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Technological Breakthroughs in Ground Segment for Deep Space Optical Communications

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Abstract

This paper presents recent breakthroughs by the European Space Agency (ESA) and its industry partners in developing ground segment technologies for deep space optical communications. Complementary to RF design, optical communication technology is the primary candidate for meeting the data-intensive needs of spaceborne systems, particularly for future science and exploration missions beyond Earth orbit. ESA is advancing a modular and scalable optical ground segment architecture that includes a cryogenic photon-counting Ground Laser Receiver (GLR), a containerized high-power Ground Laser Transmitter (GLT), and a CCSDS-compliant High Photon Efficiency (HPE) modem. These components are optimized for photon-starved deep space links and have been engineered for interoperability with NASA's Deep Space Optical Communications (DSOC) terminal onboard the Psyche spacecraft. In parallel, ESA is investigating scalable segmented mirrors for 6-meter-class optical ground terminals and adapting astronomical observatories to host communication ground laser receiver, enabling greater flexibility and link availability. These developments contribute directly to the roadmap for ESA's initiatives, including LightShip-1/MARCONI, Solar System Internet Pathfinder, and the Voyage 2050 science vision. This paper presents system-level performance results, validation campaign outcomes, and a concept of operations (CONOPS) for the upcoming NASA-ESA DSOC Psyche demonstration

Keywords: Deep space optical communication, laser communication, High Photon Efficiency (HPE), superconducting nanowire detectors, multipixel, Optical Ground Station, Segmented Mirror, ESA Voyage 2050, DSOC, Psyche Mission.

1. Introduction

In the past decade, successful experiments have been conducted for spacecraft-to-ground optical communication links beyond near-Earth range, including Lunar Laser Communication Demonstration (LLCD) on board Lunar probe LADEE [1] and more recently the Deep Space Optical Communication (DSOC) project. The DSOC payload onboard the Psyche Mission is the first demonstration of viable laser communication through a distance greater than 1.5 AU [2]. The success of these experiments demonstrates that the technologies are now sufficiently mature to consider optical communications as a solution for deep space missions, which would drastically improve the amount of scientific data returned by providing high downlink bandwidth. ESA will participate in the DSOC demonstration in 2025, and work has begun to develop the required cutting-edge ground infrastructure (e.g., high power laser technology, single-photon detection system).

2. ESA Optical Communication Infrastructure and Projects

Over the past decade, the European Space Agency has initiated a series of targeted development activities to build the foundational infrastructure for deep space optical communications. These efforts span early prototyping, flight terminal studies, and the progressive deployment of ground-based systems. Pioneering projects such as the Lunar Optical Communication Link (LOCL) laid the groundwork by validating modular optical receiver concepts under controlled observatory conditions, establishing baseline designs for future photon-starved terminals. Complementary efforts under OPTEL-D, a modular laser terminal developed for deep-space applications, and DOCS (Deep-space Optical Communication System), a next-generation terminal design for missions such as space weather monitoring from Lagrange Point L5, have explored the architecture and feasibility of space-based terminals suited for lunar and interplanetary missions [8].

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Building on this foundation, ESA has developed a modular optical ground segment, composed of independently engineered yet interoperable systems. These include a photon-counting Ground Laser Receiver (GLR) based on integrated cryogenic Superconducting Nanowire Single Photon Detectors (SNSPDs) and quadrant-tracking capability, a high-power Ground Laser Transmitter (GLT) using multi-channel Yb-doped fiber amplifiers combined with transmit modules allowing high precision beam pointing, and a High Photon Efficiency (HPE) modem designed to decode CCSDS-compliant optical signals under ultra-low photon flux conditions. These ground assets will be used for the NASA/ESA demonstration with NASA/JPL DSOC terminal onboard Psyche mission [2].

