Ongoing and future AO projects at Subaru

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ABSTRACT

In this paper, we present our ongoing adaptive optics (AO) activities and future plans at Subaru Telescop toward the next 5-10 years and the extrem large telescope (ELT) era. AO188 has been operated since 2008 as a facility curvature-based single-conjugate AO (SCAO) system at Subaru Telescop. We are recently upgrading AO188 with recent technologies, such as real-time control software with high-performance computing technology, high-power TOPTICA laser system, and high actuator-count DM, to improve its AO performance and operability for the next 5-10 years. Also, a laser-tomography AO (LTAO) mode plans to be added to AO188 by installing additional 4 wavefront sensors (WFSs) behind AO188 to enhance the AO correction in visible wavelength. These upgrades are important also for development and validation of technologies toward the next facility ground-layer AO (GLAO) system at Subaru Telescope, called the ULTIMATE-Subaru project. The ULTIMATE-Subaru will develop wide-field near-infrared (NIR) instruments assisted by a wide-field GLAO correction to boost the wide-field capability of Subaru Telescope in NIR wavelength. The GLAO system will be driven by 4 laser-guide star (LGSs), 4 Shack-Hartmann WFSs, and an adaptive secondary mirror (ASM). The conceptual study of the GLAO system was completed in 201 is project and now we are going to move forward to the preliminary design phase. The first light of the ULTIMATE-Subaru will be at the Nasmyth infrared (NsIR) focus in 2025 and at the Cassegrain focus in 2027. In addition to these wide-field AO activities, we also are putting effort to high-contrast imaging capabilities with SCExAO, which is an extreme AO system (ExAO) placed behind AO188. SCExAO applies additional high-order correction after the AO188 correction and feeds diffraction-limited image to variety of modules in visible and NIR, optimized for a large range of science cases. SCExAO is also demonstrating new technologies, such as prediction control, sensor-fusion control, and high-speed control with GPU, toward future high-contrast imaging instruments for ELTs.

Keywords: Adaptive Optics, Subaru Telescope

1. INTRODUCTION

Subaru Telescope has been operating two adaptive optics (AO) instruments: AO188 and SCExAO. AO188 is a facility single-conjugate AO (SCAO) system working with a 188-elements curvature wavefront sensor (WFS) and a 188-elements bimorph deformable mirror (DM), shown in Figure 1. AO188 provides a natural guide star (NGS) mode (SR< 0.6 at K-band[1]) and a laser guide star (LGS) mode (SR<0.3 at K-band[2]). There are two science instruments operated with AO188: Infrared Camera and Spectrograph (IRCS[3]), shown in Figure 1, and Infrared Doppler (IRD[4]).

Another AO system operated at Subaru Telescope is SCExAO, which is a PI-type extreme AO (ExAO) system led by Olivier Guyon,[5] shown in Figure 1. SCExAO is operated behind AO188 and performs further high-order wavefront correction after AO188, working as a woofer system for SCExAO, to achieve extreme AO performance (SR> 0.8 at H-band) for the detection and characterization of exoplanets and stellar environments. The AO control is performed with a optical pyramid WFS, 2000-actuators Mems DM, and 3.5kHz high speed wavefront control. The main science instruments used with SCExAO are VAMPIRES and CHARIS, and in addition to two, other modules are in commissioning phase. The detail of the SCExAO system and related engineering/science modules are summarized in Julien et al. (2018).[6]

We have been working on upgrades of AO188 since 2017. The goals of the upgrades are 1) making the AO188 performance competitive and provide new capabilities for the next 5 years, 2) improving the downstream

