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Laser Crosslink Experiment: A Mission Overview

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ABSTRACT

The Laser Crosslink Experiment (LaCE) is an ongoing optical communication campaign with ground, stratospheric, and orbital elements. The principal LaCE experiment is two 6U CubeSats, LaCE 1 and LaCE 2, which were launched to a shared sun-synchronous Low Earth Orbit (LEO) on March 4, 2024. LaCE was originally conceived in 2015 as an integration effort for a series of Small Business Innovation Research (SBIR) proposals. Its primary experiment is the Skylight laser terminal, an experimental optical communications device.

Due to the experimental nature of key subsystems, LaCE was expanded in 2020 from the initial small satellite mission to a hybrid land, air, and space campaign. Ground experiments validated experimental LaCE subsystems, several of which are now commercially available products. The Stratospheric Optical Link Demonstration (SOLD), which launched on a high-altitude balloon (HAB) in 2023, successfully performed an optical link from a ground platform to a balloon flying in the stratosphere using LaCE hardware. The LaCE satellites are currently on orbit and are executing commissioning and early mission operations. LaCE plans to execute a space-to-ground optical link in Summer 2024, with a co-orbital space-to-space experiment planned for late 2024

BACKGROUND

Optical communication is the use of optical devices, such as lasers, to perform long distance communications. Optical communication has multiple benefits: these systems can provide high data throughput and power efficient communication over long distances and can provide non-RF communication methods to aid with radio spectrum congestion. Optical communication in LEO is an active area of research and development. While large satellites, such as the SpaceX Starlink constellation, have begun to deploy bespoke optical communication systems for inter-vehicle communications, the technology is still generally less mature than radio frequency communication in small satellites.

The LaCE mission began in 2015 as a Navy SBIR effort to identify and develop nascent low Size Weight and Power (low-SWaP) technologies, particularly those relevant to small satellite optical communications. Systems identified through this initial proposal process included the Pumpkin Supernova bus, Vulcan Wireless CSR-SDR-U/S Software Defined Radio (SDR), and SA Photonics (now CACI) Skylight communication terminal. LaCE was an early recipient of several of these subsystems and performed significant Verification and Validation (V&V) services on these devices.

Figure 1: LaCE launch aboard Transporter 10 (March 4 2024).

LaCE vehicle integration began in 2018, initially targeting a late-2020 launch. COVID-19 and R&D delays resulted in the launch being rescheduled to March 2024; in the intervening time, LaCE was expanded to a multi-environment testing effort including the launch of the companion SOLD high-altitude balloon.

MISSION OVERVIEW

The expanded LaCE mission comprises three linked testing campaigns: ground, stratosphere, and space. This approach was pursued to accommodate complex V&V requirements of the program's lower Technology Readiness Level (TRL) components. Testing these devices in progressively more complex and representative environments was identified as a key risk reduction path, as well as a venue to provide accelerated scientific and engineering data to the system designers and stakeholders.

Ground Mission

The LaCE ground mission performed essential V&V for the key LaCE payload components. This included in-house NASA General Environmental Verification Standard (GEVS) vibration and Thermal Vacuum (TVAC) testing of standalone and integrated subsystems, and full testing of the Skylight range, tracking, and data transfer capabilities.[1]

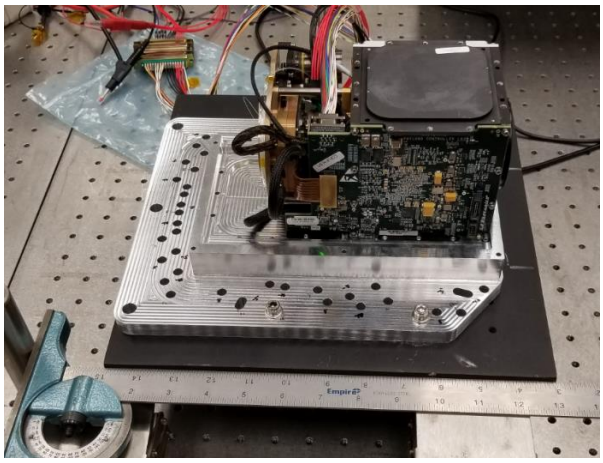

Figure 2: Skylight optical payload in the NIWC Pacific laboratory. Ruler for scale.

