MicroSat laser communication terminals and IR imaging payloads for space-based applications

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ABSTRACT

Predictive, intelligence-driven Space Situational Awareness (SSA) requires autonomous, cued sensors in a BMC3 architecture that will likely benefit from free space optical laser communication links. In this paper, we describe the development of a pair of 12U CubeSats with infrared imaging payloads and 5 Gbps 1550 nm laser communication terminals (LCTs) for space-based applications. The LCTs use a software defined modulation scheme and a novel acquisition technique that yields a bus-agnostic and manufacture-able architecture that can be used for multiple missions without necessitating extensive redesign and qualification. The CubeSats are expected to launch to LEO on a NASA rideshare in March 2021.

1. INTRODUCTION

Proliferated Low Earth Orbit (LEO) constellations of Micro Satellites (MicroSats—satellites of mass between 10 and 100 kg) and Mini Satellites (MiniSats—satellites with mass between 100 and 500 kg) hosting high-end payloads and sharing data via Optical Inter-Satellite Links (OISL) will provide the foundation of future, resilient, affordable space architectures delivering critical space-based services for national security and commercial endeavors. Additionally, such architectures will undoubtedly benefit from the low-probability of detection and low-probability of interception attributes of high-bandwidth OISL enabling secure sharing of large amounts of data and information between optically-networked spacecraft.

Under its Independent Research and Development (IRAD) program, General Atomics Electromagnetic Systems (GA-EMS) has developed a free-space laser communication terminal (LCT) design that can now demonstrate the LEO-to-LEO OISL concept from a MicroSat, and that can scale to provide optical links across larger distances including between LEO and Geosynchronous Equatorial Orbit (GEO) and beyond to the entire cislunar volume. Predictive, intelligence-driven Space Situation Awareness/Domain Awareness (SSA/SDA) requires autonomous, cued sensors in a BMC3 architecture that will likely benefit from high bandwidth OISL. Spacecraft with optical links and hosting infrared (IR) imaging payloads (as well as other payloads) can perform multiple national security space missions including missile detection, earth-imaging, and GEO SSA.

GA-EMS, under funding from the Space Development Agency (SDA), is building and plans to launch a pair of 12U MicroSats to carry GA-EMS IRAD-developed LCTs and IR imaging payloads to demonstrate high bandwidth LEO to LEO crosslinks and to perform space-based imaging. The two GA-EMS 12U CubeSat busses with their integrated payloads are presently scheduled to launch in March 2021 as rideshares on the NASA-USGS Landsat 9 mission aboard a United Launch Alliance Atlas V launch vehicle. The 12U CubeSats will be placed into a near-polar, sun-synchronous orbit at a 550 km altitude. (Landsat 9 will be placed into a higher, 705 km, altitude.) After insertion, the two CubeSats will drift to as much as a 2,400 km separation. As the spacecraft separate, long-range laser communication (lasercomm) cross-links and down-links will be demonstrated. To our knowledge, this will be the first U.S. space-to-space demonstration of lasercomm links from MicroSat-class spacecraft.

The focus of this demonstration is not SSA. Rather, it is to mature the compact LCT and IR imaging payloads. Once proven and matured to the highest Technology Readiness Level (TRL) in the space domain, the SSA community will have a greatly expanded set of technologies from which to select for next-generation, resilient space-based SSA and complementary space superiority capabilities.

The OV1 for the March 2021 demonstration is shown in *Fig. 1*. As the propulsionless CubeSats drift apart, they will establish OISLs and validate the predicted performance of the LCTs. Simultaneously, they will image sections of the earth in a pair of IR bands. Each satellite bus will provide 100 W of onboard average power for the LCTs, IR imaging payloads, onboard processing, and satellite operations. Thermal vacuum chamber (T-VAC) testing on components was performed at the GA-EMS facility in Huntsville, AL during initial design phases. System assembly and ground-testing is being performed in late 2020.

