Status of the SCExAO instrument: recent technology upgrades and path to a system-level demonstrator for PSI

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ABSTRACT

The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) instrument is a high-contrast imaging system installed at the 8-m Subaru Telescope on Maunakea, Hawaii. SCExAO is both an instrument open for use by the international scientific community, and a testbed validating new technologies that are critical to future high-contrast imagers on Giant Segmented Mirror Telescopes (GSMTs). Since its first light, SCExAO has grown in capabilities and complexity to integrate the most advanced technologies available today in detectors, wavefront sensors, coronagraphs, real-time control, and starlight suppression. Its modular design allows for collaborators to implement their own hardware and algorithms, and to test them on-site or remotely. We are now commissioning

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the Microwave Kinetic Inductance Detector (MKID) Exoplanet Camera (MEC) for high-speed speckle control, as well as high frame rate low noise NIR detectors such as the Leonardo SAPHIRA detector. New coronagraphic modes include the Phase Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC), or the vector Apodizing Phase Plate (vAPP) coronagraph. New wavefront control algorithms are also being tested, such as predictive control, multi-camera machine learning sensor fusion, and focal plane wavefront control. We present the status of the SCExAO instrument, with an emphasis on current collaborations and recent technology demonstrations. We also describe upgrades planned for the next few years, which will evolve SCExAO –and the whole suite of instruments on the IR Nasmyth platform of the Subaru Telescope– to become a system-level demonstrator of the Planetary Systems Imager (PSI), the high-contrast instrument for the Thirty Meter Telescope (TMT).

Keywords: Manuscript format, template, SPIE Proceedings, LaTeX

1. INTRODUCTION

For the past 10 years, The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO)[1] evolved into a modular high-contrast imaging instrument and testbed, capable of developing and testing new technologies, hardware and algorithms, in laboratory conditions and on-sky. This unique capabilities is crucial to test the necessary technologies that future high-contrast instruments for Giant Segmented Mirror Telescopes (GSMTs) will require. One such instrument, the Planetary Systems Imager (PSI)[2] developed for the Thirty Meter Telescope (TMT),[3] will be composed of two main parts, PSI-blue and PSI-red. PSI-red will provide the first level of correction with a common deformable mirror (DM) and analyze the light between 2 and 5 μm, while the more challenging PSI-blue will provide Extreme Adaptive Optics (ExAO) performance between 0.6 and 1.8 μm with a second DM, and analyze the light at these wavelengths. SCExAO is already close to the PSI-blue configuration, but future major hardware changes inside and in front of SCExAO will change the instrument configuration at the Nasmyth platform of Subaru into a combination of PSI-blue and red.

In this paper, we present the current status of SCExAO, especially the main components similar to other high-contrast imagers, then we describe the experimental modules that are unique to the instrument, and what makes SCExAO a great platform for collaborations. Finally, we detail the major upgrades planned for SCExAO and AO188, that will bring the instrument closer to a system-level demonstrator of PSI.

2. "CLASSICAL" MODULES OF HIGH-CONTRAST IMAGING MODES OF SCExAO

Similar to SPHERE[4] and GPI,[5] SCExAO has the key components of high-contrast imagers and the main one is the extreme AO loop. While SPHERE has a single ExAO stage and GPI has a two-stage correction with a woofer and a tweeter DM, SCExAO relies on an independent first stage correction from Subaru Telescope's facility adaptive optics AO188, a 188-element AO correcting the atmospheric turbulence to typical Strehl ratios of 20 to 40%.[6] On top of that, SCExAO performs the second level of correction, using a 2000-actuator deformable mirror (DM) to achieve ExAO performance (Strehl ratios >80%).[1,7]

Figure 1 presents a diagram of the wavefront control loops of SCExAO. The ExAO loop uses the visible light between 800 and 900 nm, while the infrared light (>900 nm) is mostly used for science. The wavefront sensing is performed by a modulated Pyramid Wavefront Sensor (PyWFS) that combines a double roof prism pyramid optics and a First Light Imaging OCAM2K EMCCD camera.

An asymmetric pupil mask can be inserted to sens and correct low-order static errors, i.e. mostly non-common path errors between the visible and the IR path.[8] Since SCExAO is only equipped with one DM, the commands from the other correction loops are applied by offsetting the reference of the ExAO loop.

