Wide-Field Adaptive Optics for ground based telescopes: First science results and new challenges

Edinburgh– 25th March 2013

Presented by B. Neichel
A brief Introduction to Adaptive Optics (AO) and Wide Field AO

GeMS: the Gemini MCAO system

Tomography & Calibrations

First science results with WFAO

New challenges
A brief Introduction to Adaptive Optics (AO) and Wide Field AO (WFAO)
Adaptive Optics

Earth’s atmosphere

Spatial resolution is lost...
Adaptive Optics

Earth’s atmosphere

Spatial resolution is restored

Wave-Front Sensor
Adaptive Optics

Earth's atmosphere

Wave-Front Sensor
Adaptive Optics works close to a bright guide star.
Adaptive Optics works close to a bright guide star.
Anisoplanatism

High atmosphere’s layers are not sensed when looking off-axis
High atmosphere’s layers are not sensed when looking off-axis.
Anisoplanatism

High atmosphere’s layers are not sensed when looking off-axis.
Tomography

High atmosphere’s layers are not sensed when looking off-axis

Solution => Combine off-axis measurements
Tomography
Many different flavors of 3D phase reconstruction:
LSE, MMSE, MV, L&A, FRIM, POLC, Neuronal Network, …

Usually done in 2 steps (1) Reconstruction ; (2) projection

How to combine the WFSs measurements to do the tomography?
MCAO

- Combine off-axis measurements
- Add deformable mirrors
Good correction in a larger FoV!

=> Combine off-axis measurements

=> Add deformable mirrors
Adaptive Optics works close to a bright guide star

How many Guide Stars are available?

3 stars with $R < 16$ in a 2 arcmin FoV

- 10%
- 1%
- 0.1%
When no guide star are available, we can create one

**Gemini AO Laser**

- Solid State
- Sodium Laser
- 14 Watts
- 589 Nanometers
22 January 2011

First LGS constellation at Gemini South
- In summary -

Tomography for Astronomy means:

(1) Access to larger FoV
(2) Access to better sky Coverage

Where the first AO systems are limited to small and bright objects, new WFAO system opens the way to a multitude of new science cases. (We’ll see some nice images at the end of this talk)

BUT requires LGS

(We’ll see some of the LGS issues latter in this talk)
All the ELTs are based on multi-LGS WFAO systems
Introduction to GeMS – The Gemini MCAO system
**GeMS Intro.**

**GeMS** = Gemini (South) MCAO system

**GeMS** = Facility instrument delivering AO corrections in the NIR, and over a 2arcmin diameter FoV
50W Laser
Beam Transfer Optics (BTO)

50W Laser
Beam Transfer Optics (BTO)

50W Laser
Instruments fed by GeMS

**GSAOI**

*Near-Infrared wide field imager*

- 2 x 2 mosaic Rockwell HAWAII-2RG 2048 x 2048 arrays
- 0.9 - 2.4 µm wavelength
- 85" x 85" field-of-view
- Pix. scale of 0.02"/pixel

**Flamingos-2**

*Near-Infrared wide field imager and multi-object spectrometer*

- 0.95-2.4 µm wavelength
- FoV = 120" diameter
- Pix. Scale 0.09 arcsec/pix
- Long Slit (slit width from 1 to 8 pixels)
- MOS (custom masks)
- R = 1200-3000

**GMOS**

- 0.36-0.94 µm (New Hamamatsu-Red-Sensitive CCDs)
- Imaging, long-slit and multi-slit spectroscopy

**Integral Field Unit (IFU)**

- pix = 0.1arcsec - FoV = 17arcsec - R150 to 1200
Gemini Observatory, GeMS-GSAOI first light

NGC288, H band
13mn exposure
Field of View 87''x87''
FWHM = 0.080''
FWHM rms = 0.002''
Gemini Observatory, GeMS-GSAOI first light

NGC288, H band
13mn exposure
Field of View 87"x87"
FWHM = 0.080"
FWHM rms = 0.002"

distance=0"

GeMS
GeMS’s Tomography
Calibrations & Limitations
GeMS’s Tomography
Calibrations & Limitations

Tomography is easy, calibrations are difficult...
GeMS’s Tomography
Calibrations & Limitations

Tomography is easy, calibrations are difficult…

Differential aberrations between WFSs
Fratricide effect
Non-Kolmogorov turbulence
Quasi-static aberrations
Impact of differential aberrations between WFSs
Impact of differential aberrations between WFSs
Origin of differential aberrations between WFSs?