ESA's optical communication roadmap extends beyond technology demonstration toward operational deployment in upcoming missions such LighShip-1/MARCONI and SSI Pathfinder. These initiatives aim to provide high-bandwidth connectivity for scientific return, navigation support, and secure communication services in cislunar and interplanetary environments. As a result, ESA is positioned not only as a contributor to international optical link demonstrations but as a provider of strategic communication infrastructure supporting scalable deep space exploration**.**

3. Demonstration with NASA DSOC

As part of its strategic commitment to international interoperability and next-generation communication systems, ESA is building in partnership with industry, a complete optical ground assets to join the technological demonstration of DSOC flying onboard- of the Psyche mission. This first-of-its-kind technical demonstration marks the first time an interplanetary spacecraft has carried a laser communication payload designed to transmit high-rate optical data from beyond the Earth-Moon system. NASA/JPL had successfully demonstrated successful links for more than one year of operation. ESA's involvement is focusing on enabling ground-based reception, beacon uplink, and signal decoding using a system composed of a GLR composed of Optical GLR (OGLR) and a HPE Modem, and a GLT for the European demonstration.

3.1 ESA's Optical Ground Laser Receiver

The ESA OGLR is optimized for single-photon-level detection over interplanetary distances. It forms the downlink terminal for ESA's contribution to the Psyche DSOC demonstration [3] (Figure 3).

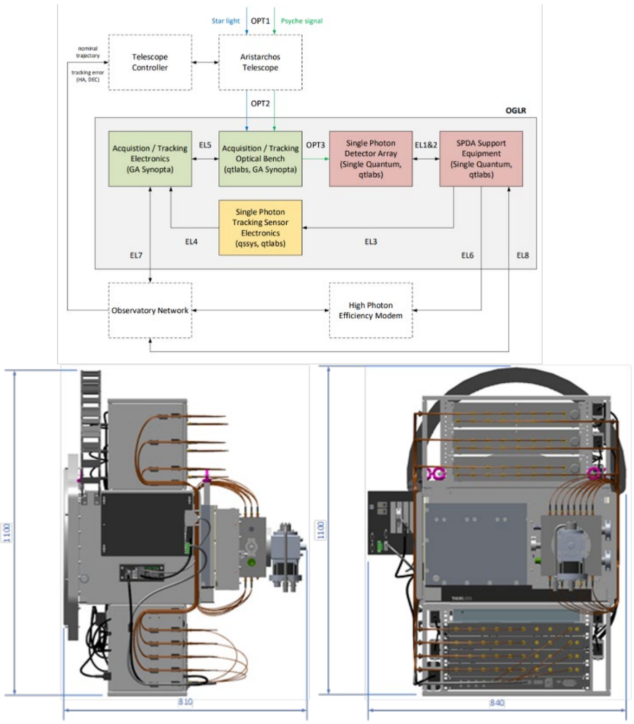

*Figure 1:**Top,** Functional block diagram of the ESA OGLR, including Single Photon Detector Array and support electronics, Single Photon Tracking Sensor Electronics and Acquisition / Tracking Subsystem. **Bottom**, Dimension of the OGLR including Optical bench, integrated SNSPD and all the electronics system.*

At the core of the Optical Ground Laser Receiver (OGLR) is a 6×6 array of Superconducting Nanowire Single Photon Detectors (SNSPDs), developed by Single Quantum BV [4]. The 36-pixel array is arranged in a square grid covering an area of 66 × 66 µm², enabling precise photon event detection with approximately 50 % quantum efficiency, 18 ps timing resolution and <20 ns dead time. The array is physically and electrically grouped into four quadrants, supporting both single-photon signal acquisition and real-time angular tracking. Each quadrant is read out via a dedicated channel that simultaneously biases the detectors with DC current and amplifies the cryogenically pre-amplified SNSPD pulses. The electrical architecture groups and sums photon events within each quadrant to enable spatial resolution and multiple-event discrimination. A signal conditioning and combiner board delivers four output channels, one per quadrant, which feed both the angular tracking controller and the HPE modem, independently of the array's pixel count (Figure 2).

