ULTIMATE-START:Subaru Tomography Adaptive optics Research experimenT project overview

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ABSTRACT

ULTIMATE-Subaru Tomography Adaptive optics Research experimenT (ULTIMATE-START) is a laser tomography AO project on the Subaru telescope. The project is planned to achieve high Strehl Ratio AO correction in NIR bands, and moderate AO correction in visible bands above 600nm. An asterism of 4 laser guide stars (LGSs) will be launched from the laser launching telescope behind the secondary mirror. The tomography wavefront sensing unit with four 32×32 Shack-Hartmann wavefront sensors will be installed behind the current facility LGS AO system, AO188. The deformable mirror of AO188 will be upgraded to a 64×64 element DM. The corrected light will be fed to the optical integral field spectrograph, 3DII, and NIR camera and spectrograph, IRCS, through a beam switching optics for IR-side Nasmyth focus instruments under development. The first light of the laser launching system and wavefront sensing unit is planned in 2021.

Keywords: Adaptive optics, laser guide star, tomography

1. INTRODUCTION

ULTIMATE-Subaru Tomography Adaptive optics Research experimenT (ULTIMATE-START) is a project to realize a laser tomography AO system on the Subaru telescope and to achieve good AO correction in the wide wavelength range between 600nm and 2500nm. The performance of a single LGS AO system is limited by the cone effect, and the residual wavefront error is not negligible especially in the short wavelength range. Utilizing a tomography AO system with multiple LGSs, sufficiently good AO correction with Strehl Ratio ~ 0.1 in the visible wavelength range can be achieved.

The scientific targets of the projects are (1) cosmological evolution of the distribution of stars inside galaxies at high redshifts with high-resolution NIR imaging observations, and (2) cosmological evolution of the dynamical structure of galaxies at high redshifts with high-resolution visible integral field spectroscopy. Additionally, the high-resolution visible IFS is capable to explore low-mass super massive black holes at the center of low-mass galaxies in the local universe.

There are two milestones in the project. The first milestone is to upgrade the existing facility AO188 LGS AO system by implementing 20W TOPTICA SodiumStar 20/2 laser as one LGS. By increasing the brightness of the LGS by a factor of 10, we expect close to the diffraction limited AO correction in the NIR wavelength. The second milestone is to conduct tomography AO experiments with 4 LGSs and tomography wavefront sensing unit with 4 LGS wavefront sensors (WFSs). The laser input from the laser will be divided into 4 beams and launched with the current laser launching telescope (LLT) to make an LGS asterism with 4 LGSs with diameter of 10''-40''. The details of the LGS LLT system are explained in Section 3. The tomographic wavefront measurement unit will be installed on the Nasmyth focus behind the AO188 as shown in Figure 1, and the tomographic wavefront

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measurement will be done in a closed-loop manner with the currently available 188 element bimorph deformable mirror. The details of the unit is described in Section 4). Real time calculation system for the tomographic estimation will be installed, and the calculated correction will be send to the upgraded AO188 real time control system based on CACAO¹ The overview of the WFS data acquisition and control system are shown in Section 5.

Based on the availability of the new laser light source, detectors for Shack-Hartmann wavefront sensor (SH-WFS) (Hamamatsu OrcaFlash 4.0 v2 sCMOS camera), existing facility AO system (AO188), and the LLT, we determine the baseline parameters of the system. Furthermore, in collaboration with the extreme AO development for the Subaru telescope, SCExAO, the upgrading of the DM in the AO188 system with 64×64 large-stroke ALPAO DM is scheduled. A quick parameter survey of the tomography AO system is conducted with MAOS AO simulator developed for TMT.² The results are summarized in Figure 2. Based on the results, we determine the nominal system configuration with $> 25 \times 25$ elements, 4 LGSs with < 20'' diameter asterism (< 10'' from the center of FoV), and > 400Hz WFS sampling. Further specifications of the system parameters are made based on more detailed AO simulation as described in Section 2.



