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ABSTRACT

The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) serves both a science instrument in operation, and a prototyping platform for integrating and validating advanced wavefront control techniques. It provides a modular hardware and software environment optimized for flexible prototyping, reducing the time from concept

* Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.
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formulation to on-sky operation and validation. This approach also enables external research group to deploy and test new hardware and algorithms.

The hardware architecture allows for multiple subsystems to run concurrently, sharing starlight by means of dichroics. The multiplexing lends itself to running parallel experiments simultaneously, and developing sensor fusion approaches for increased wavefront sensing sensitivity and reliability. Thanks to a modular realtime control software architecture designed around the CACAO package, users can deploy WFS/C routines with full low-latency access to all cameras data streams. Algorithms can easily be shared with other cacao-based AO systems at Magellan (MagAO-X) and Keck.

We highlight recent achievements and ongoing activities that are particularly relevant to the development of high contrast imaging instruments for future large ground-based telescopes (ELT, TMT, GMT) and space telescopes (HabEx, LUVOIR). These include predictive control and sensor fusion, PSF reconstruction from AO telemetry, integrated coronagraph/WFS development, focal plane speckle control with photon counting MKIDS camera, and fiber interferometry.

We also describe upcoming upgrades to the WFS/C architecture: a new 64x64 actuator first stage DM, deployment of a beam switcher for concurrent operation of SCExAO with other science instruments, and the ULTIMATE upgrade including deployment of multiple LGS WFSs and an adaptive secondary mirror.

Keywords: Adaptive Optics, High Contrast Imaging, Wavefront Sensing, Atmospheric Turbulence

1. INTRODUCTION

High contrast imaging systems on large space and ground telescopes enable direct imaging and spectroscopic characterization of exoplanets and circumstellar disks.[1–6] Large ground-based telescopes are particularly well suited for near-IR thermal imaging of young massive planets,[7–9] while the deeper contrast levels accessible from space provide access to starlight reflected off giant planets and circumstellar disks.[10–12] From both ground and space, direct imaging and spectrocospic analysis of potentially habitable planets should become possible with future planned telescopes, but remains a significant technical challenge.[13–15]

While starlight suppression systems have achieved deep raw contrast in vacuum testing, high contrast imaging perfromance will be limited by the ability to accurately and efficiently measure residual wavefront errors. High perfrormance Wavefront sensing (WFS) is essential to both **achieve deep raw contrast** by way of wavefront control, and to **calibrate residual light** in the science image to reliably recover faint companions, ideally to the photon noise limit. Accurate and efficent WFS is thus essential to high contrast imaging instruments and missions, both ground and space-based.

On ground-based telescopes, rapidly evolving atmospheric turbulence can be mitigated by extreme adaptive optics (XAO) correction.[16] Current XAO systems can deliver up to 10^{-4} raw contrast on typical bright targets at angular separations of a few λ/D.[17] The main fundamental limits to this raw contrast level are :

1. **Temporal lag**. Fast, low-latency correction is required to keep up with continuously evolving atmospheric turbulence. Allowable latency scales as the 6/5-th power of required wavefront error, so XAO systems are particularly demanding.
2. **WFS sensitivity to photon noise**. XAO systems require high precision wavefront measurements over a large number of degrees of freedom at high speed. Even on bright stars, photon noise is therefore a major source of error.
3. **Differential chromatic effects between WFS and science image** due to the wavelength dependence in refractive index of air, and due to diffraction propagation between atmospheric layers.
4. **Amplitude (scintillation)** created by diffraction propagation through turbulence.

Powerful point-spread function (PSF) subtraction techniques[18,19] used in conjunction with angular and spectral differential imaging (ADI, SDI)[20,21] can yield contrast levels $\approx$ 10–100 $\times$ deeper than raw contrast.[22] But this level of suppression is still falls well short of the photon noise limit. Unknown residual wavefront errors creating speckle noise in the focal plane limit detection robustness and detection contrast limit, as there is ambiguity between speckles and actual astrophysical sources.

Space-based HCI systems suffer from the same fundamental limits, but at a different scale. Without atmospheric turbulence, wavefront errors are smaller and slower, allowing deeper raw contrast. The XAO correction control loop operates slower, gathering more starlight for each measurement so that WFS photon noise can be reduced to the required contrast level. Measurements are primarily performed in the focal plane to avoid non-common path errors, and low-order aberrations can be tracked with a faster sensor making use of bright starlight rejected by the coronagraph. Ultimately, contrast depth and detection limit are also limited by WFS accuracy and sensitivity, as picometer-level wavefront variations can create speckles with brightness comparable to a habitable planet orbiting a Sun-like star.