The capstone experiments of the ground mission were a 1-km free space laser test at NIWC Pacific's SPARTA laser range, and a 16km endurance test at the CACI facility. The results of these tests helped inform several engineering revisions on the Skylight unit and provided valuable capability and operational metrics to support the following stratospheric and orbital campaigns.

Stratospheric Mission

The Stratospheric Optical Link Demonstration (SOLD) was a HAB experiment flown in August 2023 using spare engineering parts and optical devices from the LaCE mission.[2] SOLD was developed and flow as a collaboration between NIWC Pacific and the NASA Ames Flight Opportunities office.[3] It was designed explicitly as an efficient risk-reduction mission to the LaCE flight vehicles and as a way to advance free-space optical communication on high altitude platforms.

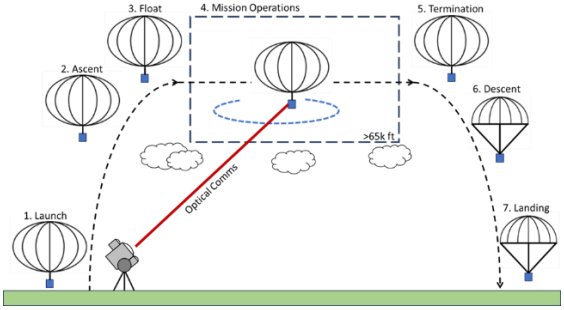

Figure 3: SOLD Mission Profile

The SOLD mission profile was a ground-to-air optical link, completed between a mobile ground station and a stratospheric HAB. This mission was achieved using spare parts, including qualification and engineering optics from the LaCE space mission, in order to reduce cost and ensure future risk reduction for the LaCE program.

SOLD was a rapid development effort and flew on August 30, 2023, less than two years after its initial proposal. SOLD flew in the stratosphere above 65000ft altitude and completed an optical uplink at speeds up to 100 Mbps.[2] SOLD was recovered intact approximately 14 hours after launch, and its components were successfully recycled back into the LaCE ground support program.

Orbital Mission

The Laser Crosslink Experiment (LaCE) flight mission is the capstone of the broader LaCE program and consists of two 6U CubeSats operating in a shared sun-synchronous LEO orbit. The LaCE vehicles are multi-mission spacecraft intended to execute the following experiments:

1. **Primary**: Skylight Laser Communication Terminal crosslink.[4]
2. **Secondary**: Extremely Low Resource Optical Identifier (ELROI) satellite identification system.[5]
3. **Secondary**: Nanosatellite Tracking Experiment (NTE) satellite identification system.[6]
4. **Tertiary**: V&V of experimental commercial hardware.
5. **Tertiary**: Characterization of space-to-space Iridium Short Burst Data (SBD) link.

The primary mission is a laser communication experiment intended to validate the Skylight laser terminal, an ultra-low-SWaP, actively steered laser communication payload intended for distributed LEO

small satellite constellations.[4] The goal is to establish an optical link between the two LaCE vehicles and characterize link budget performance at varying distances as the two spacecraft separate. In addition to this primary link mission, LaCE will also pursue a Space-to-Ground link, similar to the SOLD mission.

