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Preliminary design of the Laser Guide Star Facility for the ULTIMATE-Subaru Ground Layer Adaptive Optics system

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ABSTRACT

The Ground Layer Adaptive Optics (GLAO) system for ULTIMATE, the next generation instrumentation project for the Subaru telescope, will generate and use four laser guide stars on sky in side-launch configuration. The design of the GLAO is led and coordinated 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 responsible for the wavefront sensor subsystem and the Laser Guide Star Facility.

The GLAO Laser Guide Star Facility (LGSF) includes two Sodium guidestar lasers to be split in a total of four, generating an asterism of four artificial stars on the Hawaiian skies. Divided into three main subsystems (beam transfer optics, beam diagnostics, and beam projection), the GLAO LGSF accounts for the conditioning, splitting, and steering of the laser beams as well as for their launching configuration over a patrol field of 20 arcmin on sky.

This paper presents the preliminary design of the GLAO Laser Guide Star Facility including different approaches for the most efficient splitting of the guidestar lasers, and specifications summary for the final selection of the laser launch telescopes.

Keywords: Laser Guide Star facility, Ground Layer Adaptive Optics, Subaru telescope, ULTIMATE-Subaru

1. INTRODUCTION

ULTIMATE-Subaru Ground Layer Adaptive Optics will equip the Subaru telescope with ambitious wide field AO-corrected instrumentation; ULTIMATE will have an expected spatial resolution of about 0.2 arcsec FWHM in K-band under moderate seeing conditions at Subaru telescope over a 20 arcminutes diameter field of view.[1]

Four laser beams must be projected to create the Subaru ULTIMATE GLAO LGS asterism, with a maximum asterism diameter of 20 arcminutes and a minimum of 4 arcminutes. The ULTIMATE-Subaru Laser Guide Star Facility operates in side launch configuration to avoid fratricide effects in the Laser Guide Star wavefront sensors (Figure 1).

The ULTIMATE-Subaru Laser Guide Star Facility includes two Laser Guide Star Units located at the front and rear sides of the Subaru telescope centre section. The LGSF is also equipped with a Laser Acquisition System (LAS) and all the laser safety components required for the safe operation of the facility. The Laser Guide Star Control System (LGS-CS) operates both Laser Guide Star Units and interfaces with the Laser Safety PLC. Figure 2 shows the architecture of the ULTIMATE-Subaru Laser Guide Star Facility.

Each Laser Guide Star Unit (Figure 3) includes: 1 Guidestar Laser System (GLS), 1 Beam Transfer Optics and 1 Beam Diagnostics (BTO and BD), and the Beam Projection System with 2 Laser Launch Telescopes (LLT).

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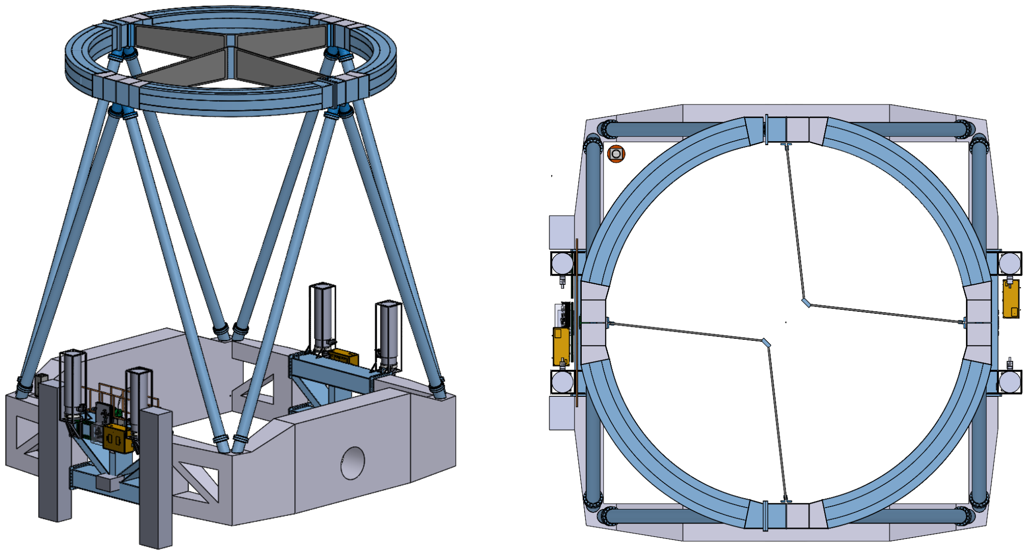