- Registration Look-Up Table
  - Static aberrations - Centroiding gains
    - Laser Spots
  - Differential LGS focus
    - Non-linear effects
Origin of differential aberrations between WFSs?

- **Registration Look-Up Table**
  - Static aberrations - Centroiding gains
    - Laser Spots
  - Differential LGS focus
    - Non-linear effects
LUTs are everywhere...
LUTs are everywhere...

Ex: LGS WFS zoom mechanisms
When elevation / temperature / flexure change, need to keep the registration and magnification right on each LGSWFS.
LGSWFS LUT versus elevation / temperature

LUT is built with calibrations sources moved to different LGS range.

8 mechanisms in the LGSWFS are adjusted to keep registration / magnification right.
WFS differential aberrations

LGSWFS LUT versus elevation / temperature

Need to be done daily when observing.

No ways to check while observing, “Trust the LUT” (Can do some on-sky checks, but “science destructive”)

Would require non-destructive, on-line calibration tools! (Cf. ESO AOF ?)
Origin of differential aberrations between WFSs?

- Registration Look-Up Table
  - Static aberrations
- Centroiding gains - Laser Spots
  - Differential LGS focus
  - Non-linear effects
No NCPA == SR of 50 (±10)% (H-band) in the field.

Goal: find slope offsets that would provide the best image quality in the science path.
No NCPA == SR of 50 (±10)% (H-band) in the field.
Static tomography for NCPA

Method 1, 2 steps: Phase Diversity + Tomography

Method 2, 1 step: Tomographic Phase Diversity

[Rigaut et al. AO4ELT2
Gratadour et al. AO4ELT2]
No NCPA == SR of 50 (±10)% (H-band) in the field.

Goal: find slope offsets that would provide the best image quality in the science path.

==> Static differential aberrations between WFS should be absorbed by NCPA.
Origin of differential aberrations between WFSs?

- Registration Look-Up Table
  - Static aberrations
- Centroiding gains - Laser Spots
  - Differential LGS focus
  - Non-linear effects
Quad-cells transfer function & centroid gain

Centroid gain depends on spot size. Spot size changes with seeing / sodium layer characteristics.
Quad-cells transfer function & centroid gain

Centroid gain depends on spot size.
Spot size changes with seeing / sodium layer characteristics

An error on the centroid gains can produce:
- Wrong loop gain in CL (minor effect) (What in OL ?)
- Wrong NCPA (major effect if NCPA are large)
- Differential aberrations between the WFSs and wrong tomography

=> Centroid gains need to be calibrated on-line
Quad-cells transfer function & centroid gain

=> Centroid gains need to be calibrated on-line

Method: Apply a “sine wave” on the DM at a given frequency and do a lock-in detection.

- Insensitive to vibrations
- Not (really) seen by the WFSs, so not corrected
- Small amplitude required (20nm rms)
- Would create satellite spot on the images, but lost in noise.

Seems to be working, but no direct way to cross-check results
Origin of differential aberrations between WFSs?

- Registration Look-Up Table
  - Static aberrations
- Centroiding gains - Laser Spots
  - Differential LGS focus
    - Non-linear effects
Differential focus introduced by Na-layer transversal variations
Differential focus introduced by Na-layer transversal variations

For 8m, differential focus does not seem to be an issue. But large error bars. Could be few hundreds of nm for 30-m telescopes.
Origin of differential aberrations between WFSs?

- Registration Look-Up Table
  - Static aberrations
- Centroiding gains - Laser Spots
  - Differential LGS focus
  - Non-linear effects
Non-linear effects

Lasers not properly centered

LGS spot Clipping?

Field stop Vignetting?
And telescope field aberrations!!

