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Orbiting Configurable Artificial Star Multi-Wavelength Laser Payload

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Abstract. We establish a viable laser payload design for the Orbiting Configurable Artificial Star (ORCAS) mission. We share observational considerations and derive the engineering requirements for the laser payload. Developed by General Atomics Electromagnetic Systems, the dual-wavelength laser will operate at 1064 nm and can be frequency-doubled to 532 nm, with two possible beam divergence modes and tunable power. The laser payload can be operated at pulse repetition rates greater than 10 kHz to enable compatibility with Adaptive Optics systems and to maintain pointing requirements. We show that such a laser payload can be constructed based upon a high-TRL amplified fiber Laser Communication Terminal modified to meet the mission requirements.

1 Introduction

Astrophysical observations in the visible and infrared, capable of expanding our understanding of the universe, are heavily supported by both space and ground-based telescopes. Major scientific advances have been achieved in the past few decades due to the expansion of the technological capabilities of Hubble Space Telescope (HST), W. M. Keck Observatory (WMKO), Spitzer Space Telescope, the twin Gemini telescopes, and many others.[1,2] A significant impact of ground-based astronomy previously has been in aiding the discoveries made which received the 2011, 2019, and 2020 Nobel prizes,[3–5] the latest of which used Keck Adaptive Optics. However, with the expansion of our scientific aspirations, existing telescopes struggle to obtain the required measurements. Such measurements require advances in multiple technological lanes, including increased angular resolution, contrast, sensitivity, and efficiency. While space-based telescopes are restricted by cost, launch, and technical complexity, ground-based telescopes are limited by the blurring, emission, and absorption induced by the Earth's atmosphere.

Adaptive Optics (AO) systems correct for the blurring introduced by the Earth's atmosphere, making them essential in the advancement of ground-based observations.[6] Such AO systems are highly dependent on the existence of either Natural Guide Stars (NGS) or Laser Guide Stars (LGS). Guide stars provide essential information used to compensate for the disturbances introduced by the atmosphere. Ideally, they should be bright and located in a favorable position to allow for such compensation; however, NGS at the required brightness to support extreme AO systems (brighter than 8th magnitude) are rare and cover less than 0.1% of the sky.[7–9] LGS operated from the ground allow for wide coverage of the sky, but they suffer from an array of challenges due to reliance on sodium atoms in the Earth's mesosphere.[10]

ORCAS will overcome many of the NGS and LGS challenges.[11–13] It will provide a configurable star up to 1st magnitude brightness, nearly anytime and anywhere on the sky at the required wavelengths (multiple narrow-band sources). Such capability would enable near-diffraction-limited performance from the ground at visible wavelengths for the first time, allowing us to further explore our

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universe. Work has been ongoing on ORCAS, and several papers on the mission are currently in progress, representing work on other aspects of the mission.[14,15]

In this paper, we present a design for ORCAS's laser payload developed by General Atomics Elecromagnetic Systems. In Section 2 we define the mission requirements for ORCAS, specifically those relating to the laser system. Section 3 discusses some of the laser characteristics used in response to the given engineering requirements. In Section 4, the design of the ORCAS laser is presented, which includes a discussion of the Second Harmonic Generation approach used by General Atomics for the laser design. Finally, Section 5 discusses the results and summarize the conclusions of the paper.

2 Mission Requirements

The laser payload engineering requirements have been defined by the science and technology definition teams to ensure the mission is able to meet its science goals. These engineering requirements are summarized in Table 1.

Table 1 The engineering requirements for the ORCAS laser payload based on the science goals of the mission.

Requirement Traceability Matrix			
Label	**Parameter**	**Requirement**	**Expected Performance**
1	AO Source Brightness	> 5th Magnitude	1st-5th Magnitude
2	Payload Used	Laser 532 nm or 1064 nm	532 / 1064 nm
3	Laser FOV	4' x 4'	8' x 16'
4	Laser Volume	$\leq$ 6U	4U
5	Laser Mass	$\leq$ 6kg	4kg
6	Laser Power	$\leq$ 150W	75 - 130W
7	Laser Pointing	$\leq$2"	0.2"
8	Radiation Tolerance	15 krad	40 krad

Traditional sodium layer guide stars range in apparent brightness from 11th magnitude to 8th magnitude at a wavelength of 589 nm; however, to enable correction at the shorter visible wavelengths, a much brighter 5th magnitude reference star is required. Enabling the system to provide up to a 1st order brightness will ensure that ORCAS will be able to support future extreme AO systems. The ORCAS laser beacon is therefore required to provide the ground-based observatory with the flux equivalent of a 1st magnitude star in its high brightness mode and reduce the flux provided to the equivalent of a 5th magnitude star in low brightness mode. The beacon will need to be able to do this at two different wavelengths, one in the visible, and one in the near-IR, and be able to transmit either wavelength alone, or both together. For ORCAS to point its beacon laser at the observatory, the observatory would need to provide a ground-based beacon to ORCAS that the ORCAS laser system can track on. For this ground-based beacon we plan to leverage the existing Sodium Laser Guide Star lasers (wavelength 589nm) already present at most large observatories.