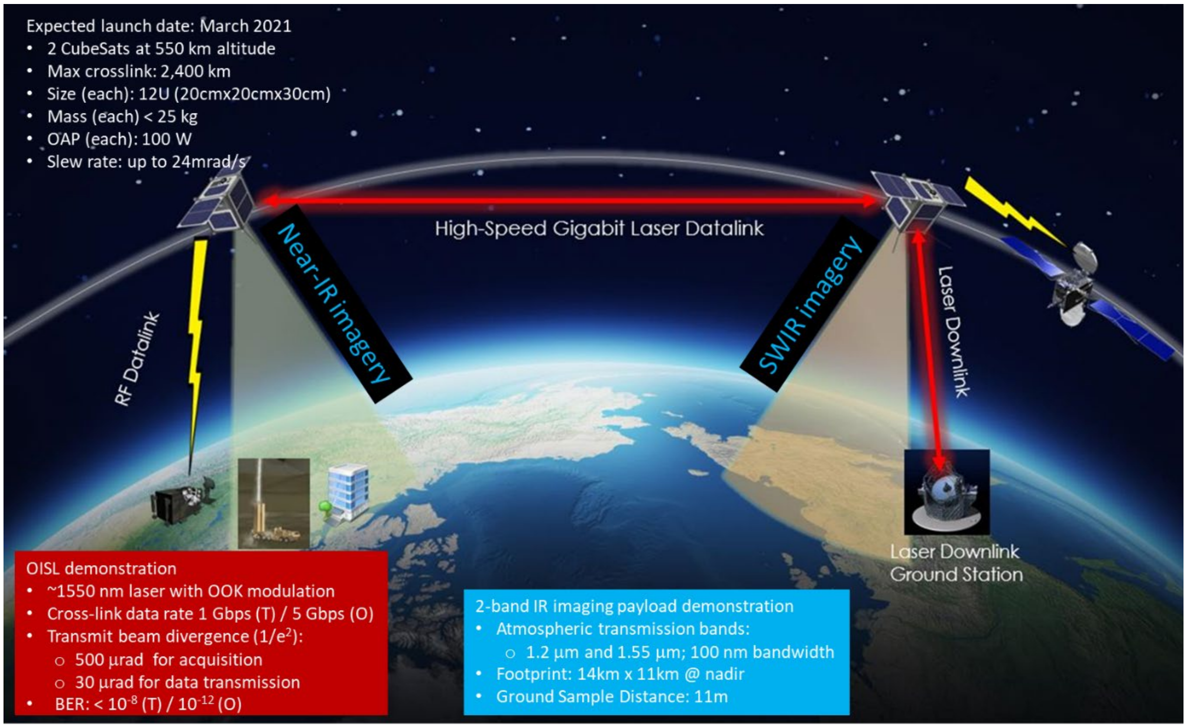

Fig. 1. OV1 of the GA-EMS 12U CubeSat demo of OISL LCT and IR imaging payloads planned for March 2021 launch.

Each satellite contains controller electronics providing command and control for the LCT as well as providing an interface to the bus and the IR imaging subsystem. The design leverages a Field Programmable Gate Array (FPGA) System on a Chip (SOC) paired with a radiation hardened supervisory microcontroller monitoring the power rails and internal logic for any latching failure modes. *Fig. 2* shows the GA-EMS 12U CubeSat layout including LCT and IR imaging payloads. The potential ramifications for space-based GEOINT and SSA are noteworthy.

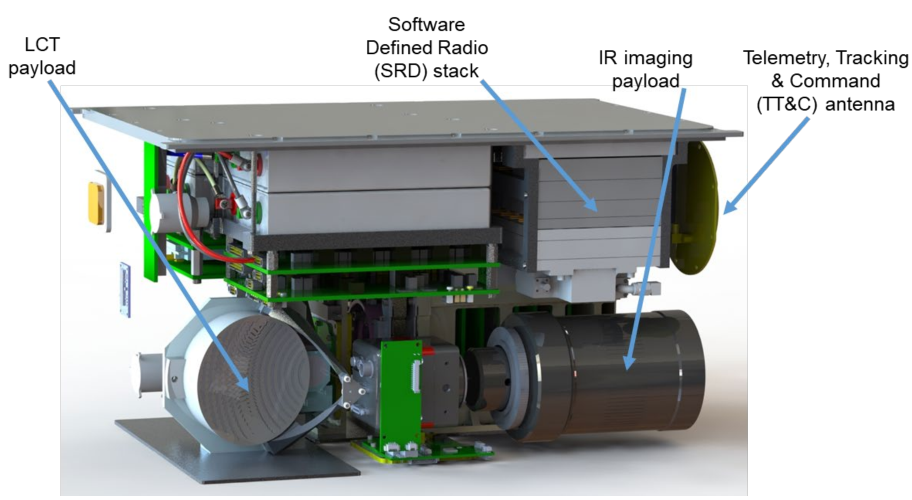

Fig. 2. Layout of the GA-EMS 12U CubeSat bus with LCT and IR imaging payloads.

In this paper, we provide an overview of the GA-EMS OISL LCT subsystem, and describe the LCT hardware. Next, we provide an overview of the GA-EMS IR imaging payload subsystem, and describe the imaging hardware and its application for earth imaging. Finally, we recap the capability and discuss possible extensions to space-based SSA.

