# Subaru Telescope
# Next-Generation Wide-Field Adaptive Optics
# Study Report
# (Draft)

Subaru Next-Generation AO Working Group

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# Contents

# Acronyms

| | |
|---|---|
| AGN | Active Galactic Nucleus |
| AO | Adaptive Optics |
| ASM | Adaptive Secondary Mirror |
| DM | Deformable Mirror |
| ExAO | Extreme Adaptive Optics |
| FoV | Field-of-View |
| FWHM | Full Width at Half Maximum |
| GC | Galactic Center |
| GLAO | Ground-Layer Adaptive Optics |
| HST | Hubble Space Telescope |
| IMF | (Stellar) Initial Mass Function |
| JWST | James Webb Space Telescope |
| LAE | Lyman $\alpha$ Emitter |
| LBG | Lyman Break Galaxy |
| LGS | Laser Guide Star |
| LGSAO188 | Subaru 188-element laser-guide-star adaptive optics system |
| LTAO | Laser Tomography Adaptive Optics |
| MAOS | Multi-Thread Adaptive Optics Simulator |
| MCAO | Multi-Conjugate Adaptive Optics |
| MOAO | Multi-Object Adaptive Optics |
| MOS | Multi-Object Spectroscopy |
| NBF | Narrow-Band Filter |
| NGS | Natural Guide Star |
| NFIRAOS | Narrow-Field Infrared Adaptive Optics System |
| PSF | Point Spread Function |
| SDSS | Sloan Digital Sky Survey |
| SED | Spectral Energy Distribution |
| SMBH | Super-Massive Black Hole |
| TMT | Thirty-Meter Telescope |
| TTGS | Tip/tilt Guide Star |
| WFE | Wavefront Error |
| WFS | Wavefront Sensor |
| WISH | Wide-field Imaging Surveyor for High-redshift |

# Chapter 1

# Executive Summary

## 1.1 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.

## 1.2 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.

### 1.2.1 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 $\sim$1,000 actuators) can be higher than that achieved with the AO188.

### 1.2.2 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.**

## 1.3 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 $2\mu$m. 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.**

## 1.4 Science with Wide-Field AO and New Instrument

### 1.4.1 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:

- 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

[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

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.

### 1.4.2 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 $\alpha$ 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 $\alpha$ 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 $\alpha$ emitting galaxies. Various studies such as systematic survey of star-forming galaxies with H$\alpha$ emission should have a large benefit of wide-field near-infrared instrument assisted by GLAO.

### 1.4.3 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

## 1.5 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

[3]The spectral coverage of PFS is 0.38$\mu$m – 1.3$\mu$m.

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.**

## 1.6 Development Plan

### 1.6.1 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.

### 1.6.2 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.

# Chapter 2

# Introduction

## 2.1 Future instrument plan for Subaru Telescope

## 2.2 Next generation AO system

## 2.3 Wide field Near Infrared Instrument

# Chapter 3

# Science with ULTIMATE-SUBARU

In this chapter we introduce science cases proposed to be carried out with Subaru Telescope Next-Generation AO (ngAO) and clarify specifications ngAO and associated new instruments should satisfy.

The GLAO system we are studying have following features (see Chapter 6 for details):

- Wide-field seeing improvement by correcting WFE caused by ground layer of the Earth's atmosphere. Seeing improvement will provide not only better angular resolution, but also the significant improvement of sensitivity especially for point-like sources. On the other hand, the WFE correction (and subsequently angular resolution) for individual sources are not as good as classical AO systems (such as AO188 of Subaru) which are designed to achieve diffraction-limited image for narrow-field.
- Number of optical component should be reduced by using the Adaptive Secondary Mirror. This means that thermal emission from telescope and instrument should be reduced, and that sensitivity at longer wavelength ($\gtrsim 2\mu$m) will be improved.

We have developed studies of the science cases under the recognition of these features, and with strong interactions with technical studies of the GLAO system and the associated instruments.

We have two primary scientific objectives (or 'Science Drivers') of this project. The one is 'Complete Sensus of Galaxy Evolution with Large-Scale Near-IR Surveys', and the other is 'Discovery of the Most Distant Galaxies and Understanding of the Process of the Cosmic Reionization'.

