First in-orbit results of the QUBE mission hosting a laser communication terminal for experiments towards quantum key distribution from CubeSats

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Abstract

Free-space optical communication is an inherently secure and robust method to transfer information over large distances. To increase the level of secure communication even further, it marks the base for quantum key distribution, a tap-proof encryption method based on the principles of quantum mechanics. The ever-increasing number of small spacecrafts and the growing global threats require secure communication channels, robust against jamming, spoofing, and eavesdropping. Classical radio-frequency communication is, due to its physical properties and its wide-angled beacons sensitive for unwanted interceptions. The technology transfer of laser communication to small satellites like CubeSats provides solutions to overcome the limitations of classical communication, but it comes with the necessity of very precise and accurate pointing. To demonstrate quantum key distribution technologies on a CubeSat, the project QUBE has the goal to verify two experimental quantum sources which signals are transmitted over an optical link from a 3U CubeSat. Two quantum sources, developed by the Ludwig-Maximilian University of Munich and the Friedrich-Alexander University in Erlangen, are coupled into the laser communication terminal OSIRIS4QUBE, an evolution of OSIRIS4CubeSat developed by the German Aerospace Center. These systems are integrated into the 3U CubeSat QUBE built by the Center for Telematics. Establishing an optical connection between the laser terminal and the optical ground station requires precise and accurate pointing of the satellite. This task is handled by a high-precision attitude determination and control system. This paper presents the first results of the launch and early orbit phase of the QUBE mission. It highlights the achievements of the attitude determination and control system and the commissioning of the OSIRIS4QUBE terminal. The paper focuses on these two topics and explicitly excludes the results of the experimental quantum payloads.

Keywords: Quantum Key Distribution, ADCS, Laser Communication, CubeSats, New Space

1 Introduction

The number of satellites with an integrated laser communication terminal (LCT) is on the rise. The efficient design with respect to size, weight and power (SWaP) compared to radio-frequency (RF) systems with similar data rates, enables the use of free-space optical communications (FSOC) also on small satellites like CubeSats. With the increased maturity of FSOC, further applications like quantum key distribution (QKD) are now emerging as feasible applications in the space domain. LCTs for CubeSats were already successfully demonstrated in space, but QKD was so far demonstrated only on small satellites [1, 2, 3]. The crucial part of FSOC is the dependency of the precision and the accuracy of the laser beams pointing. Nowadays, a cascaded control loop consisting of a coarse pointing assembly (CPA) and a fine pointing assembly (FPA) is used to orient the laser beam within the spacecraft's body. CPAs can be realized either by mechanical systems like gimbals or by the satellite itself. The FPA is located inside the LCT and can be realized with a much faster control mechanism. A CPA is required to lower down the complexity of the LCT to avoid wide field of view sensors and sophisticated optical systems which would overcome the SWaP capabilities of CubeSats.

The QUBE mission has the goal to demonstrate preparation technologies towards QKD in a low complexity environment – a CubeSat [4]. Following the New Space approach, it was intended to reuse principles which were already developed and successfully demonstrated, to decrease mission risks and development time. Thus, the chosen LCT was OSIRIS4QUBE (O4Q), an evolution of the OSIRIS4CubeSat (O4C) laser terminal which was successfully demonstrated on the 3U CubeSat CubeL [5]. O4C and O4Q use the so-called pointing acquisition and tracking (PAT) principle, where the FPA acquires and tracks on a laser beacon sent by the optical ground station (OGS) [6]. Both terminals achieve their compactness due to their low complexity. One contribution to this is the absence of a mechanical CPA. To acquire (and track) the beacon, the beacon has to be inside the field of view (FoV) of the FPA. This means that the satellite acts as a CPA and has to point with a precision (stability) and an accuracy (the correct location) of better than ±1°.

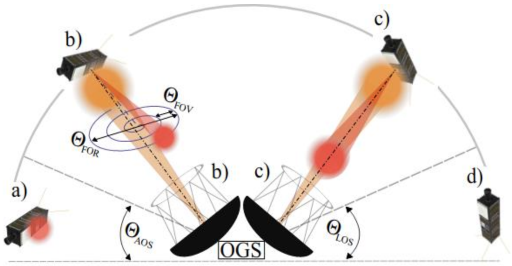

Figure 1: PAT sequence of OSIRIS4CubeSat [7].

