Adaptive Optics at the Subaru Telescope: current capabilities and development

Olivier Guyon[a], Yutaka Hayano[a], Motohide Tamura[b], Tomoyuki Kudo[a], Shin Oya[a], Yosuke Minowa[a], Olivier Lai[a], Nemanja Jovanovic[a], Naruhisa Takato[a], Jeremy Kasdin[c], Tyler Groff[c], Masahiko Hayashi[b], Nobuo Arimoto[a], Hideki Takami[b], Colin Bradley[d], Hajime Sugai[e], Guy Perrin[f], Peter Tuthill[g] and Ben Mazin[h]

[a] Subaru Telescope, National Astronomical Observatory of Japan, 650 N. A'ohoku Plane, Hilo, HI 96720, USA;
[b] National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan;
[c] Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544, USA;
[d] University of Victoria, Victoria, BC V8P 5C2, Canada;
[e] Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), The University of Tokyo, Chiba 277-8583, Japan;
[f] LESIA, Observatoire de Paris, Section de Meudon, 5 place Jules Janssen, 92195, Muedon, Cedex, France;
[g] Sydney Institute for Astronomy, School of Physics, Physics Road, University of Sydney, N.S.W. 2006, Australia;
[h] Department of Physics, University of California, Santa Barbara, CA 93106, USA

ABSTRACT

Adaptive optics is a key component of Subaru Telescope's current and future observational capabilities.

Current AO observations rely heavily on the AO188 instrument, a 188-elements system that can operate in natural or laser guide star (LGS) mode, and delivers diffraction-limited images in near-IR. In its LGS mode, laser light is transported from the solid state laser to the launch telescope by a single mode fiber. AO188 can feed several instruments: the infrared camera and spectrograph (IRCS), a high contrast imaging instrument (HiCIAO) or an optical integral field spectrograph (Kyoto-3DII). Adaptive optics development in support of exoplanet observations has been and continues to be very active. The Subaru Coronagraphic Extreme-AO (SCExAO) system, which combines extreme-AO correction with advanced coronagraphy, is in the commissioning phase, and will greatly increase Subaru Telescope's ability to image and study exoplanets. SCExAO currently feeds light to HiCIAO, and will soon be combined with the CHARIS integral field spectrograph and the fast frame MKIDs exoplanet camera, which have both been specifically designed for high contrast imaging. SCExAO also feeds two visible-light single pupil interferometers: VAMPIRES and FIRST. In parallel to these direct imaging activities, a near-IR high precision spectrograph (IRD) is under development for observing exoplanets with the radial velocity technique. Wide-field adaptive optics techniques are also being pursued. The RAVEN multi-object adaptive optics instrument was installed on Subaru telescope in early 2014. Subaru Telescope is also planning wide field imaging with ground-layer AO with the ULTIMATE-Subaru project.

Keywords: Adaptive Optics, High angular resolution, Laser guide star, Spectroscopy, Exoplanets, Coronagraphy

Further author information: (Send correspondence to O.Guyon)
O.Guyon: E-mail: guyon@naoj.org

1. INTRODUCTION AND OVERVIEW

The 8.2m Subaru Telescope, operated by the National Astronomical Observatory of Japan, is located on the summit of Mauna Kea (HI, USA). It offers a wide range of adaptive optics instruments, which we describe in this paper.

Figure 1 shows the current and near-future adaptive optics instrumentation. All adaptive optics instrumentation modes except RAVEN are fed by the AO188 system, a 188-element curvature system supporting both natural guide star (NGS) and laser guide star (LGS) modes. We descibe AO188 in §2 and the imaging and spectroscopy instruments it feeds: IRCS and Kyoto-3D. A large suite of instruments makes use of adaptive optics for exoplanet science, as detailed in §3, including the SCExAO high constrast imaging system and its modules, as well as the infrared Doppler spectrograph IRD. In section §4, we describe wide field adaptive optics instrumentation: RAVEN, a multi-object adaptive optics system currently in operation, and the Ultimate-Subaru project, which aims at delivering wide field ground-layer correction. Together the suite of current and future AO instruments offer unique observational capabilities in exoplanet science and wide-field high angular resolution astronomical imaging.

