PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Wavefront sensing over a 20-arcmin field in the ULTIMATE-Subaru Ground Layer Adaptive Optics system

Noelia Martinez, Nicholas Herrald, David Chandler, Dionne Haynes, Andrew Kruse, et al.

Noelia Martinez, Nicholas Herrald, David Chandler, Dionne Haynes, Andrew Kruse, Wasantha Ramasundara, Francois Rigaut, Julien Tom Bernard, Tony Travouillon, Israel Vaughn, Yosuke Minowa, Yoshito Ono, Yoko Tanaka, Koki Terao, Celine D'Orgeville, "Wavefront sensing over a 20-arcmin field in the ULTIMATE-Subaru Ground Layer Adaptive Optics system," Proc. SPIE 12185, Adaptive Optics Systems VIII, 121856K (29 August 2022); doi: 10.1117/12.2627738

Event: SPIE Astronomical Telescopes + Instrumentation, 2022, Montréal, Québec, Canada

Wavefront sensing over a 20-arcmin field in the ULTIMATE-Subaru Ground Layer Adaptive Optics system

Noelia Martinez[a], Nicholas Herrald[a], David Chandler[a], Dionne Haynes[a], Andrew Kruse[a], Wasantha Ramasundara[a], Francois Rigaut[a], Julien Tom Bernard[a], Tony Travouillon[a], Israel Vaughn[a], Yosuke Minowa[b], Yoshito Ono[b], Yoko Tanaka[b], Koki Terao[b], Celine D'Orgeville[a]

[a]Australian National University, Research School of Astronomy and Astrophysics, Mount Stromlo Observatory, Cotter Road, Weston Creek 2611, Australia;
[b]Subaru Telescope, National Astronomical Observatory of Japan, Hilo, USA

ABSTRACT

The ULTIMATE Ground Layer Adaptive Optics (GLAO) system is part of ULTIMATE-Subaru, the next generation facility instrumentation project at the Subaru telescope in Hawaii. GLAO is led by the Subaru Telescope in collaboration with Tohoku University, Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), and the Australian National University (ANU).

ANU is currently designing the Laser Guide Star Facility and the Wavefront Adaptor Flange with four Laser Guide Star wavefront sensors, and four Natural Guide Star wavefront sensors. The GLAO Wavefront Adaptor Flange will provide Adaptive Optics capability to the wide-field imager (WFI) instrument to be installed at the Subaru Cassegrain focus in 2027.

Four Laser Guide Star wavefront sensors mounted over a fabricated steel structure enable the acquisition of LGS asterisms of up to 20 arcmin in diameter. Each WFS has been designed to also account for the telescope optical aberrations and the non-telecentricity. The NGS instance consists of four Natural Guide Star wavefront sensors for tip-tilt and focus measurement.

In this paper, we present an overview of the GLAO Wavefront Adaptor Flange including the preliminary design for the opto-mechanical assembly of both LGS and NGS instances, and the mechanisms control system that enables fine acquisition of the guide stars over the wide patrol field of the GLAO system.

Keywords: Wavefront sensing, Ground Layer Adaptive Optics, Subaru telescope, ULTIMATE-Subaru

1. INTRODUCTION

The next generation Ground Layer Adaptive Optics (GLAO) for the 8-m Subaru telescope, Mauna Kea (Hawaii) is being developed in the framework of ULTIMATE-Subaru, a National Astronomical Observatory of Japan (NAOJ) flagship program that involves a telescope upgrade, a GLAO system, and Wide-Field NIR instruments. ULTIMATE-GLAO is design to improve the seeing by a factor of 2 over a wide-field of view (up to 20 arcmin) by only compensating the turbulence close to the ground.[1]

The GLAO Wavefront Sensor module is a high level subsystem of the ULTIMATE-GLAO project; it will be located at the Cassegrain flange of the Subaru telescope, in an annular space above the Cassegrain focal plane. Divided into two main sub-assemblies, the GLAO WFS consists of four Laser Guide Stars (LGS) mounted to a common rotating structure, and four Natural Guide Stars (NGS) assembled to what is known as Wavefront Adaptor Flange (WAF).

Figure 1 presents the asterism configuration for the GLAO system and the science field of view at the Cassegrain focus.