2. GA-EMS OPTICAL INTER-SATELLITE LINK (OISL) SUBSYSTEM OVERVIEW

The LCT developed by GA-EMS operates at 1550 nm and uses on-off keying (OOK) to support a data rate of up to 5 Gbps at LEO-LEO ranges. The selection of 1550 nm and OOK was in response to our Government customer's desire for maximum compatibility across LCT suppliers. The system architecture is expandable to enable scalable output power to support communication links from a variety of orbits up to and including GEO-GEO as predicted by amplifier testing and link budget analysis. Our modular laser amplifier evolved from a TRL-9 system originally used by General Atomics for airborne applications. It has been redesigned for space applications and is currently TRL-6 based on T-VAC tests conducted in 2018. The system uses a software defined modulation scheme that can change between non-return-to-zero (NRZ) and return-to-zero (RZ) to support various crosslink distances by transitioning between RZ and NRZ. While the current LCT uses OOK, the design can support alternative modulation schemes including Differential Phase Shift Keying (DPSK) which was demonstrated as part of the 2018 T-VAC test. Binary Phase Shift Keying (BPSK) can deliver extra margin, but generally requires atmospheric compensation on the downlink which increases system complexity and satellite size, weight, and, power (SWaP).

Coarse pointing during the 2021 on-orbit demonstration is provided by the bus, and the LCT uses a novel acquisition scheme to enable rapid acquisition of other LCT systems—even when the bus level pointing accuracy exceeds 350 μrad. This creates a bus-agnostic LCT architecture that can be used for multiple missions without requiring extensive redesign and qualification.

Fig. 3 shows the optical design and layout of the current LCT within the 12U CubeSat. The seed laser assembly provides dual wavelength capability within the telecom optical C-Band (1530-1565 nm), which provides full duplex communications, serves as a spare for on-orbit redundancy, demonstrates wavelength division multiplexing and removes A/B-terminal mating requirements. On-off keying allows for maximum compatibility with future terminals, and supports data rates of up to 5 Gbps (depending on range) with corresponding maximum Bit Error Rate (BER) of 10^{-8} before Forward Error Correcting (FEC) and interleaving, which is expected to provide BER margin.

The LCT hardware design has been analyzed and tested at a component level for Falcon 9, Atlas V, and General Environmental Verification Specification launch load specifications, and has margins in performance for all launch vehicles considered.

Deriving the primary system parameters involves two fundamental phases of the link: acquisition and communications. During the acquisition phase and before data transmission can begin, the incoming signal must be detected, acquired, and tracked by the receiving satellite. To detect and acquire the incoming signal, a SWIR imager is used. A fast steering mirror (FSM) is then used to center the beam spot on the imager. A signal to noise ratio (SNR) threshold of 6 is assumed to identify a successfully detected and tracked signal. However, lower SNRs can still be detectable if robust image processing algorithms are employed on the receiving end to boost the signal at the expense of acquisition time. During the communication phase, the divergence is lowered to the diffraction limit. A 10^{-8} BER (pre-error correction) is used for this configuration; however, higher BERs can still transmit data if FEC is implemented within the receiving end.

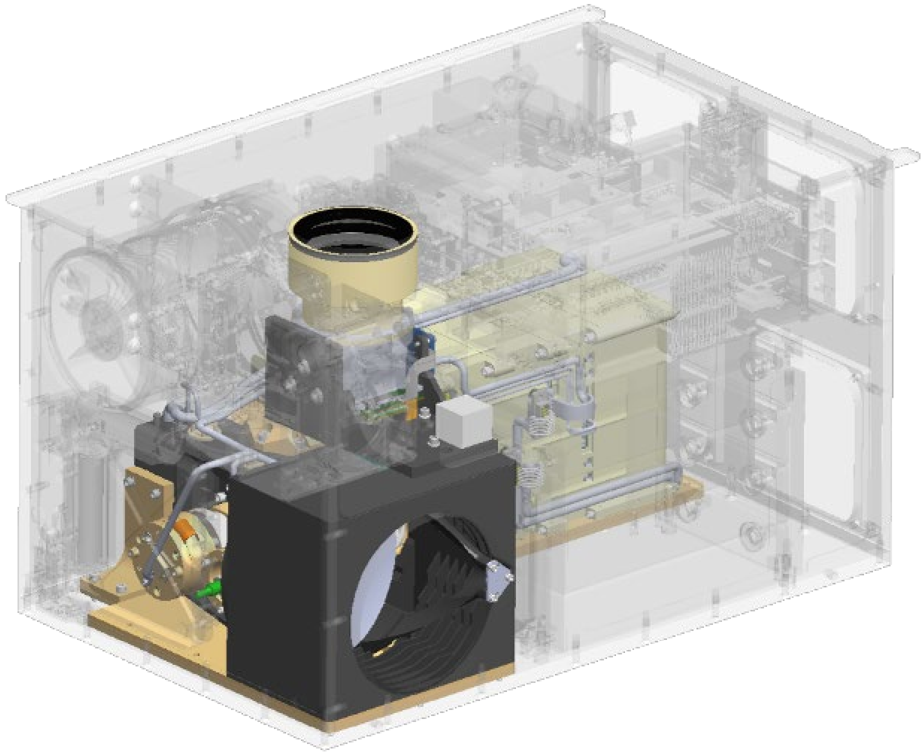

Fig. 3. Optical architecture and layout of the current OISL LCT integrated within 12U CubeSat host system

For all communication systems, there exists a balance between aperture size and transmitter power. The transmit/receive (Tx/Rx) components in the GA-EMS OISL LCT comprise a 2-stage fiber laser amplifier and 72 mm (~2.8 in) Rx telescope, which provides a Gaussian diffraction limited half angle divergence of ~30 µrad. A divergence of 500 µrad is used for acquisition via variable divergence functionality, which enables Pointing, Acquisition, and Tracking (PAT) with a bus error in excess if ~200 µrad while maintaining ≤ 1 µrad pointing from the internal fine steering mechanism. *Table 1* contains a summary of key attributes of the GA-EMS OISL LCT.

