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STATISTIC RELIABILITY OF THE MESO-NH ATMOSPHERICAL MODEL FOR 3D C_N^2 SIMULATIONS

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RESUMEN

La técnica numérica es, actualmente, la única metodología que puede proporcionar mapas en $3D$ de C_N^2 en una región alrededor de un telescopio. Estudios anteriores han demostrado que el modelo atmosférico no-hidrostático Meso-Nh puede simular perfiles verticales de C_N^2 confiables. Recientemente, se ha propuesto una nueva técnica de calibración para el modelo para mejorar la confiabilidad de las simulaciones. Con el fin de estudiar la confiabilidad estadística, en este trabajo se aplica dicha técnica a una muestra de 10 noches de la campaña de estudio de sitio de San Pedro Mártir, llevada a cabo en mayo del 2000. Las medidas de los perfiles de C_N^2 proporcionadas por diversos instrumentos se comparan con simulaciones y los resultados se analizan estadísticamente después de la calibración. Por primera vez, la comparación entre las medidas y las simulaciones se realiza considerando las contribuciones de la turbulencia proporcionadas por todas las regiones de la atmósfera (capa límite, atmósfera libre y capa superficial) y por la cúpula del telescopio. Los resultados demuestran que la dispersión entre las medidas y las simulaciones es comparable a la dispersión obtenida entre las medidas proporcionadas por diversos instrumentos (el error relativo para la campaña completa es $\leq 30\%$ en ambos casos). Se presentan sugerencias para mejoras que se pueden implementar en el modelo Meso-Nh.

ABSTRACT

The numerical technique is, at the present time, the only approach that can provide $3D$ C_N^2 maps in a region around a telescope. Previous studies showed that the non-hydrostatic atmospherical Meso-Nh model can simulate reliable C_N^2 vertical profiles. Recently, a new calibration technique for the model was proposed in order to improve the reliability of the simulations. In this paper we apply this technique to a sample of 10 nights of the San Pedro Mártir site testing campaign of May 2000 in order to study the statistical reliability. Measurements of the C_N^2 profiles provided by different instruments are compared with simulations and the results are analysed statistically after the calibration. For the first time, the comparison between measurements and simulations is done considering the turbulence contributions provided by all the regions of the atmosphere (the boundary layer, the free atmosphere, and the surface layer) and by the dome of the telescope. Our results show that the dispersion between measurements and simulations is comparable to that obtained between measurements provided by different instruments ($\leq 30\%$). Suggestions are presented for improvements to be implemented in the Meso-Nh model.

Key Words: **ATMOSPHERIC EFFECTS — METHODS: NUMERICAL — SITE TESTING**

1. INTRODUCTION

The possibility of simulating $3D$ C_N^2 maps in a region around a telescope using a non-hydrostatic atmospherical model (Meso-Nh) has been tested in previous studies in the past few years. Simulations

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were compared to measurements provided by different instruments (Generalized Scidar (GS) (Fuchs, Tallon, & Vernin 1998; Avila, Vernin, & Masciadri 1997) and radiosoundings) and reliable results were obtained applying the model to two astronomical sites considered to be among the best in the world: Cerro Paranal - Chile (Masciadri, Vernin, & Bougeault 1999a; Masciadri, Vernin, & Bougeault 1999b), and Roque de los Muchachos - Canary Islands (Masciadri, Vernin, & Bougeault 2001). One of the most critical aspects of the numerical technique is its statistic reliability. Good agreements between measurements and simulations could be reached in the past but the failures of the model were in some cases non negligible. In a previous paper (Masciadri & Jabouille 2001), a new technique of calibration of the model was proposed in order to eliminate some systematic errors and improve the reliability of the simulations. This technique is based on an *a posteriori* comparison of measurements with simulations. Preliminary results showed that the new technique could give better qualitative and quantitative results than the previous ones but we could not test the reliability of the model from a statistical point of view because we used just a poor sample of nights: 3 nights of the San Pedro Mártir (México) site testing campaign of March-April 1997.

A further site testing campaign was planned on May 2000 on the same site to characterize the site and to validate the Meso-Nh model. The campaign lasted 15 nights (6-21/5/2000) and different instruments worked simultaneously in order to monitor the optical turbulence in different regions of the atmosphere. The GS and balloons were used to retrieve the vertical distribution of the optical turbulence (C_N^2 profiles) and a Differential Image Motion Monitor (DIMM) was employed to measure the integrated turbulence over the whole troposphere. An instrument mast monitored the C_N^2 vertical distribution in the surface layer (first 15 m) during the whole campaign and a modified version of the GS adapted to measure the seeing in the dome was employed (Avila, Vernin, & Sánchez 2001). This is the first time that these two last contributions (seeing from the surface and dome seeing) were considered for the validation of the model and for the calibration technique. This improvement permitted us to obtain, for the first time, an *absolute* and not a *relative* calibration, that is, without offsets. The calibration procedure is done by fitting, in a suitable way that will be described in § 3.1, the GS measurements with simulations. The measurements provided by the other instruments are employed to complete the calibration and/or to estimate the statistic reliability of the numerical technique. In § 2 the observational aspects are treated. In § 2.1 we describe the site testing campaign and the instruments that were employed. In § 2.2 we describe how we selected the GS C_N^2 profiles. In § 2.3 we briefly recall the technique used to measure the seeing provided by the dome of the telescope and we show the measurements of the dome seeing for all the selected nights. In § 3.1 the principle of the calibration technique is described and in § 3.2 the obtained results are shown. In § 4 we discuss the reliability of the Meso-Nh model presenting a statistic analysis and we suggest some possible solutions to improve the reliability of the Meso-Nh model. Finally, in § 5 we summarize the principal results of this study. Further details related to the simulation procedure used to obtain C_N^2 profiles can be found in Masciadri (2002).

