Brief Summary of Subaru Next-Generation AO Study Report published in Aug. 2012

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1 Background: Subaru Telescope Future Instrument Plans

Subaru Telescope Science Advisory Committee (SAC) is an association of scientists in universities and institutions in Japan. As a representative of Japanese optical-infrared astronomical community, they have made advisory comments and recommendations to Subaru Telescope, NAOJ. In the recommendation report published in March 2009, SAC listed desirable future instruments of Subaru Telescope. There are four candidates, namely,

1. Very Wide-field optical imager (which refers Hyper Suprime-Cam),
2. Wide-field multi-object spectrograph (which refers WFMOS that now turns into Prime Focus Spectrograph),
3. Wide-field near-infrared (NIR) camera, and
4. NIR integral-field spectrograph.

The third and fourth candidates are NIR instruments. Unlike Hyper Suprime-Cam and Prime Focus Spectrograph, there has been little activity on the study of such future NIR instruments for Subaru Telescope. In response to such recommendation from Japanese community, Subaru Telescope initiated internal discussions on future instrumentations. During the course of such discussions, we recognized the significance of wide-field adaptive optics system and wide-field NIR instrument corresponding to such wide-field AO as a strong candidate of the Subaru future instrument in NIR wavelengths. Then we have formed the working group for the Subaru next-generation AO system which consists of not only scientists in Subaru Telescope but also some members in Japanese universities, and started conceptual study of the next-generation AO system.

We had the first science workshop for Subaru next-generation AO in September 2011 in Osaka, and based on science case discussions made there and thereafter and technical studies such as AO simulations and conceptual study of optical design of NIR instrument, we published the study report in August 2012 (in Japanese).

This document is an English translation of the executive summary section of the study report.

2 Subaru Telescope Next-Gen AO System

There are some different ways to implement Wide-Field AO, and each of them has its own characteristics. Among them the working group investigated extensively on two kinds of AO, namely, **Ground-Layer AO (GLAO)**, and **Multi-Object AO (MOAO)**.

GLAO will achieve seeing improvement over the entire $\phi \gtrsim 10'$ field of view (FoV) by correcting only for the disruption of wavefront caused by the ground layer of the Earth's atmosphere. Although the Strehl ratio achievable with GLAO should be much less than those by AO systems which provide diffraction limited images, GLAO can correct images over much wider FoV compared to the existing AO systems.

On the other hand, in MOAO, the wavefront errors not over the entire FoV but toward multiple specific objects within a patrol area are corrected.

We made numerical simulations to evaluate performance of these systems with Subaru Telescope.

2.1 Ground Layer AO (GLAO)

Our major findings from simulations for GLAO are as follows.

- Under a typical natural seeing condition (FWHM$\sim 0.4''$ in K-band), GLAO will be able to provide FWHM $\sim 0.2''$ in K-band.
- Factor of 1.5–2 gains are expected on ensquared energy for point sources, compared to observations under natural seeing.
- Approximately uniform wavefront correction over FoV diameter $\sim 20'$ will be achieved. Thus performance of GLAO would not be a primary factor in determining the FoV of the system; mechanical and optical limitations from the telescope structure and instruments would restrict available FoV.
- No significant performance degradation is expected with Tip-Tilt guide stars (TTGS) as faint as 18 mag., which is the limiting magnitude of the present AO188. Thus it is expected that the sky coverage of GLAO would be similar to that of AO188/LGS.

Since the fraction of the ground layer among atmospheric turbulence components is thought to be relatively high in Mauna Kea, Subaru GLAO could provide good performances. Additionally, we found that on-source wavefront correction with the adaptive secondary mirror (with ∼1,000 actuators) can be higher than that achieved with the AO188.

2.2 Multi-Object AO (MOAO)

Our major findings with simulations for MOAO are as follows:

- If we use 6 GLSs, wavefront correction better than that of GLAO system will be achieved for those within a patrol area of a radius smaller than $\sim 3'$.
- In order to achieve good wavefront error corrections, TTGS should be reasonably close to the target. Consequently, the sky coverage to be achieved with MOAO might be fairly similar to the FoV of the current AO188.

Through these studies we have understood expected performances of GLAO and MOAO with the Subaru Telescope in reasonably realistic observing conditions. MOAO will achieve high Strehl ratios for multiple targets, but for the case with 8m-class telescopes, their sky area where MOAO can perform well will be limited; MOAO should be a strong system for 30m-class telescopes. On the other hand, GLAO can provide seeing-improved wide-field images which would not be easily achieved with 30m-class telescopes. Such capability is greatly complimentary to 30m-class telescopes. We concluded that GLAO is the primary candidate for the Subaru next-generation AO.

