of the kind of information that can be retrieved by the model, Fig. 4 shows the temporal evolution (over 3 hours) of a few of the different parameters coded in the model. These outputs are related to the same simulation done over the San Pedro Mártir site. More precisely, the integral parameters are calculated with respect to the same (x,y) point, in our case the coordinates of the astronomical site. The reader can retrieve a whole identity card of the turbulence state above the site during that night. Changing the (x, y) point, we can obtain a 3D iden-

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TABLE 2

SUMMARY OF THE SEEING MEASURED AND SIMULATED DURING THE WHOLE CAMPAIGN

| GS[a] (“) | GS-dome[b] (“) | MNH[c] (“) | MNH-Surf.[d] (“) | Balloons[e] (“) | |
|---|---|---|---|---|---|
| 0.94 | 0.62 | 0.79 | 0.77 | 1.00 | $\varepsilon_{\rm BL}{}^f$ |
| 0.42 | 0.42 | 0.45 | 0.45 | 0.29 | $\varepsilon_{\rm FA}{}^f$ |
| 1.08 | 0.79 | 0.97 | 0.93 | 1.07 | $\varepsilon_{\rm TOT}{}^f$ |

[a] Measured by the GS

[b] Measured by the GS without dome contribution

[c] Simulated by Meso-NH

[d] Simulated by Meso-NH without surface contribution

[e] Measured by the balloons

[f] Seeing in the boundary layer ($\varepsilon_{\rm BL}$), free atmosphere ($\varepsilon_{\rm FA}$) and whole atmosphere ($\varepsilon_{\rm TOT}$)

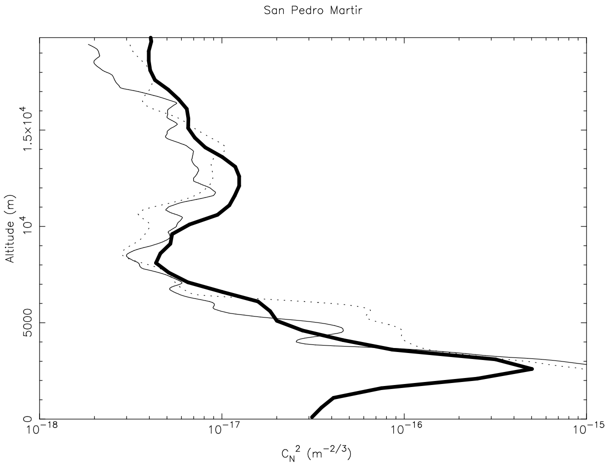

Fig. 3. Mean vertical $C_{\rm N}^2$ profiles measured and simulated over the whole SPM2000 campaign. Bold line: GS. Thin line: radiosoundings. Dotted line:Meso-Nh model.

tity card of the OT in a region around the site. Figure 4a, on the top left hand side shows a simulated vertical $C_{\rm N}^2$ profile at the time $t = 3$ h. The position of the conjugated plane for the two deformable mirrors (DMs) used to calculated $\theta_{\rm M}$ are marked in the figure ($H_1 = 2830$ m, $H_1 = 15000$ m from the sea level; the observatory altitude is 2800 m). Figure 4b, on the top right hand side, shows the temporal evolution of the $C_{\rm N}^2$ over 3 simulation hours. From the left hand side, top to bottom we have: $\tau_{\rm AO}$ (c), $\varepsilon$ (d), $\mathcal{L}_0$ (e), $\theta_{\rm AO}$ (f), $\theta_{\rm M}$ with 1 DM (g), $\theta_{\rm M}$ with 2 DMs (h). The last image on the bottom shows the $\theta_{\rm PCAO}$ (i), calculated for $D = 8$ m and the first correction order ($\alpha_1 = 0.''56$). The model can simulate $\theta_{\rm PCAO}$ up to the third order and the values of $\theta_{\rm PCAO}$ are scaled as the following: $\alpha_2 = 0.''30$, $\alpha_3 = 0.''21$ (Roddier et al. 1993). We underline the following points:

**(1)** the parameters simulated by the model have coherent values if compared between them. This is a sign of a good level of reliability of the model.