Figure 1. ULTIMATE-Subaru Laser Guide Star Facility in side launch configuration.

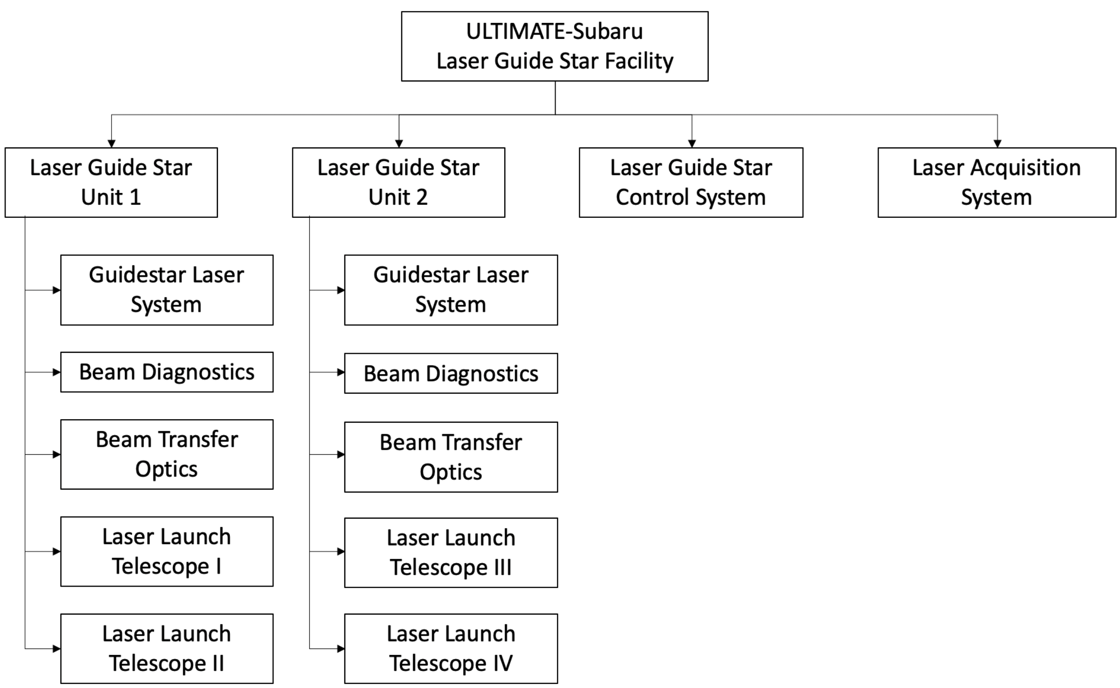


Figure 2. ULTIMATE-Subaru Laser Guide Star Facility Architecture

The current Subaru Laser Guide Star Facility is equipped with one TOPTICA SodiumStar 20/2 for classical LGS AO using the AO188. This TOPTICA system will be redeployed in the ULTIMATE-Subaru LGSF and duplicated for the second Laser Guide Star unit.

The Beam Diagnostics, Beam Transfer Optics, and Beam Projection modules of each Laser Guide Star Unit are described in detail in the following sections.

2. BEAM DIAGNOSTICS

The Beam Diagnostics (BD) system gather all the tools required to align the system at low power, monitor and measure the optical performance of the LGSF, and diagnose abnormal behaviour of the elements in the optical path. It is located between the Guidestar laser head and the Beam Transfer Optics and therefore, it is equipped with periscope mirrors to feed the laser beam into the Beam Expander Unit in the BTO. Both BD and BTO are mounted on the same breadboard in the telescope centre-section.

