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ABSTRACT

This paper presents the overview of on-going and future adaptive optics (AO) activities at the Subaru telescope on the top of Maunakea in Hawaii. Currently, two AO systems are running at the Subaru telescope: AO188, a facility single-conjugate AO system with a bimorph deformable mirror and a curvature wavefront sensor with 188 elements, and SCEXAO, an additional extreme AO system operating behind AO188 and specialized for exoplanet sciences. We recently started AO188 upgrade project to improve its performance for the next 5–10 years, which will also help improving SCEXAO performance. These upgrades are in line with a development for the ULTIMATE-Subaru ground layer AO system.

Keywords: Subaru telescope, Adaptive Optics, AO188, ULTIMATE-Subaru, GLAO

1. INTRODUCTION

The adaptive optics (AO) history at the Subaru telescope started with the first generation single-conjugate AO (SCAO) system, AO36,¹ at the Cassegrain focus in 2001, based on a curvature-type wavefront sensor (WFS). After the decommission of AO36 in 2008, the second generation SCAO system, AO188,^{2,3} has started its science operation in the natural guide star (NGS) mode at the Nasmyth focus. In 2011, the laser guide star (LGS) mode of AO188 has been implemented. In the same year, Subaru Coronagraphic Extreme AO (SCEXAO),⁴ which is an extreme AO (ExAO) system, had the first light at the Subaru telescope. We also succeeded on-sky observations with an experimental AO system, called RAVEN,^{5,6} in 2014 and 2015. RAVEN was a technical/scientific demonstrator of multi-object AO (MOAO) system developed at the University of Victoria Adaptive Optics Lab and the National Research Council (NRC) in Canada in collaboration with the Subaru telescope.

Currently, AO188 and SCEXAO are operated at the Subaru telescope and are highly demanded for science observation. Updating these AO systems is important not only to strengthen their abilities for the next 5–10 years but also to lead to technical developments and demonstrations for the ULTIMATE-Subaru (Ultra-wide Laser Tomographic Imager and MOS with AO for Transcendent Exploration at SUBARU Telescope), a future near infrared (NIR) wide-field instrument at the Subaru telescope assisted with a ground layer AO (GLAO) correction.

Many upgrades for SCEXAO are on-going to provide high-contrast imaging, spectroscopy and polarimetry in order to detect and characterize exoplanets and also to provide a flexible platform for technology developments and validations toward a TMT high-contrast instrument. The current status and on-going upgrades of SCEXAO are summarized in literature.⁷ In this paper, we present on-going upgrades of AO188 and the current status of the GLAO system in the ULTIMATE-Subaru project.

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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.

2. AO188 UPGRADES

AO188, in the left most panel of Figure1, has been operated almost for 10 years since 2008. The main components of the system are a curvature-WFS with 188 subapertures and a bimorph deformable mirror (DM) with 188 electrodes shown in the second panel of Figure1. The LGS mode is driven by a sum-frequency solid-state 589 nm (sodium) laser whose on-sky laser power is 1–2 W (corresponding to 12–13 mag in R-band), shown in the third panel of Figure1. One of the facility instrument, Infrared Camera and Spectrograph (IRCS⁸), covers a wide spectral range (0.9–5 μ m) and is covered for a variety of science cases such as solar planets, exoplanets, Galactic and high redshift galaxies studies. The on-sky performance provided by AO188 is the K-band strehl ratio (SR) of <0.6 in the NGS mode and <0.3 in the LGS mode.^{2,3}

Currently two science instruments are used with AO188: IRCS, an imaging and spectroscopy in NIR (0.9–5.3 m), IRD (InfraRed Doppler),⁹ a new PI-type NIR high-precision radial velocity instrument for earth mass planets search around M-type dwarfs.

In addition, SCEXAO, shown in Figure1, is also operated behind AO188 and applies further high-order correction on top of AO188. More than 90% SR in H-band can be achieved by SCEXAO. Currently, two science modules are used with SCEXAO: VAMPIRES,¹⁰ a high-angular resolution interferometric imager in visible wavelength in combination with fast-switching differential polarimetry, and CHARIS,¹¹ a high-contrast NIR integral-field spectrograph (IFS). In addition to the two instruments, MEC¹² (MKID Exoplanet Camera) has been recently installed behind SCEXAO, which is designed as a J-band IFS for high contrast imaging and as a focal plane wavefront sensor. Additionally, IRD will be installed and operated behind with SCEXAO.

The upgrade of AO188 follows three aims:

- improving AO188 performance, stability, and operability for the next decade by replacing aging and old systems with new technologies.
- strengthening exoplanet sciences by achieving flexible joint-control between AO188 and SCEXAO
- developing and demonstrating new technologies for the ULTIMATE-Subaru GLAO system and future AO systems for Thirty Meter Telescope (TMT).