Further author information: (Send correspondence to N.M.)
N.M.: E-mail: noelia.martinezrey@anu.edu.au

Adaptive Optics Systems VIII, edited by Laura Schreiber, Dirk Schmidt, Elise Vernet,
Proc. of SPIE Vol. 12185, 121856K · © 2022 SPIE
0277-786X · doi: 10.1117/12.2627738

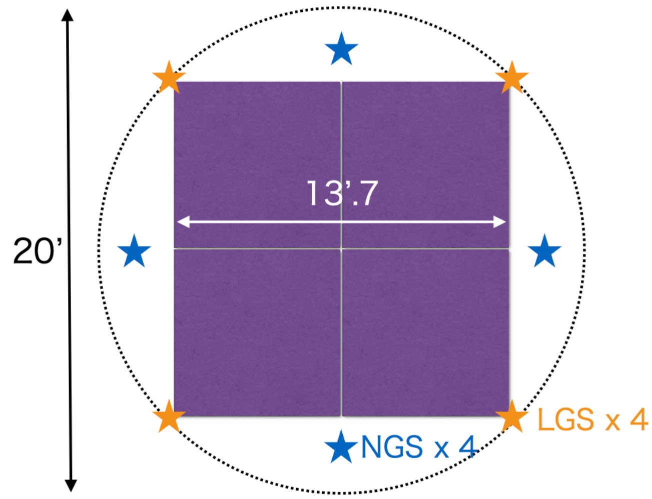


Figure 1. GLAO Laser Guide Star and Natural Guide Star asterisms at the Cassegrain focus; the purple square represents the science field of view.

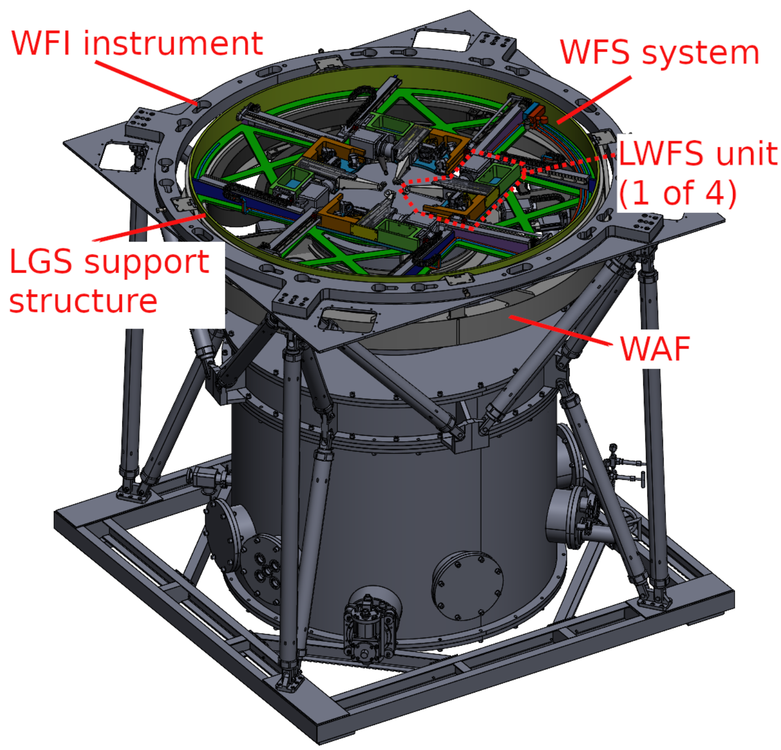


Figure 2. Cassegrain Wavefront Sensor system preliminary mechanical design, including the Wide Field Imager (WFI) instrument preliminary design. The WFS model is provided by Sumitomo Heavy Industries and OptCraft in Japan.

Both LGS and NGS instances are stacked within the available annular volume at the Cassegrain focus above the Wide Field Imager instrument (WFI) (Figure 2). The annular space reserved for the wave front sensors is restricted by the internal diameter of the Cassegrain instrument interface ring, and by the space along the telescope axis between the instrument focal plane and the interface ring top surface. This annular space is divided vertically, with the LGS envelope above the NGS envelope.

The Wavefront Sensor Adaptor Flange is the structural component of the Wave Front Sensor Assembly that supports each of the individual NGS wave front sensor modules, the LGS Assembly bearing system and the interface of the WFS to the telescope via the flange used by the Wide Field Instrument to attach to the Cassegrain port.