Because GLAO can provide images with better spatial resolution and improved sensitivity, the GLAO system can be a 'significant upgrade of Subaru Telescope' rather than an introduction of a new instrument. Various reseaches should be benefitted with the system. In Septermber 2011 we had a science workshop in the Japanese community titled 'Science Workshop for Subaru Telescope Next-Gen AO System' in Osaka, Japan[1]. We also had 'Subaru GLAO Science Workshop' in June 2013 in Hokkaido Univ. Some Canadian researchers as well as those from Taiwan has participated the workshop and presented their prospects. Through these workshops, we received important suggestions and proposals for wide-range of researches, such as galaxy evolution, growth of massive black holes, galaxy archaeology, the Galactic center, star-forming regions, and exoplanets. From this science workshop we started more extensive discussions on various science cases, and this chapter represents the current outcomes of such discussions and studies.

[1]http://www.naoj.org/Projects/newdev/ws11b/

## 3.1 Search for Galaxies at $z > 7$ with Narrow-Band Imaging

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### 3.1.1 Introduction

Subaru has been one of leading facilities pushing the frontier of the distant universe. A unique capability of the prime focus camera (Suprime-Cam) have enabled us to conduct wide-field survey which is essentially important to find very rare objects such as luminous distant galaxies. One of the efficient methods to find distant star-forming galaxies is to detect Ly$\alpha$ emission using narrow-band filter (NBF) imaging. A strongly star-forming object with a redshift $z = \lambda_{\rm NBF}/\lambda_{\rm Ly\alpha} - 1$ could appear to be bright compared to those with adjacent broad-band filters. Galaxies detected with this methods are called as 'Ly$\alpha$ emitters (or LAEs)'. The current most distant galaxy with a spectroscopic confirmation is an LAE at $z = 7.215$, which was discovered by **?** using Suprime-Cam with a narrow-band filter NB1006 (central $\lambda$ is 10,052Å).

Currently a new prime focus camera for Subaru Telescope in optical wavelength, Hyper Suprime-Cam (HSC), is under testing. HSC has more than seven times wider field-of-view, and it is expected to enable us conducting deep surveys much more efficiently than the current Suprime-Cam. HSC will have a NBF called NB101 which has a central $\lambda$ is 10,095Å, which will be used to detect many $z \sim 7.3$ LAEs. However, the wavelength of the redshifted Ly$\alpha$ is almost at the long wavelength limit of the CCDs, and finding galaxies at $z > 7.5$ with cameras with CCDs is impossible. So deep near-IR surveys are mandatory to push the redshift frontier further.

(Cosmic reionization)

### 3.1.2 Surveys with ULTIMATE-SUBARU

We will use special narrow-band filters which are designed to trace photons with wavelength ranges between the strong OH air glows from the Earth's atmosphere. Here we assume three wavelength ranges as a fiducial set to study the feasibility.

| $\lambda_c$ | FWHM | $z_{\rm Ly\alpha}$ |
|---|---|---|
| 1.0625 | 0.015 | 7.74 |
| 1.340 | 0.019 | 10.0 |
| 1.550 | 0.022 | 11.75 |

Table 3.1: Central wavelengths ($\lambda_c$ in $\mu$m), FWHM (in $\mu$m), and redshifts of Ly$\alpha$ emission at $\lambda_c$ for NBFs considered here.

[Very narrow band width filters]
[What should be clarified with ULTIMATE-SUBARU.]

### 3.1.3 Proposed Observations

[Target objects: sample selection, number of objects, number of observing fields, sky area.]
[Observing modes: imaging or spectroscopy.]
[Required observing time:]
[Special requirements for ULTIMATE-SUBARU other than baseline specifications, if any.]

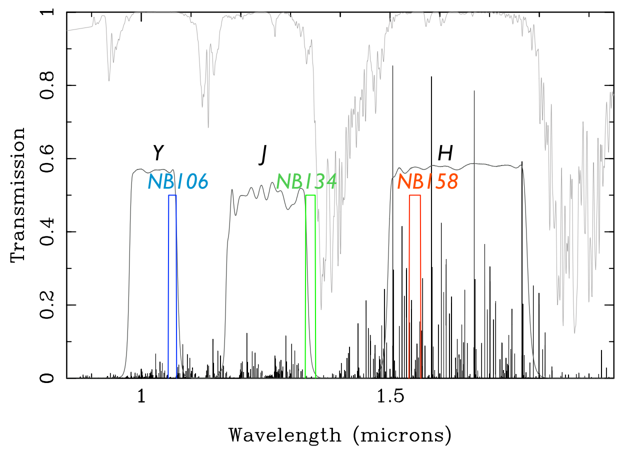


Figure 3.1: Transmission curves of NBFs considered. Transmission curves for $Y$, $J$, $H$-bands and the atomospheric transmission, and OH air glow strength (in arbitrary unit) are also shown.

