Subaru Coronagraphic Extreme Adaptive Optics (SCExAO): Wavefront Control Optimized for High Contrast Imaging

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SPIE, Aug 9, 2017
Flexible high contrast imaging platform (Nas port)

- Meant to evolve to TMT instrument and validate key technologies required for direct imaging and spectroscopy of habitable exoplanets

Telescope time available to US community (Keck & Gemini time exchange) and non-US through collaborations with team

Modules/instruments funded by Japan + international partners:
- MKIDS IFU built by Princeton Univ (Japan-funded)
- MKIDs built by UCSC (Japan-funded)
- SAPHIRA camera provided by UH
- VAMPIRES instrument funded and built by Australia
- FIRST instrument funded and built by Europe
- RHEA IFU provided by Australian team

Strong research collaborations with multiple groups:
- Univ. of Arizona / MagAO(-X) (shared dev., wavefront control, coronagraphy)
- Kernel group @ Observatoire de la Cote d'Azur (wavefront control)
- Leiden Univ, JPL (coronagraphy)
- Northwestern Univ (detector dev)
- Univ. of Sydney (Photonics techs, nulling interferometry)
- Keck (near-IR WFS)
Contrast and Angular separation

1 \( \lambda / D \) = 1600 nm

D = 8 m

1 \( \lambda / D \) = 1600 nm
D = 30 m

1 \( \lambda / D \) = 10000 nm
D = 30 m

Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired [ assumes 1e-8 contrast limit, 1 \( I / D \) IWA ]

K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to \(~1e^{-7}\) (models tell us it's possible)

Thermal emission from habitable planets around nearby A, F, G type stars is detectable with ELTs

1 \( Re \) rocky planets in HZ for stars within 30pc (6041 stars)
SCExAO
Subaru Coronagraphic Extreme Adaptive Optics
Fiber-fed instruments (not visible here):
- RHEA (visible IFU, R=70,000)
- IRD (near-IR spectrograph, R=70,000)
+ experimental photonics spectro
SCExAO Light path

Facility AO
[yr 2020 configuration shown here]
Under heavy development:
Currently curvature WFS, 188 elements
Ongoing upgrade to high performance RTS, new WFSs and DM

Active WF correction
Dedicated WFS
Visitor port
Mixed science/WFS

Dedicated science instrument

ADC
64x64 DM
2 kHz

2-5um IFU
Modulated Visible PyWFS
0.4-1.0 um

Weakly/un-modulated NearIR PyWFS
0.8-2.0 um

BEAM SWITCHER

50x50 DM
3.5 kHz

Weakly/un-modulated Visible PyWFS
0.6-1.0 um

VAMPIRES (2 cameras)
Polarimetry
Dual band
Aperture masking

FIRST
Polarimetry
Interferometry

RHEA
visible IFU

Coronagraph

Photonic nuller

IRD
1-1.7 um HR spectrograph

MKIDS
focal plane WFS

SAPHIRA
Imager

111 DM segmented

Coronagraphic LOWFS
Subaru Coronagraphic Extreme Adaptive Optics
Wavefront Control loops

VAMPIRES (2 cameras)
- Polarimetry
- Dual band
- Aperture masking

CHARIS
- nearIR IFU
- FIRST
- Polarimetry Interferometry

MKIDS
- focal plane
- WFS
- Weakly/un-modulated
- NearIR PyWFS
- 0.8-2.0 um

FIRST
- Polarimetry
- Interferometry

Modulated Visible PyWFS
- 0.4-1.0 um

Weakly/un-modulated Visible PyWFS
- 0.6-1.0 um

coronagraphic LOWFS

VAMPIRES (2 cameras)
- Polarimetry
- Dual band
- Aperture masking

SAPHIRA Imager

Polarimetry
- Dual band
- Aperture masking

MKIDS focal plane
- WFS

Sci path viewing cam

FIRST
- Polarimetry
- Interferometry

Photonic nuller

LOWFS

Sci path viewing cam

64x64 DM
- 2 kHz

50x50 DM
- 3.5 kHz

6 kHz modulation

Open loop control

Linear, pupil plane

Linear

Fast focal plane WF control (non linear)