At a wavelength of 532 nm, a photon flux equivalent to a 1st magnitude star is about 1.2 million photons/cm^2/s. The ORCAS mission has established the operational range of its spacecraft at 165,000 to 240,000 km. This range was selected based on the design of an astrostationary orbit which will accommodate the desired exposure time associated with our scientific targets.[15,16] Based on this range,

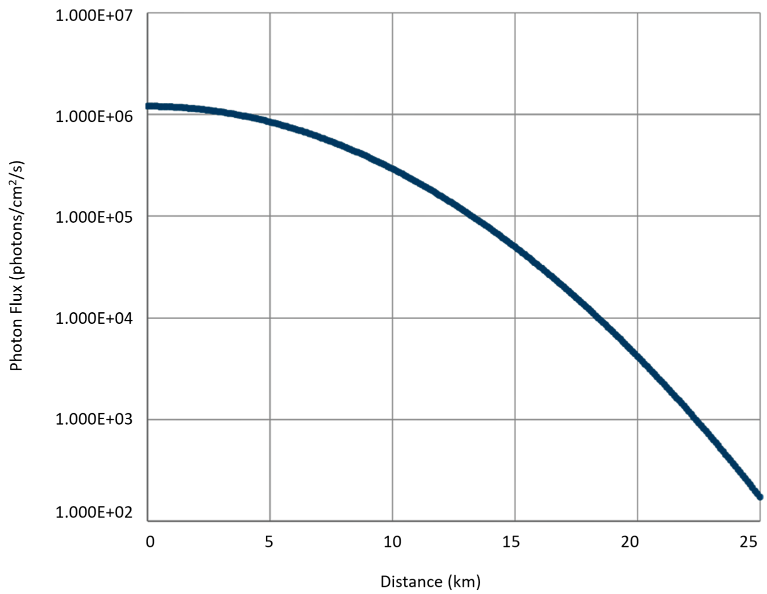

Fig 1 Photon flux vs distance from center of beam at a range of 200,000km for a 1W 532nm laser with divergence of 65μrad.

ORCAS will need to provide this flux at the observatory from a range of 200,000 km. This requires only a modest laser power to be transmitted by the ORCAS laser instrument. A Gaussian beam with a total power of 1W and 1/e^2 divergence radius of 65 μrad will create a spot at a distance of 200,000km with a maximum photon flux of 1.2 million photons/cm^2/s. The 1/e^2 radius of this spot would be 11.9 km. Figure 1 shows the photon flux versus radial distance from the center of the beam. Note that a beam with the same total power and a 1/e^2 divergence radius of 500 μrad will create a photon flux of 30,000 photons/cm^2/s, which would be equivalent to a 5th magnitude star.

Figure 2 shows the ORCAS flux as a function of power and aperture for wavelengths of 532 nm and 1064 nm. As shown, for the desired flux of 1.2 million photons/cm^2/s, the laser power would need to be between 300 and 1000 mW. A lower laser power would come at the cost of a smaller beam divergence, which would require increased beam pointing precision and lower pointing jitter. Figure 2 also shows the ORCAS pointing requirement as a function of aperture and wavelength.

In principle, the ORCAS laser could be a Continuous Wave (CW) output, or pulsed at a very high rate; however, ORCAS requires a pulsed laser version at a rate greater than that of the wave-front sensor camera to provide a constant signal to the AO system and to allow for fast wavelength choice switching and other technological maturity considerations. Additionally, the system is required to be radiation tolerant to a level of 40 krad, maintain an operating temperature of -10 to 45°C, and maintain a survival temperature of -30 to 60°C due to its use in a highly elliptical orbit.

