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Demonstration of Bidirectional Tracking and Data Transfer with the CubeISL Optical Communication Terminal

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ABSTRACT

This paper presents the experimental results of a free-space optical link validating the capabilities of two integrated CubeISL terminals. The campaign serves as a verification of the tracking, pointing and acquisition of the terminals before launch of the CubeISL mission. The link was conducted over a distance of 6600 m between the rooftop of the DLR Institute of Communication and Navigation in Oberpfaffenhofen and an 80 m high radio tower in Schöngeising. To ensure robust link establishment, the system employed a Pointing, Acquisition, and Tracking scheme utilizing both a 10 kHz modulated beacon for initial acquisition and a Continuous Wave signal for tracking during data transmission. The terminals, operating at a maximum output power of 1300 mW, were evaluated under various conditions, including day and night operations. Specifically, the performance of different automated acquisition patterns including Spiral-Spiral and Spiral-Rose was analyzed to determine their efficiency in overcoming initial pointing errors. The paper concludes with the results of the Pointing, Acquisition, and Tracking and data transmission experiments demonstrating the viability of the CubeISL terminals for high-stability, bidirectional optical communication in a satellite-to-satellite configuration.

INTRODUCTION

Free-Space Optical Communication

Free-space optical (FSO) communication has the potential to overcome the limitations in data rate of classical Radio-Frequency (RF) communication. The narrow beam divergence achievable with optical systems increases the possible data density at comparable power consumption, making FSO an ideal complement to RF, particularly on small satellites with tight constraints on size, weight and power.[1,2] Beyond throughput, FSO links are inherently harder to jam, spoof and eavesdrop[3], which makes them attractive not only for commercial applications but also for governmental and defense users requiring secure, high-capacity connectivity.

The German Aerospace Center (DLR) has developed FSO terminals for small satellites for more than two decades, beginning with larger platforms such as the Flying Laptop satellite and progressively miniaturizing the technology.[4,5] Under the Optical Space Infrared Downlink System (OSIRIS) program, DLR developed several Laser Communication Terminals (LCT) that established Direct-To-Earth (DTE) links between a satellite and an Optical Ground Station (OGS).[4] The most compact of these, OSIRIS4CubeSat (O4C), was developed together with industrialization partner Tesat-Spacecom GmbH as the world's smallest laser communication terminal[6] and serves as the base technology for subsequent developments.[7] O4C was first demonstrated on the 3U CubeSat CubeL of the PIXL-1 mission, launched in January 2021, with first light received by DLR's Transportable Optical Ground Station in August 2021.[7]

CubeISL Mission

CubeISL transfers this DTE heritage into the Optical Inter-Satellite Link (OISL) domain. The terminal reuses the optomechanics and Fine Pointing Assembly (FPA) of O4C and is extended with a data receiver, an optical amplifier to compensate for the reduced receive aperture of a partner terminal compared to an OGS telescope, and a dedicated Data Handling Unit.[7] Two near identical CubeISL terminals are designed to establish a bidirectional link at 125 Mbps over distances of up to 1330 km, and increasing the DTE downlink capability from 100 Mbps in O4C to 1 Gbps.[8] The terminals will be demonstrated in orbit on two 6U with the mission led by DLR's Responsive Space Cluster Competence Center (RSC³) and operated by the German Space Operations Center (GSOC).[8]

Unlike the DTE scenario, where a wide, high-power beacon from the OGS covers the pointing uncertainty of the satellite, the ISL scenario requires both terminals to search for and align with each other using comparatively low-power and narrow-divergence beams, since no equivalent high-power ground-based beacon is available.[7,9] This motivates a dedicated Pointing, Acquisition and Tracking (PAT)

concept in which combinations of scanning patterns e.g. Spiral, Rose, Lissajous or Grid are executed simultaneously and asynchronously by both terminals to reduce the time to acquisition while maximizing the probability of a successful first hit.[10] A Monte Carlo-based optimization of such pattern combinations predicted mean acquisition times on the order of a few seconds and success rates between 82.3% and 99.9%, assuming a field of uncertainty of ±0.2 deg. [10]

These predictions are, however, based on simulation and had not yet been validated with flight hardware operating in a bidirectional, closed-loop configuration. Unidirectional tracking was already successfully demonstrated in a 143 km FSO link between the astronomical sites of La Palma and Tenerife.[5] Before the launch of the CubeISL in-orbit demonstration mission, it is additionally necessary to verify the PAT scheme, the ability to establish and hold a bidirectional link, and the subsequent data transfer capability of the terminals in a relevant, hardware-in-the-loop test. To this end, a ground-based test link campaign was set up between the rooftop of the DLR Institute of Communications and Navigation in Oberpfaffenhofen and an 80 m radio tower in Schöngeising, using the CubeISL Flight Model (FM) and a Prototype Model (PTM) terminal. This paper reports the results of this campaign, covering acquisition performance under static and dynamic pointing conditions, and data transfer.

