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ESTIMATION OF THE OPTICAL TURBULENCE (C_N^2) AND SEEING FROM MM5 DATA IN PARANAL/ARMAZONES SITE

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RESUMEN

El modelo meteorológico MM5 se ha testeado como una buena herramienta de pronóstico de variables meteorológicas en el norte de Chile. Configurando el MM5 en alta resolución horizontal, vertical y temporal se probaron dos modelos para estimar el perfil vertical de la turbulencia óptica (C_n^2) y seeing en Paranal y Armazones. El modelo AFGL (M1) y el modelo de Masciadri (M2) calculan la estructura vertical de C_n^2 usando en sus ecuaciones parámetros meteorológicos como la magnitud del viento, temperatura, presión, humedad, temperatura potencial y TKE. Se probaron diferentes parametrizaciones de los procesos físicos atmosféricos en el modelo MM5, donde la parametrización de capa límite Gayno-Seaman y el método M2 tienen el mejor resultado. Estos resultados fueron comparados con los datos registrados en las campañas de medición en Paranal entre noviembre y diciembre de 2007, donde se usaron simultáneamente los instrumentos SCIDAR y DIMM midiendo C_n^2 y seeing. Los resultados muestran que el C_n^2 simulado tiene muy buena correspondencia en casi todo el perfil comparado con las mediciones de SCIDAR, pero cerca de la superficie la diferencia es alta, porque los instrumentos toman en cuenta la turbulencia provocada por los edificios de los telescopios, y cerca del suelo el modelo MM5 tiene errores sistemáticos. En Paranal el RMSE de seeing en promedio sobre 12 días es 0.45 arcsec y en Armazones el RMSE de seeing promedio es 0.19 arcsec.

ABSTRACT

MM5 meteorological model was tested that is a good tool to estimate and forecast the meteorological variables in astronomical sites in the north of Chile. Configuring the MM5 in high horizontal, vertical and temporarily resolution we tested two models to estimate the vertical profile of the optical turbulence (C_n^2) and seeing in Paranal and Armazones sites. AFGL model (M1) and Masciadri's model (M2) are methods to estimate the vertical structure of the C_n^2 using meteorological parameters like wind magnitude, temperature, pressure, humidity, potential temperature and TKE in his equations. We tested different parameterizations for the atmospherical physics processes in the MM5 model, where Gayno-Seaman parameterization of the boundary layer and the M2 method have the best results. These results were compared with a measurement campaign developed in Paranal between November and December of 2007 where using simultaneously two instruments, SCIDAR and DIMM, to measurement the C_n^2 and seeing. The results shows that the C_n^2 simulated profile have very good correspondence in almost all profile compared with SCIDAR measurements, but near of the ground the difference is big, because the instruments take in account also the turbulence provoked by telescopes buildings and near of the ground the MM5 model have systematic errors. In Paranal the RMSE average seeing over 12 days is 0.45 arcsec and in Armazones the RMSE average seeing is 0.19 arcsec.

Key Words: atmospheric effects — site testing — turbulence

1. INTRODUCTION

For the astronomical observatories in special for the new generations of the big and complex telescopes is very important knows of the optical turbulence (C_n^2) profile and seeing. At the last years instruments were development to measurement this astronomical-atmospheric parameters, DIMM, SCIDAR and MASS are standard optical tools that could using different techniques, measurement the C_n^2 profile and seeing. This paper shows the relevant results of the simulation of C_n^2 and seeing using data from the MM5 mesoscale meteorological model applied in Paranal an Armazones site, compared with the measurement from a campaign developed in Paranal and the data from site testing in Armazones.

Two models to obtain the C_n^2 profile were compared, first one is used in Mauna Kea Weather Center in Hawaii (Businger et al. 2002). AFGL model (Dewan et al. 1993) obtain the C_n^2 profile based in