Figure 1 depicts the PAT principle with the four phases:

- a) Pointing: OGS and satellite orientate to each other
- b) Acquisition: OGS sends beacon, LCT searches this beacon
- c) Tracking: FPA of LCT tracks actively on the beacon and OGS vice versa
- d) Link termination below minimum elevation

The PIXL-1 mission already showed the high dependency on the absolute sensors of the attitude determination and control system (ADCS) [1]. If the reference is incorrect or unreliable, the ADCS can neither point precise nor accurate enough. To increase the reliability, extensive on-ground validation is essential. Before launch, especially the required fine-pointing of the ADCS was heavily tested with state-of-the-art hardware-in-the-loop testbeds [8, 9]. This paper describes the measurements and results of the launch and early orbit phase (LEOP) of the QUBE mission in this regard. Furthermore, the paper depicts the first results of the commissioning of O4Q.

2 Attitude precision and accuracy dependencies

The pointing capabilities of a satellite are highly dependent on its attitude sensors. High accuracy sensors are mandatory to achieve a high precision. Well aligned systems are required to achieve the relevant accuracy. Differences between the coordinate systems, caused by settling effects during launch or mechanical tolerances result in a deviation between the assumed pointing vector and the real pointing vector of the LCT.

CubeL in the PIXL-1 mission used the same absolute sensor (star tracker) that is used in QUBE. Thus, all lessons learned during the in-orbit mission could directly be fed into the design and development of the ADCS of QUBE. The PIXL-1 mission showed that the reliability and availability of the star sensor is mandatory as the absolute pointing error increases exponentially when relying only on relative sensors like gyroscopes. This results in exceeding the pointing requirement of ±1° within a few seconds after the ADCS uses relative sensors only.

Nevertheless, it could be shown that whenever the star tracker was available and the satellite reduced the control error, an optical connection was always established [7]. Precondition was the measurement of the real target pointing location to achieve the sufficient accuracy. Therefore, the satellite was used to perform search patterns until the offset between assumed and real target pointing was measured. This offset was then added to the original pointing vector to reduce the residual pointing error [1]. These processes can directly be transferred into the commissioning phase of the QUBE mission.

The major differences between O4C and O4Q lie in the optical system, the mechanical system and the command and control software. The electronics (expect a change of the microcontroller) and the principle of the firmware were derived from the pre-development project. The most important functionality of the software is the implementation of the FPA. The appropriate mode and transitions must be controlled in the O4Q payload segment. The software is responsible for the control process during the PAT procedure. These software components and the internal communication were inherited from O4C directly.

The satellite is built on the UNISEC (University Space Engineering Consortium) architecture, in which all subsystems must be compatible with the CubeSat Electrical Interface [10]. In QUBE, all subsystems also employ the COMPASS protocol for inter-subsystem communication as well as communication with the satellite operator [11]. This protocol was developed by the ZfT and the University Würzburg based on the extensive experience of the UWE (University Würzburg Experimental Satellites) missions. This protocol suite enables message routing within the COMPASS network, extending from the ground segment to each subsystem of the satellite. In addition, it offers a wide range of services and APIs for subsystems, including a commanding interface, support for generic data types and their remote manipulation, non-volatile storage of variables in the microcontroller’s flash memory, and advanced recording and inter-subsystem reporting of variables. The reference implementation of the COMPASS stack was made possible by the upgraded microprocessor on the OSIRIS4QUBE terminal, which provides sufficient memory and computational capacity.

3 Satellite and ADCS commissioning

Following the successful launch, the Launch and Early Orbit Phase (LEOP) focused on verifying the satellite’s core functions and conducting initial operational tests. This phase included the activation of

ADCS, sensor calibration, and troubleshooting communication and software issues. After the successful checkout of the basic systems of the satellite, the scientific payloads were commissioned. The commissioning of LCT O4Q is described in the last subchapter of this section.

3.1 Launch and early orbit phase (LEOP)

Right after launch, QUBE passed over the ultra-high frequency (UHF) ground station in Würzburg. However, since deployment happened just some minutes ago the antennas were not deployed yet for safety reasons. Immediately after being powered on, the ADCS successfully initiated the detumbling process, bringing the satellite’s rotation rate within the targeted range of 2.5°/s to 4°/s during the first orbit which can be seen in Figure 2. During the first contact, system checks confirmed the healthy state of the electrical power system and the proper operation of all subsystems.