### 3.1.4 Synergy and Competitions

#### Synergy with TMT

#### Competitions with other facilities

Instruments for 8–10m class telescopes.

ELT instruments.

Space-based projects.

## 3.2 Scientific Requirement

This section describes a top-level science requirement.

# Chapter 4

# System Overview

This section describes overview of the system.

## 4.1 Top level requirements

## 4.2 System Requirement

This section describes a top-level science requirement.

# Chapter 5

# Next-Generation AO Simulation Study

本章ではすばる望遠鏡次世代広視野補償光学系のためのシミュレーションに基づく検討結果をまとめる。補償光学装置 (AO: Adaptive Optics) の視野を広げるためには、大気ゆらぎの 3 次元構造を考慮する必要があり、この技術をトモグラフィーと呼ぶ。トモグラフィー技術を観測目的に応じて実装するこになるが、その方式には複数ある (??節参照)。その中で地表層補償光学系 (GLAO: Ground-Layer Adaptive Optics) と多天体補償光学系 (MOAO: Multi-Object Adaptive Optics) に対してシミュレーションによる検討を行った。

すばる望遠鏡に次世代広視野 AO を用いた赤外線観測装置が活躍し始める頃には、口径 30m 望遠鏡も始動すると期待される。すばる望遠鏡の将来計画を考える上では、目指すサイエンスとそれを実現する技術という両面において 30m 望遠鏡との相補性あるいは 30m 望遠鏡への発展を意識せざるをえない。GLAO と MOAO という 2 つの広視野 AO の方式もこの様な背景を踏まえてシミュレーションによる検討を進める候補として選択した。GLAO は視野直径 10 分以上という広視 AO の中でも最大の視野を達成できる方式である。補正性能は回折限界ではなくシーイングの改善であるが、この視野を活かすことで 30m 望遠鏡と相補的な科学的研究成果が期待できる。特にマウナ・ケアは大気ゆらぎ全体の中で地表層が占める割合が大きいことが知られており GLAO に適したサイトであると言える。MOAO は広い視野に亘って同時に複数の天体を観測することで観測効率を上げることができる方式である。各天体には回折限界の空間分解能が期待でき、面分光との相性も良い。MOAO の実現には新しい技術開発が必要である。暗い観測天体から離れた方向にある十分明るい複数の波面参照星 (ガイド星) から、観測天体方向の波面を推定するトモグラフィー技術、推定された波面を波面センサ (WFS) が見ていない方向の可変形鏡 (DM) で補正するオープンループ制御技術等が挙げられる。すばる望遠鏡において技術的、科学的経験を蓄積していくことで 30m 望遠鏡の次期観測装置に発展させることが期待される。

ここでのシミュレーションは広視野化検討のためであるので、いずれの方式に対しても視野をどこまで広く確保できるかが最も重要な確認すべき点になる。GLAO の場合は補正性能がシーイングに近いので、回折限界を扱う一般的な AO とは状況が異なりシーイングの影響も大きい。このような領域でシミュレーション結果が正しいか、またシーイングモデルをどう定義するかに注意が必要である。MOAO の場合は、個別天体に対する高ストレール比が魅力であるので回折限界の性能を維持できる視野がどの程度か、またそのために必要となる tip/tilt ガイド星 (低次ガイド星) の数等の条件が着目すべき点である。これらの項目をシミュレーションによって確認してそれぞれの方式の概要を把握した上で、検出感度やスカイカバレージなどのさらに詳細な検討へと発展させていくことになる。

Sec.**??**と Sec.**??**では、GLAO システムでの遠方銀河観測がどのようなものになるか、ナチュラルシーイングでの観測や回折限界が達成された場合と比較して検討する。Sec.**??**では撮像観測について、Sec.**??**では分光観測についてまとめる。

## 5.1 Simulations of Subaru Next-Gen AO System: GLAO

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**Abstract**

ここでは広視野補償光学系の中でも 10 分角を超える最も広い視野を確保できる地表層補償光学装置 (GLAO: Ground-Layer AO) の検討結果に関して記述する。この方式は上層の大気ゆらぎを補正しないため、回折限界の性能を得ることではなく広い視野にわたってシーイングを改善することを目的としている。GLAO の実現方法としては可変副鏡を導入する方向で検討を進めている。可変副鏡は GLAO 以外にも狭視野の天体に対して高いストレールを達成することができるので、十分明るい単一星に対する自然ガイド星 (NGS) 観測、コーン効果を低減するための複数レーザーガイド星 (LGS) トモグラフィ観測も合わせ検討するべきだと考えている。シミュレーション・コードは TMT の NFIRAOS のために開発された MAOS を使用した。

