Modelling the Cn² and wind profiles for space-ground optical links with parametric models: cross-comparison with mesoscale models and in-situ measurements

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¹ ONERA (France)
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High increase in data rate transfer

- For spatial applications
  - 2020 – 2025: high resolution images download -> 1 Tbits/day
  - From 2025: telecommunication with GEO links (1 Tbits/s)
- Air-ground applications (> 1 Gb/s)
- Marine applications: 10 -> 100 Mb/s

RF bandwidth saturation

Using higher frequencies as optics

Comparison Optics / RF

- Suspend and complete congestion problem in RF band
- No frequency regulation
- Low divergence beam ⇒ secure links, mass and power consumption reduction
- More sensitive to atmospheric effects (cloud, fog, turbulence)
Turbulence profiles impacts telecom transmissions

Turbulence \( (C_n^2) \) profiles

Wind profile [2]

Threshold = \( f(r_0, \sigma_I^2) \)

Hypotheses on profiles to be confirmed experimentally and numerically
Characterization of the turbulent atmospheric channel

Optical channel Characteristics

- **direct**
  - Optical/RF data
    - Optical Instruments
      - PBL/PBS
      - CO-SLIDAR
      - SCO-SLIDAR
      - GDIMM
      - SH Odissée
    - Radiometric Instruments

- **indirect**
  - Auxiliary data
    - Parametric Models
      - HAP
      - Tatarskii
      - Most
      - Cn²@ 5m
    - Measures
      - Balloons
      - Meteo
      - stations
      - CT²-meter
    - Numerical Models
      - NCEP/NCAR
      - ERA-interim
      - WRF
      - Meso-NH

**Comparison**

We look for an automatic characterization of the turbulent channel on the globe
Turbulence measurements: how?

SH WFS @ MEO

CT²

GDIMM

micro-thermometers

Weather station: Cn²@5 m Bulk Model

Altitude 1270 m
Cross-comparison: measures & models with metrics

1. Measures
   A. Shack-Hartmann -> $r_0$, $\sigma^2_1 @ \lambda = 600$ [976] nm on the line of sight
   B. Weather data -> Bulk models -> $\text{Cn}^2@5$ m for parametric profiles
   C. CT$^2$ -> $\text{Cn}^2@3$ m -> to compare with $\text{Cn}^2@5$ m for parametric profiles
   D. GDIMM -> seeing, $r_0$, $\sigma^2_1 @ \lambda = 500$ nm & @ zenith

   -> We compare all parameters @ zenith

2. Parametric turbulence profiles ($\text{Cn}^2$ and wind) provided by ONERA
   - MOST+Tatarskii
   - MOST+HAP

3. Numerical profiles ($\text{Cn}^2$ and wind) from ASTRO-Meso-NH provided by INAF

The criteria proposed for the comparison study are:
- Fried parameter $r_0$
- Scintillation index $\sigma^2_1$
- $\text{Cn}^2@5$ m above ground
- $\text{Cn}^2$ piecewise integrals: $J_1 [0-150]$ m, $J_2 [3-5]$ km, $J_3 [10-14]$ km
- wind averages $V_1 [0-150]$ m, $V_2 [9-13]$ km
MOST+Tatarskii Cn² profiles in MATISSE V3.5

Diurnal evolution in the ABL

TIGR data base (PTU) in the free atmosphere
Temporal evolution of the $C_n^2$ profile by the Astro-Meso-NH

The turbulence close to the ground in day time disappears during the night.
### Selection of data & measurements