Table 1. Key attributes of GA-EMS Optical Inter-Satellite Link Laser Communication Terminal
Compliant with CCSDS 141.0-B-1 standard, Optical Communications Physical Layer
5 Gbps data rate (depending on range)
2,400 km max range at 550 km altitude (range limited by earth-orbit geometry)
$< 10^{-8}$ Bit Error Rate (BER)
2π str field of regard (FOR)
Transmit beam divergence (1/e2): 500 µrad for acquisition; 30 µrad for data transmission
100 W Onboard Average Power (OAP)
8 W CW laser transmit power from 2-stage erbium-doped fiber amplifier (EDFA)
Day/night operation
Full-duplex communications capable

Tunable Tx laser frequency (1550-1560 nm), RHCP polarization
Low latency (<15ms photons to bits)
Doppler compensation enabled
Point-ahead capability for time of flight compensation
Digital interface compatible with 1G or 10G
Command & Telemetry compatible with RS-422, and Ethernet (Spacewire, 1553, can be accomodated with modifications)
Environmentally hardened for LEO environment and sun survivable
Shock and Vibe compatible with ESPA ring environment
Built-in Self-Test functionality

3. LCT HARDWARE OVERVIEW

The erbium-doped fiber amplifier (EDFA) design is based on a TRL-9 GA-EMS system that is deployed in an airborne environment. The modularity of the OISL architecture enables straight-forward adaptation to emerging mission requirements and to facilitate compatibility with a variety of modulation schemes and waveforms. The common hardware multi-stage stackable laser amplifier designed by GA-EMS allows the same laser architecture to be employed for missions and multi-layer constellations with link distances ranging from LEO-LEO through GEO-GEO by increasing the number of amplifier stages. For example, if longer range communication requirements emerge, or data rates are required to be increased, the modularity of the OISL LCT allows for an additional fiber laser amplifier (3rd stage) to be employed to boost laser power to the level required for longer range communication (up to 30 W) at the aperture. The additional stage is intended to be a “bolt-on” stand-alone unit. Both 1- and 2-stage amplifiers have been built and tested, and a 3-stage system is currently being built. The 2021 LEO-LEO demonstration with use a 2-stage EDFA. The modular EDFA is illustrated in *Fig. 4*.

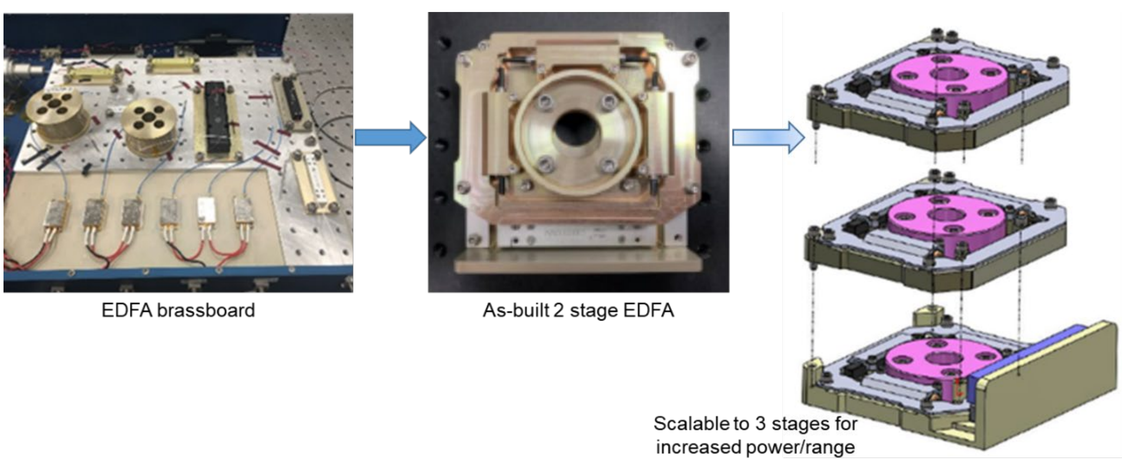

Fig. 4. EDFA brassboard of the 2 stage high power optical amplifier (left), and the as-built 2-stage high power optical amplifier for the OISL LCT (middle). CAD rendering of a 3-stage amplifier for increased power and range (right).