3 Laser Characteristics

In this section, we discuss some of the laser requirements given in the previous section and how they interact with one another. We also discuss some recommendations for designs of subsystems that

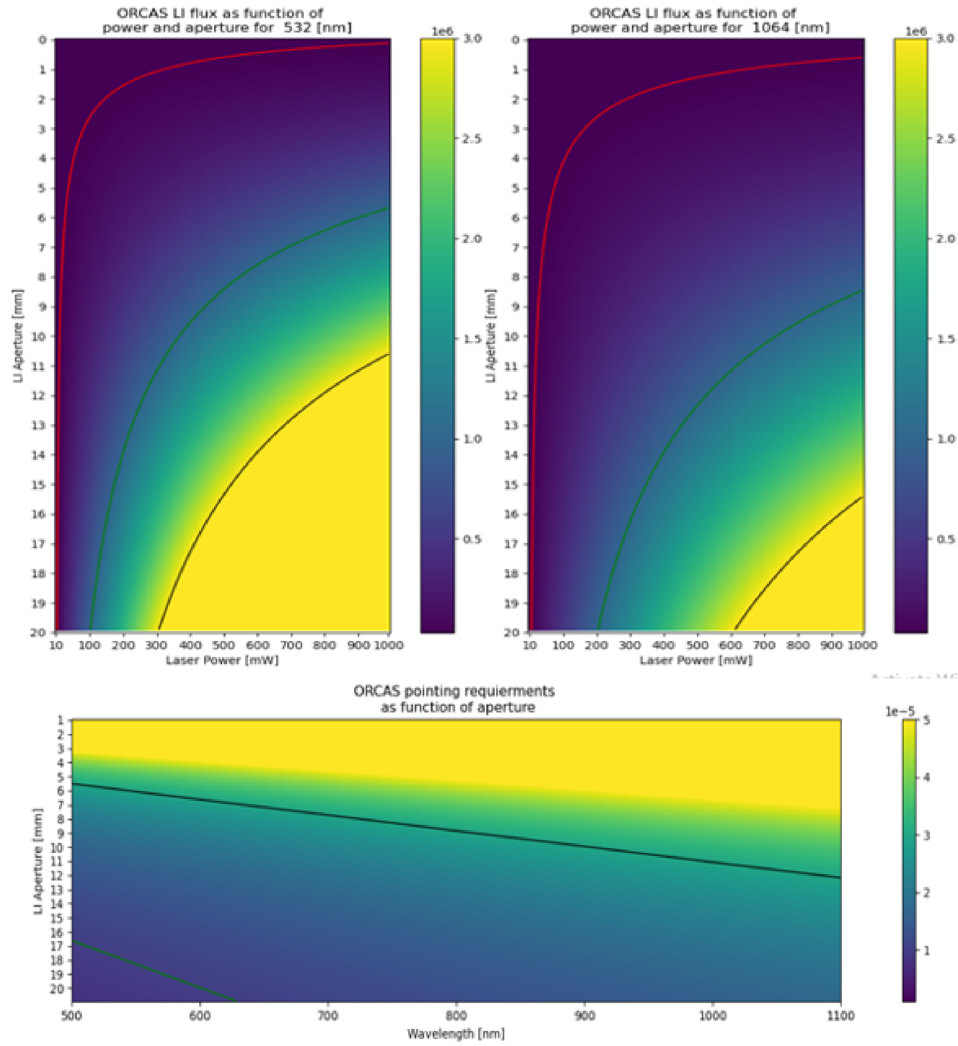

Fig 2 (Top left and right) ORCAS laser flux (photons/cm^2/sec) payload as a function of telescope aperture (mm) and laser power (mW). Red and black lines represent photon flux from a 5th and 1st magnitude star respectively. (Bottom) ORCAS pointing requirement as a function of aperture and wavelength. Black and green lines represent 30 μrad and 10 μrad requirements respectively.

could be used to meet the requirements. This section goes through the power consumption, the laser divergence, and the divergence half-angle calculations.

3.1 Power Consumption

In order to keep the electrical power consumption less than 150W (requirement 7), the ORCAS laser needs to be efficient. The need for a compact and efficient laser source and the need for excellent beam quality naturally suggest a fiber laser source for ORCAS. A ytterbium laser source at $\sim$1064nm would be an efficient way to generate the 1064nm beacon required for ORCAS. The use of a nonlinear frequency doubling crystal would allow the 1064nm output to be doubled to provide the 532nm visible wavelength also required. Filters could be used to determine if 1064nm, 532nm or both wavelengths together are transmitted. The photon flux of the ORCAS beacon at the observatory can be adjusted by changing the fiber laser output power and/or the beam divergence.

3.2 Laser Divergence

The laser divergence will set the pointing requirements of the ORCAS optical beam director. In order to ensure that the fluctuation in intensity seen by the observatory is less than about 10%, the pointing wander of the ORCAS beacon should be kept to less than 20% of the beam divergence. In the above example with a beam divergence of 65 μrad, this means that the pointing jitter of the ORCAS laser be kept less than 13 μrad. Existing commercial laser communications space terminals are able to keep pointing jitter well under this amount.

As discussed in the requirements, ORCAS will have two different beam divergence options, which will create the photon flux equivalents of a 1st and a 5th magnitude star. These divergences will be at 65 and 500 μrad, respectively.