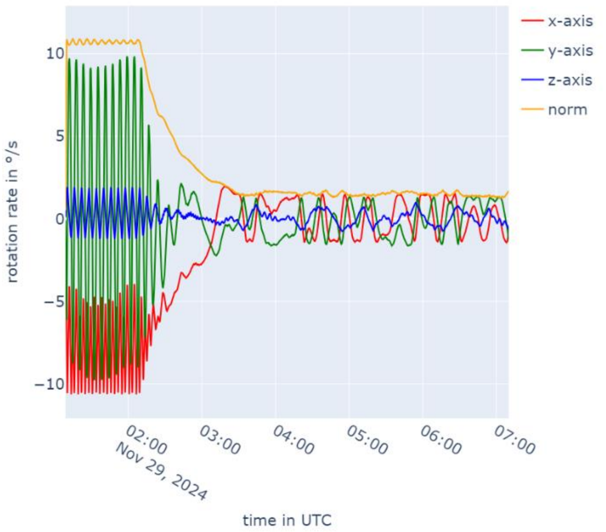

Figure 2: Rotation rate decrease of the satellite during active detumbling.

In the subsequent phase, the satellite's hardware underwent systematic verification to ensure functional integrity following launch. The satellite is equipped with a comprehensive set of sensors and actuators to fulfil critical attitude determination and control tasks. These tasks include maintaining a controlled and safe rotational rate, orienting the solar panels toward the Sun to charge the batteries, preventing the payload and star tracker from direct Sun exposure to avoid damage, and achieving fine-pointing with an absolute pointing accuracy of <1°.

The satellite employs a redundant sensor suite for its ADCS, consisting of six gyroscopes, six magnetometers, four sun sensors and additionally a non-redundant star tracker. The actuator system includes five magnetorquers and six reaction wheels, with redundancy ensured by two wheels per axis.

To verify the functionality of the sensors and actuators, the ADCS was transitioned into ‘Command Mode’, in which all autonomous control functions are disabled [8]. This allowed operators to individually address and test each component. After a few passes, it was confirmed that all sensors and actuators were fully operational.

Initially, ZfT’s UHF ground station experienced interference from a nearby carrier signal, which the integrated filter in the low-noise amplifier (LNA) failed to sufficiently suppress. This resulted in high packet loss rates of about 70% on the downlink, with strong dependence on azimuth and elevation. To address this issue, an additional filter solution was implemented. Fortunately, SatNOGS [12] provided strong support during this period, as the interference only affected the receive chain. By injecting packets received by other SatNOGS users into the operations software, the effects of the faulty downlink reception could be compensated. After a month of debugging, integration, and testing with a new band-pass filter, reliable signal reception was achieved. With this, we were able to continue with ADCS and payload commissioning.

3.2 ADCS commissioning

During magnetometer tests, ZfT identified the need for in-orbit calibration due to significant discrepancies in the data and mismatches with expected magnetic field magnitudes. These differences suggested sensor misalignment, environmental factors, or launch-induced offsets. The ability to run JavaScript on both the ADCS and panels provided an efficient method to perform the necessary calibration in orbit. This led to a mean error of $< 0.5\mu T$ and root mean square error (RMSE) of $\leq 2\mu T$ for the panel magnetometer measurements. Calibration of the ADCS magnetometer yielded less accurate results, with a mean error $< 1\mu T$ and RMSE $< 2.8\mu T$ due to magnetic disturbances from internal satellite components. Consequently, the ADCS magnetometer is only used if all other magnetometers are non-functional. Subsequently, ZfT successfully demonstrated the detumbling mode using magnetorquers to reduce the rotation rate around all three axes. For this test, the satellite was actively spun up with a tumbling controller implemented in JavaScript. After reaching the desired rotation rate of 10°/s, the detumbling mode was initiated.

As shown in Figure 2, the rotation rate was reduced to the targeted range in less than one hour. The success of this test was crucial to ensure that, after fine-pointing, the reaction wheels can properly be desaturated and the satellite will be returned to a safe and operational state.

To verify the functionality of the mission-critical and most complex mode, the fine-pointing, in-orbit tests were conducted early on. In this mode, the star tracker and gyroscope provide attitude measurements, and the reaction wheels precisely control the satellite's orientation. The procedure for preparing the fine-pointing test was carried out using again JavaScript. Given the time-consuming nature of the in-orbit tests, extensive ground testing was crucial to ensure its success and avoid unnecessary failure due to insufficient pre-flight validation. The test procedure involves scheduling GNSS recordings on the satellite up to 24 hours before the targeted pointing test. The recorded data is downloaded, post-processed on the ground, and used to accurately compute the desired attitude trajectory. During the subsequent overpass, the generated guidance file is uploaded to the satellite. In the final preparation step, key parameters such as start and stop times for fine-pointing, the directory and filename of the guidance file, and telemetry recording settings must be configured.