GLAO is our primary candidate as Subaru Telescope Next-generation AO system. It will achieve FWHM $\sim 0.2''$ @K-band over the entire $> 10'$ field of view, under a typical seeing condition.

3 New Near-Infrared Instrument

With GLAO we expect almost uniform seeing improvement for FoV out to $\sim 20'$. MOIRCS, the current NIR imaging and multi-object spectrograph for Subaru Telescope, has FoV of $4' \times 7'$. In order to fully utilize the capability of GLAO, we definitely need to develop new wide-field instruments. There are much more challenges in designing wide-field NIR instrument compared to designing instruments for optical wavelength; fragile optical components with high throughput in NIR, need of cooling to suppress thermal emission, expensive detectors, and so on. We started optical design studies of the new wide-field NIR instrument for the Cassegrain focus of Subaru Telescope to assess its feasibility.

We found that there is a possible design with a $13'$ diameter FoV for the case with the same optical design parameters of the secondary mirror as those of the current infrared secondary mirror. It was also found that if we change the optical parameters of the primary and secondary mirrors, we will be able to achieve a $\sim 16'$ diameter FoV[1]. There is no such wide-field NIR instrument than the systems considered here. With the seeing improvement achieved by GLAO, this instrument should be very unique and competitive.

Although the current optical design is for imager and multi-object spectrograph using slit masks, from the science case discussions it has been pointed out that the Integral-Field Spectroscopy (IFS) is a key function. IFS will enable us to resolve internal structures of extended objects, and it has become an indispensable observing method for studying the galaxy evolution. There are some IFS instruments which can be used with the assistance of AO, such as VLT/SINFONI, Keck/OSIRIS, and Gemini/NIFS. The spatial resolution achieved by GLAO should not be as high as those by current single-conjugate AO systems, simultaneous IFS for multiple objects in wide FoV can be very unique and strong capability[2].

We also recognize that GLAO will be able to improve image quality in optical wavelength ($\lambda > 0.6\mu$m). Possibilities of new instruments in optical wavelength would be worth to be explored. Moreover, the use of adaptive secondary mirror could reduce the number of optics compared to classical AO systems, and thus thermal background radiation from telescope and instruments can be suppressed. That would benefit observations in wavelength longer than 2μm. The adaptive secondary mirror (ASM) would also achieve very high on-source strehl ratio. ASM / GLAO is not a single instrument but can be regarded as significant telescope upgrade, and it will open up various unique opportunities with Subaru Telescope.

We have found an optical design of the Cassegrain instrument with field-of-view of $13'$–$16'$. The GLAO-assisted wide-field NIR instrument should have exciting capabilities over existing instruments.

4 Science with Wide-Field AO and New Instrument

4.1 Complete Census of the Galaxy Evolution with Large-Scale Near-IR Surveys

Intensive studies of distant galaxies using 8–10m class telescopes, 4m class survey telescopes as well as space telescopes in the past 15 years have revealed the outline of global history of galaxy formation and evolution from the early stage of the universe to the present epoch. We now know that the cosmic star formation rate density or the average star formation rate for individual galaxies peaked around the cosmic age of 2–5 billion years ($z \sim 1-3$), and since then the global star formation activity is slowly declining. Stellar mass of individual galaxies has been growing, and morphologies of giant galaxies such as spirals and ellipticals have emerged. At the same time, it has been strongly suggested that super massive black holes which reside in the center of galaxies have evolved in close connection with star-formation activities. The big questions in the field of galaxy evolution include:

[1]These configurations are systems without split of the FoV.
[2]KMOS, a new NIR multi-IFS for VLT, will not be connected to AO systems

- what are the key parameters to drive the galaxy evolution among various phenomena that affect star formation activities in the galaxies?
- what determines morphologies of the galaxies?

Since distant galaxies are apparently small, many of past researches have been limited to observations of giant massive galaxies, and especially in many cases internal structures of such distant galaxies have been neglected. Recent development of adaptive optics and sensitive integral field spectrographs have enabled to resolve those distant galaxies.

With *imaging observations*, we can obtain morphological information such as size, radial profiles of light sources (stars and ionized gas), asymmetry, and color distribution. From the simulations of imaging observations with GLAO, we found that we will be able to measure effective radii for less massive galaxies compared to seeing-limited observations. Measurements of morphological parameters for huge number of galaxies in various epochs and in wide range of mass will enable us to clarify the evolutionary paths of stellar mass assembly, size, and morphology. We should also emphasize that we can install new narrow-band filters which are designed to capture important emission lines at specific redshifts to trace star formation activities in the multiple galaxies within the target field. Such addition of new filters (and also new dispersion elements for spectroscopy) are one significant advantage of ground-based facilities over the space-bourne telescopes.

