OPTICAL TURBULENCE SIMULATIONS WITH MESO-SCALE MODELS

"TOWARDS A NEW GROUND-BASED ASTRONOMY ERA"

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3D Optical Turbulence Forecasts above Astronomical Sites

http://forot.arcetri.astro.it
Outline

- Meso-scale models challenges in Astronomy
- **Dynamic** and **Optical** Turbulence Parameterization
- Review “mesoscale simulations” in astronomic field
- **MESO-NH**\* Model Reliability
- **ForOT**: an answer to the missing link between astronomy/meteorology

\*Meso-Nh code: CNRM-LA, Toulouse, France
Astro Meso-Nh code: Masciadri et al. 1999

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Ground-based astronomy is still competitive with respect to the space-based one

- Lower financial investment
- Longer typical lifetime
- Better angular resolution thank to the larger pupils size of ground-based telescopes

AO techniques can correct perturbations induced by atmospheric turbulence

**PROBLEM**

Instruments provide **LOCAL** measurements
Meso-scale models potentiality

3D

\[ D_N(\rho) = \left\langle \left[ n(r) - n(r+\rho) \right]^2 \right\rangle = C_N^2 \cdot \rho^{2/3} \]

\[ l_0 < \rho < L_0 \]

Kolmogorov Model

3D \( V, T, p, L_0, C_N^2 \)

\( (x,y,z) \)

wind speed

2D

\[ \int_{0}^{\infty} F(h, V, L_0) \cdot C_N^2 \, dh \]

\( \rightarrow \varepsilon, \theta_0, \tau_0, \sigma^2, L_0, h_M, \theta_M \) \( (M=1,2,3) \)

ForOT

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Meso-scale models challenges in Astronomy

- To forecast the optical turbulence ➔ flexible-scheduling
- To reconstruct $3D C_n^2$ maps in a region around a telescope
- To perform a climatology of the optical turbulence extended over decades (access to “past”)

No other tools of investigation for these scientific goals

Seeing @ Cerro Paranal – black dots
Parameterization

GCM (General Circulation Models)

\[ w' \theta' = K \frac{\partial \theta}{\partial z} \]

TEMPORAL SCALE

- micro
- macro

SPATIAL SCALE

- eddy diffusivity approach

< 1 cm

10 m

1 km

102 km

104 km

< 10^{-3} \text{ sec}

1 \text{ min}

10^4 \text{ sec}

GCM (p, V, T, H)

TURBULENCE PARAMETERIZATION

OPTICAL TURBULENCE

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Parameterization in **MESO-NH**

- **Dynamic Turbulence Parameterization**
  - Mixing length - $L_0(h)$
  - Turbulent kinetic energy
    
  \[
  w' \theta_v = -0.16 \cdot L \cdot \sqrt{e} \cdot \phi_3 \cdot \frac{\partial \theta_v}{\partial z}
  \]
  - Microscopic
  - Macroscopic
  - Thermo-dynamic stability term
    - Redelsperger & Sommeria 1981

- **Optical Turbulence Parameterization** (**Astro-MesoNh**)
  - Mixing length - $L_0(h)$
  - Potential temperature
    
  \[
  C_T^2 = 0.58 \cdot \phi_3 \cdot L^{4/3} \cdot \left( \frac{\partial \bar{\theta}}{\partial z} \right)^2
  \]
  \[
  C_N^2 = \left( \frac{80 \times 10^{-6} \cdot P}{T^2} \right)^2 C_T^2
  \]
  - Masciadri et al. 1999a
  - Masciadri et al. 2001

**Buoyancy term of TKE equation**

- Bougeault et al. 1989
- Cuxart et al. 1995

**Gladstone’s law**

- Gladstone’s laws

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Review in Astronomical field (1)

- 1995 Bougeault et al.  [Ref: Applied Optics, 1995, 34, 3481]
  - First Hydrostatic model (PERIDOT)
  - Orographic model (3-10 km)
  - First Non-hydrostatic model (MESO-NH)  [Ref: 1999b, A&ASS, 137, 203]
  - First employment of vertical turbulence distribution ($C_n^2$ profiles)
  - New calibration method
  - First evidence of the horizontal finite extent turbulent layers
Review in Astronomical field (2)

- **2002 Businger et al.** [Ref: 2002, BAMS, 858]
  - The Mauna Kea Weather Center is announced

- **2003 Masciadri** [Ref: 2003, RMxAA, 39, 249]
  - Mesoscale models and near ground wind speed for ELT site selection
  - Mesoscale models (25-45) % better than GCMs

- **2004 Masciadri, Avila, Sanchez** [Ref: 2004, RMxAA, 40, 3]
  - First model validation in statistic terms (10 nights - San Pedro Mártir)
  - Measurements: GS, thermosondes, mast, DIMM

  - First statistic analysis (1 year) of $C_{N}^{2}$ & ALL astro-climatic parameters $\varepsilon$, $\theta_0$, $\tau_0$, $\sigma^2$, $\mathcal{L}_0$, $h_M$, $\theta_M$ ($M=1,2,3$)

Cherubini Adair

\{ MM5 developed by NCAR (US) \}
Can we simulate the optical turbulence?

