Laboratory for Adaptive Optics

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A better title:

Laboratory Experiments for Astronomical Adaptive Optics
Outline of talk

• Why lab experiments?
• How are lab AO experiments done?
• Design issues for AO testbeds
• Current astronomical AO testbeds:
  – ESO
  – Lund University
  – University of Victoria
  – University of Durham
  – UC Santa Cruz - CfAO
• Conclusions
Why lab experiments? Shouldn’t we do experiments at the telescope?

• Both are important. Lab experiments: controlled conditions
  – “Turbulence” is made from custom optical aberration plates under your own control
  – Constant temperature, low vibration, etc

• Role of lab experiments:
  – Test new hardware concepts, new algorithms (e.g. MCAO)
  – Compare results with computer simulations
  – Develop precision AO calibration methods in controlled environment, e.g. for Extreme AO (very high Strehl)
    • If you can’t make it work in the lab, it won’t work on the telescope either
  – Provide place where students, postdocs can learn about hardware, system integration
  – Test and evaluate new components

• Can be a useful stepping-stone to telescope experiments
History: series of lab testbeds for various military and NASA AO projects

- Lincoln Labs
- Air Force Research Lab
- Lockheed
- Airborne Laser: Boeing, Lockheed Martin and TRW
- Also NASA Goddard Space Flight Center (AO for James Webb Space Telescope)
- Others...
How are lab experiments done?

• **Approximate Scheme: (details will differ)**
  
  – Observe a fiber-optic source or a known scene with a small telescope on a lab bench
  
  – Between the optical source and the telescope, insert artificial source that mocks up turbulence. Example:
    
    • Optics that introduce known phase errors
    
    • Either transparent or reflective
    
    • Can be made to have Kolmogorov turbulence spectrum
    
    • Can be moved or rotated to give time dependence
  
  – Then an AO system tries to correct the known phase errors
  
  – Can even have surrogate laser guide stars
  
  – A “scoring camera” of some sort evaluates system performance
Typical lab layout to simulate MCAO

Fiber optic guidestar simulators

Phase aberrator plates

Deformable Mirrors

Wavefront sensors

Kolmogorov phase aberrator plates simulate the atmosphere

from Don Gavel, UCSC
How to produce artificial turbulence in lab?

- **General concept:**
  - Introduce spatially variable optical phase difference into beam path
  - Usually want statistics to be close to those of atmospheric turbulence: Kolmogorov spectrum

- **Methods:**
  - Use heat to generate turbulence
    - Works, but not easy to control
    - Kolmogorov spectrum hard to make
  - Glass plates in transmission (etched in some way)
  - Layers of oil sandwiched between glass or plastic plates (in transmission)
  - Microfabricated: pattern deposited on substrate. Either transmission or reflection
  - Generate with a fine-scale liquid crystal display (or other spatial light modulator)
Example 1: An exact computed pattern of phase aberrations can be etched onto a glass plate

256 x dynamic range (100nm – 25μm) is achieved with 8 etch steps

Most significant bit

Least significant bit

LLNL, Don Gavel et al.
Fig. 1. Schematic demonstration of near index matching. When the refractive indices of the two materials are close in value, the magnitude of the aberration produced in the transmitted wave front is much less than the physical deviation at the interface.
Example 3: Hot-air turbulence generator, U. Victoria

- Maximum $D/r_0 = 38$
- $\Delta T$ up to 163 °K
Scaling issues to simulate Extremely Large Telescope MCAO in lab

- How to faithfully scale 30 m - 100 m primary mirror and ~40 km of atmosphere onto a lab bench
- Laser guide star simulator, including correct scaling of sodium layer height (laser spot elongation)
- How to make atmospheric phase aberrator plates
- AO relay - what optical train to use
- What deformable mirrors to use – (e.g. conventional, liquid crystal, MEMs)
- What wavefront sensors to use
- Allowed to scale both time and wavelength (e.g. can use $\lambda = 0.5 \text{ m}$)
Scaling Diffraction and Scintillation effects from Earth to laboratory scales

The key diffraction parameter: Fresnel number

\[ n = \frac{a}{\sqrt{\lambda L}} \]

where:
- \( a \) = aperture or subaperture size
- \( \lambda \) = wavelength
- \( L \) = propagation distance

Determine:
- Rayleigh range (geometric/diffractive transition - ‘far-field’)
- Depth of focus
- Fresnel zone size
- Resolution
- Scintillation variance

Scaling to preserve diffraction (\( M \) is transverse magnification from earth to lab scale):

\[ a = Ma \quad L_{testbed} = M^2 L_{ELT} \frac{\square_{ELT}}{\square_{testbed}} \]