2. MEASUREMENTS

2.1. *SPM2000 Site Testing Campaign*

The site testing campaign (Avila et al. 2002) of May 2000 took place at the San Pedro Mártir Observatory in Ensenada, Baja California, México (2800 m) (31.0441 N, 115.4569 W) in the region of Baja California in the north part of the country. A forthcoming paper will be dedicated to a detailed analysis of all the measurements. In this paper we treated and used the measurements just to calibrate the model and to prove its reliability. Figure 1 shows the geographic position of the site marked by an arrow. A GS worked at the focus of the 1.5 m telescope during 9 nights (6-14) and at the focus of the 2.1 m telescope during 6 nights (16-21). A set of radiosoundings, adapted to measure the C_N^2 vertical profiles, were launched from the site during the campaign. The wind made it impossible to launch the balloons from the observatory because of the pine trees, thus most of the balloons were launched from Vallecitos (2400 m), an unforested area close to the Observatory about 3 km away from the 2.1 m. A DIMM, placed at 2 m from the ground worked during the campaign providing integral values of the optical turbulence extended over the whole troposphere. An instrument mast monitored the temporal evolution of the C_N^2 at 5 levels in the first 15 m (2.3, 3, 6, 10, and 15) m. Details related to surface measurements can be found in (Sánchez et al. 2003). We only report here (Table 1, second column) the estimations useful in our context, that is, the integral value obtained over the [2.3 – 15] m range for each night. Table 1 (third column) reports the seeing calculated in the first 20 m, that is the contribution provided

Fig. 1. Geographic map of the Baja California region in the north part of México (North is on the top, West on the left). The extremities of the arrow mark the position of the San Pedro Mártir Observatory (on the right side) and of Pta. Colonet (on the left side) near the seaside. A radiosounding was launched from Pta. Colonet each night of the observation campaign at a time ∈ [05:00 – 07:00] U.T.

by the whole air mass between the ground and the dome of the telescope (2.1 m). These last estimates are useful for the calibration of the model (see § 3.1). The C_N^2 is temporally averaged over the whole night for each night. For both the [0 – 2.3] m and [15 – 20] m ranges a linear extrapolation (Borgnino 2001, private communication) was done from the data obtained in the [2.3 – 15] m range.

A meteorological radiosounding, measuring classical meteorological parameters (p, T, and V), was launched each night from Pta. Colonet, a locality on the seaside (the left end of the arrow in Fig. 1) about 80 km to the west of San Pedro Mártir Observatory. 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. Moreover, because of the proximity to the sea, the soundings sample the whole 20 km of the atmosphere (∼ [68 – 20,000] m). These last measurements were used to initialize the Meso-Nh model. Each Pta. Colonet radiosounding was launched in the [05:00 – 07:00] U.T. ([22:00 – 24:00] local time) time range so that the simulations could be representative of the central part of the night.

2.2. C_N^2 *Vertical Profiles from the GS*

The calibration procedure is based on a comparison between simulated and measured C_N^2 profiles. These last are considered as a reference, in other words, as the most representative estimation of the real state of the atmosphere. The spatial C_N^2 distribution is normally considered (theoretical aproximation), 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 inhomogenities of the horizontal distribution of the C_N^2 was observed in $3D$ C_N^2 simulations (Masciadri et al. 2000; Masciadri, Avila, & Sánchez 2002). This result was recently confirmed by C_N^2 measurements taken at different zenithal angles by a GS (Masciadri et al. 2002). The measurements were taken for temporal intervals sufficiently short to consider the measurements as *instantaneous* and sufficiently long to have a reasonable statistic reliability of the measurements. In the same study it was shown that the mean horizontal spatial fluctuations of the seeing can reach the order of 0.″30 over a maximum angle of 40°. No statistical study has yet been done on this subject and it is not yet known how troublesome this effect could be for the adaptive optics applications.

We recall that, althought the Meso-Nh model can simulate $3D$ C_N^2 maps, the numerical calculations to retrieve C_N^2 profiles are somewhat different if we consider lines of sight away from zenith. These differences are related principally to numerical problems. Just as an example we recall that the model levels are parallel to the orographic model (and not plane) and this fact forces us to calculate the C_N^2 values in a different way.

In order to deal with homogeneous simulations (i.e., C_N^2 profiles calculated in the same way) and in order to better calibrate the model (avoiding mixing of numerical and physical free parameters), we decided to restrain the calibration procedure to simulations done with respect to the zenith and to use, as a reference for our study, only the C_N^2 profiles measured by the GS at a zenithal angle smaller than 10 degrees. In this way we can eliminate possible spurious effects due to the non-uniform C_N^2 horizontal distribution. A study on the numerical control of the algorithms used to calculate the C_N^2 along different lines of sight is planned in the near future after the calibration of the model. The effective analyzed number of nights was reduced to 10 instead of 15 because no measurements were taken by the GS during 4 nights at zenith angles below 10 degres. Moreover, one night was eliminated because of bad weather conditions.