In the infrared path, the starlight is masked by a coronagraph, in most cases a classical Lyot coronagraph with an Inner Working Angle (IWA) of 113 mas. The light rejected by the Lyot stop can be directed towards a low-order wavefront sensor (LOWFS) that removes dynamic low-order aberrations seen by the coronagraph.[9]

A speckle control loop can be added to create and stabilize a dark hole on one side of the field of view. This work is still in progress and is not yet available for science observations.[10]

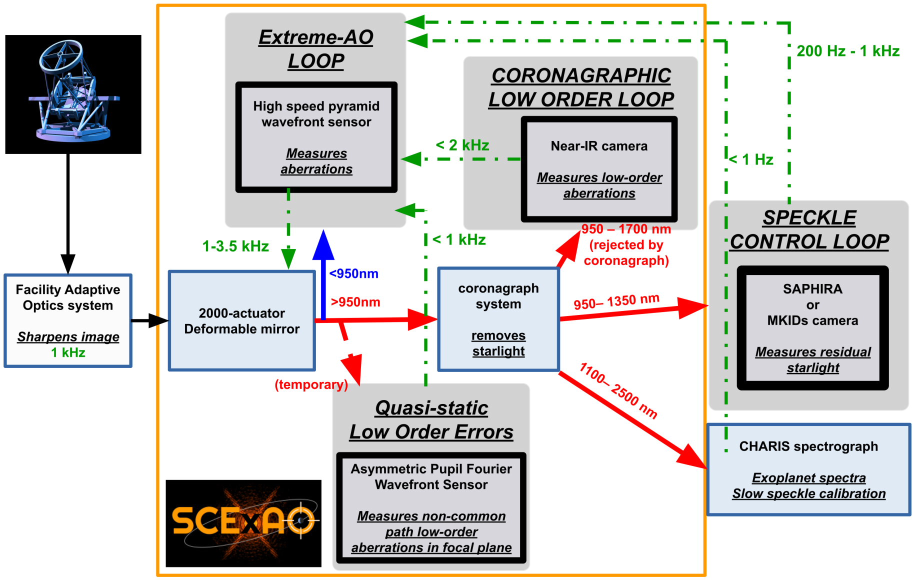

Figure 1. Control loops of SCExAO.

Most of the science in NIR is performed by the Integral Field Spectrograph (IFS) CHARIS,[11] using J-, H- and K-band (1.1 to 2.4 µm). Figure 2 presents a few results taken with SCExAO and CHARIS. Typical targets are planetary mass companions such as kap And b (Fig. 2 b)) and perform some spectroscopic analysis using CHARIS (Fig. 2 c)).[12] We also observe transition disks, debris disks and protoplanetary disks such as the one around LkCA 15 (Fig. 2 d)).[13] In that case, careful modelizations show that the candidate planets previously observed were only parts of an inner disk. Other cameras can also be used in parallel with CHARIS, like SCExAO's fast internal NIR camera from y- to H-band (0.95 to 1.7 µm), used for example to acquire this image

