An asterism generator for Keck All-sky Precision Adaptive optics

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ABSTRACT

As part of the Keck All-sky Precision Adaptive optics (KAPA) project a laser Asterism Generator (AG) is being implemented on the Keck I telescope. The AG provides four Laser Guide Stars (LGS) to the Keck Adaptive Optics (AO) system by splitting a single 22W laser beam into four beams of equal intensity. We present the design and implementation of the AG for KAPA. We discuss the optical design and layout, the details of the mechanical design and fabrication, and the challenges of designing the assembly to fit into the limited available space on the Keck telescope.

Keywords: KAPA, LGS, laser tomography, adaptive optics

1. INTRODUCTION

A laser asterism generator (AG) has been implemented on the Keck I telescope inside the Keck telescope secondary mirror module. The AG is a collaborative effort between W. M. Keck Observatory (WMKO) and OMP Inc. The AG divides an input 22W, 589nm laser beam into four beams of equal intensity in order to provide four laser guide stars (LGS) for laser tomography adaptive optics (LTAO). The AG is a key component of the Keck All-sky Precision Adaptive optics (KAPA) project.[1] KAPA will upgrade the existing Keck I adaptive optics (AO) system to add four laser guide stars (LGS) and laser-tomographic reconstruction to correct for the cone-effect. KAPA also adds a faster real-time controller computer, support for IR tip-tilt sensing with TRICK, and PSF reconstruction. The gains will include increased sky coverage, improved image quality, and better extraction of scientific information from the resulting images and spectra.

Several performance and volume constraints drove the opto-mechanical design of the AG. The primary opto-mechanical requirements that drove the design are listed in Table 1.

Table 1. Primary asterism generator optical requirements.

AG #	Requirement
1	At the output of the laser launch telescope, the four beams shall have tilts of 7.59"±0.6" in the direction away from the launch telescope optical axis, without using any of the range of the asterism up-link tip-tilt control.
2	At the output of the asterism generator, the four beams shall have tilts of 540″±9″ toward the center of the asterism.
3	All of the asterism generator requirements must be met at all angles between 1° and 65° zenith.
4	The weight of the asterism generator assembly, including the AG, mirrors, mounts, position sensor, KM6 camera, and enclosure shall be ≤ 32 kg.
5	A beam compressor shall be incorporated just prior to the asterism generator, and within the KM6/7 enclosure, to reduce the beam $1/e^2$ diameter from 9 mm to 4 mm for the single and four LGS asterism modes.
6	The asterism generator shall be able to be moved out of the beam to support single LGS operation.
7	The LGS asterism generator shall rotate to maintain its orientation on the sky to a positioning accuracy of ≤ 0.62°
8	The asterism generator assembly shall be able to be removed, for repair or maintenance, from the KM6/7 enclosure and repeatably reinstalled while the enclosure is mounted in the Keck telescope secondary mirror module.
9	Each of the four beams shall have up-link tip-tilt control with an on-sky range of ≥ 6" radius.

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To minimize the size of the assembly and to fit within other space constraints, the AG is located inside the telescope secondary socket. Figure 1 shows the layout of the Free Space Transport (FST) optics inside the secondary socket. These include the KAPA Mirror (KM) 6/7 enclosure, where the AG is located, the Beam Transport Optics Bench (BTOB) and the laser Launch Telescope (LT). The space allocated for the AG enclosure (not including the mounting support structure) has a footprint of about 250mm wide by 800mm long by 400mm high. This limited space is the largest available option within the FST system and was a driving factor behind the layout of the opto-mechanical design.

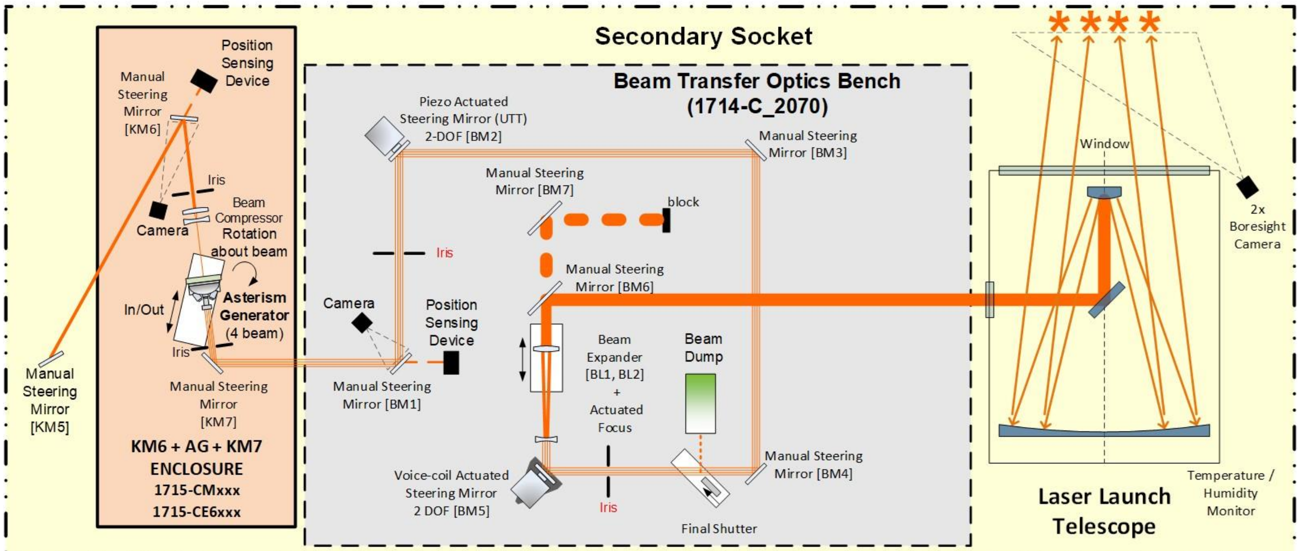

Figure 1: Free space transport optics within the secondary socket.

