Adaptive Optics
(Presented by N. Hubin)
Overview

- **Adaptive Optics concepts and performances**
  - Single Conjugate Adaptive Optics (SCAO)
  - Ground Layer Adaptive Optics (GLAO)
  - Multi Object Adaptive Optics (MOAO)
  - Multi-Conjugate Adaptive Optics (MCAO)
  - High Contrast Adaptive Optics (EPICS)

- **Demonstrators & pathfinders**
  - MCAO demonstrator (MAD)
  - High Order Test bench (HOT)
  - VLT Adaptive Optics Facility
  - VLT Planet Finder
  - Required field tests on Laser Guide Star issues

- **Enabling technology roadmap**
  - Deformable mirrors & wavefront sensor detectors
  - Real Time Computers & algorithms
  - Lasers and beam transport/projection
ADAPTIVE OPTICS CONCEPTS & PERFORMANCE
Single Conjugate AO concept

On-axis, NIR, medium Strehl ratio AO using NGSs

- Visible Shack-Hartmann WFS
- IR pyramid WFS
- $97^2$ sub-apertures
- Zero noise $582^2$ pixels CCD
- Low noise $194^2$ pixels IR detector
- 500 Hz update frequency
- 2' patrolled field
- $98^2$ actuators
- 2.5 m Deformable Mirror at M6
- Computing power:
  - $2000 \times$ NAOS
  - Or $10 \times$ VLT AO Facility
SCAO Wavefront sensor pick-up arm

- Patrolling pick-up arm in the Adapter-rotator
- Same wavefront unit (s) for all 6 focal stations
Single Conjugate AO performance *

**Good seeing: 0.53”**

**Bad seeing: 1”**

*AO only*

**Strehl ratio**

**Photons/sub-aperture/frame**

K, H, J

**Strehl ratio**

**Off-axis angle (”)**

K, H, J

*AO only*
Ground Layer AO concept

- 6 Visible Shack-Hartmann WFSs
- $97^2$ sub-apertures (id. SCAO)
- 6’ Patrolled FoV
- Zero noise $582^2$ pixels CCD
- 500 Hz update frequency
- 2.5 m Deformable Mirror at M6
- 3-6’ and narrow FoV modes
- Computing power:
  - $10 \times$ VLT AO Facility
  - $0.3 \times 10^4 \times$ AOF with full reconst.
Ground Layer AO performance

**Good seeing: 0.53”**

Gain in EE in 50 mas pixel

**Bad seeing: 1”**

Gain in EE in 50 mas pixel

*AO only*
Multi-Conjugate AO concept

1-2’ FoV, Near IR, medium Strehl ratio AO using NGSs

- 6 Visible Shack-Hartmann WFSs
- $97^2$ sub-apertures (SCAO)
- 6’ Patrolled FoV
- Zero noise $582^2$ pixels CCD
- 500 Hz update frequency
- 2.5 m Deformable Mirror at M6
- 3.5 m Deformable Mirror at 7km
- $145^2$ actuators over meta-pupil
- Computing power $10^4$ x VLT AOF
- 1’ corrected FoV
Multi-Conjugate AO performance*

Good seeing: 0.53", 1’ FOV

Bad seeing: 1”, 1’ FOV

NGS flux: 1ph/subap/frame

*AO only
GLAO & MCAO sky coverage using NGSs

North Galactic Pole, 6’ FoV

Left to right
\( m_R < 16 \)
\( m_R < 17 \)
\( m_R < 18 \)
\( m_R < 19 \)

\( l=0^\circ, b=50^\circ, 6’ FoV \)

- \( \text{Sr}(K) = 6\% \quad \text{EE}(K) \times 3 \)
- \( \text{Sr}(K) = 25\% \quad \text{EE}(K) \times 3.5 \)
- \( \text{Sr}(K) = 29\% \quad \text{EE}(K) \times 4.5 \)

MCAO
GLAO
Multi Conjugate AO Point Spread Functions

Good seeing, 0.5”

Bad seeing, 1”

NGS flux: 1 ph / subap / frame
## Multi Conjugate AO Point Spread Functions

### Good seeing, 0.5” J-Band

<table>
<thead>
<tr>
<th></th>
<th>on-axis</th>
<th>[1',0’]</th>
<th>[30'',30’’]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4%</td>
<td>1.3%</td>
<td>1.3%</td>
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</table>

