SCExAO: Combining high speed, high sensitivity wavefront control and low inner working angle coronagraphy


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Subaru Coronagraphic Extreme AO (SCExAO)

AO188 - Facility AO
30% Strehl in H-band

Telescope

AO188 - Facility AO
30% Strehl in H-band

SCExAO

HiCIAO

High contrast imaging instrument optimized for very small inner working angle (1 λ/D)

Uses advanced technologies, continuously evolves to take advantage of new concepts, detectors etc...

Prototype for ELT habitable planets spectroscopic characterizer
→ visitor instrument on TMT
Reflected light Earth-sized planets with ELTs

1 Re rocky planets in HZ for stars within 30pc (6041 stars)

Angular separation (log10 arcsec)

Log Separation [arcsec]

Log Contrast

log10 contrast

Log Contrast max

log SNR max

1hr SNR cut off

Telescope

Coronagraph Instrument

Sources

You can “play” with this tool:
www.naoj.org/staff/guyon
→ Research
→ Imaging habitable planets with ELTs
→ Input Catalog
3D viewing tool (bottom of page)
Wavefront sensing:
- Non-modulated pyramid WFS (VIS)
- Coronagraphic low order wavefront sensor (IR) for non-common tip/tilt errors
- Near-IR speckle control

2k MEMS DM

Numerous coronagraphs – PIAA, Vector Vortex, 4QPM, 8OPM, shaped pupil (IR)

Visible Aperture Masking Polarimetric Interferometer for Resolving Exoplanetary Signatures (VAMPIRES) (VIS)

Fibered Imager for a Single Telescope (FIRST) (VIS) Fourier Lucky imaging (VIS)

Broadband diffraction limited internal cal. Source + phase turbulence simulator
SCExAO visible bench →

SCExAO near-IR bench
SCExAO: wavefront control loop

**Extreme-AO LOOP**
- High speed pyramid wavefront sensor
  - Measures aberrations
- 3.7 kHz

**CORONAGRAPHIC LOW ORDER LOOP**
- Near-IR camera
  - Measures low-order aberrations
- 10-200 Hz
- 800 – 1350 nm (rejected by coronagraph)
- ~2 kHz

**SPECKLE CONTROL LOOP**
- MKIDs camera
  - Measures residual starlight
- 800 – 2500 nm

**Facility Adaptive Optics system**
- Sharpens image
- 2000 actuator Deformable mirror
- 800nm
- >800nm

**CHARIS spectrograph**
- Exoplanet spectra
- Slow speckle calibration
- 1350 – 2500 nm
Facility Adaptive Optics system

Sharpens image

High speed pyramid wavefront sensor

Measures aberrations

3.7 kHz

<800 nm

>800 nm

Extreme-AO LOOP

2000 actuator Deformable mirror

CORONAGRAPHIC LOW ORDER LOOP

Near-IR camera

Measures low-order aberrations

10-200 Hz

800 – 1350 nm

800 – 2500 nm (rejected by coronagraph)

SPECKLE CONTROL LOOP

MKIDs camera

Measures residual starlight

800 – 1350 nm

1350 – 2500 nm

CHARIS spectrograph

Exoplanet spectra

Slow speckle calibration

Currently available

End CY 2016

End CY 2016
How SCExAO achieves high contrast

(1) Small IWA, high throughput Coronagraphy
→ removes diffraction (Airy rings), transmits $r>1$ l/D region

(2) Extreme-AO with fast diffraction-limited WFS
→ removes wavefront errors

(3) Near-IR LOWFS
→ keeps star centered on coronagraph and controls Focus, Astig, etc..
→ records residual WF errors to help process data

(4) Fast Near-IR Speckle control
→ modulates, removes and calibrates residual speckles
Coronagraphy

SCExAO's coronagraphs (PIAACMC, Vector Vortex) offer ~1 I/D IWA and high throughput

New coronagraphs can reach 1-2 I/D IWA at ~1e-7 raw contrast in nearIR... on almost any pupil (compared to ~1e-3 at best on today's best ExAO systems)

![Image](image.png)

- <1e-9 contrast monochromatic
- 1e-8 contrast in 10% band

2-4 I/D dark hole, high system throughput
PIAA testbed at NASA JPL
lab results demonstrate PIAA's high efficiency and small IWA (B. Kern, O. Guyon et al.)
→ now moving to PIAACMC
Pupil Plane

PIAACMC lens 1 front surface (CaF2)

PIAACMC lens 2 front surface (CaF2)

PSF at 1600nm
3e-9 contrast in 1.2-8 I/D
80% off-axis throughput
1.2 I/D IWA
CaF2 lenses SiO2 mask
**Extreme-AO loop**

**Pyramid WFS**
Pyramid optical element with sharp apex (5 um)
Spare from MagAO system (loan, to be replaced by custom dual roof prism assembly)

**Detector: Ocam2k**
Deep depletion EMCCD, 120x120 (binned), 3.7 kHz frame rate, photon-counting

**Can run with or without modulation:**
- PZT tip-tilt mirror for modulation, amplitude selectable
- on-the-fly control matrix change for bootstrapping from modulation to no modulation
- Full image is multiplied by control matrix to include light diffracted by pyramid apex (14400 x 2000 matrix)

WFS operates in diffraction limited mode

Highly sensitive
\[ (D/r_0)^2 \] gain for TT over seeing-limited WFS

Excellent closed loop performance
Real time control processes: CPU threads + GPUs (optional)  
Heavy use of standardized shared memory image structure. Same code for LOWFS  
Easy to add processes (monitoring, viewing, data logging, multiple loops offloads)  
[ code available at https://github.com/oguyon/AdaptiveOpticsControl ]
Extreme-AO results (Apr 9, 2015)