Paranal 1992
(VLT site testing)

San Pedro Martir 1997

Paranal 1993
(VLT site testing)
Meso-Nh model Validation & Reliability

San Pedro Martir - Baja California, Mexico

Averaged estimates on 10 nights

Dotted line: Meso-Nh
Thin line: thermosondes
Bold line: GS

Masciadri, Avila, Sanchez, 2004, RMxAA, 40, 3
**Meso-Nh model Validation & Reliability**

San Pedro Martir - Baja California, Mexico

### Averaged estimates on 10 nights

<table>
<thead>
<tr>
<th></th>
<th>GS - dome</th>
<th>Meso-Nh - surf.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{E}_{TOT}$</td>
<td>0.79&quot;</td>
<td>0.93&quot;</td>
</tr>
<tr>
<td>$\mathcal{E}_{BL}$</td>
<td>0.52&quot;</td>
<td>0.77&quot;</td>
</tr>
<tr>
<td>$\mathcal{E}_{FA}$</td>
<td>0.42&quot;</td>
<td>0.45&quot;</td>
</tr>
</tbody>
</table>

$\Delta \mathcal{E}_{TOT} = 0.14"$

Dotted line: Meso-Nh
Thin line: thermosondes

Masciadri, Avila, Sanchez, 2004, RMxAA, 40, 3

**Kona - Hawaii March 2007**
Meso-Nh model Validation & Reliability (3)

- **GS/Meso-Nh**  \( \Delta \varepsilon \sim 30 \% \)
  - San Pedro Martir
  - Masciadri, Avila, Sanchez, 2004, RMxAA, 40, 3
  - 10 nights

- **GS/thermosondes**  \( \Delta \varepsilon \sim 30 \% \)
  - San Pedro Martir
  - Masciadri, Avila, Sanchez, 2004, RMxAA, 40, 3
  - Azouit & Vernin, 2005, PASP
  - 4 weeks
  - Cerro Pachon

- **GS/MASS**  \( \Delta \varepsilon \sim 20 \% \) @ 8-16 km
  - 50-100 \% @ 0-4 km
  - Mauna Kea
  - Tokovinin et al., 2005, PASP, 117, 395
  - 4 nights
Meso-Nh model Validation & Reliability  (4)

- **GS/Meso-Nh** \(\Delta \varepsilon \sim 30\%\)  
  Masciadri, Avila, Sanchez, 2004, A
dAA, 40, 3  
  San Pedro Martir

- **GS/thermosondes** \(\Delta \varepsilon \sim 30\%\)  
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  4 nights  
  Mauna Kea

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Meso-Nh can be used to characterize OT on long time extent

Optical Turbulence Climatology
First statistical analysis of ALL astroclimatic parameters

SPM - 80 nights - uniformly distributed along 1 year

- Is this seasonal trend universal?
- Which is the physical explanation of such a trend?
- Which effects on other astro-climatic parameters?

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SPM - 80 nights - uniformly distributed along 1 year

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80 nights


16 nights

Egger, Masciadri, McKenna, to be submitted

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Simulations vs. Measurements


**SIMULATIONS**

- **Masciadri & Egner (2006)**
  - $\varepsilon_{(10-15)\text{km}} \sim 0.22''$
  - $\theta_0 \sim 1.42''$

**MEASUREMENTS**

- **Avila et al. (2004)**
  - $\varepsilon_{(10-15)\text{km}} \sim 0.24''$
  - $\theta_0 \sim 1.87''$

**Seasonal variation**

\[ \Delta \varepsilon_{\text{summer-winter}} \]

- **Masciadri & Egner (2006)**
  - $\Delta \varepsilon_{\text{sum.-wint.}} \sim 0.22''$

- **Michel et al. (2003)**
  - $\Delta \varepsilon_{\text{sum.-wint.}} \sim 0.22''$ (DIMM)

- **Echevarría et al. (1998)**
  - $\Delta \varepsilon_{\text{sum.-wint.}} \sim 0.11''$ (SST)
ForOT: an answer to the missing link astronomy/meteorology

NEXT STEPS

1. Forecast of the optical turbulence

2. Search and selection of NEW sites

3. Implementation of models on autonomous machines ➔ research group

ForOT
an independent research group
funded by the European Community
ForOT Core Project

**Mt. GRAHAM**

30 km

\[ \Delta x = 500 \text{ m} \]

**ANTARCTIC PLATEAU**

6000 km

\[ \Delta x = 100 \text{ km} \]

**MESO-NH model**
**ForOT Core Project**

**Mt. GRAHAM**
- 30 km
- \( \Delta x = 500 \text{ m} \)

**ANTARCTIC PLATEAU**
- 6000 km
- \( \Delta x = 100 \text{ km} \)

**Main goal**:
- Forecasting for flexible-scheduling
- Site independent calibration for sites searches

**LBT**

**DOME C**

**MESO-NH model**
Physics of the Atmosphere

Wavefront perturbations by atmospheric turbulence

Adaptive Optics

Interferometry

Image Processing

ASTROPHYSICS

METEOROLOGY

ForOT

HAR traditional

NG-HAR
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