### Bad seeing, 1”

<table>
<thead>
<tr>
<th></th>
<th>on-axis</th>
<th>[1’,0’]</th>
<th>[30'',30’’]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5 e-5</td>
<td>8.7e-5</td>
<td>8.5e-5</td>
<td></td>
</tr>
</tbody>
</table>

NGS flux: 1 ph / subap / frame
Multi-Object AO concept

Multi narrow field AO over 6’ FoV using NGSs

- 10 Vis. WFSs patrolling 6’, f=500Hz
- 1st stage GLAO using M6 DM
- 10 kact. MDMs for WFSs & IFUs
- Optimized correction in N directions
- Linear MDMs; pseudo closed loop
- Computing power $3 \times 10^5 \times \text{NAOS} \times 10$
EPICS:
Earth-like Planets Imaging Camera Spectrograph

- Primary science goal: Rocky planets in habitable zone up to 25 pc in VIS and NIR
- Goal: contrast of $2 \times 10^{-10}$ at 50 mas
  - Need high Strehl Ratio $\Rightarrow$ large number of actuators: $1.7 \times 10^5$
  - Need high halo rejection $\Rightarrow$ fast correction
- Double stage system
  - Shack-Hartmann $500^2$ at 1 kHz, Fourier reconstructor
  - Pyramid $150^2$ at 3 kHz, Matrix-Vector reconstructor
- Computationally feasible with OWL/SPARTA + ~10 years
- Very tight error budget for systematic errors control
  - Need active correction of non common-path errors at 0.3 nm rms
    (similar achieved with HCIT) for spat. freq. 10 – 75 cycles/pupil

*HCIT: High Contrast Imaging Test bed TPFC
EPICS Adaptive Optics performance (AO only)

- Mv=7 G2 star at 25 pc
- Strehl (J band) 91 %
- Perfect Coronagraph

![Graph showing normalized halo intensity vs. separation ("""). The x-axis represents separation in arcseconds, ranging from 0.01 to 1.00. The y-axis represents normalized halo intensity, ranging from $10^{-9}$ to $10^{-6}$. The graph includes areas corrected by SH system, PYR system, and dominated by chromatic seeing. There is a perfect coronagraph with a separation of 0.4" and 1.6".]](image-url)
Reduction of Co-phasing residuals after XAO

Effect on coronagraphic image, $\lambda = 1600$ nm

- PSF without corono
- Coro. PSF without correction of co-phasing errors
- Coro. PSF after correction by DM$_2$
Use single LGS on ELT
- Cone effect Low Strehl ratio
- Ground layer Correction
- “High” sky coverage
1st analysis shows promising results
Assumed ELT LGSs issues solved (spot elongation,...)
Multi Conjugate AO with Laser Guide Stars

- 5 LGSs
- High sky coverage
- High WFS flux
  - More sub-apertures
  - More DMs
- Assumed ELT LGSs issues solved (spot elongation, …)

Good seeing: 0.53”

K-Band
Optimized FoV: 2’

Position from center (“”)
Demonstrators and Pathfinders
MAD: The GLAO & MCAO demonstrator

Demonstrate Ground Layer and Multi Conjugate AO

- Star Oriented 3 SH WFSs
- Layer Oriented pyr. WFS
- Study control algorithms
- 3 D turbulence generator
- MAD status:
  - SCAO
  - GLAO loop: 06.05
  - MCAO loop: 10.05
  - Layer oriented: 2Q ‘06
  - On-sky 3Q ‘06
- Study calibration issues:
  - Non-common aberrations
  - Interaction matrix
MAD design & implementation
MAD preliminary results

- Star oriented mode
- 3 Visible SH WFSs
- 8^2 sub-apertures
- K-band

Open Loop

GS #1

Peak: 11.8x
EE(0.1''): 7.8x

GS #2

Peak: 2.3x
EE(0.1''): 2.0x

GS #3

Seeing(V): 0.7''

SCAO

Peak: 4.3x
EE(0.1''): 3.3x

GLAO

Peak: 3.6x
EE(0.1''): 3.0x

MCAO

Peak: 8.1x
EE(0.1''): 5.3x

Peak: 6.9x
EE(0.1''): 4.8x
MCAO closed loop of MAD

K Band; Seeing 0.7”; $\tau_0=3.3$ ms

Gs magnitudes = 8

200Hz frame rate
**HOT: High Order Test bench**

**Demonstrate Extreme AO & High contrast imaging**

- Study optimum wavefront sensor for high contrast imaging
  - Spatially filtered SH WFS with weighted centre of Gravity
  - Pyramid WFS in diffraction regime w &w/o modulation
- Study error sources & final contrast: misregistration, aliasing,..)
- Study Point Spread Function characteristics & residual aberrations
- Investigate coronagraph concepts
- Study pupil segmentation effect on final PSF after AO correction
- Validate new components:
  - Micro Deformable mirrors
  - New low noise CCD for WFS
  - ESO Real Time computer platform
  - New control algorithms
  - Focal plane WFS
  - Super polished filters for differential imaging
HOT: a high contrast imaging test bench