2 DMs

DM0 only
GeMS’s Tomography
Calibrations & Limitations

Tomography is easy, calibrations are difficult…

Differential aberrations between WFSs
Fratricide effect
Non-Kolmogorov turbulence
Quasi-static aberrations
Fratricide Effect
Fratricide Effect

Fratricide in multi-laser AO
Idea: Benoit Neichel & Francois Rigaut
Realisation: Francois Rigaut
Fratricide Effect

224 subapertures lost (~20% of the subapertures!)
Fratricide Effect

Diag(zcmat^2), unmasked, masked wfs1 (red), masked wfs2 (green)
Fratricide Effect

Impact of “Fratricide Leaks”
GeMS’s Tomography Calibrations & Limitations

Tomography is easy, calibrations are difficult…

Differential aberrations between WFSs
Fratricide effect
Non-Kolmogorov turbulence
Quasi-static aberrations
Theoretical covariance maps are built from realistic simulations (yorick/yao model of GeMS)

Profile is retrieved by fitting the data with the theoretical maps

[Cortes et al. – MNRAS – 2012]
Some examples of on-sky data:

GeMS’ SLODAR

Turbulence profile at Pachón, April 16th 2013
GeMS’ SLODAR

Limitations of the method: presence of strong dome seeing
GeMS’ SLODAR

Limitations of the method: presence of strong dome seeing

[Guesalaga et al. AO4ELT3]
GeMS’ SLODAR

Limitations of the method: presence of strong dome seeing

[Guesalaga et al. AO4ELT3]
Non-Kolmogorov (or non stationary) turbulence does exists!

What is the impact on tomographic performance?

However:
- Wind speed and direction can be predicted and measured.
- Frozen Flow assumption holds for long enough for predictive reconstructors.  

GeMS’s Tomography
Calibrations & Limitations

Tomography is easy, calibrations are difficult…

Differential aberrations between WFSs
Fratricide effect
Non-Kolmogorov turbulence
Quasi-static aberrations
Quasi-static aberrations

Cf. CANARY
Science with MCAO

WFAO is opening new opportunities for a large range of science cases
3 Fields:
OMC1 – North
OMC1 – Center
OMC1 – South-East

Filters:
Mol. Hydrogen (H2) - 2.122 µm (orange)
[Fe II] - 1.644 µm (blue)
Ks continuum - 2.093 µm (white)

Exposure Time per field:
H2 = 12min
[Fe II] = 10min
Ks continuum = 10min

<FWHM>:
H2 = 90mas
[Fe II] = 100mas
Ks continuum = 90mas

Natural seeing:
0.6" to 1.1" @ 550nm
VLT/NACO infrared adaptive optics images of small scale structures in OMC1

F. Lacombe¹, E. Gendron¹, D. Rouan¹, Y. Clénet¹, D. Field², J. L. Lemaire³, M. Gustafsson³, A. M. Lagrange⁴, D. Mouillet⁴, O. Roussel⁴, T. Fusco⁴, L. Rouset-Rouvière⁴, B. Servan⁵, C. Marlot⁴, and P. Feautrier⁴

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VLT/NACO infrared adaptive optics images of small scale structures in OMC1

Star Clusters

ISOCHRONES from Dotter et al. 2007 WEBsite
Z=0.001 age=10Gyr

P. Turri – PhD thesis
MCAO for Sky Coverage

Pulsar

SV412 – R. Mennickent

Isolated galaxy

SV411 – P. McGregor

Quasar

SV409 – D. Flyod
The Vela pulsar and its likely counter-jet in the $K_s$ band

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MCAO for Sky Coverage

Pulsar

Isolated galaxy

Quasar

SV412 – R. Mennickent
SV409 – D. Flyod
SV411 – P. McGregor

1 arcsec

FWHM = 0.13 arcsec
Filter = Ks
Exposure Time = 92 min
SV411 P. McGregor

Clumpy K-band continuum structure

1 arcsec
Abell 780 – z ~ 0.1

SV403
R. Carrasco & I. Trujillo
Filter = Ks
1h on-source
<FWHM> = 77mas
2 NGS only

85" ~ 150kpc
New challenges for WFAO
WFAO challenges

Current WFAO science instruments:

- GeMS
- SOAR Adaptive Module

Current WFAO demonstrators:

- CANARY
- RAVEN

Near future WFAO science instruments:

- ESO

AO Facility 2015
All the ELTs are based on multi-LGS WFAO systems
All the ELTs are based on multi-LGS WFAO systems