Linear (LDFC)

ADC
- 1 Hz

64x64 DM
- 2 kHz

Fast DM modulation
SCExAO Light path

Facility AO

ADC
1 Hz

64x64 DM
2 kHz

Modulated
Visible PyWFS
0.4-1.0 um

Weakly/un-modulated
NearIR PyWFS
0.8-2.0 um

2-5um IFU

2-5um imager/spectro (IRCS)

BEAM SWITCHER

50x50 DM
3.5 kHz

Weakly/un-modulated
Visible PyWFS
0.4-1.0 um

VAMPIRES (2 cameras)
Polarimetry
Dual band
Aperture masking

First
Polarimetry
Interferometry

RHEA
visible IFU

Coronagraph

Photonic
nuller

IRD
1-2 um HR spectrograph

Sci path
viewing cam

Facility AO

Dedicated WFS

Visitor port
dichroic
beam switch

Mixed science/WFS

Active WF correction

Dedicated science instrument

Coronagraphic
LOWFS

First
Polarimetry
Interferometry

RHEA
visible IFU

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Coronagraphic
LOWFS
Preliminary VAMPIRES science
Diffraction-limited imaging in visible light

Summed image

750nm, 1kHz imaging
log scale

Video
Current PSF stability @ SCExAO

Stable PSF for coronagraphy
SCExAO provides sensing and correction at 500 Hz - 3.5 kHz
14,400 pixel WFS → 2000 actuators

1630nm (SCExAO internal camera)
3 Hz sampling
SCExAO Light path

Facility AO

ADC 1 Hz
64x64 DM 2 kHz
Modulated Visible PyWFS 0.4-1.0 um
Weakly/un-modulated NearIR PyWFS 0.8-2.0 um

2-5um IFU
2-5um imager/spectro (IRCS)

50x50 DM 3.5 kHz
Coronograph

VAMPIRES (2 cameras)
Polarimetry Dual band Aperture masking

111 DM segmented
FIRST Polarimetry Interferometry

RHEA visible IFU

Photonic nuller
IRD 1-2 um HR spectrograph

MKIDS focal plane WFS
CHARIS nearIR IFU

coronagraphic LOWFS

Sci path viewing cam.

SAPHIRA Imager

Active WF correction
Dedicated WFS
Visitor port
Mixed science/WFS
dichroic
beam switch
SAPHIRA camera

1.68 kHz frame rate, H-band
(played at 90 Hz)
SCExAO PyWFS ON → OFF
HR8799 Observations by J. Chilcote & T. Groff
preliminary data processing by T. Brandt

\( \lambda = 1.93 \, \mu m \)
SCExAO Light path

Facility AO

- Active WF correction
- Dedicated science instrument
- Mixed science/WFS

Dedicated WFS

Visitor port
- dichroic
- beam switch

ADC 1 Hz

BEAM SWITCHER

64x64 DM 2 kHz

Modulated Visible PyWFS 0.4-1.0 μm

Weakly/unmodulated NearIR PyWFS 0.8-2.0 μm

2-5μm IFU

2-5μm imager/spectro (IRCS)

50x50 DM 3.5 kHz

Weakly/unmodulated Visible PyWFS 0.6-1.0 μm

VAMPIRES (2 cameras)
Polarimetry
Dual band
Aperture masking

111 DM segmented

FIRST
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Interferometry

RHEA visible IFU

Photonic nuller

IRD 1-2 um HR spectrograph

MKIDS focal plane WFS

SAPHIRA Imager

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Coronagraph

Coronagraphic LOWFS

CHARIS nearIR IFU

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IFU 2-5μm

BEAM SWCHER

Facility AO

ADC 1 Hz

64x64 DM 2 kHz

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Coronagraph

Coronagraphic LOWFS

CHARIS nearIR IFU

Active WF correction

IFU 2-5μm
MKIDS camera (built by UCSB for SCExAO)
Phonon-counting, wavelength resolving 140x140 pixel camera

Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

Delivery to SCExAO in sept 2017
Building community RTC / Software Ecosystem to support WFC development

**Provide low-latency to run control loops**
→ Use mixed CPU & GPU resources, configured to RTC computer system
On SCExAO, control matrix is 14,000 x 2000. Matrix-vector computed in 100us using 15% of RTC resources @ 3kHz

**Portable, open source, modular, COTS hardware**
→ No closed-source driver
→ std Linux install (no need for real-time OS)
→ using NVIDIA GPUs, also working on FPGA use
→ All code on github: [https://github.com/oguyon/AdaptiveOpticsControl](https://github.com/oguyon/AdaptiveOpticsControl)

**Easy for collaborators to improve/add processes**
→ Hooks to data streams in Python or C
→ Template code, easy to adapt and implement new algorithms
→ Provide abstraction of link between loops
→ Toolkit includes viewers, data logger, low-latency TCP transfer of streams

RTC code used at Keck, MagAO-X, OCA ...
→ community support and development
Collaboration with OCA: speckle

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
OCA/KERNEL – developed software

- Address NCPA
- Asymmetric mask (pupil)
- On-sky closed-loop control
- Focal plane based WFS
  Low-order (Zernike and LWE) modes.
- mode compatible with coronagraphy in development
Measuring system response matrix at 3kHz

Full speed DM modulation to measure response matrix
DM motion occurs during EMCCD frame transfer
2000 modes measured in 1.33 sec @ 3kHz, 2sec @ 2kHz. Multiple cycles averaged to build up SNR
Coherent Speckle Differential Imaging
Linear Dark Field Control (LDFC)
See also: Miller et al. 2017, Guyon et al. 2017 (astro-ph)

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

Intensity of speckles outside geometric DF is a linear function of wavefront errors
dark field (DF) speckles
Intensity of speckles outside spectral range is a linear function of wavefront errors

HCIT PIAA images

770 nm 790 nm 810 nm 830 nm
avg = 760-840 nm

high contrast spectral range
Using SCExAO instrument

← slack channel to coordinate instrument use over multiple continents
Conclusions

SCExAO is a flexible platform for testing and deploying new techniques (hardware, algorithms).
Allows for smooth evolution from Daytime testing with internal source to nighttime on-sky validation

Coordinated development with MagAO-X (→ GMT), Keck (→ TMT), SPHERE upgrades (→ ELT), + fundamental research in WFC for space missions

Major ongoing effort to develop software ecosystem to facilitate algorithm development and test across observatories/instruments/labs.

Multiple opportunities to get involved:
Test algorithms, reduce data, new hardware, looking for exoplanets, cool project for postdoc fellowship?
→ talk to us
Backup slides
Data Stream Format

Uses file-mapped POSIX shared memory → multiple processes have access to data

Supports low latency IPC through semaphores → us-level latency

Drivers written for:
OCAM2k, BMC DM, SAPHIRA camera, InGaAs cameras
Data flow from WFS to DM

WFS image → WFS modes pixels → modes

Telemetry

Extract Open Loop WFS modes [aol#meol] in aol#RT
runs in AoloopControl, CPU

Extract WFS modes [aol#mexwfs] in aol#RT
auxscripts/modesextractwfs
GPU or CPU

Main process [aol#run] in aol#RT
script auxscripts/aolrun
CPU (+ GPU)

Zonal DM only

Modal DM only

WFS modes pixels → modes

if modal

Direct DM Write → actuators

if DMprimaryWrite_ON

Current modal DM correction
aol#_modeval_dm_now

Current modal DM correction, filtered
aol#_modeval_dm_now_filt

DM map (test) script aolPFcoeffs2dmmap
GPU or CPU

Modal filtering (clipping)

Predictive Filter

Predicted mode coefficients
aol#_modevalPF

Predicted mode coefficients
aol#_modevalPFb0

Predictive filter compute [aol#PFb0comp]

Predictive filter block input watch
[aol#PFb0watchin]