3.3 Divergence Half-Angle Calculations

If we assume a laser output of just 1W of power at λ = 532 nm transmitting a diffraction-limited beam out of a $\sim$1cm diameter aperture on the ORCAS satellite located at the anticipated distance of 200,000 km, a laser beam with a 1/e^2 beam waist radius of w = 0.5cm, the diffraction-limited laser beam divergence half-angle is given by:

$$\theta = \frac{\lambda}{\pi w} \tag{1}$$

This yields a divergence half-angle of $\sim$33 μrad or $\sim$7 arcsec. After propagating the 200,000 km to Earth, the beam 1/e^2 radius will be $\sim$5.9 km. Tunable laser power spread uniformly over a spot with a radius of 5.9 km will give an intensity of 9 nW/m^2. In actuality, since the beam will be Gaussian, the intensity at the center of the spot will be 18 nW/m^2 and fall off as a Gaussian to 2.4 nW/m^2 at 5.9km from the center of the spot.

4 System Design

In response to a Request for Information (RFI) for the ORCAS laser instrument, two companies provided conceptual designs based on existing laser communications space terminals. In this paper we present the design developed by General Atomics Electromagnetic Systems (GA-EMS). This design includes a laser beacon which will operate at 1064nm and 532nm while tracking a ground based 589nm source. In the development of the laser payload for ORCAS, GA-EMS largely based their design on the existing space-qualified Laser Interconnectivity and Networking Communications System (LINCS), which allows the design to maintain space heritage while introducing the required new features. GA-EMS has proposed updating the LINCS platform to contain a 1064nm laser being frequency doubled via Second Harmonic Generation (SHG), which will allow it to create a 532 nm output with an estimate 1W of output power. GA-EMS will be able to leverage the knowledge gained from the initial LINCS system in regard to materials, bonding, and testing, as well as during the design and integration of the ORCAS components, increasing the current Technology Readiness Level (TRL) of the design.

The overall system concept block diagram for the ORCAS laser payload and Free Space Optical (FSO) terminal is shown in Figure 3 below. As shown, the payload will include the laser assembly, the laser amplifier, a frequency doubling crystal, a signal selection band pass filter, a beam splitter, and a beam steering device.

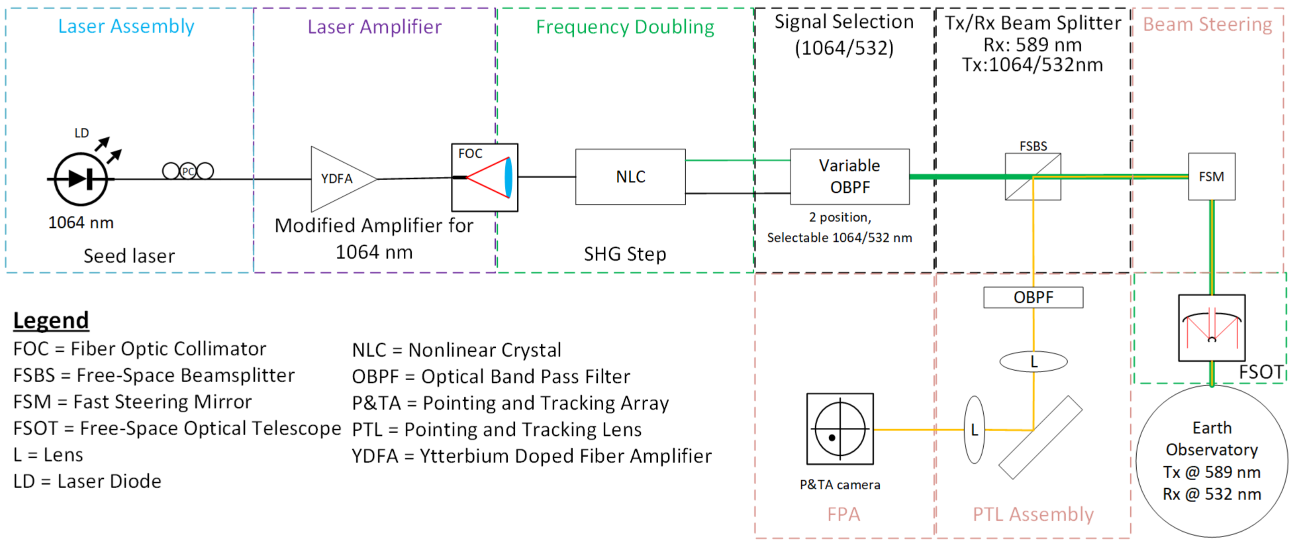

Fig 3 Overall system concept block diagram for the ORCAS laser payload and FSO.