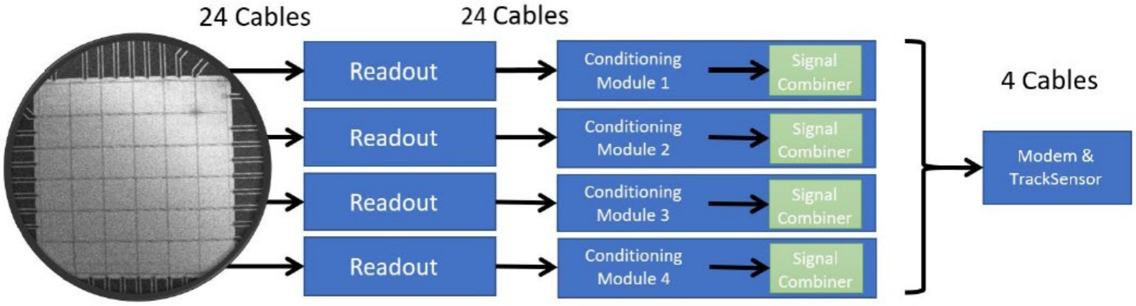

Figure 2: Electrical chain from SNSPD array to signal converter and combiner board. Each quadrant is grouped in one single output toward the HPE Modem and the Single Photon Tracking Controller (SPTC).

The OGLR features a Single Photon Tracking Controller (SPTC), which computes real-time pointing corrections from quadrant data. The SPTC uses a fast-steering mirror (FSM) with sub-arcsecond precision, operating in a closed-loop system with <10 ms latency. This feedback system corrects for telescope jitter, atmospheric turbulence, and signal drifts in real time.

The tracking loop is further enhanced by FPGA-based logic and a signal simulation module that enables end-to-end PAT (Pointing, Acquisition, and Tracking) testing under lab and field conditions.

The ESA OGLR will be installed at Helmos Observatory for the demonstration in summer 2025. The Helmos observatory is located in Greece, on Mount Helmos in Peloponnese at an altitude of 2340 m, approximately 220 km west of Athens, near the city of Kalavryta. At this location the observatory benefits from clear and dark skies with low atmospheric interference, crucial for high-quality astronomical observations as well as optical telecommunications. The Aristarchos telescope (Ritchey- Chrétien design) It has a 2.3 m diameter aperture and a focal length of 17.8 m. The telescope is mounted on an Altitude/Azimuth system with an automatic image de-rotation in its Cassegrain focus. The telescope's positional accuracy is better than 2 arcseconds, while it can follow targets with a positional offset better than a fraction of an arcseconds within an hour [6].

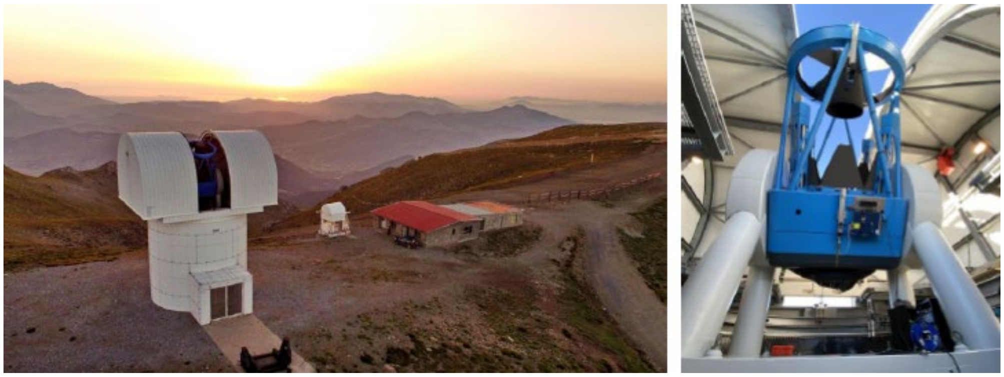

*Figure 3: **Left**, Helmos observatory at an altitude of 2340 m, and **right**, the 2.3 m Aristarchos telescope (Ritchey- Chrétien design).*

3.2 ESA's High Photon Efficiency Modem

The ESA High Photon Efficiency (HPE) optical modem, developed in collaboration with SAFRAN Data Systems, is a critical component of ESA's deep space optical ground segment. Fully compliant with CCSDS 141.0 and 142.0 standards [12,13], the modem supports serially concatenated PPM (SC-PPM) formats and is designed for interoperability with photon-counting detectors such as SNSPDs. It accommodates multiple PPM orders (e.g., 8-PPM, 64-PPM, 128-PPM) and uses maximum-likelihood (ML) synchronization combined with hybrid correlation-based techniques for robust timing acquisition in the Poisson channel regime [5].