The Guidestar laser power can be adjusted between 2W and 23W by rotating a half-wave plate that will change the angle of the linearly polarised light coming from the laser head; downstream, and due to the polarisation change inferred, a thin film polariser reflects a fraction of the laser power towards a water cooled beam damper. A COTS wavefront sensor is used for beam quality diagnostics of the Guidestar laser and for determining the aberrations introduced by the LGSF optical components; it is located behind a fold mirror on a linear stage moving in and out of the optical path. There are three possible configurations: (1) the fold mirror is not in the optical path and the WFS is measuring the aberrations in the Guidestar laser beam; (2) the fold mirror is in the optical path and is reflecting off the Guidestar laser light and directing it towards the Laser Launch Telescopes (WFS not in operation); and (3) the fold mirror is in the optical path and is reflecting off starlight captured by each LLT (one at a time) and directing it to the WFS for the diagnostics of the LGSF optical quality as a whole.

The Guidestar laser alignment is monitored at all times using a Position Sensitive Device (PSD) located behind a back polished fold mirror. A back polished mirror with 589 nm coating will transmit a very small portion ($\leq 1\%$) of the incident light within the coating band. This set-up enables utilising the PSD without adding a splitting element to the optical path.

The laser wavelength and power are measured using a Sodium gas cell and a water cooled powermeter, respectively. The fold mirror that leads the light towards the powermeter is also back polished to enable on-line measurement of the laser wavelength and power. The powermeter is part of the laser safety shutter that prevents the laser propagation in case the Laser Safety System is triggered.

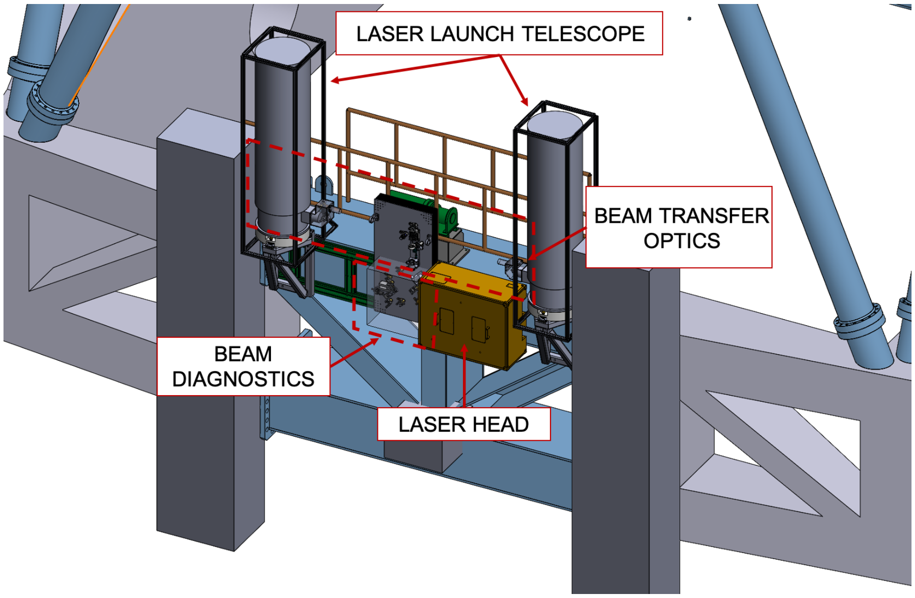
The Beam Diagnostics module is also equipped with phase plates to manipulate the polarisation of the laser beam being propagated on sky. A Half Wave Plate (HWP) together with the Quarter Wave Plate (QWP) at each LLT input port adjust the angle of the linearly polarised beam from the Guidestar laser head and transform it into circular polarisation at the LLT output.

3. BEAM TRANSFER OPTICS

The Beam Transfer Optics system encompasses the optical elements that condition and transport the laser beams exiting the TOPTICA laser head to the two Laser Launch Telescopes. The Beam Transfer Optics (BTO) is responsible of transporting the beam from a single laser head to a beamsplitter cube that split the laser into two paths and then transporting each split beam to their respective LLT.