Global vision & walking before running

- All AO systems for E-ELT are challenging & costly:
  - Many new concepts are still in demonstration phase or have not been fully operated on smaller telescopes for science ➔ Pathfinders
  - Technologies required are often one step behind ➔ Dev. needed
  - Operation, Control & calibration strategies are still being figured out ➔ crucial effective operation of AO system for science ➔ Pathfinders
WFAO is opening new opportunities for a large range of science cases
Tomographic phase diversity:

- The classical PD approach can be extended to process data over an extended field of view.
- Instead of solving for a 2D phase, solve for a 3D phase (discrete or continuous). E.g. 2-3 phase planes + a tomographic projector
- Naturally more overconstrained/robust than PD in individual direction + tomographic reconstruction (assuming # of field positions/images is larger than the # of phase planes).
Static tomography for NCPA
(NCPA optimizes the wave-front in the science beam, but may degrade it severely in the NGSWFS path!)

(NCPA issues for wide-field AO systems: Impossibility to compensate for anything that’s not close to a DM conjugation altitude!)
Wind profiler method (Wang et al. 2008)

Time-delayed cross correlation between two wave front sensors, WFS\textsubscript{A} and WFS\textsubscript{B}, is:

\[
T^{AB}(\Delta u, \Delta v, \Delta t) = \frac{\sum_{u,v} S^A_{u,v}(t) \cdot S^B_{u+\Delta u,v+\Delta v}(t + \Delta t)}{O(\Delta u, \Delta v)}
\]

\(S^{WFS}_{u,v}(t)\): X and Y slopes of the WFS in subaperture \((u,v)\) at time \(t\)

\(O(\Delta u, \Delta v)\): overlapping illuminated subapertures for offset

\(\Delta t\): is a multiple of the acquisition time

Signal is retrieved by deconvolution \(\text{FT}^{-1}\left[\text{FT}\left[T^{AB}\right]/\text{FT}[A]\right]\)

\[
A(\Delta u, \Delta v) = \frac{1}{2} \frac{\sum_{u,v} S^A_{u,v}(t) \cdot S^A_{u+\Delta u,v+\Delta v}(t)}{O(\Delta u, \Delta v)} + \frac{1}{2} \frac{\sum_{u,v} S^B_{u,v}(t) \cdot S^B_{u+\Delta u,v+\Delta v}(t)}{O(\Delta u, \Delta v)}
\]

\(A\) is the average of the autocorrelations of WFS\textsubscript{A} and WFS\textsubscript{B}
GeMS’ 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.
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.
GeMS' wind profiler

Cross-Check with wind predictions
GeMS’ wind profiler

Wind profiler solves the “negative Cn2” issue

GeMS’ wind profiler

Wind profiler solves the “negative Cn²” issue

Also allows to study the Frozen Flow hypothesis

Star Clusters

Low mass cluster
Age estimation based on PMS
~ 10Myr cluster

HAFFNER 16: A YOUNG MOVING GROUP IN THE MAKING; Version 5.0; May 8, 2013
T. J. Davidge
Dominion Astrophysical Observatory,
National Research Council of Canada, 5071 West Saanich Road,
Victoria, BC Canada V9E 2E7

Rodrigo Carrasco, Claudia Winge, Peter Pessev, Benoit Neichel, Fabrice Vidal
Gemini Observatory, La Serena, Chile

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Australian National University
Why MCAO is good for astrometry?

- Active control of plate scales
- Large FoV => more reference stars
- PSFs are uniform over the field
MCAO for Astrometry

Why MCAO is good for astrometry?
- Active control of plate scales
- Large FoV => more reference stars
- PSFs are uniform over the field

Rigaut, Neichel et al. 2012
Why MCAO is good for astrometry?

- Active control of plate scales
- Large FoV => more reference stars
- PSFs are uniform over the field

But astrometry is challenging:

Distortions in Science plane are difficult to calibrate.

Multi-epoch astrometric performance is ~ 1 mas

For crowded fields, it can be calibrated
For sparse fields, looking for hardware solutions
MCAO for Astrometry

Diffraction grid for high-precision astrometry programs

Guyon+12
Bendek+12
Ammons+12.