An on-line turbulence profiler for the VLT’s adaptive optics facility (AOF)

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Visitor at Université Nice, Sophia-Antipolis, Feb. 2018
Staff
- 8 professors (permanent positions)
- 7 postdocs
- 14 graduate students

Some research activities
- High resolution spectroscopy (Vanzi et al.)
  Echelle spectrographs, Fibre optics characterization
- Planet finding (Jordán, Suc, et al.)
  Hat-South member
- Cosmic microwave background (Dunner & Cactus group)
  ACT (145, 220 and 280 GHz)
- Cosmological Simulations (Padilla et al.)
- Wide-field adaptive optics (Bechet, Guesalaga et al)
  Atmospheric Characterization, Vibrations Mitigation, Laser shaping
Teaching Observatory @ Sta. Martina (outskirts of Santiago)
- Undergraduate teaching
- Testing of instruments
- ESO 50 cm, CTIO 40 cm

Laboratory equipment (Adaptive optics)
- 5 optical tables (1 MOAO experimental setup)
- 3 Boston MEMS DM, 140 actuators
- 1 Xinetics DM, 37 actuators
- 3 bimorph DMs, 48 actuators
- 5 Shack-Hartman WFS (24 x24 subapertures)
- Phase-screens for turbulence simulation
“Embedded” (on-line) turbulence profilers
(profilers using WFS of telescopes’ facility instruments)

Motivation for embedded profilers:
• An on-line profiler can help to characterize the performance of the AO system
• Predictive control via estimation of wind speed and wind direction
• Gather turbulence statistics of the site
• Characterization of the telescope environment (dome seeing, vibrations, mis-reg.)
• Optimize tomographic reconstructor and conjugation altitudes for DMs according to \( C_n^2 \) (h), \( L_0(h) \), wind, dome seeing, etc.

SLODAR using AO WFS data

A Profiler for GeMS (Gemini-South MCAO System)
(The beginning)

- 16x16 grid Shack-Hartmann
- 204 active subapertures (total: 1020)
- sampling rate <= 800 Hz

5 WFSs

3 DMs

- 917 actuators in total
- 684 valid actuators (seen by the WFSs)
- 233 extrapolated actuators
GeMS: The $Cn^2(h)$ and “wind profiler”

For $T = 0$ s, the turbulence profile in altitude is extracted from the baseline.

For $T > 0$, the layers present can be detected and their velocity estimated.

$w = 8.8$ m/s
$\alpha_w = 187.1^\circ$

$w = 21.3$ m/s
$\alpha_w = 227.7^\circ$

GeMS: statistics for 1000+ profiles
(Several campaigns in 2012, 2013 and 2014)
GeMS: statistics for 300+ $\mathcal{L}_0(h)$ profiles
(Several campaigns in 2012, 2013 and 2014)

Wind direction (polar plot histogram)

High altitude wind direction. $h>7\text{Km}$

Outer-Scale Profile
continuous line: mean
dotted line: median

Comparing GeMS wind profiles to Meso-NH model

Red crosses are from GeMS profiler, continuous line is the meso-NH model
GeMS: frozen flow study

Turbulence profiles at Pachón, April 16th 2013

Wind speed = 21.3 m/s
Wind direction = 227.7°
GeMS: Frozen flow study

Dependence of frozen flow to wind speed

$y = -0.157x - 0.365$

the slope is in $m^{-1}$

Problems with GeMS profiler

- Resolution in altitude limited by subaperture diameter.
- Strong effect of $L_0(h)$ on accuracy, specially for layers near the ground or system operating under strong dome turbulence conditions.
- When trying to isolate individual layers, there are multiple functions to deconvolve the cross-correlation image (depending on height and outer-scale), so it is not a practical approach.
- Long processing time ($t > 7$ mins).

