“Extreme” AO fundamentals

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Outline

• **ExAO science in two slides or less**
• **Components of the high-contrast PSF**
  – Fourier relationships
  – Diffraction and how to control it
  – Phase errors and their effects
• **ExAO hardware requirements**
  – Wavefront reconstructor
  – MEMS deformable mirrors
• **Sample ExAO systems**
Current AO vs ExAO

- Current AO systems produce sharp images but still have a diffuse halo of scattered light.
- Very roughly, ability to see faint things goes as $D^2(\text{Strehl})/(1-\text{Strehl})$
  - Strehls $\to 1$ provide huge benefit
  - Spatial and temporal frequency of residuals are crucial
- ExAO systems are designed for very high strehl and optimized to control scattered light.
- Similar but not identical requirements for general-purpose visible-light AO.
Known planets

Mass / (Jupiter mass)

Orbital radius [AU]

Mercury 1.0 10.0 100.0

Earth

Venus

Saturn

Jupiter

Neptune

Uranus
AO system layout

Atmosphere parameters:
- Coherence length $r_0$
- Wind velocity $v$

DM conjugate to telescope primary

$D =$ primary mirror diameter

d = actuator spacing

WFS conjugate to DM & primary

$W_0$ and $d$
Light is scattered by both diffraction and phase (Sivaramakrishnan et al 2002, Perrin et al 2003)

Pupil P(u,v) → Fourier Transform → Image I(x,y)

Pupil-plane period \( u \)  
Power spectrum of phase

Image-plane angle \( \theta = \lambda/u \)  
Speckles in PSF
Shaped-pupil coronagraphs (Kasdin et al. 2003)

- Apodized pupils are physically difficult to manufacture (esp. without introducing wavefront errors)
- A variety of hard-edged shapes exist which can produce apodization-like effects
- Tuning these is a problem in optimization (e.g. Vanderbei et al 2003)
- Optimization for ExAO case is different and not studied
1-D Lyot Coronagraph

So much for diffraction

- Diffraction correction is the easier part of the problem (except very close to the star, <4 λ/D)
- Many coronagraph designs exist
- Now, on to correcting phase
Error terms: atmospheric fitting

5 second monochromatic image
Aliasing error = $1/3$ of fitting error (Rigaut et al 1999)

5 second monochromatic image
Band-limiting for anti-aliasing: spatial filter

\[ \lambda/d_{ap} \]

Position (arcsec)
Spatial filter (Poyneer and Macintosh 2004) implementation

Deformable Mirror

Dichroic

Wavefront Sensor

Science Camera+Coronagraph

Focal stop spatial filter $\lambda/d=0.9''$
Atmospheric fitting reduction $\Rightarrow$ high actuator count

$\lambda/d_{ap}$

5 second monochromatic image
MEMS deformable mirrors

- Conventional deformable mirrors are ~1 cm and $1000/actuator
- Silicon Micro-Electro-Mechanical-Systems are manufactured on microchip scales of size and cost
- Current state of the art is 32x32
- Near-future: 64x64 actuator continuous-facesheet MEMS mirror
- 1-2 micron stroke
Temporal bandwidth is largest source of scattered light

5 second monochromatic image
WFS measurement noise dominates on dim stars

5 second monochromatic image
AO system parameter space

AO systems

Update rate (Hz)

Degrees of freedom

Rochester 1
Houston
LLNL SLM
Indiana
LLNL MEMS
Rochester 2
Lick
PALAO
Keck
ALTAIR
AEOS
XAOPI
1000s of actuators at 1000s of Hz!

Reconstruction computational burden

Operations per second

number of subapertures

Conventional VMM
Wavefront reconstruction options

- Vector Matrix Multiply: classic but slow
- **Local control**: truncate the control matrix so that only subapertures close to an actuator are included
- Sparse matrix: adjust the problem so that the AO control matrix is mostly diagonal
  - Conjugate-gradient and minimum-variance versions use additional knowledge about the wavefront to try and condition the problem
- **Fourier reconstructors**: reassemble the wavefront in the Fourier domain
A given actuator only strongly influences nearby subapertures.

- Can truncate the number of subapertures used in $M^{-1}$
- Can do a local LS ‘mini-matrix’: $O(n^{4/3})$

- However, low frequency information is lost by this approximation.
• Many modes are truly global: local control has the most error on these
• Can ameliorate with extra layers of estimation

Pure local control would miss low-order modes
Fourier reconstruction (Poyneer et al 2002)

- Fourier transforms turn derivatives into multiplication by a phase term
- Discrete Fourier Transforms turn differences into multiplication
Filter is derived from a model of the wave-front sensor geometry

- Filter inverts the slope measurement process
- Simplest model: Hudgin geometry

\[
s_x[m, n] = \phi[m + 1, n] - \phi[m, n]
\]

\[
S_x[k, l] = \Phi[k, l](e^{j2\pi k/N} - 1)
\]
Flow chart of reconstruction process

- WFS slopes
- FFT
- Filter
- FFT inv
- Phase
Model requires certain slope conditions to be satisfied