In order to achieve these aims, we are currently working on AO188 real-time controller (RTC) upgrade, LGS system upgrade, and ULTIMATE-START project which is a initial stage of the ULTIMATE-Subaru project to implement a laser tomography AO (LTAO) mode into AO188.

2.1 RTC upgrade

Although the current RTC achieves a pseudo real-time AO loop with a 1 kHz speed, we cannot access on-sky telemetry data in real-time which is essential to optimize the operation and performance of AO188. This limitation also interferes with the performance of SCEXAO that uses AO188 as a woofer system. Furthermore, because the current AO188 and SCEXAO RTCs are run completely separately, we are not receiving the full benefit of the combination of the two AO systems.

In order to overcome these limitations and improve performance of AO188 and SCExAO, we are replacing the current RTC by a new system based on a open real-time software CACAO (Compute And Control for Adaptive Optics*).¹³ CACAO is a C-based open software realizing high-speed AO control with shared memory and POSIX semaphores optimized with multi-core CPUs and multiple GPGPUs. This software is used to control SCExAO. CACAO supports many useful functions:

- High-speed AO telemetry access, which allow us the detail performance evaluation of AO188, the automatic AO loop optimization, the turbulence profiling, and the PSF reconstruction,
- Advanced AO control such as the prediction control to suppress the telescope vibration and the temporal delay in the AO loop.

In addition, using the same RTC software between AO188 and SCExAO will enable the joint-control of AO188 and SCExAO and will give us more flexibility in the control such as feedback from SCExAO WFSs into AO188 control.

The new RTC will also be the basis for control systems of future LTAO and GLAO systems at the Subaru telescope when the tomographic wavefront reconstruction into CACAO.

Currently, the interface software that connects shared memories in CACAO and each hardware in AO188 (such as APDs in the curvature-WFS and the bimorph DM) is developed. The first on-sky engineering test of the new RTC, using the NGS mode, is in July 2018, and the implementation of the LGS mode into the new RTC will be expected to complete after this summer. More details about the RTC upgrade is summarized in literature.¹⁴

2.1.1 Performance Evaluation

As a part of the RTC upgrade, we are working on the performance evaluation of AO188 to understand the current on-sky performance of AO188 by creating the wavefront error breakdown using a numerical simulation based on OOMAO¹⁵ (MATLAB-based AO simulation code) and the on-sky WFS telemetry data, which is expected to be

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

Figure 2. AO188 K-band SR as a function of NGS R-band magnitudes. The lines show the simulation results for different seeing conditions: good (blue), median (red) and bad (yellow). The black circles represent the on-sky performance under a good condition.²

obtained from the new upgraded RTC. This detailed performance evaluation is important to consider possible improvements and to conduct future upgrade plans.

Here, we present the first result of the AO188 performance evaluation for the NGS mode from the OOMAO simulation. The basic parameters used for the simulation are 8 m telescope diameter, a 188 elements curvature WFS, and a bimorph-like DM. The curvature WFS measurement is computed through the Fresnel propagation, and the influence function of the DM is computed by solving Poisson equation, i.e. a DM voltage is proportional to a local curvature. The turbulence profile used in the simulation is based on the statistics of seeing measured at the Subaru telescope and the seeing monitoring campaign at the Maunakea.¹⁶ The optical throughput model in the simulation is based on the actual measurements and values from the optical design of AO188.¹⁷ The simulated photon count on the curvature WFS has a good agreement with the on-sky measurement.²

Figure 2 shows the observed K-band SR as a function of NGS R-band magnitudes compared to the simulation results. The on-sky data were taken under a good seeing condition,² and therefore should be compared with the simulated performance under a good condition (the blue line) as well. When the NGS is bright, the simulation overestimates the K-band SR compared to the on-sky result. This is because either several components are not taken into account in the simulation and/or different from the actual values. For instance, the non-common path aberration and the telescope vibration are not included in the current simulation, and the DM influence function and the temporal delay in the AO control may be different from the actual values. In order to solve this discrepancy between the simulation and the on-sky results, more experiments are required to understand the system.

While we still need more work on bright NGS cases, the discrepancy between the simulation and the on-sky is smaller for faint NGSs. In the case of faint NGSs, the measurement noise dominates the residual wavefront error, and the influence of the measurement noise would be well simulated.

The on-sky telemetry given by the new RTC is essential to complete the performance evaluation and understand the system. In the future, the result of the performance evaluation will be extended to the performance optimization.