The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) is both a science instrument and a prototyping platform for integrating and validating XAO wavefront control techniques. We describe in §2 its hardware configuration and in §3 how it provides an environment suitable for flexible prototyping, reducing the time from concept formulation to on-sky operation and validation. Main current research themes supported by SCExAO are described in §4 along with specific examples.

2. HARDWARE CONFIGURATION

The SCExAO instrument is installed on the Nasmyth platform of the 8.2m Subaru Telescope. The instrument platform spans $\approx 8 \times 7m$, and hosts the facility AO system as well as SCExAO and its instrument modules. Light from the telescope is first corrected by the AO facility system, then sent to SCExAO for additional correction by a 2000-actuator MEMS type deformable mirror.

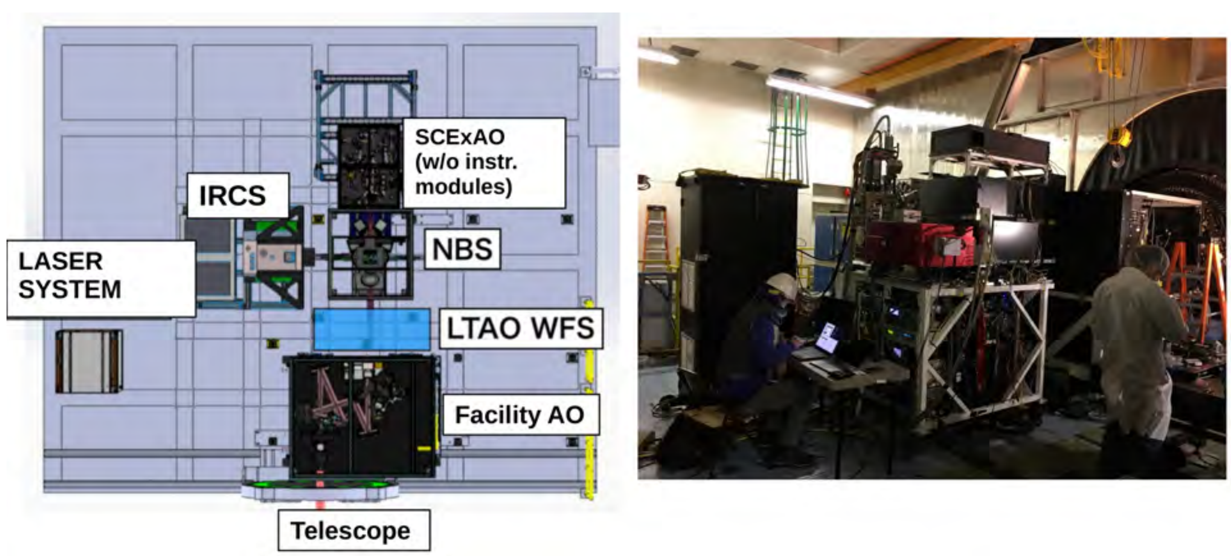

Figure 1. (left) Instrument layout on Subaru's Nasmyth infrared platform. The layout shows the configuration after deployment of the Nasmyth beam switcher (NBS) currently in development. (right) Image of the SCExAO instrument on the platform.

2.1 Nasmyth Platform Layout

The facility AO system, currently a 188-element curvature system, will be upgraded in 2021 to a 3200-element deformable mirror and a near-IR pyramid WFS. Wavefront sensing can be provided by visible or near-IR starlight, or by four LGS sensors for laser tomography.

The facility AO system can feed multiple instruments, including SCExAO and the Infrared Camera and Spectrograph (IRCS). The overhead crane is currently (2020) used to physically move instruments in the AO focus. A Nasmyth beam switcher (NBS) currently under development will provide crane-free beam switching, and will enable modes of operation where multiple instruments can operate simultaneously with the appropriate dichroic splitter setting. Figure 1 (left) shows the final configuration with the NBS.