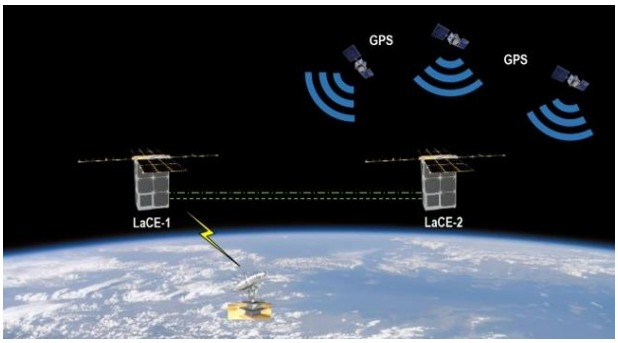

Figure 4: LaCE Mission Profile

The ELROI and NTE missions are both satellite identification systems, intended to aid ground-based tracking stations with detecting and identifying small spacecraft on orbit. ELROI, developed by Los Alamos National Laboratory (LANL), utilizes a series of low-power, modulated, hemispherical red lasers to beacon at an experimental telescope at LANL. NTE, developed at NIWC Pacific, performs a similar task via a passive Ka-band retroreflector that interfaces with a ground-based Ka-band radar.

In addition to these experiments, LaCE is also a technical demonstration and V&V partner for several internally developed and commercial developed microsatellite subsystems. These include:

1. The CACI Skylight laser communication terminal.[4]
2. The Pumpkin Supernova Bus.
3. The Vulcan Wireless CSR-SDR-U/S.
4. The ELROI satellite identifier.[5]
5. The NTE satellite identifier.[6]
6. A NIWC Pacific developed space-comms interface for the Iridium SBD 9603N modem.

Prototype V&V for these systems was a significant part of the LaCE ground & development effort. Since LaCE's V&V work, multiple of these systems have flown on other space missions and developed proven flight heritage; LaCE is still the initial flight for several others, including the SDR and skylight.

LaCE coordinated its launch via the Department of Defense (DoD) Space Test Program (STP). It launched on March 4, 2024, and is currently undergoing early-stage operations in support of the Skylight and ELROI missions.

DESIGN AND TESTING

Ground Mission Design

The Skylight terminal is an experimental, self-steering 1550nm optical communications terminal intended for commercial operation.[4] As an initially low-TRL prototype system it required significant on-ground testing to verify its orbital viability.

The Skylight was run through aggressive environmental testing separate from the LaCE vehicle. This included GEVS compliant TVAC testing between -15°C and 50°C temperatures and standard GEVS qualification vibration tests.[1] This testing helped inform engineering revisions on pre-flight prototypes and provided critical mission risk reduction and TRL advancement by identifying the relevant flight characteristics of the system.

The optical performance of the skylight was also stress tested, both in laboratory and operational conditions. NIWC Pacific set up a 10-meter laboratory range to fully characterize the tracking, power, and broadcast capabilities of the skylight. This range was also equipped with a smaller windowed TVAC chamber, allowing precision characterization of the laser's performance in flight conditions.

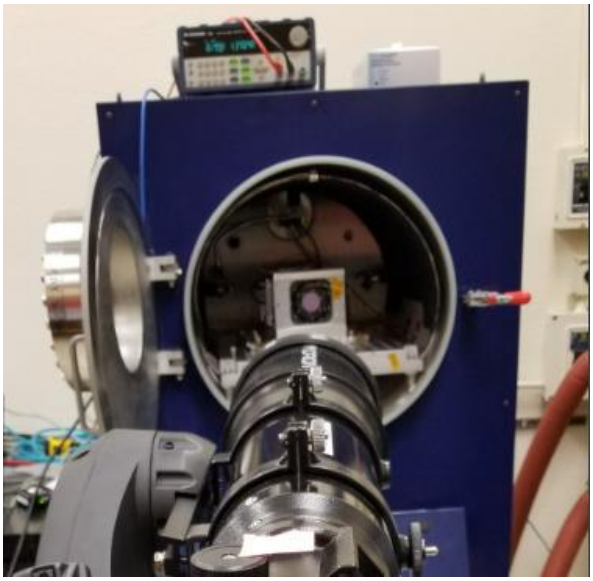

Figure 5: LACE TVAC chamber instrumented for Skylight testing.

These design reviews and stress tests helped increase the robustness of the system, enabling further outdoor, long-range testing of the laser system. These included a NIWC Pacific-led 1km test at the onsite SPARTA laser range, and a CACI-led test at their 16km facility. These tests are discussed further in the Experiment Discussion below.