- 60 actuators
- Bimorph mirror as "woofer"

- Turbulence Generator
- MACAO test bench

- 32x32 actuators

- Pyramid & Shack Hartmann WFS
- IR Camera

- Phase screens
- 0 noise CCD

- Real-Time Computer
VLT AO Facility: A Pathfinder for OWL

- Concept of Active/Adaptive Telescope
- Four Sodium Laser Guide Stars
- 2 GLAO syst. (GALACSI, GRAAL)
  - 10’ NIR seeing reducer (HAWK-I)
  - 1’ visible seeing reducer (MUSE)
- Laser Tomography AO: Sr(v)~10%
- Enabling technologies:
  - 1.1 m convex aspherical Deformable M2, 1170 act.
  - 2 mm Zerodur thin shell
  - Raman fibre laser
  - ~0 noise, 240^2 pix., 1kHz WFS-CCD
  - Computing power 200 x NAOS
- Laboratory testing facility (ASSIST)
VLT Planet Finder: An XAO Pathfinder for OWL

Planet detection with contrast $10^{-5}$ at 0.1” separation

- Detection
  - Extreme AO (SR ~ 90% in H band)
  - Coronagraphy (contrast at 0.1” separation)
  - Differential imaging (residual halo)

- Characterization
  - Integral Field Spectroscopy

- Visible Channel
  - Imaging / Polarimetry (SR 90% in H at 65% in R)

Courtesy J. L. Beuzit
Required field tests on LGS issues

Perspective spot elongation

- D = 100m
- $\theta \approx 10''$
- $\Delta H = 10\text{km}$
- H = 100km

Cone effect

Defocus

- Dynamic refocusing
- Custom CCD

ELT

- WFS spot aberrations: Optical corrector in WFS
- Fratricide effects: Number of launch telescopes, Pulsed lasers
- Low order with NGS: In some cases, helped by outer scale

NEW LGS CONCEPTS BETTER SUITED FOR ELTs NEEDED?
Enabling technology roadmap
Large Deformable mirrors: from VLT to OWL

**VLT Deformable M2**
- Ø 1.1m convex
- 1170 actuators
- 29 mm pitch
- 1 ms response
- Stroke 50 / 1.5 µm

**OWL M6**
- 2.6 x 2.4 m flat
- 7000 actuators
- 24 mm pitch
- 1 ms response
- Stroke 25-90 µm
- Inter-stroke: 3-6 µm

Hexapod for centring & fine focusing
Cold Plate; heat evacuation & act. attachment

2mm Thin Shell
Reference body

Lightweight reference body
Zerodur or SiC

ADS International
MICROGATE
OPTICON
High density Deformable Mirror roadmap

***VLT Planet Finder***
- $41^2$ act. Piezo DM (1370)
- 4.5 mm pitch; 10 KHz
- 8 µm stroke

***OWL Planet Finder & MOAO***
- 10k & 100 k actuators
- 1 mm pitch; 3-5 KHz
- 1-5 µm stroke
- WF error: 1-10 nm rms

Funded by OPTICON

- 19 actuators; continuous membrane
- 1mm pitch
- 4.5 µm mech. stroke for 60V
- WF error: 1.5nm rms

- 2k actuators with 1mm pitch
- 5-10 µm mechanical stroke
- 1-2 µm inter-actuator stroke
- 10 nm rms
Wavefront Sensor detectors roadmap

**VLT Planet Finder**
- $240^2$ pixels. L3CCD
- 8 outputs
- 1.5 kfr/s, 90 Mpixels/s
- 0.2 e$^{-}$ RON
- Blue QE low depletion

**OPTICON-JRA3**
- $264^2$ pixels
- 528 outputs
- 1.1 kfr/s
- 3 e$^{-}$ RON ↓
- High QE deep depletion

**OWL SC- GL- MC- MO- X AO**
- 600$^2$ to 1000$^2$ pixels
- 500 to 1 kfr / s (goal 3kHz)
- 0 e$^{-}$ RON ↓
- High QE
- Good PSF
Real-Time Computers roadmap

