ULTIMATE-Subaru : Requirement analysis of the WFS system for GLAO

Yoshito Ono[1], Yosuke Minowa[1], Yoko Tanaka[1], Koki Terao[1], Hiroshige Yoshida[1], Masayuki Akiyama[2], Noelia Martinez Rey[3], Nicholas Herrald[3], Celine D'Orgeville[3], Francois Rigaut[3], Israel Vaughn[3], David Chandler[3], Dionne Haynes[3], and Warrick Schofield[3]

1)Subaru Telescope (National Astronomical Observatory of Japan), 2)Tohoku University(Japan), 3)Australian National University

ULTIMATE-Subaru

ULTIMATE-Subaru (**U**ltra-wide **L**aser **T**omographic **I**mager and **M**OS with **A**O for **T**ranscendent **E**xploration) [1] is a project to develop the next generation wide-field near-infrared instrument for the Subaru Telescope. ULTIMATE-Subaru will implement a Ground Layer Adaptive Optics (GLAO) system covering a wide scientific field of view of 14 x 14 sq. arcmin. The GLAO development is currently in the preliminary design phase. In this poster, we present how the WFS specifications are determined / optimized based on the numerical simulations and analytical methods and summarize the requirements for GLAO WFS system for further optical/mechanical design work [2][3].

Top-Level Requirements

Item	Requirements
Science wavelength coverage	1 – 2.5 um
Science FoV	14 x 14 sq. arcmin
Image Quality (FWHM)	FWHM = 0.25"※1 EE50 = 0.5" (K-band, 50%-ile seeing condition)
Sky coverage	> 90%

Tab.1 : Top-level performance requirement [4]

※1 Including the image quality of the science instrument (Gaussian PSF with 0.1" FWHM)