The beam conditioning elements of the BTO have four functions: maintaining polarisation stability, beam expansion, spot size adjustment, and alignment corrections. The beam transporting elements fold the laser path and split it into two paths of equal optical length to maintain the same spot size on-sky and yield cost savings in terms of design, procurement, fabrication, integration and testing. The high degree of symmetry also ensures ease of alignment and calibration as well as operation. The BTO design guarantees that the laser beam goes through or is reflected off the smallest possible number of surfaces.

The differences between the two optical paths for laser beam 1 and laser beam 2 lies in the addition of an extra fold mirror in the straight path (laser beam 1) and unequal distances between the Beam Centering Mirror



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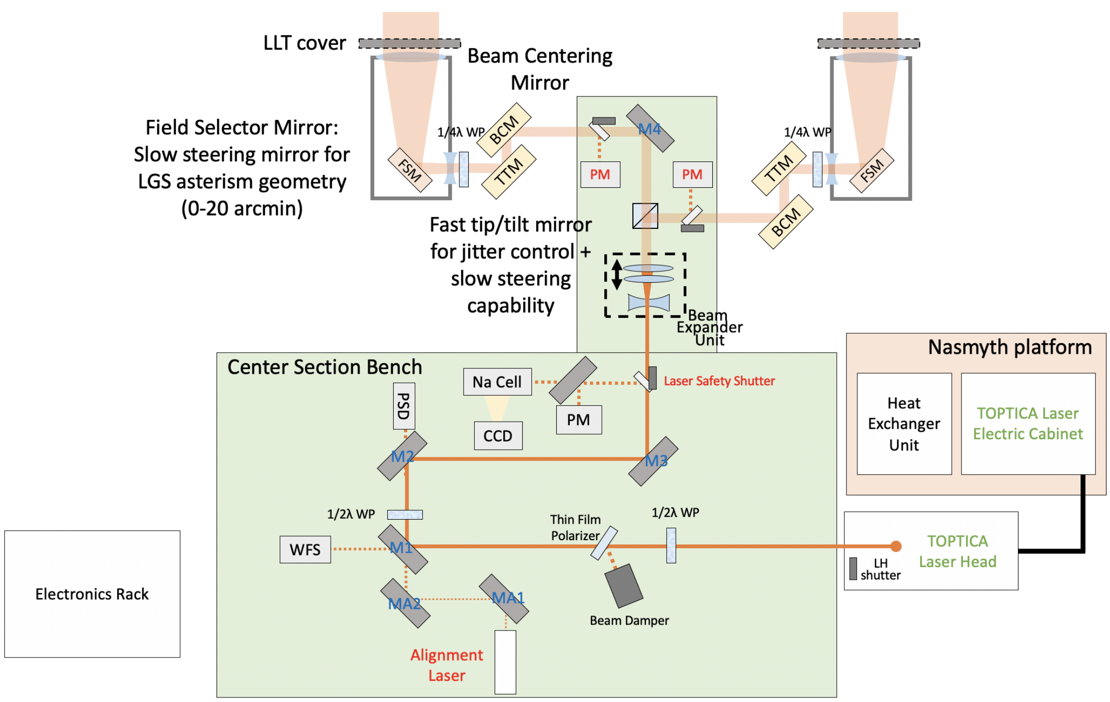

(b)

Figure 3. The ULTIMATE-Subaru LGSF consists of two mirrored Laser Guide Star Units at the front and rear centre-sections of the Subaru telescope. (a) CAD view of one Laser Guide Star Unit and its optical modules; (b) Schematic of one Laser Guide Star Unit with all the elements.

(BCM) and the Tip Tilt Mirror (TTM) on each split beam. The beam pointing strategy takes into account this unavoidable break in the symmetry and ensures the beam pointing control is not thereby affected.