The payload will have a 532 nm laser outputting 1 W of optical power with an output divergence of 65 μrad in its main form, which will give it the appearance of a roughly 1st magnitude star. In the secondary state of the payload, a solenoid driven arm will insert a diverging lens into the system to increase the output divergence to 500 μrad, which will make the artificial star appear as a 5th magnitude star a the 200,000 km range. The payload will also be able to receive a 589 nm signal for tracking. A rendering of the GA-EMS ORCAS payload can be seen in Figure 4 below. The payload includes the Laser Electronics Assembly (LEA) and Laser Telescope Assembly (LTA), as well as the FSO terminal, all of which will be further discussed in subsequent sections.

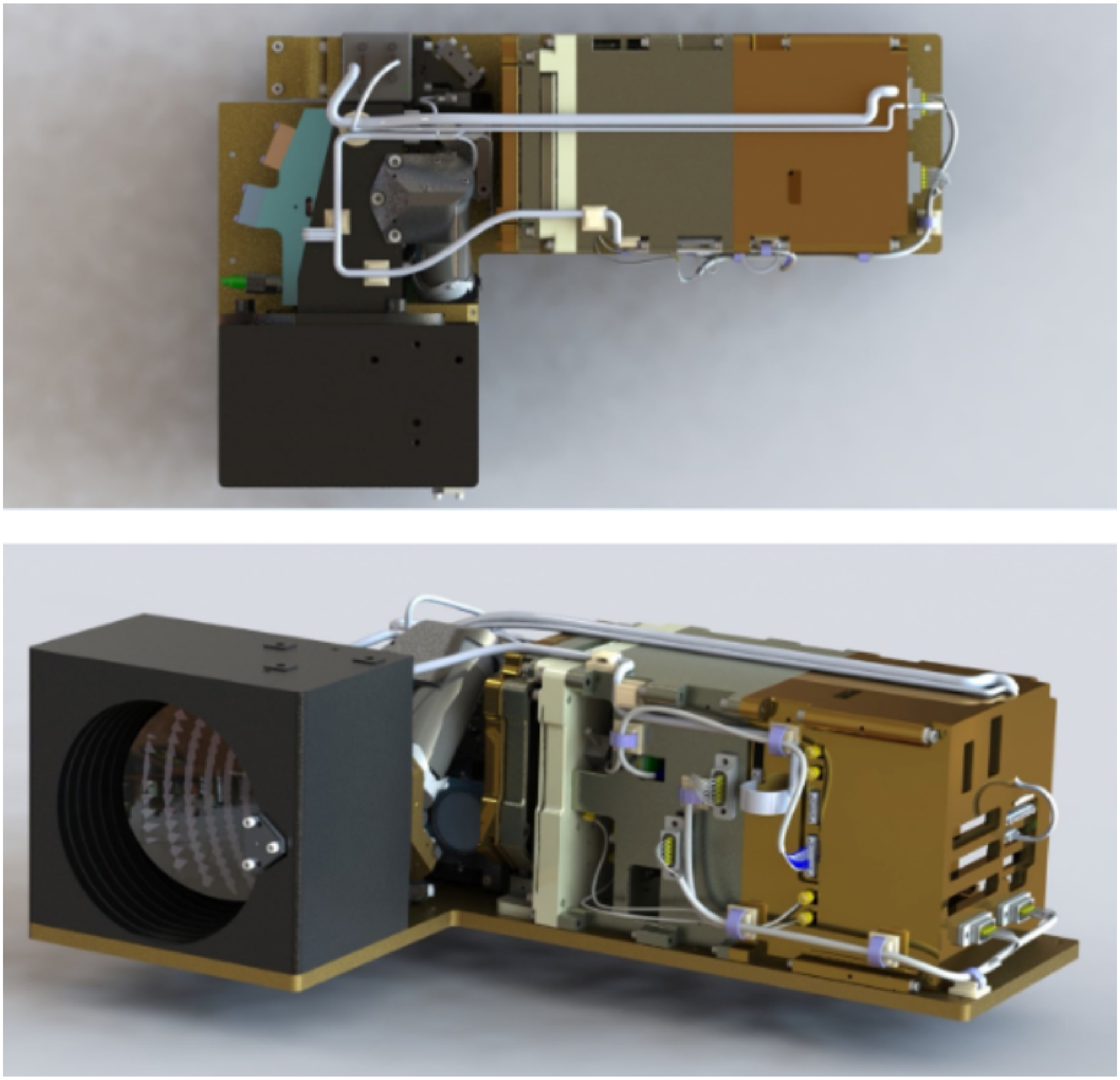

Fig 4 Rendering of the GA-EMS ORCAS payload from different angles, showcasing the combined LEA and LTA shown in the top image as the rightmost section and the black foot of the "L", respectively.