2. AO188

2.1 Overview

With the exception of RAVEN (see section §4.1), AO188 is the first stage of all current and near-future AO instrument configurations at Subaru Telescope. AO188[1,2] is a curvature-based 188-element general purpose single conjugate system, which can operate in natural guide star or laser guide star mode. Its optical layout is shown in Figure 2, and delivers a 2 arcmin field of view with a F/13.9 beam. The optical train, consisting of 8 mirrors and a beam splitter, includes an image rotator and also includes an atmospheric dispersion compensator. A calibration unit allows system-level tests without requiring on-sky operation.

Avalanche photo-diodes are used by the WFS to provide high speed low noise low latency wavefront measurements. AO188's bimorph deformable mirror, mounted on a fast tip-tilt stage, is operated at 1kHz frame rate.

AO188 delivers K-band SR of about 60% in good atmospheric conditions, and maintains K-band diffraction limit for natural guide stars down to $m_R \approx 12$ brightness.

2.2 Laser Guide Star mode

The sum-frequency 589nm 6.8W laser is located on the telescope IR Nasmyth platform next to AO188's optical bench. Light is transported to the 500mm diameter laser launch telescope by a single mode fiber. The laser launch telescope is located at the telescope's aperture center to minimize spot elongation. The LGS brightness is approximately equal to a $m_R = 12$ source as seen by the high-order wavefront sensor.

AO188's LGS mode allows near-IR diffraction-limited imaging over a large fraction of the sky. The K-band SR is approximately 45% in good atmospheric conditions, and is maintained for tip-tilt natural guide stars brighter than $m_V \approx 17$.

2.3 IRCS

The Infrared Camera and Spectrograph[3] (IRCS) offers imaging and spectroscopy in the near-IR (0.9 - 5.6 μm) after AO188. The camera and spectroscopy channels each use a 1024 x 1024 pixel array. The camera channel offers a 20mas plate scale (20 arcsec field of view) and grism spectral resolutions R = 100-2000. The spectroscopy channel is a cross-dispersed echelle providing spectral resolution up to 20000.

2.4 Kyoto 3DII

The Kyoto tridimentional spectrograph II (Kyoto3DII)[4] is an optical multi-mode spectrograph fed by the AO188 system. Kyoto3DII can operate in standard imaging, slit-spectrograph, integral field spectrograph (IFS) and Fabry-Perot observation modes. In IFS mode, it offers R=1200 from 640 nm to 920 nm, with a 3.1 arcsecond field of view sampled by 84mas lenslets. In Fabry-Perot, long-slit spectroscopy and direct imaging modes, the field of view is 1.7' with 50mas pixels. Kyoto 3DII is particularly well suited to study galaxy and star forming region dynamics.