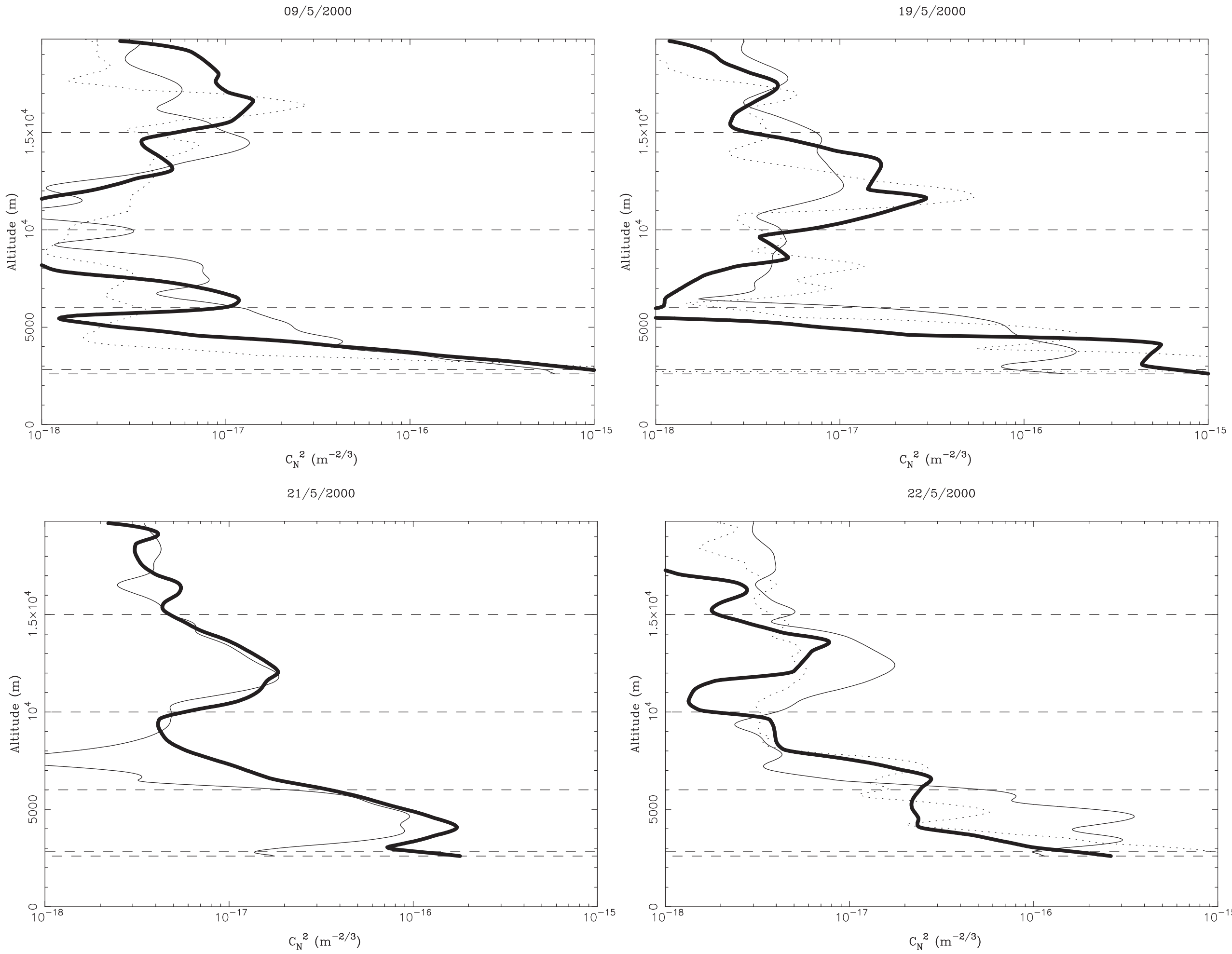

Fig. 2. Vertical C_N^2 profiles measured and simulated during 4 nights of the SPM2000 campaign: 8-9/5/2000, 18-19/5/2000, 20-21/5/2000, and 21-22/5/2000. Bold line: GS, thin line: Meso-Nh model, dotted line: balloons.

2.3. *Seeing from the Dome*

The estimation of the dome seeing is retrieved by GS measurements at the same time as the C_N^2 and wind vertical profiles (Klückers et al. 1998; Avila et al. 2001) and is based on the anaysis of the cross-correlation of a double star scintillation maps taken at temporal interval Δt. We recall a few concepts useful for the discussion of our results in § 4. The cross-correlation produced by each turbulent layer is characterized by three peaks (the so called *triplets*). The position of the central peak with respect to the origin (center of the cross-correlation plane) and the knowledge of Δt give us the velocity vector (intensity and direction) of the detected turbulent layer. The separation of the lateral peaks ($d = \rho H$) with respect to the central one gives us the altitude h of the same turbulent layer with respect to the ground. We recall that $H = |h - h_{gs}|$ is the altitude of the turbulent layer with respect to the conjugated plane, ρ is the double star separation and h_{gs} the altitude of the conjugated plane with respect to the ground level (in our case $h_{gs} < 0$). The seeing inside the dome is characterized by turbulence with a mean velocity $V = 0$ so the triplet is placed at the origin $\pm\ \Delta V$ (ΔV is the velocity resolution of the instrument). The position of the central peak at the origin is a necessary but not sufficient condition to define the dome contribution. Because of the relatively low vertical resolution of the GS near the ground some turbulence in the boundary layer, external to the dome and characterized by a mean velocity smaller than ΔV, could be associated to a triplet such as the one just described. The only case in which we could be reasonably sure that the detected triplet is associated to turbulence placed in the dome is when at least two triplets are detected at the same altitude ($h = 0 \pm \Delta H/2$): the first one characterized by a V

TABLE 1

SUMMARY OF THE SURFACE LAYER SEEING[a]

Night	Seeing ($''$) [2.3 – 15] m	Seeing ($''$) [0 – 20] m
11-12/5/2000	0.15	0.19
12-13/5/2000	0.08	0.10
13-14/5/2000	0.08	0.11
14-15/5/2000	0.08	0.12
15-16/5/2000	0.04	0.05
16-17/5/2000	0.09	0.13
17-18/5/2000	0.07	0.10
18-19/5/2000	0.03	0.04
19-20/5/2000	0.04	0.06

[a]Estimated from measurements done with an instrument mast in the first 20 m during the SPM2000 campaign.

TABLE 2

SUMMARY OF THE DOME SEEING[a]

Night	ε_d ($''$)
6-7/5/2000	0.85
7-8/5/2000	0.67
8-9/5/2000	0.60
9-10/5/2000	0.78
12-13/5/2000	0.95
13-14/5/2000	0.74
17-18/5/2000	0.41
18-19/5/2000	0.51
20-21/5/2000	0.34
21-22/5/2000	0.39

[a]Measured during 10 nights of the SPM2000 campaign. The ε_d of the first 6 nights is related to the 1.5 m, the ε_d of the last 4 nights are related to the 2.1 m.

$< \Delta V$ and the second one by a $V > \Delta V$.

It is evident that the precision of the dome seeing detection is correlated with the values of ΔH (Vernin & Azouit 1983) and ΔV during the observation. We calculated that, for the SPM2000 observations, in the case in which $h = 0$ (ground level) we have $\Delta H \in [300 - 1900]$ m and the detection of the velocity near the ground is provided with a resolution equal to $\Delta V \in [1 - 2]$ m/s for the 2.1 m and $\Delta V \in [0.67 - 1.35]$ m/s for the 1.5 m. In other words, we can define a velocity V with an error equal to ΔV. The C_N^2 profiles retrieved by the GS and related to the 10 selected nights were treated following this methodology to estimate the dome seeing (ε_d). Table 2 shows (second column) the ε_d values estimated for each of the 10 selected nights. The first 6 nights are related to the 1.5 m, the last 4 nights are related to the 2.1 m. The ε_d estimations were selected on the same temporal interval as the one used for the GS measurements selected for the calibration.