4.1 LINCS System

GA-EMS has previously built both 1064 nm laser systems using Ytterbium Doped Fiber Amplifiers (YDFA) and 1550 nm variants that used Erbium Doped Fiber Amplifers (EDFA). The EDFA variants have been built for several airborne missions with overall optical output power levels of up to 100W and have been qualified to TRL 9 in both terrestrial and airborne applications. The EDFA variants have ranged from 8 to 20 W of optical power. The 8 W version was recently packaged for a CubeSat mission as part of LINCS. The laser payload for LINCS is currently at TRL 6 based on component level operational thermal vacuum testing. LINCS launched in June of 2021 and once it will demonstrates optical inter-satellite communication links the TRL of the system will be increased to 9. The LINCS payload, including electronics, occupies approximately 3U of volume, or 10 cm x 10 cm x 30 cm.

As stated, the LINCS payload currently operates at a wavelength of 1550 nm using an erbium fiber laser. GA-EMS therefore proposes changing the erbium fiber to ytterbium fiber and replacing some components to produce a 1064 nm output. This output will be based in free space through a frequency doubling crystal in order to produce the required wavelength of 532 nm. The existing system has optical beam directors that easily meet our pointing requirements. The proposed design uses under 150 W of spacecraft power and has a mass and volume that fit within the ORCAS requirements of 6kg (label 5 in Table 1) and 6U (label 4 in Table 1).

The overall scope of this effort can be defined as taking the TRL 9 fiber amplifier, and paring with a TRL 6 FSO terminal. While this will result in an overall TRL for the laser payload of 4 to 5, there is little redesign that needs to occur, just re-qualification testing. The elements of redesign required will include the removal of the receiver, the addition of the frequency doubling hardware, and modification of the coatings and materials in the FSO portion which are currently optimized for 1550 nm. Removal of the receiver, which is a critical element of the lasercom payload but is not required for ORCAS, will open up volume for the insertion of the frequency doubling hardware. The baseline plan is to perform the frequency doubling in free space, but the possibility of performing it in the fiber is still being considered. One of the largest departures from GA-EMS's existing design was the addition of the frequency doubling crystal, but they have proposed a path to mitigate this risk.

4.2 *Laser Electronics Assembly*

The LINCS laser uses a continuous wave (CW) seed which is modulated and then amplified. The ORCAS system would not require modulation but would still require amplification of the 1064 nm seed source. The architecture of the ORCAS laser, which is the common architecture used for the other mentioned lasers at GA-EMS, is shown below in Figure 5. It includes a two stage YDFA to increase the 1064 nm seed laser to the requisite power level to accomplish the guide star mission.

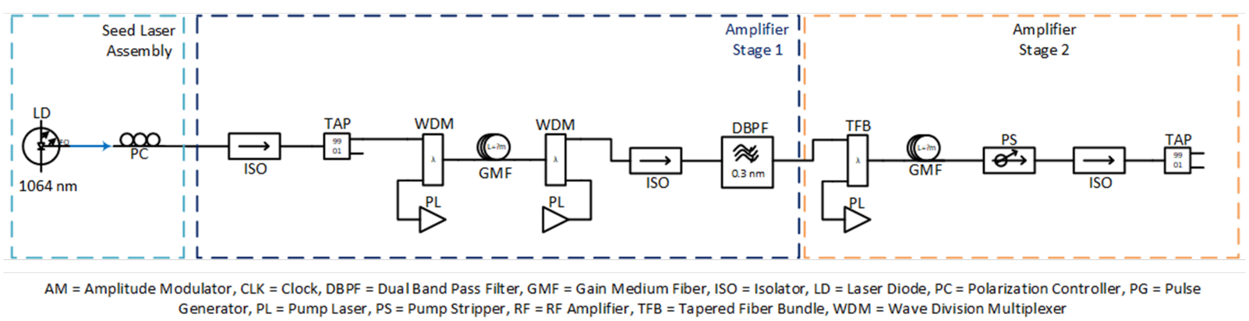

Fig 5 Proposed laser architecture for performing the ORCAS mission.

4.3 *Laser Telescope Assembly*

The mechanical design, as well as the as built 2-stage fiber laser amplifier is shown in Figure 6. The divergence requirement indicated previously will be met by using the same beam expander utilized for

LINCS. This afocal beam expander utilizes a confocal set of parabaloids to expand the incoming beam by a factor of 12. The as built beam expander for the LINCS mission is shown in Figure 7.