TEST LINK SETUP

The FM, designated Terminal A, was installed on the DLR rooftop inside a laser safety enclosure and mounted on a hexapod as shown in Figure 2. The CubeISL Prototype Model, designated Terminal B, was mounted on a tip-tilt unit on the radio tower in Schöngeising as shown in Figure 4. Both actuator stages served the purpose of enabling precise initial alignment of the terminals and providing a controllable attitude for each terminal during testing. The hexapod was additionally used to apply representative body-pointing trajectories to Terminal A. The differentiation between Terminal A/B is necessary as the terminals operate on different transmit and receive wavelengths.

The 6600 m distance shown in Figure 1 was chosen so that each terminal's transmitted beam illuminates the entire receive aperture of the counterpart terminal. Both terminals were operated at up to 1300 mW output power whereas an OD2 attenuation filter was mounted in front of Terminal A to provide an eye-safe working environment around the terminal as well as to simulate expected losses during operations in orbit.

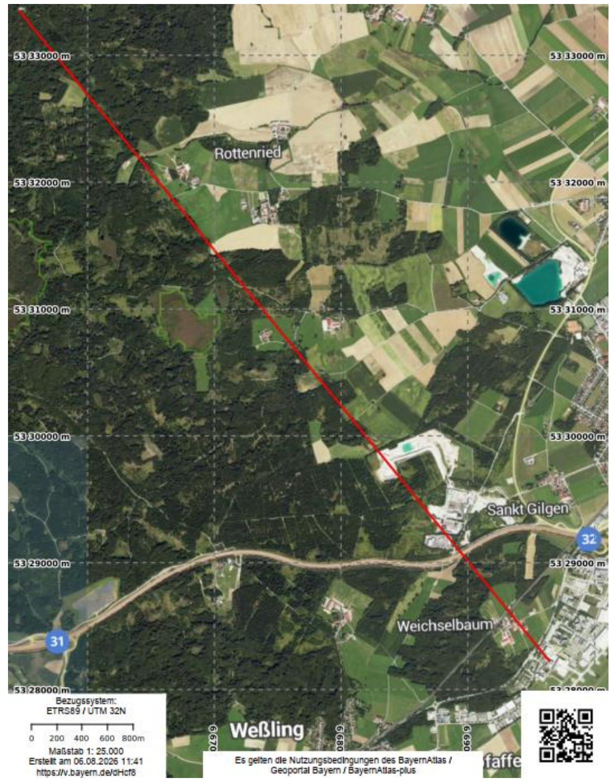

Figure 1: Link geometry between the DLR rooftop and the radio tower in Schöngeising at a distance of 6600m © Bayerische Vermessungsverwaltung 2026

Figure 2: Terminal A mounted on the rooftop of DLR on the leftmost position in the container to avoid a treetop in the optical path

Infrared cameras were mounted alongside each terminal to establish initial alignment and to provide visual status information on the link and on atmospheric conditions, since the CubeISL operating wavelengths lie outside the visible spectrum. Laser safety enclosures were required only at the DLR rooftop site, as equivalent safety enclosure was already installed at the tower. Prior to automated testing, a finder scope mounted on the enclosure of Terminal A was used to pre-align the FM against the counterpart terminal, simplifying the first acquisition attempt as seen in Figure 3.