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the Tatarski's equation:

$$C_n^2 = 2.8 M^2 L^{\frac{4}{3}}\,, \tag{1}$$

where

$$M^2 = \left[\left(\frac{79 \times 10^{-6} P}{T^2}\right)\left(\frac{\partial T}{\partial z} + \gamma\right)\right]\,, \tag{2}$$

where P is the pressure, T is the air temperature and γ is the dry adiabatic lapse rate. To obtain L (outer scale) Dewan et al. (1993) propose apply the next rule:

$$Ri = N^2/S^2 < 0.25\,, \tag{3}$$

where Ri is the Richardson number, N is the buoyancy frequency and S is the vector vertical shear of the horizontal velocity defined as:

$$S = \left[\left(\frac{\partial u}{\partial z}\right)^2 \left(\frac{\partial v}{\partial z}\right)^2\right]^{\frac{1}{2}}\,, \tag{4}$$

where u and v are the zonal and meridional wind component. Then they take data from radiosonde with information every 300 m and using a statistical model found L

$$\text{troposphere}: Y = 157 + 40 S_{\text{raw}}\,, \tag{5}$$

$$\text{stratosphere}: Y = 0.503 + 51.2 S_{\text{raw}}\,. \tag{6}$$

Finally the model is:

$$C_n^2 = 2.8(0.1)^{\frac{4}{3}} M^2 10^Y\,. \tag{7}$$

The equation (7) (M1) is the optical turbulence in function of meteorological parameters, like a pressure, air temperature and gradient of shear from horizontal wind.

A second method to obtain the C_n^2 is propose by Masciadri & Jabouille (2001) and is based on the Glastone's law:

$$C_n^2 = \left(\frac{80 \times 10^{-6} P}{\theta^2}\right) C_\theta^2\,, \tag{8}$$

where P is the pressure, θ the potential temperature and the temperature fluctuation in the path L:

$$C_\theta^2 = 0.59 L^{\frac{4}{3}} \left(\frac{\partial \theta}{\partial z}\right)\phi\,, \tag{9}$$

where ϕ is a thermal and dynamic stability in the atmosphere with estimated value of 0.78. L can be express in function of potential temperature θ and turbulent kinetic energy (TKE) by the next relation:

$$L = \sqrt{\frac{2E}{\frac{g\partial\theta}{\theta\partial z}}}\,, \tag{10}$$

where E is the TKE and g is the gravity acceleration. Replacing the equation (10) in equation (9) we obtain:

$$C_\theta^2 = 0.20\theta^{\frac{2}{3}} \left(\frac{\partial \theta}{\partial z}\right)^{\frac{4}{3}} E^2\,. \tag{11}$$

The equation (11) is the temperature fluctuation (C_θ^2) in function of the TKE. Then we replacing in equation (8)

$$C_n^2 = 3.35 \times 10^6 P^2 (1 - \frac{2R}{c_p})\theta^{\frac{-10}{3}} \left(\frac{\partial \theta}{\partial z}\right)^{\frac{4}{3}} E^{\frac{2}{3}}\,. \tag{12}$$

The equation (12) (M2) is the optical turbulence in function of meteorologic parameters like the pressure, potential temperature and TKE.

To obtain the seeing that represent the quality of the image in the telescope, we need obtain the Fried number r_0 by vertical integration of the refractive index structure coefficient C_n^2 along the optical path L:

$$r_0 = \left[0.423 \left(\frac{2\pi}{\lambda}\right)^2 \int_0^L C_n^2(z) d(z)\right]^{\frac{-3}{5}}\,, \tag{13}$$

where λ is the wavelength at which the telescope observing (0.5 μm). Then the seeing have the next relation

$$\phi = 0.98 \frac{\lambda}{r_0}\,. \tag{14}$$

Finally we have two models (M1: equation 7 and M2: equation 12) which ones could be to obtain the optical turbulence and seeing by meteorologic variables, it will be extracted form MM5 mesoscale model adapted to Paranal and Armazones sites.

2. METHODS AND DATA

To obtain the data for the models M1 and M2 we implement the MM5 meteorological mesoscale model for Paranal and Armazones sites. The MM5 model was tested like a very good tool to simulate the atmosphere in the Los Andes mountain like Macn in Argentina (E-ELT site testing) (Cuevas et al. 2008) and the north of Chile (TMT site testing) (Cuevas et al. 2009). The MM5 was configured with 4 domains with the next horizontal resolutions mesh: D1=27 km, D2=9 km, D3=3 km and D4=1 km. In the vertical the model was configured with 80 sigma levels for every domain until 100 hPa and with high time resolution every 10 minutes output. For the boundary conditions we tested 3 sources of