The modem interfaces with the four-quadrant SNSPD array of the ESA'OGLR to be installed at the Helmos Observatory, enabling both high-resolution signal demodulation and quadrant-based feedback for optical tracking. Each quadrant's signal is independently digitized and processed through a high-speed decoding chain, which supports slot durations from 0.5 ns to 8 ns, addressing the stringent timing requirements of high-rate, photon-starved downlinks. While optimized for SNSPDs, the architecture is adaptable to other single-photon detectors such as MCT APDs. This modem will be deployed at Helmos Observatory in collocation with the OGLR system and to be sued during the NASA Psyche DSOC demonstration foreseen in July/August 2025 timeframe.

3.3 Compatibility Test of the Ground Laser Receiver at JPL

ESA and NASA/JPL conducted a dedicated compatibility and performance test campaign at NASA JPL to verify interoperability between ESA's photon-counting receiver and High Photon Efficiency (HPE) modem, and the engineering model (EM) of the DSOC Flight Laser Transceiver (FLT). The testbed setup included the full ESA detection chain—based on a cryogenic SNSPD array and quadrant signal combiner and the HPE modem, both interfaced with the DSOC EM FLT through a fiber-linked and free-space-coupled test facility. The objectives were to establish "bits in = bits out" compatibility, validate signal decoding across PPM orders, and identify operational thresholds in count rate for various data rates. The ESA system successfully demonstrated decoding at multiple rates, including 0.163, 0.651, and 1.3 Mbps, with count rate thresholds ranging from 0.8 to 2 Mcps depending on configuration and background conditions.

3.4 ESA's Ground Laser Transmitter

The Ground Laser Transmitter (GLT) is located at Kryoneri Observatory, 37 km from the GLR, and provides the optical uplink beacon needed for acquisition and tracking by Psyche's DSOC terminal. The GLT consists of two main subsystems: the Multi-Beam Laser System (MBLS) and the Multi-Beam Transmit System (MBTS) [11]. The MBLS generates a laser beacon signal at 1064.1 nm with power scalable up to 9.1 kW total, using a modular architecture of up to seven Yb-doped fiber amplifier channels, each capable of delivering 1.3 kW average power.

The MBLS comprises (Figure 4) a distributed feedback (DFB) seed laser with electro-optic spectral broadening for stimulated Brillouin scattering (SBS) suppression and coherence length reduction, a fiber-optic splitter module dividing the pre-amplified seed output into several channels to seed each of the high-power amplifiers. These comprise a two-stage Yb doped amplifier. The MBLS provides two modulation schemes:

1) 1 MHz square wave, 50% duty cycle implemented for a first pointing validation with the geostatinary satellite Alphasat. This validation will be executed by using a single beam at 50 W output power. In this case an Acusto-optcial modulator (AOM) is used to provide high repetition rate modulation, and the amplifier is run with CW pumping.

2) 3.81 kHz square wave, 50% duty cycle, required for the deep space links with Psyche. In this regime the AOM is left open and the high-power pump diodes for the final amplifier stage are directly modulated.

The MBTS comprises a Planewave T-600 mount with a mechanical supporting structure for up to 7 beam transmit modules. Three optical paths are implemented in the MBTS modules:

1. Starlight detection path from protective front window to star sensor camera. This path provides high transmission in the visible and high extinction in the NIR spectral range to avoid self-blinding of the camera with feedback from the high-power uplink beam. This path gives SNR>10 for stars up to mv=8.

2. Transmit beam path for the high-power uplink beam from the fiber output collimator to the protective front window. This path includes a fine steering mirror (FSM) and diplexer.

3. A transmit beam retro-reflection path from fiber collimator to the star camera allows a small fraction of the uplink beam to be imaged to allow uplink beam pointing drift to be corrected within the tracking control software.

The entire transmitter system, including amplifiers and optics, is integrated in a containerized 20-foot platform (Figure 5), equipped with a motorized lifting mechanism, laser safety interlocks, aircraft detection based on visible and thermal infrared cameras, and a control console. The GLT foundation as well as the necessary infrastructure, including power and communication connections have been provided by the National Observatory of Athens.

The system represents a low cost, size and weight solution which is transportable and easily deployable in other locations. The highly modular architecture is scalable in power both upwards for larger link distances within the solar system beyond Mars and downwards to suit shorter range scenarios such as Lunar communication links.

