A Sodium Laser Guide Star Facility for the ANU/EOS Space Debris Tracking Adaptive Optics Demonstrator

Céline d'Orgeville *[a], Francis Bennet[a], Mark Blundell[b], Rod Brister[b], Amy Chan[b], Murray Dawson[b], Yue Gao[b], Nicolas Paulin[a], Ian Price[a], François Rigaut[a], Ian Ritchie[b], Matt Sellars[c], Craig Smith[b], Kristina Uhlendorf[d], Yanjie Wang[b]

[a]Research School of Astronomy and Astrophysics, Australian National University, Advanced Instrumentation & Technology Centre, Canberra, Australia; [b]EOS Space Systems, Mount Stromlo Observatory, Canberra, Australia; [c]Laser Physics Centre, Australian National University, Canberra, Australia; [d]Jenoptik Optical Systems GmbH, Jena, Germany

ABSTRACT

The Australian National University and EOS Space Systems have teamed up to equip the EOS laser space debris tracking station on Mount Stromlo near Canberra, Australia, with sodium Laser Guide Star (LGS) Adaptive Optics (AO). The AO system is used to correct for laser beam degradation caused by the atmospheric turbulence on the upward infra-red laser pulse used to illuminate space debris. As a result, the AO-equipped laser tracking station can track smaller and more distant debris. This paper presents the joint ANU/EOS AO Demonstrator LGS facility requirements, architecture, and performance at the time of the conference.

Keywords: Space debris tracking, Adaptive Optics, Sodium Laser Guide Star, Guide Star Laser

1. INTRODUCTION

Sodium Laser Guide Star (LGS) Adaptive Optics (AO) techniques and technologies which have been successfully employed to sharpen images of objects located outside of the earth's atmosphere in astronomical applications as well as satellite surveillance applications can also be used to improve the tracking of space debris. The rationale for tracking space debris at optical or near infra-red wavelengths by LIDAR as opposed to RADAR is presented in details elsewhere in this conference[1]. When applied to sharpening the infra-red laser beam used by space debris laser tracking stations, Adaptive Optics have the potential to enhance the tracking performance and overall station efficiency by enabling tracking of smaller and more distant debris.

The Adaptive Optics group at the Australian National University (ANU) Research School of Astronomy and Astrophysics (RSAA) have teamed up with EOS Space Systems to equip the EOS laser space debris tracking station located at the ANU Mount Stromlo Observatory with an Adaptive Optics Demonstrator (AOD). The AOD project is a joint project whereby ANU provides LGS AO expertise and EOS provides space debris tracking and laser expertise. While the AO bench itself is developed mostly by the ANU[1], the LGS facility is a more collaborative effort that uses expertise from both the ANU and EOS teams.

This paper provides an overview of the LGS facility subsystem of the AOD system, including the LGS facility design requirements and architecture (this section), and a description of its major subsystems (sections 2 to 5). The paper concludes with a short section on the LGS facility fabrication status and describes future commissioning plans (section 6).

1.1 AOD LGS Facility Performance Specifications

The LGS facility requirements are derived from the system-level, AOD requirements which were initially formulated for the project. These requirements are presented elsewhere in this conference[2]. Because the AOD project is about an AO *demonstrator* as opposed to a facility AO instrument, many of the AO-enhanced laser tracking station top-level specifications were actually expressed in terms of performance goals, including the orbital height and size of space debris to be tracked, and the availability of the AOD throughout the year. The project was also developed with various

Adaptive Optics Systems IV, edited by Enrico Marchetti, Laird M. Close, Jean-Pierre Véran, Proc. of SPIE Vol. 9148, 91483E · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2055050

hardware constraints in mind, including for instance the choice of deformable mirror and Laser Launch Telescope (LLT) opto-mechanical components which EOS already owned.

A summary of the environmental and design constraints most relevant to the LGS facility subsystem of the AOD is presented in Table 1. The LGS facility top-level performance requirements guiding the design of the LGS facility system and subsystems is presented in Table 2.

Table 1: AOD LGS facility environmental and design constraints

Design Constraint	**Value**
Space debris orbital height	1000 kms
Space debris angular speed	2000 arcsec/s
Fried parameter r_0 @ 589nm (*Uplink seeing accounts for LLT seeing and other uplink perturbations with respect to downlink seeing)*	(Downlink) 121 mm (Uplink*) 80 mm
Sodium column density	2.0-8.0 10^{13} atoms/m^2
EOS telescope aperture (resp. obscuration) diameter	1.752 m (0.251 m)
LLT design	Refractive telescope, off-axis launch
LLT to EOS telescope boresite error (per on-sky measurement)	< 100 arcsec

Table 2: AOD LGS facility top-level performance requirements

Performance Parameter	**Requirement**
Type of LGS	Sodium
Photon return on the ground	1500 photons/cm^2/s
LGS spot size on LGS WFS subaperture at zenith	1.6 arcsec
Laser projection system focusing accuracy	0.1 arcsec
LGS steering range	135 arcsec
LGS blind pointing accuracy	2 arcsec
LGS residual on-sky jitter @ 500Hz	0.1 arcsec rms

Note that all the functional requirements which typically apply to a LGS facility designed for astronomical applications also apply to a LGS facility designed for space debris tracking applications, with one important exception: in order to track space debris, the LGS must be pointed ahead of the telescope optical axis along the debris trajectory. The rationale for this unusual requirement is presented in the following section.

1.2 LGS Point-Ahead Angle

As explained in reference[1], it takes time for the infra-red laser pulse to leave the telescope, reach the space debris and illuminate it, and then for the infra-red light reflected off the debris to come back to the telescope. This time of flight effect takes on the order of a few milliseconds per round trip from the ground, to the debris and back. Meanwhile, the atmospheric turbulence is changing, and care must be taken for the Adaptive Optics system to be correcting the appropriate turbulence patch, at the correct time. In this case, the AO correction must be applied at the time when an infra-red laser pulse leaves the telescope, so as to correct the turbulence ground layer which is likely to be the major aberration contributor. This also corresponds to the time when infra-red light from an earlier laser pulse that retro-reflected off the space debris eventually reaches the telescope.

Thus the LGS light must probe the atmospheric turbulence along the direction that the next infra-red laser pulse is going to follow upon leaving the telescope. For practical reasons associated with high power laser propagation, it is preferred for the infra-red laser pulses to be emitted along the telescope axis. Because the time of flight of the 589nm laser to the sodium layer and back is non-negligible as well, this means that the 589nm laser must be pointed ahead of the telescope axis along the debris trajectory.

