Center for Adaptive Optics: Overview for the AO Roadmap Panel

Lick Dual-Channel AO Polarimeter, Perrin and Graham

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Outline of talk

• Intro to the Center for Adaptive Optics

• CfAO research plans for next 5 years, in areas relevant to AO Roadmap

• My personal opinions about what the next AODP Roadmap should emphasize
CfAO Mission and Themes

Mission:
To advance and disseminate the technology of adaptive optics in service to science, health care, industry, and education.

Themes:
1) Education
2) AO for Extremely Large Telescopes
3) “Extreme AO” - very high contrast
4) AO for vision science (imaging the living human retina)
The CfAO today

- Center headquarters at UCSC

- Current partners: universities, laboratories, observatories
  - UCSC, UCB, UCI, UCLA, Chicago, Rochester, Indiana, Houston, Montana State, LLNL, JPL, Gemini, Keck, NSO, ...

- Many industrial partners

- NSF Funding:
  - Approx. $4M per year for 10 years (Nov ‘99 - Nov ‘09)
CfAO research plans for next 5 years

- **AO for Extremely Large Telescopes**
  - Concepts, analysis, simulations of wide-field AO
  - Partnerships for long-term hardware development
  - Methods for using sodium laser guide stars for astronomy
  - Astronomical science with laser guide stars and to test PSF reconstruction techniques

- **Extreme Adaptive Optics**
  - Concepts, simulations, and conceptual design of an instrument for an 8-10m telescope
  - Concepts for extremely large telescope ExAO systems
  - High-contrast science
Concepts, simulation, analysis of wide-field AO for ELT’s

- How is planned CfAO work differentiated from, e.g., work of the Thirty Meter Telescope Project?
  - CfAO: Deeper exploration of concepts such as tomography; analysis, modeling, and simulation to compare performance; fast wavefront reconstruction algorithms; develop common base of simulation codes
  - TMT: Focus on first-light AO systems for TMT
  - Both: Lab and telescope tests

- CfAO projects structured so as to include students, postdocs (the next generation of AO leaders)
<table>
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<th>TMT AO Systems and Science</th>
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<td><strong>Wavelength range</strong></td>
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Tomographic reconstruction is at heart of wide-field-AO efforts

- Use multiple laser guide stars to measure wavefront in several directions
- Reconstruct 3-D profile of turbulence over the telescope
- This can be done either in closed-loop (with the deformable mirror in the path to the wavefront sensors) or in open-loop
Laboratory for Adaptive Optics: MCAO Testbed

- Fiber optic multiple guidestar simulators
- Phase aberrator plates
- Deformable Mirrors
- Wavefront sensors

Funding from Moore Foundation
Recent strong interest in open-loop tomographic reconstruction

- From point of view of overall system complexity, it is very desirable to be able to separate measurement process from correction process
  - Concept of one “Measurement engine” - multiple laser guide stars and tip-tilt stars, each with its wavefront sensor. Feeds information on 3D turbulence structure to all AO systems

- Heritage: Euro50, LLNL horizontal-path AO systems, ...

- Technology requirements:
  - Multiple laser guide stars for high reliability
  - LINEAR and STABLE wavefront sensors
  - Deformable mirrors that have high accuracy, high stroke, high actuator count (e.g. 5000 - 10,000), low hysteresis
  - Calibration systems for high-accuracy measurement of non-common-path errors
  - Simulation and analysis of all parts of this concept
  - Test of all of the above in the lab and on telescopes
ELT AO with Adaptive Secondary

Low order adaptive secondary

Stroke reduction for AO DMs

Seeing improvement for mid-IR
ELT AO with Adaptive Secondary

High order adaptive secondary

Full Mid-IR AO

Inst.

Dewar

WFS

MCAO

GLAO

ExAO
Why Do Multi-Object AO?

• MOAO could provide moderately good turbulence compensation across a (relatively wide) field for multi-IFU spectroscopy
  - e.g., 50-70% encircled energy within a 0.1” pixel over a 3 arc minute diameter field

• Eliminates one of the two fundamental error sources for MCAO, the correction of a continuous 3-dimensional turbulence profile with a finite number of DM’s

• ...but it doesn’t correct the second error source, which is estimating a continuous turbulence profile with a finite number of guide stars
Multi-Object AO Concept: Wide-field
Adaptive Optics for Diffraction Limited ELTs

- **DMs:** need ~5000 actuators per DM, ~20 μm stroke
  - Adaptive secondaries
  - Large (e.g. >30cm) DMs *may* be needed to satisfy Lagrange invariant
  - For MOAO, ExAO: MEMS with large # of actuators, low hysteresis
  - For Mid-IR: cryogenic operation