<table>
<thead>
<tr>
<th>N°</th>
<th>dates</th>
<th>Time TU</th>
<th>Sources Star mag</th>
<th>Elevation, Azimuth</th>
<th>Wind speed [m/s] avg, min, max</th>
<th>SH frame rate Central wavelength and spectral band</th>
<th>Other data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15/07/2013</td>
<td>14:25 -&gt; 14:52</td>
<td>Arcturus, 0.15</td>
<td>36-41°, 98-103°</td>
<td>1.5, 0, 3.6</td>
<td>700 Hz; $\lambda_0 = 600$ nm, d$\lambda$=80 nm</td>
<td>Weather station</td>
</tr>
<tr>
<td>2</td>
<td>15/07/2013</td>
<td>22:31 -&gt; 23:02</td>
<td>Vega, 0</td>
<td>85-82°,176-229°</td>
<td>0.75, 0, 1.34</td>
<td>1500 Hz ; $\lambda_0 = 600$ nm, d$\lambda$=80 nm</td>
<td>Weather station</td>
</tr>
<tr>
<td>3</td>
<td>16/07/2013</td>
<td>09:17 -&gt; 09:56</td>
<td>Sirius, -1.45</td>
<td>26-28°,157-167°</td>
<td>2, 0, 4.9</td>
<td>700 Hz; $\lambda_0 = 600$ nm, d$\lambda$=80 nm</td>
<td>Weather station, CT²</td>
</tr>
<tr>
<td>4</td>
<td>16/07/2013</td>
<td>21:05 -&gt; 21:09</td>
<td>$\alpha$ Herculis, 3.35</td>
<td>60°, 179°</td>
<td>2, 1.3, 2.7</td>
<td>1500 Hz ; $\lambda_0 = 600$ nm, d$\lambda$=80 nm</td>
<td>Weather station, CT²</td>
</tr>
<tr>
<td>5</td>
<td>21/07/2015</td>
<td>22:37 -&gt; 22:39</td>
<td>SOTA</td>
<td>21°-&gt;44.5°</td>
<td>0.05</td>
<td>1450 Hz ; $\lambda_0 = 976$ nm</td>
<td>Weather station, GDIMM</td>
</tr>
</tbody>
</table>

The criteria proposed for the comparison study are:
- Fried parameter $r_0$
- Scintillation index $\sigma^2_I$
- $Cn^2$ @ 5 m above ground
- $Cn^2$ piecewise integrals: $J_1$ [0-150] m, $J_2$ [3-5] km, $J_3$ [10-14] km
- wind averages $V_1$ [0-150] m $V_2$ [9-13] km
### Metrics for each model/measures vs. selected cases

<table>
<thead>
<tr>
<th>Case N°</th>
<th>Numerical Cn² Profiles Astro-Meso-NH</th>
<th>Parametric Cn² profiles MOST+Tatarskii</th>
<th>Parametric Cn² profiles MOST+HAP</th>
<th>Other data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SH : Shack Hartmann</td>
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<td></td>
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<td>CT² : micro-thermal sensor</td>
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<td></td>
<td></td>
<td>GDIMM : generalized DIMM</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>SH</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
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<td>S</td>
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<td>4</td>
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<td>4</td>
<td>4</td>
<td>CT² @3m</td>
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<tr>
<td>5</td>
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<td>5</td>
<td>S</td>
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<td>CT² @3m</td>
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<td>S</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GDIMM</td>
</tr>
<tr>
<td>Seeing (&quot;)</td>
<td>3.7 2.1 3.9 1.9 1.1</td>
<td>3.3 1.6 3.2 1.4 1.1</td>
<td>3.0 2.1 3.5 1.1 1.1</td>
<td>2.1 1.3 1.7 0.8</td>
</tr>
<tr>
<td>r0 (cm)</td>
<td>2.7 4.8 2.6 5.2 9.4</td>
<td>3.0 6.4 3.1 7.4 9.0</td>
<td>3.3 4.9 2.9 9.6 9.5</td>
<td>4.9 8.1 7.4 13.1</td>
</tr>
<tr>
<td>σ²_I (%)</td>
<td>41 22 67 20 22</td>
<td>26 20 26 18 16</td>
<td>49 27 59 14 15</td>
<td>6 4 6 1</td>
</tr>
<tr>
<td>Cn² x 10¹⁴</td>
<td>11 2 14 1 3</td>
<td>11 1 15 1 1</td>
<td>12 6 15 1 1</td>
<td>10 1</td>
</tr>
</tbody>
</table>