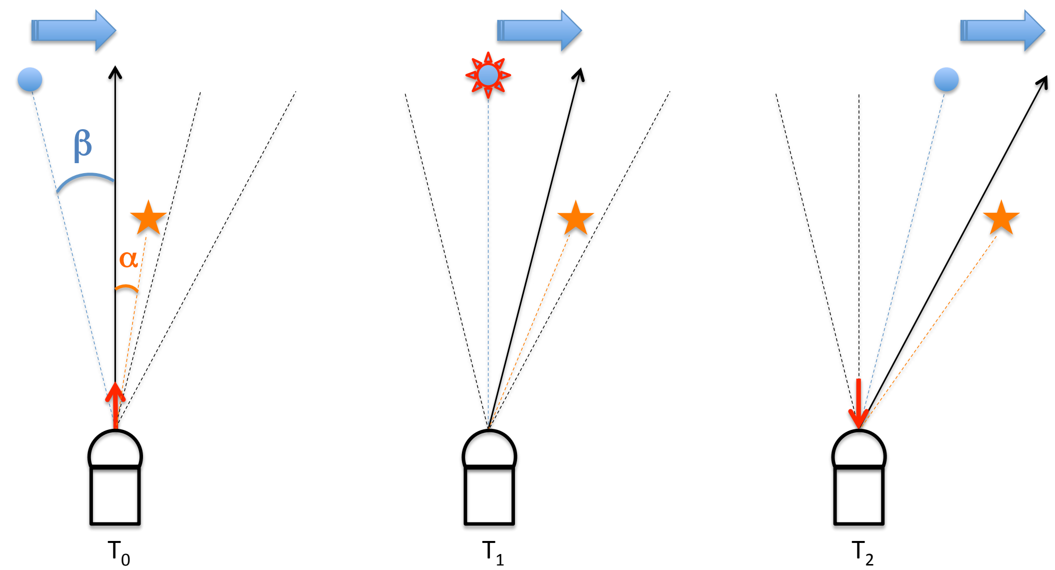


Figure 1: Telescope and LGS point-ahead angle schematic

Figure 1 provides a visual tool to understand the various angles and times involved in the LGS point-ahead angle calculation. At time T_0, the infra-red laser pulse leaves the telescope along the telescope optical axis. The telescope is pointing ahead of the space debris position along the debris orbit, so that by the time the infra-red light reaches the orbit altitude, the space debris has moved in position and is illuminated. This happens at time T_1. At time T_2 (where T_2-T_1 roughly equals T_1-T_0), the infra-red light which was retro-reflected off the space debris reaches the telescope. For AO correction to be applied at time T_0, and as a result of the natural AO loop latency, LGS wavefront sensing measurements of the atmospheric turbulence along the direction where the telescope is pointing at time T_0 must be made earlier than T_0. Additionally, it also takes time for the 589nm laser light to travel up to the sodium layer and back to the telescope where 589nm light can be sensed by the LGS wavefront sensor. These two delay terms (latency and time of flight to the sodium layer and back) are the reason why the 589nm laser must be pointed ahead of the telescope optical axis.

The largest sodium laser point-ahead angle α occurs when tracking debris near zenith where the debris apparent velocity is the largest. Assuming the space debris height (z=1000kms) and angular speed (ω=2000arcsec/s) listed in Table 1, a sodium layer altitude of h=100kms, an AO loop sampling frequency f=1500 Hz and an AO loop delay n/f where n is an integer, we have:

$$\alpha = \omega \left[2h/c + n/f \right]$$

This angle α is to be compared to the angle β between the effective position of the debris and the pointing of the telescope:

$$\beta = \omega\, z/c$$

Numerical applications provide:

$$\beta = 6.7 \text{ acsec}$$

$$\alpha=5.3 \text{ arcsec for } n=3,\ \alpha=6.7 \text{ arcsec for } n=4$$

Note that preliminary AOD simulations indicate that optimum performance should be obtained with latencies on the order of 4/1500 = 2.7 ms (n=4), corresponding to point ahead angles on the order of a few arcseconds. In practice, the instantaneous point ahead angle value will be determined dynamically depending on the space debris position and current, optimum performance of the AO loop.

1.3 LGS Facility Architecture

The LGS facility architecture for the AO demonstrator project is presented in Figure 2 below. The LGS facility system includes the following subsystems, with primary responsibility from EOS (color-coded in purple in figure 2) or the ANU (color-coded in blue) as indicated in parenthesis:

- Guide Star Laser Prototype – GSLP (EOS)
- Guide Star Laser Enclosure – GSLE (EOS)
- Beam Transfer Optics – BTO (ANU)
- Laser Launch Telescope – LLT (EOS and ANU)
- LGS Control System – LGS CS (ANU)
- Safety Systems (EOS)

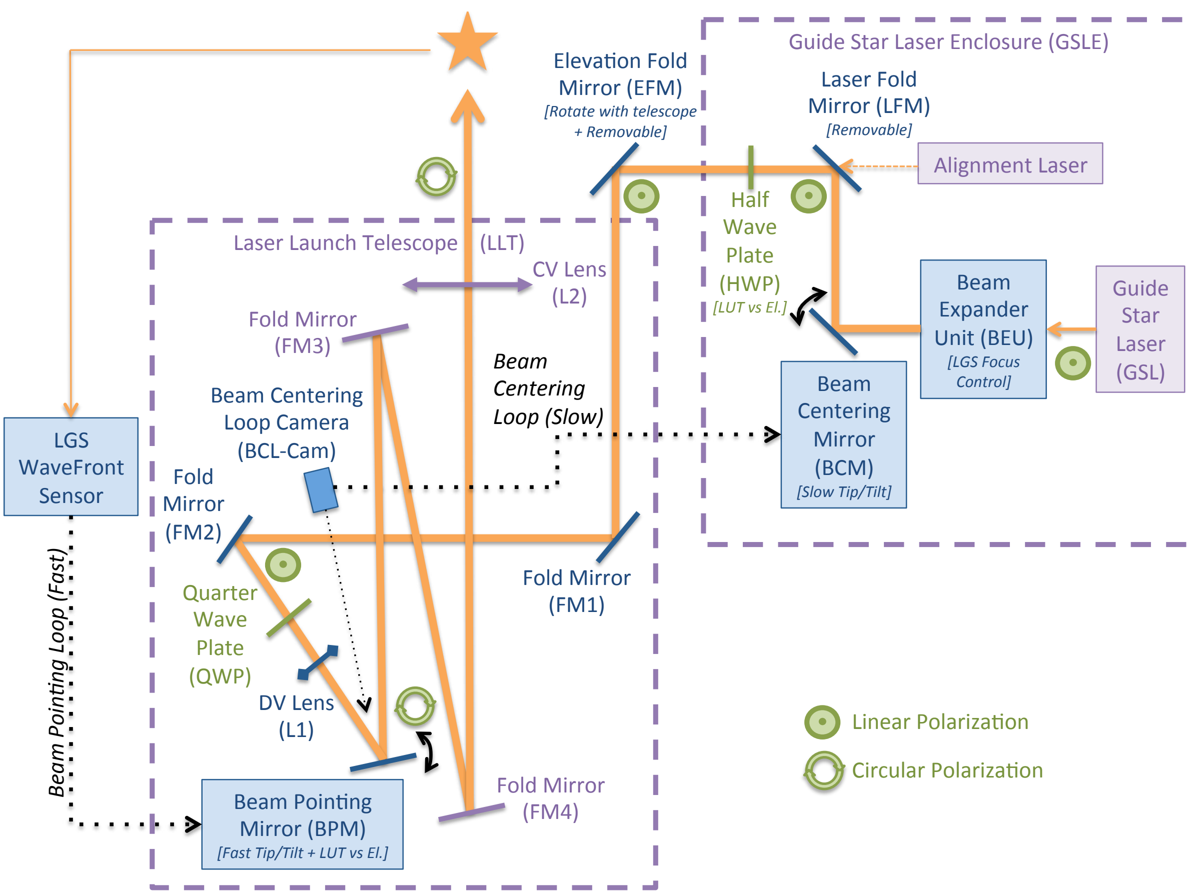


Figure 2: AOD LGS facility schematic showing all components along the 589nm laser beam path. Purple components are the responsibility of EOS, blue and green components are the responsibility of the ANU.

2. GUIDE STAR LASER PROTOTYPE

2.1 Sodium Laser Source

Since 2000 EOS has been investigating different types of lasers, including flashlamp-pumped and diode-pumped solid state lasers with continuous wave (CW) and pulsed formats suitable for sodium guide star operating at the D_2 resonance line close to 589 nm[3]. Various wavelength conversion schemes, including optical parametric generator, optical parametric amplifier, and Sum Frequency Generator (SFG) have also been investigated[4]. Through these investigations the advantages, disadvantages, and reliability of different types of lasers, and wavelength conversions schemes have been evaluated.

Generating a sufficiently bright laser guide star in the sodium layer depends on the suitable format and operating parameters of the laser. The spectral line needs to be stable, and the laser power needs to be delivered in diffraction-limited beams with a M^2-value close to 1. In addition to a suitable laser, many optical, electronic, mechanical, and opto-mechanical technologies and assemblies are required to achieve a practical and reliable laser guide star system.