Example: \( M = 30 \text{ mm} / 30 \text{ m} = 1000, \ M^2 = 10^6 \quad \square_{testbed}/\square_{ELT} = 0.5 \)

\[ L_{testbed} = \frac{40 \text{ km} \times 2}{10^6} = 80 \text{ mm} \]

while a more realistic number is \( \sim 200 \text{ mm} \). SO... compromise on diffraction behavior

from Don Gavel, UCSC
Additional consideration: Lagrange invariant

Diffraction-scaling at fixed wavelength preserves the Lagrange invariant:

\[ x_1 = y_1 q_1 = y_2 q_2 = \text{const} \]

Field angle \[ \frac{\theta_2}{\theta_1} = \frac{y_1}{y_2} = M \]

Result: 2 arc min field of view on a 30m telescope scales to 1.8 radians at a 10mm MEMS aperture. Makes optical design impossible - angles are just too big.

Conclusion: compromise on Fresnel number, just keep it large
### Example lab scaling

<table>
<thead>
<tr>
<th></th>
<th>ELT AO system</th>
<th>Laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture diameter, D</td>
<td>30 m</td>
<td>26 mm</td>
</tr>
<tr>
<td>Atmospheric path, L</td>
<td>15 km</td>
<td>22.5 cm</td>
</tr>
<tr>
<td>Wavelength, ( \lambda )</td>
<td>1 ( \mu )</td>
<td>0.5 ( \mu )</td>
</tr>
<tr>
<td>Field angle at pupil, ( \theta )</td>
<td>1'</td>
<td>57'</td>
</tr>
<tr>
<td>Subaperture size, d</td>
<td>30 cm</td>
<td>260 ( \mu ) m</td>
</tr>
<tr>
<td>Coherence cell, ( r_0(\theta) )</td>
<td>46 cm</td>
<td>400 ( \mu ) m</td>
</tr>
<tr>
<td>DM size</td>
<td>30 cm</td>
<td>2 cm</td>
</tr>
<tr>
<td>Angle at DM</td>
<td>100'</td>
<td>75'</td>
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<tr>
<td>Fresnel number, ( D/(\lambda L)^{1/2} )</td>
<td>245</td>
<td>77</td>
</tr>
<tr>
<td>Scintillation variance, ( \sigma^2 )</td>
<td>0.03</td>
<td>0.2</td>
</tr>
<tr>
<td>Scintillation Strehl, ( \exp(-\sigma^2) )</td>
<td>0.97</td>
<td>0.81</td>
</tr>
<tr>
<td>Equivalent WF err</td>
<td>28 nm</td>
<td>37 nm</td>
</tr>
</tbody>
</table>

from Don Gavel, UCSC

Compromise in Fresnel number

Results in slightly increased scintillation
Current astronomical MCAO testbeds

- ESO
- Lund University
- University of Victoria
- University of Durham
- UC Santa Cruz - CfAO
ESO’s MAD: Multiconjugate AO Demonstrator

• **GOALS:**
  - Test MCAO concepts in lab
  - Compare layer-oriented and star-oriented methods
  - After about 6 months of lab tests, bring to VLT telescope
  - Test on telescope using a small number of selected natural guide star configurations

• **Some details:**
  - Two deformable mirrors
  - Layer-oriented and star-oriented wavefront sensors
Why an MCAO demonstrator?

Medium to High angular resolution is essential for OWL
Goal 60k x 60k resolution elements

Promising avenues:
Multi-Conjugate AO & atmospheric tomography

Star Oriented wavefront sensing + Global reconstruction

Layer Oriented wavefront sensing + Local reconstruction

MAD research tool:
test both concepts in lab, then demonstrate on sky
MAD optical design

- wavefront sensor
- objective
- 1st deformable mirror
- Nasmyth focus
- 2nd deformable mirror
- collimator
- dichroic
- to IR imaging camera
- derotator

Scale: 0.10  ESO  05-Mar-02
MAD on a VLT Telescope

- Optical derotator
- Layer Oriented WFS
- Star Oriented WFS
- VLT Rotator/Adapter
- Nasmyth Platform
MAD uses 2 bimorph deformable mirrors

Heritage: MACAO-VLTI and MACAO-SINFONI on VLTs
Lund Dual Conjugate Adaptive Optics Demonstrator (LUDDE)

- Per Knutsson, Mette Owner-Petersen, Torben Andersen

- Lab demonstrator that emulates:
  - layered atmosphere (static)
  - 7.5 m telescope
  - Dual Conjugate Adaptive Optics at $\lambda=2.2\,\text{m}$
  - 5 natural guide stars in a cross
Layered Atmosphere

- **Phase screen**
  - Holographic film, exposed with laser speckles, bleached and developed varying optical path difference

- **Property of phase screens**
  - Add phase disturbance at experiment $\lambda=550\text{nm}$ equivalent to parent $\lambda=2.2 \text{mm}$