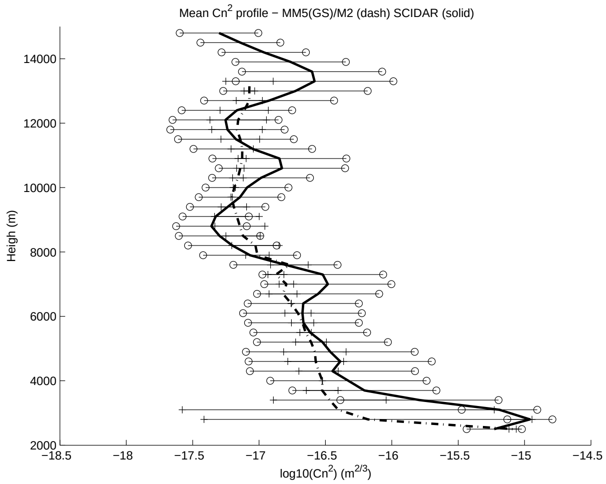

Fig. 1. C_n^2 mean profile (Nov-Dec). The solid line is SCIDAR profile and circles are the variability. Dash line is MM5/M2 and plus are the variability.

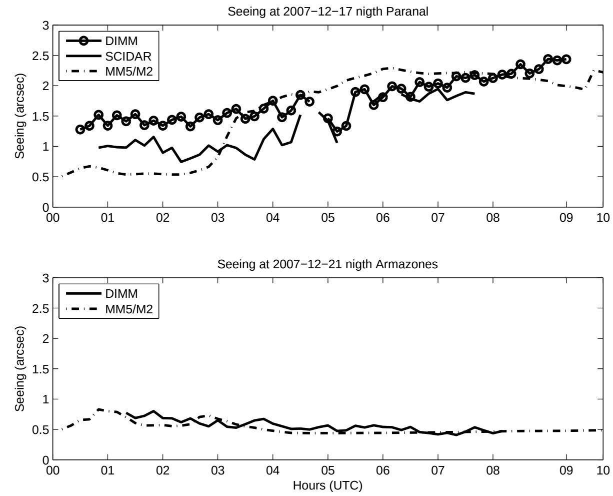

Fig. 2. Nocturnal Seeing. Top is the MM5/M2 in Paranal, bottom is MM5/M2 in Armazones.

data: ERA40 analysis from ECMWRF[3], GFS[4] operational and FNL[5] (Analysis) from NCEP[6]/NCAR[7]. The MM5 have the option to choose parameterizations of the physic process in the atmosphere, in this case we compare two parameterizations of the boundary layer, ETA and Gayno-Seaman (Cherubini et al. 2007), boot calculate TKE from Mellor-Yamada[8]. Also the model started to run at 18 UTC of the before day because this help to stabilize the dynamic interpolation in the model and six hours after the quality of the data are better.

In November and December of 2007 in Paranal developed an optical turbulence and seeing measurement campaign using SCIDAR instrument that measurement the C_n^2 in 300 meters layers, also using a DIMM instrument to measurement the seeing[9]. Over Armazones the data of seeing is from a DIMM instrument, measurement by TMT site testing campaign.

3. RESULTS

Two configurations of the MM5 model was tested using two different planetary boundary layer parameterization that calculate TKE. The meteorological data in horizontal, vertical and temporally high resolution was using in the models M1 and M2 to estimate the C_n^2 and seeing. The C_n^2 profile simulated (Figure 3) show correspondence with profile of SCIDAR in the free atmosphere (over 4000 m.a.s.l.), three zones of high values of C_n^2 show the SCIDAR profile, in aprox. 7000 m, 11000 m and 13000 m, where the last one is the Jet Stream zone. The simulated profile of C_n^2 show this zones but the values are minor than the measurement and the variability is always minor than the variability of the SCIDAR profile. Also this show that the synoptic patterns (Jet Stream or instabilities) have influence in the C_n^2 distribution that is in addition of the turbulence near of the surface, this zone is where the performance of the model have deficiency, the systematic error of the MM5 model also the resolution of the orography provoke errors in the surface variables. The model show a turbulent layer very close of the ground, different of the SCIDAR profile that shows a turbulent layer distributed between 2600 to 4000 m.