Basic Parameters of ULTIMATE-GLAO

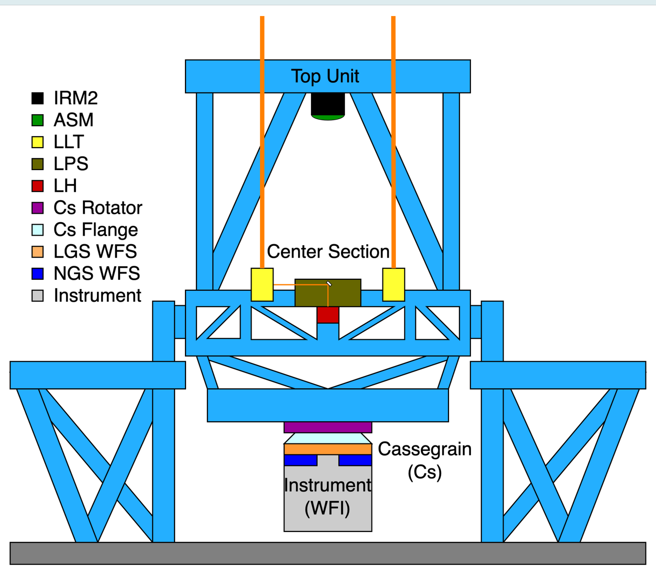

Fig.1 ULTIMATE-Subaru Configuration

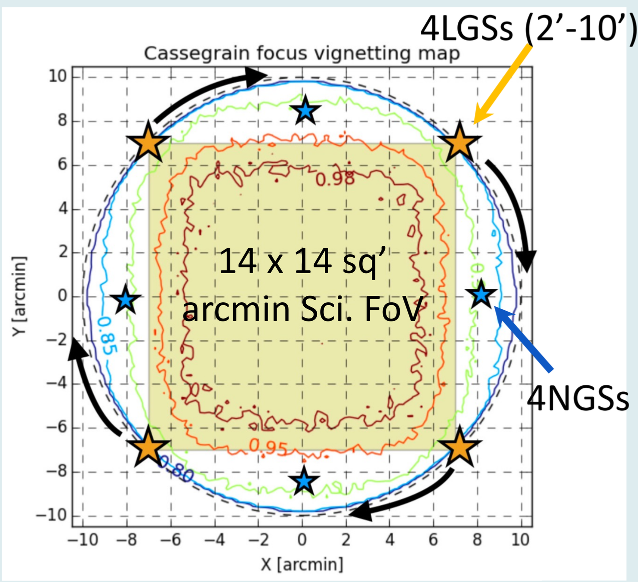

Fig.2 Field Configuration

DM	Values	
Number of actuators	924	
Control mode	350 KL modes	
Guide Stars	**Values**	
	NGS	**LGS**
Number of GSs	Up to 4	4 (using 2 Toptica lasers)
Asterism	See Fig.2	
Brightness	Up to 18 mag in R-band	720 ph/s/cm²/LGS at the telescope M1
WFS	**Values**	
	NGS	**LGS**
Number of WFSs	1 (Tip/Tilt/Focus) 3(Tip/Tilt)	4
Patrol area (radius)	7' – 10'	2' – 10'
Number of sub-aperture	2x2(Tip/Tilt/Focus) 1x1 (Tip/Tilt)	32 x 32
Framerate	≦ 500Hz	500 Hz
Detector	Science CMOS, readout = 1.6e⁻rms	

Tab.2 : Parameters pre-determined in the GLAO conceptual design study [5]

LGS WFS FoV Optimization

The FoV size of the LGS WFS is determined to cover the expected spot movement on the detector, which depends on

- Initial spot offset due to the telescope/WFS optical aberrations (S_0)
- Variance of the spot movement due to the atmosphere (σ_s)
- LGS spot size (S_{lgs})

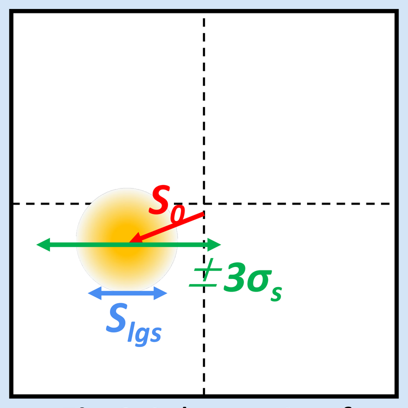

Fig.3 Schematic of WFS FoV breakdown

Item	Values	Source
S_0	0.276"	Max value from the Zmax model Mainly astigmatism mode
$3\sigma_s$	GLAO = 1.803" Seeing = 1.935"	From analytical evaluation. Assume 3σ value under the worst seeing condition
S_{lgs}	1.0"-2.0"	From the numerical simulation

Table.3 WFS FoV breakdown

With the largest LGS spot (2.0"), the WFS FoV of 7" is required to cover the expect spot shift on the WFS detector with the compensation of the initial offset due to the telescope aberration (see [2]).

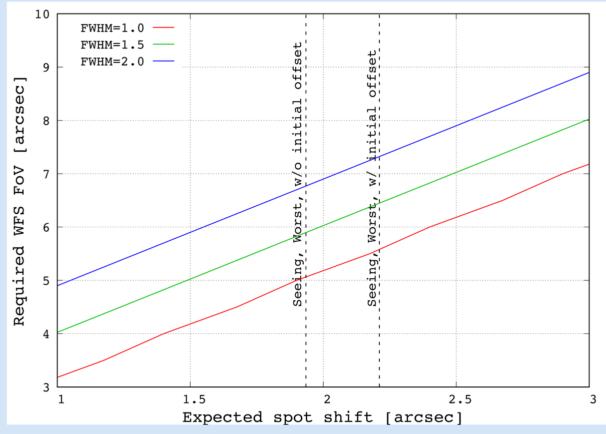

Fig.4 CoG simulation for LGS WFS with a given FoV, spot shift, and spot size. Required WFS FoV (CoG error due to the spot truncation < 0.05") as a function of the spot shift [$3\sigma_s$ (+S_0)] in arcsec for different spot size from 1.0" to 2.0".

