Progress in Adaptive Optics and Multi-Conjugated Adaptive Optics

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Sydney, 17th July 2003
**Adaptive Optics (AO)**

To control the wavefront from a single reference star and to compensate, as the deleterious effects of atmosphere on the image quality would vanish.

**MultiConjugated Adaptive Optics (MCAO)**

to control the wavefront from an ensemble of reference stars in such a way that the wavefront can be compensated over a defined Field of View.

<table>
<thead>
<tr>
<th>Typical numbers:</th>
<th>AO</th>
<th>MCAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near InfraRed</td>
<td>30”</td>
<td>2’</td>
</tr>
<tr>
<td>Visible</td>
<td>5”</td>
<td>30”</td>
</tr>
</tbody>
</table>
Galactic Center (ESO)

Solar surface (von Der Luhe)
Adaptive Optics (AO)
- System Engineering (VLT and Keck systems, others coming soon)
- InfraRed WaveFront Sensors (for tagret embedded in dark clouds)
- Novel concept WaveFront Sensors (Pyramid: from the lab to the sky)
- Adaptive Secondary Mirror (the telescope is AO)

MultiConjugated Adaptive Optics (MCAO)
- Laser Guide Stars: big facilities at VLT and Keck
- Concepts demonstrated in the lab at different level by different groups (Arcetri, Durham, Lund)
- One full system, LGS-based, under way (GEMINI)
- One demonstrator with two competing tecnologies under way (VLT)

Development of concepts for MCAO on 30..100m telescope in progress
### NAOS WFS characteristic

<table>
<thead>
<tr>
<th></th>
<th>Visible WFS</th>
<th>InfraRed WFS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength range</strong></td>
<td>0.45-1.0 mm</td>
<td>0.8-2.5 mm</td>
</tr>
<tr>
<td>14x14 FOV</td>
<td>2.3 arcsec</td>
<td>5.15 arcsec</td>
</tr>
<tr>
<td>Mag. range</td>
<td>0-13</td>
<td>0-11</td>
</tr>
<tr>
<td>7x7 FOV</td>
<td>4.6 arcsec</td>
<td>5.15</td>
</tr>
<tr>
<td>Mag. range</td>
<td>13-19</td>
<td>11-15</td>
</tr>
<tr>
<td>Detector</td>
<td>128x128 EEV</td>
<td>1024x1024</td>
</tr>
<tr>
<td></td>
<td>CCD50</td>
<td>Rockwell hawaii</td>
</tr>
</tbody>
</table>

VLT-NACO and Keck demonstrated High-order AO compensation in the NIR on 8..10m class telescopes.
Novel concepts: Pyramid WaveFront Sensor

(Koechlin)  (Ragazzoni 1996 J.Mod.Opt.)
Coma

Response on WFS detector

Signal

$S_x$  $S_y$

Coma + modulation

Response on WFS detector

Signal

$S_x$  $S_y$

(Verinaud, ESO)
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Solid line : PYR : RMS = 71 nm
Dashed: SH : RMS = 77 nm

Solid line : PYR: RMS = 75 nm
Dashed: SH: RMS = 90 nm

Valid only for very low order modes!

Behaviour at bright end:
less aliasing and less sensitivity to misalignment

Behaviour at faint end:
gain in limiting magnitude

(Verinaud, ESO)
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Pyramid WaveFront Sensor as pupil-plane WFS

Image modulation performed at an intermediate focal plane and re-imaging of the telescope pupil onto the detector.


Equivalent to Shack-Hartmann under geometrical approximation

Larger SNR achievable under closed-loop on NGSs conditions.


Pyramid WFS

Are we at the limits?
WFS+Coronography can led to sub-Poisson limit sensitive WFSs...

