

LEO-to-ground laser link and Optical Ground Station in the Keraunos project

Martin Rabault^a, Domitille Schanne^a, Henri Lehec^a, Aubin Beauland^a, Maxime Joos^a, Laurie Paillier^a, Pu Jian^{a*}, Matthieu Meunier^a, Olivier Pinel^a, Guillaume Labroille^a

^a *Cailabs, France*

* Corresponding Author: pu@cailabs.com

Abstract

In recent years, space-based laser communications have emerged as a pivotal industrial and commercial sector, offering significantly higher throughput than traditional RF communications. This advancement is attributed to free-space optical communications' capacity for greater data transmission rates, discretion, and the elimination of the need for frequency allocation. The deployment of Optical Communication Terminal (OCT) equipment by various industrial entities has marked the maturity of this technology for satellite applications. On the other hand, the use of Optical Ground Stations (OGS) for satellite-to-ground optical communications is still at the early stage of commercial deployment.

This presentation outlines the advancements achieved in the Keraunos project, supported by the French Agency for Defense Innovation, through the experimentation of a Low Earth Orbit (LEO) to ground optical link. The OGS developed in the project is developed for commercial use and incorporates an 800 mm telescope with an architecture tailored for high data rates, low elevation angles, and significant atmospheric turbulence.

The presentation delves into the OGS's architecture and subsystems' design and performance. It presents the initial results from first light received from a commercial OCT mounted on a LEO Cubesat satellite operated by Unseenlabs in the context of Keraunos, demonstrating optical communication links with the optical ground station.

Keywords: (maximum 6 keywords)

Acronyms/Abbreviations

Optical Communication Terminal (OCT)
Optical Ground Station (OGS)
Low Earth Orbit (LEO)
Commercially Off-The-Shelf (COTS)
Receive (Rx)
Transmit (Tx)
Multimode Fiber (MMF)

1. Introduction

Optical free-space communication has transitioned in a single decade from laboratory curiosity to operational reality for inter-satellite. Its inherent advantages—terabit-scale bandwidth, immunity to jamming and interception, licence-free spectrum—are decisive for both commercial Earth-observation constellations and government secure networks [1]. On the satellite side, compact coherent and direct-detection OCTs are now flying routinely [2]. By contrast, the ground segment must still cope with rapidly varying line-of-sight, atmospheric turbulence and eye-safety constraints, all while delivering very high availability, in order to offer operational capabilities.

The Keraunos project, initiated in 2021 and funded by Agence Innovation Défense and the French Ministry of Defense, addresses these challenges through the experimentation of LEO-to-ground optical links [3]. In the course of the project, Cailabs has designed, developed, manufactured and commissioned an OGS based on mostly COTS components and Cailabs' proprietary turbulence mitigation technologies.

This paper is structured as follows: Section 2 presents the global architecture of the OGS; Section 3 describes how a satellite-to-ground optical link is operated; Section 4 reports experimental results; Section 5 concludes and outlines the deployment roadmap.

2. Optical Ground Station design

An OGS is not a mere combination of a telescope and a modem. It is a fully integrated system that requires the seamless operation of multiple subsystems following a precise protocol to communicate effectively with a LEO satellite. To achieve high data rates, integrating a turbulence compensation mechanism is essential.

The main overall function of the OGS is to optically transfer data from a satellite to the OGS modem, and vice-versa. To achieve this, the following main functions are necessary:

- Acquire and emit laser with the satellite
- Communicate with the local data network
- Generate Tx optical signal
- Manage the station
- Monitor and assess the environment

The Keraunos OGS is located on a structure comprising a concrete tower supporting a 4.2m slit dome and a separate pier supporting the Laser acquisition and emission subsystem (described below). The tower is 12.8m high, providing 360° visibility down to less than 5° elevation. The dome includes a lower level that can be climate controlled and that houses the communication and the laser generation subsystems. Environment monitoring equipment (weather station and turbulence monitoring station) are located on an exterior walkway around the dome.



Figure 1 – Picture of the OGS on its concrete tower.