Figure 1. Location of the laser tomography adaptive optics (LTAO) WFS unit on the IR-side Nasmyth platform of the Subaru telescope. The unit will be put after AO188, facility AO system, and apply the AO correction using the deformable mirror inside AO188. The light after LTAO WFS unit will go through Ns beam switching system, and will be delivered to science instruments, such as infrared camera and spectrograph (IRCS) and visible integral field spectrograph (3DII). Calibration light source and low-order WFS of AO188³ are used for the calibration of the tomography wavefront sensing unit and for removal of the fast tip-tilt and slow focus components.

2. TOMOGRAPHY AO PERFORMANCE SIMULATION AND PARAMETER SPECIFICATION

2.1 SH-WFS Parameters Optimization with Centroiding Error Simulation

In order to determine the parameters of the LTAO system, at first we consider the FoV of each subaperture of the SH-WFS. Left panel of Figure 3 shows the size of spot wondering as a function of the number of subapertures across the pupil. Atmospheric turbulence profiles at Subaru Telescope is assumed in the same way as in Oya et al. (2014).⁴ Under the bad condition with outer scale $L_0 = 30$ m and 32×32 sampling, the spot wondering is estimated to be 2.7". Right panel of the figure shows the required FoV to achieve the linear range for the centroiding. If we follow the most demanding case, LGS size of FWHM=2.0" with centroiding by the center of gravity without thresholding, subaperture FoV of 6.0" is required to achieve the 2.7" linear range.

In order to determine the pixel sampling, we conduct Monte Carlo simulations of the centroiding errors. Assuming science CMOS camera, Hamamatsu Photonics OrcaFlash 4.0 v2, for the SH-WFS, we use the readout noise of $\sigma_{\text{RON}} = 1.6 \text{ e}^{-1} \text{ pixel}^{-1}$ in the simulation. The TOPTICA laser photon return rate is measured to be



Figure 2. Tip-tilt removed high-order wavefront errors with a tomographic AO system with different orders (left) and integration time (right) evaluated with MAOS AO simulation code.² Dashed lines represent the fitting errors expected for system order of each case. Parameters for each simulation are summarized in the label, siglev means photon counts per subaperture with 800Hz sampling for LGS WFSs and rne is read-out noise of the SH WFS. In the right integration time evaluation, subaperture photon count per frame is fixed to focus on the effect of time delay.

1000 ph cm⁻² s⁻¹ at the Keck telescope.⁵ Considering we divide the TOPITCA laser light into 4 LGSs, photon number per 25cm × 25cm subaperture is estimated to be 156 photons per 2msec with 50% total throughput. The size of the LGS spot is assumed to be FWHM of 1.0", 1.5", and 2.0". Using the current AO188 LLT, LGS image size is measure to be 1.5"⁶ or 1.0".⁷ By the simulations, it is suggested that the optimal centroiding method for low photon count case (~100 counts per subaperture) is TCoG with $3-5\times\sigma_{RON}$ threshold. The results of centroiding simulations as a function of photon count and pixel scale are shown in Figure 4. 2000 realizations are made at each bin. TCoG with $3\times\sigma_{RON}$ threshold is used. The optimal samping of the SH-WFS is 1.0" for photon count less than 400 photons per subaperture. In summary, 1.0" per pixel sampling and 6.0" FoV per subaperture is determined.

2.2 End-to-end performance simulations

Following the quick parameter survey of the system shown in Figure 2, end-to-end performance simulations have been conducted⁸ with OOMAO AO simulation tool.⁹ In the simulation median condition with $L_0 = 30$ m is assumed. Following the centroiding simulation, 200 photons per subaperture with 2 msec exposure and 25cm×25cm subaperture, and one step control latency are assumed.

At first, optimal number of subapertures are further examined. Figure 5 shows the results of error breakdown as a function of number of subapertures. The top-left and -right panels show the case for current 188 elements DM and upgraded 64×64 DM. Fitting error is the largest error component for both cases, but tomography and delay error terms are comparable in the upgraded DM case. Increasing the number of subapertures, fitting and tomography errors decrease and noise error increases. Total WFE in the high-order modes are summarized in the bottom panel with upper and lower lines with current 188 elements and upgraded DMs, respectively. Considering the increase of the noise with 40×40 , we decided to use 32×32 for the number of subapertures.