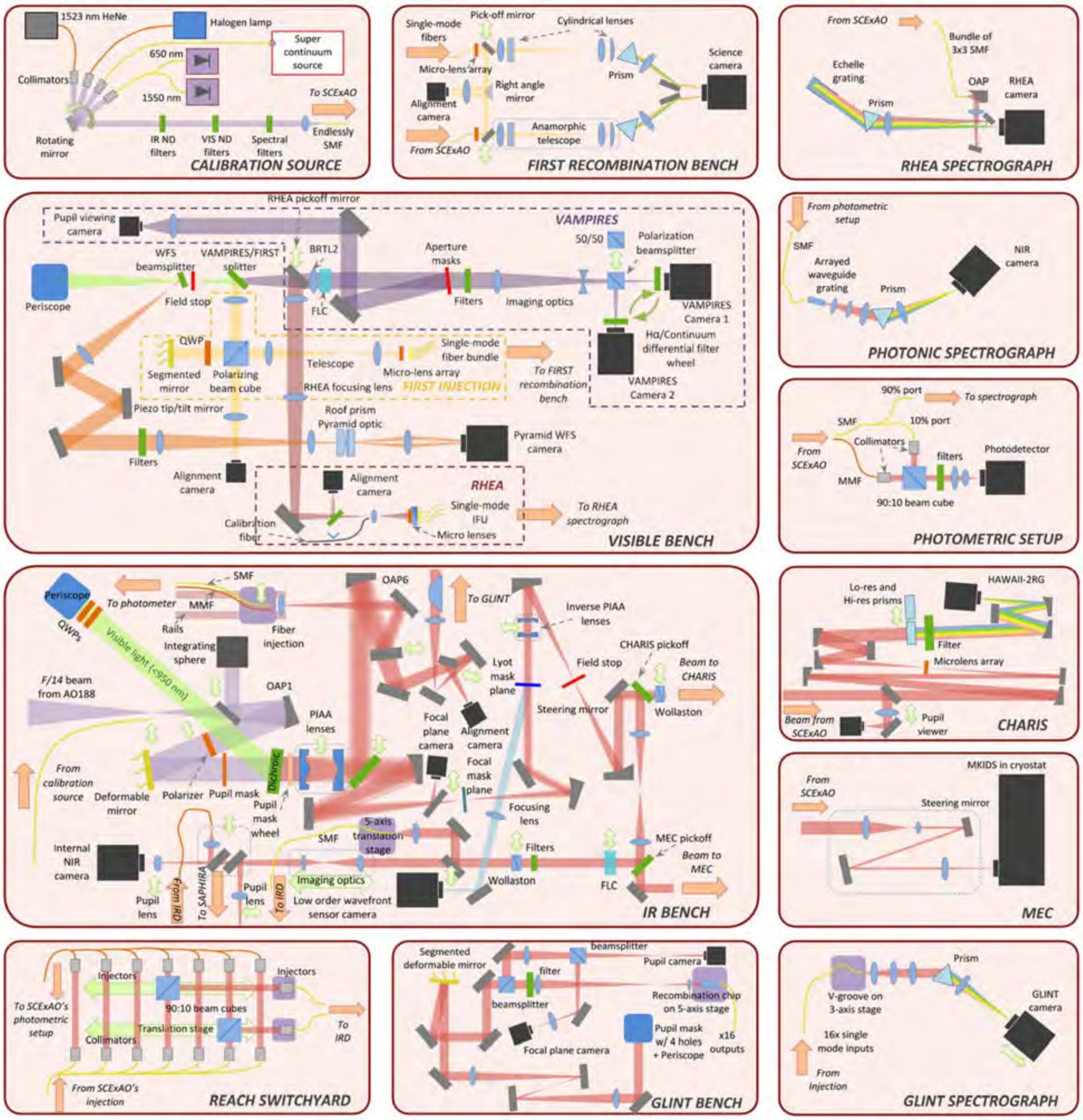

Figure 2. SCExAO instrument optical train showing the two main optical bench and instrument modules.

2.2 SCExAO System Overview

The SCExAO system, shown in Fig. 1 (right), delivers fine wavefront correction and starlight suppression for mutliple instrument modules. Current (2020) SCExAO instrument modules are routinely available for both on-sky and off-sky operation :

- **CHARIS**,[23] a near-IR integral field spectrograph operating from 1.1 to 2.4 μm, which is the main workhorse high-contrast science instrument used with SCExAO, achieving contrasts of 10^{-6} at $0''\!.5$[24](see paper 11448-330 of this meeting). SCExAO/CHARIS has yielded new discoveries of substellar companions, spectral characterization of known exoplanets and other objects, and multi-wavelength spatial characterization of planet-forming disks.[25–30]
- **VAMPIRES[31]**, a dual-beam visible light imager, with polarization and spectral differential imaging modes, and aperture masking. SCExAO/VAMPIRES is used to resolve circumstellar material at small angular separations and can detect accreting protoplanets in H_α.[32]
- **FIRST**, a visible light spectro-interferometer.[33]
- **GLINT**, a near-IR photonic nuller.[31,34]
- **MEC[35]**, the MKID exoplanet camera, a wavelength-resolving noise-free photon counting imaging camera. MEC typically operates in parallel with CHARIS taking shorter wavelength light.
- **REACH**,[36] which injects planet light into a single mode fiber for high resolution (R $\approx$ 100,000) near-IR spectroscopy with the existing IRD spectrograph.
- **NIR-PDI**[37] uses a high frame rate near-IR camera for polarization differential imaging
- **RHEA**,[38] a narrow-field visible high resolution integral field spectrograph

Additional experimental hardware can be deployed for specific tests.