3. CALIBRATION

3.1. *Principle of the Calibration*

As described in a more detailed way in a previous paper (Masciadri & Jabouille 2001), the model needs a minimum kinetic energy (E_{min}) to start a simulation. A system that starts with an $E = 0$ energy does not evolve. It was proven that **(1)** E_{min} cannot be measured and, **(2)** at least in the stable regions of the atmosphere, i.e., the major part of the atmosphere in the nighttime regime, E_{min} depends analytically on the C_N^2 as $C_N^2 \div E_{\min}{}^{2/3}$. This means that we can calculate *a posteriori* an optimized E_{min} fitting measured with simulated C_N^2 profiles. It was also observed that better results can be obtained if we calculate a set of E_{min}s, each of them characterizing a different region (vertical slab) of the atmosphere. We previously (Masciadri & Jabouille 2001) defined five regions that seem to be characterized by the same E_{min}.

Because the presence of the contribution of the seeing from the dome and from the surface, some modifications in the calibration procedure had to be introduced. We summarize in the following the principal steps that constitute the calibration technique that is based on the classical least-squares method:

1. We select 5 different regions of the atmosphere: [2719 – 2819] m, [2819 – 6000] m, [6000 – 10,000] m, [10,000 – 15,000] m and [15,000 – 20,000] m, in which the turbulence has different behaviours.

2. We resample the measured and simulated C_N^2 profiles with the same vertical resolution: 50 m. We recall that the simulated C_N^2 profiles do not have a regular vertical sampling.

3. For each night m (m = 1, M) we compute the C_N^2 average profiles provided by the Generalized Scidar measurements: $y_{m,i}$, (i = 1, N) where N is the number of vertical levels of the model.

4. At the ground level, in order to match the simulated with the measured C_N^2 profiles we need

TABLE 3

SUMMARY OF THE SEEING[a]

Night	$\varepsilon_{surf.}$ ($''$)	D (m)
12-13	0.06	1.5
13-14	0.06	1.5
17-18	0.10	2.1
18-19	0.04	2.1

[a]From the surface ([0 – 20] m for the 2.1 m and [0 – 2.5] m for the 1.5 m), measured during 4 of the nights of the SPM2000 campaign. See the text.

to calculate, for each night m, an equivalent seeing ($\varepsilon_{m,eq,ug}$) and a corresponding equivalent C_N^2 ($y_{m,eq,ug}$) related to the *fictitious* underground turbulence detected by the GS. To correctly do the calibration this contribution ($y_{m,eq,ug}$) has to be added to the C_N^2 (h_{i^*}) measured by the GS where $h_{i^*} = 2719$ m is the ground level. C_N^2 (h_{i^*}) is the C_N^2 value calculated at the altitude h_{i^*} (y_{m,i^*}). If we translate the analytical expression of the seeing into a numerical formulation we can define such an equivalent seeing for each night m as:

$$\varepsilon_{m,\mathrm{eq,ug}} = 19.96{\cdot}10^6 \left[\sum_{i=1}^{i^*-1} y_{m,i}\left(h_{i+1} - h_i\right)\right]^{3/5} . \quad (1)$$

The correspondent equivalent C_N^2 is defined as:

$$y_{m,\mathrm{eq,ug}} = \left[\frac{\varepsilon_{m,\mathrm{eq,ug}}}{19.96 \cdot 10^6}\right]^{5/3} \cdot \left[h_{i^*+1} - h_{i^*}\right]^{-1} . \quad (2)$$

For each night m, the C_N^2 (h_{i^*}) (that is the C_N^2 value at the altitude h_{i^*}), is now: $y_{m,i^*} + y_{m,eq,ug}$.

5. We calculate, for each night m, an equivalent C_N^2 ($y_{m,eq,dome}$) related to the seeing contribution derived from the dome ($\varepsilon_{m,dome}$) and an equivalent C_N^2 ($y_{m,eq,surf}$) related to the seeing contribution derived from the surface ($\varepsilon_{m,surf}$) in the same way as indicated in the Eq. 1 and Eq. 2.

6. For each night m and for each atmospherical region k (k = 2, 5) we compute:

$$\chi^2_{m,k} = \sum_{j=1}^{P}\sum_{i=1}^{N}\left[a_{m,k}\cdot x_{m,i,j} - y_{m,i}\right]^2 . \quad (3)$$

For each night m and for k = 1 we compute:

$$\chi^2_{m,k} = \sum_{j=1}^{P}\sum_{i=1}^{N}\Big[a_{m,k}\left(x_{m,i,j} - y_{m,\mathrm{eq,surf}}\right) - \left(y_{m,i} - y_{m,\mathrm{eq,dome}}\right)\Big]^2 , \quad (4)$$

where P is the number of simulated profiles for each night. We have a C_N^2 simulated profile every 2 minutes. $a_{m,k}$ is the free coefficient that has to be fixed minimizing the function $\chi^2_{m,k}$. $x_{m,i,j}$ are the values of the simulated C_N^2 sampled on N levels, for each profile j and for each night m. The solution of the minimization gives the following coefficients:

$$a_{m,k} = \frac{\sum_{j=1}^{P}\sum_{i=1}^{N}\left(x_{m,i,j}\right)\cdot y_{m,i}}{\sum_{j=1}^{P}\sum_{i=1}^{N}\left(x_{m,i,j}\right)^2} \quad (5)$$

for (k = 2,5), and

$$a_{m,k} = \frac{\displaystyle\sum_{j=1}^{P}\sum_{i=1}^{N}\left(x_{m,i,j} - y_{m,\mathrm{eq,surf}}\right)\times\left(y_{m,i} - y_{m,\mathrm{eq,dome}}\right)}{\displaystyle\sum_{i=1}^{N}\left(x_{m,i,j} - y_{m,\mathrm{eq,surf}}\right)^2} \quad (6)$$

for k = 1. Finally, for each k we compute:

$$a_k = \frac{\sum_{m=1}^{M} a_{m,k}}{M}, \qquad k = 1, 5. \quad (7)$$

The C_N^2 vertical profiles are then modified for each region as follows:

$$C^{2^*}_{N,k} = C_N^2 \cdot a_k, \qquad k = 1, 5 . \quad (8)$$

Knowing the value of a_k for $k = 1, 5$, the kinetic energy is modified as:

$$E^*_{min,k} = E_{min}\cdot a_k^{3/2}, \qquad k = 1, 5. \quad (9)$$

3.2. *Results*

We calibrated the model using the GS C_N^2 profiles of the 10 selected nights. We underline that the nights for which the surface seeing was measured are not necessarily the same 10 selected GS nights.

