Adaptive Optics for High contrast imaging

“Extreme-AO”

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High contrast AO example
Coronagraphs can now be built to deliver $>1\times10^8$ contrast

PIAACMC lab performance @ WFIRST pupil (Kern et al. 2016)

Operates at $1\times10^{-8}$ to $1\times10^{-7}$ contrast, 1.3 I/D IWA
Visible light

non-coronagraphic PSF
Remapped pupil
Coronagraphic image
The REAL challenge: Wavefront error (speckles)

What is a speckle? What is a planet?
Astronomical AO system diversity: Field of view vs. Wavefront error

- Narrow field LGS in near-IR
- Narrow field NGS in near-IR
- "Low order AO"
- Laser Tomography AO (LTAO)
- Multi Conjugate AO (MCAO)
- Multi Object AO (MOAO)
- Ground-layer AO

Wavefront Error (nm)

Field of view

- 10 nm
- 100 nm
- 10" (1 guide star OK)

- AO loop speed
- Optics size, optical layout complexity
- Need more photons

Easy

Challenging
D=8m telescope
High contrast imaging at 1.6 μm
Wavefront sensing at 0.8 μm
30% efficiency WFS
40% wide WFS spectral band
1 kHz WFS frame rate
Integrator controller with optimal gain setting
Wind speed = 8 m/s
Fried parameter $r_0 = 0.15$ m at 0.5 μm
$m_I = 8$ target
SHWFSm 15cm subapertures
Zenith angle = 40 deg
Aliasing and readout noise ignored

Contrast Error Budget
(Primary WFC)
Temporal lag and WFS photon noise dominate

→ need fast loop
→ need efficient WFS (not a SHWFS !)
→ predictive control
Contrast Error Budget
(Primary WFC)

Chromatic terms in atmospheric OPD
→ need WFS at/near science band

Raw Contrast Terms in ExAO High Contrast Imaging

- Uncorrected Scintillation [CP_UAMP]
- Residual phase correction error - WFS photon noise [CP_OPHN]
- Residual phase correction error - Temporal error [CP_OTEM]
- Residual amplitude correction error - WFS photon noise [CP_APHN]
- Residual amplitude correction error - Temporal error [CP_ATEM]
- Chromatic OPD - Multiplicative refractivity [CC_OMUL]
- Chromatic amplitude - Multiplicative refractivity [CC_AMUL]
- Chromatic OPD - Fresnel propagation [CC_OPRO]
- Chromatic amplitude - Fresnel propagation [CC_APRO]
- Chromatic OPD - refractive light path [CC_ORPA]
- Chromatic amplitude - refractive light path [CC_ARPA]
Contrast Error Budget
(Primary WFC)

Scintillation

→ need amplitude measurement
.. or
→ need focal plane (speckle) control

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Angular separation [arcsec]

Log10(Raw Contrast)
Wavefront Control: challenges & solutions

**WFS efficiency**
M stars are not very bright for ExAO → need high efficiency WFS
For low-order modes (TT), seeing-limited (SHWFS) requires $(D/r_0)^2$ times more light than diffraction-limited WFS
This is a **40,000x gain for 30m telescope** (assuming $r_0=15$ cm) → 11.5 mag gain

**Low latency WFC**
System lag is extremely problematic → creates “ghost” slow speckles that last crossing time
Need ~200us latency (10 kHz system, or slower system + lag compensation), or multiple loops

**WF chromaticity**
Wavefront chromaticity is a serious concern when working at ~1e-8 contrast
Visible light (~0.6 – 0.8 um) photon carry most of the WF information, but science is in near-IR

**Non-common path errors**
It doesn't take much to create a 1e-8 speckle !

**PSF calibration**
What is a speckle, what is a planet ?

**Diffraction-limited pupil-plane WFS**
Low or no modulation PyWFS is diffraction-limited
This is a **40,000x gain for 30m telescope** (assuming $r_0=15$ cm) → 11.5 mag gain

**Fast WFC loop**
Fast hardware (Cameras, GPUs) can now run loop at ~5 kHz on ELT
Example: SCExAO runs 2000 actuators, 14,400 sensors at 3.5kHz using ~10% of available RTS computing power

**Predictive Control**
Eliminates time lag, improves sensitivity

**Fast speckle control, enabled by new detector technologies**
Addresses simultaneously non-common path errors, (most of) lag error, chromaticity, and calibration

**Real-time telemetry → PSF calibration**
WFS telemetry tells us where speckles are → significant gain using telemetry into post-processing

**Spectral discrimination (HR)**
Especially powerful at high spectral resolution
ExAO system architecture

New systems include secondary WFC loop (WFS performed within and after coronagraph)

Science camera(s)
Can perform:
- Imaging
- Spectroscopy
- Polarimetry

Post-Coronagraphic WFS
(usually focal plane WFS)
Example system architecture with instrumentation