This section describes the main functions of the BTO in the same order as they are encountered by the laser beam when travelling along the optical path from the TOPTICA Laser Head to each Laser Launch Telescope.

3.1 LGS Spot Size Adjustment

Following the laser beam path from the Guidestar Laser System to the sky, one of the first functions performed by the BTO is to increase the laser beam size between the output of the laser system and the input of the LLT. The TOPTICA SodiumStar 20/2 laser has a Gaussian beam output diameter of 3 mm @ $1/e^2$ intensity points; the desired laser beam diameter at the input of the LLT is 10.8 mm @ $1/e^2$ intensity points. The magnification ratio sought from the BTO is thus $10/3 = 3.3$x.

The beam expander function of the BTO is performed by the Beam Expander Unit (BEU). The BEU consists of Galilean beam expander with two fixed lenses plus a third lens on a translation stage: a double-concave negative lens and a plano-convex positive lens expand the 3 mm diameter ($1/e^2$) beam from the laser head to 10.8 mm diameter ($1/e^2$); a movable third lens located after the beam expander adjusts the divergence of the beam going into the Laser Launch Telescope (LLT). The spot size on-sky is determined by the location and size of the laser waist after exiting the LLT, which is affected by the divergence of the entering beam. Therefore, the translation of the third lens is directly responsible for producing an optimal spot size on-sky. The GLAO requirements on sky coverage determines the LGS spot focus range to be 85 km to 300 km.

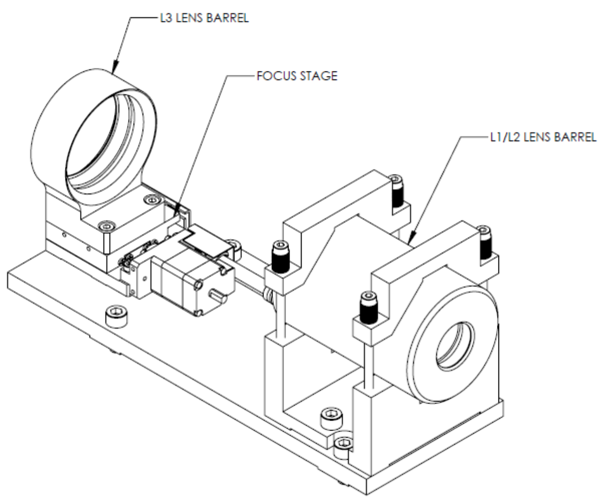

Figure 4. Beam Expander Unit in the LGSF Beam Transfer Optics

The lens barrel mounts, including the stage, will be precisely located relative to the base plate using dowel pin and slot arrangements (Figure 4). The common base plate allows the beam expander to be assembled and tested before being installed on and aligned to the BD/BTO breadboard.

3.2 LGS Splitting

The total power from each TOPTICA laser is split between the two LLTs that it supplies. Thus, the laser power is required to be as evenly split as possible to ensure that the guide stars appear equally bright. In the BTO system, the biggest potential source of differential beam power between the two beam paths is the splitting element.

Two main options have been considered for the splitting element: (1) the use of a Diffractive Optical Element (DOE) and only one Laser Launch Telescope per Laser Guide Star Unit projecting the two beams through the same aperture; and (2) a beam splitter cube and two Laser Launch Telescopes per Laser Guide Star Unit.

Diffractive optical elements (DOE)[2] modify the light by redirecting and partitioning using the interference property of light to produce a variety of light patterns from one incident beam. One feature that DOEs have is the ability to split laser beams into an N by M array of identical output beams. Each of these output beams can be configured to only differ from the input beam by the power and the angle of propagation, however, can also be configured to give the output beams certain qualities including a particular polarisation. DOEs have no impact on the polarisation of the laser beams, which is ideal for this application.