The main challenge associated with laser guide star technology is to obtain sufficient photon return from the guide star to provide good signal to noise ratio for the LGS wavefront sensor. In the case of infra-red astronomy, the required photon return is quite low, on the order of 100 photons/cm^2/s, whereas for visible satellite ranging and space debris tracking, the required photon return is much larger at >1000 photons/cm^2/s.

Over the past several years much progress was made to identify the most efficient, reliable and economical laser solutions to create sodium laser guide stars. In practice, CW lasers with MHz spectral linewidths have demonstrated the highest photon returns to date[5]. The photon return obtained depends strongly on the polarization property of the laser output, i.e. if it is linearly or circularly polarized. The quantum selection rules indicate optical pumping by circularly polarized light is generally preferable and can provide substantial increases in photon return when compared to linearly polarized light[6]. It was also found that the sodium photon return can be further enhanced (by factors of up to 4 depending on the laser format and its pointing at a particular site)[7] through the simultaneous excitation of the sodium D_{2a} and D_{2b} lines with ~10% of the laser power emitted at the D_{2b} line. This is called re-pumping.

In 2006, EOS initiated their sodium laser developments with a diode pumped sodium guide star system based on direct sum frequency mixing of the two spectral lines of Nd:YAG at 1.064 and 1.319 µm to generate output at 589 nm. About 5 W of output power at 589 nm with ~25% conversion efficiency from the 1.064 and 1.319 µm inputs to 589 nm output have been achieved with good beam quality ($M^2_{1.064,\ x/y}$=1.00/1.06; $M^2_{1.319,\ x/y}$=1.10/1.00; $M^2_{589,\ x/y}$=1.27/1.14)[4]. However, some technical issues were identified. It is well known that the 1.319 µm spectral line of Nd:YAG is of low gain. It has an emission cross section of ~ 0.95 x 10^{-19} cm^2 so a lot of pump radiation is transferred into heat in the process of generating 1.319 µm output which leads to issues such as thermal lensing, thermally induced birefringence and depolarisation in the gain media for the 1.319 µm oscillator and amplifiers, which in turn leads to beam wander. Beam wander makes the sum frequency generation process which spatially combines the 2 beams at 1.064 and 1.319 µm difficult at high power levels such as those required for space debris tracking applications.

To further increase the output power at 589 nm, a new gain medium that should have higher gain at ~1.3 µm must be considered so that less heat is generated, causing less thermal lensing, less birefringence, less depolarization, and minimum beam wander. Nd:YVO_4 has been identified as the desirable gain medium for the development of the AOD sodium laser source. Because the Nd:YVO_4 emission cross section of ~ 6 x 10^{-19} cm^2 at 1.34 µm is much higher than that of Nd:YAG at 1.319 µm (~ 0.95 x 10^{-19} cm^2), the overall system conversion efficiency can also be higher. This enables a more compact system design as well.

A CW laser system including 1.34 µm and 1.05 µm oscillator and amplifier chains, and direct sum frequency mixing of the two spectral lines as illustrated in Figure 3, has been designed and developed. The system has the potential to meet all key AOD Guide Star Laser Prototype (GSLP) performance requirements including power, spectral linewidth, beam quality, re-pumping side band and other requirements listed in Table 3 below.

The 1.05 µm output is achieved with Yb-doped fiber as the gain medium. The 1.05 µm wavelength branch contains a single frequency oscillator and 2 stages of fiber amplifiers. The 1.34 µm wavelength branch is based on Nd:YVO_4 as the gain media. It consists of a single frequency oscillator and 2 stages of amplifiers, as shown in Figure 4.

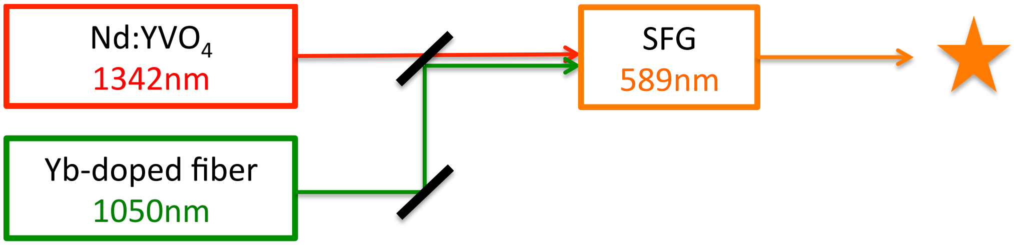


Figure 3: GSLP wavelength conversion scheme

Table 3. AOD Guide Star Laser Prototype Performance Requirements

Performance Parameter	**Requirement**
Laser Format	Continuous wave
Average Output Power	30 W
Beam Quality	$M^2 \leq 1.3$
Output Wavelength	589.159 nm (in vacuum)
Spectral Linewidth	Within 100 kHz to 5 MHz
Polarization	Linear
Side Band Wavelength	Peak of sodium D_{2b} line, 1.717 GHz blue-side of the peak of the sodium D_{2a} line
Side Band Power	~3W
Beam Diameter	2.8mm at the $1/e^2$ intensity points
Beam Pointing Stability	≤ 35 μrad (RMS)

The GSLP integrates the following technologies and assemblies:

- Resonant sum frequency generation in a bow-tie-shaped cavity;
- Spectral line width selection;
- Wavelength tuning and stabilization;
- Single frequency monitoring, stabilization, and locking to the sodium D_{2a} spectral absorption line;
- Optical re-pumping at the D_{2b} line frequency;
- Beam pointing stability control assembly for improving the spatial overlapping of two laser beams at two laser wavelengths;
- Very stable single frequency reference to which the high power oscillators are phase locked using the Pound-Drever-Hall (PDH) technique;
- Piezo-electric transducer mounted mirror in the oscillator acts as the actuator for the phase-locked loop;
- Phase side bands for the PDH technique are created using resonant EO modulators;
- The same phase side bands are used in the PDH phase locking of the SFG cavity.

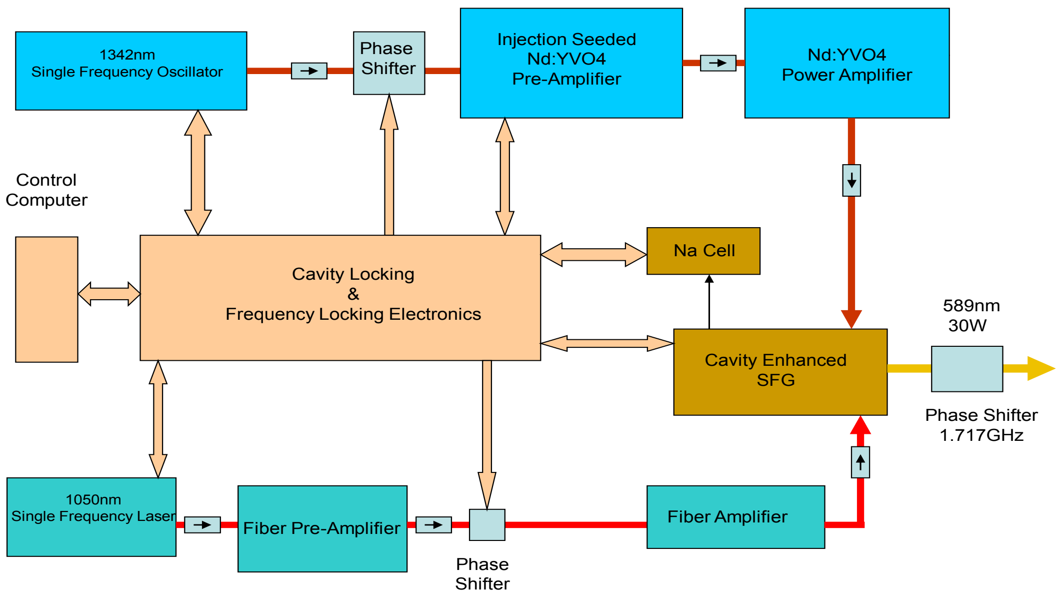


Figure 4: Guide Star Laser Prototype architecture.