The NGS and LGS assemblies each include four individual wavefront sensors. The Natural guide star Wavefront Sensors (NWFS) incorporate mechanisms allowing polar motions within their respective quadrants in order to enable individual selection of natural stars from the available field ranges for each NWFS. NGSs can be extracted over a 7-10 arcmin region, with excluded zones at the edges of the quadrants where ribs of the WAF interrupt the NWFS motion envelope. The four LGS wavefront sensors (LWFS) are mounted on a common structure to maintain a static asterism pattern, which is fixed on sky with respect to the telescope. The LGS structure is supported by a rim bearing arrangement, carried by the Wavefront Adapter Flange, which allows the LWFS system to undo the field derotation imparted by the Cassegrain rotator. The LWFSs are able to move radially to accommodate radial asterism range of 2 to 10 arcmin.

The architecture of the GLAO Wavefront Sensors Module is shown in Figure 3.

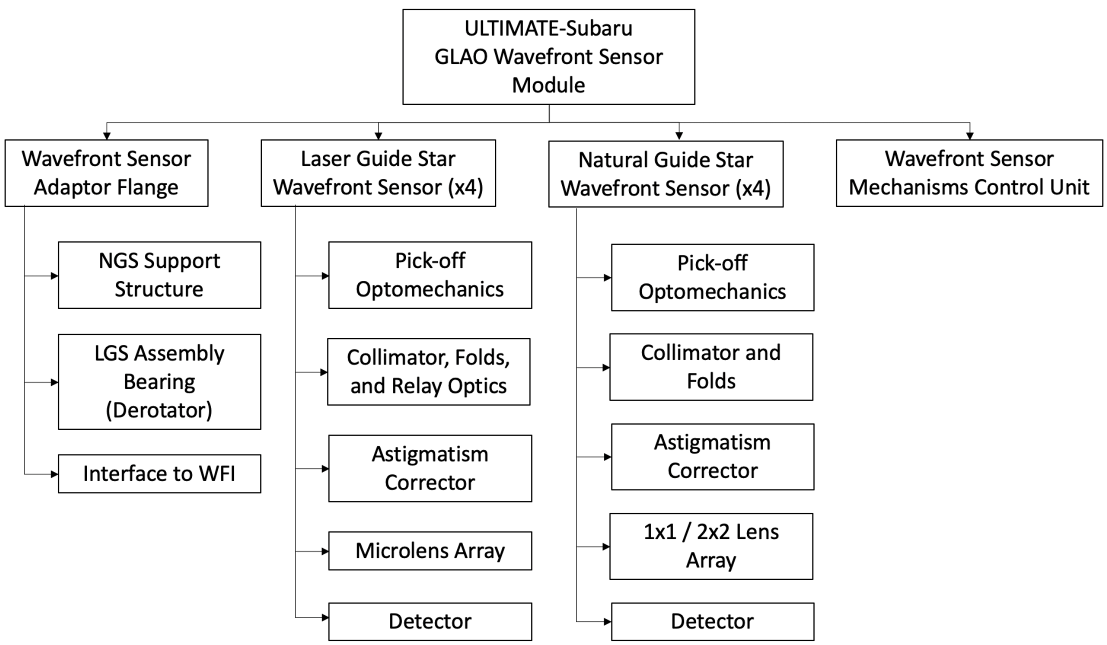


Figure 3. GLAO Wavefront Sensor Module Architecture

2. LASER GUIDE STAR WAVEFRONT SENSOR

The LGS WFS sub-system incorporates four Laser Guide Star Wavefront Sensors (LWFS) (Figure 4). Laser Guide Stars are extracted from the GLAO field by pick off mirrors as part of each WFS, supported by slender arms that minimise vignetting. Each individual WFS captures the image of a single guide star. All of the LWFS optics following the pick-off mirror are mounted on a common base plate, whose base is parallel to the Asterism mechanism motion axis. After the pick-off mirror, the LGS light gets collimated and transferred to a 32x32 microlens array and the WFS detector by fold mirrors and relay optics. An astigmatism corrector element is located on the base plate to reduce telescope aberrations (see Section 2.2).

The LGS WFS sub-assembly is equipped with a bearing system, which forms the interface between the LGS support structure and the Wavefront Sensor Adaptor Flange; this mechanism allows the LGS support structure to rotate relative to the WAF, in order to reverse the field derotation imparted by the Cassegrain instrument rotator.