In this paper we will discuss the opto-mechanical design and implementation of the AG. Related papers at this conference will discuss other components of the KAPA project as well as providing an update on the project status.[1-3]

2. OPTO-MECHANICAL OVERVIEW

Laser light from the 22W TOPTICA/MPB laser originates from the laser head mounted on the Keck I telescope elevation ring and is propagated up to the secondary socket using a series of fixed and actuated mirrors.[4-5] The laser beam travels approximately 20m from the laser head to the secondary socket where it has a $1/e^2$ diameter of approximately 9mm. As the laser beam enters the secondary socket it, is reflected towards the AG by KM6 and enters a beam reducer assembly that decreases the $1/e^2$ diameter of the 22W beam to 4mm. The reduction is necessary in order to keep the AG assembly as small as possible. After the reducer the beam enters the primary AG optical assembly, which consists of the beamsplitter prism assembly, four piezo controlled mirrors and a beam compressor assembly. The beamsplitter prism assembly splits the incoming laser beam into four beams of equal intensity separated by 90°. Next, the beams are reflected off piezo steering mirrors which control the individual pointing of the beams on-sky. The beam compressor prism assembly is necessary to reduce the overall footprint of the asterism on the BTOB and LT optics. The AG assembly has the ability to rotate the asterism for tracking on-sky and to translate out of beam for single LGS operation. The final optic in the enclosure is KM7 which sends the laser light into the BTOB.

Figure 2 shows a CAD model of the AG enclosure mounted within the secondary socket and Figure 3 shows a detailed CAD model of the AG enclosure. Figure 4 shows the overall dimensions of the AG enclosure attached to the support structure.

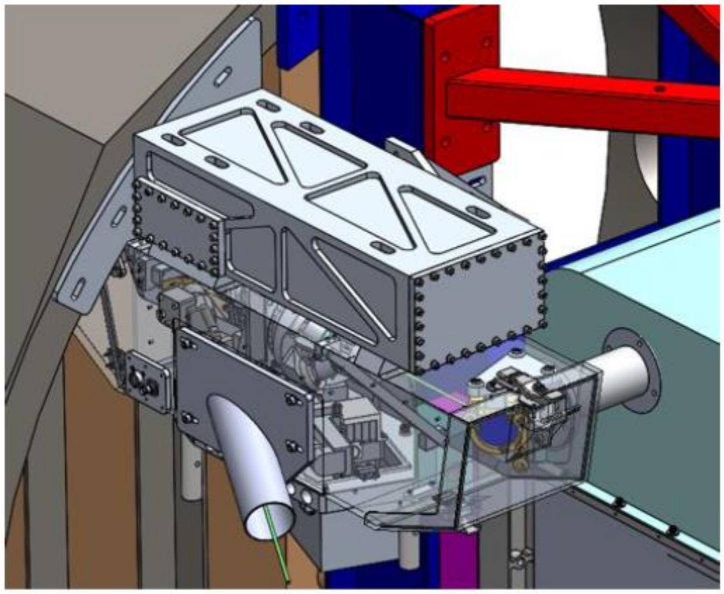

Figure 2: CAD model of the AG enclosure mounted on the telescope secondary module.

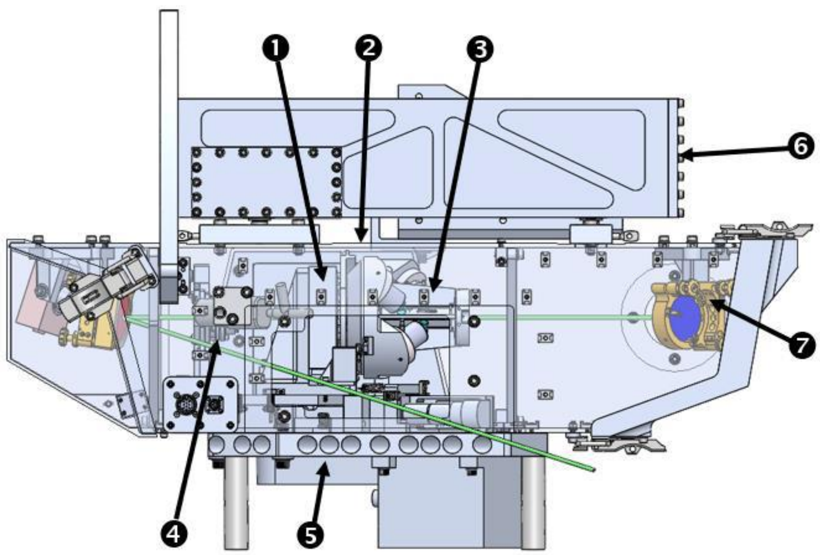

Figure 3: Detailed CAD model of the AG enclosure pointing out: (1) the motorization system, (2) the enclosure, (3) the optical beamsplitter assembly, (4) the beam reducer assembly (5) the support plate, (6) the structural support brace and (7) the KM6/7 mirror mount.