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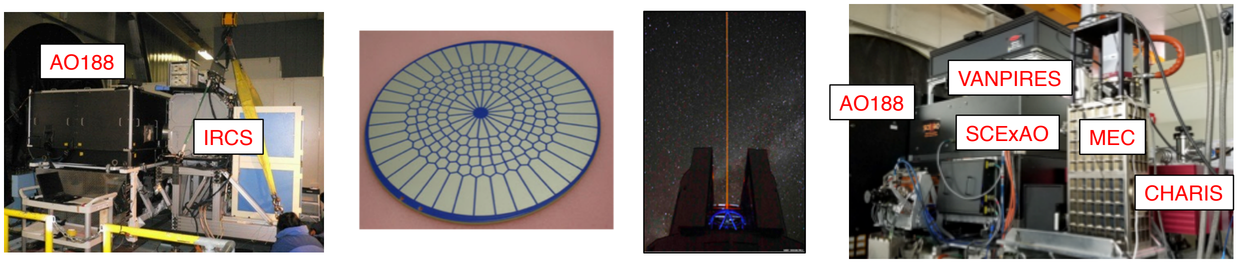

Figure 1. From the left, AO188 and IRCS at the Nasmyth platform of the Subaru telescope, Bimorph DM used in AO188, Laser guide star system at the Subaru telescope and SCExAO with science modules, respectively.

SCExAO high-contrast performance, and 3) developing and demonstrate new technologies for future AO systems at Subaru Telescope and extreme large telescopes (ELT), especially Thirty Meter Telescope (TMT). One of the upgrade projects is to add a laser-tomography AO (LTAO) mode into AO188, called ULTIMATE-START project, for better AO correction so that we can extend AO sciences to optical wavelength and also for demonstration of some key technologies for future AO systems at Subaru Telescope. We also working on a future facility ground layer AO (GLAO) project, called the ULTIMATE-Subaru project, aiming the first light in 2025.

In this paper, we present our ongoing AO activities and future plans at the Subaru telescope especially on AO188 and the ULTIMATE projects.

2. AO188 UPGRADE

AO188 has been operated since 2008 at the Nasmyth infrared (NsIR) platform of Subaru Telescope, and used for variety of science observations. However, since major upgrades has not been performed after the LGS mode was commissioned in 2011 and the AO system has been aging, more maintenance works are required to stabilize the system and the AO performance becomes worse. Especially, obsolescence of the LGS system has a non-negligible impact on the AO188 performance, and it is therefore imperative to upgrade the system. In addition, new capabilities are demanded from some science cases and the downstream ExAO system, SCExAO.

We started massive upgrades of AO188 in 2017 motivated by these situations and demands. The goals of the upgrades are

- improving AO188 (and downstream SCExAO) performance and operation and providing new capabilities for the next 5-10 years,
- developing and demonstrating new technologies for future AO systems at the Subaru telescope and TMT.

The upgrade includes replacing a real-time control system by a new high-performance, flexible system, upgrading the LGS system to one with more powerful laser, upgrading deformable mirror to one with more actuators, and installing a near-infrared (NIR) WFS. In addition, we are planning to install a beam switching system behind AO188 for more flexible instrument exchange behind AO188.

In this section, each upgrade project is shortly explained. Some of them are presented in this conference, and please see the proceedings for more details.

2.1 Real-time control system

The current real-time control system (RTS) has been operated since 2006 and achieves 1kHz AO control speed. However, it has several limitations. Access to the real-time telemetry data, which is crucial for optimization of AO control and operation, is very limited with the current system. Also, the system is not flexible to implement new functions. In addition, the current RTS is completely separated from the SCExAO RTS, and thus two systems need to be operated independently during the SCExAO observations, which is not efficient for operation and makes it difficult to optimize performance by combining wavefront control of AO188 and SCExAO.