## Chapter 6

# System Design for Subaru Next-Generation AO

## 6.1 Components of GLAO: Deformable Secondary Mirror

## 6.2 Components of GLAO: Wavefront Sensing System

## 6.3 Components of GLAO: Laser System

## 6.4 Components of GLAO: RTC

Chapter 7

# Interface with Subaru Telescope

## 7.1 Telescope Modifications: Top Unit

## 7.2 Telescope Modifications: Cassegrain Focus

## 7.3 Telescope Control Software

## 7.4 Other Areas?

# Chapter 8

# Instruments for Subaru Next-Generation AO

## 8.1 Requirements on Instrument from Scientific Objectives

すばる望遠鏡次世代 AO システムを考える上で、これと組み合わせる新観測装置について検討することは、特に科学的要求の観点から非常に重要である。

Chapter 3 で見たように、すばる望遠鏡次世代 AO としては、広い視野にわたって改善された像質を達成する Ground-Layer AO(GLAO) が有力である。GLAO では、conventional な AO では実現できない広い視野での星像の改善が期待できる。可変副鏡を用いた GLAO での像質改善は、既存の観測装置を用いた観測においても大きなメリットをもたらすと期待できるが、より効果的な観測を行うためには、GLAO の仕様 (視野、典型的な像質など) に最適化した新たな観測装置を開発することで GLAO の特長を十分発揮できるようにすることが必要である。

ここでは特に近赤外線撮像分光装置についての検討を記述する。Section **??**にてまとめた科学的要求に応えるために近赤外線装置に必要な主な仕様は以下のようにまとめられる:

- カセグレン装置としてできるだけ広視野化を図る
- 多天体分光機能
- (多天体) 面分光機能
- 波長域: 0.9–2.5$\mu$m
- 分散: 500-3,000
- 狭帯域フィルタを含むフィルタ交換の高い自由度
- 空間分解能: GLAO として 0.2$''$ @ $K$-band、狭い視野での観測モードでは 50–60 mas

これらの中でも特に、広視野化の feasibility が本計画の要であるといえる。Chapter 5 で見たように、シミュレーションによると、GLAO による像質の改善は、視野の広さへの依存はあまり大きくなく、20 分角 $\phi$ 程度の視野でも均質な像質改善を達成できるという結果が得られている。よって、GLAO+新装置で達成可能な視野の広さは、観測装置側でどこまで視野を拡大できるかでほぼ決定されると考えてよい。以下では特に、すばる望遠鏡のカセグレン観測装置において、どこまでの広視野化を図ることが可能かを調査する。

## 8.2 Studies of the Optics for the Wide-Field Near-IR Instrument

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以下の検討結果は、オプトクラフト社による「すばる望遠鏡 次世代広視野補償光学用近赤外線装置 基礎検討」(文書番号 CP0046–11–RP001) からの抜粋である。なお、報告書には各設計での光学パラメータテーブルも掲載されている。

### 8.2.1 Optical Design without FoV Split

### 8.2.2 Optical Design with FoV Split

## 8.3 Studies of the Mechanics for the Wide-Field Near-IR Instrument

**TBD**

# Chapter 9

# Operation

## 9.1 Operations of GLAO

## 9.2 Operations of NIR instrument

## 9.3 Laser operation

## 9.4 DSM exchange

## 9.5 Instrument exchange

## 9.6 Maintenance

# Chapter 10

# Technical Challenges and risk

## 10.1 AO tomography

## 10.2 Calibration method of deformable secondary mirror

## 10.3 Exchange strategy of deformable secondary mirror

## 10.4 Wavefront sensor unit in Cassegrain frange

## 10.5 Realtime computer

## 10.6 Sodium LGS or Rayleigh LGS

## 10.7 Wide FOV instrument design

## 10.8 MOS exchanger

## 10.9 Integral Field Spectrograph

## 10.10 High contrast instrument and Extreme AO mode

## 10.11 MOAO mode

## 10.12 Compatibility with existing instruments

# Chapter 11

# Development plan

## 11.1 Management plan

## 11.2 Budget plan

## 11.3 Schedule

## 11.4 Risk management

## 11.5 Descope option