We have simultaneous measurements (GS and surface) only during 4 nights. Besides this, we observe that for the calibration we also need the contribution ($\varepsilon_{m,surf}$) provided by a layer of the atmosphere equivalent to the vertical size of the telescopes (i.e., Δz = 20 m for the 2.1 m and Δz = 2.5 m for the 1.5 m). The seeing measured in the surface layer during these 4 selected nights is really small ($< 0.10''$, see Table 3) so the surface contribution

TABLE 4

SUMMARY OF THE SEEING CALCULATED IN DIFFERENT REGIONS OF THE ATMOSPHERE AND RELATED TO 10 NIGHTS OF THE SPM2000 CAMPAIGN [a]

Night	GS (″)	GS-dome (″)	MNH (″)	MNH-SF. (″)	Bal.(**a**) (″)	Bal. (**b**) (″)	Bal. (″)	
6-7/5/2000	1.17	0.69	0.97	···	···	···	···	ε_{BL}
”	0.29	0.29	0.50	···	···	···	···	ε_{FA}
”	1.24	0.79	1.15	···	···	···	···	ε_{TOT}
7-8/5/2000	1.02	0.68	1.45	···	···	···	···	ε_{BL}
”	0.47	0.47	0.60	···	···	···	···	ε_{FA}
”	1.18	0.88	1.64	···	···	···	···	ε_{TOT}
8-9/5/2000	1.28	1.05	0.69	···	0.86	1.34	1.1	ε_{BL}
”	0.32	0.32	0.36	···	0.25	0.25	0.25	ε_{FA}
”	1.36	1.14	0.82	···	0.93	1.38	1.15	ε_{TOT}
9-10/5/2000	1.09	0.66	0.88	···	0.39	0.63	0.51	ε_{BL}
”	0.24	0.24	0.41	···	0.24	0.24	0.24	ε_{FA}
”	1.15	0.73	1.02	···	0.49	0.70	0.59	ε_{TOT}
12-13/5/2000	1.43	0.94	0.92	0.91	···	···	···	ε_{BL}
”	0.27	0.27	0.52	0.52	···	···	···	ε_{FA}
”	1.49	1.01	1.12	1.12	···	···	···	ε_{TOT}
13-14/5/2000	0.96	0.51	0.98	0.97	0.55	0.84	0.69	ε_{BL}
”	0.18	0.18	0.44	0.44	0.27	0.27	0.27	ε_{FA}
”	0.99	0.56	1.13	1.13	0.64	0.91	0.77	ε_{TOT}
17-18/5/2000	0.57	0.33	0.89	0.87	0.37	0.60	0.78	ε_{BL}
”	0.44	0.44	0.57	0.57	0.35	0.35	0.35	ε_{FA}
”	0.77	0.59	1.12	1.12	0.54	0.74	0.89	ε_{TOT}
18-19/5/2000	1.24	1.06	0.44	0.43	1.75	1.75	1.75	ε_{BL}
”	0.72	0.72	0.58	0.58	0.61	0.61	0.61	ε_{FA}
”	1.52	1.36	0.78	0.78	1.92	1.92	1.92	ε_{TOT}
20-21/5/2000	0.46	0.27	0.20	···	···	···	···	ε_{BL}
”	0.66	0.66	0.54	···	···	···	···	ε_{FA}
”	0.86	0.75	0.60	···	···	···	···	ε_{TOT}
21-22/5/2000	0.48	0.24	0.54	···	0.78	1.09	0.93	ε_{BL}
”	0.35	0.35	0.82	···	0.40	0.40	0.40	ε_{FA}
”	0.64	0.45	1.05	···	0.92	1.21	1.06	ε_{TOT}

[a] The boundary layer contribution ε_{BL} is calculated in the [2719 - 3800] m range, the free atmosphere contribution ε_{FA} in the [3800 – 20,000] m range and the total contribution ε_{TOT} in the [2719 – 20,000] m range. The second column contains the seeing measured by the GS; the third, the seeing measured by the GS without the contribution of the dome; the fourth, the seeing simulated the Meso-Nh model; the fifth, the seeing simulated by the model without the surface contribution measured by the instrument mast; the sixth and seventh columns list the seeing measured by the balloons. In case **(a)** the boundary layer starts from 2719 m, and in the case **(b)** it starts from 2400 m. The eighth column lists the mean value obtained from cases **(a)** and **(b)**.

can be probably neglected with respect to the contributions from the other parts of the atmosphere. Because of this, we decided to treat the data with the following procedure. As a first step we calibrate the model without the contribution of the surface. The error introduced is probably small because of the reasons given previously. The advantage of this choice is that it allows us to manage a statistical sample (all 10 nights) and to estimate how good or bad is the reliability of the Meso-Nh if it is calibrated following this more practical and common procedure (without surface measurements). In the final anal-

TABLE 5

SUMMARY OF THE SEEING MEASURED AND SIMULATED IN DIFFERENT REGIONS OF THE ATMOSPHERE DURING THE WHOLE SPM2000 CAMPAIGN [a]

GS ($''$)	GS-dome ($''$)	MNH ($''$)	MNH-Surf. ($''$)	Balloons ($''$)	
0.94	0.62	0.79	0.77	1.00	ε_{BL}
0.42	0.42	0.45	0.45	0.29	ε_{FA}
1.08	0.79	0.97	0.93	1.07	ε_{TOT}

[a] In the first column is shown the seeing measured by the GS; in the second column the seeing measured by the GS without the contribution provided by the dome; in the third, the seeing simulated by the Meso-Nh model; in the fourth, the seeing simulated by the Meso-Nh model without the contribution provided by the surface; in the fifth, the seeing measured by the balloons.

ysis made on the whole campaign (averaged values over 10 nights) we consider, anyway, the surface contribution. As a second step, we carry out an *absolute* calibration considering the surface contribution with respect to 4 nights, that is, a reduced statistical sample. In this way we can estimate the impact of the surface contribution on the calibration.