2.2 LGS system upgrade

The sum-frequency generation technique 589 nm Laser has been used for the LGS mode at the Subaru telescope. Although initially this laser provide 5.4 W on average (2.4 W/R=11.7 mag on sky), the power gradually decreases down to 4–5 W (1–2 W/R~13 mag on sky) now, and therefore the AO performance is degraded. Other issues of the current laser include the clean room for the laser system occupying a huge space at Nasmyth platform, and the operation and maintenance of the laser system being complicated.

Figure 3. K-band SR for the LGS mode, expected by a simulation using MAOS, as a function of AO correction order.

In order to solve these issues while improving the AO performance and the operability of the laser system, we are replacing the current laser system by a new powerful fiber laser system developed by TOPTICA/MPBC. The TOPTICA fiber laser is now used at many 8-10 m class large telescopes over the world and being a standard system for the LGS system. This laser is also expected to be installed into the future extremely large telescopes. The TOPTICA laser gives more than 20W power laser and will increase the LGS brightness to 8–9 mag in R-band. A numerical simulation shows that the K-band SR provided by a SCAO with the LGS mode will be improved from current 0.3 to 0.6, as shown in Figure3. The TOPTICA laser consists of a laser electrical cabinet and laser head and is more compact than the current sum-frequency laser system. By removing the current huge laser clean room from the Nasmyth platform, we can save a space on the Nasmyth platform.

The TOPTICA laser has been already shipped and installed at a laboratory in the Hilo office in the beginning of June, 2018. Optical and mechanical designs of the mirror-based beam transfer optics, which transfer the laser beam from the laser head at the center section to the laser launch telescope (LLT) behind M2 of the telescope, will be finalized in August 2018. The current LLT will be re-used with modifications. The lab tests and software development will be completed in 2018B and the installation and commission of the TOPTICA laser at the telescope will be in 2019. More details of the LGS system upgrade is summarized in the different paper.¹⁸

This TOPTICA laser will also be used in the future LTAO and GLAO system at the Subaru telescope. For the LTAO system of the ULTIMATE-START project, one laser beam will be split to 4 beams to generate 4 LGSs. For the GLAO system of the ULTIMATE-Subaru project, we plan to purchase one more laser system and generate 4 LGSs by splitting each of the two laser beams into 2 beams.

2.3 ULTIMATE-START

The effect of the atmospheric turbulence on images is more severe in visible than NIR, and the current AO188 correction is not enough to achieve a high SR > 0.4 in visible, as shown in Figure4. Especially for the LGS mode, even if we perform very high-order correction more than 500 AO correction order, the SR is still limited below 0.2 by the cone effect. In order to overcome this limitation, the atmospheric turbulence has to be measured tomographically using multiple LGSs by a LTAO system. The goal of the ULTIMATE-START project is to implement a LTAO mode into AO188 and improve the LGS AO performance in visible so that we can spatially resolve galaxies with a visible IFS.

In order to achieve a LTAO mode, we will install a new tomographic WFS unit behind AO188. The tomographic wavefront measurement is performed using 4 LGSs generated by splitting one TOPTICA fiber laser into 4 beams. The new 4 LGSs design is discussed in the different paper.¹⁸ The optical design of the tomographic

Figure 4. SR in a visible wavelength (700 nm) provided by a SCAO with single LGS (open squares) and a LTAO with 4 LGSs (filled circles) as a function of the AO correction order. The SR is expected by the same simulation as Figure3.

Figure 5. Schematic of SCAO system with single LGS and LTAO system with multiple LGSs.

Figure 6. Optical design of the tomographic WFS unit of the ULTIMATE-START LTAO system.

WFS unit is shown in Figure 6. The unit includes four 32×32 Shack-Hartmann WFS, focusing lenses, and an image rotator. The focusing lenses track the time variation of the Sodium layer altitude and the altitude change depending on the observing elevation angle. The image rotator corrects the rotation of the LGS asterism. The light coming from AO188 is split into the LGS light at 589 nm and a science light by a beam splitter. The light from 4 LGSs are observed with WFSs after the focusing lenses and the image rotator. For the LGS WFSs, science CMOS (sCMOS) camera will be used as a detector. The low-order wavefront aberration, which is not measurable from LGSs, will be observed by a low-order Shack-Hartmann WFS in AO188. The science light is observed by Kyoto-3DII,¹⁹ which is a visible IFS system at the Subaru telescope.

The expected performance of the LTAO system is shown in Figure 4. The LTAO system improves the AO performance up to a SR of ~ 0.3 at 700 nm compared to ~ 0.1 using the SCAO system with single LGS. We are also planning to replace the bimorph DM in AO188 by a new DM with >500 actuators. In this case, the LTAO performance is expected 0.5 SR at 700 nm.