- **Wavefront sensors:** need ~512 x 512, 1 kHz, low noise
  - Present technology: 128x128, 2 kHz
  - *Need to be linear, high dynamic range*

- **IR tip/tilt sensor**
  - 30e- read noise is state of the art; lower noise is better
  - IR APDs an option

- **Computers** - present technology most likely sufficient, if we use ‘fast’ algorithms
  - Fast algorithms need to be proven stable in closed loop
  - Algorithms must measure and adapt to changing $C_n^2$ profile

- **Lasers and LGS AO components, methods**
Sodium guide-star lasers: What is Needed

- Currently available Na guide star lasers:
  - CW and pulsed dye lasers (ESO, Lick, Keck)
  - Solid-state sum-frequency lasers (U Chicago, CTI, Air Force)
  - CW fiber laser (LLNL)

- Challenges for all of these:
  - Engineering a highly robust system
    - Current state of the art, except for Air Force laser:
      - Send engineer or technician to mountain at least a week ahead of run, to tune up system
      - Operate laser with highly trained, dedicated crew
    - Even with the above, lasers are not yet efficiently doing astronomy (e.g. with high on-sky efficiency)
  - Sufficient laser power for near-IR AO, at all seasons.
  - Develop pulse format or other methods to minimize spot elongation and Rayleigh scatter fratricide for ELTS
Example of pulsed laser format to mitigate spot elongation

- < 3 µs pulse width (small broadening)
- 3-15 kHz pulse rate (only 1 pulse in Na layer)
- How hard is it to make a laser like this, with adequate power?
- What is best way to follow focus? Dynamic refocus, special CCDs?
Current CfAO partnerships for long-term hardware development

• **Na laser development:**
  - Complete macro-pulse micro-pulse sum-frequency laser, put on Palomar 200” telescope
  - Complete CW fiber laser, (put on a 3-5m telescope?)
  - Develop new pulse formats to mitigate spot elongation

• **MEMS Deformable mirrors (≥1000 degrees of freedom)**

• **Collaborate with 4 AODP Projects:**
  - Nanolaminate DMs
  - Pulsed fiber laser
  - New CCDs for wavefront sensing
  - New micro-channel-plate wavefront sensor concept
CfAO and LAO are funding some MEMS DM research

- Fabrication run of 1000-actuator MEMS (Boston Micromachines)
  - Characterize each device, iterate
  - Aiming for zero defects
- Preliminary efforts on high-stroke MEMS (IrisAO, MEMEX)
- Design (only) of a 4000 actuator MEMS for 8-10m telescope ExAO
- Above 4000 actuators, new technology is needed (e.g. for ELTs). Can no longer bring wires out the 4 sides of the chip - probably need integrated electronics.
Preliminary tests of Boston machines 1000-actuator MEMS DM look good

- Compare actual displacement with prediction from influence function (Poyneer):
Key CfAO Science Project: CfAO Treasury Survey (CATS)

- Collaborative project started in 2002
  - UCSC, UCLA, UH, Caltech
- Laser guide star AO observations of three very deep fields: GOODS, COSMOS, GEMS
- Ambitious “legacy project” - will take 4-5 years, require >40 nights of observing time at Keck, Gemini and Subaru
- Effective observations require specific developments:
  - Coverage of HST, CHANDRA and SIRTF deep fields requires laser
  - Better knowledge of the PSF and its variation across large fields
  - Address issues of putting AO observations in a meaningful archive
  - AO Integral Field Spectrograph (OSIRIS at Keck)
GEMS Fields (H.W. Rix, et al.)

~30’x30’ Field, to V~27 mag with deep CHANDRA images. SED’s and photometric redshifts for 10,000 galaxies.
Arrow shows 10 kpc at each redshift.

Source: Larkin and Barczys
Extreme AO Theme at the CfAO

- **ExAO Theme Purpose**
  - Development and utilization of AO systems and instrumentation to enable revolutionary ultra-high-contrast astronomical observations.

- **ExAO Theme Primary Objective**
  - Discovery and characterization of extrasolar planets through direct imaging

- **Unique capability for the study of planetary systems and their formation**
CfAO Extreme AO plans for next 5 years

- Concepts, simulations, and conceptual design of an instrument for an 8-10m telescope
- Concepts (only) for extremely large telescope ExAO systems
- High-contrast science
CfAO goal: an ExAO instrument on an 8-10m telescope

- XAOPI instrument approved for further study by Keck Science Steering Committee
- Proposal submitted to Gemini to begin work on an extreme AO instrument and camera
- Co-funding by CfAO (for conceptual work and base technology, e.g. metrology and calibration), and by Lab for Adaptive Optics at UCSC
- Biggest technology challenge: calibration of non-common-path errors
  - Need 1 - 3 nm residual static errors
Work on **ELT** ExAO systems at CfAO?