Another critical parameter of the LTAO system is the separation of the LGSs. In order to reduce the cone effect associated with a single LGS, the light path from an object at infinity needs to be covered by the metapupils of the LGSs at the highest turbulence altitude. The highest turbulence layer at 16km altitude can be covered with the 4 LGSs on a circle of d = 20''. End-to-end simulation and analytical performance evaluation



Figure 3. Left) Size of spot wondering $(6 \times \sigma_{slope})$ as a function of the number of subapertures. Median and bad conditions represent median 7-layers turbulence profile model for Subaru⁴ at a zenith angle of 30 degree and bad 7-layers model at a zenith angle of 60 degree, respectively. Solid and dashed lines show the size for outer scale of $L_0 = 30$ m with and without Tip-Tilt component, respectively, and dotted line for no outer scale. Right) WFS subaperture FoV required to achieve a certain linear range for the centroiding (linear FoV). LGS size is assumed to be FWHM of 1.0", 1.5", and 2.0". Different line types correspond different centroiding methods, CoG: center of gravity, TCoG1: CoG with threshold with $3 \times \sigma_{RON}$ and spot with 1000 photons per subaperture, TCoG2: CoG with the same threshold and spot with 200 photons per subaperture.



Figure 4. Centroiding error as a function of photon count per subaperture and per frame and pixel scale for image FWHM=1.5'' and 2.0'' conditions, respectively. The yellow lines show the pixel scale giving minimum centroiding error for each photon count.

results are summarized in Figure 6. In order to evaluate the accuracy of tomographic estimation for the highorder wavefront components, the SR is calculated without the low-order tip-tilt wavefront error. The results show SR can be maximized with LGS asterism diameter of 16" as expected from the simple evaluation. If the targets are at higher zenith angle, the optimal diameter decreases down to 8" for zenith distance of 60 degree due to the larger effective distance to the turbulence layers with larger zenith distance.

End-to-end simulation results including low-order WFE are summarized in Figure 7. In this calculation, tiptilt NGS is assumed at the center of the FOV, i.e., anisoplanatic error of the tip-tilt correction is not included. Low-order WFS system inside the AO188¹⁰ is assumed for the tip-tilt measurement. It should be noted that the WFS is not optimized for tip-tilt measurement with light only wavelength range below 575nm,³ which is picked off by NGS low-order WFS beam splitter in Figure 15), the tip-tilt component significantly contributes. in the current performance simulations with fainter guide stars. Left panel shows the K-band SR as a function of the brightness of the natural guide star. Significant increase of SR is expected compared to the current NGS/LGS AO188 performance. On the right hand side, predicted SR is shown as a function of wavelength. SR of ~ 0.1 can be achieved in the visible wavelength range (> 600nm).



Figure 5. Top: Estimated high-order wavefront error for the tomography AO system with AO188 DM (left) and upgraded ALPAO DM (right). SH-WFSs with 25×25 , 32×32 , and 40×40 are assumed. Bottom: Total high-order WFE as a function of number of subapertures accross the pupil. In the current simulations, it is assumed that the turbulence profile is given, and the effect of uncertainty in the turbulence profile is not included.

3. LASER GUIDE STAR

3.1 Laser Fratricide Effect

In ULTIMATE-START experiment, we will launch the laser in the center launch configuration behind the secondary mirror of the Subaru telescope using the current laser launch telescope for the AO188 system.¹¹ If we launch multiple laser guide stars, contamination of Rayleigh back scattered light needs to be considered (laser fratricide effect), especially in the center launch configuration.¹² The Rayleigh back scattering is observed up to 16.4 km. In the right panel of Figure 8, the contamination of the Rayleigh back scattering in the WFS pupil is shown as a function of LGS asterism diameter. At zenith, we can hide the Rayleigh back scattered light behind the shadow of the secondary mirror cone by a LGS asterism smaller than diameter of 16", and the asterism needs to be smaller at lower elevation, 10" at z = 60 deg. Those diameters match with the optimal diameter shown in Figure 6. Considering the dependence of the optimal asterism diameter on the zenith distance and the fratricide effect, we consider the multiple LGS launching system with variable asterism diameter with 10" to 40"



Figure 6. Simulated Strehl Ratio (SR) as a function of LGS asterism diameter. Tomography wavefront measurement with 32×32 elements and correction with the current AO188 DM are assumed. WFE associated with the tip-tilt component is not considered. Solid line represents analytical calculation results, and points show the end-to-end numerical simulation results.