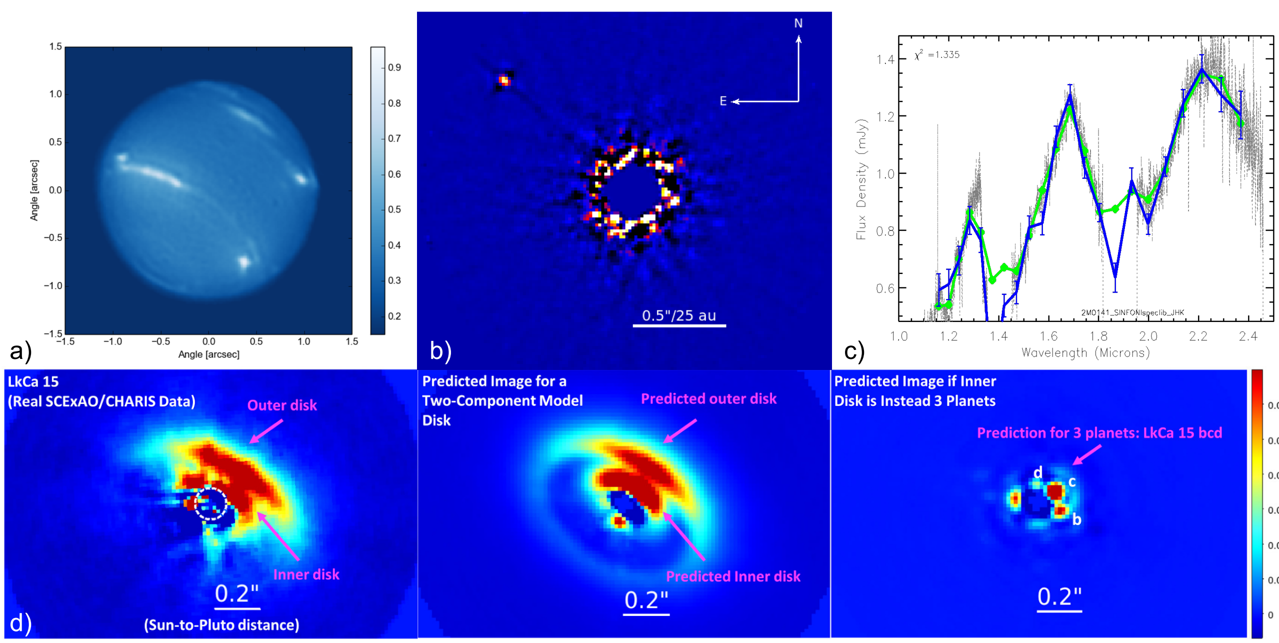

Figure 2. Examples of science images taken with SCExAO: a) Image of Neptune taken with the internal NIR camera, b) image of the planetary mass companion kap And b taken with CHARIS, c) spectrum of kap And b taken with CHARIS, d) protoplanetary disk around LkCa 15 taken with CHARIS (left), simulation of that same disk (middle) and simulation of potential planets, showing that the planet candidates imaged previously may be coming from the inner disk instead.

of Neptune (Fig. 2 a)).

One of the most successful features of SPHERE and GPI are their capacity to measure polarization, mostly to image disks. SCExAO was equipped from the beginning with VAMPIRES, a module doing polarization differential imaging (PDI) in visible using a couple of fast EMCCD cameras, and a Ferroelectric Liquid Crystal (FLC) capable of modulating the polarization at the frequency of the cameras. VAMPIRES is also equipped with some aperture masks to increase slightly the resolution for some targets. New PDI modes were added on the NIR path recently, and are described in detail in the author's other proceeding of this conference, titled "New NIR spectro-polarimetric modes for the SCExAO instrument".