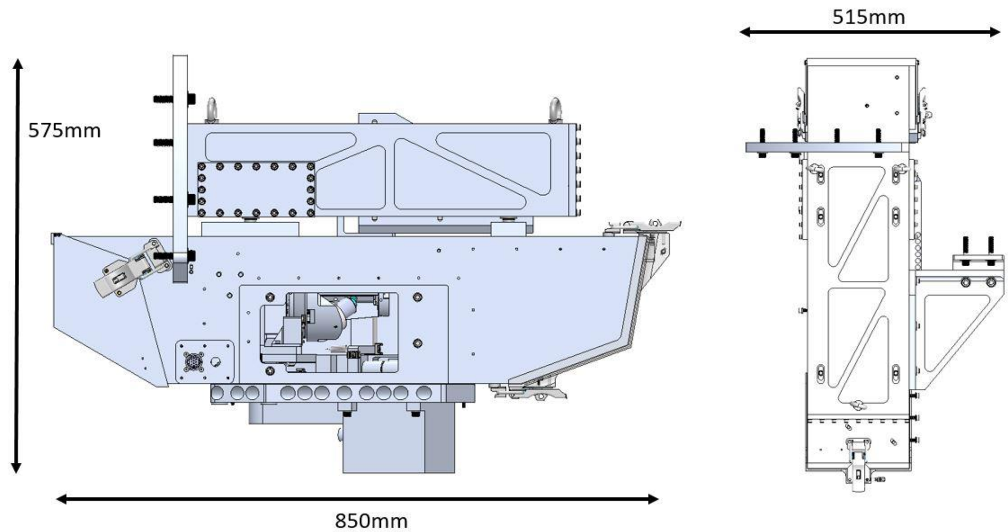

Figure 4: Dimensions of the AG enclosure with support structure.

3. OPTICAL DESIGN

The optical design for the AG enclosure consists of an afocal beam reducer and a combination of beamsplitters, mirrors and prisms. An update to the BTOB Beam Expander (BXP) was also included as part of the AG project. Figure 5 shows the optical layout within the AG enclosure.

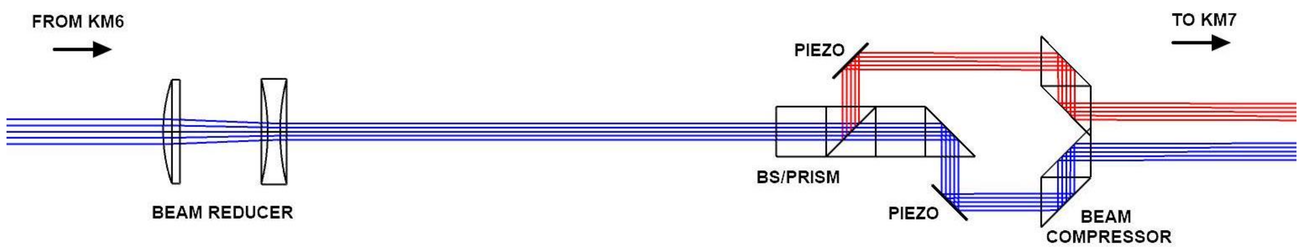

Figure 5: Optical layout within the AG enclosure.

3.1 Beam reducer

The optics for the AG needed to be as compact as possible in order for the assembly to fit within the space constraints within the secondary module. A preliminary opto-mechanical design determined that the cube beamsplitters could be no more than 12mm in width. This required that the incoming beam be reduced in size to avoid vignetting and throughput loss at the AG. The afocal beam reducer is shown in Figure 6 and consists of two commercial off-the-shelf (COTS) lenses with a high throughput 589nm coating.

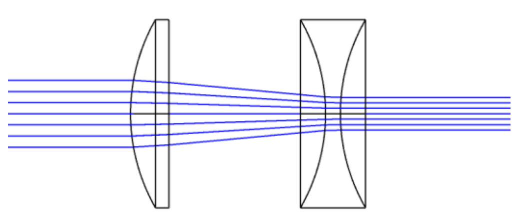

Figure 6: Beam reducer optical layout.

The beam reducer was assembled and aligned to have a RMS wavefront error of 0.061 waves at 589 nm. Figure 7 shows the post-processed wavefront over a 5mm diameter exit pupil.