Figure 7. Results of end-to-end simulations. NGS are assumed at the on-axis and tip-tilt anisoplanatism is not included. Left: K-band SR as a function of tip-tilt NGS magnitude in R-band. Right: Expected SR as a function of wavelength. NGS with R = 12 mag is assumed.

3.2 Launching System for Four Laser Guide Stars

Schematic diagram of the laser transfer path is shown in Figure 9. Details of the system are described in Mieda et al. $(2018)^{13}$ and Morris et al. $(2020).^{14}$ Laser electric cabinet for TOPTICA SodiumStar laser will be put on the NsIR platform and the laser head will be attached to the center section of the telescope structure with the laser diagnostic bench. The cabinet and laser head will be connected through 30m fiber, which goes through the elevation cable wrap of the telescope. The diagnostic bench has optics to control the circular polarization properties of the beam. The beam from the diagnostic bench will go through truss and reach the optical relay

box attached to the top ring structure of the telescope. After the relay the beam is finally transferred along the spider to the bench attached to the laser launching telescope (LLT). Beam positions measured at four PSDs (one in the diagnostic bench, one in the optical relay, and the other two in the LLT bench) will be adjusted by three fast steering mirrors (FSM) in the optical path before the division of the beam. The beam will be divided into 4 beams with 3 beam splitters (BS1-3). There is a flip-mirror (FM) which can switch between one and 4 LGS modes. In the diagram, only 4 LGS mode is shown. The divided beams will go through a pair of a tip-tilt and compensation mirrors, which enable to change the diameter of the asterism of 4 LGSs by adjusting the tilt of pairs of mirrors. Asterism diameter from 10" to 40" will be realized under the current design. The 4 beams go through the asterism rotator and beam expander, and are fed to the LLT. The last FSM before the LLT will off-load the tip-tilt component measured with the LGS WFSs. There is a tip-tilt correction mirror in each SH-WFS, and high frequency wondering of each LGS will be corrected with the tip-tilt mirror, details are discussed in Section 4.1.

Mechanical structures of the diagnostic bench, relay truss, and optical relay box are shown in the top panel of Figure 10. The beam path go through the spider relay to reach the side of the LLT as shown in the bottom panel of the figure. The mechanical design of the 4 LGS launching system is shown in Figure 11. The optical bench occupies two side of the current LLT, and the beam is injected through a blue tube on the OPT view. The divided 4 beams are transferred to the Read view and fed to the LLT through the asterism rotator and beam expander.

The size of the secondary mirror (M2) of the current LLT (D = 42mm) limit the size of the beam and possible diameter of the LGS asterism. We expand the beam with ×6.0 expander, and the final $1/e^2$ (5%) beam diameter at the exit window of LLT will be 225mm (300mm). The beam diameter of 225mm is optimal for the spot centering error for wide range of the seeing condition.¹³



Figure 8. Laser fratricide effects for the center-launch behind the secondary mirror. In the calculation, Rayleigh scattering is assumed to appear up to 16.4km. The blue and red lines represent the effect from a LGS on the same axis and on the diagonal point, respectively. Solid and dashed lines are for zenith distance (z) of 0 and 60 degrees. The Rayleigh back scattered light will be behind the shadow of the secondary mirror center cone (equivalent to 2.213 m on the primary mirror) below the lower horizontal dotted line. The vertical solid and dashed lines represent the optimal asterism diameter for z = 0 and 60 deg, respectively (from Figure 6).