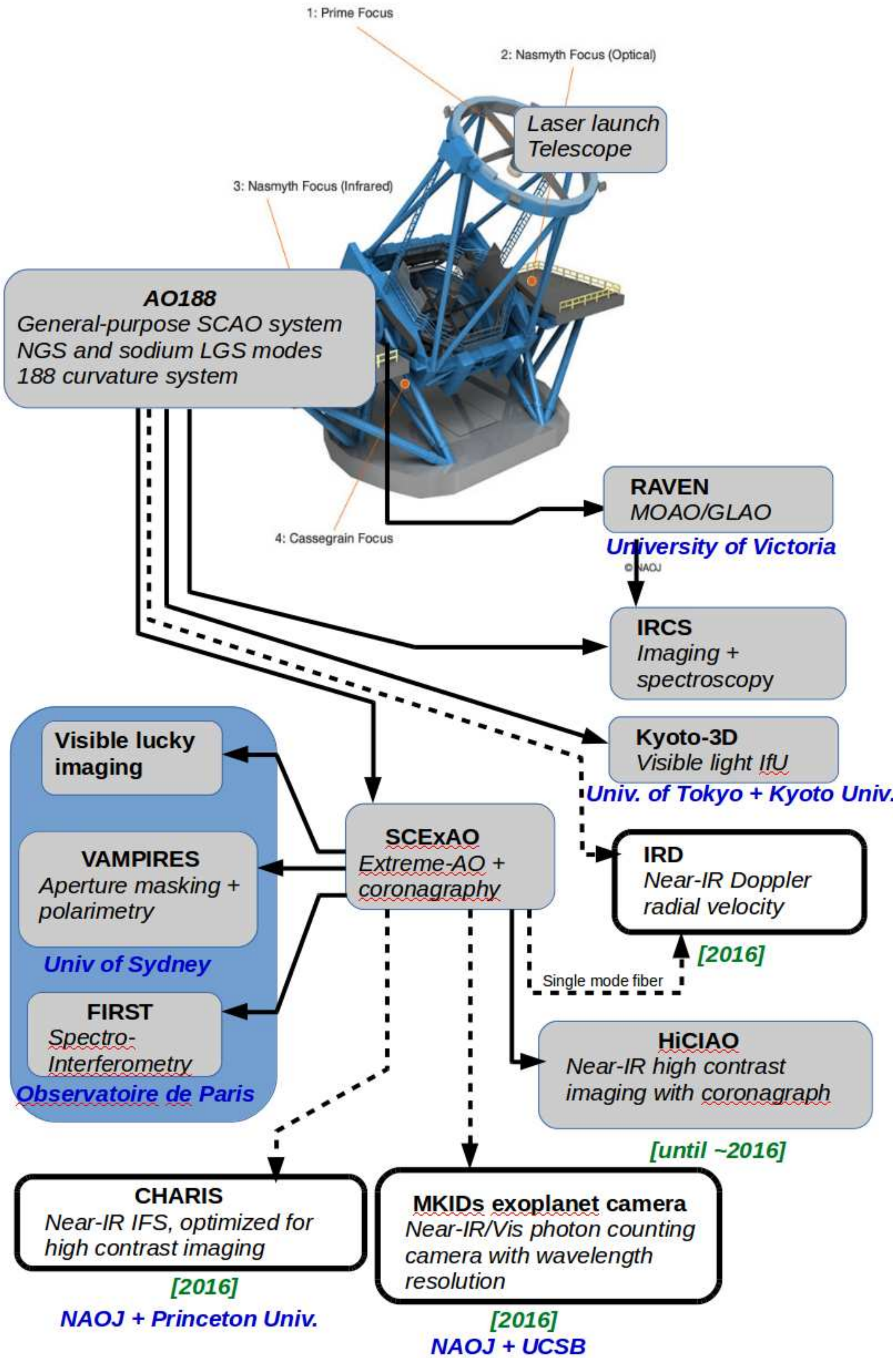

Figure 1. Current (shaded boxes) and near-future (white boxes) adaptive optics instrumentation at the Subaru Telescope.