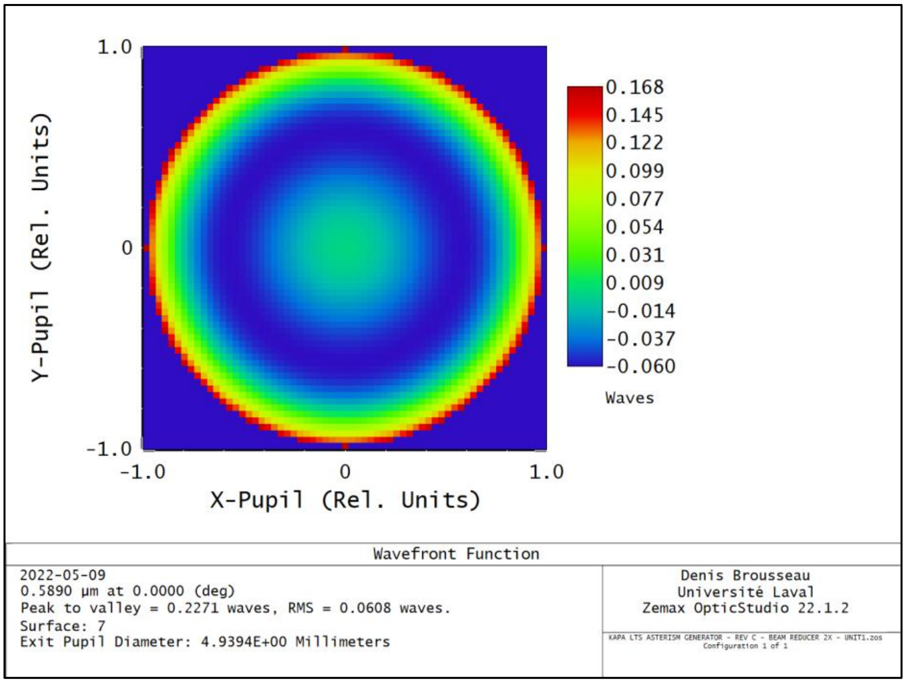

Figure 7: Beam reducer alignment result (rms = 0.061 waves at 589 nm).

3.2 AG beamsplitter, piezo mirrors and compressor

The heart of the AG is the beamsplitter prism assembly which splits the incoming beam into four beams of equal intensity. The beamsplitter assembly consists of three polarization maintaining cube beamsplitters followed by a right-angle prism as shown in Figure 5. As the laser propagates through the beamsplitter assembly it is split into four beams of equal intensity. Figure 8 shows the beamsplitter assembly being tested in the lab before integration into the AG assembly. Power meters were placed at the output of each reflection and a half waveplate (HWP) was use to change the input polarization to the beamsplitter assembly.

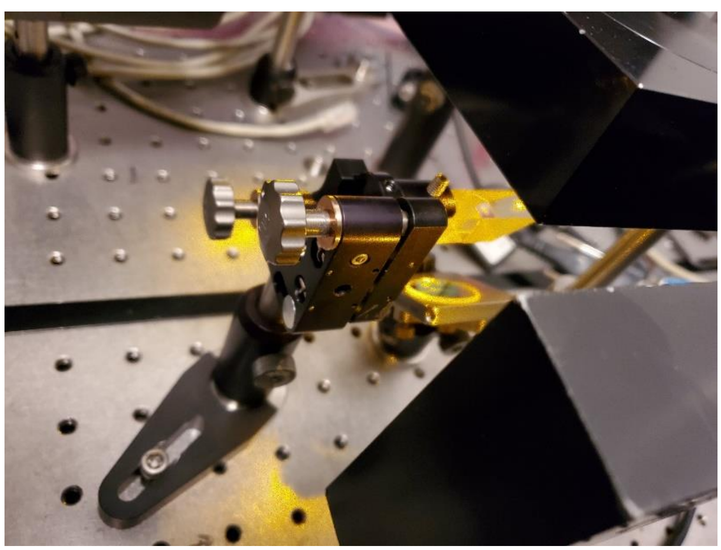

Figure 8: Beamsplitter assembly test in lab.

Table 2 shows the results of the throughput measurement conducted in the lab. All of the beamsplitters meet the requirements for throughput and polarization.

Table 2: Beamsplitter (BS) measured throughput.

HWP angle (deg)	Throughput				
	First reflection	**Second reflection**	**Third reflection**	**Fourth reflection**	**Total**
0	23.67%	25.59%	24.62%	24.09%	97.97%
45	24.02%	24.93%	24.36%	25.78%	99.09%
90	23.81%	25.54%	24.54%	24.23%	98.12%
135	24.16%	25.19%	24.58%	25.77%	99.70%
180	23.81%	25.67%	24.58%	23.92%	97.98%

Following reflection from the beamsplitters the individual beams encounter the piezo steering mirrors which control the individual positioning of the beams on-sky. The piezo mirrors are 12.7mm in diameter and are mounted to PI S-331 fast piezo tip/tilt stages. The piezo stages are mounted to have an inward tilt of 268.3 arcseconds in order for the output beams to have an on-sky radius of 7.59 arcseconds.

After reflection off the piezo mirrors the beams pass through the beam compressor prism assembly which reduces the physical separation of the four beams while maintaining their angular offset. Without the beam compressor assembly, the total footprint of the four beams would be too large for the BTOB optics. The beam compressor prism assembly is composed of four N-BK7 prisms that laterally displace each beam approximately 12mm while maintaining polarization and throughput to better than 99%.

3.3 BTOB BXP optical design

The BXP is located within the BTOB and serves two functions; expand the beam to the proper size on the LT secondary mirror (22mm) and control the focus of the LGS on-sky. Figure 9 shows the layout of the BXP optics. The laser beam $1/e^2$ diameter is expanded from 4mm to 22mm diameter by use of a two-lens afocal system. The second lens is mounted to a translation stage which is used to optimize the focus of the LGS on-sky. Both BXP lenses are custom singlets with the same high throughput 589nm coating as the beam reducer optics.