- **$r_0$-equivalent**
  - Obtained from tilt variance:

\[
\sigma^2 = 0.364 \frac{\lambda^2}{D^{1/3}r_0^{5/3}}
\]
LUDDE’s AO Components

- **2 OKO MMDMs**
  - One at 0 km and one at 10 km
  - 37 actuators each

- **AOA miniWavescope**
  S-H sensor
Uncorrected Average PSFs

Guide star 4
Guide star 1
Guide star 3
Guide star 5
Guide star 2

Normalised intensity

arc sec (in parent)
Average PSFs - Conventional AO
Average PSFs – Dual Conjugate AO
University of Victoria and HIA

- B. Wallace, C. Bradley, H. Richardson, J. Kennedy, O. Keskin, P. Hampton, D. Robertson, L. Jolissaint, A. Hilton

- **Goals**
  - MCAO laboratory bench including turbulence generators
  - Demonstrate MCAO concept, assess performance
  - Develop and test new control algorithms
  - Investigate miniature AO (MEMs)
  - Use the bench to educate students

- **Two turbulence layers, two DMs (MEMS, 140 actuators)**

- **Scaled-down 8m telescope, 2 arc min field of view**

- **Hot-air turbulence generator**
Natural Star Light Sources → Turbulence Simulator → Upper DM → Lower DM

- PC’s and control system
- Slow WFS or a fast-reading CCD as science camera
- Natural Guide Star cameras for tip/tilt sensing

Science Light Source

1 2 3 4 "Laser beacons"

Laser Guide Stars WFS’s
University of Durham MCAO system

- C. Saunter, M. Langlois, C. Dunlop, Gordon Love
- Uses four liquid crystal spatial light modulators:
  - Two for deformable mirrors
  - Two for turbulence generators (two layers)
- Status
  - Have demonstrated MCAO performance, need to improve Strehl performance
Dual Layer Turbulence Emulator Layout

5-lenslets

Lower Layer Spatial Light Modulator

Crossed Slits

5-guide star images

Upper Layer Spatial Light Modulator

L : Lenses

Relay Optics

To MCAO
Durham optical design

Dual Layer, 5 Guide Stars
LC Turbulence Generator

SLM Upper

SLM Lower

Upper LC Corrector

OAP #1

Lower LC Corrector

Imaging Camera

WFS Camera

Lenslet Array

OAP #2
Laboratory for Adaptive Optics at UC Santa Cruz

GOALS:

• Develop Adaptive optics techniques for extremely large ground-based telescopes
• Develop and build planet finder instrument using “extreme” adaptive optics techniques
• Test and evaluate new components/technologies as they become available
• Visitor program for CfAO researchers, industrial community
• Provide a laboratory where students and postdocs can become trained in adaptive optics hardware and software

• Don Gavel, Director. PI’s: Claire Max, Jerry Nelson, Joe Miller
Laboratory for Adaptive Optics at UC Santa Cruz

- Funded by the Moore Foundation for 5 years; 1500 sq ft lab
- Phase 1 of facility available this fall
- Will be used to test new hardware concepts, validate models and simulations, train young people
- Will house Extreme AO and MCAO experiments
Extreme Adaptive Optics Planet Imager

- Very high-Strehl AO system for an 8-10m telescope
- Science goals:
  - direct detection of extrasolar planets through near-IR emission
  - characterization of circumstellar dust
- 2002-2003 conceptual design study
- System is intended to be facility-class
  - Wide variety of high-contrast science programs will be possible
  - Bright targets: $m_R \leq 7-10$
- Bruce Macintosh, PI

Hardware tests, system integration at UCSC Lab for AO and at LLNL
## ExAO Planet Imager design concept

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current Keck AO</th>
<th>XAOPI</th>
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<tbody>
<tr>
<td>Subaperture size d</td>
<td>60 cm</td>
<td>~20 cm</td>
</tr>
<tr>
<td>Number of subapertures</td>
<td>241</td>
<td>~2000</td>
</tr>
<tr>
<td>Deformable mirror</td>
<td>~20 cm glass</td>
<td>~3 cm MEMS</td>
</tr>
<tr>
<td>System rate</td>
<td>670 Hz</td>
<td>2000 Hz</td>
</tr>
<tr>
<td>Controller</td>
<td>16 x PowerPC</td>
<td>4 x Xeon</td>
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<tr>
<td>Strehl ratio at 1.65 μm</td>
<td>0.2 - 0.4</td>
<td>0.9 - 0.95</td>
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<tr>
<td>Limiting magnitude</td>
<td>R ~ 13</td>
<td>R ~ 7</td>
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<tr>
<td>Internal Static wf error</td>
<td>~150 nm</td>
<td>~5 nm (!)</td>
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</table>
ExAO Test Layout in Lab: Can we reach the required precision?