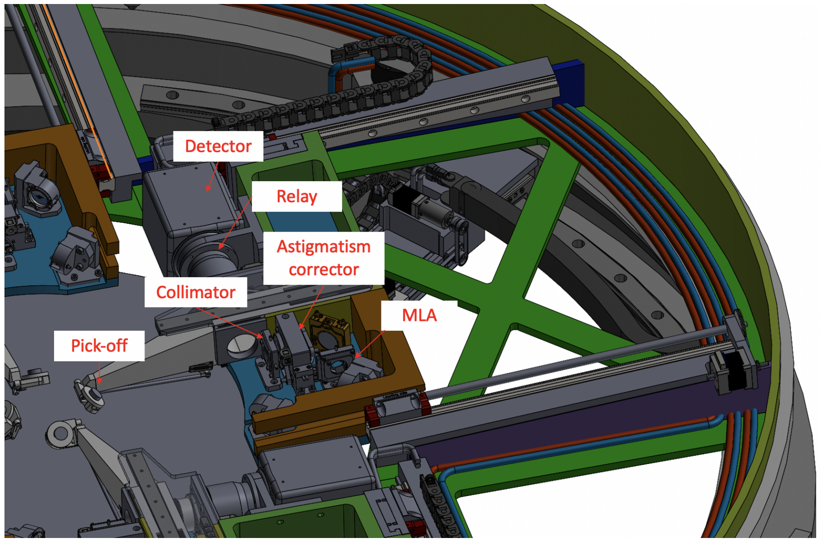


Figure 4. Overview of a single Laser Guide Star WFS (LWFS) mounted on the LGS WFS sub-assembly.

Each LWFS has four mechanisms (Figure 5): the focus and asterism mechanisms, the astigmatism compensator, and the pick-off angle adjustment. All the LWFS mechanisms remain active during the GLAO operation and therefore, minimising power dissipation has been fundamental in the final hardware selection. Motion type and range of the LWFS mechanisms are summarised in Table 1.

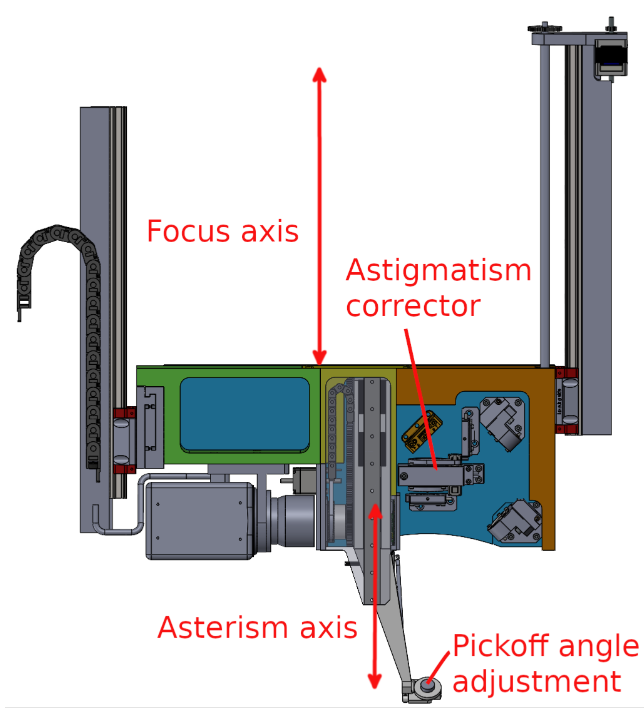


Figure 5. Mechanisms overview in a single LWFS.

Table 1. LWFS mechanisms

Mechanism	Motion type	Range
Asterism axis	linear	123 mm
Focus axis	linear	230 mm
Pick-off angle	rotational	0.43 deg
Astigmatism corrector	rotational	360 deg

2.1 LGS Asterism and Focus

Each LWFS unit has an asterism range of 2 to 10 arcmin in radius, which is covered by moving the LWFS pickoff mirror radially with respect to the telescope optical axis.

The Asterism Axis refers to the mechanism which moves the pick-off mirror radially, relative to the LGS baseplate, across the instrument focal "plane" in order to access laser guide stars across the stated asterism range. The components moved by the Asterism Axis are those which are mounted on the pick-off arm.