Stratospheric Design

The SOLD mission is a custom payload gondola that interfaces with the Aerostar Thunderhead balloon. Core Command and Control (C2) operations (flight controls, power generation, communications) are performed by the host Thunderhead vehicle; the SOLD gondola is responsible for pointing, power-distribution, computing, and payload operation. The primary SOLD payload is LaCE's engineering qualification Skylight terminal.

Figure 6: SOLD flight vehicle before launch.

The low-stratosphere flight environment is similar to LEO. The near-vacuum atmosphere (approximately 0.11atm) produces a similar non-convective environment where heat transfer is almost purely radiative. Night-time temperatures are similar to the LEO eclipse environment, with ambient temperatures near –80°C.

To test against these conditions, all relevant optical and computing subsystems were tested to extreme environmental conditions including extended cold soaks in TVAC at –60degC vacuum.[2] All subsystems survived this test and operated without noticeable error.

Orbital Mission Design

The LaCE space mission consists of two identical 6U CubeSats in the same LEO plane. Core systems include:

Table 1: Key LaCE Subsystems

Subsystem	hardware
Primary Radio	Vulcan Wireless CSR-SDR-U/S (UHF up / S-Band down)
Secondary Radio	Iridium 9603N SBD Modem
GPS	Novatel OEM716
Attitude Control	Blue Canyon XACT
Power System	Pumpkin 8.2V Battery / 56W Solar Array

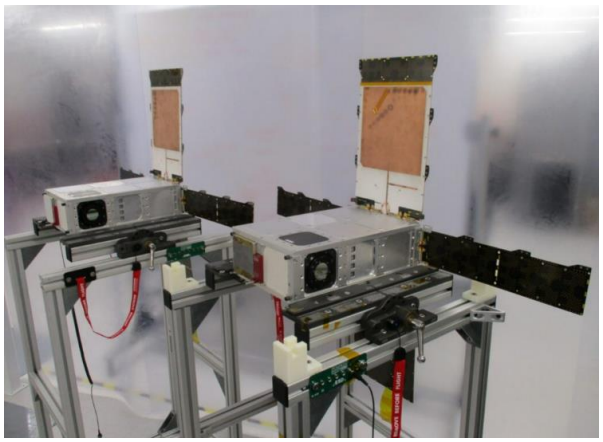

Figure 7: Assembled LaCE vehicles. SDR antenna, Skylight, and ELROI are visible.

The LaCE vehicles were initially built and tested over a four-year period between 2018 and 2021. During this period each vehicle was tested in subsystem-level and integrated states against environmental and functional test conditions. Environmental testing included several rounds of TVAC between -15°C and 50°C and vibration performed in accordance with GEVS acceptance and workmanship standards.[1]

A mechanical anomaly was identified in the LACE-1 vehicle during a 2021 GEVS protoflight vibration, requiring de-integration and mechanical rework of key subsystems. This resulted in a launch delay from Spring 2022 to Spring 2024 but was identified as a valuable discovery that ensured launch survivability.

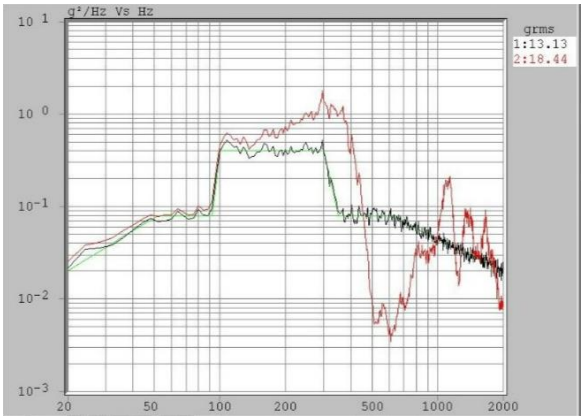

Figure 8: July 2021 Protoflight vibration test results. Total vibration is 13.1 GRMS.