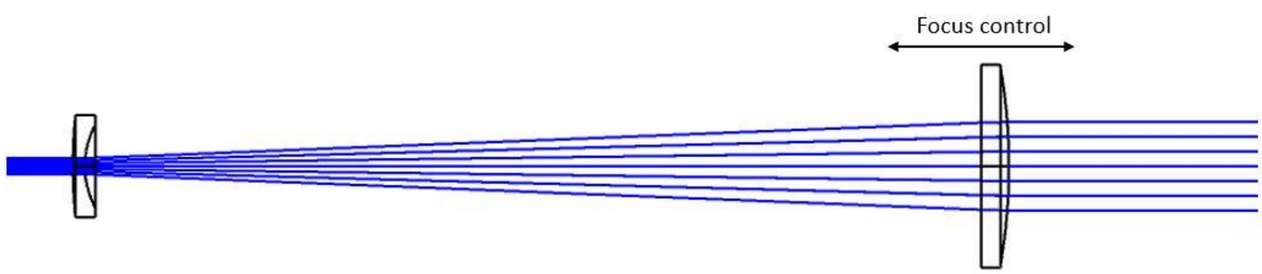

Figure 9: BTOB BXP layout.

4. ASTERISM GENERATOR MECHANICAL DESIGN

Perhaps the most challenging aspect of the AG was the mechanical design. Volume constraints and optical requirements drove the overall mechanical layout and the precision manufacturing requirements for various mechanical components. The following sections describe the AG mechanical design.

4.1 AG main assembly

Figure 10 shows the AG assembly CAD model which contains the opto-mechanical components that generate the asterism for laser tomography and allow switching between single LGS and multiple LGS. This component is part of the entire assembly as shown in Figure 3 and can be removed from the enclosure without affecting single LGS operations. All the optical components (beamsplitter prisms, piezo actuated mirrors, and beam compressor) are housed within the main optical assembly which is shown in Figure 11. The main optical assembly is mounted to a rotation stage which can rotate the asterism up to 280° on-sky (limited by cabling). The rotation stage, linked to the image rotator in the AO system, maintains the orientation of the asterism with respect to the wavefront sensor as the science target is tracked across the sky. A linear stage is used along with the rotation stage to position the AG optics for single LGS operations. In this configuration the main optical assembly is moved out of the beam and the full 22W beam passes through a clear aperture as shown in Figure 11. The linear stage is attached to the main base plate which supports the opto-mechanical assembly and links it to the enclosure.

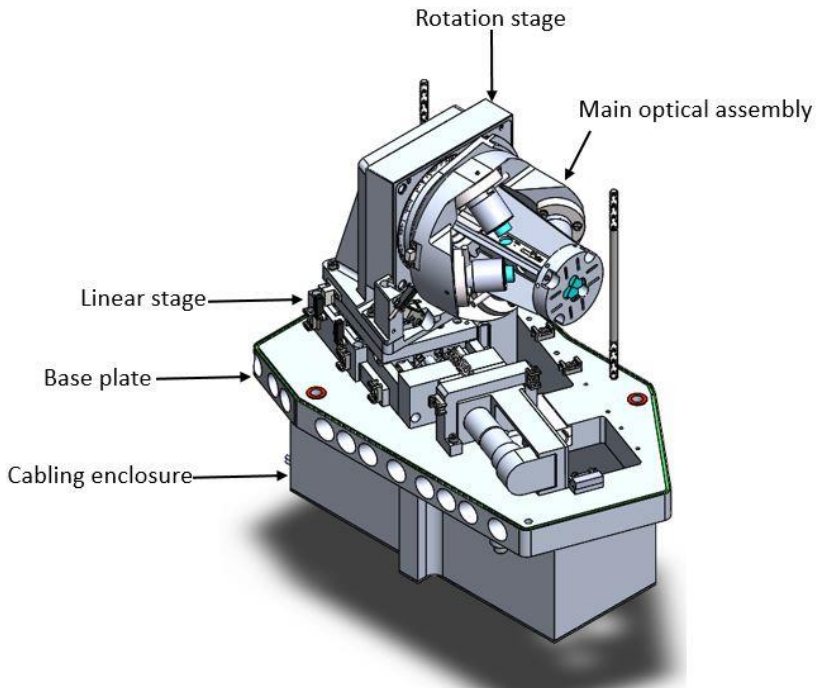

Figure 10: AG assembly.

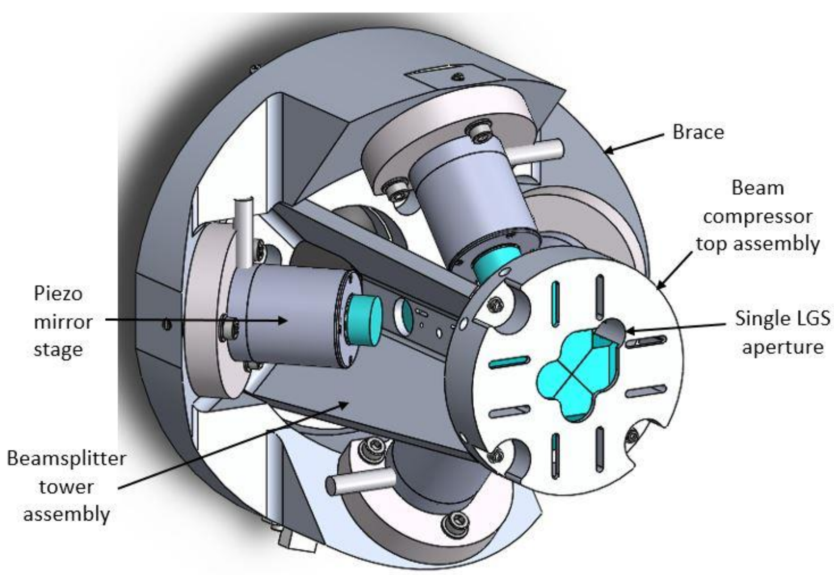

Figure 11: AG main optical assembly.

