SCExAO as a prototype platform available to the GSMT extreme-AO community

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Contrast and Angular separation

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

K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to \( \sim 1e^{-7} \) (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)
The REAL challenge: Wavefront error (speckles)

H-band fast frame imaging (1.6 kHz)
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

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
**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 $r0=15cm$) → 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 $r0=15cm$) → 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
High Speed Speckle Control & Calibration

Uncalibrated image

Sum

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

Fast DM modulation
Fast focal plane images

COHERENT DIFFERENTIAL IMAGING

subtract

Calibrated image (incoherent planet light)

Speckle SENSING

Known Speckle field (coherent)

Speckle NULLLING
Coherent Speckle Differential Imaging

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

(c) Normalized intensity

(d) Probe imaginary component, Probe real component
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
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.
Key technologies need rapid maturation from paper concepts to system integration

- High performance coronagraphy
- Multi-lambda WFS
- Diffraction-limited WFS
- Coronagraphic LOWFS
- Atmospheric speckle control
- Optimal predictive control
- Real-time WFS → PSF calibration
- Coherent differential imaging
- High spectral R template matching
- Linear Dark Field Control
• **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:
• CHARIS IFU built by Princeton Univ (Japan-funded)
• MKIDs built by UCSB (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)
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

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)

Weakly/un-modulated Visible PyWFS
0.6-1.0 um

BEAM SWITCHER

50x50 DM
3.5 kHz

Coronagraph

Photonic nuller

IRD
1-2 um HR spectrograph

Sci path viewing cam

VAMPIRES (2 cameras)
Polarimetry
Dual band
Aperture masking

RHEA visible IFU

FIRST Polarimetry Interferometry

coronagraphic LOWFS

CHARIS nearIR IFU

MKIDS focal plane WFS

SAPHIRA Imager

Active WF correction

Dedicated WFS

Visitor port

dichroic
beam switch

Dedicated science instrument

Mixed science/WFS
Subaru Coronagraphic Extreme Adaptive Optics
Control loops

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

- **CHARIS nearIR IFU**
  - FIRST Polarimetry Interferometry
  - Modulated Visible PyWFS 0.4-1.0 um
  - Weakly/un-modulated NearIR PyWFS 0.8-2.0 um
  - coronaographic LOWFS

- **MKIDS focal plane WFS**
  - Sci path viewing cam
  - Calibration speckles

- **64x64 DM 2 kHz**
- **50x50 DM 3.5 kHz**

- **FIRST**
  - Polarimetry Interferometry
  - Photonic nuller
  - Weakly/un-modulated Visible PyWFS 0.6-1.0 um

- **SAPHIRA Imager**
  - 2 kHz modulation

- **CHARIS nearIR IFU**
  - 2-5um IFU

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

- **MKIDS focal plane WFS**
  - Sci path viewing cam

- **6 kHz modulation**

- **Sci path viewing cam**

- **Open loop control**
  - ADC 1 Hz
  - 64x64 DM 2 kHz
  - Fast DM modulation
SCExAO Light path

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 0.6-1.0 um

111 DM segmented

Coronagraph

VAMPIRES (2 cameras)
Polarimetry Dual band Aperture masking

FIRST Polarimetry Interferometry

RHEA visible IFU
coronagraphic LOWFS

Photonic nuller

IRD 1-2 um HR spectrograph

Sci path viewing cam

CHARIS nearIR IFU

MKIDS focal plane WFS

SAPHIRA Imager

Active WF correction
Dedicated WFS
Visitor port
dichroic beam switch

Facility AO

Mixed science/WFS
Preliminary VAMPIRES science

Diffraction-limited imaging in visible light

Summed image

750nm, 1kHz imaging
log scale

Video
SCExAO Light path

Facility AO

ADC
1 Hz

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

2-5um imager/spectro (IRCS)

Weakly/un-modulated Visible PyWFS
0.6-1.0 um

111 DM segmented

Coronagraph

Photonic nuller

IRD
1-2 um HR spectrograph

Charis nearIR IFU

MKIDS focal plane WFS

LowFS

FIRST Polarimetry Interferometry

VAMPIRES (2 cameras)
Polarimetry Dual band Aperture masking

RHEA visible IFU

Coronagraphic

Sci path viewing cam

Dedicated science instrument

Mixed science/WFS

Active WF correction

Dedicated WFS

Visitor port

beam switch

dichroic
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
SAPHIRA camera

1.68 kHz frame rate, H-band
(played at 90 Hz)
SCExAO PyWFS ON → OFF
SCExAO Light path

Facility AO

Dedicated science instrument
Mixed science/WFS
Active WF correction
Dedicated WFS
Visitor port
dichroic
beam switch
HR8799 Observations by J. Chilcote & T. Groff
preliminary data processing by T. Brandt
SCExAO Light path

Facility AO

- 64x64 DM (2 kHz)
- ADC (1 Hz)
- 2-5um IFU
- 2-5um imager/spectro (IRCS)
- Weakly/un-modulated Visible PyWFS (0.6-1.0 um)
- 50x50 DM (3.5 kHz)
- BEAM SWITCHER
- Coronagraph
- 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
- MKIDS focal plane WFS
- SAPHIRA
  - Imager
- Sci path viewing cam
- coronagraphic LOWFS

Active WF correction
Dedicated science instrument
Mixed science/WFS

Dedicated WFS
Visitor port
- dichroic
- beam switch
MKIDS camera (built by UCSB for SCExAO)

Photon-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

**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
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
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
**Hardware Latency measured on SCExAO**

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

**SCExAO 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

**HardwareLatency = DM soft + DM elec + DM phys + CAM readout/transfer + CAM processing + ½ exposure time**

HardwareLatency = 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
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
Control loops

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

- **CHARIS**
  - nearIR IFU

- **FIRST**
  - Polarimetry
  - Interferometry

- **MKIDS**
  - focal plane
  - WFS

- **Modulated Visible PyWFS**
  - 0.4-1.0 um

- **Weakly/unmodulated Visible PyWFS**
  - 0.6-1.0 um

- **NearIR PyWFS**
  - 0.8-2.0 um

- **2-5 um IFU**

- **Sci path viewing cam**

- **64x64 DM**
  - 2 kHz

- **50x50 DM**
  - 3.5 kHz

- **Fast DM modulation**

- **Open loop control**

- **6 kHz modulation**

- **ADC**
  - 1 Hz

- **SAPHIRA Imager**
- **Photonic nuller**
- **coronagraphic LOWFS**
- **Fast focal plane WF control (non linear)**
- **Linear (LDFC)**
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!

LOWFS offsetting notes
- Do not turn on zonal offsetting ZP1
- Turn on zero pt offset process

OFFSETTING
LOWFS (loop #1, dm01) → PyWFS (loop #0, dm00)

Green color: process is part of loop #1
Using SCExAO instrument

→ slack channel to coordinate instrument use over multiple continents
Conclusions

**GSMTs can image and characterize habitable planets around nearby M-type stars**

Significant progress is being made in high contrast imaging techniques…
testing on current large telescopes is critical to be ready & efficient for GSMTs era

SCExAO is a powerful platform for testing and deploying new techniques (hardware, algorithms).
Daytime testing with internal source → nighttime on-sky validation

Coordinated development with MagAO-X (→ GMT), Keck (→ TMT), SPHERE upgrades (→ ELT)
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