At the time of this conference, ~30 W output power has been achieved with the 1050 nm oscillator and amplifier channel. Development, packaging and testing of the 1342 nm oscillator and amplifier channel are in progress. Design and development of the digital single frequency stabilization and locking electronics assembly based on the Pound-Drever-Hall (PDH) technique are also in progress. The basic PDH characteristics have also been demonstrated in the laboratory.

The final GSLP bench layout will include three horizontal optical benches, arranged on top of one another as shown in Figures 5 and 6. The top bench will host the 1342nm laser, the bottom bench will host the 1050nm laser, and the middle bench will host the SFG cavity and frequency locking components. The GSLP will be mounted at the Nasmyth port of the EOS telescope in a clean, thermally stable environment. Details of the Guide Star Laser Enclosure (GSLE) and laser mounting details are provided in the following section.

2.2 Guide Star Laser Enclosure

The GSLE shown in Figure 6 will be manufactured from precut 100 mm BondorPanel® with an 'R' value (m^2K/W) of 2.63. BondorPanel® is a lightweight, non ozone-depleting structural panel made with an insulating EPS core and COLORBOND® pre-painted galvanized steel facings. The GSLE will be constructed on level 3 of the co-rotating dome and will be 'connected' to the insulated enclosure on the telescope fork tine via a flexible bellows arrangement. The existing steel grating floor will be overlain with plywood flooring and anti-static vinyl.

The cleanroom environment of the GSLE will be temperature and humidity controlled with pressurized, conditioned air delivered via a 1200 mm x 600 mm HEPA filter mounted in the ceiling. The HEPA filter can deliver 300 l/s (635 cu ft/min) of conditioned air or approximately 65 air changes/hour; equivalent to an ISO Class 7 cleanroom. Generally the temperature within the GSLE will be controlled to ±0.5 °C of the target temperature and the humidity controlled to within 35-50% RH.

The Guide Star Laser Prototype (GSLP) is mounted on three CFRP CarbonVision breadboards (shown in Figure 5) that are kinematically attached to a steel frame; the assembly is bolted to the right side fork tine of the EOS 1.8 m telescope (opposite side to the Coudé path). The existing fork tine covers will be replaced with an insulated enclosure; this enclosure has removable panels that allow access to encoder read heads and to the elevation drive system without disturbing the integrity of the GSLE.

Control electronics will be mounted in standard 19” racks, which will be adjacent to the laser either inside or outside of the GSLE depending on cable length limitations.. Rack-mounted chillers will be placed outside the GSLE.

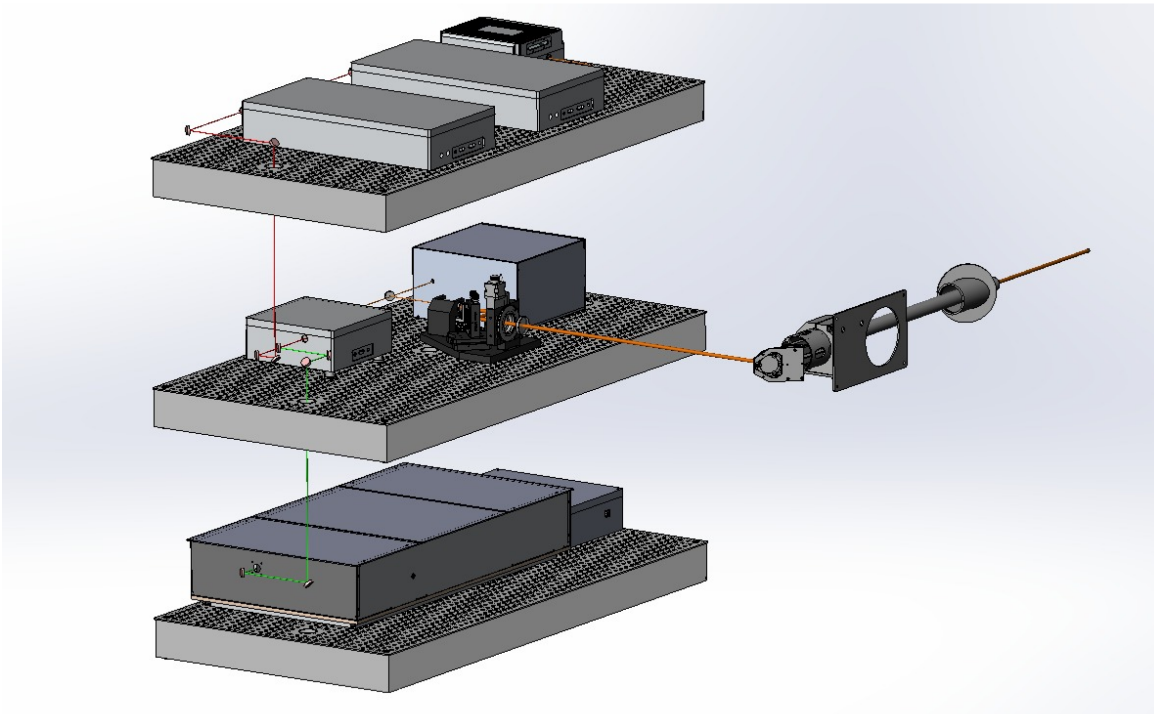


Figure 5: Guide Star Laser Prototype optical bench layout including Beam Transfer Optics mounted on middle bench and Elevation Fold Mirror hardware.

3. BEAM TRANSFER AND LAUNCH SYSTEMS

Various AOD project design constraints impose that the LGS beam be launched off-axis. Firstly, it would not be possible to launch the beam on-axis from behind the EOS telescope 250mm diameter secondary, which is too small to hide a laser projector of similar aperture diameter, and does not provide enough room to hide extra hardware behind it. Secondly, it would not be advisable either to use part or all of the 1.8m EOS telescope aperture to launch the 30W 589nm laser beam at the same time as the laser tracking station launches its powerful, multi-hundred-Watt infra-red laser beam, a scenario which would likely result in unacceptable noise levels on the LGS wavefront sensor. Thirdly, an earlier, off-axis Laser Launch Telescope (LLT) had already been designed and fabricated by EOS which the team whished to retrofit for the AOD project. This modified LLT will be mounted on the telescope primary cell support structure, hanging off the side of the telescope as shown in Figure 7.

3.1 Beam Transfer Optics

The resulting Beam Transfer Optics optical train for the AOD LGS Facility is as short as it can possibly be in order to relay the Guide Star Laser Prototype (GSLP) output beam to the Laser Launch Telescope (LLT). Following the laser beam path shown in Figure 1, the BTO includes:

- A Beam Expander Unit (BEU, 3 lenses) that increases the 2.8mm diameter at $1/e^2$ intensity points collimated beam provided by the GSLP to a beam diameter of 10mm at the $1/e^2$ intensity points; one lens of the BEU is mounted on a remotely-controlled M-461-X-M Newport linear translation stage to provide real-time focus adjustment of the LGS on the sky;