**(2)** The model can reconstruct a good temporal variability for the seeing, the wavefront coherence time and the spatial coherence outer scale. This is principally due to the strong variability of the turbulence in the first kilometers, well evident in panel B. This fact proves that the model is not passive, and that the OT evolution changes from its initial conditions because the the effect of the orographic waves. This is a fundamental point for a model in which the OT is parameterized and not explicitly resolved.

**(3)** The isoplanatic angle $\theta_{\rm AO}$ shows a quite constant value as a function of time. This is due to the fact that this parameter is particularly sensitive to the turbulence at high altitudes and, as we can observe in panel B, the turbulence above 10 km is temporally uniform for this simulation. From a general point of view we can affirm that, being that the turbulence fluctuations in the high part of the atmosphere are lower than in the low part of the atmosphere, the isoplanatic angle should present a lower variability than that of the $\varepsilon$, the $\tau_{\rm AO}$ and the $\mathcal{L}_0$.

**(4)** $\theta_{\rm M}$ (Eq. 2 - Masciadri 2000c) with 1 DM is quite similar to $\theta_{\rm AO}$ because the first DM is conjugated at an altitude that differs from the pupil plane of only 30 m. On the other side, the choice of such a low altitude, in the case of a system with only one DM, is a convenient solution because it kills the larger part of the turbulence concentrated near the ground. This is interesting for the application of a wide field AO technique (Rigaut et al. 2001, Chun 1998).

**(5)** the $\theta_{\rm PCAO}$ (Eq. 3 - Masciadri 2000c) fluctuations are larger than those of the other isoplanatic angles. We can explain this as follows. In $\theta_{\rm M}$ (the $\theta_{\rm AO}$ is a

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particular case of the $\theta_{\mathrm{M}}$), the weight function $F_{\mathrm{M}}$, in the case in which at least one DM is conjugated at an altitude near the pupil level as is our case, kills the $C_{\mathrm{N}}^2$ near the ground, i.e. the region of the atmosphere in which the turbulence variability is the largest. In $\theta_{\mathrm{PCAO}}$ we have in the numerator the contribution given by the integral of the $C_{\mathrm{N}}^2$ over the whole atmosphere. In this case, the variability related to the near ground turbulence survives.

**(6)** We underline that the spatial coherence outer scale $\mathcal{L}_0$ is coded in the model using the exact relation introduced by Borgnino (1990) in which $\mathcal{L}_0$ is proportional to the integral of the $C_{\mathrm{N}}^2$ weighted by the dynamical outer scale $L_0$. In other words, we give estimations that are *model independent*. Knowing that instruments such as the GSM (Martin et al. 2000) give $\mathcal{L}_0$ measurements that are *model dependent*, the comparison between the simulations and the measurements could provide interesting information for the comprehension of the relationships between the seeing and the $\mathcal{L}_0$. Indeed, until now, no systematic correlation trend between the two quantities was detected.

## 4. FINITE EXTENT OF THE HORIZONTAL TURBULENT LAYERS

We want to mention here a study done with both Meso-Nh simulations and measurements from GS and balloons obtained above San Pedro Mártir. This study is not strictly related to the characterization of the SPM site at this level of progress but it investigates the typical horizontal extent of the turbulent layers. The impact that this extent could have on the AO techniques is still an open problem. A few of the potential implications that a finite horizontal extent could have on the AO techniques are discussed by Masciadri et al. (2002). The spatial $C_{\mathrm{N}}^2$ distribution is normally considered (theoretical approximation), at least in astronomical applications (Roddier 1981), as uniform over the horizontal $(x,y)$ plane and only the modulations of the optical turbulence along the vertical coordinate $z$ are considered. On the other hand some evidence of the presence of non negligible inhomogeneities of the horizontal distribution of the $C_{\mathrm{N}}^2$ was observed in 3D $C_{\mathrm{N}}^2$ simulations (Masciadri et al. 2000; Masciadri 2002a). More precisely, the integration of the $C_{\mathrm{N}}^2$ profile along lines of sight different from the zenith gave seeing differences that can be larger than $0\farcs50$. This is a sizable quantity and for this reason we decided to attack the problem (Masciadri et al. 2002) following two different approaches. (1) we compared measured and simulated $C_{\mathrm{N}}^2$ profiles along the same lines of sight during the night 16/17 May 2000. The measured profiles are provided by a GS that worked at the focus of the 2.1 m telescope during the site testing campaign SPM2000 and the simulations are provided by the Meso-Nh model. (2) we compare $C_{\mathrm{N}}^2$ profiles retrieved with the GS from the scintillation of different binary stars observed during the same night (21/22 May 2000) at different lines of sight.