The optical bench is a 12x beam expander telescope and a common 72 mm diameter aperture for both Tx and Rx with a closed-loop steering mechanism for fine pointing. For the current design, coarse pointing is provided by the bus; however, the laser components and aft optical assembly are bus agnostic and can support gimbaling systems. The optical bench employs optical and polarization filters for stray light reduction and separation of outgoing and incoming light. The Rx signal is split from the common path of the Tx signal and sent to the tracking and receiving assemblies. A small portion of the light is sent to a camera, where the closed-loop tracking system maximizes detector irradiance.

The remaining photons are sent to the receiving assembly for demodulation de-encoding, and transferred to the on-board electronics for processing or dissemination. *Fig. 5* illustrates the current OISL LCT payload architecture.

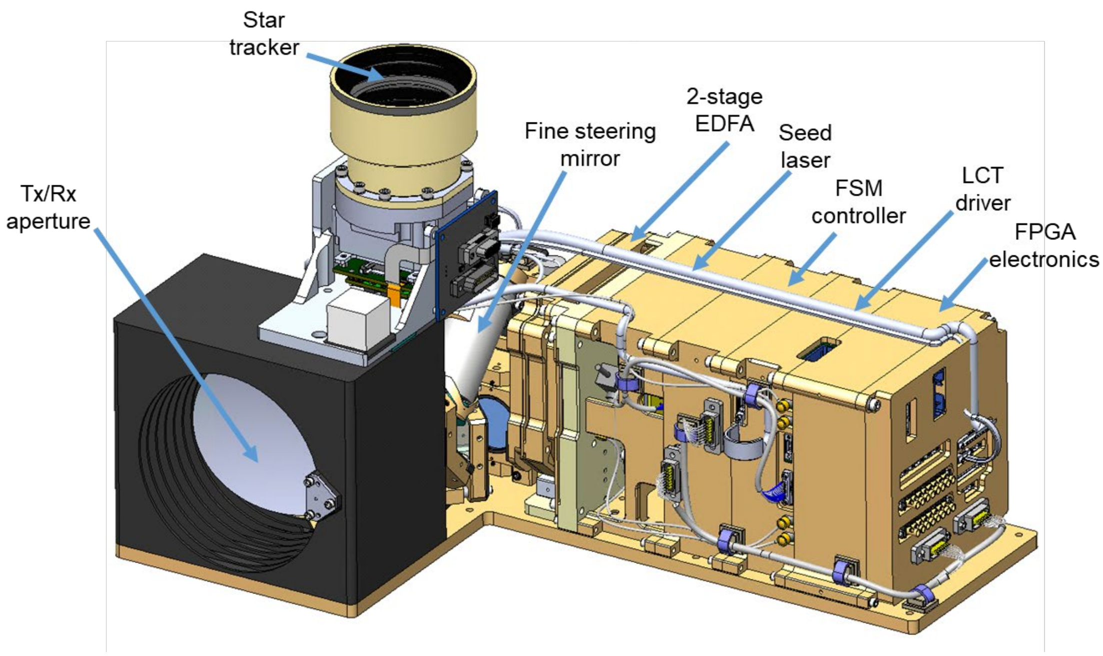

Fig. 5. GA-EMS Modular OISL LCT Payload

The PAT subsystem employs a High-TRL SWIR camera (see *Fig. 6*) for initial spatial acquisition and tracking. PAT leverages the position and pointing knowledge of the space vehicle, ephemeris knowledge of the second satellite involved in the link, and the payload pointing ability to provide the pointing accuracy needed to establish line of sight and maintain an optical link.

Fig. 6. COTS SWIR camera employed by the OISL provides a high precision tracking solution. (This graphic shows a COTS lens which is not part of the GA-EMS OISL design.)

Closed-loop control of the pointing system is accomplished by imaging a small portion of the incoming beam on an acquisition sensor, adjusting the pointing control to boresight the incoming beam, and executing these general steps: a) search-and-scan, b) detection, c) fine alignment, d) transition to full duplex communication mode, e) aim-point maintenance (throughout communication).

We developed a benchtop OISL Hardware-In-The-Loop (HWIL) system, shown in *Fig. 7*, to develop our PAT techniques. In addition to maturing the PAT scheme, we demonstrated encoding/decoding and modulation of data on the optical link. We inserted a second steering mirror to inject pointing errors and jitter that are representative of the expected satellite system-level pointing errors and jitter to prove that the optical link can be maintained in the space OISL demonstration system. Upcoming *Day-in-the Life* testing will exercise the MicroSat and its payloads through on-orbit tasks using GE-EMS' on-site space vehicle HWIL/Software-in-the-Loop (SWIL) facility. This process simulates an active mission profile to validate communications, payload interoperability, routine functions, and state/mode management.