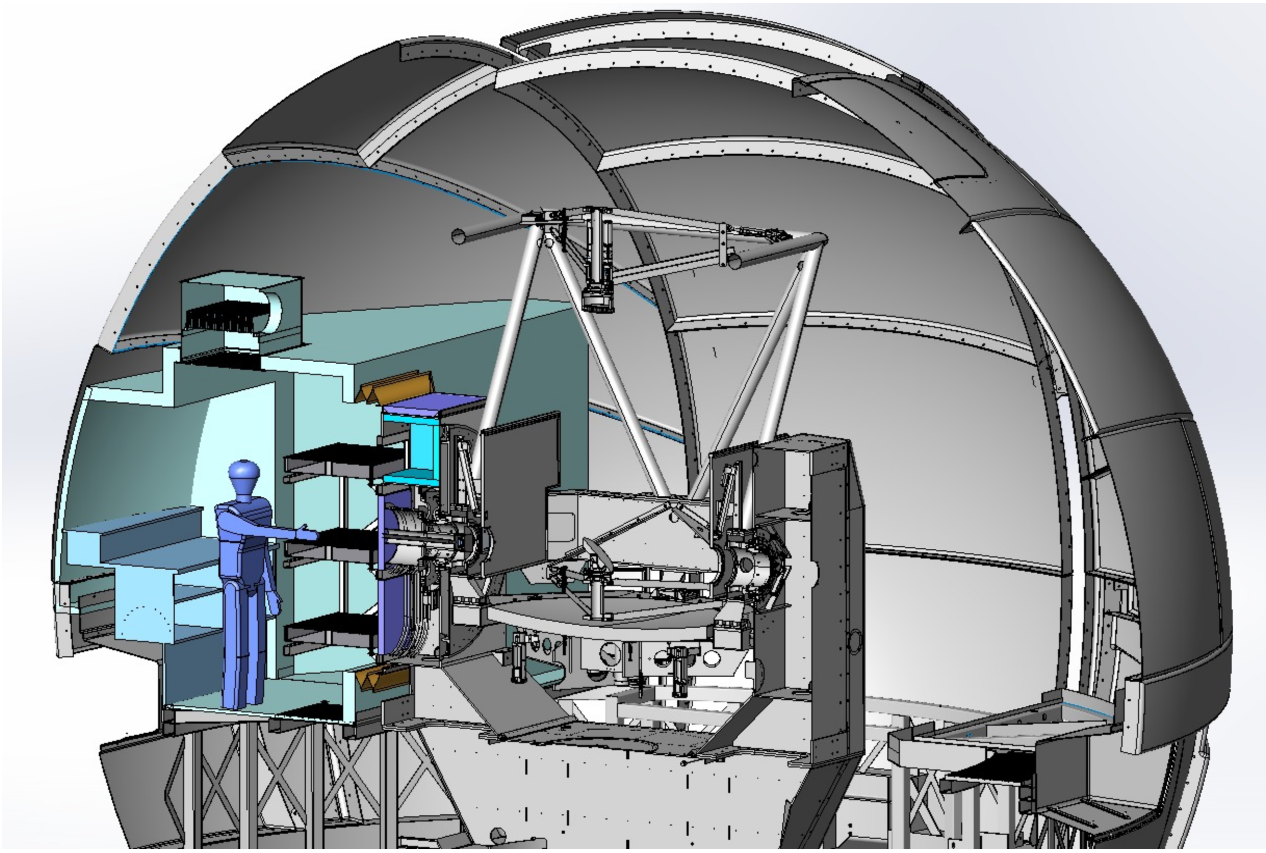


Figure 6: Section view showing Guide Star Laser Prototype and Enclosure in EOS 1.8m telescope dome.

- A Beam Centering Mirror (BCM) mounted on a remotely controlled Optics In Motion OIM202.3 tip/tilt platform; the BCM enables real-time beam steering adjustment so as to keep the laser beam centered on the Beam Pointing Mirror located on the LLT optical bench downstream. The Beam Centering Loop (BCL) uses feedback provided by the BCL camera that images the laser beam footprint on BPM as shown on the LGS facility schematic (Figure 1);
- A Laser Fold Mirror (LFM) feeding the laser beam onto the EOS telescope elevation axis; the LFM is mounted on a BKL-4 Newport kinematic base that enables easy removal of the mirror for direct viewing access of the elevation axis, should this be required for laser or EOS telescope alignment procedures;
- A Half Wave Plate (HWP) mounted in a remotely controlled NR360S/M Thorlabs rotator stage; the HWP rotates with the telescope elevation to maintain a fixed linear polarisation of the laser beam on optical components downstream;
- An Elevation Fold Mirror (EFM) mounted on the EOS telescope elevation axis that folds the laser beam towards the LLT; mechanical mounting of the EFM is fully custom as this mirror must be installed in a significantly crowded space and made to fit without modification of the existing EOS telescope infrastructure; EFM is fixed with respect to the EOS telescope.

All BTO components except EFM are physically located on the GSLP optical bench. Figure 8 below shows the 2.8mm diameter GSLP laser output beam entering the BEU and the 10mm diameter exit beam beam reflected off BCM and LFM passing into the HWP before leaving the GSLP optical bench along the EOS telescope elevation axis towards EFM.

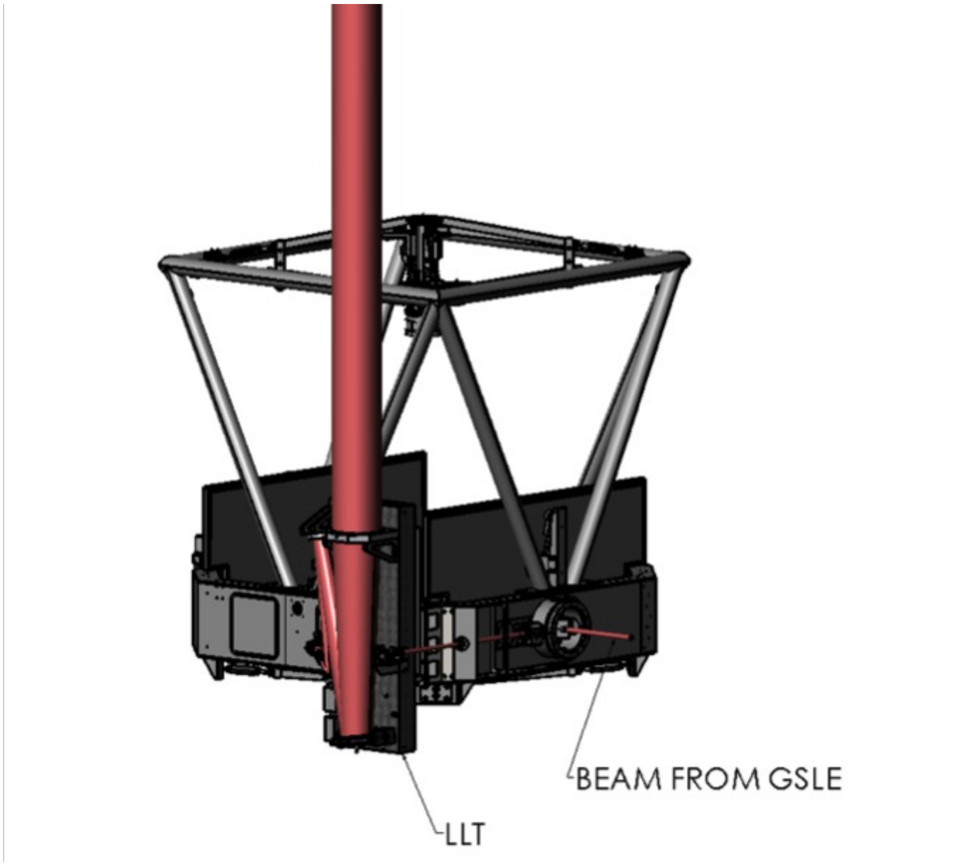


Figure 7: Laser beam optical path on telescope.