- SPARTA-for-OWL concept shows **feasibility** of the RTC for OWL projecting the current architecture for VLT 2nd Gen AO
- Even better architecture will be available at that time

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<thead>
<tr>
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<tbody>
<tr>
<td>SCAO</td>
<td>13800*7600@500Hz</td>
<td>52</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>82800*7600@500Hz</td>
<td>314</td>
<td>6</td>
</tr>
<tr>
<td>GLAO</td>
<td>13800*7600@500Hz</td>
<td>52</td>
<td>1</td>
</tr>
<tr>
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<td>82800*7600@500Hz</td>
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<tr>
<td>MOAO</td>
<td>14400*7600@500Hz</td>
<td>54</td>
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<td>43200*7600@500Hz</td>
<td>164</td>
<td>3</td>
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<td>MCAO</td>
<td>82800*24000@500Hz</td>
<td>993</td>
<td>19</td>
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<td>XAO</td>
<td>400.000*200.000@1kHz</td>
<td>80000</td>
<td>1500</td>
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<tr>
<td></td>
<td>35000*18000@3 kHz</td>
<td>2000</td>
<td>40</td>
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SCAO@52 GMAC achievable in 3-4Y
Moore’s law in 10 Y factor 100
SCAO@52 ➔ 5200

G-FMAC: Giga Floating Point Multiply accumulate

European Southern Observatory
Computer power & new algorithms

- All RTCs but X-AO possible with standard methods (Matrix Vector Multiply)
- New algorithms reducing computing power needed for X-AO
- Can be retrofitted to the other systems to lower their cost
- Current portfolio of methods:

<table>
<thead>
<tr>
<th>Method/gain</th>
<th>98x98</th>
<th>250x250</th>
<th>500x500</th>
<th>Precision</th>
<th>f(D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct sparse</td>
<td>1-50</td>
<td>7-340</td>
<td>10 - 1300</td>
<td>Perfect</td>
<td>$\frac{D^2}{k \cdot \alpha}$</td>
</tr>
<tr>
<td>Iterative Multi-grid - PCG</td>
<td>1-30</td>
<td>4-200</td>
<td>15-800</td>
<td>High</td>
<td>$\frac{D^2}{N_{iter}}$</td>
</tr>
<tr>
<td>Iterative FD-PCG &amp; Fourier-domain</td>
<td>45-230</td>
<td>250-1250</td>
<td>1250-5000</td>
<td>High</td>
<td>$\frac{D^2}{\log(D^2)}$</td>
</tr>
<tr>
<td>Local &amp; hierarchic</td>
<td>~600</td>
<td>~3700</td>
<td>~15000</td>
<td>low</td>
<td>$k$</td>
</tr>
</tbody>
</table>

PCG: Pre-conditioned Conjugate Gradients
Laser Guide Stars enabling Technologies

- Components being developed:
  - Fiber laser sources (Raman and Sum-frequency [LLNL]) (IPF Technologies, Volius)
System design roadmap

- Explore actual limit of “classical” Laser schemes for GLAO, LTAO, MCAO & MOAO systems
- Study promising novel LGS-AO concepts & field test (FP6, FP7)
- Science cases – instrument & AO designs trade-offs
- Fully design SCAO with M6 adaptive mirror
- NGS- LGS design trade-offs for GL-LT-MC-MO AO
- Pursue AO key technologies roadmap (FP7, OWL Phase B):
  - Large & micro deformable mirrors
  - Visible & NIR WFS detectors
  - Lasers & beam projectors
  - New control algorithms and Real Time Computers
- Feedback from VLT AO systems & demonstrators
- Explore fundamental limits of EPICS with HOT
Conclusions

- Several AO concepts studied; performance evaluated
- LGSs - NGSs trade-off to be explored further
- Ground Layer & Multi-Conjugate Demonstrators on-track
- VLT AO Facility & Planet Finder pathfinders for OWL
- EPICS design study calls for several bread boards (HOT)
- LGS-ELT demonstrators needed
- Aggressive roadmap for AO key technologies (OPTICON, FP6)
  - CCD, IR WFSs
  - Large & µ DMs (two competitive M6 feasibility studies; CfT out)
  - Control & algorithms
  - Lasers
- Strong involvement of the AO community; THANKS….!
- Active preparation of a FP7 AO R&D program (2007-2014)
- 33% of the OWL R&D effort for AO