Canary, spring 2002

Canary, fall 2001
**MMT336 Secondary Adaptive Mirror**

- mirror diameter 642 mm
- mirror thickness 2 mm
- membrane in-plane restraint
- 336 moving magnet actuators
- nominal air gap $\sim 50 \, \mu m$
- reference body 50 mm thick
- AL cold plate: actuators support & cooling (7 cooling channels)
- 24 absolute gap sensors
- fixed hexapod
- support frame & interface to Hexapod
- electronics cooled crates
- hub interfaces (power, signal & cooling)
Cap. sensor armatures (ref. plate)

MMT336 ASPHERIC SHELL

642mm diam. 2mm thick

Magnets (12mm diam)
• Max stroke: ±17µm (mirror displacement), when settling time is 1.7ms
• 336 actuators, 642 mm diameter
• No Hysteresis
• 30nm rms of non correctable high-spacial freq.
• Chopping capabilities at 5Hz ±5arcsec on-sky (90% duty-cycle, max stroke: ±38µm)
Secondary Adaptive Optics technology is entering its mature phase. Currently, the two Units for LBT are in progress, and a study for an adaptive M2 unit aboard VLT is ongoing.
Laser Guide Star

- Generated by resonant scattering in mesospheric Sodium layer ~92km
- Challenging for telescopes > 20 m, (macrophotography or… microscopy?)
- A novel concept based on inverse Bessel beams can deal with these, so maybe…

Sodium Laser Guide Star at Calar Alto Observatory
They are generated at the frequency of excitation of the Sodium doublet and sent along the same line of sight of the telescope, usually from an auxiliary smaller telescope.
Power is of the order of 2..10W, this is a 4W dye laser in Souther Spain

View into the Laser cabin with activated Laser beam.

Calar Alto, October 1996
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DSAZ 3.5 m Telescope and the ALFA LGS-System

Optic and Supply Schematic of the ALFA Laser Facility
Technology is still very complex and we have to see Alfa (now Decommissioned) & Lick as precursors or technology test-bed. Two big facility are today underway (Keck, below, and LGSF aboard VLT) and, given the efforts that are spent therein, these will represent the real milestone of how much reliable & cost effective are LGS firing technology.
The laser beacon is not a star but a cylinder in the sky…

Sodium layer…

Telescope aperture
MIBB naturally fit with Z-invariant WFS, conceived for Rayleigh LGSs on 8m class telescopes

First prototype of a reflective rod in MPIA lab
The pupil illumination is perturbed by the cylindrical rod and by the circular slit in a way to give an high-sensitive Laplacian Signal on the pupil plane. It is a sort of curvature Roddier-like Wavefront sensor, but for axial sources instead of point ones. The Laplacian actually operates on the polar rather than Rectangular coordinates on the pupil.
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Extension to Multiple Inverse Bessel Beam in Layer-Oriented fashion is straightforward:

- Z-invariant is a pupil plane WFS
- most NGS MCAO technology retained
- MIBBs as retro-fit of NGSs MCAO.

Please note that in these configurations LGSs are used as lamps illuminating the slits rather than reference sources….

LGL: Laser Guide Lamps
PIGS: Pseudo Infinite Guide Stars

Courtesy: P. Dierickx
Resonant back-scattering from mesospheric Sodium layer…

100km over 100m

Scattering from Low atmosphere

4km over 4m
**AO summary:**

- System engineering is well shaped for 8..10m class telescopes
- New WF sensors are explored and novel concepts are being discussed
- Secondary Adaptive Mirror technology has been proved on-sky on large (D=6.5m) apertures and is improving to an engineered system
- At least two Laser Guide Stars facilities are underway and expected to produce science within one year time-scale
- Novel concepts for LGS-sensing, suitable to 100m scales are being tested in lab and will be tested on scaled down versions soon.
Reality is more complex...
... and need Multi Conjugated Adaptive Optics: MCAO
Turbulence over a Large Field of View

(Rigaut, GEMINI)
Corrected by a conventional Adaptive Optics system at the center of the FoV…

(Rigaut, GEMINI)
Full correction by means of two DMs…

(Rigaut, GEMINI)
Multi-Conjugate Adaptive Optics

- Wide field-of-view turbulence compensation
- Uniform point spread functions
- Satisfactory sky coverage
- Feasible AO component requirements
- 5 x 10-W class sodium lasers
- Planned as an upgrade to a conventional LGS AO system
- Concept enables use of AO on 30 meter class telescopes

AO Module Opto-Mechanical design for MCAO

Performance of MCAO vs Classical AO

The GEMINI, 5 LGSs system
In the Star-Oriented concept, each star is associated to a WFS.
In the Layer-Oriented concept, WFSs are coupled to a given altitude layer.
Pyramid WFS based system easily complies with such an approach. Complexity scales mostly with the number of sensed layers rather than with the number of references.