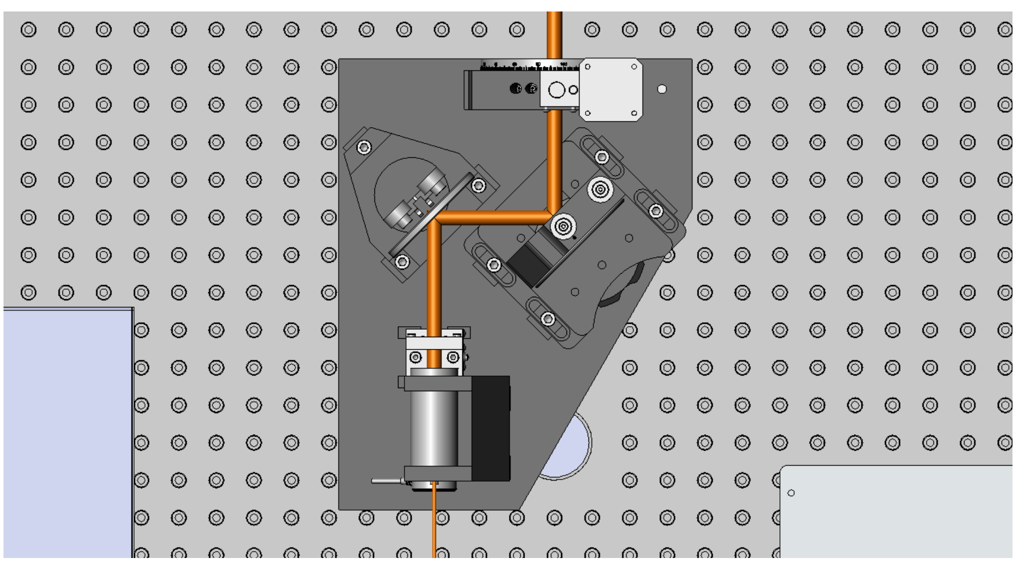


Figure 8: Close-up, top-level view of Beam Transfer Optics components mounted on GSLP middle bench.

3.2 Laser Launch Telescope

The Laser Launch Telescope (LLT) used for this project was previously designed for a fiber-fed input laser beam and is being modified to meet the AOD requirements, after it was determined that optical losses in the fiber-fed design would be too high to meet the LGS brightness requirements.

The existing Optable is made from a 10mm thick carbon-fiber aluminum honeycomb core with metallic inserts bonded into the top and bottom panels for mounting the optical mounts and other elements (Figure 9). Existing mounting inserts are used where possible with the exception of new metallic inserts bonded into the top and side panels for Fold Mirror 1 (FM1) to receive the laser beam from the Elevation Fold Mirror (EFM) of the BTO. FM1 has manual adjustment in tip/tilt for initial alignments.

Fold Mirror 2 (FM2), PI M505.1PD linear stage (0.25 micron minimum incremental motion), Quarter Wave Plate (QWP), LLT input diverging lens, Beam Pointing Mirror (BPM), and Beam Centering Loop Camera (BCL-Cam) are mounted on a machined aluminum block as a sub-assembly to utilize existing mounting interfaces of the Optable. FM2 has manual adjustments in tip/tilt for initial alignments. The QWP is located between FM2 and the LLT diverging lens in a manually adjustable mount to transform the beam linear polarization into a circular polarization prior to propagation on the sky. The LLT input diverging lens provides x20 magnification ratio to the exit lens. The BPM is a 2”x3” zerodur mirror mounted on an OIM202.3 fast steering platform (limited to maximum operating frequency of 200Hz) to provide beam steering capability over the full LLT field of view. The BCL-Cam has a converging lens to look at the beam position on the BPM, providing feedback to the Beam Centering Mirror (BCM) located within the Guide Star Laser Enclosure (GSLE) to steer the beam onto the center of the BPM. The beam from the BPM is directed to an existing Ø6” fold mirror, to a Ø9”fold mirror then to the Ø330mm LLT exit lens providing the path length for beam expansion.

A carbon-fiber cover encloses the optical components of the LLT except for FM1 which resides outside this cover to pickup the beam from the EFM of the BTO.

The LLT Optable is attached to an interface frame and mounting plate to the main telescope which provides elevation and azimuth adjustments for boresighting to the main telescope optical axis. The interface frame is mounted overhung to the right side of the main telescope center section to pickup the laser beam from the EFM and provide space for other telescopes mounted on the main telescope. When pointing at zenith the interface frame provides three points of contact and when pointing at horizon five points of contact are available.

The beam from EFM of the BTO which exits the main telescope center section is covered from the main telescope center section up to and including FM1 on the LLT.

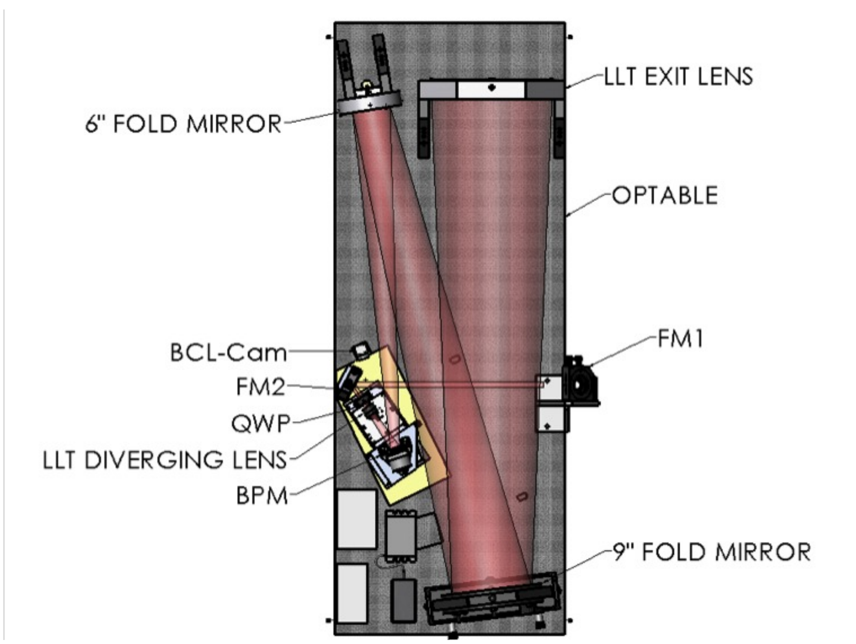


Figure 9: Plan view showing LLT component layout.

4. LGS CONTROL SYSTEM

There are four active optical elements in the beam transfer path of the AOD LGS facility. All four of these elements are controlled as part of the larger adaptive optics control system. The foundation of this control system is an x86 architecture PC running a Linux OS. The EtherCAT field bus, in conjunction with the Etherlabs kernel module implementation (v1.5.2) of an EtherCAT master, has been used to bring electromechanical components from different vendors into a consolidated control architecture.

The first mechanism is the Beam Expander Unit linear stage for control of the LGS focus. The stage is positioned by a stepper motor-based linear actuator, controlled by an EL7031 EtherCAT module. The stage position is set based largely on the anticipated distance to the sodium layer. Low frequency feedback based on analysis of the spot sizes from the LGS WFS may be used to make a limited correction to the Sodium layer distance.

The second and third mechanisms are two tip-tilt mirror platforms, referred to as the Beam Centering Mirror (BCM) and the Beam Pointing Mirror (BPM). The BPM serves to steer the LGS off-axis, along the target trajectory, but ahead of the target. In addition to blind pointing, a feedback loop from the LGS Wave Front Sensor (LGSWFS) makes small, fast corrections to this mirror to keep the LGS aligned to the WFS optical axis. The BCM is located near the laser and serves to maintain alignment of the laser through the BTO. A low frequency feedback loop is based on an inexpensive CMOS camera (BCL-Cam), which images laser light scattered from the BPM, providing position error information.

The BPM and BCM tip-tilt mirrors are both voice-coil actuated. A vendor-supplied hardware controller facilitates tip and tilt control via analog voltages in the +/-10V range. An EL4132 module (2 Channel analogue output) for each mirror provides the field bus control component. The host-level control algorithm is an implementation of a leaky integrator for BCM. In the case of the BPM the blind pointing is an open-loop signal derived from the target trajectory and the telescope axes. A leaky integrator provides the error correction terms for stabilization at the LGSWFS.

Finally, the fourth and last mechanism is a stepper motor driver rotary stage that supports a Half Wave Plate (HWP). The HWP is oriented to maintain a consistent orientation of the linearly polarized laser beam through the BTO. The required rotary state position is a function of the telescope elevation angle. The precision requirements of this mechanism orientation are low. The motor controller for the HWP is an EL7031. The stepper motor is therefore operated open-loop, with velocity (step rate) control implemented in the EtherCAT module. The host-level control software that manipulates the EtherCAT process image data implements a PID for position control.