This program delay gave the engineering team the opportunity to perform additional hardware-in-the-loop testing of critical subsystems, including the radio and attitude control systems. The re-integrated vehicles were manifested on the Transporter 10 launch and tested to a lighter GEVS profile. Acceptance was completed in Fall 2023, with a delivery and launch window in Spring 2024.

LaCE uses an on-site ground station, consisting of an actively steered UHF-up/S-band down SDR antenna array and a mast-mounted iridium SBD modem similar to the flight hardware. These systems are operated at an adjacent on-site flight operations center.

MISSION EXECUTION

Ground Mission: 16km Range Test

The 16km test was the initial long-range test of the Skylight terminal, performed on March 22-24, 2023 by CACI with support from NIWC Pacific. During this test the LaCE1 and LaCE2 terminals were secured in approximately sea-level enclosures and tasked to perform a 16km tracking and communication crosslink. At this range, the expected atmospheric losses were expected to simulate comparable distance losses to those anticipated on the SOLD and LaCE flights.

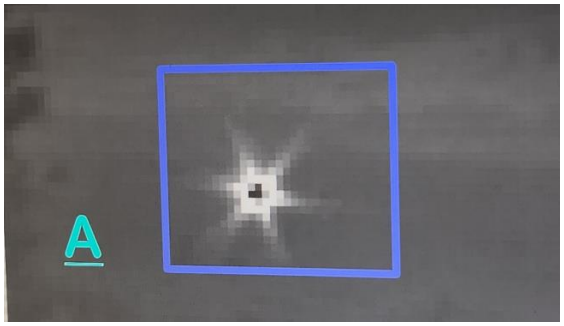

Figure 9: Skylight beam observed at 16km over the ground.

Both terminals were able to acquire and communicate well at these ranges. The terminals were operated under a variety of lighting and weather conditions and performance metrics (e.g. beam jitter, SNR, throughput) were measured and recorded.

Ground Mission: 1km Operational Test

The 1km outdoor test was a major operational ground test of the skylight performed by NIWC Pacific at the on-site SPARTA laser range. In this test the LaCE qualification skylight (the SOLD flight skylight) was tested against NIWC Pacific's skylight-compatible ground hardware and the SOLD beacon and acquisition software stack.

This test verified the SOLD control scheme and identified operational constraints (field of view, lighting conditions, stability) on NIWC Pacific's ground receiver hardware. This was a significant risk-reduction for the SOLD flight and demonstrated the viability of an alternate space-to-ground mission profile for the LaCE flight.

Stratospheric Mission

The SOLD stratospheric mission launched at 12:50 AM on August 30, 2024 and remained airborne in the stratosphere for approximately 14 hours, after which it separated from the balloon and was recovered intact near the point of launch. The SOLD aircraft performed well at altitude and exhibited no vacuum or thermal related anomalies during the flight. A successful laser communications uplink was established and maintained over a one-hour period, during which the skylight performed up to its rated 100Mbps bandwidth.[2]

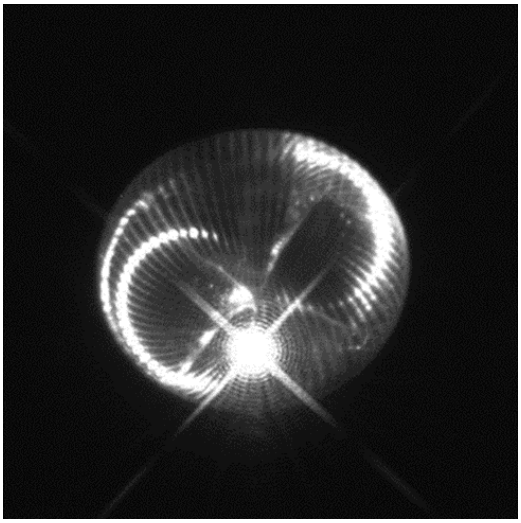

Fig. The SOLD flight vehicle during mission operations.[2]

Orbital Mission

The LaCE orbital mission launched on March 4, 2024, as part of the Transporter 10 rideshare mission. Both vehicles successfully deployed into a 550km sun synchronous orbit. The LaCE orbital mission is still ongoing; the team is actively executing mission objectives. Key mission events and milestones are discussed below.