At the designated start time, the satellite autonomously transitions into fine-pointing mode. The test was successfully demonstrated on the first attempt, maintaining a control error below 0.5° throughout the entire overpass. A slight increase in error was observed at higher elevations due to increased dynamic forces. The control error of one conducted in-orbit fine-pointing test is shown in Figure 3.

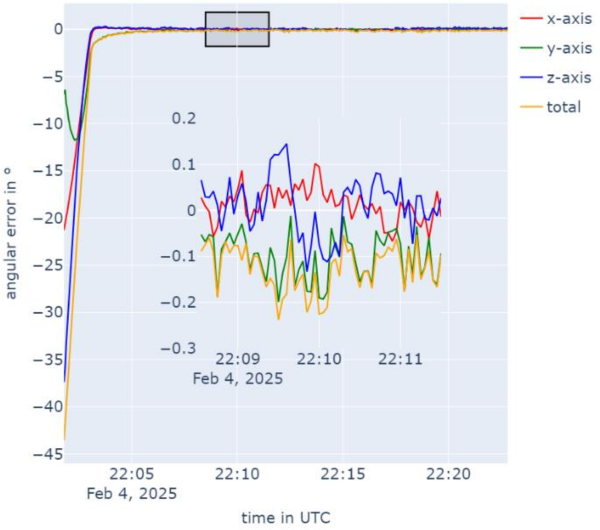

Figure 3: Control error of satellite during fine-pointing.

The plot shows the angular error of the satellite around the x-, y-, and z-axes, as well as the total angular error (in orange). The error around the z-axis (blue) represents the rotation about the pointing axis and is therefore less critical for tracking performance. In contrast, deviations around the x-axis (red) and y-axis (green), which are orthogonal to the line of sight, have a direct impact on pointing accuracy. The plot demonstrates that after an initial transient phase, the control error stabilizes well within the required threshold, with x- and y-axis errors remaining consistently below ±0.2°. A zoomed-in view highlights the stability and low amplitude of the residual oscillations during steady-state operation.

During repeated fine-pointing tests, the ADCS was unable to enter fine-pointing mode due to recurring 'Guidance File Error' messages during the preparation phase. The onboard fault detection, isolation, and recovery (FDIR) system correctly identified the issue and consequently aborted the mode transition.

To diagnose the problem, we replicated the scenario on the ground and successfully reproduced the error. The root cause was traced to the software component responsible for reading and interpolating guidance file data. If trajectory data from a previous test was not entirely read, residual data persisted in the satellite's memory. Upon initiating a new test, outdated trajectory data was erroneously accessed first, leading to an inconsistency as the referenced timestamps were already in the past.

The issue has in the meantime been addressed by modifying the software to ensure proper handling of residual data. The fix was integrated into a scheduled software update. In the meantime, to continue in-orbit testing, we implemented a workaround by resetting the ADCS before each fine-pointing test to clear any residual trajectory data.

3.3 LCT commissioning

During the commissioning of O4Q, a time synchronization issue was observed. The problem originated from the placement of the satellite's side panels, which carry the GNSS receivers, and O4Q on separate communication buses, which prevented direct communication between the subsystems for time synchronization. However, using advanced on-board scripting, a data relay logic was implemented on the ADCS to forward time synchronization information to O4Q effectively.

Another hurdle the satellite operator faced was a software issue in the file transfer protocol implementation of the payload controller (PCON), a stand-alone subsystem of the experimental payloads from Friedrich-Alexander University in Erlangen (FAU). Here, file chunks were wrongly ordered, caused by packet loss during downlink, leading to the need of adapting on-ground data processing software.

In order to commission the LCT, tests of essential subsystems were performed to confirm basic functionalities that are necessary to enable subsequent pointing, acquisition and tracking tests that follow. After the first power on, the power consumption was measured and compared with recordings on ground (see Figure 4).