- For correct reconstruction, two conditions must be satisfied
  - All loops (under Hudgin or Fried geometry) must sum to zero
  - Both slope signals must be spatially periodic (for DFT)

*Spatial periodicity*

*Loop continuity*
Slope extension solves this problem (Poyneer et al 2002, 2003)
Flow chart of reconstruction process

- Extend slopes
- WFS slopes
- FFT
- Filter
- FFT inv
- Phase
FFT reconstructor reduces computation

Reconstruction computational burden

Operations per second

Conventional VMM vs FFT reconstructor

Number of subapertures
XAOPI 0 nm static errors, 5 MJ/500 MYr planet, 15 minute integration
XAOPI 1 nm static errors, 5 MJ/500 MYr planet, 15 minute integration
XAOCI 2 nm static errors, 5 MJ/500 MYr planet, 15 minute integration
XAOPI 5 nm static errors, 5 MJ/500 MYr planet, 15 minute integration
Other classes of errors

- ExAO systems have small subaperture sizes and hence need bright stars!
- Quad-cell gain errors when working off null due to non-common-path
  - SFWFS suppresses these
- Residual telescope errors
- Scintillation
- Chromatic errors from WFS vs science wavelength (Dekany et al 2004 PASP submitted)
Sort-of-extreme AO: USAF

- USAF AO systems designed for visible-light AO observations
- AEOS at Haleakala and similar system at Starfire
- “Lyot project” coronagraph now on AEOS (www.lyot.org)

<table>
<thead>
<tr>
<th>System</th>
<th>D (m)</th>
<th>d (m)</th>
<th>Rate (Hz)</th>
<th>Strehl</th>
<th>GS mag</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>AEOS</td>
<td>3.7</td>
<td>0.12</td>
<td>2500</td>
<td>0.3 @ 0.8 μ</td>
<td>m_V&lt;4</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;0.7 @ 1.6 μ</td>
<td></td>
<td></td>
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<tr>
<td>Starfire</td>
<td>3.6</td>
<td>0.12?</td>
<td>2500?</td>
<td>0.4 @ 0.8 μ</td>
<td>m_V&lt;4?</td>
<td>50 W laser</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>soon</td>
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Future ExAO: VLT

- Two groups studying planetfinders for the ESO VLT
- Studies to complete in 2004
- Deploy in 2008?

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<tr>
<td>VLT planetfinder</td>
<td>8.2</td>
<td>~0.2</td>
<td>1000</td>
<td>0.8 @ 0.8 μ</td>
<td>m_R&lt;10</td>
<td>Pyramid WFS?</td>
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Future ExAO: XAOPI / Keck

- CfAO design study for an ExAO system for an 8-10m telescope
- Specific solutions to segmented-mirror issues
- SFWFS, ultraprecise calibration (<2 nm RMS)
- Now studying similar instrument for Gemini

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<tr>
<td>Current Keck</td>
<td>10</td>
<td>0.56</td>
<td>670</td>
<td>&gt;0.4 @ 1.6 µ</td>
<td>m_V&lt;10</td>
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<tr>
<td>XAOPI</td>
<td>10</td>
<td>0.18</td>
<td>2500</td>
<td>0.95 @ 1.6 µ</td>
<td>m_I&lt;8</td>
<td>SFWFS</td>
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</tbody>
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XAOPI schematic

Update rate: 2500 Hz

Actuators: 4096

Subaperture d=18 cm
Space ExAO: Planet finders

- NASA studying space telescopes with coronagraphs and active optics for planet finding
- Terrestrial Planet Finder (TPF-C) planned for 2014 launch
- Various interim 2-m class missions proposed
- Science camera used for WFS
- Near-perfect static wavefront errors needed

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<tr>
<td>2-m class</td>
<td>2</td>
<td>~0.04</td>
<td>0.00001</td>
<td>&gt;0.99 @ 0.8 μ</td>
<td>&lt;5?</td>
<td>&lt;1 nm static</td>
</tr>
<tr>
<td>TPF-C</td>
<td>4x6</td>
<td>~0.04</td>
<td>0.00001</td>
<td>&gt;0.99 @ 0.8 μ</td>
<td>&lt;5?</td>
<td>&lt;0.1 nm static WFE</td>
</tr>
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Further into the future

- At high strehl ratios, more advanced wavefront sensors are possible
- Interferometric wavefront sensors (Angel 1994)
- Focal-plane wavefront sensors that combine the wavefront sensor and science camera (Codona and Angel 2004)
- These remove many error sources and are more efficient
Conclusions and platitudes

- Science needs exist for “extreme” adaptive optics systems
  - Planet finding, also visible-light AO (but only on bright stars!)
- Extreme AO PSF can be broken down into separate components
  - Diffraction, fitting error, aliasing error, etc.
- Careful WFS and system design can minimize these errors
- ExAO requires high-density DMs (MEMS), efficient reconstructors
  - FFT reconstructor well suited to ExAO
- Several groups studying ExAO systems for a variety of telescopes
• Vanderbei et al 2003 Ap.J. 599, 686 (more shaped pupils)