Main conclusion: including $L_0(h)$ in every step of the profiling process is a must.
An On-line Profiler for ESO’s Adaptive Optics Facility (AOF)

Colaborators from ESO: J.Kolb, S.Oberti, J.Valenzuela

AOF main characteristics:
- 3 operational modes: GALACSI x 2 and GRAAL
- 4 sodium laser asterism
- WFSs: 40 x 40 subapertures (20cm diameter)
- Deformable secondary mirror (1170 actuators)
**GRAAL** feeds **HAWK-I**, a NIR imager (0.85 - 2.5 µm). The science field of view is 7.5 arcmin square. **GRAAL** compensates for the lowest layers of the atmospheric turbulence (up to ~ 2 km).
ESO’s Adaptive Optics Facility (AOF)

**AOF main characteristics:**
- 4 sodium laser asterism
- WFSs: 40 x 40 subapertures, 20cm diameter
- 2 altitude resolutions (star separations)
- Deformable mirror for GLAO and LTAO
- 3 operational modes: GALACSI x 2 and GRAAL

![Diagram of AOF](image)

<table>
<thead>
<tr>
<th>AOF Mode</th>
<th>Low Resolution (LR) Baseline</th>
<th>High Resolution (HR) Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\theta_{LR}$</td>
<td>$h_{max,LR}$</td>
</tr>
<tr>
<td>GAL NFM</td>
<td>14.1</td>
<td>-</td>
</tr>
<tr>
<td>GAL WFM</td>
<td>90.6</td>
<td>12.4</td>
</tr>
<tr>
<td>GRAAL</td>
<td>492</td>
<td>2.49</td>
</tr>
</tbody>
</table>

Range is due to the LGS cone effect
The method: Cross-Correlations of Pseudo Open Loop Slopes (POLS) for pairs of WFSs

Notice that turbulence on the edge of WFS1-2 is out of the detectable region of WFS2-4.
The method: Reference or response functions

The first step in the profiling technique is to generate (only once) the reference functions: cross-correlations between pairs of WFSs POLS for different values of layer height and outer scales.

A grid of 33 altitude divisions and 12 outer-scale values is constructed

- Discrete values for $h$: \{1: N\} $\cdot \Delta h$, $N$ is chosen $\approx 80\%$ of maximum number of bins
- Discrete values for $L_0$: \{1, 2, 3, 4, 6, 8, 11, 16, 22, 32, 50, 100\}

$symmetric$ shapes

The method: Search for minimum using interpolated functions from reference grid

Search for minimum:

\[
\underset{\omega, \mathcal{L}_0, h}{\text{Min}} \left( \left( C_{\text{meas}} - \sum_{i=1}^{N_z} \omega_i \cdot C_{\text{ref}}^i (\mathcal{L}_0, h) \right)^2 \right)
\]

Interpolation:

\[
C_{\text{ref}} (\mathcal{L}_0, h) = \left( (1-\alpha) \cdot C_{\text{ref}} (\mathcal{L}_0^i, h^j) + \alpha \cdot C_{\text{ref}} (\mathcal{L}_0^{i+1}, h^j) \right) \cdot (1 - \beta) + \\
\left( (1-\alpha) \cdot C_{\text{ref}} (\mathcal{L}_0^i, h^{j+1}) + \alpha \cdot C_{\text{ref}} (\mathcal{L}_0^{i+1}, h^{j+1}) \right) \cdot \beta
\]
The method: Choice of $\mathcal{L}_0(h)$ for the response functions in the reference grid

Discrete values for $\mathcal{L}_0$: \{1, 2, 3, 4, 6, 8, 11, 16, 22, 32, 50, 100\}

Discrete values for $h$: \{1:N\}·Δ$h$, $N$ is chosen $\approx 80\%$ of maximum number of bins
The method: Fitting sequence
The method: Fitting sequence

Mode: GALACSI - WFM

Maximum probed height for GALACSI WFM

Unsensed turbulence
The method: Temporal Cross-Correlation (wind speed)
Comparison against an independent technique for seeing and global $L_0$

seeing

Global outer-scale

Seeing linear regression

Seeing_{ESO} = 0.92 \cdot \text{Seeing}_{PUC} + 0.06
Implementation in SPARTA (AOF’s RTC)

Mode: GALACSI - NFM of 28/01/18, !!! FIXED SODIUM LAYER DISTANCE !!!

Altitude (km)

Ratio of turbulence in the first 3 km

UT Time (hours)
Conclusions for turbulence profiling

• The information exists for accurate profiling (in quantity and quality)

• Profiles for $C_n^2$, $L_0$ and wind direction & magnitude are currently in use in the AOF (automatic wind profiles under development)

• Including the outer scale in the profiling methods is a must

• In the ELT, the outer scale estimation will be essential

• Reliable estimation of larger outer scales is limited to 3 or 4 times the diameter of the telescope (30m for the VLT; 150m for the ELT)

• Processing times compatible with system operation ($t < 2$ mins @ 8 layers)

• A comprehensive comparison with simultaneous with Durham’s Stereo-SCIDAR data is coming soon