2.1 Acquire and emit laser with the satellite

This function enables the establishment and maintenance of an optical communication link between the OGS and a satellite in orbit. More specifically, it involves three main processes:

- Pointing and tracking the satellite: the OGS precisely aligns its telescope and optical system to detect and lock onto the incoming laser signal from the satellite during the whole pass above the OGS.
- Acquiring the Rx optical signal: the optical chain is designed to collect the light at the output of the telescope and process it to inject it into an optical fiber to the communication chain.
- Emitting the Tx optical signal: the OGS emits a modulated laser beam potentially carrying data to the satellite. This requires precise beam pointing and synchronization to maintain a stable, high-bandwidth link with minimal signal loss.

This function is assured by a subsystem comprised of the following main components:

- A receive telescope in a Ritchey-Chrétien configuration with a primary mirror of diameter 800mm. The telescope has 2 Nasmyth exit ports.
- An Alt-Az mount supporting the telescope.
- 2 emit telescopes (refractors) with diameter 125mm.
- Large field-of-view cameras for tracking
- An optical subsystem for processing the collected light and injecting it in a multimode fiber to the communication chain.

3D views and pictures of the Laser acquisition and emission subsystem are shown in Figure 2 and Figure 3.

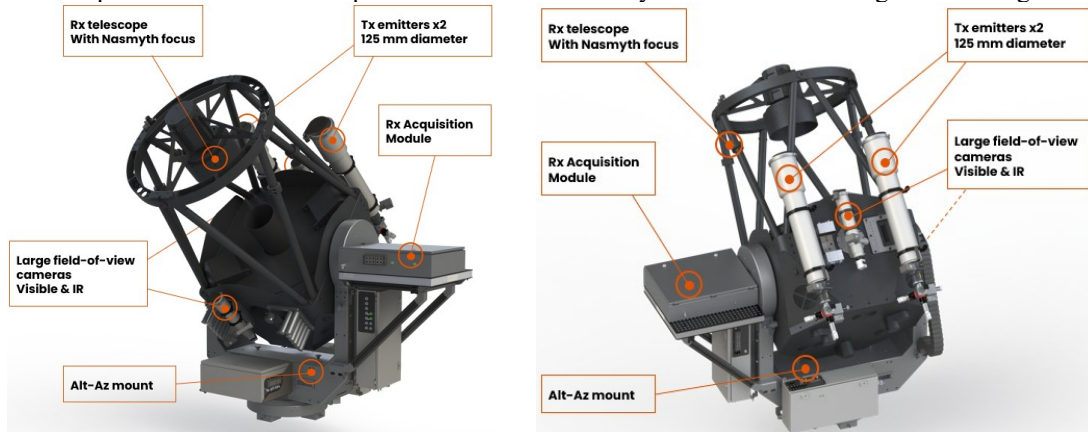


Figure 2 – 3D views of the Laser acquisition and emission subsystem, with description of the main components

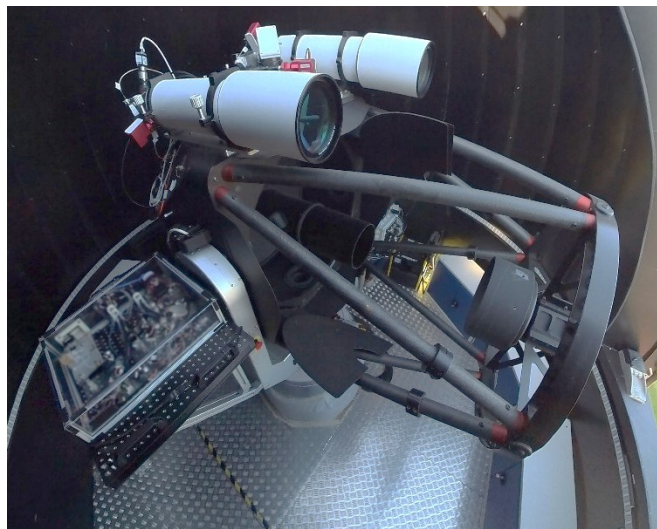


Figure 3 – Photo of a typical Laser acquisition and emission subsystem installed in the Keraunos OGS

2.2 Communicate with the data network

This function enables seamless integration between the OGS and the customer's data network, ensuring reliable bidirectional data transfer using an optical modem.

Due to chaotic changes in the atmosphere, i.e. atmospheric turbulence, a propagating beam becomes distorted, manifesting in rapidly varying losses at the receiver. This phenomenon, called scintillation, leads to irrecoverable signal loss and is detrimental to link quality and availability. In order to mitigate the effects of atmospheric turbulence, mitigation solutions are included in our OGS between the reception/emission of the signal and the modem.