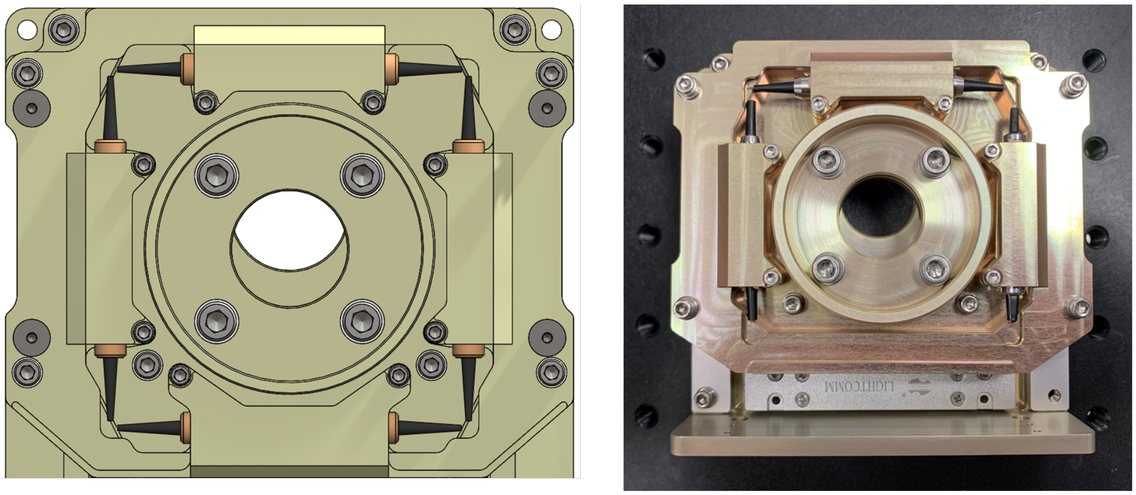

Fig 6 Left - Space qualified fiber laser amplifier design. Right - As built hardware of the two stage fiber laser amplifier.

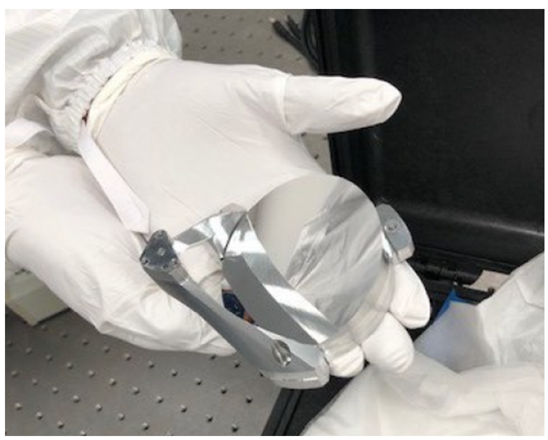

Fig 7 As built LINCS 12X beam expander.

4.4 Free Space Optical Terminal

The system architecture is based on a fiber amplified laser at 1064 nm and a frequency doubling crystal to achieve the appropriate wavelength of 532 nm. The other major elements of the design include a jitter rejection steering mirror, a beam expander, and a sensor for acquisition and tracking. The Free Space Optical (FSO) terminal shown in Figure 8 was designed and built for a 1550 nm laser communication effort for low Earth orbit.

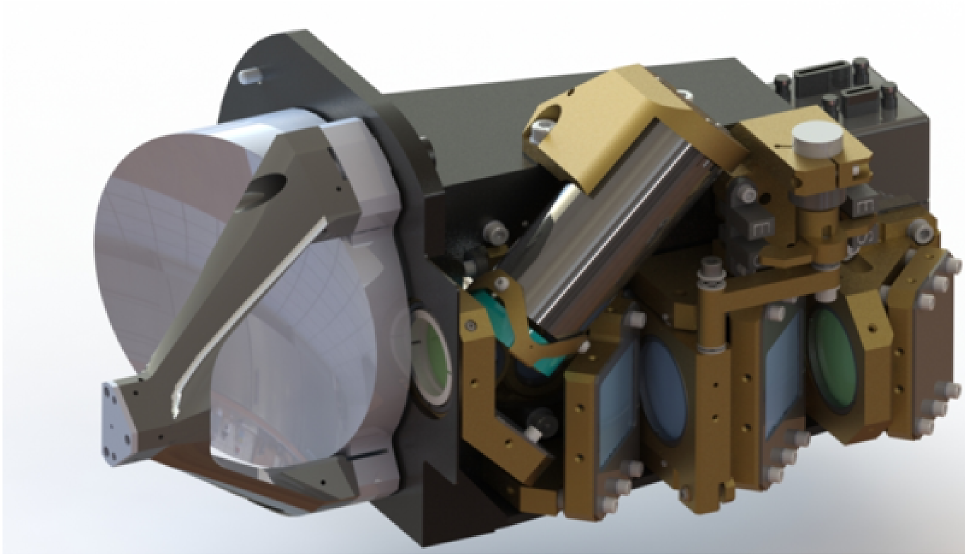

Fig 8 GA-EMS free space optical terminal including jitter rejection and acquisition sensor. Volume of ∼2U or 10 cm x 10 cm x 20 cm.