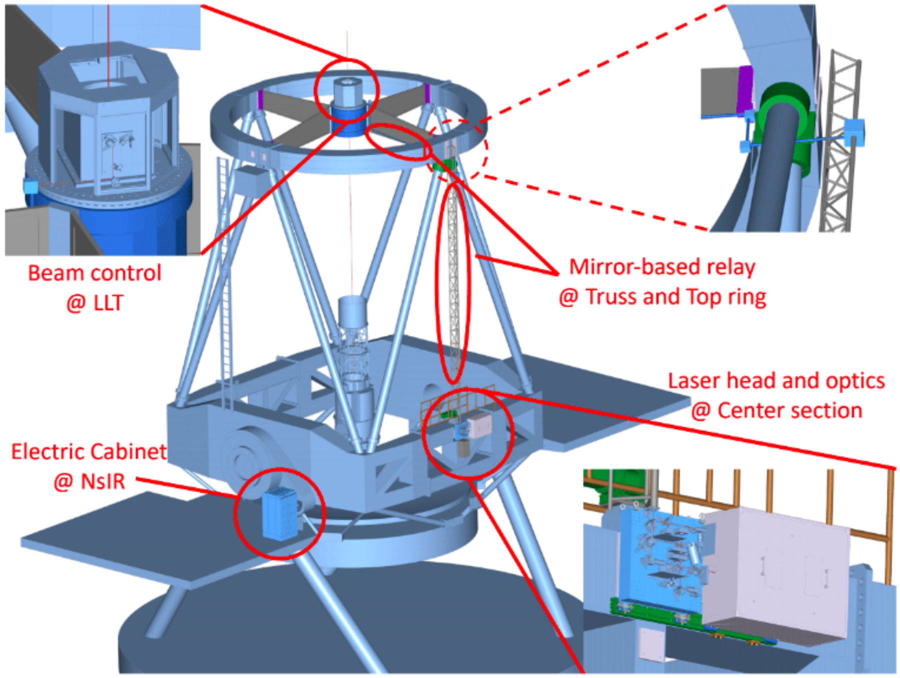

Figure 2. CAD model of Subaru Telescope and new LGS system components at NsIR, the center cection, the top ting, and LLT

In order to overcome these limitations and improve performance and efficiency of operation of AO188 and SCExAO, we are replacing the current RTC by a new system based on the CACAO software (Compute And Control for Adaptive Optics*),[7] which is an open software for AO control originally developed for SCExAO. CACAO realizes high-speed and precise-timing AO control on multi-core CPU/multiple-GPUs systems and provides the high-speed telemetry access and the advanced control functions, such as prediction control.

The basic development of the new RTS has been mostly completed. The AO loop for NGS and LGS mode with the new RTS was tested on sky. For NGS mode, it is validated that the new RTS provides a similar performance to one with the old RTS. More validation is still needed for LGS mode. We are now finalizing the integration of the new RTS into the Subaru control system for NGS mode and planning to open the NGS mode using the new RTS for open-use science observation in this year. Since the old LGS system was decommissioned in this summer for LGS upgrading, the final validation for the LGS mode will be completed when the new LGS system is ready.

We are also working on further performance investigation using AO188 and SCExAO high-speed, real-time telemetry, implementing the advanced AO control into AO188 using CACAO, and joint control of AO188 and SCExAO. These development leads to improving performance and operation efficiency of AO188 and SCExAO. Also, this RTS development links to the RTS development for ULTIMATE-START LTAO and ULTIMATE-Subaru GLAO system.

Further detail of this project is explained in Clergeon et al. in this conference.[8]

2.2 Laser guide star system

Our first generation LGS system used the sum-frequency solid-state laser technology to generate 589 nm sodium laser. The laser generation was performed in a clean and temperature-controlled room at the NsIR platform, and then the laser was transferred to the laser launch telescope (LLT) behind the telescope secondary through the optical fibre. Although the old laser initially provided 4W at the LLT (corresponding to roughly 10.4 mag in R-band[2]), the on-sky power gradually decreased down to 0.4W (R∼13–14 mag on sky) in 7 years. This caused