Fig. 2 shows a block diagram of SCExAO including the above modules.

3. ACCESS AND OPERATION AS A TEST PLATFORM

3.1 Testbed capabilities

The SCExAO instrument platform has been optimized to facilitate off-sky testing to support development and validation of new WFS concepts prior to on-sky deployment. The instrument is continuously available (day and night) for off-sky testing outside of the pre-scheduled on-sky operation nights (typically $\approx$ 16 nights per yr).

Off-sky testing uses an internal calibration source (top left, Fig. 2) capable of simultaneously feeding optical and near-IR broadband light with selectable independent brightness settings. Multiple high cameras and sensors are available for WFS development, as listed in table 1. Most of these can run simultaneously thanks to selectable dichroic splitters, so that source light can be split in wavelength of flux according to the goals of the experiement.

Table 1. Wavefront sensors and high speed cameras.

Sensor	Wavelength	Speed	Type	Status
Curvature APD array	VIS	2 kHz	188 APDs	in operation
LTAO SHWFS x5	VIS	kHz	25x25 cells, sCMOS	2021
VIS Pyramid	600nm-900nm	3.5 kHz	120x120 EMCCD	in operation
LOWFS	0.9-1.7μm	<6 kHz	InGaAs array	in operation
MKID Exoplanet Camera	0.9-1.4μm	2 kHz	MKID photon counting	in operation
VAMPIRES (FPWFS) x2	0.6-0.8μm	1 kHz	512 x 512 EMCCD	in operation
NIR Pyramid	0.9-1.8μm	3 kHz	MCT array	2021
GLINT interferometer	0.9-1.7μm	1.4 kHz	InGaAs	in operation

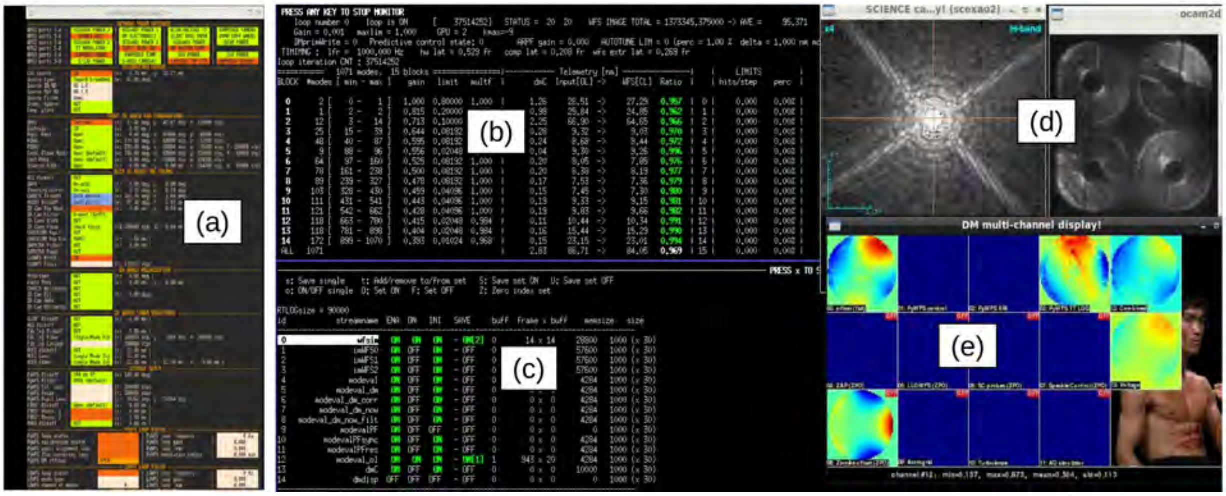

Figure 3. SCExAO control screens. (a) Status of control stages, filter wheels and other opto-mechanical devices. (b) Summary of real-time modal telemetry for the main AO control loop. (c) Telemetry storage to disk control screen. (d) Viewers for real-time image streams: focal plane image (left) and pyramid WFS camera (right). (e) Deformable Mirror (DM) control channels.

3.2 Access and User interface

Remote access to the instrument is provided by remote login to the instrument control and real-time control computers. An example screenshot of the instrument control screen is shown in Fig. 3.

Scheduling for tests is coordinated with a shared calendar, and live interaction with the support team is done through the Slack communication platform.

3.3 Software

To aid WFS development activities, the instrument software supports saving all telemetry to disk and provides uniform software interfaces for deployment of algorithms. Software frameworks and data formats are based on the open-source milk and cacao packages which are also used for the MagAO-X system at the Magellan telescope, and inter-compatible with the COMPASS simulation framework.