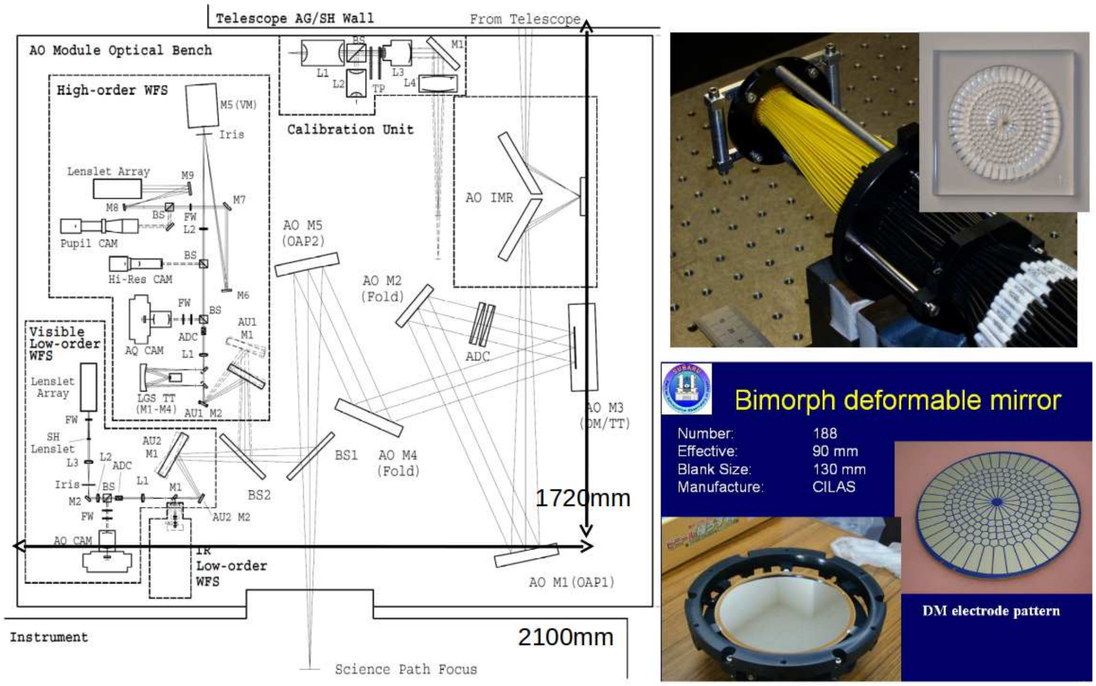

Figure 2. AO188 optical layout (left) and images of selected elements: 188-element lenslet array injecting light into multimode fibers for the wavefront sensor flux measurements (top right); 188-actuator bimorph deformable mirror (bottom right).

3. EXOPLANET SCIENCE INSTRUMENTS

3.1 HiCIAO

HiCIAO[5–7] is a differential imaging camera, equiped with a Lyot type coronagraph for high contrast imaging. Until 2014, HiCIAO was used directly after AO188, and it is now fed by SCExAO. Its Hawaii-2RG detector operates in J, H and K bands and delivers a 20 arcsec x 20 arcsec field of view. HiCIAO includes spectral differential imaging and polarimetric differential imaging modes. Its double Wollaston prism allows four images to be projected on the detector.

3.2 SCExAO

The Subaru Coronagraphic Extreme-AO (SCExAO)[8] instrument is a high contrast imaging systen, and is located downstream of AO188. SCExAO includes both extreme-AO wavefront sensing/correction and coronagraphy.

As shown on Figure 3, it consists of two optical benches. The lower bench contains all near-IR optics and coronagraphs, and is dedicated to high contrast imaging and near-IR wavefront sensing. Visible light is directed to the top bench, which contains SCExAO's high speed Pyramid wavefront sensor as well as visible light science modules described in section §3.3.

SCExAO features a multi-tier wavefront control system to deliver high contrast, well calibrated PSFs with little static speckles. Following AO188's initial wavefront correction (188 modes, visible light wavefront sensing), SCExAO uses a 2000-actuators MEMS type deformable mirror for further wavefront correction. A non-modulated pyramid WFS (currently in development) operates at 3.7 kHz to provide high sensitivity correction of the 2000 DM modes. To achieve this speed, a binned EMCCD is used as the WFS detector (120 x 120 pixel after binning), and a set of GPU boards performs the matrix multiplication required for closing the loop. A non-modulated PyWFS was chosen for its superior photon sensitivity. SCExAO also includes two slower near-IR WFSs: a low-order WFS uses light rejected by the coronagraph to measure and control low-order aberrations; and a