WFS Pixel Scale and Spot Size

LGS WFS noise vs GLAO performance

Fig.5 show the GLAO performance as a function of the CoG error of LGS WFS. The LGS WFS error is a minor error term and we can achieve the science requirement even with 0.2" CoG error.

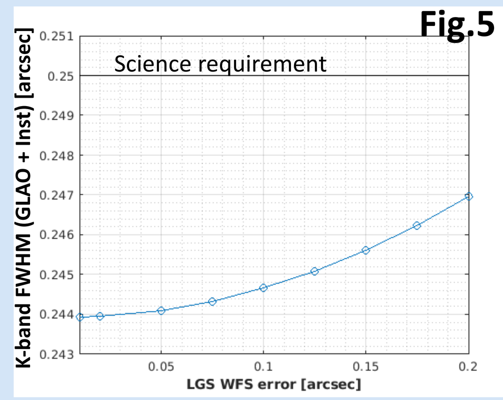

Fig.5

LGS WFS pixel scale and spot size

A pixel scale of 1.0" is reasonable. The spot size might become larger than the original LGS size due to the LGS WFS optical aberration. However, the science requirement (0.25" FWHM at K) can be achieved even with a spot size of 3.0". We set the maximum spot size on LGS WFS as 2.5" (corresponding to spot size 1.5" due to optical quality assuming the original LGS spot size of 2.0").

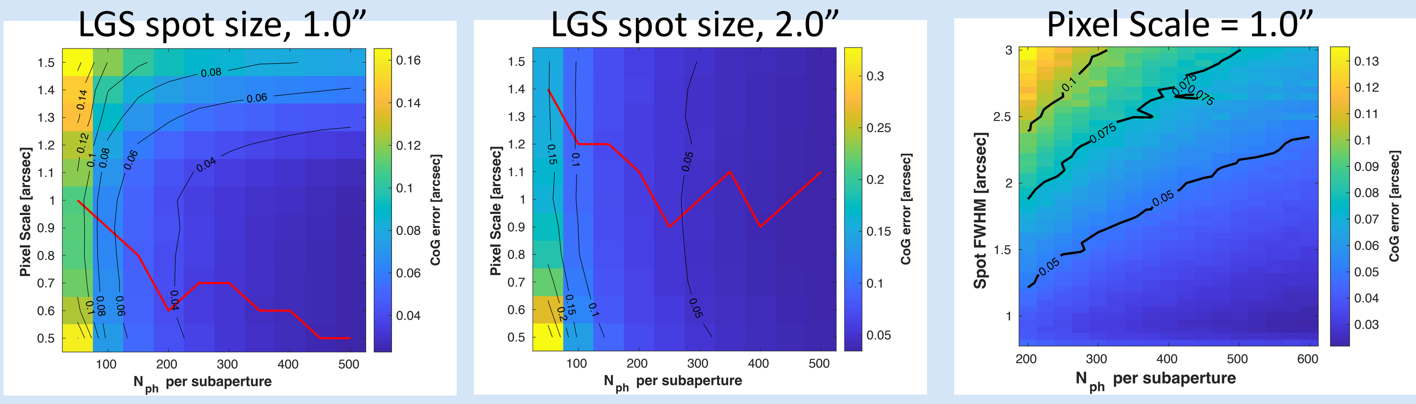

Fig.6 Left and Middle: CoG error of LGS WFS vs the pixel scale and photon count for spot size of 1.0" and 2.0". Right: CoG error of LGS WFS vs the LGS spot size and photon count assuming 1.0" pixel scale. The red lines : the best pixel scale for each photon count.

NGS WFS pixel scale and spot size

Basically, the larger pixel scale provides better GLAO performance because of the number of photon. Considering a difficulty of the optical design to realize the large pixel scale, we select a pixel scale of 0.3" with 4x4 binning (i.e. 0.075" pixel scale before binning). Also, in order to minimize the performance loss, the spot size on the NGS WFS has to be less than 0.7" (corresponding to spot size of 0.36" FWHM for optical quality assuming the NGS spot size due to the atmospheric turbulence is typically 0.6" in the median condition).