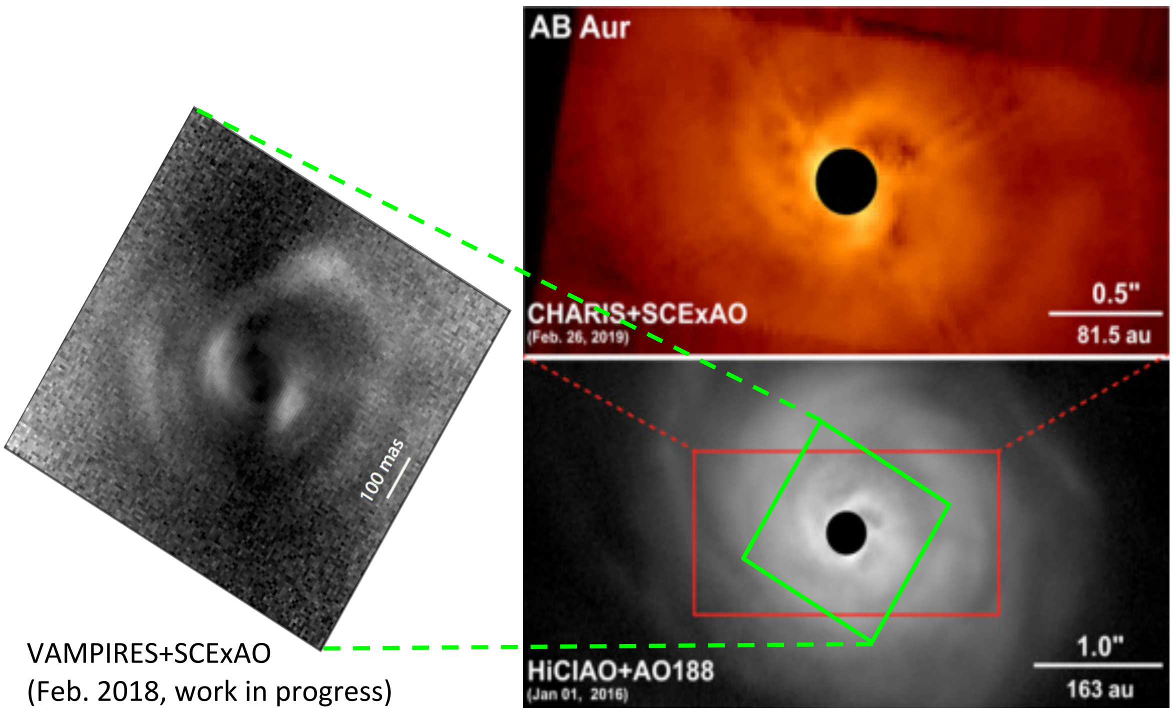

Figure 3. Comparison of the polarimetric intensity images between old HiCIAO observations (2016), and CHARIS observations (2019). In the CHARIS images, the wavelengths were collapsed. The CHARIS image shows a slightly better resolution and inner working angle. In comparison, we also present a VAMPIRES image (work in progress) of the central region. Residual spider diffraction is still visible in the CHARIS image, probably due to uncorrected distortion.

Figure 3 is an example of polarization imaging of the swirling disk of dust around AB Aur[14] in visible with VAMPIRES, and comparing the old PDI mode of HiCIAO and the new one with CHARIS. Some work is still needed to have all these modes fully ready for science, but they will be available for open-use next semester.

Despite having all the components of other high-contrast imagers, SCExAO is not planing on doing the same type of surveys yet. This is mostly because the instrument is constantly evolving, with new hardware and algorithms. The modular design of the instrument allows to test new technologies, necessary for future high-contrast imagers, therefore compromising on the stability necessary for long surveys.

3. AN INFRASTRUCTURE FOR EXPERIMENTAL WORK

During the past 10 years of operation, SCExAO underwent through several major redesign, to accommodate new modules and other hardware upgrades. The instrument is mostly based on collaborative efforts with multiple teams around the world, building its various components. It is now equipped with 3 independent visible modules: VAMPIRES, FIRST —a non-redundant mapping interferometer with spectroscopic capability—[15] and RHEA —a single-mode fiber high-resolution IFS.[16] in IR, SCExAO has 4 external ports: CHARIS, a high-speed photon counting camera SAPHIRA,[17] the Microwave Kinetic Inductance Detector (MKID) Exoplanet Camera (MEC),[18] and the NIR nulling interferometer GLINT. Finally, the IR bench is also equipped with two single-mode fiber injection ports: on for an IR version of RHEA, and one for post-coronagraphic single-mode coupling with the high-resolution IR Doppler spectrograph IRD.[19]