With *spectroscopic observations*, abundant physical information such as star formation rate, amount of dust, metallicity, gas kinematics, and outflow from galaxies into inter-galactic space can be obtained. Especially, multi-IFS (or slit-scan observations using multi-slit masks) is an effective way to collect 'data cube' (spatial information and spectral information). IFS studies of distant galaxies have been made primarily for those with the most active star formation at those epochs, and because only one galaxy can be observed at a time, the number of sample galaxies are limited (several tens at most). If we consider the cost of telescope time, significant increase of the number of sample galaxies through such single-object IFS might not be expected. Survey using multi-IFS with a wide-field NIR instrument assisted by GLAO can be a very unique observing capability in 2020s.

It is well known that the history of galaxy evolution strongly depends on their environment. Systematics census of of (proto-)clusters of galaxies including their outskirt is a key observation to understand environmental effects, and GLAO + wide-field instrument is the best instrument for such studies. The large survey of galaxies at $z \lesssim 3$ with Subaru GLAO will produce the first statistically robust (possibly integral-field) spectroscopic database of distant galaxy populations.

4.2 Discovery of the Most Distant Galaxies and Understanding the Cosmic Reionization with Narrow-band Imaging Surveys

Deep observations in NIR are challenged by strong OH lines of the Earth's atmosphere. However, we can suppress background noise for imaging with narrow-band filters (NBF) which are designed to trace photons with wavelengths between such strong OH lines. In the study report we discuss the possibility of searching Lyman α emitting galaxies at $z > 7$ with NBFs. Researches based on the Subaru Telescope's unique capability of wide-field imaging using the prime focus camera have achieved discoveries of many of the most distant galaxies. For the redshift of the current most distant galaxies, however, Lyman α emission is redshifted to the very end of the wavelength coverage of the optical instruments. In order to push the frontier of the most distant galaxies further and to understand the process of the cosmic reionization, we definitely need sensitive observations in the NIR.

Applications of NBF are not restricted to the search of distant Lyman α emitting galaxies. Various studies such as systematic survey of star-forming galaxies with Hα emission should have a large benefit of wide-field near-infrared instrument assisted by GLAO.

4.3 Observing the Galactic Center

- Imaging and spectroscopy of globular clusters toward the Galactic center: kinematics of the Galactic bulge and dark matter distribution
- Nuclear star clusters as a key population to explore the co-evolution of the supermassive black hole and the Galactic bulge
- Wide-field astrometry of Hyper-velocity stars around the Galactic center

5 Synergy with the Extremely Large Telescopes

We aim at operation of Subaru GLAO around the end of 2010s or early 2020s. That is the epoch when Extremely Large Telescopes (ELTs) such as the Thirty Meter Telescope are expected to start their first-light observations. ELTs will have light collecting power and spatial resolution substantially superior to the current 8–10m class telescopes. Observations with ELTs will enable us to explore much fainter targets, and investigate very details of internal structure of various objects. On the other hand, wide-field (i.e., FoV larger than $\gtrsim 10'$) observation with ELTs are extremely challenging. Wide-field capability of Subaru Telescope has been extended by the telescope modification and installation of the new prime-focus camera Hyper Suprime-Cam (1.5 deg. diameter), and the massive fiber-fed spectrograph Prime Focus Spectrograph (PFS)[3] is under development. To implement observational capability which cannot be achieved by ELTs and to execute observations complimentary to those by ELTs should be key strategies for 8–10m class telescope in 2020s and later. A combination of Subaru GLAO and wide-field NIR instruments is one of the most significant projects which further develop the uniqueness and advantage of Subaru Telescope and feed astronomical targets to ELTs for detailed characterizations.

Wide-field instruments for survey are key instruments in the era of TMT and other ELTs. Subaru Telescope should work in cooperation with TMT and be complimentary to the TMT's capabilities. The Development of a wide-field near-infrared instrument is essentially important for Subaru Telescope.

6 Development Plan

6.1 Development Organization and Funding

- Core group: next-generation AO study working group (Subaru Telescope AO team + scientists in Subaru and universities in Japan)
- Subaru Telescope staff + NAOJ (Mitaka) staff + international partnership
- Fund-raising from external competitive grants from the Japanese government
- NAOJ budget for Subaru Telescope modifications should be considered.
- International partnerships are essentially important for both human resources and funding.

6.2 Development Schedule

In order to maximize scientific outcomes, it is important to develop the wide-field instrument with GLAO prior to the science observations of TMTs, to execute survey observations, and to construct list of target objects for detailed studies with TMT. We should construct a development plan to start science observation by 2020.

[3]The spectral coverage of PFS is 0.38μm – 1.3μm.