**INSTRUMENTATION**

- **Thermal IR**
  - Imaging & spectroscopy

- **Visible light**
  - Imaging, spectroscopy, polarimetry, coronagraphy

- **Near-IR**
  - Imaging, spectroscopy, polarimetry

- **Woofer DM**
  - ~2 kHz speed
  - 120 x 120 actuators
  - Delivers visible diffraction-limited PSF to visible WFS

- **Tweeter DM**
  - 10 kHz response
  - 50x50 actuators
  - Provides high contrast

- **Low-IWA coronagraph**
  - **High efficiency**
  - Speckle control afterburner WFS
  - Speed ~kHz
  - Photon-counting detector

- **Coronagraphic Low-order WFS**
  - Uses light rejected by coronagraph
  - Catches aberrations BEFORE they hurt contrast
  - Stellar leakage derived from telemetry

- **Visible light low-latency WFS**
  - Diffraction limited sensitivity

- **WFS pointing**

- **TT, focus?**

**High-res spectroscopy can detect molecular species and separate speckles from planet spectra**
Extreme-AO ground-based system

4 wavefront sensors:
- Coarse correction (visible WFS)
- Extreme-AO (visible pyramid)
- Low-order (near-IR)
- Speckles (near-IR)

3 deformable mirrors:
- 188 element bimorph
- 2000 element MEMs
- 37 segments MEMs
Managing Chromaticity: TipTilt and Low Orders

Near-IR low-order coronagraphic WFC
(Singh et al. 2015+)

Closed loop atmospheric dispersion compensation
(Pathak et al. 2016, 2017)
High Speed Speckle Control & Calibration

Uncalibrated image

Sum

Unknown planet light (incoherent)

Unknown Speckle field (coherent)
High Speed Speckle Control & Calibration

Uncalibrated image

Sum

Unknown planet light (incoherent)

Unknown Speckle field (coherent)

Fast DM modulation

Fast focal plane images

Speckle SENSING

Known Speckle field (coherent)
Coherent Speckle Differential Imaging

(a) Pupil amplitude, DM probe #0, DM probe #1, DM probe #2, DM probe #3, DM probe #4

(b) Real → Imaginary

(c) Normalized intensity

Real → Imaginary
High Speed Speckle Control & Calibration

Uncalibrated image

Sum

Fast DM modulation

Fast focal plane images

Unknown planet light (incoherent)

Unknown Speckle field (coherent)

Known Speckle field (coherent)

Speckle SENSING

Speckle NULLING
Speckle Control

Speckle nulling, in the lab and on-sky (no XAO).

Experience limited by detector readout noise and speed.

KERNEL project: C-RED-ONE camera.

From:
- 114 e- RON
- 170 Hz frame rate

To:
- 0.8 e- RON
- 3500 Hz frame rate

Expect some updates
High Speed Speckle Control & Calibration

**COHERENT DIFFERENTIAL IMAGING**

- **Uncalibrated image**
  - **Sum**
  - **Fast DM modulation**
  - **Fast focal plane images**

**Speckle SENSING**

- **Unknown planet light (incoherent)**
- **Unknown Speckle field (coherent)**

**Speckle NULLING**

- **Calibrated image (incoherent planet light)**
- **Known Speckle field (coherent)**
Coherent Speckle Differential Imaging
Coherent Speckle Differential Imaging
Linear Dark Field Control (LDFC)

Speckle intensity in the DF are a non-linear function of wavefront errors → current wavefront control technique uses several images (each obtained with a different DM shape) and a non-linear reconstruction algorithm (for example, Electric Field Conjugation – EFC)

Speckle intensity in the BF are linearly coupled to wavefront errors → we have developed a new control scheme using BF light to freeze the wavefront and therefore prevent light from appearing inside the DF
Predictive control & sensor fusion → 100x contrast gain?

See also: Males & Guyon 2017 (astro-ph)

**Fig. 3.**—Top left: 2D-tracks for true pointing (red), predicted pointing (blue) and last measured position (green). Top right: Residual pointing error. Bottom: Single axis (x) values.
Differential Detection Techniques

**Angular Differential Imaging (ADI)**
Does not address noise limit from slow speckles

**Spectral Differential Imaging (SDI) (low spectral resolution)**
Limited by chromaticity in speckles

**High Resolution Spectroscopy (Snellen et al., Mawet et al.)**
Very clean signal (narrow lines) not present in starlight
But few % of planet light used → photon noise (from starlight) limits use
(See Wang et al. 2017)

**Polarization Differential Imaging**
Polarized light fraction is small (<10% ?)
→ photon noise (from starlight) limits use

**Coherent Differential Imaging**
Can use 100% of light
Challenging to implement, calibration issues