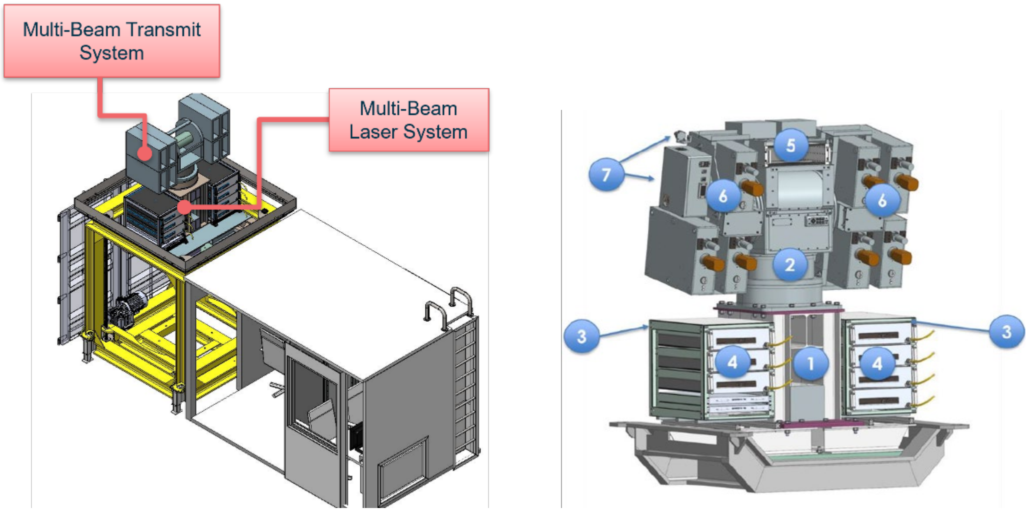

*Figure 4: 3D representation of the ESA's Ground Laser Transmitter (**left**) and main elements accommodated on the lifting platform within the GLT (**right**): 1. Mount supporting structure, 2. Planewave T-600 mount, 3. Amplifier rack units, 4. Amplifier units, 5. Tracking controllers & electronics, 6. Multi-beam transmit units, 7. Aircraft detection system.*

3.5 ESA preliminary DSOC CONOPS

The current concept of operations (CONOPS) for ESA's deep space optical communication system represents a preliminary architecture intended to guide upcoming rehearsals and system integration activities related to future interplanetary laser communication demonstrations, such as support to NASA's DSOC payload on Psyche. The CONOPS is designed to address the challenges of photon-starved signal acquisition, point-ahead correction, and ground-based signal decoding under dynamic atmospheric and geometrical conditions. The proposed operational sequence includes the following key steps (Figure 6):

1. System Preparation: Ground systems (GLT, GLR) are initialized with telescope alignment, health checks, environmental condition assessment and calibration routines to mitigate systematic errors. Uplink and downlink configurations are loaded based on predicted pass geometry.

2. Blind Pointing and Beacon Transmission: The Ground Laser Transmitter (GLT) performs blind pointing using ephemeris data and transmits a beacon signal toward the spacecraft's Flight Laser Transceiver (FLT).

3. Uplink Beacon Acquisition: The FLT detects the uplink beacon and applies point-ahead correction based on the beacon's characteristics, refining its own pointing toward Earth.

4. Downlink Transmission: Once aligned, the FLT initiates its downlink toward the Ground Laser Receiver (GLR) using a PPM-modulated optical signal.

5. Signal Acquisition and Tracking: The GLR acquires the incoming signal using a four-quadrant SNSPD array and applies real-time pointing corrections via a fast-steering mirror, guided by the Single Photon Tracking Controller (SPTC).

6. Demodulation and Decoding: The optical signal is digitized and decoded by the High Photon Efficiency (HPE) modem, implementing SC-PPM demodulation and CCSDS-compliant forward error correction.

7. Closed-Loop Adjustment: If acquisition fails or the signal is lost, the GLT performs scan-based reacquisition, while updated pointing commands can be issued to the FLT via an RF uplink provided by a separate ground station.

8. Data Handling and Reset: Successfully decoded data is stored locally at Helmos and forwarded to mission systems at later stage. The ground segment is reset for subsequent passes if required.