To analyze the results in a quantitative way, we calculated the seeing in different regions of the atmosphere (boundary layer: ε_{BL} - $[2719 - 3800]$ m, free atmosphere: ε_{FA} - $[3800 - 20,000]$ m and the whole troposphere: ε_{TOT} $-$ $[2719 - 20,000]$ m) integrating measured and simulated C_N^2 profiles. Table 4 summarizes the obtained results. All seeing values given here are calculated for a $\lambda = 0.5$ μm wavelength. The first column lists the nights, the second column shows the seeing measured by the GS, the third column the seeing measured by the GS without the contribution of the dome, the fourth column the seeing obtained by integrating the simulated C_N^2, the fifth column the seeing obtained by integrating the simulated C_N^2 without the surface contribution, the last three columns show the seeing obtained by integrating the C_N^2 measured by the radiosoundings.

As stated in § 2.1, most of the balloons were launched from Vallecitos, a locality about 3 km away from the 2.1 m telescope and at an altitude of about 2400 m. Following the methodology presented in a previous paper (Vernin & Muñoz-Tuñón 1992) we consider two cases: (a) the boundary layer is calculated starting from the Observatory ground level (2719 m); (b) the boundary layer contribution is calculated starting from 2400 m which is the ground level at Vallecitos. Finally, the last column shows the seeing obtained with the mean values of the boundary layers of the cases (a) and (b).

Indeed, case (a) underestimates the seeing because the integration starts at about 400 m above the ground, so the whole surface contribution is lost, and case (b) over-estimates the seeing because the integration starts from a ground level lower than the Observatory level. From Table 4 one can appreciate, night by night, the Meso-Nh performances. The calibration done with the surface contribution (i.e., the *absolute* calibration) gives a difference of the values of the calibration coefficients a_k described in § 3.1 which is lower than the precision with which we calculated the a_k. We therefore conclude that the surface contribution is negligible for the calibration, from a quantitative point of view.

Figure 2 shows C_N^2 profiles measured by the GS and radiosoundings and profiles simulated by the Meso-Nh model related to 4 nights of the SPM2000 campaign. This gives a qualitative estimation of the ability of Meso-Nh in reconstructing the shape of the C_N^2 profiles. One can observe that the simulated C_N^2 reproduces well the vertical distribution of the turbulent layers over the whole atmosphere during all 4 nights. No radiosoundings were launched during the $20 - 21$ night. In the next section a statistic analysis of these measurements is presented.

4. DISCUSSION

Here we give an estimation of what we could call the *climatological* reliability of the model estimated over the mean values of the seeing (in our case obtained over 10 nights). The mean value of the dome seeing and the seeing from the surface over the whole campaign are respectively $\varepsilon_d = 0\farcs62$ and $\varepsilon_{surf.} = 0\farcs10$. Table 5 lists the values of ε_{BL}, ε_{FA} and ε_{TOT} averaged over the whole campaign and related to measurements and simulations. We underline that the average is done on the C_N^2 profiles and then the seeing in the different regions of the atmosphere is calculated. To estimate the reliability of the model we compare the dispersion between measurements and simulations with the dispersion between measurements provided by different instruments. We recall that the Meso-Nh model, in the configuration that we use at the present time, does not provide a C_N^2 maps at a precise time but rather provides a 3D C_N^2 distribution representative of a precise night. We refer to Masciadri (2002) for further details related to the simulation procedure. We define a relative error as:

$$\varepsilon_{rs} = \frac{|\varepsilon_{GS} - \varepsilon_{MNH}|}{\varepsilon_{GS}}, \qquad (10)$$

$$\varepsilon_{rm} = \frac{|\varepsilon_{GS} - \varepsilon_{Bal.}|}{\varepsilon_{GS}}, \qquad (11)$$

and we define an absolute difference as:

$$\Delta_{GS-MNH} = |\varepsilon_{GS} - \varepsilon_{MNH}|, \qquad (12)$$

$$\Delta_{GS-Bal.} = |\varepsilon_{GS} - \varepsilon_{Bal}|. \qquad (13)$$

This means that we consider the GS measurements as the reference, i.e., the *correct* value. We calculate the absolute difference ($\Delta_{GS-Bal.}$, Δ_{GS-MNH}) and the relative error (ε_{rs}, ε_{rm}) for the boundary layer and the free atmosphere. Table 6 lists the results.

We underline that, for the calculation of the boundary layer contribution, the absolute difference between measurements provided by different instruments is calculated using the values of the first and fifth columns (Table 5), and the absolute difference between measurements and simulations is calculated using the values of the second and fourth columns (Table 5). We observe that the relative error ε_{rs} is smaller than the ε_{rm} in the free atmosphere and that it is larger than the ε_{rm} in the boundary layer. We can state that, over the whole atmosphere, the ε_{rs} is no larger than the ε_{rm} and both of them are no larger than $\sim 30\%$.

Figure 3 shows the vertical C_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 profile is good and the turbulence is well reconstructed over the whole troposphere by the model. We note that, for the estimations given in Table 5 and the averaged profiles shown in Fig. 3, we used all the radiosoundings launched during the campaign in order to improve the statistics.

The statistical analysis done with the mean values of the C_N^2 allows us to put in evidence the systematic behaviour of the turbulence at different altitudes, so that this is the most representative estimation from the point of view of the calibration. It gives us an estimation of the ability of the model to reconstruct the climatological features and variations of the optical turbulence.

It is also interesting to calculate the night by night absolute differences ($\Delta_{GS-Bal.}$, Δ_{GS-MNH}) and the relative errors (ε_{rs}, ε_{rm}). This allows us to put in evidence the reliability of the model over the timescale of a single night.