4.2 Enclosure

The enclosure assembly houses the AG as well as the remainder of the beam train components prior to the BTOB. Figure 12 shows a detailed CAD model of the KM6/7 enclosure and Figure 13 shows the light path through the enclosure. A position sensing device (PSD) is located behind KM6 and uses the leakage from the mirror to detect the position of the incoming laser beam. An actuated mirror (KM5) prior to the enclosure is used in closed loop with the PSD to ensure the beam remains fixed on the KM6 mirror as the telescope tracks in elevation. The enclosure itself is made from extruded aluminum and provides structural support to mount the KM6 and KM7 mirrors, PSD, beam reducer assembly, AG main assembly and irises. The KM6 and KM7 mirrors are mounted in adjustable COTS mounts, some of the few COTS components in the entire assembly. Figure 14 shows the structural details of the enclosure.

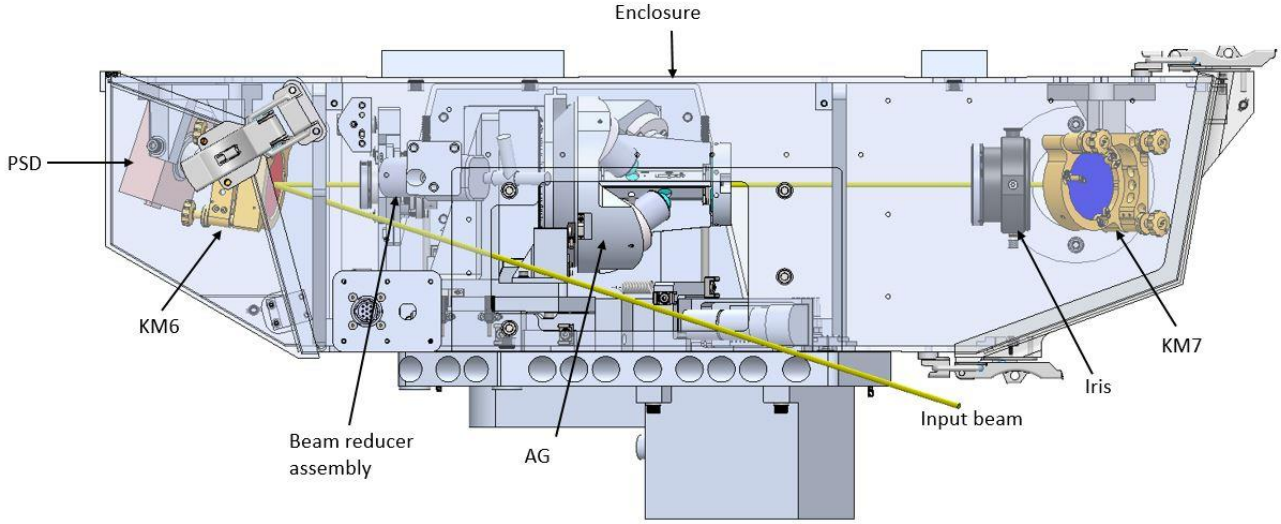

Figure 12: CAD model of the enclosure.

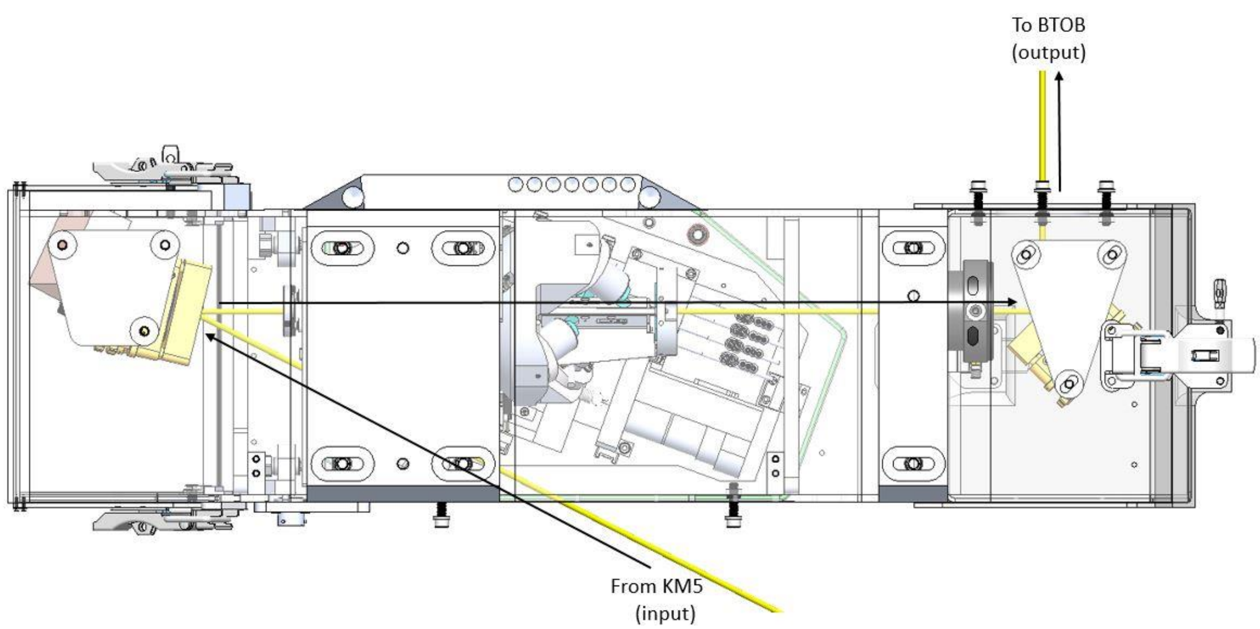

Figure 13: Light path through the AG enclosure.