Launch and Early Operations (LEOPS)

Communications were established with both vehicles via their Iridium SBD terminals within four hours of launch. These early communications indicated the vehicles were in stable sun-tracking attitudes and had healthy power systems. Subsequent checkouts over the following weeks confirmed the health of critical survival systems and the flight vehicles were determined to be ready for early mission operations.

May 10 G5 Magnetic Storm

On May 10, 2024 a series of large Coronal Mass Ejections (CME) from the sun struck the earth's

atmosphere causing a G5 (EXTREME) geomagnetic storm, the strongest recorded since 2003. During the storm, we observed an approximately 12-hour gap in iridium communications; this was expected in the high radiation environment. As space weather conditions improved on May 11 communications were re-established with no further anomalies.

Skylight Checkout

The Skylight experiment is currently in early stages. We have successfully performed laser checkout on orbit and are able to command the skylight to representative mission durations and laser power levels. The operations team is currently executing calibration checklists; we expect to attempt the ground link in summer 2024.

ELROI Experiment

The ELROI experiment is performed in conjunction with a ground station at Los Alamos National Laboratory (LANL). ELROI transmits a low-power, approximately hemispherical laser identification sequence that is detectable by specialized telescope hardware at LANL. LaCE has performed several overflights of the LANL ground station and will continue mission operations through 2024.

EARLY RESULTS

In Atmosphere

The initial in-atmosphere testing by the LaCE ground campaign and SOLD have provided important V&V efforts for multiple commercial systems.

The Skylight terminal has been fully validated in space-like conditions and has demonstrated link and tracking capabilities in-line with its design performance specifications in harsh, complex environments. Ground V&V efforts aided Skylight prototype revisions, improving the system's TRL and decreasing the LaCE mission risk profile.

SOLD's mission success demonstrated the viability of a Skylight link through the atmosphere, supporting the LaCE alternate downlink mission.

SOLD and LaCE both provided significant laboratory expansion and staff training opportunities for NIWC Pacific. These programs have benefited NIWC Pacific's flight heritage and readiness for future flight efforts.

In Space

Both the Skylight and ELROI optical devices have passed orbital checkouts are confirmed to function on orbit. The LaCE Iridium SBD performance, averaging approximately one link ever two hours on a single antenna, is performing in line with other experimental iridium devices flown by NIWC Pacific and NASA groups.[7] [8]

NEXT STEPS

LaCE is finishing flight checkouts and is pursuing its planned flight missions. We are actively performing the ELROI mission and skylight checkout process, with plans to transition from ELROI execution to Skylight execution in Summer 2024.

GLOSSARY

Table 2: Glossary of terms.

Acronym	Term
C2	Command and Control
CACI	Skylight Developer
CME	Coronal Mass Ejection
CSR	CubeSat Radio
DoD	Department of Defense
ELROI	Extremely Low Resource Optical Identifier
G5	Extreme Geomagnetic Storm
GEVS	NASA General Environmental Verification Standard
GRMS	Root Mean Square Acceleration
HAB	High Altitude Balloon
LaCE	Laser Crosslink Experiment
LANL	Los Alamos National Laboratory
LEO	Low Earth Orbit
LEOPS	Launch and Early Operations
Mbps	Megabits per Second
NIWC Pacific	Naval Information Warfare Center Pacific
NTE	Nanosatellite Tracking Experiment
RF	Radio Frequency
SBIR	Small business Innovation Research
SDR	Software Defined Radio
SOLD	Stratospheric Optical Link Demonstration
SNR	Signal to Noise Ratio
STP	Department of Defense Space Test Program
SWaP	Size, Weight, and Power
TRL	Technology Readiness Level
TVAC	Thermal Vacuum
UHF	Ultra High Frequency
V&V	Verification and Validation

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- Los Alamos National Laboratory, for development and mission support of ELROI.
- The Air Force Research Laboratory, for engineering and technical support.

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