Figure 9. Schematic view of the laser launching path with 4 LGSs. Diagnostic bench with the laser head will be installed on the center section of the telescope as shown in the top panel of Figure 10. Power meters (PMs) monitor the output power during the shutter mirrors are closed. Position sensitive devices (PSDs) measures the position of beam center to keep the alignment of the beam transfer with the fast and slow steering mirrors (FSM and SSM). Diameter of the asterism will be changed between 10" and 40" with 4 pairs of tip-tilt and compensation mirrors (TTM and CM). The 4 laser beams will transfer though asterism rotator and beam expander before launching from the laser launching telescope.



Figure 10. Top: Mechanical structure for transferring laser beam from laser head to top ring of the telescope through relay truss structure. Bottom: Beam transfer from telescope top ring to the LLT attached behind the secondary mirror of the telescope.



Figure 11. LLT with 4 LGSs launching optics. Bottom two panels show the views of the optical system from OPT and rear sides of the telescope.

4. TOMOGRAPHY WAVEFRONT SENSING UNIT

4.1 Opt-mechanical design

The parameters of the WFSs are summarized in Table 1. The current optical design of the tomography wavefront sensing unit is shown in the top panel of Figure 12. The light from AO188 focus will be picked-off into the unit. The fore optics of the system has focusing optics, image rotator, and pupil monitor. The fore optics are optimized such that an ideal point source at the AO188 focus with object distance between 75km and infinity to be imaged as an point source at the fixed entrance of the SH-WFSs. The focusing optics is designed to accommodate focus change due to the variation of the distance to the LGSs depending on the altitude of the sodium layer and zenith distance of an observation, and the distance range from 75 km to infinity is considered as shown in the bottom panel of the figure. The LGS asterism diameter from 10" to 40" is considered. The pupil monitor will be used to check the tilt of the optical axis due to the image rotator in the AO188 system¹⁰ (AO IMR). The image rotator in the wavefront sensing unit will be used to track the asterism rotation in case the asterism is fixed to the DM in AO188 (not to the sky). Table 2 summarize the possible operation modes for the image rotators of the LGS LLT asterism rotator, AO188 IMR, and WFS image rotator. One operation mode will be selected based on the wavefront sensing performance.

As shown in the bottom panel, the image position will be changed when the asterism diameter is changed from 10" to 40". The change will be absorbed by the change of the focus position by 9.03mm and the pyramid mirror that is movable along the optical axis. Therefore, the optical path after the pyramid mirror is fixed. The light from the 4 LGSs will be split into 4 directions with the pyramid mirror. In order to realize the LGS asterism as small as diameter of 10", the LGS images are focused at the pyramid mirror whose ridges have 0.2mm (0.33" with F15.6) non-effective area. Finally, the light from the fore optics will be fed to the SH-WFS system through

Parameter	Designed value	Note	
Number of Elements	32×32	see Section 2.2	
Subaperture scale	0.248m	7.95m effective aperture	
Sub-aperture FoV	6.84"	see Section 2.1	
Pixel sampling	$0.99'' {\rm pixel}^{-1}$	see Section 2.1	
Number of pixel per sub-aperture	6.93 pixel	Close to be an integer. see Section 5.1.	
Micro lens array	APO-Q-P300-R5	f=10.9mm Advanced Microoptic Systems	
Number of pixel total	224 pixel		
Frame rate	> 400 fps	max 952 fps 224 lines with OrcaFlash 4.0 v2	
Pixel size	$6.5 \mu m$	OrcaFlash 4.0 v2	
Read out noise	$rms 1.6 e^{-1} pixel^{-1}$	OrcaFlash 4.0 v2	
QE at 589nm	82%	OrcaFlash 4.0 v2	

Table 1. Parameters of the LGS SH-WFS.

a steering mirror. The steering mirror will correct the shift of the pupil against the micro lens array (MLA) in the SH-WFS. The shift can be measured with the spot illumination pattern of the SH-WFS as well as the pupil monitor described above.