This CONOPS is intended as a baseline sequence to be validated through future test campaigns and joint rehearsals with NASA/JPL prior to ESA demonstration. It reflects ESA's current system architecture and anticipates iterative refinement as interoperability and system-level coordination mature.

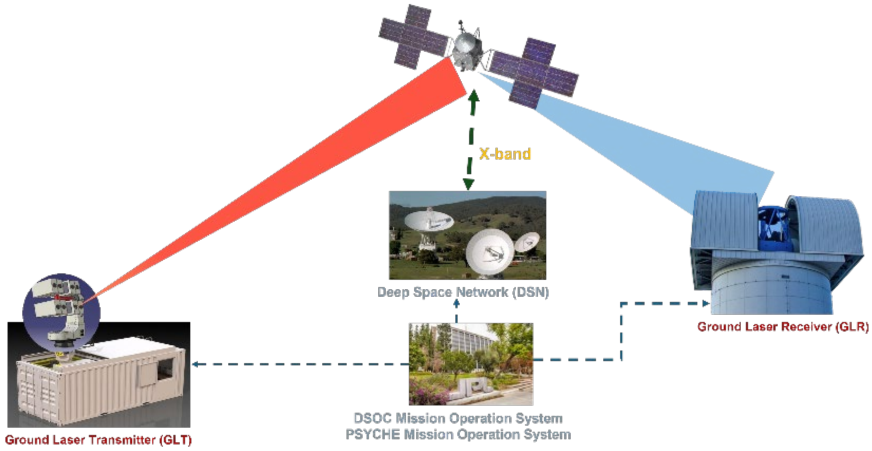

Figure 5: Preliminary CONOPS for ESA DSOC demonstration.

4. Toward Large Telescope for ESA Deep Space Optical communication

An advanced optical ground station architecture necessitates the development of telescopes with substantially increased apertures, as delineated in ESA's roadmap. This advancement will significantly enhance link budget performance and received optical power, thereby facilitating the implementation of direct-to-Earth deep space optical communication with considerably enhanced data rates.

4.1 Adaptation of Large Telescope for Deep Space Optical Communication

To extend the photon-collection capability of ESA's Ground Laser Receiver (GLR) beyond its current deployment at the 2.3-meter Aristarchos Telescope, ESA has initiated a project to assess and enable the integration of the GLR with telescopes larger than 3 meters. The activity includes the development of a dedicated GLR Emulator (GLR-E), designed to replicate the optical and mechanical interfaces of the full system without requiring cryogenic operation. A comprehensive survey and trade-off analysis has identified the New Technology Telescope (NTT) in Chile and the

3.5-meter telescope at Calar Alto in Spain as promising candidates. These efforts aim to validate integration strategies through on-sky tests in Q1 2026, targeting faint celestial sources at large apertures. The mobile and containerized nature of the GLT complements this adaptability, allowing ESA's ground segment to be flexibly deployed in proximity to compatible large-aperture facilities around the globe. This work supports future implementation of future GLR deployments on 6-meter-class telescopes or even segmented aperture systems.

4.2 Scalable Optical Apertures: 6-meters Segmented Mirror Telescope

As part of ESA's roadmap toward scalable ground infrastructure, a cost-effective segmented mirror concept is under development to enable future high-aperture optical ground stations. In collaboration with ESA, Advanced Mechanical and Optical Systems (AMOS), has designed, built, and tested a three-segment breadboard unit of a 6-meter-class telescope using identical hexagonal segments. Each 1-meter segment is actively controlled in piston, tip, and tilt using commercial off-the-shelf (COTS) actuators and edge sensors, avoiding the complexity of diffraction-limited co-phasing required in astronomical telescopes [9,10].

The system employs a spherical primary mirror architecture to reduce fabrication and alignment cost, with relaxed requirements adapted to the narrow field-of-view needed for optical communications. Initial prototypes using Zerodur® and aluminium alloy segments demonstrated surface errors below 50 nm RMS and pointing stability consistent with 1 arcsecond on-sky resolution. A full optical raytraced analysis confirms that 85% of the optical energy is enclosed within a 30 µm fiber core, supporting compatibility with existing photon-counting detectors.

This demonstrator is a significant step toward the deployment of large-aperture segmented telescopes dedicated to direct-to-Earth deep space optical communications, particularly for missions operating at Mars distances and beyond. The approach paves the way for a modular, reconfigurable antenna concept that aligns with ESA's infrastructure goals.