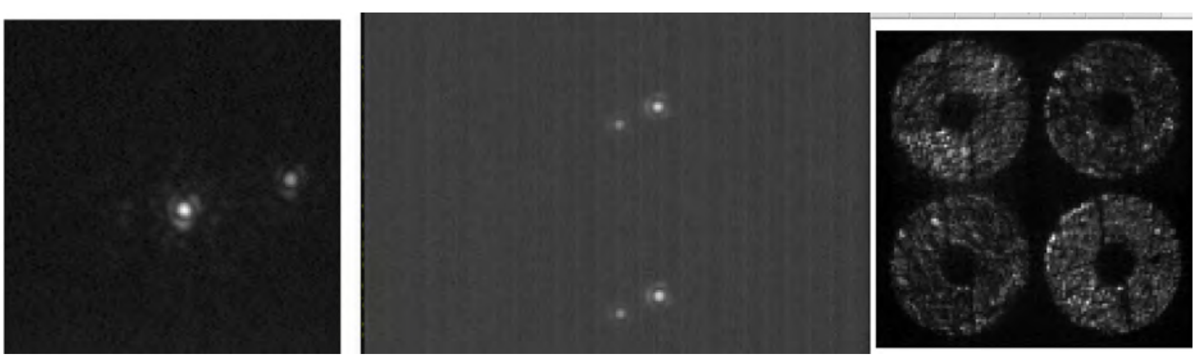

Figure 4. Example telemetry. Simultaneous on-sky frames from VAMPIRES cam1 at 675nm (left, single frame from 500 Hz stream), Near-IR scicam at 1630nm (center, single frame from 1 kHz stream) in PDI mode, and visible Pyramid WFS (right, single frame from 2 kHz stream). Data acquired on σ Ori double star, 0.25 arcsec separation, on Aug 8, 2020.

3.3.1 Telemetry

The WFS cameras listed in table 1 are made available for real-time use as streams in shared memory. A common format, using the ImageStreamIO format is adopted, providing read/write access through C and Python languages APIs. Streams can be saved to disk for later inspection, as illustrated in Fig. 4. Sub-frame synchronization between streams at the $\approx 20\mu s$ level is achieved by accurate measurement of each stream latency, using poking on the system DM for common time reference. A common TCP-based stream transfer routine is used to move real-time streams originating from separate computers to the same physical computer for real-time processing, as required. Dedicated 100GBE and 10GBE fiber links between computers provide low-latency connectivity.

3.3.2 Algorithm Deployment

Several options are supported for algorithm deployment for WFS development. Low latency real-time code can be deployed as compiled C or C++ code using the telemetry stream API. Python code can also be deployed for less performance-critical code. Finally, raw WFS frames and DM commands can be exchanged by file system or network independently of the stream API if the associated latency is acceptable.

The SCExAO real-time control software, provided by the compute and control for adaptive optics (CACAO) package,[39] provides high-level functions that are particularly useful for WFS algorithms deployment:

- **Deformable mirror (DM) multi-channel control** – The system DM is exposed to the users not as a single actuator array, but as twelve (12) independent DM channels. Low-latency software automatically adds all channels whenever one of the channels is updated, and send to the physical DM the sum of all 12 channels. It thus appears to users as if the system has 12 DMs, and a specific experiment can take control of one of these channels without requiring coordination with other processes writing to the DM.
- **Automatic zero point offload between control loops** – Individual DM channels can be configured to be offload channels, where each update to the channel will both issue a command to the DM and change the convergence point (zero point) of the primary AO control loop. This is necessary for WFS algorithms requiring DM probing, so that the probes are not erased by the primary AO control loop.

4. AREAS OF ACTIVE RESEARCH

Hardware and software capabilities described in §2 and 3 are supporting multiple WFS research activies, which fall under four main themes: **Wavefront control algorithms**, **Focal plane sensing and referencing**, and **high efficiency wavefront sensing**.

4.1 Wavefront control algorithms (making optimal use of available WFS information)

Wavefront control systems operate in a control loop consisting of three steps: (1) wavefont sensor data is acquired; (2) wavefront is estimated from measurements, and (3) the new estimate is converted to a correction which is incrementally applied to the corrective elements (such as deformable mirror).

Advances in wavefront control algorithms are aimed at better using available WFS information to improve wavefront correction and calibration.