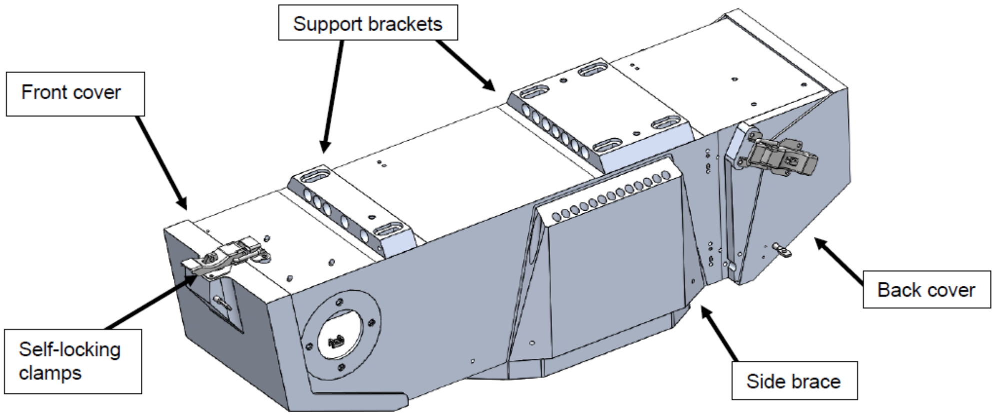

Figure 14: AG enclosure structural details.

Both the front and back covers are switch interlocked with the laser safety system (LSS) to prevent inadvertent exposure to laser light.

4.3 Structural support brace

The structural support brace is shown in Figure 3 (item 6) and acts as the interface between the enclosure assembly and the secondary module. The brace uses the same mounting points as the old KM6/7 enclosure and has been designed to meet all of the structural, temperature and elevation requirements. Figure 15 shows the details of the support brace.

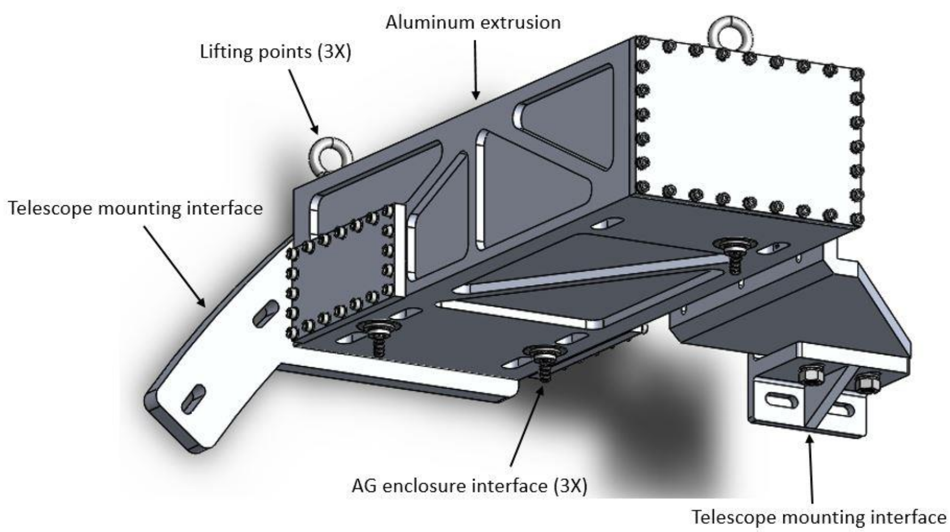

Figure 15: Brace.

Significant effort was required to meet the stiffness requirement while not adding significant weight. The support brace is designed to minimize flexure of the enclosure as the telescopes changes gravity orientation while also meeting a >100Hz natural frequency requirement.

5. TELESCOPE INTEGRATION

The AG enclosure and support brace were integrated onto the Keck I secondary module in November 2021. During this first integration phase the AG enclosure, which includes the KM6 & 7 mirrors and the beam reducer, was mounted to the secondary module and aligned to the FST beamtrain. Figure 16 shows the enclosure and brace mounted in the secondary module with the BTOB and LT enclosures shown as well.

During the initial assembly and alignment the AG was replaced by a weighted cover to simplify the integration. After lab testing of the AG, it was straightforward to install the AG in the enclosure. Guide rods to protect the assembly while inserting into the enclosure and dowel pins to constrain the position were part of the design. The weighted cover insured the AG did not affect the telescope balance.