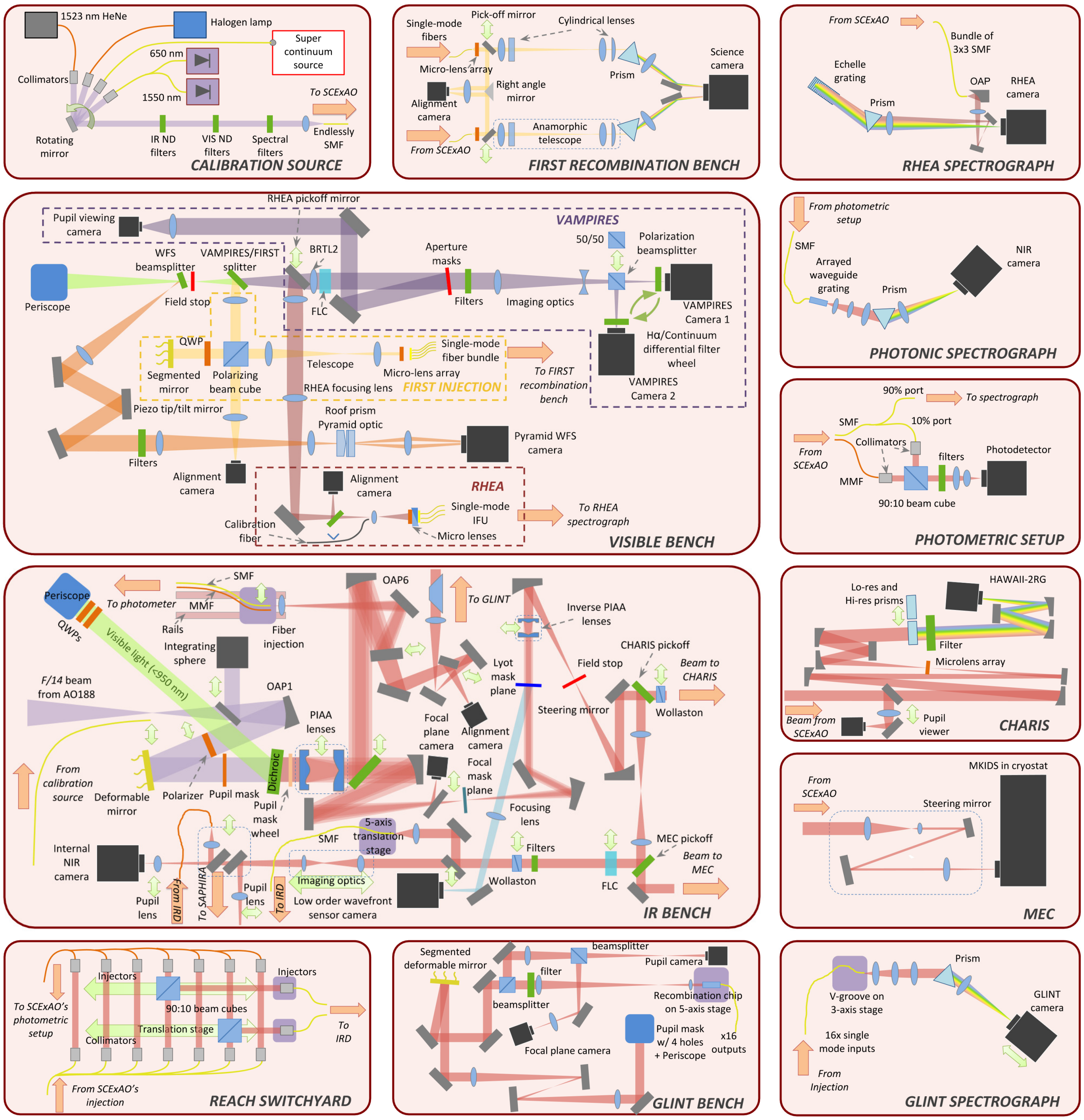

Figure 4. Current configuration of the SCExAO instrument, will all its modules.

Figure 4 resumes the optical configuration of SCExAO and all its modules. The IR path is equipped with several wheels allowing to add optics and masks in the various pupil planes and focal planes along the way, as well as dichroics, beam-splitters and pickoff mirrors, distributing the light to the different modules. A calibration source can be inserted in the focal plane instead of the beam coming from AO188, for laboratory testing even when the instrument is not installed behind the telescope.

This modularity allows us to test a variety of small IWA coronagraphs, such as the vector vortex coronagraph, the 8-octant phase mask coronagraph, or the phase-induced amplitude apodization complex mask coronagraph.[20] Pupil masks changing the diffraction pattern for high-contrast imaging are also tested, such as the shaped pupil[21] or the vector Apodizing Phase Plate (vAPP).[22]