Research questions under this research theme include :

- **Predictive control: Can the temporal wavefront evolution be leveraged to improve wavefront correction?** Wavefront errors exhibit strong spatial and temporal correlations due to wind-driven turbulence (ground telescopes), thermal drifts or vibrations (space and ground telescopes).
- **Non-linear WF estimation: Can additional wavefront information be extracted from non-linear reconstruction?** Current WFS schemes assume linearity between pixel intensity and wavefront phase (pupil plane sensors), or between deformable mirror displacement and focal plane complex amplitude (focal plane sensors). Including non-linear effects can increase wavefront estimate accuracy over a wider range of conditions.
- **Dynamical self-calibration: Can the wavefront reconstruction algorithm optimally learn and adapt?** Most wavefront control system rely on pre-computed or pre-measured calibration of WFS response to deformable mirror commands. This response does evolve with time, and is itself a function of the wavefront state. Wavefront sensor telemetry contains valuable information to derive or constrain the system response.

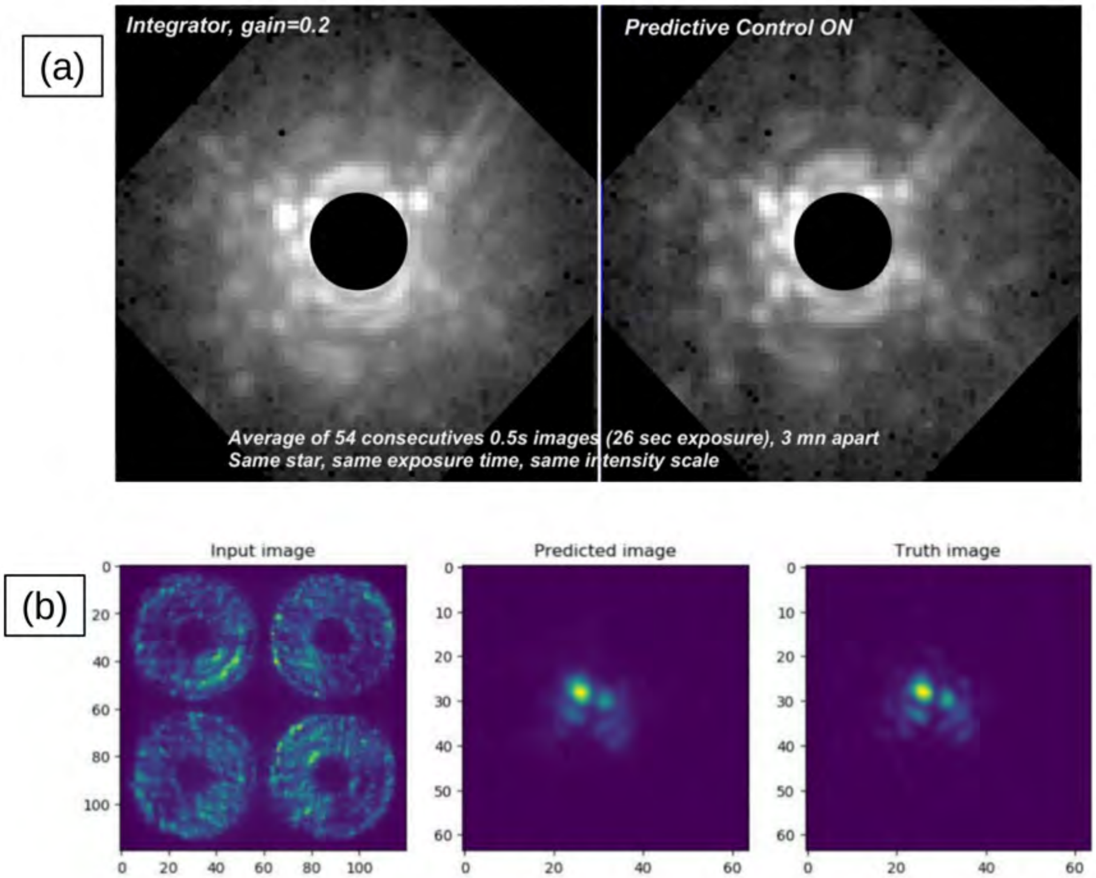

Figure 5. Advanced wavefront control algorithms - selected examples. (a) On-sky demonstration of predictive control using the EOF framework, yielding a 3x contrast gain. (b) Evidence of non-linear wavefront sensing information recovery using a neural network. See text for details.

4.2 Focal plane wavefront sensing and referencing

Focal plane images, including the post-coronagraphic science image, are uniquely powerful for high contrast imaging wavefront sensing and control, offering both sensitivity and immunity from non-common path aberrations.

Such images can be used for wavefront sensing, either as the primary source of wavefront estimation, or as a reference for fast control loops using pupil-plane wavefront sensors. SCExAO provides multiple high speed low noise focal plane sensors in visible and nearIR. They are made available for real-time processing to support this research theme.