During the conceptual design phase, a LGSF with central launch behind the Subaru secondary mirror was discarded on the baseline that a >20 arcmin field of view LLT would have been technologically very difficult. Choosing to project two laser beams out of one side-launch projector only reduces the laser projector field of view requirement by a factor of $\sqrt{2}/2 = 0.7$ from >20 arcmin to >14 arcmin: this field of view is challenging, but achievable with the current Laser Launch Telescope technology. However, Diffractive Optical Elements that achieve large separation angles (> 6 degrees) between the laser beams are only efficient to the ≈75 % based on consultations with potential manufacturers. Therefore, a beam splitter cube has been selected as the design baseline.

The choice between polarising and non-polarising beam splitter cubes has been analysed. Polarising beam splitters are designed to transmit P-polarisation through the straight path and reflect S-polarisation out at a right angle. Non-polarising beam splitters are meant to transmit a certain fraction of the beam and reflect the remaining regardless of polarisation. In reality, non-polarising beam splitters do have some polarisation sensitivity. As well, polarising beam splitters are limited in how well it separates the two linear polarisation states. This study produced two main insights: 1) non-polarising beam splitters can offer adequate power differential (< 4%) without introducing unintended polarisation changes, and 2) polarising beam splitters can remove the power differential if fine-tuning of the polarisation angle is achieved, but suffer from poor folded-path PER due to significant p-polarisation leakage. The effect of these two effects (4% power differential vs PER < 97%) on the photon flux return from the LGS will be analysed to select the final beam splitter cube.

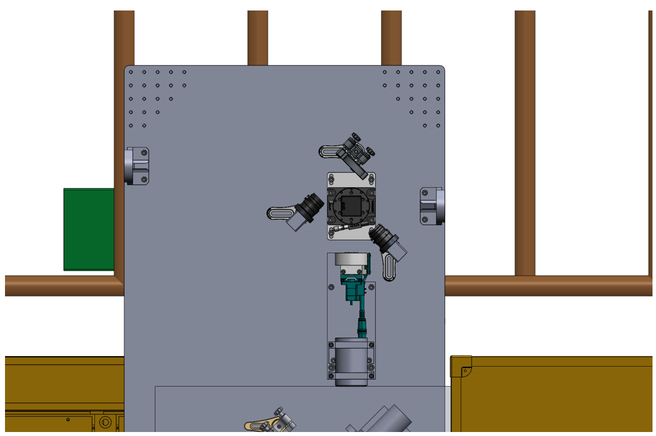

Figure 5. The Beam Splitter Unit is located after the Beam Expander Unit in the LGSF Beam Transfer Optics. Monitoring cameras image the beam footprint on the beam splitter.

The beam splitter will be mounted on a rotation stage to allow angular alignment of the folded (right hand) beam (Figure 5). The interface between the stage and the breadboard includes slots in both orthogonal directions to enable position adjustment in the plane of the breadboard.

3.3 LGS Pointing Control

The Beam Transfer Optics is equipped with slow steering and fast steering capability required to (1) maintain the alignment of the beam at the optical STOP of the Laser Launch Telescope (Field Selector Mirror); and (2) to compensate for the high frequency jitter in the LGS caused by the atmospheric turbulence. Notice the asterism pointing is performed by the Field Selector Mirror inside each LLT and the initial pointing will be carried out with the help of a Laser Acquisition System (LAS). The pointing error of the wavefront sensor (WFS) (as a combination of the launch and receiver paths) must be smaller than half of the WFS pick-off field-of-view (1”) in order to avoid telescope downtime. The camera system is manufactured by ASTREL Instrument and has already been demonstrated on the VLT.[3]

The BTO slow steering needs to control the low frequency adjustments of the laser beam position and angle at the LLT Field Selector Mirror (FSM) due to mechanical flexures of the system when the telescope elevation changes, the wind buffeting on the central breadboard, and the alignment errors. The BTO fast steering needs to correct for the high frequency LGS atmospheric jitter in close-loop operation with feedback from the Laser Guide Star Wavefront Sensor (LWFS). The close loop between the BTO jitter mirror and the LWFS will stabilise the LGS image on the wavefront sensor. The combination of both slow and fast pointing compensations result in a total of 30 arcsec (plus provision for alignment errors on the optical path) that need to be accommodated by one or two steering mechanisms. The baseline choice takes into account the alignment tolerances the LLT requires.