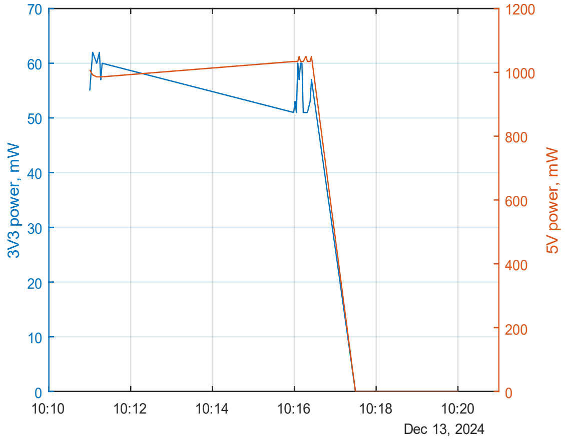

Figure 4: Nominal power recording of th 3.3V and 5V line.

As a next test, the four-quadrant diode (4QD) tracking sensor of the LCT was read out and compared with the threshold identified by the automatic offset compensation routine [7]. This threshold and the point in time where it was calculated is indicated by the horizontal and vertical black lines. Since the blue sum curve in Figure 5 remains below the identified threshold line, the acquisition phase is maintained, indicating valid behaviour in the absence of a beacon signal. This is supported by the red tracking indicator which shows "false" equalling no valid beacon signal found.

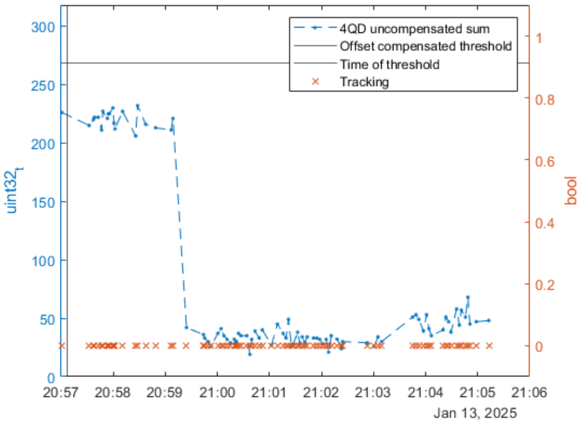

Figure 5: 4QD offset compensation test to ensure background light can be distinguished from the actual beacon signal.

To confirm the output power of the onboard high-power laser diode (HPLD), another satellite pass was used to verify the closed-loop control circuit of the transmit laser. The controller uses the internal photodiode of the HPLD as feedback to close the loop. The DAC command is therefore used to control the output power driver circuit. At a setpoint of 19mW the maximum deviation of 5 units in Figure 6 corresponds to 1mW of free-space output power over the duration of the test.

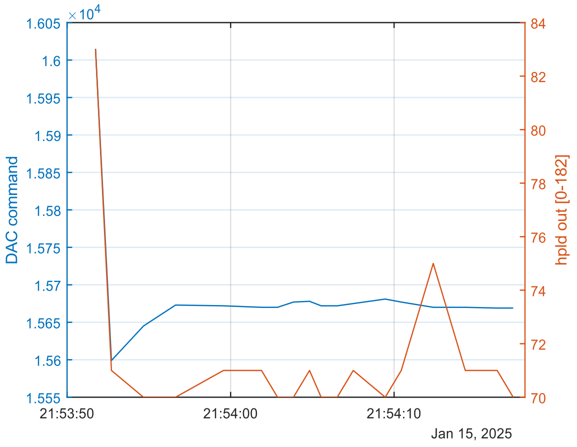

Figure 6: Measured closed-loop HPLD output power at a setpoint of 70 that correpsonds to 19mW ex-aperture.

Finally, also the temperature was monitored to ensure that the operating conditions remained within the specified limits of the electronics (see Figure 7). Similar temperature values were measured by the two sensors: one integrated into the microcontroller and the other an external sensor placed near the heat-emitting HPLD.

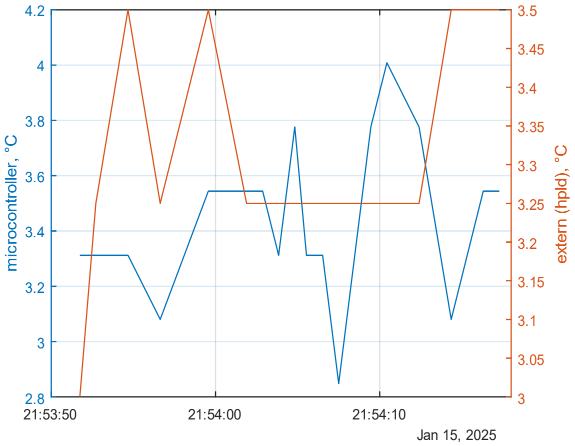

Figure 7: Temperature measurements at the LCT microcontroller and close to the HPLD showing comparable values.