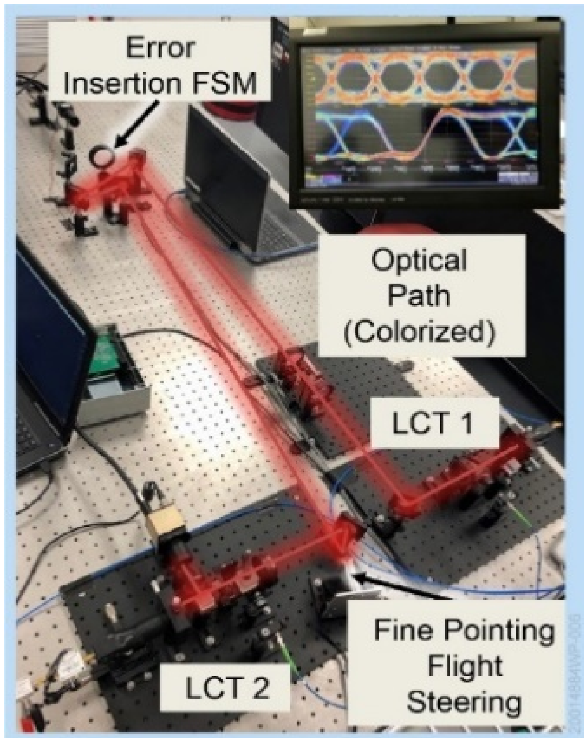

Fig. 7. OISL HWIL lab demonstration, which validated pointing, acquisition, and tracking algorithms.

Additional details of the LCTs are provided by Leboffe, Howard, Freeman, and Robie in [1].

4. GA-EMS INFRARED (IR) IMAGING PAYLOAD SUBSYSTEM OVERVIEW

The GA-EMS compact, space-based IR imaging payload is designed to perform Intelligence, Surveillance, and Reconnaissance (ISR) of earth from LEO. An IR imager and an LCT are integrated on each of the GA-EMS CubeSats. One CubeSat IR imager has a 100 nm wide IR pass band in the Near-IR centered at 1.20 µm, and the other CubeSat has a 100 nm wide pass band in the short wave infrared (SWIR) centered at 1.55 µm. Our design employs a Raptor Photonics Owl 1290 camera and a Stingray F/8 Lens, and occupies approximately 25% of the 12U volume in each CubeSat. The IR Owl 1290 cameras each have an InGaAs PIN 1280x1024 pixel photodiode focal plane array (FPA).

As the CubeSats separate after insertion into their sun-synchronous orbits, the non-gimbaled IR cameras will use spacecraft body pointing to image ground targets either independently or simultaneously. The FPA and the camera's 76 mm diameter optic F/8 lens are expected to yield an 11 m ground sample distance (GSD) at nadir from the nominal 550 km altitude. Analyzing time-sequenced data from a single satellite or simultaneous data from the pair of satellites can provide useful GEOINT (and SSA when "turned around") intelligence products. To manage data requirements and remove latency, image processing computation can be performed on the edge by the on-board NVIDIA® Jetson™ TX2 graphics processing unit (GPU).

The present system has no gimbal, so the orientation of the spacecraft bus determines the optical axis of the imaging payload as illustrated in *Fig. 8*.

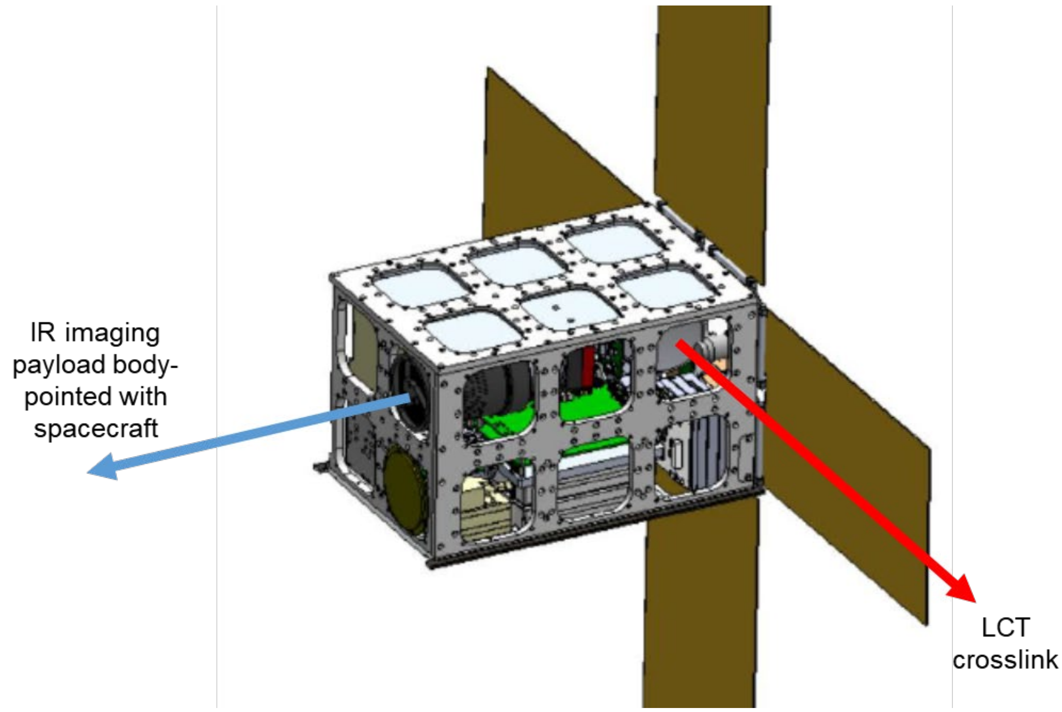

Fig. 8. 12U Space Vehicle showing orientation of IR imaging payload optic axis relative to the space vehicle and the LCT crosslink optic axis.