2.2.1 Satellite-to-Ground (Downlink)

The OGS receives the optical signal from the optical chain and provides it to the TILBA-ATMO turbulence mitigation system for downlink. Then, the modem demodulates the optical signal and retrieves the data. The data is then routed through the local network infrastructure.

Detailed description of TILBA-ATMO and its performance can be found in [4].

2.2.2 *Ground-to-satellite (Uplink)*

The network transmits data to the OGS, where it is encoded into an optical signal by the modem and sent to the uplink optical chain, including the TILBA-IBC turbulence mitigation system for uplink.

Detailed description of TILBA-IBC and its performance can be found in [5].

2.2 *Generate Tx signal*

The OGS can generate Tx optical signal either for an L-band beacon or C-band uplink signals for ground-to-satellite communications.

- Beacon signal generation (CCSDS standard): two L-band amplified sources are used to provide a beacon for satellite acquisition and tracking.
- Uplink data signal generation (SDA standard): an amplified optical signal is generated in the C-band (1553.33 nm or 1536.61 nm) to transmit data. The optical signal is modulated in Optical On-Off Keying (NRZ OOK), amplified and sent to the Tx optical chain, including the TILBA-IBC turbulence mitigation system for uplink [5].

The optical signals generated for both wavebands are compliant with international eye safety standards. This ensures that emitted optical power levels remain within safe exposure limits.

3. **Satellite pass operation**

This section details the timeline of a typical LEO pass.

3.1 *Pre-pass planning*

Typically a few hours before the pass, the ephemeris of the satellite are fetched from the satellite operator in two-line element (TLE) or OEM file format.

A few minutes (typically 10 minutes) before the pass, the telescope slews to the start acquisition point while the dome slit pre-rotates.

3.2 *Acquisition phase*

The OGS starts following the theoretical trajectory of the satellite given by the ephemeris. The open-loop mount tracking of the satellite can achieve < 1 arcsec RMS accuracy.

Depending on the laser communication terminal on board the satellite, the emitter laser uses a large divergence (typically a few 100s μ rad divergence) beam or a spiralling narrow beam. In both cases, the goal is for the satellite to see the light emitted by the OGS.

In the meantime, the OCT also points to the GPS coordinates of the OGS and sends a spiralling beam. The OGS sees flashes of light and uses them to perform closed-loop tracking. This closed-loop tracking is performed in two stages:

- A coarse tracking loop based on a large field-of-view camera attached to the Rx telescope and a feedback on the telescope mount: this achieves a tracking accuracy < 10 arcsec peak-to-peak, within the range of the fine tracking loop.
- A fine tracking loop based on an infra-red camera in the Rx acquisition module and a feedback loop on a fine-steering mirror: this achieves a tracking accuracy < 0.28 arcsec RMS, within the aperture of the multimode fiber at the input of the TILBA-ATMO turbulence mitigation system.

3.3 *Communication phase*

When the OCT is locked onto the emission beam, it starts sending its communication signal down to the OGS. The light emitted by the OCT is collected by the Rx telescope, sent through the Rx acquisition system for closed-loop tracking, and coupled into a multimode fiber (MMF). The light in the MMF goes into the turbulence mitigation system TILBA-ATMO and then to the OGS' modem.

In the case of bidirectional communication (such as SDA standard), once the OGS has started receiving light from the satellite, the OGS' modem starts sending data to the satellite via the uplink lasers. These signals are transmitted to the OCT onboard the satellite.

The OGS and the satellite can remain locked during the full pass.

3.4 Post-pass phase

After one pass, the full OGS quickly reconfigures to make itself ready for another link with another satellite, typically within a few minutes.

4. Results

Within the course of the Keraunos project, several dozens of passes have been realized. After the initial calibration phase, the first successful optical link in the CCSDS standard has been obtained in July 2024. Following this initial success, links have been routinely performed whenever the weather conditions permitted them, both during nighttime and daytime, from horizon to horizon.

The OGS has also performed optical links with other constellations of satellites, and in particular with SDA Tranche 0 OCTs. More results will follow in 2025.

5. Conclusions

These results demonstrate that the challenges of building an operationally ready Optical Ground Station for operational optical communications are mostly solved. Current and future works are focused on the industrialization of these OGSs, with a goal to achieve > 10 OGS per year in 2026, and the development of future features such as higher data rates, and transportable OGS.

References

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