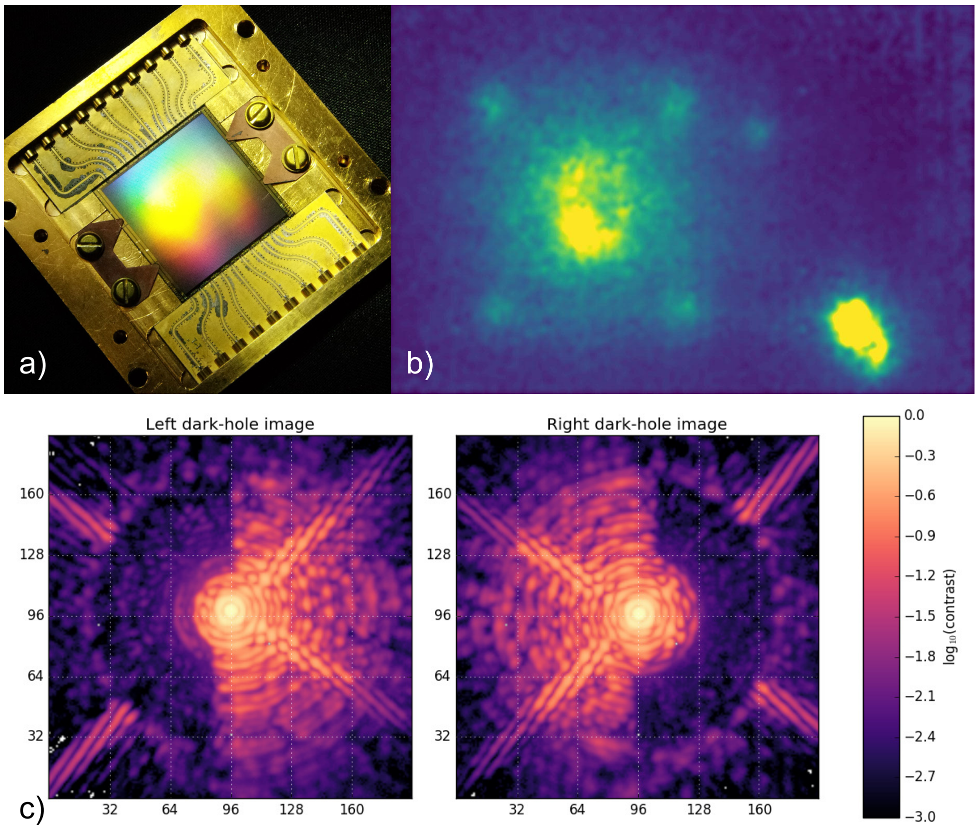

Figure 5. Testing of new hardware and algorithms on SCExAO: a) 20,000-pixel MKID detector of MEC, b) first light of MEC on-sky, on the multiple star system theta1 Ori B, the main star being behind a coronagraph, and a speckle grid is applied for astrometric and photometric calibration, c) speckle nulling performed on the laboratory source on each side of the image plane.

Thanks to its fast adaptability, several cutting-edge technologies are tested on SCExAO, such as the MKIDs technology (see Fig. 5 a) and b)), fast and low-noise visible and IR detectors, like the OCAM2K or the SAPHIRA detectors. A SAPHIRA detector was then tested for the first time as the detector of an IR PyWFS, as a demonstrator for the wavefront control of the Keck Planet Imager and Characterizer (KPIC).[7] One usage where these new sensors are becoming necessary is for the measure of the evolving speckle field at the temporal scale of the atmosphere. Focal plane wavefront sensing techniques such as speckle nulling (see Fig. 5 c)) are essential to correct aberrations unseen by the PyWFS, and reach deeper contrast over the zone of interest. We are now testing speckle nulling using both SAPHIRA detectors and MEC, and should be deployed on-sky in the near future.

The software environment of SCExAO was also upgraded several times to reduce overhead on-sky, to simplify operations, and to make the instrument more user friendly. The Compute And Control for Adaptive Optics (CACAO) framework is at the heart of most of the wavefront control loops,[23] and is now being use on other instruments, like KPIC and MagAO-X. This code is open-source and available on GitHub. A unified shared memory structure for the images coming from the various cameras, the DM commands and the offsets to apply to the PyWFS allows for anyone to implement their own wavefront control algorithm and test it in laboratory conditions and eventually on-sky. Remote operation of SCExAO is possible, thanks to a VPN connection and a set of procedures to configure and use the instrument. A slow control loop is also an option, by using an interface code sending images in a FITS format to a remote location, and receiving DM commands also in FITS format. With this interface, any programming language can be used on any operation system to perform wavefront control. This was implemented in the goal of testing Multi-Star Wavefront Control (MSWC) developed at NASA Ames.

4. STEPS TO GET CLOSER TO THE TMT-PSI CONFIGURATION

With 8-m telescopes such as Subaru, it is impossible to image Earth-like planets in the habitable zone of stars. However, the new generation of Giant Segmented Mirror Telescopes (GSMT) provides the necessary resolution to probe close to a significant number of M-type stars. But to reach the necessary contrast to image Earth-like planets around these stars, a significant improvement in wavefront control needs to be reached.