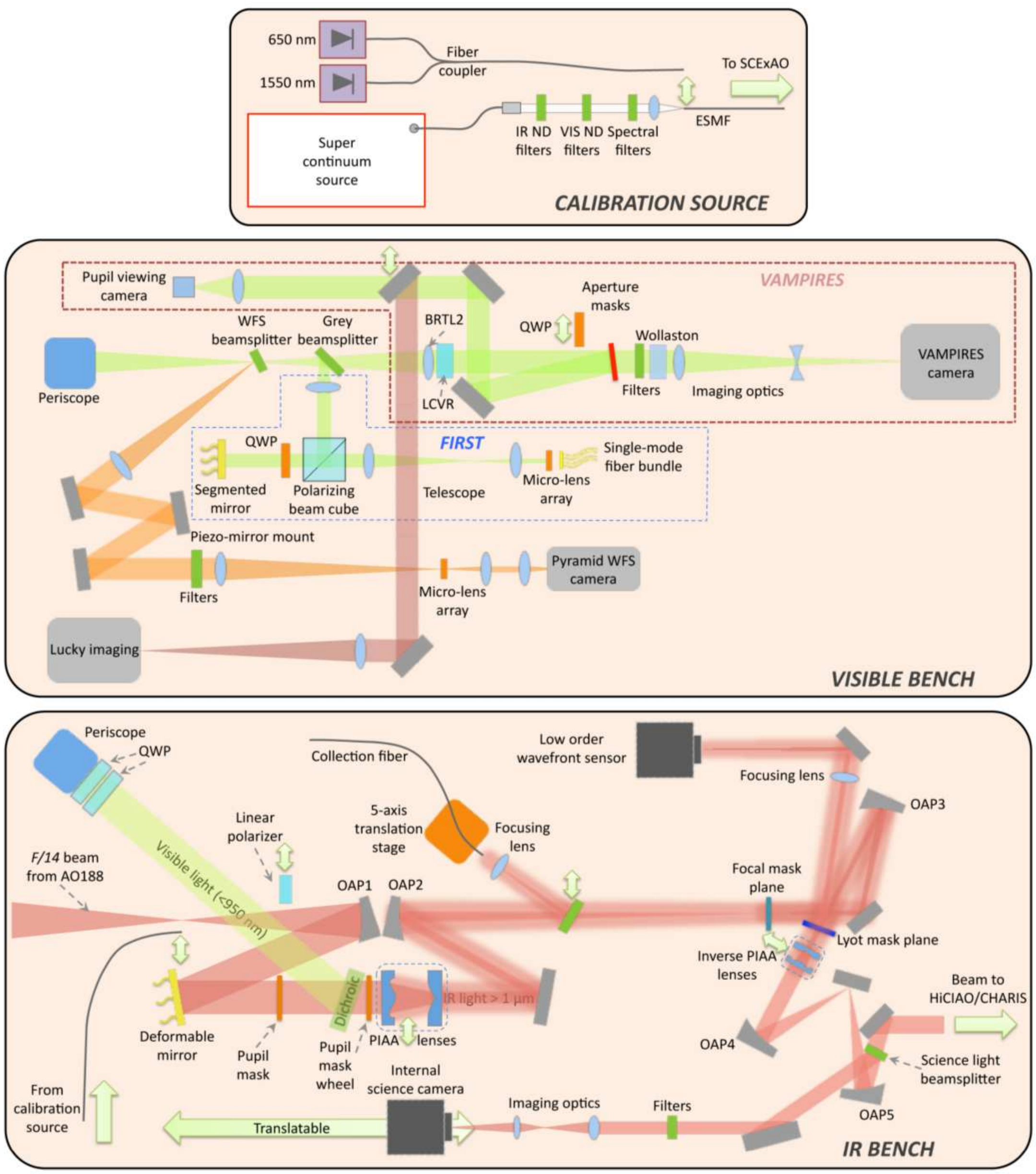

Figure 3. Optical layout of the SCExAO system.

speckle imaging camera is used to actively control speckles that are both modulated and canceled by the MEMS deformable mirror.