- SH on laser satellite (high flux) \( r_0, \sigma_i^2 \) vs. models OK
- SH/GDIMM on stars (low flux) \( r_0 \approx \text{OK}, \sigma_i^2 \) not OK vs. models
- \( \sigma_i^2 \text{ day} > \sigma_i^2 \text{ night} \) (ASTRO-Meso-NH & HAP) influence of the altitude wind
- Adequacy of Cn² @ 5 m : Bulk-model & ASTRO-Meso-NH Day > night
### Turbulence during the SOTA rendez-vous at OCA in July 2015

<table>
<thead>
<tr>
<th>21/07/2015 night (case N°5)</th>
<th>MOST+Tatarski **</th>
<th>MOST+HAP**</th>
<th>Astro-Meso-NH</th>
<th>Relative error (%) vs. Astro-Meso-NH</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOTA rendez-vous</td>
<td>Shack-Hartmann frames</td>
<td>From M4TITSE Weather station data for the Bulk-Model</td>
<td>Unstable conditions High altitude wind parametrization from Meso-NH</td>
<td></td>
</tr>
<tr>
<td>Seeing (&quot;)</td>
<td>1.17±0.08</td>
<td>1.12</td>
<td>1.06</td>
<td>1.05±0.04</td>
</tr>
<tr>
<td>r0 (cm)</td>
<td>8.84±0.65</td>
<td>9.02</td>
<td>9.47</td>
<td>9.36±0.39</td>
</tr>
<tr>
<td>σ* (m²/s²)</td>
<td>0.26±0.13</td>
<td>0.16</td>
<td>0.15</td>
<td>0.22</td>
</tr>
<tr>
<td>Cn² piecewise integrals</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1</td>
<td>2.42E-13</td>
<td>2.89E-13</td>
<td>3.76E-13</td>
<td>36</td>
</tr>
<tr>
<td>J2</td>
<td>1.76E-14</td>
<td>3.17E-14</td>
<td>5.84E-14</td>
<td>70</td>
</tr>
<tr>
<td>J3</td>
<td>4.43E-14</td>
<td>2.58E-14</td>
<td>1.01E-13</td>
<td>56</td>
</tr>
<tr>
<td>Wind averaged (m/s)</td>
<td>V1, V2</td>
<td>1.26, 8.85</td>
<td>1.70, 8.97</td>
<td>26, 1</td>
</tr>
<tr>
<td>Wind @ 5 m</td>
<td></td>
<td>0.91</td>
<td>1.25</td>
<td>1</td>
</tr>
</tbody>
</table>

C. Robert et al., SPIE Remote Sensing, 11153, 2019
doi = {10.1117/12.2534659}
Conclusions and perspectives

- Comparisons of measures & models: MOST+ Tatarskii, MOST+HAP, Bufton, ASTRO-Meso-NH, by using metrics: $Cn^2 @ 5 \text{ m}$, $r_0$, $\sigma^2_I$, $J_{1,2,3}$, $V_{1,2}$
- Adequacy of $Cn^2 @ 5 \text{ m}$: Bulk-model & ASTRO-Meso-NH, $[CT^2]$
- Profiles structure study with piecewise integrals vs. ASTRO-Meso-NH
  ✓ Bufton wind profile: good model
    - $V_2 [9-13] \text{ km OK : RE } \leq 25\%$
    - $V1[0-150] \text{ m wind shearing near ground but local ground measurement sufficient}$
  - $Cn^2$ profiles
    ✓ Mean envelope captured with MOST+Tatarskii
    ✓ best $Cn^2$ metrics on $J_{1,3}$ i.e. surface and high layers
  - Day/night variation of $\sigma^2_I$ with HAP/ ASTRO-Meso-NH → wind parametrization useful
  - need of profiles (P, T, wind) closer to the place and in time → Matisse V3.6

- Characterisation of the FSO turbulent channel
  - Global with parametric profiles including wind parametrisation
  - MATISSE V3.6 (mid 2020) in operational mode = data assimilation from Météo France
  - SH measures in situ using the laser source on a satellite optical payload
  → Data inversion to jointly get $Cn^2$ and Bufton wind profiles in prep.