*https://github.com/CACAO-org/CACAO

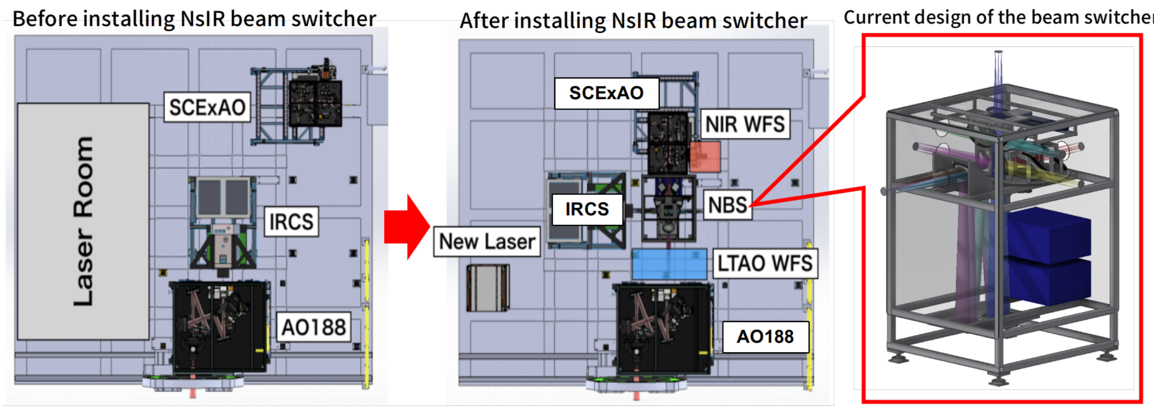

Figure 3. Schematic of configuration of the NsIR platform before installin the beam switching system (left) and after the installation (middle). Right: current design of the NsIR beam switching system.

a huge degradation in the performance of LGS mode. Also, another issue related to the old LGS system is that the laser clean room for the old laser occupied most of space on the NsIR platform and there is no space for future instruments. In order to overcome these limitations, we decided to replace this old LGS system by a new system based on a TOPTICA 20W laser,[9] which is used recently in most of 8-m and 10-m class telescopes.

The expected brightness of the new LGS will be 8.5 mag in R-band on sky. The laser head of the TOPTICA laser will be attached on the telescope center section, and the electrical cabinet, which contains pump diodes, drive electronics, and power supplies, and the heat exchanger will be placed on the NsIR platform. The electrical cabinet and the head exchanger are more compact than the old clean laser room, and therefore we will have more space on the NsIR platform for future instruments. One of the big change from the old to the new system is a beam transfer relay from the laser head to the LLT. Since the TOPTICA laser is too bright to use the fibre relay, a mirror-based relay optics needs to be designed. Figure 2 show the CAD model for the new LGS configuration.

The TOPTICA laser was already delivered to the Subaru office in 2017 and is being used for lab experiments. We are currently working on opt-mechanical design of the beam transfer optics and LLT. The first light of the new LGS system will be in the middle of 2020 and start to be used for science observations in the end of 2020.

This LGS upgrade is also considered as a technical demonstration for the future ULTIMATE-Subaru GLAO system, which will use two laser systems, including the TOPTICA laser we have, to generate 4 LGSs on sky. Further detail of this project is explained in Mieda et al. in this conference.[10]

2.3 Nasmyth-IR beam switching system

This is not an AO development but a key device for more efficient operation at the NsIR platform. Currently, two instruments are operated behind AO188: IRCS and SCExAO. Either of them is placed behind AO188 depending on the observation schedule, and the other is placed on the stand-by position on the NsIR platform, as shown in the left panel of Figure 3. The exchange of the downstream instruments is performed by crane work during daytime, requiring man power, taking almost a half day, and involving a risk to break the instruments. Also, since this work can not be done during night time, it constrains the observation schedule of using NsIR instruments. Therefore, queue-mode observation, selecting instruments depending on seeing condition and science case, is not possible with the current NsIR situation.