Because the AO188 optical path with two off-axis parabolas is optimized for on-axis object at infinity,¹⁰ the LGS images at 10'' - 40'' off-axis and finite distance do contain significant aberration at the focus as shown in the left and middle panels of Figure 13. Described above in the optimization of the fore optics, in the design of the optics we did not intend to remove the aberration in the AO188 LGS output with the LGS WFS fore optics to reduce the non-common path aberration between the science path and tomography wavefront sensing unit. Therefore, the aberration needs to be calibrated with a LGS calibration point source in the AO188 system for each WFS. Furthermore, the pattern will vary when the WFS IMR is used, i.e., LGS is not fixed to the sky, as shown by the arrow. Such time variation needs to be considered in each WFS output. We will calibrate the SH WFSs in the LTAO WFS unit using the calibration unit of the AO188.¹⁵ The calibration unit can reproduce an NGS with 655 and 1550nm LEDs and an LGS with a yellow LED plus 589nm filter. The LGS image altitude can be adjusted from 80km to 200km. The entire calibration unit is on a XZ stage and the simulated beam can be made within the FoV of 2.7' diameter.

After the AO188 focus, there are 7 reflection surfaces and 21 lens surfaces in total in the WFS optical path. All of the reflection and refraction surfaces are coated with multi-layer coating including the pyramid mirror. The reflection is higher than > 99% for the mirrors and transmittance is higher than > 99.5% for the lens surfaces at wavelength of 589nm.

Each SH-WFS for LGS has offner-relay to compensate the tip-tilt component of the LGS. A spherical mirror with 5mm thickness is attached to the tip-tilt stage, Physik Instrumente S330.8SL, and the resonant frequency is estimated to be 820Hz. Considering the performance of the voltage amplifier, Physik Instrumente E-505, we expect the tilt ranges of ± 5 mrad (with peak-to-peak voltage swing, $V_{\rm pp} = 100$) with 160Hz and ± 0.5 mrad ($V_{\rm pp} = 10$ V) with 1400Hz, which correspond to $\pm 2.3''$ and $\pm 0.23''$ correction range. The high frequency component of the tip-tilt of the LGS is corrected with the stage. Additionally, we will also apply a low frequency tip-tilt correction with the fast steering mirror (FSM) in the LLT bench (see Figure 11), because there is a pyramid mirror before the offner-relay to divide the 4 beams to the SH-WFSs, and FoV of each path is limited by the ridge of the pyramid mirror.

After the relay, the pupil will be imaged on the 300μ m pitch MLA (Advanced Microoptics Systems, APO-Q-P300-R5). The MLA for the system is selected based on the focal length, image quality, and through put analysis described in.¹⁶ The 0.15 ratio relay will form 32×32 spot images on the detector with 6.93×6.93 pixel

per subaperture. The number of pixel per subaperture is requested to close to integer in order to align with the rolling-shutter readout mode as described in Section 5.1.

The overall opt-mechanical design of the wavefront sensing unit is shown in Figure 14. The unit will locate next to the AO188 system. In addition to the LGS tomography wavefront sensing unit, we also have truth WFS to measure the corrected wavefront for a natural star to evaluate the AO performance. The optical path for splitting the beam is shown in Figure 15. The science light will be fed into the Nasmyth beam switching relay and delivered to science instrument. Low-order WFS is fed with < 575nm light by a beam splitter (BS1) in the AO188 system. After the AO188 focus, LGS WFS pick-off will reflect the light into the tomography wavefront sensing unit. In order to correct the aberration associated with the science path due to the pick-off, we put another wedge plate in the path. The pick-off and wedge plate need to be retracted to allow observation without the tomography wavefront sensing unit. The truth WFS will use the remaining surface reflection of the first surface of the wedge plate. The ghost image with the reflection at the second surface will appear 17" away from the primary image, and will not affect the wavefront measurement in the truth WFS. There will be a 6.7mm focus offset with and without the pick-off and wedge plate, and the difference will be corrected in the instrument. The total FoV of the science path has diameter of 65" to fed the sky monitor of the 3DII instrument, which cover 30" away from the center of the FoV.