The ULTIMATE-START project is a five years project funded by a Japanese grant and led by Tohoku university. Currently, the optical and mechanical design of the tomographic WFS unit is being developed, and will be finalized in 2018. The fabrication, assembly, and lab-tests of the system will be performed in 2019–2020, and the first light is planned in 2021.

This project is placed as the first step toward the future GLAO system as subsystems and techniques developed for the the LTAO system will be used also for the future GLAO system (e.g., the WFS unit based on sCMOS, the operating system and experience of the TOPTICA fiber laser, tomographic wavefront sensing and RTC).

3. ULTIMATE-SUBARU

All developments and upgrades described above are connected to the ULTIMATE-Subaru, a future facility GLAO-assisted wide-field instruments that is in line with the wide-field strategy of the Subaru telescope. In visible, Hyper Suprime-Cam (HSC)²⁰ is providing a wide-field imaging capability, and a wide-field multi-object spectroscopy (MOS) will be covered by Prime Focus Spectrograph (PFS)²¹ 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. At the first phase, mainly GLAO aspect of the project will be developed. The existing NIR imager and MOS at the Subaru telescope, MOIRCS, will be reused as the first science instrument so that we can save cost and time to develop a new

Figure 7. Vignetting map and schematic of the GS asterism at the Cassegrain focus (left) and the Nasmyth focus (right).

instrument at the first phase. The system will be installed into the Nasmyth focus first, which is easier than the Cassegrain focus. Although the maximum science FoV at the Nasmyth focus will be 10×10 arcmin², MOIRCS can cover 4×7 arcmin² FoV, as shown in the right panel of Figure 7. At the second phase, the GLAO system will be moved to 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 arcmin² science FoV at the Cassegrain focus shown in the right panel of Figure 7. At the phase 3, we plan to develop a fiber-bundle multi-object IFS for the Cassegrain focus.

The conceptual design of the GLAO system has been developed so far by the Subaru telescope in partnership with Tohoku university in Japan and Australian National University in Australia. We are currently talking to Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) in Taiwan to join our team. The basic specification of the GLAO system is summarized in Table 1. We will use four LGSs for a high-order measurement and four NGSs for a low-order measurement. The LGSs will be generated by two TOPTICA lasers by splitting each by two beams. We will use the one already shipped to our laboratory, and will purchase another laser system in the future. The turbulence correction is performed by an adaptive secondary mirror (ASM). We will need several telescope modifications to install the ASM and to achieve wide science FoV (14×14 arcmin² at the Cassegrain focus, 10×10 arcmin² at the Nasmyth focus).

Currently we are working on the conceptual design of the GLAO system including feasibility study and the design of the ASM, the optical and mechanical design of the GLAO WFS unit for both of the Cassegrain and Nasmyth focuses, the beam transfer optics to launch 4 LGSs, and a GLAO performance simulation. It is expected from the simulation that the GLAO provides 0.2 arcsec FWHM in K-band over 14×14 arcmin² FoV in a median seeing condition. More details of the GLAO conceptual design is presented in the paper.²²

The conceptual design review of the GLAO system is planned in the early October 2018. In parallel, technical developments and demonstrations for the subsystems of the GLAO system are on-going through the AO188 upgrades and the ULTIMATE-Start project. The first light of the phase 1 of ULTIMATE-Subaru will be in 2025.

Table 1. GLAO baseline specification

Item	Specification
Guide Star	4 LGSs (~ 10 W for each, ~ 500 photons/cm ² /sec) 4 NGSs ($r < 19$ mag)
Technical FoV	LGS: edge of FoV ($r < 10'$ at Cs, $r < 7'$ at Ns) NGS: 4 crescent areas at the outside of science FoV
WFS	LGS: 32×32 Shack-Hartmann ($0.''6/\text{pix}$) NGS: 2×2 Shack-Hartmann (Visible, $0.''15/\text{pix}$)
WFS frame rate	> 500 Hz
Deformable mirror	Adaptive Secondary with ~ 1000 actuators

4. CONCLUSION

In this paper, we present our on-going and future AO activities mainly on the AO188 upgrades and the ULTIMATE-Subaru project. The RTC is being replaced by a new system based on the CACAO software to enable variety of new functions and improve not only the AO188 performance but also the SCExAO performance.¹⁴ The LGS system is upgraded to the powerful TOPTICA fiber laser.¹⁸ Also, the ULTIMATE-START project, implementing the LTAO mode into AO188, started in 2017 and will perform its science observations in 2021. These upgrades lead to technical developments and demonstrations for the ULTIMATE-Subaru project, which is a future GLAO-assisted wide-field instrument at the Subaru telescope following HSC and PFS. Currently, works for the conceptual design of the GLAO system are on-going, and it will be reviewed in the early October 2018. The first light of the ULTIMATE-Subaru is planed in 2025.

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