Research questions under this theme include:

- **Speckle control: How can Focal plane speckle probing nulling be optimized for speed, sensitivity and robustness?** In speckle nulling, DM probes are added to perturb the focal plane image. This perturbation is measured to extract wavefront information as complex amplitude of the focal plane speckles, and can then be employed to null speckles (Fig. 6 (a)) or optimize PSF quality (Fig. 6 (b)). Deployment of efficient and robust real-time focal plane wavefront control for ground-based systems remains a significant algorithmic challenge.
- **Linear dark field control[40] (LDFC): Can bright speckles outside the high contrast be used to stabilize the wavefront state in a linear loop?** LDFC utilizes the linear response of the uncorrected

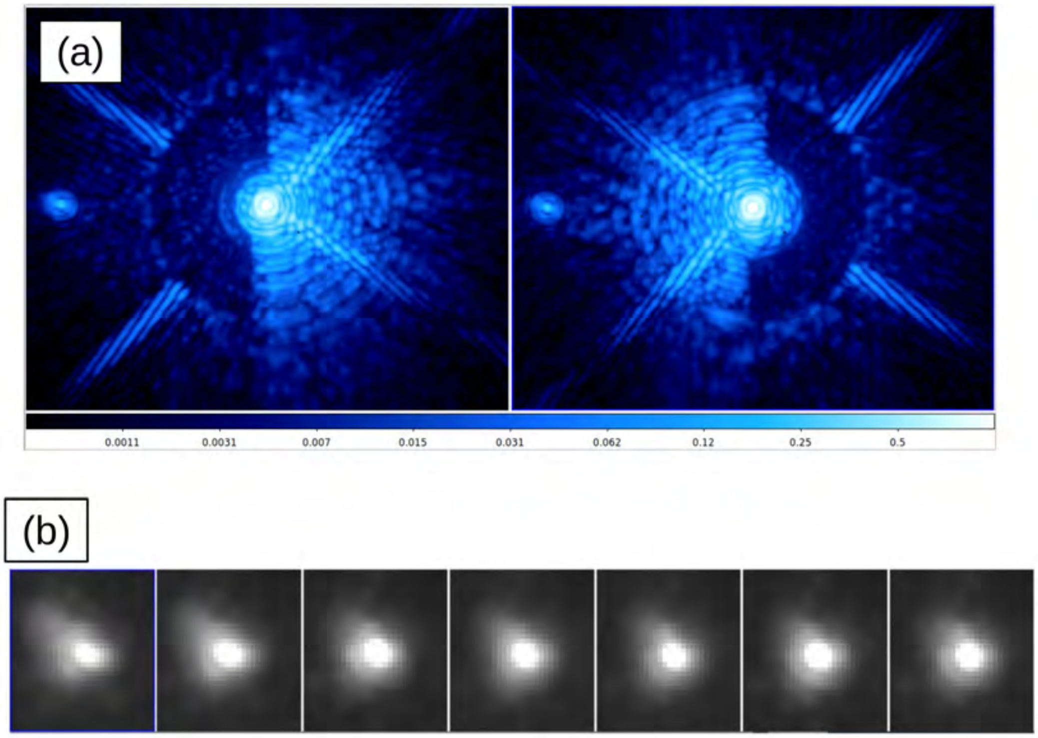

Figure 6. Focal plane wavefront control - selected examples. (a) Speckle nulling showing left and right side dark hole configurations (internal source). (b) On-sky demonstration of the DrWho focal plane image referencing algorithm. See text for details.

but photon-rich region in the focal plane (the "bright field"; BF) to wavefront perturbations that affect both the BF and the photon-starved DF. LDFC does not require DM probing to operate, resulting in a temporally correlated DF well suited for further suppression using PSF subtraction techniques. LDFC has been tested in the laboratory at contrasts necessary to image planets in reflected light;[41] tests using the SCExAO internal source and on sky thus far are encouraging (Miller et al. submitted; Bos et al. in prep.).

- **Multi-star wavefront control: Can focal-plane wavefront contol be applied to double stars?** Many targets of interest are double star, requiring focal plane wavefront control to be tailored.[42]

- **Coherent differential imaging: Can coherence be measured and can it separate speckles from planets?** Speckle modulation induced either by intentional probing or fast residual atmospheric turbulence can be used to measure both the complex amplitude of speckles and their coherence with startlight. The incoherent residual contains the planet light.

4.3 High efficiency wavefront sensing

Optimal use of the fixed available amount of starlight is essential to mitigate the photon noise WFS error.

Research questions under this theme include:

- **New optical concepts for WFS** – Development of high efficiency WFS concepts is essential to high contrast imaging. Photonics technologies, and in particular on-chip waveguides and coherent couplers, offer new possibilities to optimize WFS efficiency.