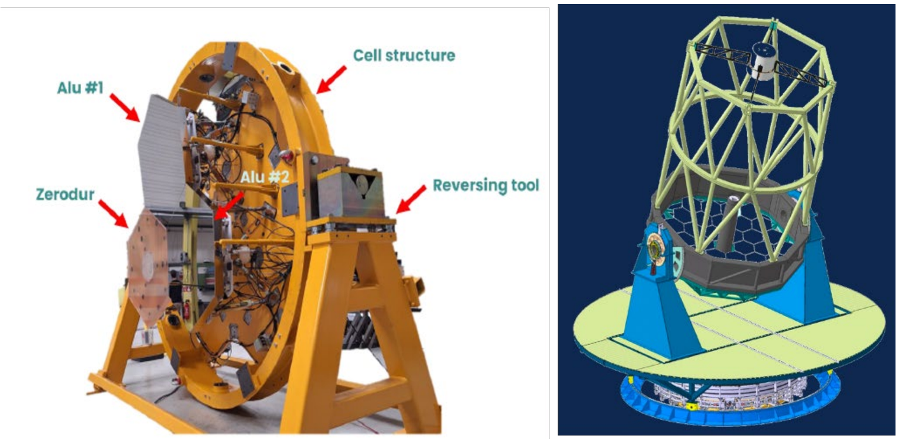

*Figure 6: **Left** testbed of three segments (2in Aluminium and 1 in Zerodur) supported by their actuated cell. **Right**, Design of 6 meters antenna based on a spherical primary mirror [9,10].*

5. Strategic study for optical communication in ESA's Voyage 2050 Programme

As part of its long-term strategy for enabling high-data-rate communications in outer Solar System missions, ESA initiated a dedicated study under the Voyage 2050 programme to define the system architecture for deep space optical links. The objective is to assess the feasibility and benefits of optical communication for future large-class planetary missions such as a flagship mission to Saturn or Enceladus by deriving both space and ground segment configurations.

6. Future Directions and Integration Roadmap

ESA envisions deep space optical communications as a critical backbone for Europe's future exploration missions and its contribution to global, interoperable infrastructure for interplanetary connectivity. This vision encompasses not only high-bandwidth communication but also seamless integration with positioning, navigation, and timing (PNT) services, enabling autonomous spacecraft operation and collaborative scientific missions.

Central to ESA's vision is the progressive deployment of a modular and scalable optical communication ground segment. This includes the development and testing of Ground Laser Receivers (GLRs) and Ground Laser Transmitters (GLTs), optimized for photon-starved links from deep space, and compatible with international optical communication terminals such as those flown by NASA. These efforts are coupled with the development of High Photon Efficiency (HPE) optical modems and Superconducting Nanowire Single Photon Detectors (SNSPDs), which together enable robust signal acquisition even under extremely low signal-to-noise ratios.

In line with its commitment to open standards and global collaboration, ESA is actively contributing to the Consultative Committee for Space Data Systems (CCSDS) efforts in defining interoperability standards for optical communication, including the standardization of Pulse-Position Modulation (PPM) schemes and forward error correction (FEC) for deep-space links. These developments also support ESA's participation in LunaNet and the emerging vision for a Solar System Internet, where optical and RF links will coexist to provide continuous connectivity across multiple planetary environments.

Looking ahead, ESA's optical communications capabilities are expected to play a foundational role in missions such as LightShip-1/MARCONI (Mars Communication and Navigation Infrastructure) and SSI Pathfinder. These initiatives collectively form a roadmap toward autonomous, scalable, and secure space-based networks serving both institutional and commercial users.

7. Conclusions

ESA's advancements in deep space optical communications mark a significant step toward high-bandwidth, long-range data transmission. The integration of HPE standards, SNSPD technologies, and dedicated ground infrastructure enhances communication efficiency, supporting future missions beyond 4.2 AU. Continued research and testing will ensure the feasibility of optical communication for interplanetary and deep-space exploration.

In line with ESA's Voyage 2050 planning cycle, deep-space optical communications are seen as essential to support missions beyond 4.2 AU including exploration of the giant planets and outer Solar System—where RF-based solutions face throughput and spectral constraints.

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