Figure 3: Radio tower in Schöngeising as seen through the pre-alignment scope

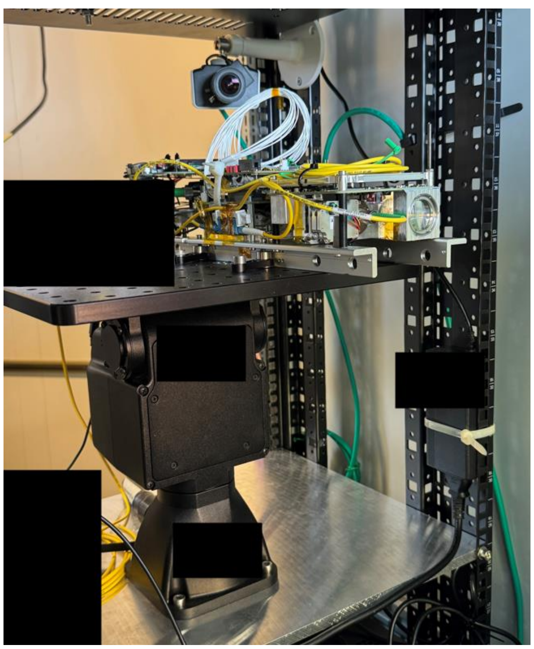

Figure 4: Terminal B mounted in enclosed rack in the radio tower in Schöngeising

EXPERIMENT RESULTS

The PAT scheme was evaluated using both a 10 kHz modulated acquisition beacon and a CW signal. The results show that the 10 kHz beacon that was used in the DTE links to differentiate between beacon and background light is not required to acquire the link once sufficient Signal-to-Noise Ratio (SNR) is present at the receiver. CW alone is therefore sufficient and was used as the baseline signal for the remaining acquisition tests. Based on these results it is expected that the 10 kHz beacon is not required in orbit either.

Acquisition Pattern Combinations

Following the acquisition scheme described in prior works by Rüddenklau, [11] the two terminals were operated asymmetrically: one terminal executes the standard Pointing, Acquisition and Tracking algorithm (T-PAT), while the counterpart runs the Detection, Adjustment and Tracking algorithm (T-DAT), which reacts to the periodic hits produced by the T-PAT search pattern. This scheme does not require time synchronization between the two terminals for the acquisition to succeed. Three pattern combinations were tested: Spiral-Spiral, DAT:Rose–PAT:Spiral, and DAT:Spiral–PAT:Rose. Of these, the Spiral-Spiral combination showed the best overall behavior with respect to Time to Acquisition (TTA) and success rate, only marginally outperforming the DAT:Rose–PAT:Spiral combination; the DAT:Spiral–PAT:Rose combination performed worse than both. Spiral-Spiral, with respective pattern periods of 16 s and 1.6 s showed the best TTA behavior with success rates above 90%. Here TTA denotes the time to the first acquisition hit, and TTT (Time to Tracking) denotes the time required after that hit to establish a stable tracking lock.

Acquisition performance was evaluated separately for static tests (no imposed satellite trajectory) and dynamic tests, in which representative body-pointing trajectories were applied to Terminal A via the hexapod as shown in Figure 5.

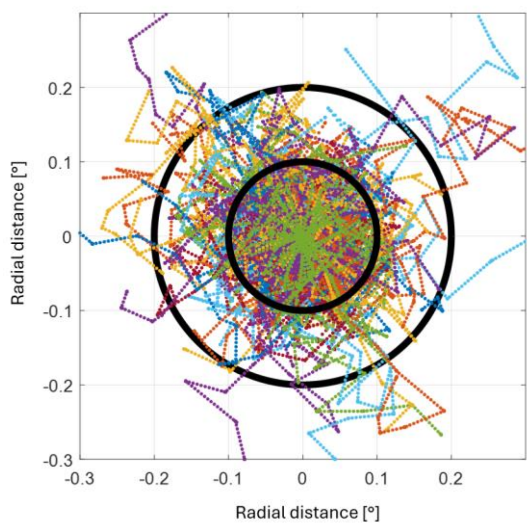

Figure 5: Trajectory paths of hexapod during dynamic tests

Under representative dynamic trajectories with a 3σ body-pointing instability of about 0.3° radial and a maximum angular rate of 0.05°/s, the median TTA was 85.5 s and the median TTT was 0.4 s, giving a median total time of 85.9 s to establish a stable tracking link.

Data Transmission

Bidirectional tracking was maintained while a unidirectional data transfer was performed, with Terminal B transmitting to Terminal A at a data rate of 125 Mbit/s. On the receiving side, Terminal A measured a mean Bit Error Rate (BER) of 5.2645×10^{-3}. A lower mean BER is expected for the in-orbit ISL scenario, as the atmospheric effects present in this horizontal ground-to-ground link are expected to be a dominant contributor to the measured BER.

CONCLUSION

This work demonstrated the Pointing, Acquisition and Tracking capability of the CubeISL optical inter-satellite link terminals in a fully integrated, bidirectional ground link over a distance of 6600 m. The campaign showed that a stable link can be reliably established and tracked under both static and dynamic pointing conditions and that data can be transferred over the established link. With this successful verification, the two CubeISL Flight Models are now ready for integration into their satellites and launch, marking the completion of a key pre-launch milestone for the CubeISL in-orbit demonstration mission and paving the way for DLR's first optical inter-satellite link between two CubeSats.

Acknowledgments

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