Table 2. Image and pupil rotation modes

LGS Asterism	AO188 IMR	DM	WFS IMR	WFS pupil
Fixed to primary (stop)	rotate	Fixed to sky	rotate	Fixed to primary
Fixed to sky (rotate)	rotate	Fixed to sky	stop	Fixed to sky/DM

In order to measure the tip-tilt component of the wavefront error in the target image, we will use the loworder wavefront sensor in the AO188 system. The low-order wavefront sensor system use 2×2 Shack-Hartmenn wavefront sensor. Each sub aperture is imaged by 4×4 lenslet array connected to an APD array. Acquisition unit for the low-order WFS covers FoV with 2.7' diameter.³ In order to have better conjugation with the AO188 DM and the secondary mirror of the telescope, the ADC system in the AO188 science path will not be used. Without the ADC compensation, guiding with the low-order WFS using <575nm can result in an offset in the science image which is targeting >600nm, however offset guiding software, which calculate the realtime offset between the guide star and science image, is implemented in the AO188 system, and we can use the software for the observation. Furthermore, LOWFS itself has an ADC system inside, thus the TT and focus measurements will not be affected by the removal of the ADC in the science path. The existing low-order WFS is not optimized for the LTAO system, and the total throughput will be ~ 10% in the wavelength range 490 – 530 nm. Replacement of low-order WFS with a higher thoughput system will be considered.

Focus component of the low-order wavefront error will be measured with the low-order WFS with NGS as well as the tomography wavefront sensing unit with LGSs. High frequency variation will be compensated based on the LGS measurements, and low frequency variation due to the time variation of the LGS altitude is corrected with the NGS measurements.

4.2 Atmospheric profiling

Atmospheric turbulence profile is an important prior information to conduct tomographic estimation of the volumetric turbulence structure. One of established methods to measure the atmospheric turbulence profile is a Slope Detection And Ranging (SLODAR). In the SLODAR method, the profiles are estimated by a fit of the theoretical auto- and cross-correlations of measurements from multiple SH-WFSs to the observed correlations. In the RAVEN experiment on the Subaru telescope, SLODAR method is applied to the three NGS WFS measurements and turbulence profiling with a height resolution δh of 1.5 (km) is achieved.¹⁷ Taking the cross-correlation between the 4 SH-WFSs with 25cm sampling, we expect a height resolution of 5.2 km (1.3 km) can be achieved with LGS asterism diameter of 10" (40"). The upper limit of the turbulence profiling will be > 16 km and the highest layer will be covered. The height resolution with the asterism diameter of 10" is not sufficiently high as



Figure 12. Optical design of the LGS tomography wavefront sensing unit. Top) optical path from the AO188 focus to the detector. Only one SH-WFS path is shown after the pyramid mirror. Red allows with numbers indicate the remotely movable optical element. Bottom) optical design of the LGS focusing system. LGS distance range from 75 km to infinity is considered. d=10'' (40'') is for asterism diameter of 10'' (40''). The difference of the image separation will be compensated by the focus difference and the pyramid mirror.

a prior for the tomographic estimation, and we may need to switch to the wide asterism (d=40'') to measure the profile during the observation.

As a future upgrade, we are also considering a dedicated small telescope for the turbulence profiling. In the telescope, we will put two SH-WFSs with 2cm subaperture sampling on a small aperture telescope to conduct the profiling with SLODAR and SH-Multi Aperture Scintillation Sensor (SH-MASS)¹⁸ to cover the turbulence component up to 16km with altitude resolution of \sim 1km.



Figure 13. Aberration of the AO188 output for LGS (90km distance with 10" off-axis) (left and middle) and NGS image (right). Labels of top and right represent the position of the LGS in the AO188 output FoV. When the WFS IMR is rotated, aberration pattern seen by a SH-WFS can vary from left to middle.

5. DATA ACQUISITION AND REAL TIME CONTROLER

5.1 Wavefront measurements with rolling-shutter sCMOS camera

Science CMOS camera sensor, OrcaFlash 4.0 v2 from Hamamatsu Photonics Co. with rolling-shutter reading out will be used in the tomography wavefront sensing unit. Partial reading out of the sensor with 224 lines will be used to cover the 32×32 SH spots with 7×7 pixels per subaperture. In the standard data acquisition mode, the pixel data of the entire frame with 224 lines will be transferred at every 1.05ms through CameraLink 80 bit configuration equivalent interface. The standard scan mode achieve read out noise with median (rms) of 1.0 e pixel⁻¹ (1.6 e pixel⁻¹). Due to the nature of the rolling-shutter readout mode, the real timing of the integration depends on vertical position (line number) on the detector as shown with white bars in Figure 16. At the time of the data acquisition from the image analysis software, which is indicated with vertical red arrows, the central lines of an image are delayed by the integration time after the end of the exposure, though the upper and lower most lines are used just after the end of the exposure.