Our Concept of Operation is to transfer captured imagery from one CubeSat via LCT crosslink to the second CubeSat, and downlink to ground station via bus RF link or LCT. We will perform on-board processing including image registration and enhancement, non-uniformity correction, and geo-rectification. Once demonstrated, this technique can, in principle, be "turned around" for space-based SSA.

The present system has two body-pointing imaging modes:

1. Normal mode providing constant nadir (or nadir plus offset) to produce a 1-dimensional "swath" of images, and
2. Latitude-Longitude mode providing images over a 2-dimensional area.

Normal mode is more susceptible to image blurring, while Latitude-Longitude mode is less susceptible to blurring, but the aspect changes slowly over time. Geo-rectification converts sensor FOV to the earth frame and can include elevation information. The present bus pointing error is expected to be less than 100 m from the nominal 550 km satellite altitude.

Several applications of IR imaging are envisioned. Material identification within imaged areas is possible through multispectral imaging. The IR payload is SWaP-limited, so we do not employ a filter wheel, but each satellite can have different spectral filters to provide unique signatures after atmospheric correction. Classification and change detection are possible via fusion of multiband images and via temporal variation respectively. Three-dimensional height estimation can be made from pairs of two-dimensional stereo images. The minimum absolute difference approach compares multiple pixels and estimates 3-D building heights and digital elevation mapping. There are two ways to get stereo pairs: via multiple satellites with simultaneous images from different perspectives, and from a single satellite with time separation between images.

Table 2 contains a summary of key attributes of the IR imaging payload.

Table 2. Key attributes of GA-EMS IR imaging payload based on Raptor Photonics Owl 1290 camera and Stingray F/8 Lens
IR camera has a space heritage and meets objective sensor specifications for this mission
Spectral bands (100 nm width) centered at 1.2 μm and 1.55 μm
InGaAs PIN 1280x1024 pixel photodiode focal plane array
Pixel Pitch: 10 μm x 10 μm
Aperture: 6.25 cm
FOV: 1.467 degrees x 1.173 degrees
Frame Rate: up to 60 Hz
Spectral Response: 0.4 μm to 1.7 μm
Quantum Efficiency: > 80% from 1 μm to 1.6 μm
Dynamic Range: 69 dB
Power Consumption: < 5 W
Augmented with Stingray SR0354-A01 500 mm focal length F/8 Lens
Lens spectral band: 0.45-2.3 μm

5. IR IMAGING HARDWARE OVERVIEW

The IR imaging payload subsystem is illustrated in *Fig. 9*.

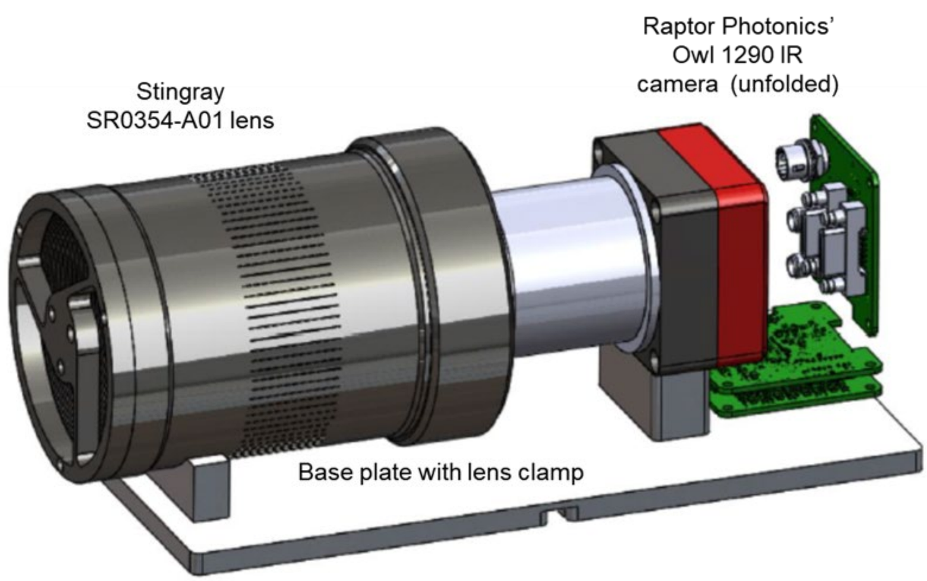

Fig. 9. Raptor Photonics Owl 1290 camera mated with Stingray SR0354-A01500mm F/8 lens for GA-EMS IR imaging payload.

