The AO modes for HARMONI: from classical to Laser-assisted tomographic AO systems

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HARMONI General Overview

- First light general purpose Integral Field Spectrograph for E-ELT
  - Work horse instrument with wide appeal
  - Early ‘highlight’ science on key objects/projects
  - Low/no technology risks
- V-K (0.47-2.45 µm) spectral coverage
- R=4000,10000,20000 resolutions
- 40,20,10 & 4mas pixel scales
- 256x128 pixel field of view (image slicer with 32000 spaxels)
  - Eight Hawaii-4 detectors
  - Diff limit field still only 1.0” x 0.5”!

N. Thatte’s Talk yesterday afternoon
Adaptive Optics systems for Harmoni

**Performance**

- **SCAO**
  - SR = 100%
  - ~ 70% in K, SC < a few %

- **LTAO: ATLAS**
  - ~ 50% in K, SC > 50%

- **GLAO-NGS**
  - reference stars
  - high altitude layer
  - ground layer
  - ground conjugate DM
  - on-axis WFS
  - Telecope

**Sky coverage**

- SC = 100%
Common key aspects for all AO systems

- Telescope residual defects after correction by M4
- Residual windshake
- Control of M4 / M5
- Pupil stabilisation
- Optical axis stabilisation
  - Coronagraphic imaging
  - Astrometry
- Overhead minimization: every second counts!
  - Should be smaller than a few minutes.
  - Identification processes rather than on-sky calibration!
Telescope residual defects

111 nm

SR = 90 % @ K
Telescope residual defects

SR = 90% @ K
Residual windshake (corrected by M4/M5)

Conservative assumption:
- 2 mas for SCAO
- 3 mas for LTAO

~1 mas

no noise
700 Hz bandwidth
SCAO for Harmoni: Why?

- Best performance for bright objects
  - Exoplanet characterisation (SPHERE follow up)
  - Solar system observation

- First year(s) of operation – risk mitigation for LTAO
  - observe as much objects as we can with a « very decent » image quality
  - acquire as much feedback as possible on the telescope before integrating complex AO system

Win-win strategy
SCAO specificities

- From science case req.
  - Solar system observation
    - Differential tracking for solar system object (up to 100”/h)
    - WFS on extended object (goal 5”)
  - Exoplanet characterisation
    - Coronagraphic imaging
    - Very accurate NCPA correction
    - Very accurate optical axis control

- Technical requirements
  - Warm AO (outside Harmoni Cryostat)
SCAO : main trade-offs

- SH or Pyramid → depend on WFS-wavelength
  - Baseline : 0.45 – 0.9 µm with SH BUT Pyramid under study !!!!
  - Sub-aperture FoV : between 2 and 5” → trade-off between pixel size and number
  - 4.2” with 0.35” pixel size and 74x74 sub-ap => 900x900 pixels
  - 4.0” with 0.50” pixel size and 74x74 sub-ap => 600x600 pixels

- Pupil derotation : numerical vs optical
- ADC or not
  - critical for Pyramid (Full pupil diffraction)
  - Less critical for SH

between 0.25 and 1 mag in the photon noise regime
(from 30 to 60° from zenith)
between 0.5 and 1.8 mag in the detector noise regime
(from 30 to 60° from zenith)
SCAO performance – on axis

Without tel. defects

\[ \text{Sr} = 76 \% \] @K

With tel. defects

\[ \text{Sr} = 69 \% \]
SCAO performance – on axis

Sr = 76 % @K Sr = 69 %

Without tel. defects  With tel. defects
### SCAO performance - anisoplanatism

<table>
<thead>
<tr>
<th>Layer nb</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
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</thead>
<tbody>
<tr>
<td>$C_n^2 [%]$</td>
<td>33.5</td>
<td>22.3</td>
<td>11.2</td>
<td>9.0</td>
<td>8.0</td>
<td>5.2</td>
<td>4.5</td>
<td>3.4</td>
<td>1.9</td>
<td>1.1</td>
</tr>
<tr>
<td>h [m]</td>
<td>0</td>
<td>600</td>
<td>1200</td>
<td>2500</td>
<td>5000</td>
<td>9000</td>
<td>11500</td>
<td>12800</td>
<td>14500</td>
<td>18500</td>
</tr>
</tbody>
</table>

Diagram showing the $C_n^2$ profile with different zenith angles and off-axis angles.
LTAO performance

9 layers to be reconstructed in the tomographic process

5/6 LGS in less than 1.25' (radius)
Without tel. defects                        with tel. defects

Sr=53.5 Sr = 48.5

In collaboration with M. LeLouarn (ESO)
LTAO performance

In collaboration with M. LeLouarn (ESO)

9 layers to be reconstructed in the tomographic process

5 / 6 LGS

In less than 1.25’ (radius)
LTAO sky coverage: mean features

LQG

Dedicated DM

Wide band+ADC

LIFT

- TTF with full pupil
- No aliasing
Sky coverage estimation: starfield count

- Generate a starfield (Besançon model)
  - Compute performance for each star (alone): highest perf=1NGS perf
  - Select the 5 « best » stars
- Form couples of stars among these 5
  - Compute performance for each couple: highest perf=2NGS perf

### Whole sky (1000 starfields)

<table>
<thead>
<tr>
<th>$L_0$ [m]</th>
<th>RON</th>
<th>SC 1NGS</th>
<th>SC 2 NGS</th>
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<tbody>
<tr>
<td>25m</td>
<td>1ph.e-</td>
<td>93%</td>
<td>99%</td>
</tr>
<tr>
<td></td>
<td>6ph.e-</td>
<td>81%</td>
<td>98%</td>
</tr>
<tr>
<td>50m</td>
<td>1ph.e-</td>
<td>54%</td>
<td>92%</td>
</tr>
<tr>
<td></td>
<td>6ph.e-</td>
<td>39%</td>
<td>92%</td>
</tr>
</tbody>
</table>

98% whole sky, 92% at galactic pole
SCAO $\Rightarrow$ LTAO

- Brigh NGS $\Rightarrow$ $SR_{\text{SCAO}} > SR_{\text{ATLAS}}$
- But: $mag < 13$ typically $\Rightarrow$ $SC < 1\%$

$\sim$ Mag 13
Up to 15 / 16 with pyramid
LTAO or GLAO (for large spaxel)

**Largest Gain for** \( \lambda = [1 – 2] \, \mu m \)

- EE(50 mas) : gain > 10
- EE(75 mas) : gain > 5
- EE(100 mas) : gain > 3
LTAO implementation?

- Decomposition of LTAO in 3 main blocks
  - LGS WFS
  - Tomography
  - NGS WFS
  - TT / defoc fast sensing = LIFT
  - Truth sensor = SCAO WFS / LIFT?

Some are common to all instruments: LGS, tomo

One is very specific to each instrument: NGS
Conclusions

- SCAO interest
  - for « bright » (< 13-15), on axis (< 10") objects
  - Several dedicated features for specific applications
    - Non-sideral objects, star environments …
- SCAO systems on E-ELT not so far from XAO system on VLT
- Feedbacks on ELT specificities (adaptive / segmented telescope …)
- From SCAO to LTAO
  - complementary aspects
  - High throughput and low emissivity
  - toward 100 % sky coverage
  - key aspects :
    - LGS tomography => very strong progress these last years (GEMs, CANARY)
    - NGS WFS on very faint GS => new and promising devices
    - TRL are quite good now !