In order to reduce the delay associated with the data transfer and centroid calculations, we are developing a readout mode that acquires data every 7×2 lines as shown with vertical black arrows in Figure 16. Such readout mode is realized utilizing line scan mode of PIXCI E4 frame grabber board from EPIX, Inc. Each 7 lines will be aligned to cover one row of SH spots, and centroid calculations for one row can be done during waiting for the next row (66µsec). The synchronization of the 4 LGS WFSs will be made with a trigger signal from an analog I/O board. The sCMOS camera can trigger start of the read-out under the read-out synchronization trigger mode with 166µsec delay.

5.2 Overall Control Architecture

The overview of the real time control system (RTS) of the tomographic wavefront measurement unit is summarized in figure 17. The right half of the system will locate on the IR-side Nasmyth platform. The right most part of the diagram shows the low-level interface to the data acquisition and motion control units. The tomographic estimation will be done in a stand-alone computer (RTC) dedicated for the system. The estimated wavefront correction is send to the AO188 RTS with CACAO software interface. The telescope control can be done separately, and the tomography RTC need status information from the telescope.

6. SUMMARY

Overview of the ULTIMATE-START project on the Subaru telescope is provided. The new laser launching system will be installed early 2021, and testing of the laser launching will be done in mid 2021. The fabrication of the tomography wavefront sensing unit is underway, and assembling of the unit in Tohoku university will happen in mid 2021. The unit will be delivered to Subaru telescope late 2021. The ALPAO DM will be delivered



Figure 14. Overview of the opt-mechanical design of the tomography wavefront sensing unit (top). Bottom panel shows the optical components only. The unit will locate next to the AO188 system. Left side of the system, we will have a truth-WFS with one SH-WFS for NGS to evaluate the tomography AO performance. The truth SH-WFS will use MLA with longer focal length (Newport MALS10 with f=18.8mm) than for the LGS SH-WFS (f=10.9mm), and realize 3.97'' subaperture FoV with 0.57'' sampling. The tomography WFS and truth WFS will be put on separate optical bench with a hexapod structure. In the bottom panel, the pupil monitor camera is not shown.

mid 2021, and the installation will follow. The planned first light of the four LGSs and the wavefront sensor unit is early 2022, and science verification observation with 3DII and IRCS will be made.

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Figure 15. Left) Beam splitting to the low-order WFS, LGS WFS, truth-WFS, and science instrument. The < 575nm light is reflected to NGS low-order WFS inside AO188 (BS1). The light from AO188 will be split at pick-off mirror for the LGS WFS. Science light > 600nm will be delivered to science instrument though a wedge plate, which will correct aberrations associated with the plate beam splitters above. The truth WFS receive light reflected on the wedge plate with anti-reflection coating, therefore only very bright star can be used with the truth WFS. Right) Throughput of the splitters shown for the LGS WFS and science paths based on the measured transmittance and reflectance after the fabrication. The science path throughput have not included the final wedge plate. Beam splitters and pick-off mirror are fabricated with IR-grade fused Silica and coated in Asahi Spectra Co.Ltd.

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Figure 16. Schematic view of the rolling-shutter camera readout for 2 WFSs. Orange and white bars indicate effective exposure of each 7 lines. Data acquisition will occur every row of SH spots to conduct centroid calculations during waiting for the next row. The minimum integration time will be 1.05msec with 952 fps in 224×224 pixel. Five WFSs including one for the truth-WFS will be synchronized by the signal shown at the top.

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Figure 17. Overview of the control system for the tomography wavefront sensing unit. Orange boxes represent main real-time computers of the unit, which will acquire the data from WFSs and calculate AO correction through tomography algorithm. We will use Ubuntu 20.04 LTS with real-time kernel for the real-time computers. Red number in brackets corresponds to the movable elements shown in Figure 12.

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