- **Can measurements from multiple sensors be combined?** Sensor fusion to combine measurements across a wide wavelenght range can increase sensitivity. This is especially relevant to post-coronagraphic

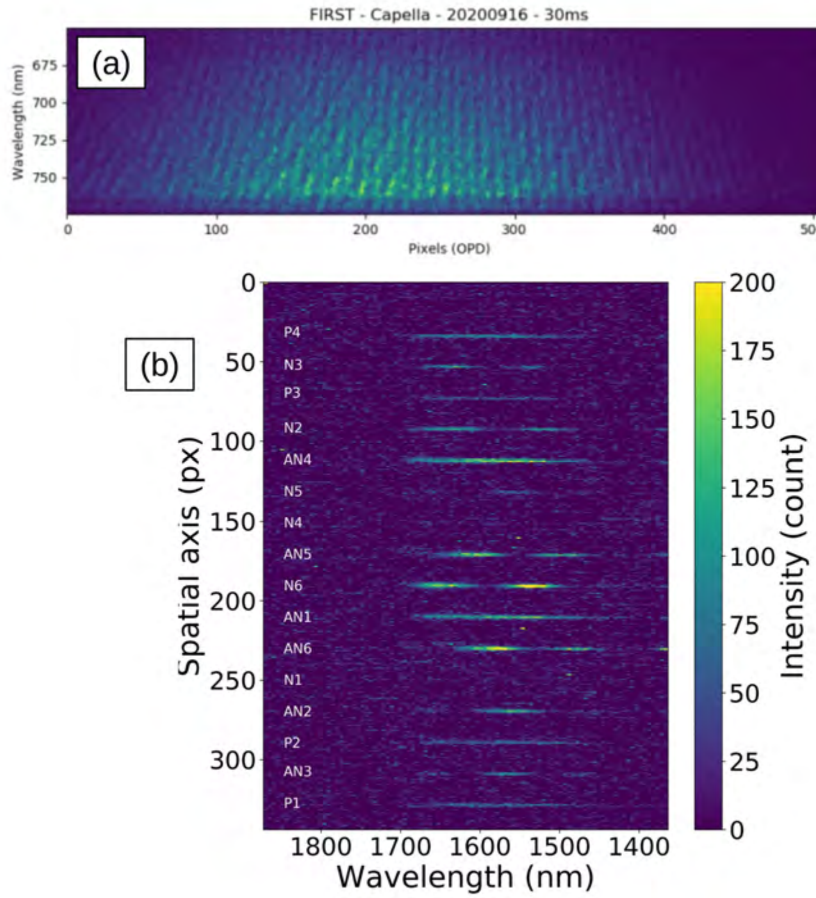

Figure 7. Interferometric WFS - selected examples. (a) On-sky image of of the Capella double star acquired with the FIRST instrument module. (b) On-sky image of Arcturus acquired with the GLINT instrument module. See text for details.

focal plane wavefront sensing approaches that only use a narrow spectral bandwidth ($\approx 20\%$, limited by the starlight suppression chromaticity).

SCExAO provides wavefront sensors that operate concurrently at several spectral bands to explore this topic. The FIRST and GLINT instruments, both interferometers, also encode wavefront information at high sensitivity with wavelength resolution, thanks to new photonics technologies (see Fig. 7).

5. FUTURE WORK AND PERSPECTIVES

The SCExAO system is well-suited for research and development of new WFS techniques thanks to its hardware configuration on the nearIR Nasmyth platform of the Subaru Telescope. Multiple research activities are supported to explore promising paths for improving wavefront correction and calibration. Most of the approaches under development are applicable to both ground and space high contrast imaging instruments and projects.

For ground-based HCI instruments, the combination of predictive control, multi-wavelength sensing, new optical sensing and smarter algorithms can potentially push performance significantly beyond the previously assumed $1e5$ raw contrast limit at small angular separations.[43] High performance computing technologies are an essential component of these developments for ground-based telescopes, as control loops operate at and above kHz frequency and handle large data bandwidth.

Additionally, precise bias-free calibration of residual wavefront errors holds the potential to acquire images and spectra of exoplanets at the photon noise limit over long exposure times. This last goal would allow future large ground and space telescopes to study the atmospheres of habitable exoplanets at high accuracy to support the search for life outside our solar system. Advances in wavefront sensing techniques, including low-noise detectors, provide the ability for **complete** real-time measurement of the wavefront state, where all disturbances producing focal plane speckles are also contained in the collection of WFS telemetry streams, making it essentially impossible for unwanted speckles to hide from telemetry. Exploiting the full potential of WFS telemetry, while a significant computational challenge, is key to achieving the photon-noise calibration limit.

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