SCExAO feeds the HiCIAO imaging camera, which will be replaced in 2015 and 2016 by the CHARIS spectrograph and the MKIDs exoplanet camera, described in section §3.5 and §3.6 respectively.

3.3 SCExAO Visible Light Modules

3.3.1 Visible light "lucky" imaging

The SCExAO visible bench includes a fast frame imaging camera for lucky imaging. Even in less favorable atmospheric conditions, this module delivers diffraction-limited imaging at its shortest wavelength ($\approx$ 600nm) with post-processing. An efficient alternative to standard lucky imaging is used on SCExAO: individual spatial frequencies are selected within each image, instead of whole frame selection. The algorithm is detailed in a separate publication.[9]

3.3.2 FIRST

The FIRST module[10,11] reshapes the Subaru Telescope beam in a non-redundant linear pattern. This is achieved by injecting light from subapertures into a set of single mode fibers (one fiber per subaperture). This injection is performed on SCExAO's visible bench. Light is then transported within the fibers to a recombination bench, where the non-redundant linear pattern is created. The linear fringe packet is dispersed in the perpendicular direction, thus yielding a 2-D image encoding the complex visibilities for multiple baselines as a function of wavelength. This approach is particularly efficient, as nearly all of the telescope pupil can be used, and the spectro-interferometry allows wide spectral bands to be used.

FIRST was originally deployed on the Lick Observatory 3m Shane telescope, and is now part of the SCExAO system. It is especially well suited for stellar physics (many stars are well-resolved by Subaru Telescope's aperture in visible light) and close binaries.

3.3.3 VAMPIRES

The VAMPIRES module combines aperture masking imaging with differential polarimetry, and is particularly well suited to study circumstellar dust at small angular separations. A detailed description of the instrument can be found in a separate publication.[12] VAMPIRES's aperture mask is selectable, and can be chosen to consist of a few large holes for faint targets, or a larger number of smaller holes for bright targets, for which it is possible to obtain dense (u,v) plane coverage. The differential polarimetric measurement is obtained thanks to a Wollaston prism which projects two images on a fast-frame EMCCD camera. A liquid crystal variable retarder (LCVR) modulates the polarization states in the two images, and is syncronized with the EMCCD camera readout. A further (slower) stage of differential calibration is provided by a half-wave plate on SCExAO's near-IR bench.

3.4 IRD

The Infrared Doppler instrument (IRD), currently under construction, is designed to perform high precision radial velocity measurements in the near-IR (0.97-1.75 μm). With a $\approx 1m.s^{-1}$ precision, it will be able to detect Earth-mass planets around nearby M-type stars and measure their masses and orbital parameters (with the orbital inclination uncertainty associated with radial velocity measurements). The Subaru Telescope's large aperture, combined with IRD's operating wavelength, makes it sensitive to potentially habitable planets around these low-mass stars, which are too faint for visible light radial velocity surveys.

IRD is fed by AO188 through a multimode fiber. As shown in Figure 4, the spectrograph is located in the telescope Coude room, which provides a more stable environment than the telescope's foci. A fiber fed laser frequency comb provides the wavelength calibration for the instrument. The 70,000 spectral resolution is imaged by a 4096 x 4096 pixel HgCdTe (HAWAII4RG-15) detector. Single-mode fiber feeding of IRD with SCExAO is currently under development,[13] and would eliminate modal noise associated with multimode fiber injection, and remove the need for fiber scrambling. First light for IRD is planned in 2015.