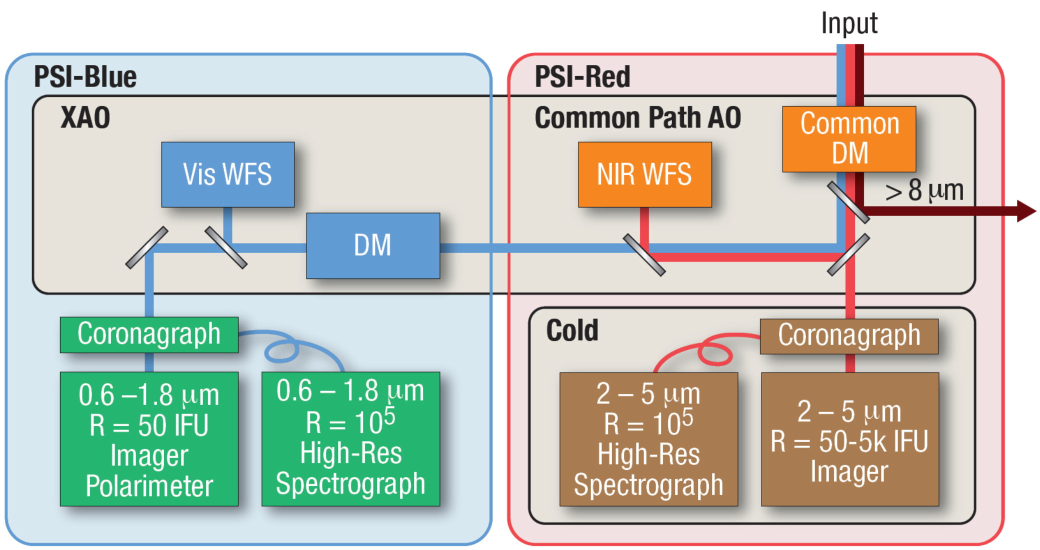

Figure 6. Configuration of PSI.

One instrument that will target Earth-like planets in the habitable zone of M-type stars is the Planetary Systems Imager (PSI), planned to be installed on the Thirty Meter Telescope (TMT). The design of PSI, presented in Fig. 6, is composed of two main parts: PSI-red and PSI-blue. PSI-red will analyze wavelengths between 2 and 5 μm, while PSI-blue will analyze wavelengths between 0.6 and 2 μm. A third port can potentially send light over 5 μm to a 10 μm imager, or a potential mid-IR IFS. An IR wavefront sensor would send the first step of correction to a woofer DM, common to all the modes. The NIR science light would go either to a low- to mid-resolution IFS, or a single-mode fiber injected high-resolution spectrograph. PSI-blue would have its own twitter DM driven by a visible WFS, and the science light would also go to either an IFS or a single-mode fiber injected high-resolution spectrograph.

SCExAO is close to the PSI-blue configuration, although both stages of wavefront control are currently only performed in visible. Over the next few years, a series of major upgrades in AO188 will bring the instrument configuration on the Nasmyth IR platform of Subaru to something closer to PSI-blue and red.

AO188 recently received an upgrade of its real-time computer with faster hardware, and the CACAO infrastructure to run the control loop.[24] This upgrade will allow to operate SCExAO and AO188 in a woofer/tweeter configuration. We can now get real-time telemetry of the AO188 wavefront sensor, and perform offsets between SCExAO and AO188.

In the next two to three years, AO188's DM will be replaced with an ALPAO 64x64 element DM, which is a half-scale version of the planned 128x128 DM used by PSI (Fig. 7 a)). The wavefront sensor will be upgraded