4.5 Second Harmonic Generation (SHG) Approach

GA-EMS has produced multiple systems that utilize Second Harmonic Generation (SHG) to frequency double 1 um class lasers. Although these lasers are typically Q-switched leading to high peak intensity, the architecture being proposed here is a direct conversion of the CW 1064 nm. Modeling at GA-EMS indicates that >1 W of 532 nm power can be produced from the CW 1064 nm LINCS system. This would be accomplished with pump depletion and dephasing of a down-collimated 1064 nm beam in conjunction with a single pass through an L = 3 cm LBO crystal cut for non-critical phasematching. While not producing optimal second harmonic conversion efficiency, the initial modeling shows that > 1 W of 532 nm power is achievable.

In addition, a survey of peer-reviewed journal articles cite optimized conversion efficiencies at the relevant 1064 nm CW power levels that are more than adequate to produce > 1 W of 532 nm power using simple single-pass techniques. These techniques utilize periodically-poled nonlinear crystals that have been engineered for robustness to surface/bulk laser damage as well as photodarkening. The experimental setup is shown below in Figure 9.

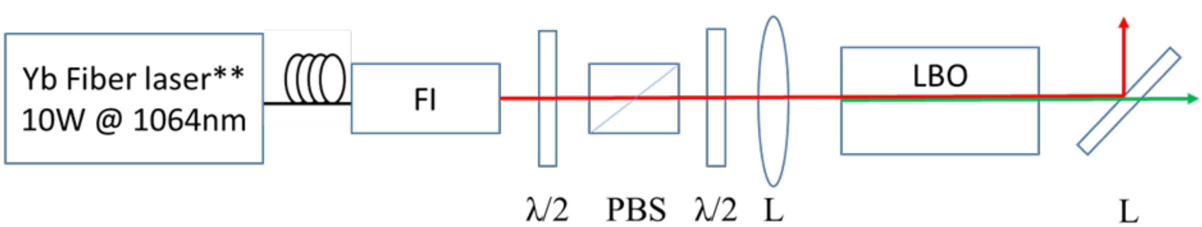

Fig 9 Experimental setup for single-pass second harmonic generation. FI: Faraday isolator, λ/2: Half-wave plate, PBS: Polarizing beam-splitter, L: Lens, M: Dichroic mirror.

While final modeling and component selection for the YDFA conversion of the LINCS system has not been performed, preliminary estimates from modeling suggest that 10 W of 1064 nm source power will be required to accomplish this mission based on an average wavelength conversion efficiency of $> 10\%$. The two stage YDFA which has been produced for other efforts has produced approximately 10 W. Based on the assumption that the same performance can be achieved following the conversion of the LINCS system to 1064 nm, this will be considered design margin, reducing overall technical risk with respect to design life on orbit.

5 Discussion and Conclusion

In support of the ORCAS mission, GA-EMS has developed a high TRL laser payload design which meets all mission requirements. The laser payload can provide the photon flux equivalent of a 5th to 1st order magnitude star. It uses a laser beacon along with a frequency doubling crystal to operate at 532 nm with an output divergence of 65 μrad, tunable to 1064 nm with an output divergence of 500 μrad. The system will be able to track a 589 nm ground source. The laser will provide a continuous wave payload and will meet pointing requirements. The laser payload meets the volume and mass requirements of being less than 6U and 6kg. Finally, it will be able to meet the power requirements, operating at less than 1W and using tunable power to offer a range of options.

The design of the laser payload is based on that of the GA-EMS LINCS mission. Currently at TRL6, LINCS launched on 30 June 2021 as part of the Transporter-2 mission. Following launch as well as on-orbit checkout and commissioning, it will carry out the mission and the system will be revised to TRL9. The unique match of the LINCS system amplifier hardware to the ORCAS mission objectives has resulted in the possibility to take a high TRL system and adapt it for this mission which reduces overall technical risks and can have a positive impact on schedule. The primary adaptations from the LINCS mission to the ORCAS mission are the conversion of the 1550 nm amplifier to a 1064 nm amplifier, the addition of the frequency doubling hardware, and adjustments to the free space optics which are currently optimized for 1550 nm.

The ORCAS mission is capable of launching approximately 4.5 years after the mission is selected. Overall, the laser system has an estimated 24-month timeline for a fully built and tested payload. Now that the LINCS mission has been launched and currently is being tested on-orbit, the modified ORCAS system will be tested to ensure the new design features are at a high TRL.

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