1205 modes corrected at 3.5kHz using 2000 act DM (1600 illuminated)
deep depletion EMCCD, 240x240 pix (binned to 120x120 to run faster)
EM gain = 600 on faint stars → true photon-counting

System can switch control matrix on-the-fly → bootstrapping between modulation
and no modulation
Full image multiplied by control matrix → uses diffraction features

*Image (left)*:
Single image of a diffraction limited PSF at 775 nm

PyWFS works at diffraction-limited sensitivity
... down to $I$ mag $\sim$ 10 (to be confirmed with further observations)
Enhanced visible light science capabilities

- Imaging
- Differential polarimetric interferometry (VAMPIRES)
- Spectro-interferometry (FIRST)

Example science result VAMPIRES without Extreme-AO

Visible light diffraction limit greatly enhances FIRST and VAMPIRES science capabilities, and ability to achieve high precision on “faint” targets (I mag ~ 10)
8m: Seeing-limited WFS ExAO system

Limited by residual OPD errors: time lag + WFS noise
kHz loop (no benefit from running faster)
>10kph per WFS required

Detection limit $\sim 1e^{-3}$ at IWA, $\sim 1e^{-4}$ at 0.2"

Assumptions:

I mag = 8  (WFS > 100 targets)
H mag = 6  (Science)

Noiseless detector
1.3 I/D IWA coronagraph
30% system efficiency
40% bandwidth in both WFS and science
Time lag = 1.5 WFS frames

Mauna Kea “median” atmosphere
8m: Diffraction limited WFS system

Assumptions:
- $I_{mag} = 8$ (WFS > 100 targets)
- $H_{mag} = 6$ (Science)
- Noiseless detector
- 1.3 I/D IWA coronagraph
- 30% system efficiency
- 40% bandwidth in both WFS and science
- Time lag = 1.5 WFS frames
- Mauna Kea “median” atmosphere

More sensitive WFS, can run faster (10kHz)
Limited by atmosphere chromaticity

Detection limit $\sim 1e^{-4}$ at 2 I/D
300Hz speckle control loop (~1kHz frame rate) is optimal

Residual speckle at ~5e-5 contrast and fast → good averaging to detection limit at ~1e-7
... and better for brighter stars

Assumptions:

I mag = 8  (WFS > 100 targets)
H mag = 6  (Science)
Noiseless detector
1.3 I/D IWA coronagraph
30% system efficiency
40% bandwidth in both WFS and science
Time lag = 1.5 WFS frames

Mauna Kea “median” atmosphere
300Hz speckle control loop (~1kHz frame rate) is optimal

Residual speckle at ∼1e-6 contrast and fast → good averaging to detection limit at ∼1e-8
MKIDs camera (CY 2016)

Build by UC Santa Barbara for SCExAO

NearIR photon counting with wavelength resolution
→ broadband light can be used for speckle control

DM state updates issued from few ph/speckle at kHz speed
Speckle control results on-sky (June 2014)

Date: June 2nd
Target: RX Boo (also repeated on Vega)
Seeing: <0.6"
No Coronagraph

Single frames: 50 us

Sum of 5000 frames: shift and add
SAPHIRA Infrared APD array (S. Goebel PhD) [ University of Hawaii IfA ]

HgCdTe avalanche photodiode manufactured by SELEX

Specifications
320 x 256 x 24μm
32 outputs
5 MHz/Pix
Astrometric + photometric calibration (Jovanovic et al. 2015)
Atmospheric Dispersion: real-time measurement & correction + water absorption/RI measurement (P. Pathak PhD)
LLOWFS: Laboratory & On-sky

Note: Simulated dynamic turbulence with amplitude: 100 nm rms and wind speed: 10 m/s is applied upstream of the coronagraph with the Laboratory experiments.

Response Matrix obtained by applying phasemaps of respective modes with amplitude of 60 nm rms onto the DM.

Residuals

Laboratory & On-sky

Laboratory experiments (a) Reference, (ii) Tip, (iii) Tilt, (iv) Focus, (v) Oblique Astigmatism, (vi) Right Astigmatism

On-sky experiments (a) Reference, (ii) Tip, (iii) Tilt, (iv) Focus

Response Matrix
Vibrations: currently ~mas level

HiCIAO upgrade (2014) →

Measured residual vibration in nearIR

2 mas residual near transit (due to telescope mount encoders)

[See Lozi et al. poster]
Conclusions

SCExAO available for use on Subaru → you can apply for time
check website (www.naoj.org → Instruments → SCExAO) for current status and capabilities / available modes

Current and future major activities in next 2 yr:

Hardware:
- MKIDs (2016)
- CHARIS IFS (2016)

Control & Software:
- Integrating speckle control loop with Pyramid and LOWFS loops
- Including predictive control in control loops
- Including WFS telemetry in data processing (real-time estimation of coronagraph leaks and coherent light PSF features)

SCExAO as a visitor instrument on TMT: Preparing scientific and technical plan
Top priority: demonstrating on Subaru on-sky performance corresponding to habitable planet imaging on TMT

Other presentations:
N. Jovanovic (current status)  J. Lozi (LOWFS, jitter control)
J. Kuhn (Vector Vortex)  E. Huby (FIRST module)
T. Groff (CHARIS IFS)  T. Currie (early science)
J. Hagelberg (early science)