Predictive filter engine [aol#PFb0apply] in aol#RT

Predicted mode coefficients
open loop = WFS residual – dm
Wfresidual = Open loop WF + dm
dm = Wfresidual – open loop

DM Primary Write

DM “actuators”

Note: DM map & coefficients show correction applied
→ open loop = WFS residual – dm
→ Wfresidual = Open loop WF + dm
→ dm = Wfresidual – open loop

gain[m] = loopgain * gainMB[block] * aol#_DMmode_GAIN[m]
mult[m] = loopmult * multfMB[block] * aol#_DMmode_MULT[m]
limit[m] = limitMB[block] * aol#_DMmode_LIMIT[m]
**Hardware Latency measured on SCExAO**

**Definition:**
Time offset between *DM command issued*, and mid-point between 2 consecutive WFS frames with largest difference

Hardware Latency measured hardware latencies:

- 1 kHz: 1253 / 1260/ 1269 → 1261 us
- 1.5 kHz: 1083 / 1065/ 1081 → 1076 us
- 2 kHz: 987 / 982 / 985 → 985 us
- 2.5 kHz: 922 / 921 / 926 → 923 us
- 3 kHz: 881 / 876 / 884 → 880 us

difference 2kHz - 3kHz = 105 us
expected difference = (1/2000-1/3000)/2 = 83 us
→ 22us discrepancy

difference 1kHz - 3kHz = 361 us
expected difference = (1/1000-1/3000)/2 = 333 us
→ 28us discrepancy

Add DM channels 15 us
Displ → voltage 13 us
DM volt process & send 80 us
DM comm and electronics 150 us
DM physical latency 45 us

Measured DM motion time = 87.5us

Half camera exposure - dt

Hardware Latency = DM soft + DM elec + DM phys + CAM readout/transfer + CAM processing + ½ exposure time
Hardware Latency = N x cam_exposure + dt
Hardware Latency measured on SCExAO

Total jitter <20us RMS = 6% of loop iteration @ 3kHz
(Camera readout + TCP transfer + processing + DM electronics)
Max jitter <40us

+/- 25us lines
Synchronizing camera stream to DM (170 Hz)

6kHz DM modulation swaps between 2 diag patterns
Linking multiple control loops (zero point offsetting)

A control loop can offset the convergence point of another loop @> kHz (GPU or CPU)
Example: speckle control, LOWFS need to offset pyramid control loop
THIS IS DONE TRANSPARENTLY FOR USER → don't pay attention to the diagram below!

OFFSETTING
LOWFS (loop #1, dm01) → PyWFS (loop #0, dm00)
Green color: process is part of loop #1
The REAL challenge: Wavefront error (speckles)

H-band fast frame imaging (1.6 kHz)
Habitable Zones within 5 pc (16 ly)

Star Temperature [K]

Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)
PREVIOUS technologies

30m: SH-based system, 15cm subapertures

Limited by residual OPD errors: time lag + WFS noise
kHz loop (no benefit from running faster) – same speed as 8m telescope
>10kph per WFS required

Detection limit ~1e-3 at IWA, POOR AVERAGING due to crossing time

Expected limit

Need 3 orders of magnitude improvement in contrast to reach habitable planets
CURRENT/NEW technologies

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

Assumes:
- high-sensitivity WFS
- speckle control

Does not take into account:
HR spectral calibration
Predictive control

Expected limit

hab planets
High Speed Speckle Control & Calibration

- Uncalibrated image
  - Sum
  - Unknown planet light (incoherent)
  - Unknown Speckle field (coherent)

- Fast DM modulation
- Fast focal plane images

- Calibrated image (incoherent planet light)

- Speckle SENSING
- Specle NULLLING

- COHERENT DIFFERENTIAL IMAGING
- subtract
- Known Speckle field (coherent)
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 \((D/r0)^2\) times more light than diffraction-limited WFS
This is a **40,000x gain for 30m telescope** (assuming \(r0=15\) 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 \(r0=15\) 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
Predictive control & sensor fusion $\rightarrow$ 100x contrast gain?

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

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**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.