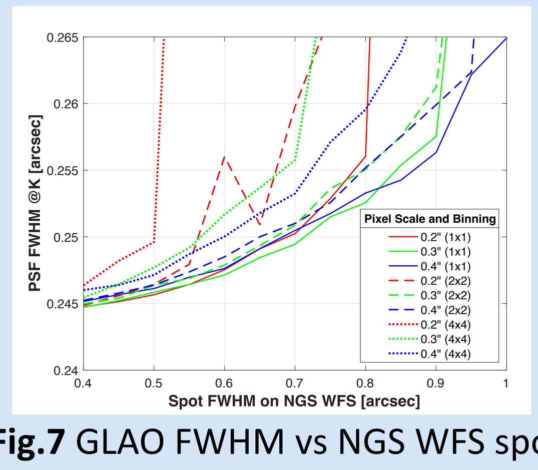

Fig.7 GLAO FWHM vs NGS WFS spot size for different pixel scale and binning estimated by the CoG simulation. Four faintest NGSs (R=18.3mag) required to achieve 90% sky coverage in deep survey field toward the galactic pole is assumed.

Mis-registration due to Pupil Shift

The pupil shift on the LGS WFS MLA causes the mis-registration between the position of the ASM actuators and the LGS WFS sub-apertures, resulting in the GLAO performance degradation. Because of small number of control modes for GLAO, our GLAO system is less sensitive to pupil shift. There is almost no performance loss with a pupil shift of 20% sub-aperture size. Also, the pupil shift effect can be minimized by calibrated interaction matrices.[6]