In order to solve this constraint and realize the flexible instrument exchange at NsIR for queue-mode observation, a Nasmyth beam switching system (NBS) is proposed (shown in the middle and right panels of Figure 3. The optical and mechanical design of the switching system is being conducted in collaboration with Australian Astronomical Optics (AAO), Macquarie University. The primary design of NBS consists of 3 spherical mirrors (Offner relay) and 3 flat mirrors to fold the beam. The current design allows for up to 6 different beam exit locations for IRCS, SCExAO, and future instruments/modules. In addition to switching the exit location, the switching system will be capable of splitting the light from AO188 into shorter and longer wavelength so that we can use two instruments attached to the beam switching system simultaneously. This allows us new AO capabilities; for example, SCExAO can be used as an additional WFS for observing with IRCS to provide advanced AO control and improved AO performance.

In addition, other AO188 upgrade projects, presented in the later of this paper, needs additional space for installing new WFSs somewhere in between AO188 and instruments, and NBS is a essential for these projects.

NBS will be installed into the NsIR platform in the end of 2021 or the beginning of 2022.

2.4 Near-infrared wavefront sensor

The near-infrared WFS is planned to be installed at the NsIR platform. The main science driver for this NIR WFS is observation of Galactic Center (GC), where there is almost no available guide star in visible due to strong interstellar extinction, to detect the general relativistic effect from the super massive black hole (SMBH) by monitoring radial velocity (RV) and the gravitational redshift of stars around SMBH. In 2018, one of the stars (S2) passed the pericenter of its orbit and is measured by IRCS in high-resolution spectroscopy mode. This result, together with the results from the other researches based on the proper motion, provides an essential data set to detect the general relativistic effect from SMBH.[11] The next similar event will happen in 2024, when the star S24 will pass the pericenter. However, S24 is 4-5 times fainter than S2. Moreover, there is no bright enough guide star in visible to obtain good AO performance for improving the signal-to-noise ratio (S/N). Since there is a NIR bright guide star around S24, the NIR WFS will play a key role for observing S24 in sufficient S/N to detect the gravitational redshift with a similar or better accuracy than S2. In addition, the NIR WFS will provide the improved AO correction to SCExAO and its science instruments.

In the current plan, the NIR WFS will be a pyramid WFS and installed between AO188 and instruments. One of possibilities is to install it in SCExAO as shown in Figure 3. NBS will be a key device to feed the NIR light to the NIR WFS at the same time as observing with science instruments. In NGS mode, the AO188 DM can be driven by the measurement from either of the NIR WFS or the current visible curvature WFS depending on the GS brightness in visible and NIR wavelength. In LGS mode, this NIR WFS can be used as the low-order WFS.

This project is already funded by the JSPS proposal. We are thinking C-RED ONE as a detector for the NIR WFS, and it will be delivered in 2020. The first light will be sometime in 2021∼2022.

2.5 Deformable Mirror

We are planning to replace the current AO188 DM by a new ALPAO DM with 64×64 actuators. One of the motivations to upgrade DM is to improve AO188 and SCExAO performance for high-contrast observations. This new ALPAO DM enables us to perform extreme AO correction only with AO188 for bright NGS, and then SCExAO can focus more on the wavefront control for high-contrast techniques. In order to realize this concept, the high-order WFS of AO188 has to be upgraded into one with higher spatial resolution so that the high-order WFS resolution matches with the ALPAO DM spatial resolution. Although the NIR WFS will be the one in NIR wavelength, we are considering to upgrade the visible WFS as well. Also, this DM will be a critical device for ULTIMATE-START project, which installs LTAO mode into AO188 and aims AO science in visible wavelength.