5. SAFETY SYSTEMS

5.1 Laser Safety Standards in Australia

As a long term developer of pulsed laser systems for space applications including satellite laser ranging (SLR) and space debris tracking, EOS Space Systems complies with Australian and US laser safety standards by default. The current default standards are: AS/NZS 2211.1:2004, and ANSI Z136.1-2014. Other national laser safety standards can be invoked by customers when required, by contract terms.

The classifications of pulsed lasers place most EOS lasers in class 3b or class 4, for the unexpanded beams. Outside of the clean zone where the unexpanded beams reside, the power density is typically much lower by factors over 100, and the safety issues are reduced to inadvertent illumination of aircraft and terrain zones. Maximum Permissible Exposure (MPE) levels are highest where the beam is unexpanded, and access to these areas is restricted to trained and certified personnel. Procedural, engineering and protective equipment safeguards are combined to keep operators and maintenance staff safe.

5.2 Laser Propagation Indoors

Working near the unexpanded beams for testing and alignment purposes, jewelry is removed and cleanroom garments are worn. Only persons who have been assessed as safe can work in the presence of laser beams. Safety glasses and goggles are available for a wide range of wavelengths, and training is provided on how to evaluate each protective device for the wavelengths present. Records of those trained are retained.

Only laser physicists will work within the laser generation space. Objects and tools placed near an active beam are handled with care by laser physicists, and the propagated laser beam is typically interrupted when placing objects into the beam path. Where alignment work to other systems must be performed, the laser physicists are involved until operations staff are shown to be safe and competent.

Laser hazard analysis applied to the Guide Star Laser Prototype (GSLP) is similar to any other ranging and tracking lasers. Being CW makes little difference in safety analysis. Lowest possible power is used when setting up the system alignment. Access to the equipment when operating is restricted to experienced laser physicists. Beam transfers are enclosed to prevent any possible exposure to scattered radiation prior to launching. Safety goggles must be worn when in the proximity of any beam.

Beam transfer to the Laser Launch Telescope (LLT) is managed with bulk optics, taking power from the Nasmyth port of the EOS 1.8 m telescope to the LLT through the elevation bearing aperture and through the telescope Optical Tube Assembly outer structure. Outside of the telescope structure, the naked beam is contained within physical conduits to ensure safe indoor propagation and minimize scatter illumination of the dome.

An affirmative signal must be created when all safety monitoring systems are in their SAFE state. Once this condition occurs, a shutter is energized and moved out of the path. Any subsystem not registering SAFE will remove power to this shutter, closing it. This is an example of an engineering protection.

Safety interlocks for the 589nm power include:

(1) System power applied;

(2) Dome E-Stops all disengaged and emergency condition reset;

(3) Telescope E-stop disengaged and emergency condition reset;

(4) Cooling water flow adequate;

(5) Telescope pointing above 20 degrees, no telescope status interlocks.

The Guide Star Laser Prototype will be enclosed in the Guide Star Laser Enclosure, a locally conditioned space which is large enough for alignment and maintenance operations to be carried out. Interlock and shutdown actuators will be available within this space, per AS/NZS 2211.1:2004.

5.3 Laser Propagation Outdoors

Whenever laser tracking experiments are performed in cooperation with any US agency, EOS cooperates with the requirements of the US Laser Clearinghouse (LCH), and submits track passes well in advance, such that the LCH may forbid the propagation of laser energy in certain passes, due to estimated close approaches to valuable surveillance assets of the US. In reality, these assets are at geostationary distances, and the possible illumination of sensitive assets is of such a low power that no damage is possible from EOS ground stations. Therefore, unless obliged by contract or custom, the LCH permissions are usually not sought. In these circumstances, EOS uses its own software propagation tool SWARMS to project all known debris orbits and compare them in real time to our laser lines of sight. Automatic interlocks are available to interrupt laser propagation when any object is predicted to approach the laser line.

Understanding the possible public concern about visible lights in the sky, and the realistic concerns about laser light illuminating aircraft windows, EOS Space Systems has compiled a study of the probabilities, and has also developed multiple aircraft detection systems over the past 15 years. ADS-B beacon location software is used for locating commercial aircraft over 20 km away, and for non commercial aircraft without beacons, the thermal imaging sensor will identify aero engines up to 40 km away. Any infringement of the telescope line of sight shuts off the laser automatically, as part of the many safety interlocks employed.

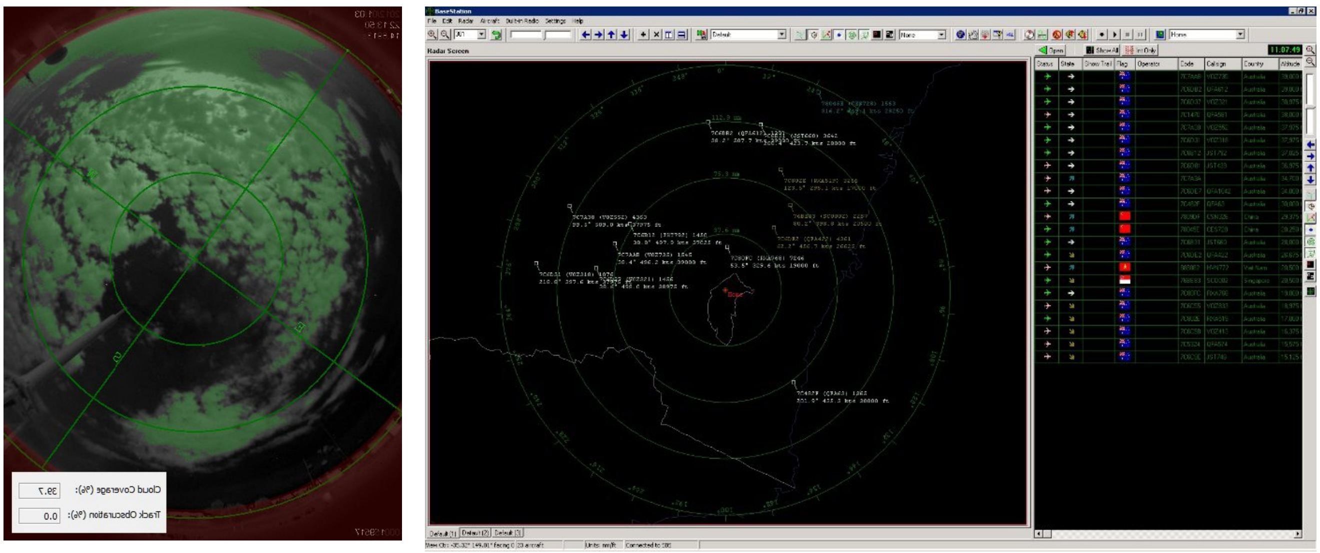
This information was supplied early to the Australian Civil Aviation Safety Authority (CASA), and after some clarifications, CASA agreed that the small probability of illuminating an aircraft with the LGS beam was adequately protected by the two safety systems already in place for use with satellite laser ranging of space debris. In this way, any public concerns directed to CASA may be managed without undue escalation or news media focus.

Once the propagated beam leaves the dome, terrain illumination and aircraft illumination are the hazards to manage. All EOS ranging lasers are enabled when their multiple safety systems report valid responses to status enquiries, such that a lack of response is the same as a status interlock. Interlock signals include:

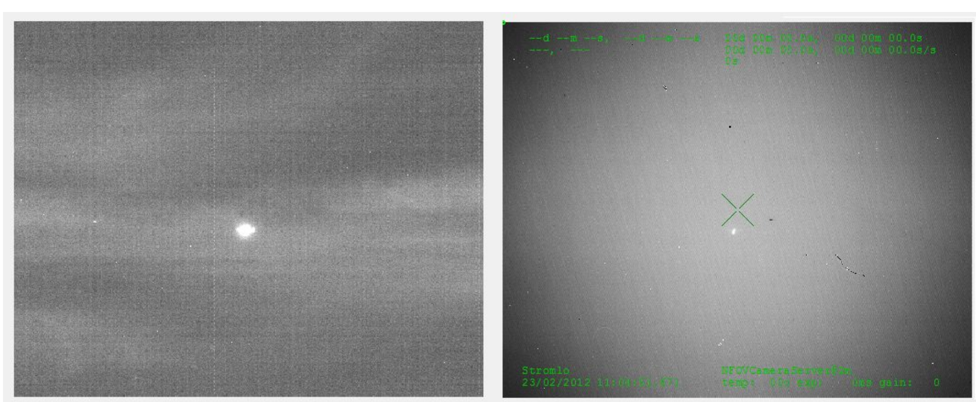
- Cloud detected near line of sight, at visible wavelengths (Figure 10a);
- Air Traffic Control Radar Beacon System (ATCRBS) location of commercial aircraft near line of sight using ADS-B receiver (Figure 10b);
- Cloud detected near line of sight, thermal image;
- Aero engine heat detected near line of sight, thermal image (Figures 11a and 11b).