Table 7 gives similar information to that of Table 6 with the following difference: in Table 6 we calculate the mean of the C_N^2 profiles and then the statistical parameters (Δ, ε_r), while in Table 7 we first calculate the night-by-night statistical parameters (relative and absolute error) and then we calculate the mean of the these values. We observe that in this case the dispersion increases: the ε_{rs} is comparable to the ε_{rm} in the boundary layer but it is larger in the free atmosphere. In this last region we have a dispersion of $0\farcs19$ between measurements and simulations compared to a dispersion of $0\farcs07$ between measurements obtained with different instruments. In this case ε_{rs} and ε_{rm} are smaller than $\sim 57\%$ over the whole atmosphere.

There is a further question to which it would be useful to give an answer:

- Is it necessary, for a calibration to be done, to compare simulations and measurements over a larger (≥ 10) number of nights?

The results obtained in the present study show that the reliability of the model is quite good from a qualitative and a quantitative point of view. On the other hand we think that there is room for further improvements in the field of the reliability of the model. A richer sample of nights would allow us to minimize the weight on the general statistic of the initialization data that are not, or are poorly, representative of the state of the atmosphere. In other words, it permits us to put in evidence, in a better way, the systematic behaviour of the turbulence.

As shown in Fig. 3, a further improvement could be obtained by increasing the number of atmospherical regions (vertical slabs) for the calibration in proximity of the edge between the boundary layer and the free atmosphere. This region is particularly critical for the calibration because of the strong gradient of the C_N^2 profiles. Besides this, we suggest that further investigations be made in order to better cross-calibrate the instruments and assure a more reliable *reference* for the simulations. We give just some examples.

(a) We note that the GS technique for retrieving the dome seeing probably has a tendency to overestimate this quantity. Following Avila et al. (2001), the presence of two triplets (the first one with a velocity equal to zero and the second one with a velocity different from zero) allows us to quantify the dome seeing from the steady triplet. We observe that, because of the low vertical resolution ($\Delta H \in [300-1900]$ m during the SPM2000), it would be possible for the two triplets to be associated with two turbulent layers outside the dome, but placed at different heights inside the range defined by ΔH (as sketched in Figure 4). It can happen that, in the presence of a low wind near the ground, the turbulence produces a velocity dispersion characterized by a mean value (V_1 in Fig. 4) smaller than the velocity resolution (ΔV, see § 2.3). It would therefore be advisable to refine in the future the criterion used to discriminate the dome seeing from the outdoor seeing in order to better estimate the turbulence in the dome. Otherwise, this effect could result in an offset of the model calibration.

(b) Figure 5 shows two vertical C_N^2 profiles measured by the GS (bold line) and a radiosounding (thin line) during the same night (17-18/5/2000). The two instruments give clearly different estimations of the C_N^2 above 10 km. Obviously, the radiosounding changes its position during its ascension and one could imagine that the turbulent regions monitored by the two instruments are different. It would be interesting to verify this possibility, for example with the support of model simulations extended over a large computational domain. Such a study could give useful informations about the level of uniformity of the horizontal distribution of the C_N^2 at high altitudes and also about the cross-calibration of the instruments. The differences detected above 10 km are indeed not negligible in this case and are extended over a large vertical slab. The relative difference in equivalent seeing calculated over the [10−20] km range is equal to $\sim 87\%$, which is a non negligible quantity.

TABLE 6

SUMMARY OF THE ABSOLUTE DIFFERENCE AND RELATIVE ERROR[a]

	$\Delta_{GS-Bal.}$ ($''$)	ε_{rm} (%)	Δ_{GS-MNH} ($''$)	ε_{rs} (%)
BL	0.06	6	0.15	24
FA	0.13	31	0.02	7

[a] Calculated over the mean values related to the all 10 selected nights (see text).

TABLE 7

SUMMARY OF THE ABSOLUTE DIFFERENCE AND RELATIVE ERROR CALCULATED OVER THE SINGLE NIGHTS

	$\Delta_{GS-Bal.}$ ($''$)	ε_{rm} (%)	Δ_{GS-MNH} ($''$)	ε_{rs} (%)
BL	0.36	56	0.37	57
FA	0.07	18	0.19	48

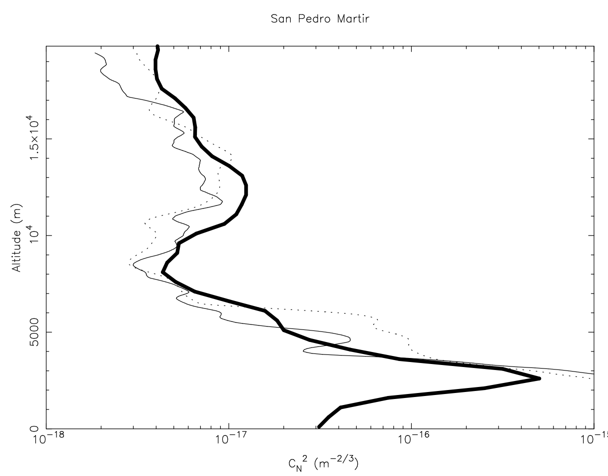

Fig. 3. Mean vertical C_N^2 profiles measured and simulated over the whole SPM2000 campaign. Bold line: GS. Thin line: radiosoundings. Dotted line: Meso-Nh model.