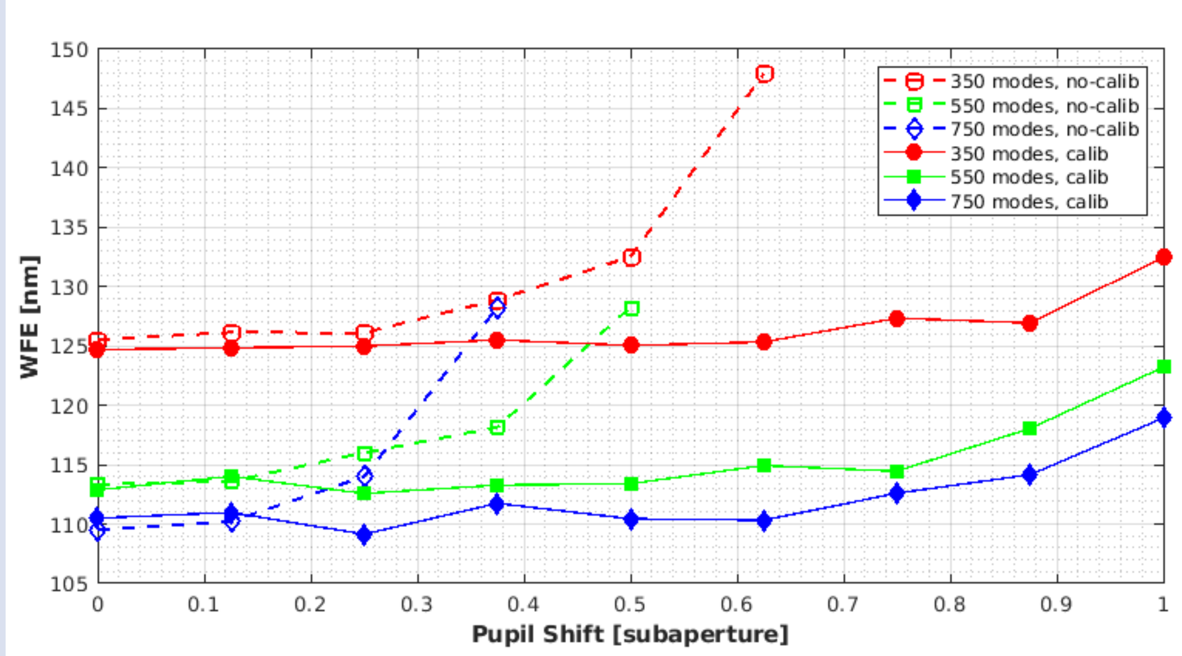

Fig.8 SCAO performance as a function of pupil shift in the fraction of sub-aperture for different number of control modes. Solid: classical IM. Dashed: IM with pupil shift.

Summary

GLAO performance

The science requirement is satisfied with the specified parameters as shown in the requirement table below under the median condition.

Performance	Requirement	Simulation
FWHM at K	0.25"	0.243"
EE50	0.5"	0.45"

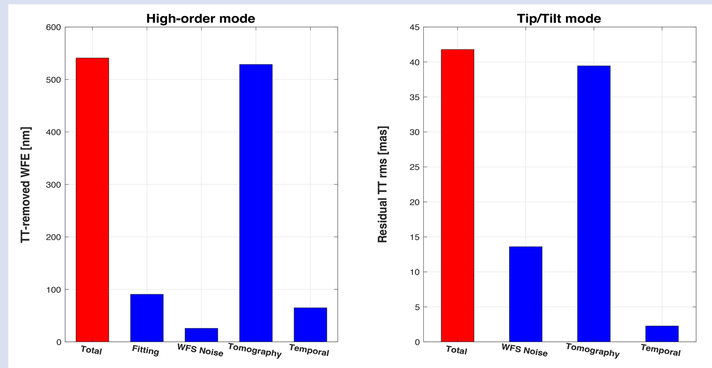

Fig.9: GLAO high- and low-order WFE breakdown from analytical evaluation with the optimized parameters. The NGS WFS noise is the second major error following the tomography error mainly caused by the uncorrected high-altitude turbulence.

Requirements of the GLAO WFS system

ITEMS	Values	
	NGS	**LGS**
WFS FoV	5"※2	7"
Pixel Scale	0.3" (w/ 4x4 binning)	1.0"
Optical quality※3	< 0.36" FWHM < 0.15" rms	< 1.5" FWHM < 0.64" rms
Telescope aberration	Need to be compensated (see [2])	
Pupil shift	-	< 20% of sub-aperture size

※2 We adopt a value used in the conceptual design study [5]

※3 The rms size is computed as rms = FWHM/2.35 with the assumption of a gaussian spot.

References

[1] Y. Minowa et al. "ULTIMATE-Subaru: GLAO preliminary design overview", Proc. SPIE 12185, Adaptive Optics Systems VIII 12185, 12185–73 (2022).

[2] Y. Tanaka et al. "Optical design of the Wavefront sensing in the ULTIMATE-Subaru Ground Layer Adaptive Optics system", Proc. SPIE 12185, Adaptive Optics Systems VIII 12185, 12185-251 (2022).

[3] N. M. Ray et al. "Wavefront sensing over a 20-arcmin field in the ULTIMATE-Subaru Ground Layer Adaptive Optics system." , Proc. SPIE 12185, Adaptive Optics Systems VIII 12185, 12185-249 (2022).

[4] Y. Minowa et al. "ULTIMATE-Subaru: system performance modeling of GLAO and wide-field NIR instruments," Proc. SPIE 11450, Modeling, Systems Engineering, and Project Management for Astronomy IX, 114500O (13 December 2020);

[5] F. Rigaut et al., "A conceptual design study for Subaru ULTIMATE GLAO," Proc. SPIE 10703, Adaptive Optics Systems VI, 1070324 (10 July 2018);

[6] S. Oberti et al., "The AO in AOF," Proc. SPIE 10703, Adaptive Optics Systems VI, 107031G (10 July 2018);