For the seeing estimation case, the M1 and M2 models was tested and compared whit 2 instruments, Paranal: DIMM and SCIDAR; Armazones: DIMM. The data shows a good correspondence, like the Figure 2 where the MM5 model follow the tendency of the seeing with both instruments. In the Paranal case of the 17-12-2007 (Figure 2 top) the MM5/M2 shows a first part of the night with low seeing close of the SCIDAR instrument, the second part of the nigth the model up the seeing values close a DIMM instrument and show a similarly tendency. The difference between the first part and second part of the

[3] European Centre for Medium-Range Weather Forecasts (`http://www.ecmwf.int/`).

[4] Global Forecast System (`ftp://ftpprd.ncep.noaa.gov/pub/data/nccf/com/gfs/prod/`).

[5] Final Analysis GFS (`http://dss.ucar.edu/datasets/ds083.2/`).

[6] National Centers for Environmental Prediction

[7] National Center for Atmospheric Research

[8] `http://www.mmm.ucar.edu/mm5/`.

[9] `http://www.eso.org/gen-fac/pubs/astclim/paranal/asm/scidar/Cute-SCIDAR-Results-Nov-Dec07.htm`.

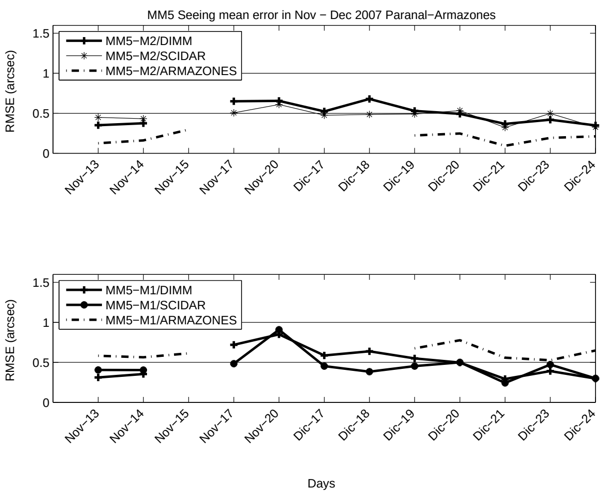

Fig. 3. Nocturnal Seeing mean error. Top is the MM5/M2, bottom is MM5/M1, both for Paranal and Armazones.

TABLE 1

MEAN SEEING ERROR BETWEEN NOV-DEC

Mod/Inst	Paranal	Armazones
M1/DIMM	0.49	0.61
M2/DIMM	0.48	0.19
M1/SCIDAR	0.45	
M2/SCIDAR	0.46	

night shows that the MM5 model have the capacity to reactions of the changes of the weather in Paranal. We must considerer that the November and December start the Altiplanic Winter that to contribute bad weather in the north of Chile where the atmospheric instability could be present on the night and could have changes in short time. For Armazones (Figure 2 bottom) the seeing is very low and stable in general in all nights studied and the model MM5 also shows very good correspondence on every night. The case of the 21-12-2007 is a very quiet and low seeing night, where the MM5 model also have the capacity of simulate in good conditions for the astronomy. The figure 3 show a seeing mean night between November and December where the M2 model is better in Armazones and also in Paranal compared with DIMM, but is more variable using M1.

4. CONCLUSIONS

This work shows the principal results of the estimation of the optical turbulence C_n^2 and seeing in Paranal and Armazones using two models for the estimation of the C_n^2 profile based in meteorological variables. The MM5 meteorological model was configured in high resolution to obtain the input variables used in M1 and M2 methods. The result show that the use of the Gayno-Seaman parameterization of the boundary layer is the best option to calculate TKE for M2 and this method have the best results to obtain C_n^2 and seeing. The Table 1 shows that in Armazones and Paranal M2/DIMM have low errors, although between M1 and M2 in Paranal the difference is small, in Armazones these difference is important.

We found that the use of the TKE is much better than the wind shear to estimate local turbulence and C_n^2, both in high vertical resolution where in Armazones to present very lows errors. The absence of the telescope building in Armazones doing much realistic the simulations than the Paranal because the turbulence provoked by the building the MM5 can not estimate it. The Altiplanic Winter like synoptic pattern could be affect the local weather, and the MM5 in some cases can to estimate this changes reflected int the C_n^2 and seeing.

These results incentives the use of the mesoscale meteorological models like MM5/WRF, to estimate astrometeorological and astroclimatological variables very important for the development and operation of the observatories and the new generation of the big telescopes.

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