The visible camera is a commercial all-sky imager, which has a wide range of exposure settings and detects clouds during the day and clouds/stars at night. Image analysis allows the clear sky areas to be identified and compared to the current line of sight for the telescope and the LGS beam.

Thermal imaging is accomplished using a MWIR imager designed and manufactured by EOS. It is mounted next to the primary mirror of the main telescope to share its line of sight with minimal parallax error (Figure 12).



Figures 10a and 10b: Visible all-sky image of cloud demarcations in green, and ADS-B image of nearby aircraft



Figures 11a and 11b: Thermal images of aero engines at two zoom levels, using the proprietary EOS imager

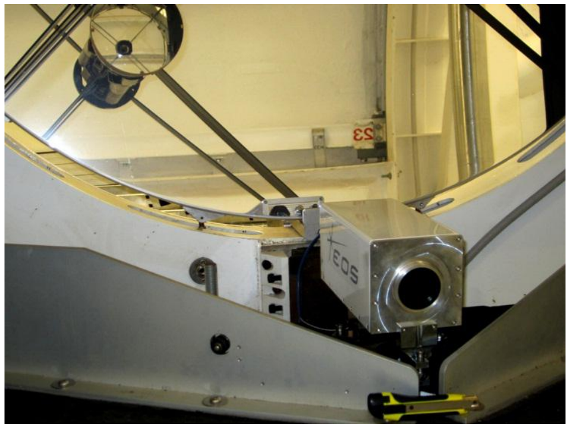


Figure 12: EOS thermal imager for aircraft detection near line of sight.

Shown in Figure 13 below is a typical client interface in the Observatory Control System (OCS) software, showing how many interlocks are typically required to enable laser propagation. This example shows a tracking laser safety interlock window.

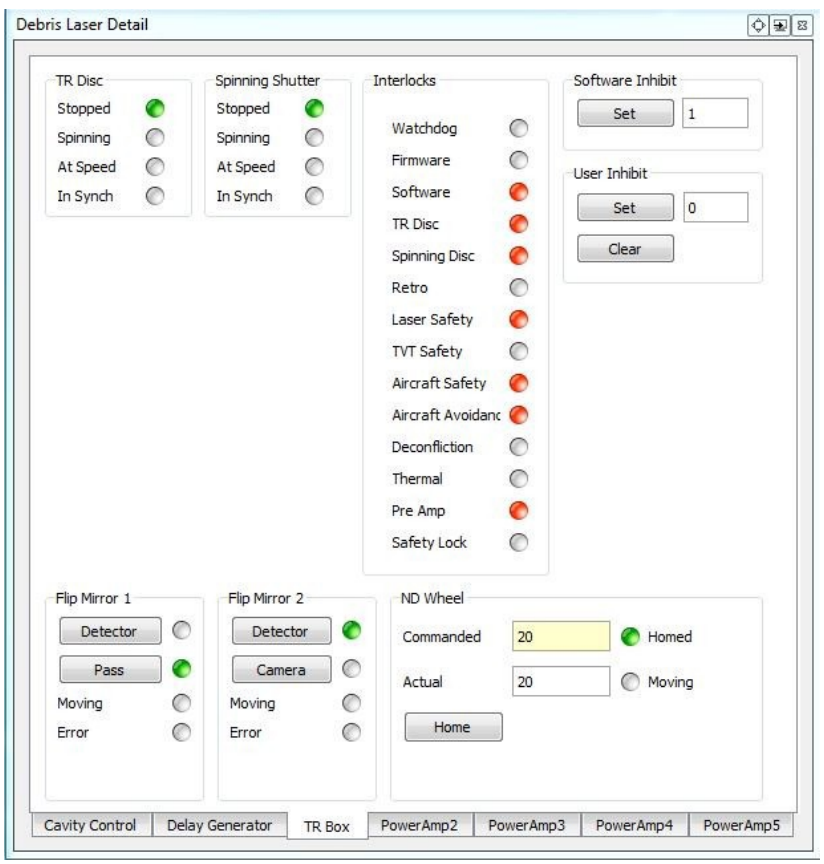


Figure 13: Typical EOS “Christmas Tree” of safety interlocks disabling laser propagation.

6. PROJECT STATUS AND PLANS

The Adaptive Optics Demonstrator (AOD) project includes three on-sky commissioning phases:

- Phase I: AO bench commissioning in Natural Guide Star (NGS) mode
- Phase II: AO bench commissioning in NGS + LGS mode
- Phase III: AO Demonstrator commissioning in space debris tracking mode

The AO system saw NGS first light in May 2014 and phase I is currently underway. Meanwhile the Guide Star Laser Prototype (GSLP) is being integrated and its performance characterized in the laboratory. GSLP installation on the EOS 1.8m telescope is foreseen near the end of 2014. Phase II is thus expected to start in early 2015, during summer time in the Southern hemisphere, which also corresponds to the period of lowest sodium abundance. Although it will be possible to commission the LGS facility and measure its performance in terms of sodium photon return, LGS spot size, and LGS pointing accuracy during that time, it will most likely be necessary to wait for the Southern Hemisphere winter when sodium abundance reaches its maximum in order to demonstrate space debris tracking enhancements with AO.

REFERENCES

[1] Bennet, F., d'Orgeville, C., Gao, Y., Gardhouse, W., Paulin, N., Price, I., Rigaut, F., Ritchie, I., Smith, C., Uhlendorf, K., Wang, Y., "Adaptive Optics for space debris tracking," Proc. SPIE 9148, 9148-51 (2014).
[2] Rigaut, F., d'Orgeville, C., Bennet, F., Price, I., Paulin, N., Uhlendorf, K., Gardhouse, W., Smith, C., Gao, Y., Ritchie, I., Wang, Y., "Requirement vs performance of the ANU/EOS space debris tracking adaptive optics demonstrator," Proc. SPIE 9148, 9148-120 (2014).
[3] Gao, Y., Wang, Y., "Guide Star Laser System Development Summary - START," EOS R&D Report for START (2009).
[4] Gao, Y., Wang, Y., Smith C., "Guide Star Laser System Development," EOS internal Report (2010).
[5] Denman, Craig A., Drummond, Jack D., Eickhoff, Mark L., Fugate, Robert Q., Hillman, Paul D., Novotny, Steven J., Telle, John M., "Characteristics of sodium guidestars created by the 50-watt FASOR and first closed-loop AO results at the Starfire Optical Range," Proc. SPIE 6272, 62721L (2006).
[6] Bienfang, J., Denman, C., Grime, B., Hillman, P., Moore, G., Telle, J., "20 Watt CW All-Solid- State 589-nm Sodium Beacon Excitation Source Based on Doubly Resonant Sum-Frequency Generation in LBO," OSA Trends in Optics and Photonics (TOPS), Advanced Solid-State Photonics, Vol. 83, 111-120 (2003).
[7] Holzlohner, R., Rochester, S. M., Bonaccini Calia, D. et al., "Optimization of CW sodium laser guide star efficiency," A&A 510, A20 (2010).