Another motivation to have the 64×64 ALPAO DM is to use AO188 and SCExAO as a testbed for a TMT high-contrast instruments, Planet Systems Imager (PSI). PSI is a modular instrument optimized for direct imaging and characterization of exoplanet and disks with the TMT. PSI will operate across a wide wavelength range (≈0.6-5μm) to image exoplanets and circumstellar disks in both reflected light and thermal emission. PSI will consist of two modules: PSI-red and PSI-blue. PSI-red will be a common AO module for whole instruments and perform AO correction in longer than 2μm for imaging and spectroscopy with a 128×128 ALPAO DM and a NIR WFS. PSI-blue will perform additional extreme AO correction after PSI-red for imaging, spectroscopy and polarimetric imaging in the 0.6μm–2μm range. PSI-blue is more challenging system and needs more technical validations. By combining the new 64×64 ALPAO DM and the new NIR WFS, AO188 can be a scale-down prototype of PSF-red. SCExAO will be a testbed for PSI-blue to develope and demonstrate cutting-edge technologies, required for the challenging high contrast performance of PSI-blue, using a 8-m class telescope.

Currently, we are discussing the specification of the 64×64 DM with ALPAO and planning to install it into AO188 in 2022.

3. ULTIMATE-START

ULTIMATE-START will install the LTAO mode into AO188. The science purpose of ULTIMATE-START is to enhance the AO performance especially in visible wavelength and investigate cosmological evolution of the dynamical structure of galaxies at high redshifts with high-resolution visible integral field spectroscopy (IFS). Also, this project is regard as a milestone project for ULTIMATE-Subaru to develop and demonstrate the key technologies for the future GLAO system. The first light of the LTAO mode will be in 2022.

The LTAO mode will use 4 LGSs generated by splitting the TOPTICA fibre laser, which is currently being installed into Subaru Telescope, into four and the LTAO WFS unit, containing 4 Sharck-Hartmann WFSs (SH-WFS), installed behind AO188. In addition, the low-order WFS and DM in AO188 will be reused for the low-order measurement and AO correction. The light corrected by the LTAO mode is redirected by NBS into the science instruments. So far, IRCS and Kyoto-3DII,[12] which is a visible IFS at Subaru Telescope, will be used with LTAO, but it is possible to add new instruments into the available slots of NBS in future.

Currently, the opto-mechanical design of the LTAO WFS unit is being finalized. Also, development of the LTAO WFS unit prototype, containing one SH-WFS, is on-going. This will be tested on sky at Subaru Telescope sometime in 2020 to characterize the upgraded LGS system and clarify the issues and challenging points of the design, alignments, and control to feedback it to the development of the LTAO WFS unit. The four-beam LGS configuration will be developed one the single-beam LGS configuration is validated on sky. The major changes from the single-beam to four-beam configurations are the beam splitting system, which splits the single TOPTICA laser beam into four by a set of beam splitters, and the asterism generation system, which control the direction of each beam with a set of steering mirrors. More detailed of the four beam configuration is summarized in Mieda et al. in this conference.[10]

The detail of this project is described in Ono et al. in this conference.[13]

4. ULTIMATE-SUBARU

ULTIMATE-Subaru is a project developing a future facility GLAO-assisted wide-field instruments that is in line with the wide-field strategy of the Subaru telescope. In visible wavelength, Hyper Suprime-Cam (HSC)[14] is providing a wide-field imaging capability, and a wide-field multi-object spectroscopy (MOS) will be covered by Prime Focus Spectrograph (PFS)[15] in a near future. Following these optical wide-field instruments, ULTIMATE-Subaru will provide the NIR wide-field capabilities. The combination of optical and NIR surveys with HSC/PFS/ULTIMATE-Subaru will deliver Subaru's original targets to follow-up on TMT and a good synergy with the future wide-field space surveys. Spatially-resolved studies of the objects found by HSC/PFS can also be performed with the GLAO correction.