- **Not** a high priority for the CfAO
  - Our emphasis is on an 8-10m telescope ExAO system

- **Key future ELT ExAO areas not** being funded by CfAO:
  - Design of **realizable** coronagraphs for segmented-mirror telescopes
  - Advanced wavefront sensor technology (e.g. IR and interferometric wavefront sensors for the ExAO regime)
  - MEMS with 16,000 to 100,000 degrees of freedom
    - Move from 8-10m telescope DM to 20-30m telescope DM
High-contrast science with today’s telescopes

- Disks around young stars
- Searches for extrasolar planets at Keck, Gemini
- LGS AO dual-channel polarimetry at Lick:

Perrin et al., SCIENCE 303, 1345 (2004)
New directions that came out of a CfAO retreat two weeks ago

- Emphasis on making current and next generation of laser guide star AO robust, efficient
  - Work out bugs in how AO system interacts with laser guide star
  - Decrease laser problems ("industrial engineering" needed)
  - Decrease amount of manpower needed to run laser and AO system together
  - Ambitious Goal: "Make LGS AO open-shutter time and optical throughput comparable to those of non-AO instruments today"
Add an area that emphasizes robustness and engineering of LGS AO systems and lasers
- Na Lasers: 3 sum-frequency lasers at the breadboard stage (CTI, U Chicago, LLNL), and one fully engineered (Air Force)
- Next step should be engineering for robustness and low mean time between failure, but...
  - I suspect there’s not enough money in either the Gemini South or the Keck procurements to pay for a fully engineered laser system
- In my opinion this is an ideal place for AODP to step in
- Industrial partners with laser engineering experience could be very important
- Issues to be resolved: this is neither pure “research” nor is it “implementation” on a telescope. Do we need a new category?
Systems engineering for AO systems (NGS and LGS)

• PUEO (CFHT curvature system) has the moral equivalent of an “on-off” switch:
  - AO system is run by the astronomer

• A plausible goal for today’s 8-10 m telescopes
  - Few “knobs” visible to astronomer
  - Optimization is behind the scenes
  - Web-based tools for pre-planning
  - Clear understanding of AO PSF
  - “Recipe book” for how to do various kinds of observations

• Robustness of the NGS or LGS AO system needs to be addressed anew, now that we have quite a bit of collective experience under our belts

• Astronomy community needs to learn how to do this from systems engineers
Understand the best way for AO system and laser to interact

- **AO system needed for LGS AO is considerably more complex than for NGS**
  - Separate tip-tilt sensor
  - New focus sensor
  - Wavefront sensor must move to keep LGS in focus
  - Calibration of LGS spot more difficult than for a star
  - Etc etc

- **AO glitches are one of the big causes of down-time for LGS systems**

- **Quite important to understand how to optimize AO design and operation, in view of fact that ELTs will have many lasers**
High-stroke, low-hysteresis deformable mirrors

- Large-diameter telescopes will require more stroke
  - Greater accumulated wavefront error across primary mirror
- Open-loop tomography architectures and ExAO require low hysteresis, high repeatability
- Each DM technology will need to address these in a different way
- One concept is to take out high stroke of low-order modes with a deformable secondary
- Xinetics Photonex technology currently has low stroke
- MEMS and MEMS-driven nano-laminates are harder to build with high stroke, though several groups have made some progress
- Promising concepts will need significant new funding to take from prototype to fieldable technology levels
Design, fabrication, testing of DMs with > 4000 degrees of freedom for ExAO

- Not funded by anyone else
- Beyond natural break-points in most DM technologies
- Example:
  - MEMS DMs with > a few thousand actuators need new architecture
  - Can’t bring wires from all the actuators out the four sides of the chip
  - Need to bond to CMOS electronics beneath each pixel
Other new areas...

- Linear, high dynamic range wavefront sensors
  - For open-loop tomography
- New wavefront sensor concepts for ExAO
- Low-noise IR tip-tilt sensors
  - For MCAO, MOAO
- Calibration methods and systems that take out non-common-path errors to high accuracy
  - For both ExAO and open-loop tomography
- Design of realizable coronagraphs for segmented-mirror telescopes
- Advanced wavefront sensor technology (e.g. IR and interferometric wavefront sensors for the ExAO regime)
My biggest worry is...

- We need to provide sufficient funding to take hardware from the prototype stage to a fully engineered component or system

- Could be done either by AODP or by individual telescope projects
  - But to date, individual telescope projects have not had access to sufficient funds to do a good job of finishing the engineering
  - Example: new Gemini and Keck lasers

- I believe AODP must take the lead in assuring that this engineering step gets done
  - Either by doing it itself, or by actively working with the various telescope projects to coordinate investments and add funding where appropriate