Atmospheric 3D geometry is mapped in the WFS volume.
Degradation of the correction away from the focused plane.
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From the idea...
From drawing to metal (and hopefully soon in the lab and then in the sky)…

- CCD focussing mechanism
- Beam-splitter box
- Stars enlarger Positioning box
Because of Lagrange invariant one needs to place additional optics. Their positioning accuracy scales with D.
Such accuracy is easily achievable for D=8..10m telescopes, Hard but feasible up to D=30m telescopes and becomes Prohibitive for D=100m telescopes, leading to the concepts Of Active WFSensor or to the introduction of new concepts:
Multiple FoV

Layer-oriented is used taking advantage of the large isoplanatic patch for ground turbulence.

**General guideline:**

*Optimum* depends upon the adopted *criteria* *Combination* of techniques, co-added in the *right space* (e.g. the Fourier one) is often the winning approach.

Layer-oriented smoothly correct turbulence located away from where the DMs are conjugated.
Near InfraRed and Visible Adaptive iNterferometer for Astronomy: NIRVANA

WFS designed for 22.8 m

LBT is a peculiar telescope.

Wow!! Testbed for ELT MCAO: current specs harder!

Sigh..

~22.8m
NIRVANA aboard LBT

The instrument is located in one of the so-called bent combined focus

A top view…
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Sydney, July 17th 2003

GND layer WFS

Mid & high altitude Layer WFS
GND layer WFS initially implemented as numerica co-addition with multi-pyramids WFS
Detailed optomechanical study performed but very expensive because of CCDs and L3CCDs technology depending.

We are currently switching to optical coaddition.
A ground-layer, 6-arcmin Wide, WFsensor
Do you recognize these two guys?

Nickname: oil towers
Laboratory setup of a full arm in mid-2004
**MCAO summary:**

- Open-loop measurements proven in the sky (early 2000)
- One full system is being built, based upon 5 LGSs
- Layer-oriented concept tested in the lab
- MCAO concept proven to some extent in a few labs (Lunds, Durham)
- MCAO demonstrator to be tested on the sky underway its first light foreseen in late 2004
- Multiple-FoV layer-oriented, promising substantial sky coverage in the NIR with solely NGSs being engineered for LBT and to be tested soon in the lab
Spin-off to and from Industry

It is not just an ethical matter…. Why astronomers can have good CCDs at reasonable costs?

The astronomical & adaptive optics community will strongly benefit from a widespread interest of industry in such a technology

- Ophtalmology
- Microscopy
- Data communication
- Laser welding
The quality of the beam waist in a confocal microscopy will depend upon the optical distortion in the media where the target is embedded…

Optometry:
- Rochester, NY (exciting single cones)
- Pyramid WFS for the eye (w/ Murcia)
- Low Cost AO (Imperial College)
- Stages with Euro-branches of Japan firms

Data Communication:
- COLORS: an AO assisted gnd-space-gnd light link
- JPL is working on a similar topic
- CIVETTA: Strategic links (high volume of data for short period of times when the satellite is in view)
Several Extremely Large Telescopes projects around…

OWL (ESO leaded, 70..100m)
Euro50 (Lund leaded, 50m)
CELT (30m)
GSMT (~50m)
Next Generation CFHT (3 projects: 20..30m)
+ others…

The stairs Colombo walked to get funds for going to the new world… (Barcelona)
Single reference AO switched to maturity and is going to Produce unique science on 8..10m class telescopes

MCAO is showing that still several novel concepts were unexplored and will be tested in the sky soon

Experiments and projects planned in the coming few years are enough well funded and well established to be some real-testbed

In a few years some of the concepts outlined here (and maybe some still to be discovered) will lead, and some will be in ash

The outcome of this boiling activity will give further strength to the ELTs that will see the light in the next decade.
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Issues for a discussion

• MCAO for ELT is a hot and resources demanding topic. How we can work together and effectively benefit from this? Coopetition is the right share between competition and cooperation.

• Performances of MCAO for ELTs can explore a new range of parameters. For instance a system with 10% sky coverage can be characterized by: several small (2’) patches on the sky or a few big chunk maybe of irregular shape but lasting a significant fraction of a degree. What is the large scale structure that is of interest? Two arcmin, half a degree?

• Also, a system designed to exploit NIR under median seeing will achieve high Strehl in the visible in the, let say, 5% best seeing night. Is there a significant science case for this or most of the work is of survey nature?