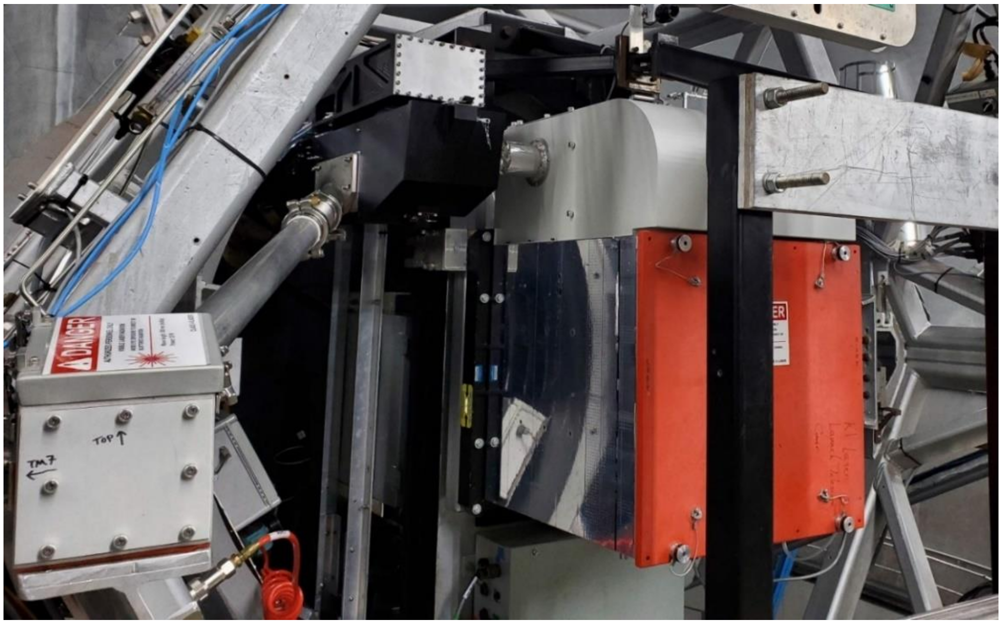

Figure 16: Enclosure and brace mounted in the secondary module.

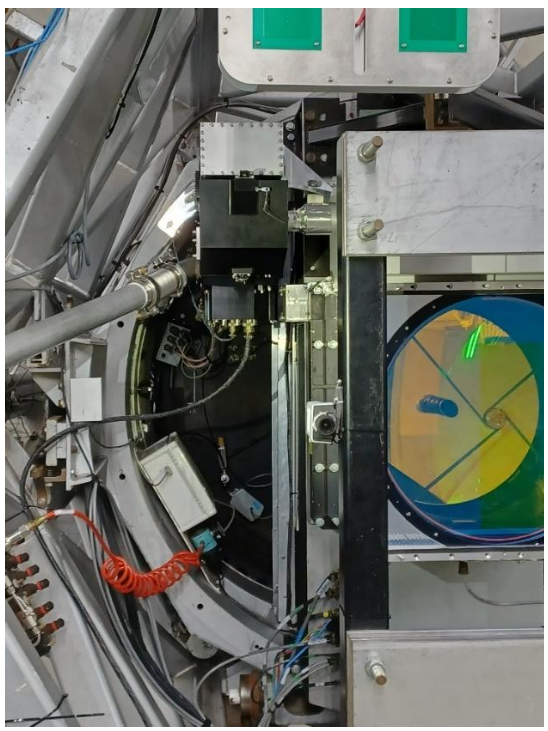

Figure 17: AG installed in the secondary module (the launch telescope is at center right).

Laboratory testing and integration of the AG concluded in May 2022 and the AG was installed in the enclosure on the Keck I telescope. Figure 17 shows the AG and associated cabling installed in the secondary module.

6. AG PERFORMANCE & FUTURE PLANS

The AG had its first on-sky testing in May 2022. During the first commissioning night the four LGS were observed on the AO acquisition camera (ACAM). Figure 18 shows the first image of all four LGS on ACAM. Commissioning of the AG on the first night included demonstrating single LGS mode by moving the AG out of beam and closing the AO loops on one of the four LGS. Subsequent commissioning nights with the AG will test individual steering of the four LGS and closing the AO loop with the WFS.

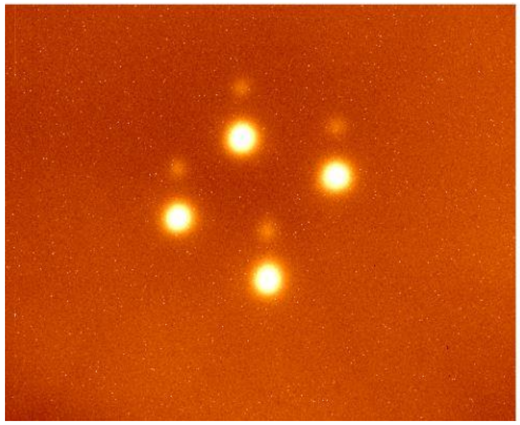

Figure 18: First image of the four LGS on-sky as imaged by the AO acquisition camera (the ghosts are from a beamsplitter in the acquisition camera path).

7. SUMMARY

An asterism generator (AG) has been successfully designed, assembled and implemented on the Keck I telescope. The opto-mechanical layout, and how it fits within the Keck I secondary module, have been described in this paper. The AG and enclosure was assembled and aligned at OMP Inc. and delivered to WMKO with the first on-sky test taking place in May 2022. Subsequent on-sky testing of the AG will take place in the summer and fall of 2022. A fully operational AG is planned for the second semester 2023.

8. ACKNOWLEGEMENT

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The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

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