Unfortunately the first test doesn't give definitive conclusion because the case studied reveal a general uniformity of the stratification of the turbulent layers in the direction of the observed binary stars. Beside this, our simulations show that the typical horizontal size of the turbulent layers in the first 10 km is finite and can produce, along different directions, variations of the seeing estimations that, quantitatively, cannot be neglected. We quantify the intensity of the spatial fluctuations of the seeing maps. For the night of 16/17 May 2000 we find fluctuations of the order of $0\farcs20$ over a maximum angle of 40 degrees. In the simulated instantaneous seeing maps the spatial modulations can attain the order of $0\farcs50$ (more details in Masciadri et al. 2002). The results obtained with simulations are confirmed by measurements. We show that the $C_{\mathrm{N}}^2$ profiles measured by a GS at different angles from the zenith can have different shapes (which means different distribution of the turbulence along the lines of sight) and different total energies (a difference of $0\farcs30$ is estimated in the night of 21/22 May 2000 (Fig. 11 of Masciadri et al. 2002). After a study of the statistical noise related to our measurements, we conclude that the non-uniformity of the turbulent layers estimated in our study cannot be due to a statistical error and it has to be considered as *real*. It would be interesting to verify, in the future, if such a modulation is reproduced by the model. Different approaches for deeper investigations on this subject can be suggested: (1) to do 3D simulations of the atmosphere with the Meso-Nh model and to calculate the typical size of decorrelation of the turbulence with respect to the horizontal dimension. (2) to measure $C_{\mathrm{N}}^2$ profiles with respect to different directions using, at least, two Generalized Scidars.

## 5. CONCLUSIONS

The most important results of this study are the following:

- the Meso-Nh model reliability was tested comparing simulated with measured $C_{\mathrm{N}}^2$ profiles extended over 10 nights. A good agreement was found between measurements and simulations