The LWFS units can focus on objects at altitudes from 80km to infinity by shortening and lengthening the distance between the pick-off mirror and the rest of the optics. The Focus Axis carries the LGS baseplate, which supports the entire LWFS Unit. Motion of the Focus Axis thereby moves all LWFS optics including the pick-off mirror, to correctly locate the focus for the various LGS conjugate distances. Accordingly, the Asterism Axis must be moved in an equal and opposite manner to the Focus Axis, in order for the pick-off mirror to remain stationary.

2.2 LGS Field Correction

The Subaru telescope is a Ritchey-Chretien reflecting telescope. While the telescope is designed to deliver a wave-front with no spherical and coma aberrations, astigmatism and field curvature remain uncorrected, which limits the aberration-free field of view.

Each LWFS unit has an astigmatism corrector element that reduces this aberration from 1.5λ RMS to 0.05λ RMS. The astigmatism corrector consists of two identical phase plates with pure astigmatism placed as close as possible to one another. The astigmatic effect varies by rotating one lens with respect to the other around the optical axis. Maximum astigmatic effect is achieved when the axis of both lenses are aligned and zero astigmatic effect is generated when the axis are 45° from one another.[2]

Due to the curvature of the Subaru telescope focal plane, the best focus plane is not flat, but curved at Cassegrain. Accordingly, the asterism and focus axes are inclined at an angle of 3.434 deg to the focal plane (Figure 6) such that the locus of the LWFS pick-off mirror over its motion range forms a shallow cone, which most closely matches the curved focal surface.

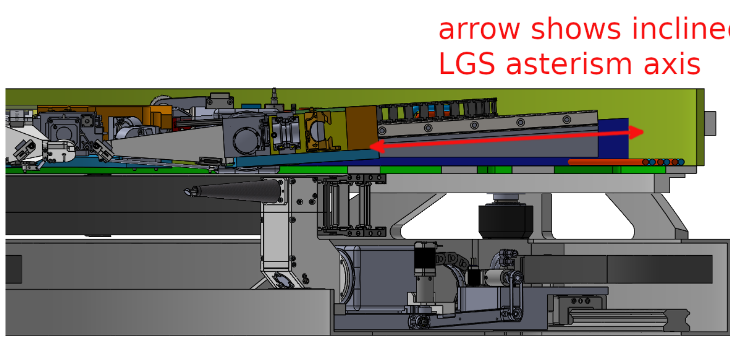


Figure 6. The LWFS pick-off mirror traces a cone to accommodate the curvature in the telescope focal plane.

The chief ray angle of the Subaru optical path changes with the patrol angle. This non-telecentricity of the Subaru Telescope requires that the pick-off mirror angle is adjusted over a range of 0.43 deg (Figure 7) according to the selected LGS system asterism to maintain the pupil alignment on the lenslet array.

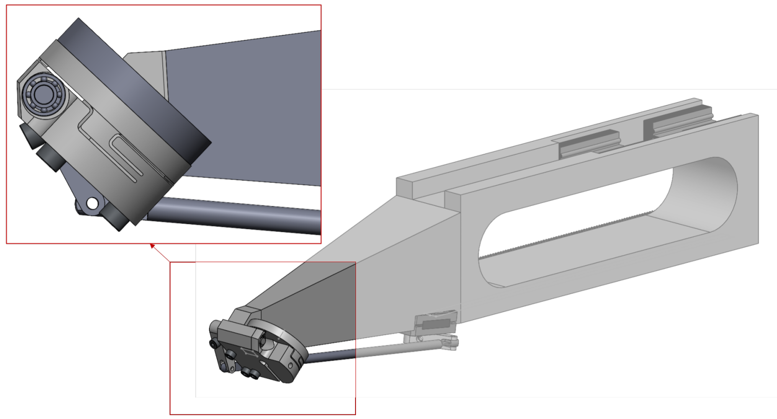


Figure 7. LWFS pick-off mirror mechanisms showing cam actuation.

3. NATURAL GUIDE STAR WAVEFRONT SENSOR

Natural stars are extracted from the GLAO field by pick off mirrors as part of each Natural Guide Star WFS (NWFS). Coverage of the accessible field region is facilitated by polar motion of the NWFS units, with separate mechanisms responsible for radial and angular axis motions. The guide stars are extracted from the science field via a pick-off mirror that is adjustable over a small range according to the field position. Three 1x1 and one 2x2 NWFS are used to extract the tip-tilt and focus information in the GLAO system.