- Laser
- Optical Fiber
- MEMS device under test
- Imaging Camera
- Interferometer camera

$\sim \sqrt{1000} \ (1\text{nm})$

40
LAO ExAO testbed (Gary Sommargren)

Phase 1 (LLNL, thru 8/03)
- Monochromatic target source
- Superpolished flat mirror
- Goal: demonstrate precision wavefront measurement and correlation with PSF

Phase 2 (LLNL, thru 10/03)
- Install 140-actuator MEMS and achieve suitable wavefront at MEMS control scale

Phase 3 (UCSC, 9/03-12/03)
- Recreate phase 2 at UCSC
Granite optical bench before set-up in Lick optics shop at UCSC
Lab layout to simulate MCAO

Fiber optic guidestar simulators

Phase aberrator plates

Deformable Mirrors

Kolmogorov phase aberrator plates simulate the atmosphere

Wavefront sensors

Scoresing camera

from Don Gavel, UCSC
The Kolmogorov atmosphere will be simulated with transmissive phase plates.

<table>
<thead>
<tr>
<th>Lab</th>
<th>Sky</th>
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<tbody>
<tr>
<td>$r_0 = 400 \text{ m}$</td>
<td>20 cm</td>
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<tr>
<td>$L = 80 \text{ mm}$</td>
<td>40 m</td>
</tr>
<tr>
<td>$dx = 39 \text{ m}$</td>
<td>1.9 cm</td>
</tr>
<tr>
<td>$\text{opd p-v} = 25 \text{ m}$</td>
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<tr>
<td>$\text{opd (8 bit)} = 100 \text{ nm}$</td>
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</table>
Structure function of phase plates: close to Kolmogorov spectrum

Phase plates
AO on

Kolmogorov Fit
$r_0 = 650 \ \mu m$
$D_\phi(x) = 6.88 (x/r_0)^{5/3}$
Experimental Structure Function

Structure Function $D_\phi(x)$ vs. Separation $(m)$
# 5 year plan: Experiments at LAO

<table>
<thead>
<tr>
<th>WBS</th>
<th>Task Name</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
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<th>2007</th>
<th>2008</th>
<th>2009</th>
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<tr>
<td>6</td>
<td><strong>LAO &amp; telescope experiments</strong></td>
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<td>Layer-oriented vs tomography, lab tests</td>
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<td>Test pyramid wavefront sensor concept</td>
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<td>Elongated guidestar wfs lab tests</td>
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<td>Test Palomar MCAO config in lab</td>
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<td>Test 30-m concept design config in lab</td>
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<td>MCAO Tests on Palomar, multi DMs</td>
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<td>Test alternative wfs dsigns</td>
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<td>Data from Gemini S MCAO</td>
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UCSC Lab for Adaptive Optics: Summary

- Hardware testbeds for MCAO, ExAO, component testing (e.g. MEMS, new wavefront sensor concepts)
- Place where grad students, post-docs can get hands-on hardware experience
- Visitor program for CfAO researchers, industrial community, other users
  - If you are interested, please talk to Don Gavel or to me!
- Will become integral part of UC Observatories after CfAO and LAO grants have ended
### Features of astronomical MCAO testbeds

<table>
<thead>
<tr>
<th>Institution</th>
<th>Lab or Telescope</th>
<th>DMs</th>
<th>Bandwidth</th>
<th>Phase screens</th>
<th>Other</th>
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</thead>
<tbody>
<tr>
<td>ESO</td>
<td>Lab, then telescope</td>
<td>High (so they can use on telescope)</td>
<td></td>
<td></td>
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<tr>
<td>Lund Univ.</td>
<td>Lab</td>
<td>2 MEMS</td>
<td>Static (to date)</td>
<td>holographic film</td>
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<tr>
<td>Univ. of Victoria</td>
<td>Lab</td>
<td>2 MEMS</td>
<td>Several hundred Hz</td>
<td>Hot-air turbulence generator</td>
<td>4 WFS’s, 1 pyramid</td>
</tr>
<tr>
<td>Univ. of Durham</td>
<td>Lab</td>
<td>2 liquid crystal devices</td>
<td>1 Hz</td>
<td>ferroelectric liquid crystal holographic</td>
<td></td>
</tr>
<tr>
<td>UC Santa Cruz</td>
<td>Lab</td>
<td>several MEMS</td>
<td>Low (a few Hz)</td>
<td>Micro-fabricated</td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

• Lab experiments on astronomical AO under controlled conditions are undergoing a renaissance
• Focused on MCAO and related issues
  – But LLNL and CfAO are also testing Extreme AO
• Variety of approaches being explored
• Viewed as preparatory step before going to telescope
• A very healthy and exciting development!