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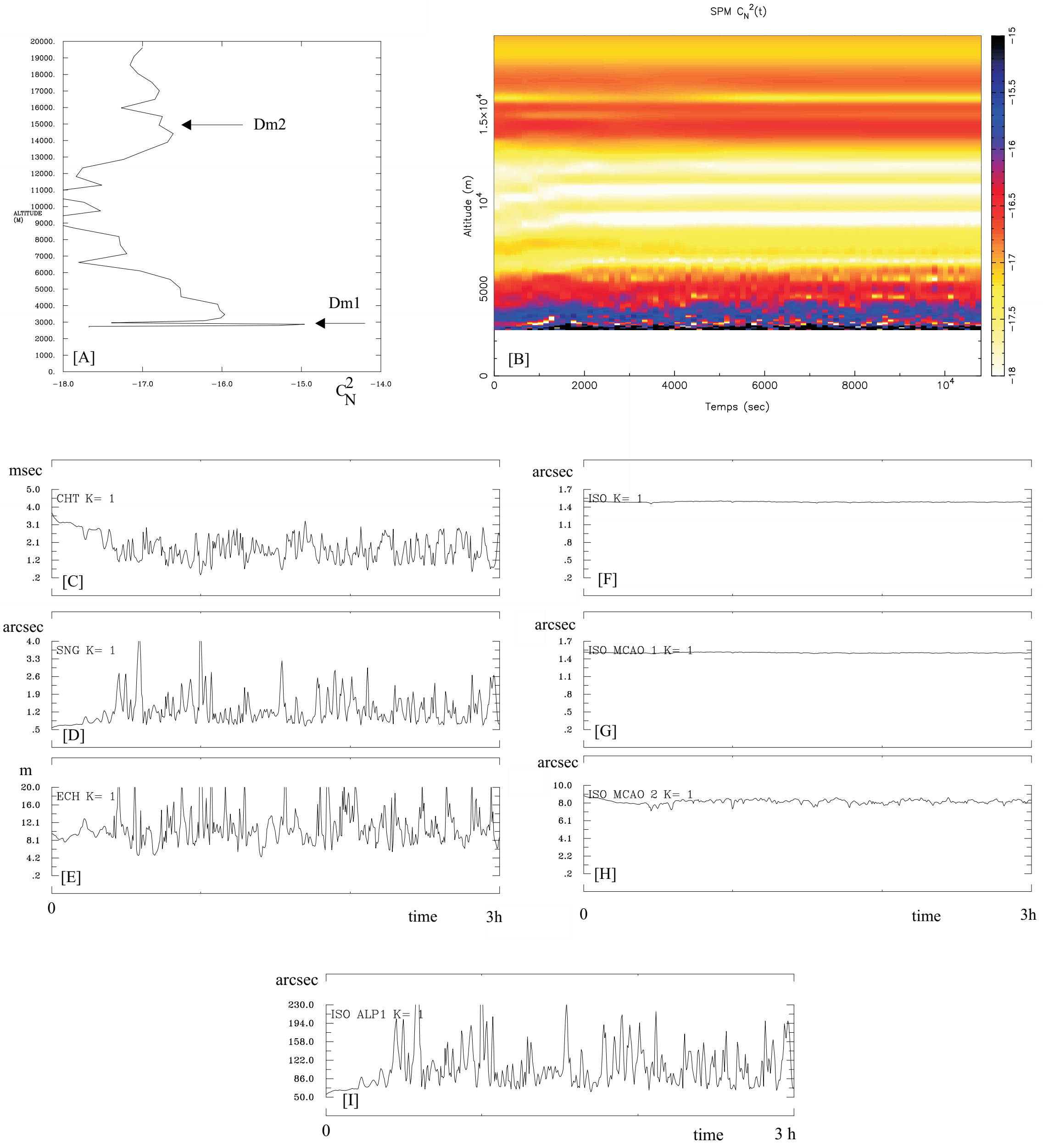

Fig. 4. Several model outputs related to the same simulation done above the San Pedro Mártir site. *(a)* Vertical $C_N^2$ profile simulated at the time $t = 3$ h. *(B)* Temporal evolution extended over 3 hours of the $C_N^2$ vertical profile. The gray scale represents $C_N^2$ values in logarithmic scale, as shown by the bar on the left. It follows the temporal evolution of the integrated astroclimatic parameters: *(C)* the wavefront coherence time $\tau_{\rm AO}$, *(D)* the seeing $\varepsilon$, *(E)* the spatial coherence outer scale $\mathcal{L}_0$, *(F)* the isoplanatic angle $\theta_{\rm AO}$, *(G)* the isoplanatic angle for the MCAO $\theta_{\rm M}$ (with 1 DM), *(H)* the isoplanatic angle for the MCAO $\theta_{\rm M}$ (with 2 DM), *(I)* the isoplanatic angle at partial correction $\theta_{\rm PCAO}$ calculated for a pupil telescope of 8 m and the first correction order (see the text).

from a quantitative and qualitative point of view. The GS, the balloons and the Meso-Nh model give a seeing of respectively: $0''.79$, $1''.07$ and $0''.93$.

- a detailed statistical analysis was done to calculate in different ways the level of the model reliability. Small variations are found in the results depending on how the statistical esti-

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mators are calculated. The dispersion between measurements and simulations is comparable to the dispersion between measurements provided by different instruments ($\leq 30\%$) if we consider average estimations of the $C_\mathrm{N}^2$ over a long period i.e. over the whole campaign. The dispersion is comparable but larger ($\leq 57\%$) in both cases if we calculate it night by night.

- the huge amount and the variety of measurements taken during the San Pedro Mártir campaign in May 2000 permitted us to improve in a consistent way the reliability of the Meso-Nh model. The study that is in progress aiming to estimate the seasonal variation of the $C_\mathrm{N}^2$ and of the principal integrated astroclimatic parameters will give us further useful information for both the site characterization and the optimization of the AO techniques.

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