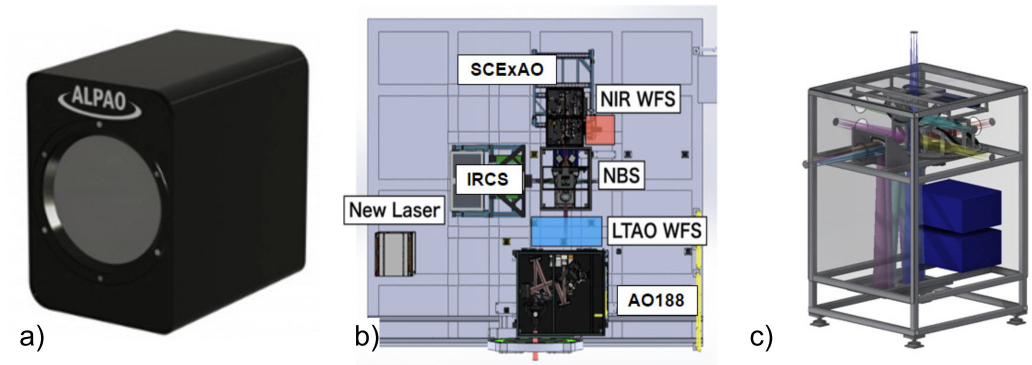

Figure 7. Hardware upgrades scheduled for AO188: a) new 64x64 ALPAO DM, b) Future configuration at the Nasmyth platform including a new beam switcher, allowing to split the light between SCExAO and IRCS, as well as other potential future instruments, c) new beam switcher with several ports on all sides.

to a modulated visible PyWFS later. In the meantime, the current 188-element curvature wavefront sensor will keep doing the sensing, while SCExAO's PyWFS can take care of higher spatial frequencies.

In the same timeline, a beam switcher will be added between AO188 and SCExAO (Fig. 7 b) and c)). This beam switcher has several ports on all sides, that can accommodate up to 4 instruments at a time. The beam switcher is equipped with pickoff mirrors and dichroics that will distribute the light to the different ports. As represented on Fig. 7 b), SCExAO and the Infrared Camera and Spectrograph (IRCS) will occupy two of the ports, and can share the light using a $\sim$2 µm dichroic. Although IRCS is not an IFS, this configuration will demonstrate an equivalent of the PSI-red+blue assembly. Logistically, the beam switcher will remove the necessity of craning either SCExAO or IRCS in front of AO188 depending on the observation, and even allow to observe in a mini queue mode depending on the atmospheric conditions.

The third upgrade is the implementation of a NIR PyWFS, using a First Light Imaging C-RED ONE camera. The camera was purchased partly using a grant which goal is to look at the galactic center with IRCS. But in combination with the beam switcher and the new DM, SCExAO would be able to benefit from its correction as well. The NIR PyWFS will be similar to the wavefront sensor driving the common DM of PSI-red, as it would perform the same function at Subaru. This will allow to achieve ExAO performances for IRCS and SCExAO, on redder stars such as M-type stars.

In parallel to these major hardware changes, new advanced wavefront control algorithms such as coherent differential imaging, predictive control, sensor fusion or real-time post-processing. In addition to demonstrate higher contrast in preparation for PSI, SCExAO will be able to image young Jupiter-mass planets closer to the habitable zone, down to $\sim$3 AU, where they should be more abundant. This will give us more insight on the planet population around the habitable zone. Finally, a few older Jupiter-size planets should be reached by looking at the reflected light for the first time.

5. CONCLUSION

Over the past 10 years, SCExAO has been evolving into a complex and modular instrument, containing all the components of classical high-contrast instrument, although with extra capabilities. This design allows the team to collaborate with groups all over the world on innovative technologies and algorithms. The hardware and software architecture provides the necessary tools for collaborators to design, install and test their own project, in laboratory conditions and on-sky, with minimal effort for the SCExAO team. We are now testing new key technologies for future high-contrast imagers on GSMTs, such as the MKIDs detectors, or fast and low-noise IR detectors. One goal of SCExAO is to become a technology demonstrator and testbench for the future TMT high-contrast instrument PSI. In order to achieve this objective, major upgrade changes in SCExAO, but also in AO188 and the whole Nasmyth IR platform of Subaru will modify the instrument configuration to get closer to the combination PSI-red+blue. AO188 will receive a new 64x64 DM that will transform the first stage of turbulence correction into an ExAO system. Then a beam switcher and an IR PyWFS will complete the upgrades and provide more flexibility in the observing modes at Subaru. Once completed, the combination of SCExAO, AO188 and IRCS will be a fully complete system-level demonstrator for PSI.

ACKNOWLEDGMENTS

The development of SCExAO was supported by the Japan Society for the Promotion of Science (Grant-in-Aid for Research #23340051, #26220704, #23103002, #19H00703 & #19H00695), the Astrobiology Center of the National Institutes of Natural Sciences, Japan, the Mt Cuba Foundation and the director's contingency fund at Subaru Telescope. F. Martinache's work is supported by the ERC award CoG - 683029. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

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