A detailed description of IRD can be found in a separate paper presented at this conference.[14]

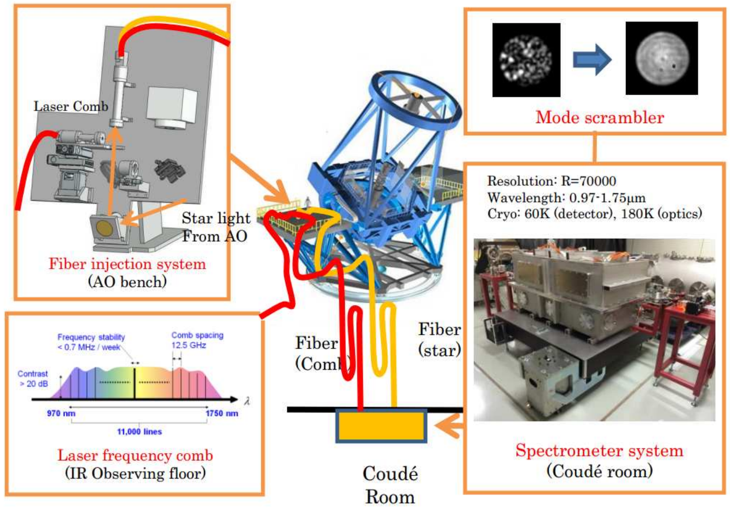

Figure 4. IRD overview.

3.5 CHARIS

The Coronagraphic High Angular Resolution Imaging Spectrograph[15] (CHARIS), is a lenslet-based, cryogenic integral field spectrograph (IFS) for imaging exoplanets on the Subaru telescope. CHARIS is fed by the SCExAO system, and will provide spectral information from 1.15 to 2.5 μm for 138 x 138 spatial elements over a 2.07 arcsec x 2.07 arcsec field of view (FOV), in two spectral resolution modes (R $\approx$ 18 (low-res mode) and R $\approx$ 73 (high-res mode)).

SCExAO's wavefront control and coronagraphic rejection, combined with CHARIS's spectro-imaging, will provide sufficient post-processed contrast to obtain spectra of young self-luminous Jupiter-mass exoplanets. CHARIS is projected to have first light at the end of 2015.

3.6 MKIDs exoplanet Camera

The Microwave Kinetic Inductance Detectors exoplanet camera is a photon counting, wavelength-resolving near-IR/optical low latency camera for simultaneous scientific imaging/low resolution spectroscopy of exoplanets and focal-plane based wavefront control. The camera, build and integrated to the SCExAO system in collaboration with University of California Santa Barbara's MKIDs group, will be deployed in 2016, and will augment SCExAO's high contrast imaging capability by providing the high speed low noise focal plane imaging necessary for active control and calibration of residual atmospheric speckles. The MKIDs techology has previously been demonstrated in a 2024-pixel camera,[16] and the Subaru MKIDs camera will use a larger $\approx$ 20000 pixels array.

4. WIDE FIELD ADAPTIVE OPTICS

4.1 Multi-Object Adaptive Optics: RAVEN

Raven is a Multi-Object Adaptive Optics (MOAO) scientific demonstrator build by the University of Victoria. First sky results are presented in a paper in this conference.[17]

Raven's design is shown in Figure 5. The instrument is mounted behind the telescope, and is currently the only AO observation mode that does not use AO188. Three steerable open loop NGS WFSs are used for wavefront sensing. Two steerable science fields are corrected with deformable mirrors (open loop control), and injected in IRCS for imaging and spectroscopy. Raven supports SCAO, open-loop GLAO and MOAO modes. The instrument's wide field of regard (3.5 arcmin) is significantly larger than other Subaru AO instruments field of view.