5. CONCLUSION

In this paper we apply the calibration technique of the Meso-Nh model proposed in a previous paper to a sample of 10 nights related to the SPM2000 campaign (May 2000) in order to study the reliability of the numerical technique in simulating $3D$ C_N^2 maps in a region around a telescope. Simulated C_N^2 profiles from the Meso-Nh model are compared to measured C_N^2 profiles provided by a GS and by radiosoundings. We prove that the reliability of the model is quite good from a quantitative and qualitative point of view. Table 4 shows, for each night, the seeing measured and simulated in different regions

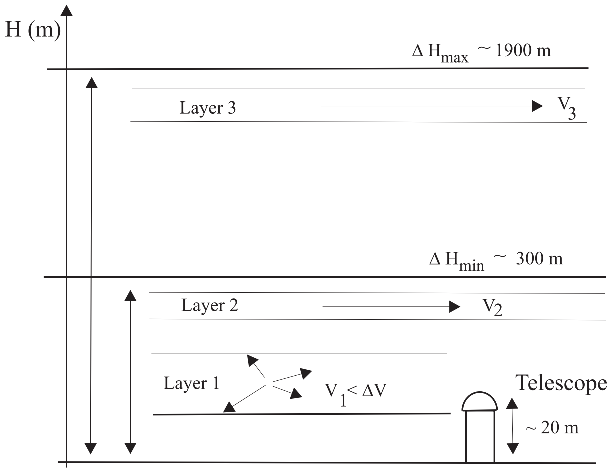

Fig. 4. $\Delta H_{min} \in [0-300]$ m and $\Delta H_{max} \in [0-1900]$ m represent the minimum and maximum vertical resolution attained by the GS during the SPM2000 campaign at ground level. The turbulent layers 1 and 2 are both external to the dome. The velocity of the layer 2 is $> \Delta V$ and the velocity of the layer 1 is $< \Delta V$ where $\Delta V \in [1-2]$ m/s for the 2.1 m. Following the criterion defined in Avila et al. (2001), the layer 1 is turbulence that can be associated to the telescope dome. The same can be said comparing layers 1 and 3.

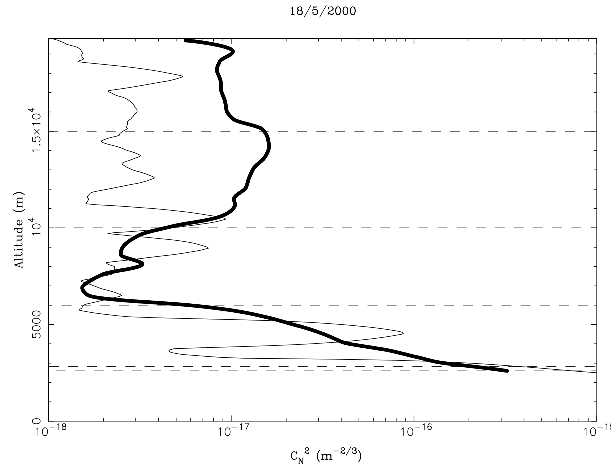

Fig. 5. Vertical C_N^2 profiles measured by the GS in the interval [07:30−08:15] U.T. (bold line) and a balloon 06:59 U.T. (thin line) during the 17-18/5/2000 night.

of the atmosphere and the ability of Meso-Nh to reconstruct the optical turbulence can be retrieved from it. Table 5 shows the same quantities but averaged over the whole campaign. We find a total mean seeing measured by the GS without the dome contribution equal to 0″.79, measured by the balloons equal to 1″.07, and simulated by Meso-Nh equal to 0″.93. We find that the dispersion between the measurements and the simulations is comparable to the dispersion obtained between measurements provided by different instruments. A detailed analysis is presented considering two different way to average the statistical estimator over the whole campaign. Small variations are found, depending on the order taken to calculate the averages and the statistical estimators. If we calculate the average of the C_N^2 profiles over the whole campaign and then the statistical estimators, the relative error is $\leq$ 30% in both cases (i.e., dispersion between measurements provided by different instruments [GS-Bal.] and dispersion between measurements and simulations [GS-Sim.]). This percentage is representative of the reliability of the model over a climatological temporal scale. The relative error is larger (in both cases GS-Bal. and GS-Sim.) if we calculate the statistical estimators for each night and then we calculate the average. In this case the maximum dispersion (in equivalent seeing) between simulations and measurements (Δ_{GS-MNH}) in the free atmosphere is estimated at 0″.19 and in the boundary layer at 0″.37. In this same case the maximum dispersion between measurements provided by different instruments ($\Delta_{GS-Bal.}$) in the free atmosphere is $\sim$ 0″.07 and in the boundary layer is $\sim$ 0″.36. Over a temporal scale of one night, both the dispersion between measurements and simulations and the dispersion between measurements provided by different instruments give a relative error $\leq$ 57% (see Table 7).

We showed that the shape of the measured C_N^2 profiles is well reproduced by the simulated ones. This could be verified night by night (Fig. 2) and over a mean estimation (Fig. 3) calculated over the whole SPM2000 campaign (10 nights).

For the first time, the calibration was done considering the turbulence contributions from all the regions of the atmosphere. This fact permits us to carry out an *absolute* calibration, i.e., without offsets. We proved that, if the surface contribution is characterized by an equivalent seeing $\leq$ 0″.10, this contribution can be neglected in the calibration procedure. For the first time we could compare the Meso-Nh without the surface contribution to the GS without the dome seeing contribution. The seeing contribution measured and simulated in the boundary layer over the whole campaign are respectively 0″.62 and 0″.77. The corresponding values for the free atmosphere are 0″.42 and 0″.45.

In this paper we use in a somewhat forced way the term 'statistical analysis' to refer to the comparison between measurements and simulations of the C_N^2 profiles over 10 nights. We think that better and more significant estimations will be available in the future and will allow to improve the statistical sample. On the other side, we underline that during each night we consider many hundreds of measured C_N^2 profiles and we simulate the same parameter over many hours. Moreover, we note that the number of nights over which a comparison between simulated and measured C_N^2 profiles was done is quite unique and this gives us a measure of the reliability of the numerical technique.

Finally, in this study we calculate, for the first time, the dome seeing (ε_d) over a large number of nights (10). We estimate that ε_d represents about 62% (for the 1.5 m) and 43% (for the 2.1 m) of the total seeing obtained by integrating the C_N^2 over the whole troposphere. At the same time we show that the criterion proposed to estimate ε_d (Avila et al. 2001) has a tendency to overestimate the latter. It would therefore be suitable to correct this criterion in order to better estimate the ε_d and, consequently, to better calibrate the model. We conclude by stating that it would be interesting to verify whether the calibration coefficients a_k are strongly site-dependent or not. This could be tested by comparing simulations with GS measurements extended over a long period of time in at least two sites. A favourite candidate would be Mt. Graham (Arizona), site of the LBT telescope. A new GS was recently built by the Stewart Observatory (McKenna et al. 2003) to support observations that will be done with the LBT and it is planned to run in a systematic way at the VATT telescope (2.1 m).

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