The pick-off arm is made from carbon fibre to maximise the specific stiffness and thereby minimise self weight deflection of the arm. After each pick-off mirror, the beam from the natural guide star is relayed via a 1:1 optical relay with a periscope arrangement of two flat mirrors, onto a detector. The detector is mounted on linear stage which allows focus motions with respect to the optical relay (Figure 8). The NWFS axes are fixed during observations.

Each NWFS unit includes five mechanisms to correctly establish their positions relative to the telescope optics in order to intercept the chosen guide stars: the two NGS asterism mechanisms, consisting of separate angular and radial axis motions, the focus mechanism, the pick-off mirror angle adjustment, and the asterism compensator. The mechanisms for the NWFS must only be actuated in order to select the natural guide stars prior to an observation. Once selected, all mechanisms other than the pick-off mounts, are powered down and held static by either deliberately applied friction, mechanical detents or stepper motor detents. Motion type and range of the LWFS mechanisms are summarised in Table 2.

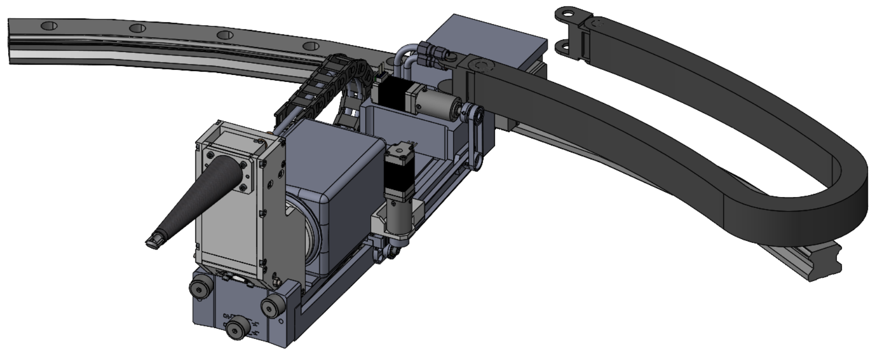
Table 2. NWFS mechanisms

Mechanism	**Motion type**	**Range**
Asterism axis	linear	87 mm
Angular axis	angular	± 45 deg
Focus axis	linear	10 mm
Pick-off angle	rotational	0.16 deg
Astigmatism corrector	rotational	360 deg

In the NGS asterism mechanism, the Angular axis and Radial axis mechanisms enable planar motion of the pick-off mirror, within the radial range of 7-10 arcmin. The focus axis allows focussing motions of the camera along the optical axis of each NWFS.

Similar to the LWFS units, each NWFS is equipped with an astigmatism compensator and pick-off mirror adjusments to account for the telescope non-telecentricity.

The same astigmatism corrector element in the LWFS is used in each of the NWFS units; however the astigmatism compensator mount is slightly modified to fit in the NWFS opto-mechanics.



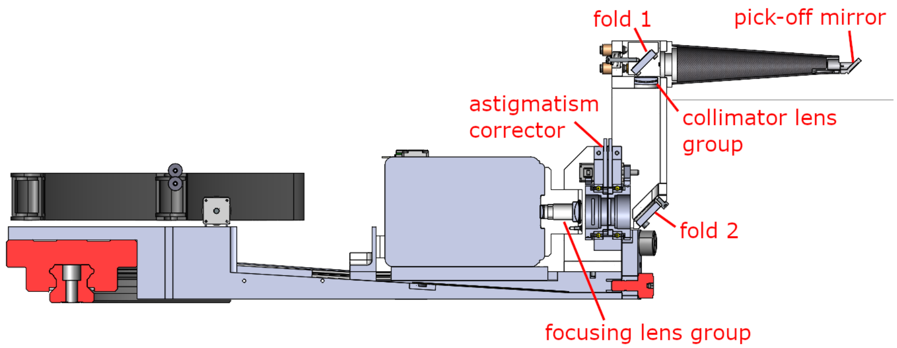


Figure 8. NWFS unit: isometric view (top) and section view (bottom).