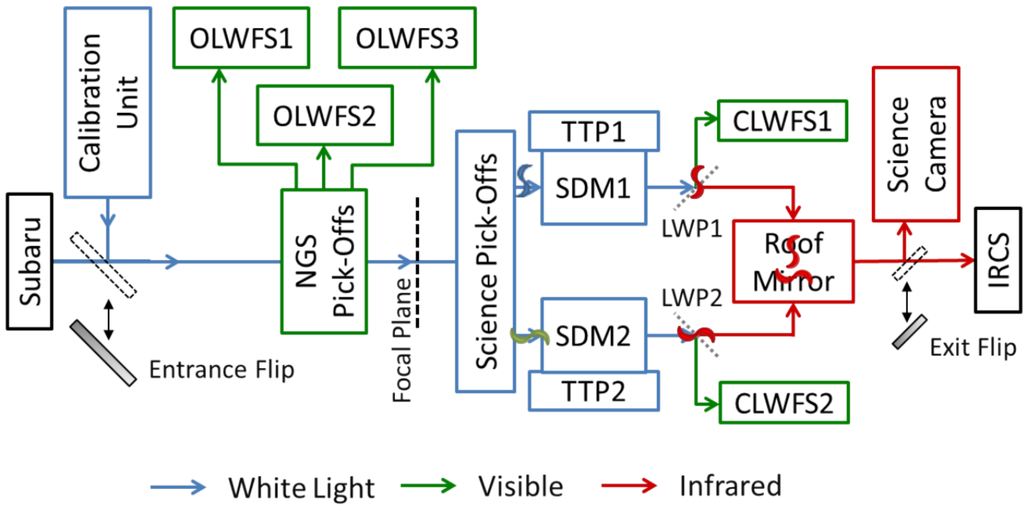

Figure 5. Raven design. See text for details.

4.2 Ground-layer Adaptive Optics development: Ultimate-Subaru

ULTIMATE-Subaru[18] (Ultra-wide-field Laser Tomographic Imager and MOS with AO for Transcendent Explorer for Subaru Telescope), is part of the trifecta of projects for Subaru Telescope in the era of TMT. The wide field capability of Subaru Telescope is unique for an 8 meter telescope, and both Hyper Suprime Cam (HSC) and Prime Focus Spectrograph (PFS) will take advantage of it. To optimize bright time use and satisfy the Subaru Telescope Astronomy community, a wide field near infrared camera (at prime focus) would have been very desirable, but feasibility studies indicate such an instrument would be prohibitive.

However, a wide-field near infrared instrument at the Cassegrain focus with an adaptive secondary mirror providing GLAO correction provides an attractive alternative. Despite of narrower field of view compared with prime focus, the improvement of the image quality provided by GLAO (roughly by factor of two in FWHM across the field of view, yielding resolutions down to 0.2 arcsecond in the K band) would provide a unique capability amongst 8 meter telescopes. A feasibility study and conceptual design have been under way since 2011. Performance simulations of GLAO show that fairly uniform images can be obtained over a 15 arcminutes field of view even with the Adaptive Secondary Mirror (ASM) mis-conjugated to -90m. However, the performance is strongly affected by an atmospheric turbulence profile, and it appears that even wider fields could potentially be corrected. The actual limits on the field of the instrument are due to the telescope's Cassegrain environment and the availability of detectors that could utilize such a field at the appropriate sampling. The ULTIMATE-Subaru system thus consists of a 1.2m adaptive secondary mirror (which could be used for single-conjugate narrow field AO mode for instruments equipped with on-board wavefront sensors and would benefit the throughput to SCExAO), 4 Shack-Hartman wavefront sensors and 4 LGS, nominally using the sodium layer, although Rayleigh beacons are also under consideration due to their suitability for GLAO. A wide field infrared imager, as well as a MOS (or starbugs IFU) would serve as the scientific detectors. The key components for GLAO, such as a deformable secondary mirror, control algorithm of GLAO, multiple laser system, wavefront sensor for multiple LGS and NGS, have had their technical feasibility demonstrated at other AO projects. The most challenging issue turns out to be the interface between these key AO components and the telescope: the impact on operations of modifying a working existing telescope system is not negligible. Nonetheless, work is ongoing to develop an feasible development & integration plan coordinated with maintenance and upgrades of telescope (including re-coating of primary mirror and replacement of obsolete telescope control system), as well as the commissioning and observation programs of HSC, PFS and other instruments

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