The pointing module (Figure 6) is located as close as possible to the LLT entrance port in order to minimise the beam wander at the LLT output; it consists of one fold mirror (Beam Centering Mirror - BCM) and the uplink TT mirror for the jitter correction (TTM). We have studied the need to also actuate the fold mirror resulting in two independent mechanisms (slow and fast) for the laser beam steering in the BTO space. If the resulted displacement of the beam at the LLT input port were larger than the LLT alignment sensitivity, the BCM would have to be actuated to compensate for the decentre introduced by this angle on the TTM. After consulting with the potential vendors, no concerns have been raised. Therefore, the baseline design of the pointing modules is to have only one mechanism that will simultaneously correct for the low and high frequency displacements of the each laser beam with provision for actuating the BCM if needed. The beam pointing modules will be prototyped during Final Design phase to verify the behaviour of a combined slow and fast mechanism.

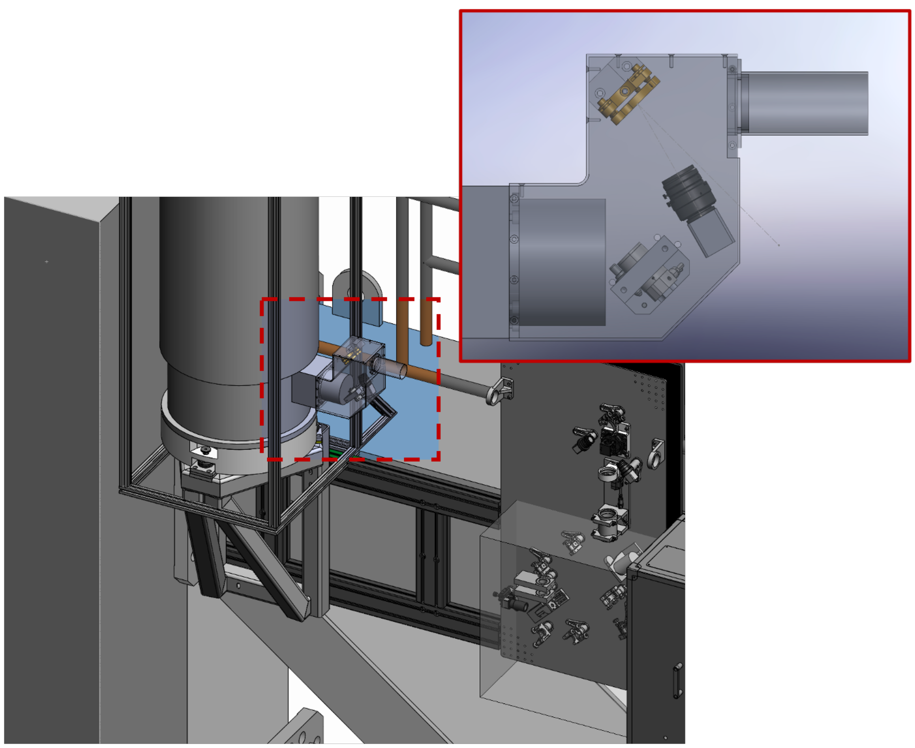

Figure 6. Beam pointing module in the LGSF Beam Transfer Optics. It includes a mirror monitoring camera for the commissioning phase.

3.4 LGS Polarisation Optimisation

Circular polarisation must be projected on the sky to yield the highest possible sodium photon return at all azimuths and elevations[4].[5] The TOPTICA SodiumStar will produce linearly polarised light with a high extinction ratio.

The combination of one Half Wave Plate (HWP) in the common beam path and one Quarter Wave Plate (QWP) per projected laser beam is used to change this linear polarisation into circular polarisation and optimise it before the beam is projected on sky. In order to ensure the highest purity of circular polarisation for both projected beams, the laser beam polarisation must be tightly controlled at each BTO surface on the laser path. This is achieved by paying close attention to the linear polarisation orientation specified at the output of the Guidestar Laser System and the relative s or p polarisation or combination thereof on each BTO surface.