The ULTIMATE-Subaru project will be proceeded with the following three phases. In the first phase, GLAO system will be the main development. The existing NIR imager and MOS at the Subaru telescope, MOIRCS, will be reused as the first science instrument for ULTIMATE-Subaru so that we can save cost and time to develop a new instrument at the first phase. The observation will start from the Nasmyth focus first, which is easier than the Cassegrain focus. Although the maximum science FoV at the Nasmyth focus will be 10×10 arcmin^2, MOIRCS can cover 4×7 arcmin^2 FoV, as shown in the right panel of Figure 4. At the second phase, the ULTIMATE-Subaru operation will start at the Cassegrain focus to achieve wider science FoV. A new wide-field imager for the Cassegrain focus will be developed to fully utilize the maximum 14×14 arcmin^2 science FoV at the Cassegrain focus shown in the left panel of Figure 4. At the phase 3, we plan to develop a fiber-bundle multi-object IFS for the Cassegrain focus.

The GLAO correction will be achieved with 4 LGSs generated by splitting 2 TOPTICA fibre lasers into 2 beams each, 4 SH-WFSs observing each LGS in different direction, and an adaptive secondary mirror (ASM) developed by ADOPTICA. The radius of LGS asterism will be adjustable from 2 arcmin to 10 arcmin. The low-order modes are measured by up to 4 NGSs located in the outer region of FoV, shown in Figure 4. The high-order

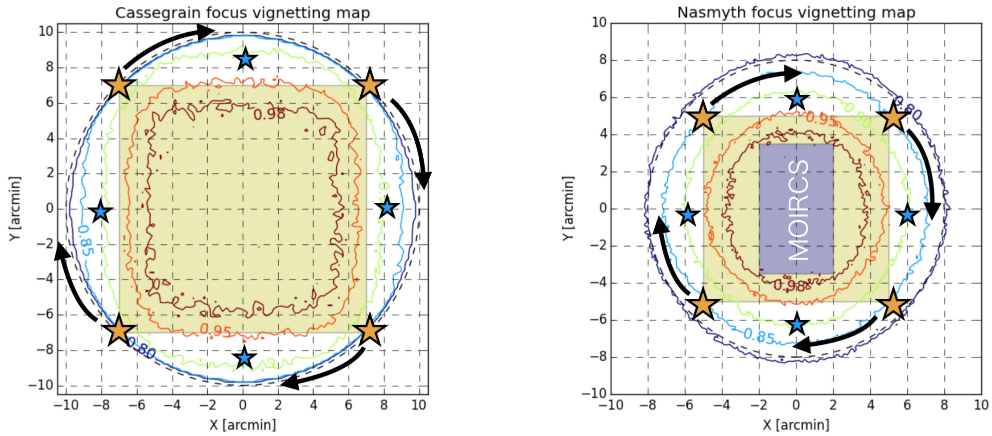

Figure 4. Vignetting map and schematic of the GS asterism at the Cassegrain focus (left) and the Nasmyth focus (right).

SH-WFS observing LGS has 32×32 sub-apertures, and science CMOS camera will be used as a detector. ASM will have roughly 1.2 m diameter and 927 actuators. The basic specification of the GLAO system is summarized in.

The conceptual study of the GLAO system was successfully completed in 2018, and now we move forward to preliminary design phase. Also, technical demonstrations of sub modules are proceeded through the AO188 upgrades and the ULTIMATE-START project.

5. SUMMARY

In this paper, we present our on-going and future AO activities at Subaru Telescope. Several upgrade projects for AO188 is on-going to improve the AO188 and SCExAO performance and opration for the next 5 years and also to provide new capabilities, including the new LTAO mode (ULTIMATE-START) and the NIR WFS. Through these upgrades, the key and novel technologies for the future GLAO system at Subaru Telescope (ULTIMATE-Subaru) and the high-contrast instruments at TMT (PSI) are developed and demonstrated. In addition, the ULTIMATE-Subaru project is actively proceeded and the conceptual design for the GLAO system has been completed. We are now stepping forward to the preliminary design phase. In the ELT era, Subaru Telescope will conduct wide-field surveys using HSC/PFS/ULTIMATE-Subaru and deliver Subaru's original targets to follow-up on TMT.

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