To compensate for the Subaru telescope non-telecentricity, the pickoff mirror angle can also be adjusted (Figure 9). The pick-off mirror mount utilises a piezo-actuator, which is potted in place within a slot in the aluminium mount, to flex the hinge causing change in angle of the NWFS pick-off mirror. The mirror angle is changed according to the NGS field position, over a range of approximately 0.16 degrees, as required by the non-telecentricity of the telescope optics, in order to maintain pupil alignment at the detector. A flexural wire-cut element in the mount acts as a hinge for the mechanism. The actuator must be powered during observations and therefore positional stability of the actuator is critical.

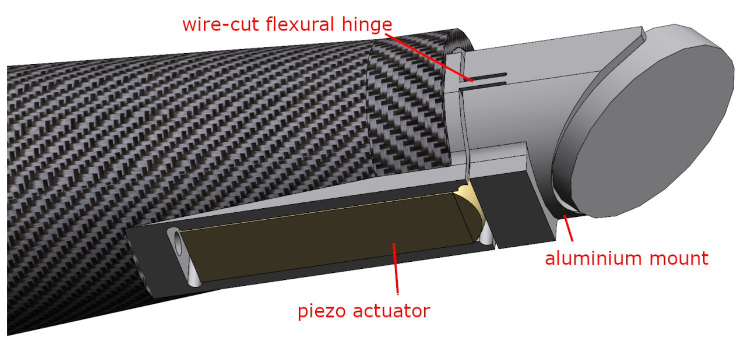


Figure 9. NWFS pick-off mirror mount showing the mechanism hinge.

4. WAVEFRONT SENSORS CONTROL UNIT

The wavefront sensor control system is limited to mechanism control and does not consider the AO control loop. Mechanisms range from rotational control of small astigmatism correction optics to positioning of entire wave front sensors to known positions within the focal plane. Generally the LWFS mechanisms require tracking the rotating field, while the NWFS mechanisms are set to a static position relative to the telescope. Both wavefront sensors have been designed around stepper motor control systems. Each mechanism utilises appropriately sized stepper motors with common stepper motor drivers and positional feedback sensors to support component and software reuse. These control systems provide a high torque, high precision and low power solution to positioning the wider range of mechanisms found in the wave front sensor systems.

One physical Beckhoff industrial PC controls the mechanisms associated with both the LWFS and NWFS units. The controller connects to individual stepper motor drivers, encoder interfaces and diagnostic interfaces via an EtherCAT field bus interface. This allows for each input and output module to be configured, set and monitored while providing the capacity for future expansion and reconfiguration of the system via a single EtherCAT master.

The industrial PC controller has been chosen to run FreeBSD, a Unix-compatible open source operating system. This enables using existing code bases as well as Beckhoff's TwinCAT suite of software components for functions such as closed loop controllers, data acquisition, alarms and diagnostics systems.

5. CONCLUSION

The ULTIMATE-Subaru Ground Layer Adaptive Optics system will use four Laser Guide Stars in a square asterism of diameter 4 to 20 arcmin and four Natural Guide Stars for tip-tilt and focus retrieval. While the entire GLAO system is lead and coordinated by the National Astronomical Observatory of Japan, the Australian National University is responsible for the Wavefront Sensor Module (besides the optical design finalised by Subaru).

The preliminary design of the Wavefront Sensor Module for ULTIMATE-GLAO has been presented and described. After the Preliminary Design Review is held in October 2022, the project will move on to final design phase. The Acceptance Review of the entire Ground Layer Adaptive Optics system is scheduled for 2027.

ACKNOWLEDGMENTS

ULTIMATE-Subaru is financially supported by the FY2021 supplementary budget from the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT).

REFERENCES

1. Y. Minowa, Y. Koyama, Y. Ono, I. Tanaka, T. Hattori, C. Clergeon, M. Akiyama, T. Kodama, K. Motohara, F. Rigaut, C. d'Orgeville, S.-Y. Wang, and M. Yoshida, "Ultimate-subaru: enhancing the subaru's wide-field capability with glao," *Advances in Optical Astronomical Instrumentation 2019* **11203**, pp. 21 – 22, 2020.
2. J. Foley and C. Campbell, "An optical device with variable astigmatic power," *Optometry and vision science : official publication of the American Academy of Optometry* **76**, pp. 664–7, 10 1999.