4. BEAM PROJECTION

The primary function of the Beam Projection System is to propagate the laser beams on the sky. It consists of four Laser Launch Telescopes (LLT) in side launch configuration: two per Laser Guide Star Unit. Each LLT is independently steered of its neighbours to position the LGS on the sky according to the LGS asterism configuration. The LGS asterism rotation is fixed with respect to the Subaru telescope. The laser projectors are located outside of the perimeter of the Subaru telescope primary mirror in order to minimise Rayleigh light pollution in the Laser Guide Star wavefront sensor (LWFS).

The optimal laser launch diameter has been chosen to be 200 mm at $1/e^2$ intensity points. Therefore, each Laser Launch Telescope will be a 30-cm 20x class beam expander, afocal design, fed by a collimated 15mm diameter input beam for the final projection of a circularly polarised laser beam onto the sky. Each LLT shall be equipped with the appropriate mechanism to steer the laser beam from ±5 arcmin down to ±1 arcmin within $\pm$ 3.5 arcsec absolute pointing error (blind pointing). It shall also contain a Quarter Wave Plate to convert the input linear polarisation into circular polarisation.

The LLTs will be mounted on the optical path via a set of brackets which take the form of steel weldments (Figure 7). The brackets are bolted (on the front side) to existing sets of aluminium profile rail, which are bolted to the steel work of the centre section. The interface between the LLT and the LLT bracket is kinematic and athermal, using a set of three canoe-sphere/v-groove interfaces, equally spaced around the circumference of the LLT interface, to exactly constrain the six degrees of freedom of the LLT.

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. While the entire GLAO system is lead and coordinated by the National Astronomical Observatory of Japan, the Australian National University is responsible of the Laser Guide Star Facility work package.

The preliminary design of the ULTIMATE-Subaru Laser Guide Star Facility 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.

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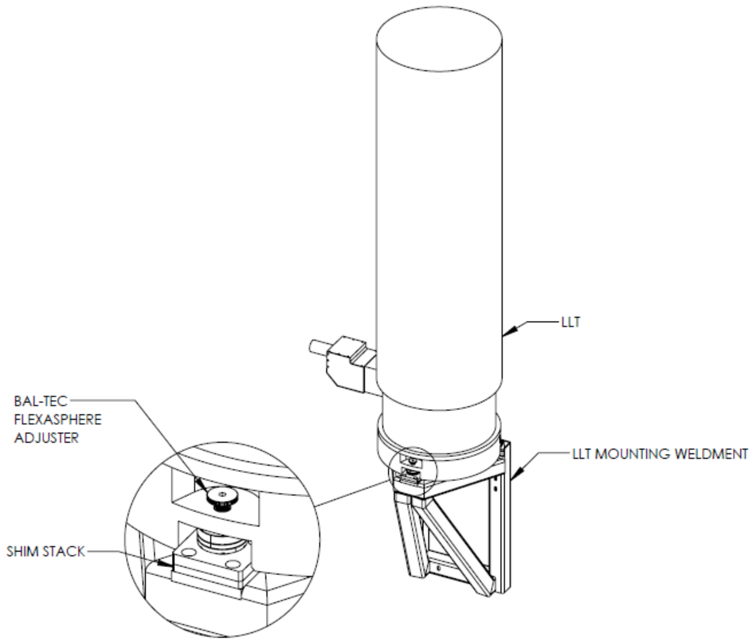

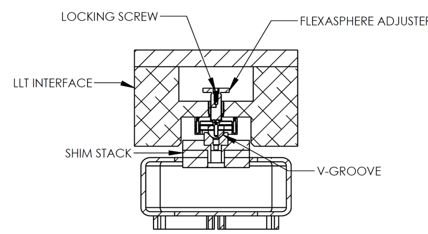

Figure 7. (a) LLT assembly as installed on the telescope centre section; (b) Detail of the angular adjustment of the LLT via a kinematic interface.

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