For terrestrial applications, the COTS Raptor camera relies on convection cooling of internal printed circuit boards which is not an option in our space-based application. GA-EMS has worked with the Raptor Photonics OEM to obtain a version that removes some of the external packaging for access to boards. The sensor printed circuit board remains inside the front block enclosure, and the FPGA requires heat sinking with a gap pad for conduction cooling.

We performed radiometric analysis to compute expected SNR as a function of sensor and scene parameters. We selected an SNR threshold of 5 for producing usable imagery, and present results for the stressing night imaging case in *Fig. 10* where we see that integration time of ≤ 1 ms is required to ensure sub-pixel image blur. Our analysis further shows that, for the 1.20 µm and 1.55 µm bandpasses, the SNR exceeds 5 for off-Nadir angles up to 25 degrees—even with only quarter moon nighttime illumination.

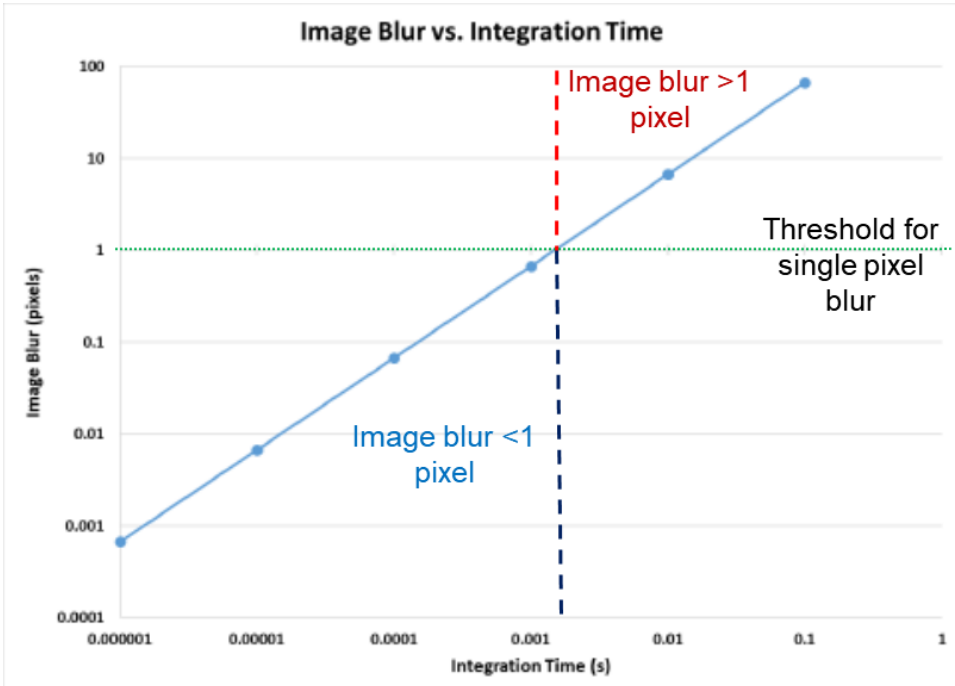

Fig. 10. Image blur of the IR imaging payload as a function of integration time.

6. CONCLUSIONS

We have described the design and expected performance characteristics of a pair of GA-EMS 12U CubeSats containing LCT and IR imaging payloads. The expected March 2021 launch will demonstrate the first U.S. OISL capability between MicroSats. In addition, the IR imaging payloads will demonstrate OISL-coordinated earth imaging and on-board processing including image registration and enhancement, non-uniformity correction, and geo-rectification.

The high-data-rate LCT developed by GA-EMS operates at 1550 nm and uses on-off keying to support interoperability with other lasercomm systems. The IR imaging payload uses mature COTS components and yields an impressive 11 m ground sample distance at nadir from the nominal 550 km altitude. Once demonstrated, this imaging technique can, in principle, be "turned around" for space-based SSA.

The previous decade saw several space-based SSA demonstrations including the Space Based Space Surveillance (SBSS) pathfinder satellites in LEO and the Geosynchronous Space Situational Awareness Program (GSSAP) satellites in GEO. With space now widely recognized as a contested domain, the need is growing for enhanced SSA. The potential for affordable MicroSats to perform space-based SSA is clear, and the GA-EMS IRAD-developed and SDA-funded demonstrations are designed to mature affordable, compact LCT and IR-imaging payload technology to TRL-9 to meet emerging requirements for space superiority and security for the U.S. and its allies.

References

[1] Eric Leboffe, Tamani Howard, Aaron Freeman, and David Robie, *Multi-mission capable 1550 nm lasercom terminal for space applications*, **2020 SPIE Photonics West,** conference paper *11272-4*, 4-6 Feb 2020.