All tests confirmed the intended functionality of O4Q, allowing the mission to proceed to the next phase of the LEOP. In this phase, the combined body-pointing of the satellite with the LCT's fine steering mirror will ensure the required pointing accuracy, ultimately enabling the LCT to acquire the OGS beacon signal and perform closed-loop optical tracking.

4 Discussion

The in-orbit tests confirmed that the extensive ground testing of the fine-pointing mode was highly effective, as all pre-validated functionalities performed as expected in space. However, we also observed that functionalities that were less rigorously tested on the ground were more prone to unexpected issues in orbit. A notable example was the guidance file handling, where an unforeseen memory issue caused repeated errors during test execution. This highlights the importance of comprehensive ground testing, particularly for software components that depend on persistent onboard data.

Another lesson learned is the necessity of incorporating the RF chain into testing for features dependent on the RF channel at an early stage. The impact of packet loss on file transfer protocols – as observed with the PCON - and the verification of operational procedures with comparable link capacity could be covered by extending the testbed from [9] with a simple software-defined radio (SDR) ground station. Although it may appear intuitive, the impact on system reliability and the accumulation of operational experience prior to launch are retrospectively regarded as key factors contributing to the success of complex CubeSat missions.

Furthermore, the ability to execute JavaScript and perform flexible onboard data recording emerged as a highly useful tool for conducting in-orbit tests efficiently. These features significantly facilitated debugging by allowing rapid identification and resolution of anomalies. Additionally, our on-board JavaScript provided a practical means to implement workarounds for minor software issues, reducing the need for time-consuming software updates unless absolutely necessary.

The basic functionalities of O4Q could be verified in orbit. Comparisons between these results, the previous tests on ground and O4C, which is in orbit for more than four years now, show similar values. The described tests provide the highest level of confidence achievable when relying solely on in-orbit telemetry. Further verifications of additional subsystems and compartments require optical feedback, such as a received signal from an OGS. Nevertheless, until now it can be derived that the LCT acts and behaves as expected.

It has to be mentioned that the optical output power of the HPLD was limited to 19mW on purpose. O4Q transmits a clock signal of 20MHz over the classical optical channel while O4C transmits – in the PIXL-1 mission – data with a data rate of 100Mbps with 60mW optical output power. An 100Mbps data signal is equivalent to a 50MHz clock. The frequency reduction led to an increase in the received optical power and compensates the reductions in the transmitted optical power so that both link budgets show a similar link margin. In other words, it is expected that even with the reduced optical output power, O4Q will achieve the same performance as it was shown by O4C. Hence, a reduction to 19mW protects the O4Q LCT as the HPLD does not has to be operated at its maximum specification.

5 Conclusion

Repeated fine-pointing tests confirmed that the control error consistently remained below 0.5°. These results provide confidence that the system can achieve the required absolute pointing accuracy and stability, marking an essential milestone towards the initiation of laser-based experiments.

Currently, ongoing efforts focus on resolving minor software bugs and bringing additional satellite operational modes into service. In parallel, we are working on automating the fine-pointing test preparation procedure to improve efficiency, reduce operational overhead, and minimize the risk of human-induced errors in future experiments.

The LEOP, along with the commissioning of the mission’s most critical subsystems – the ADCS and the LCT – have been successfully completed. The next step is to combine the satellite’s fine pointing operations with the LCT’s FPA and to acquire the optical ground station’s laser beacon. It is expected that the initial campaign will begin with a standard search procedure to determine the target pointing offset. Once this offset has been characterized, a full performance checkout of O4Q’s tracking behaviour will be conducted. Subsequently, the QKD campaign, involving the experimental payloads will commence, marking the final objectives of the QUBE mission.

Acknowledgements

This research was conducted within the scope of the project QUBE and QUBE II, funded by the German Federal Ministry of Education and Research (BMBF) under the funding codes 16KIS0767 and 16KISQ051. The authors give special thanks to the colleagues of Ludwig-Maximilians University Munich, Friedrich-Alexander University in Erlangen and OHB Systems, who worked together in this project.

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