DLR’s Optical Communication Terminals for CubeSats

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Abstract— **Free space optical communication (FSO) overcomes the challenges of traditional RF-communication in space. With its high data-rates, robustness against electromagnetic influences and being free from organizational regulations, FSO provides solutions for high-rated Direct to Earth (DTE) and Intersatellite (ISL) communication.**

With the raising CubeSat market and the increasing number of satellite constellations, the request for compact and efficient designs increases as well. Thus, German Aerospace Center (DLR) developed the world’s smallest laser communication terminal for CubeSats (OSIRIS4CubeSat, O4C). O4C is flying on the CubeL satellite in the PIXL-1 mission. The payload itself has a modular design which allows to transfer the technology into other fields of satellite communication. The basic payload can be adapted and/or extended by different subsystems to provide solutions for intersatellite communication or Quantum Key Distribution (QKD).

This paper gives an overview of the first results of the PIXL-1 mission. After the Launch and Early Orbit Phase (LEOP) the first contact between the laser terminal and DLR’s Transportable Optical Ground Station (TOGS) could be established. Afterwards, further experiments were done to demonstrate the performance of the O4C terminal. Furthermore, this paper shows the ongoing and upcoming developments. Based in the O4C dedicated terminals towards higher data rates, optical intersatellite links and QKD on CubeSats are and will be developed.

Keywords—Optical Downlinks, Small Satellites, Demonstrations, CubeSat

I. INTRODUCTION

CubeSats have gained increasing attention throughout the last years. While CubeSats started as technology demonstration, in the meantime the majority of the CubeSat launches supports Earth observation or communication missions, especially in growing constellations of hundreds of satellites.

With the increasing number of satellites and missions, also the demand for higher data rates to support Earth Observation as well as communication missions, increased. DLR’s program for optical communication terminals started back in 2015 with a feasibility study and the development of a prototype of a highly compact optical communication terminal.

Based on the feasibility study and the prototype, DLR started the development towards a first demonstration mission together with its industrialization Partner Tesat-Spacecom. In this cooperation, DLR developed the optical terminal while Tesat prepared volume manufacturing in parallel. This led to a scientific terminal with the ability to adapt to different mission needs while also the industrialization was on the way - also known as CubeLCT. The mission PIXL-1 has been launched in January 2021 with a first measurement campaign in summer 2021.

The CubeL terminal is designed with standard interfaces to ensure maximum compatibility to different satellite busses and mission needs. The terminal supports up to 100 Mbit/s in the downlink and consumes 1/3 of a CubeSat unit 400 grams and below 9 W in downlink operation. On the basis of CubeL, further scientific missions have been started.

QUBE is a first demonstration of quantum experiments together with national partners. The CubeL terminal is extended to a dual-wavelength operation to transmit two different QKD-sources in addition to the classical optical link. In January 2022, the successor QUBE-II started with the goal of demonstrating a full QKD implementation on a CubeSat.

Due to the increasing needs of optical communication links in large constellations of small satellites, CubeISL extends the CubeL terminal with bidirectional communication abilities. Due to limitations in the diameter of the optics in the compact system design, the communication is limited to 100 Mbit/s in bidirectional communication over a distance of up to 1500 km. An extended mode can bridge a loss of one satellite in the intra-plane communication.

The following chapters will give an overview of the CubeL development, the first experiment results, the QUBE and QUBE-II mission as well as the ongoing developments for a first demonstration of optical ISL.

II. OSIRIS4CUBESAT

A. *Payload*

OSIRIS4CubeSat (O4C) is the world’s smallest laser communication terminal. It was developed together with our industrialization partner Tesat Spacecom who sells the terminal as a product with the name ”CubeLCT”. O4C is developed to serve the CubeSat market with Free Space Optical (FSO) communication. With a data rate of 100 Mbps and its high miniaturization factor, it overcomes the limitations of classical Radio-Frequency (RF) communication on pico- and nanosatellites. Due to its compact size of 1/3 of a CubeSat unit (U), a weight of 395 g and a power consumption of 8.5 W during operation it is the smallest and most efficient terminal in the OSIRIS program.

Common CubeSats can achieve a pointing accuracy of ±1°, with respect to a target pointing on Earth. The beam divergence of O4C is diffraction-limited (96.5 µrad for $1/e^2$ radius) to gain the highest possible power density on ground. To compensate the inaccuracy of the satellites pointing, the payload is equipped with a Fine Pointing Assembly (FPA) consisting of a 4-Quadrant Diode (4QD) and a Fast Steering Mirror (FSM). To establish a link, the Optical Ground Station (OGS) sends an L-band laser beacon with 1590 nm to illuminate the satellite. The 4QD measures the angular offset to the beacon and the FSM corrects the error. The transmission laser (C-band with 1550 nm) is coupled into the same optical path to guarantee that it hits the target. The Field of Regard (FOR) of the FPA is ±1° (ex-aperture) to cover the whole range of the remaining satellites pointing error.

O4C follows the approach of a modular design. Even though the terminal is highly integrated, the single subsystems can be handled separately. The terminal mainly consists of the following subsystems:

- Mechanical System
- Optical System
- Electronical System
- Control Loop
- Software
- Interfaces

This allows to use O4C as a basic technology for future developments. Beside classical communication in the Direct To Earth (DTE) sector, DLR’s research also follows the technology transfer of FSO into other fields like Quantum Key Distribution (QKD) and Inter-Satellite Links (ISL). This modular approach enables short development times as subsystems can be easily adapted or exchanged without changing the whole terminal design. Furthermore, it reduces the qualification effort as most of the subsystems were already qualified in the basic development. Figure 1 shows the integrated O4C flight model.

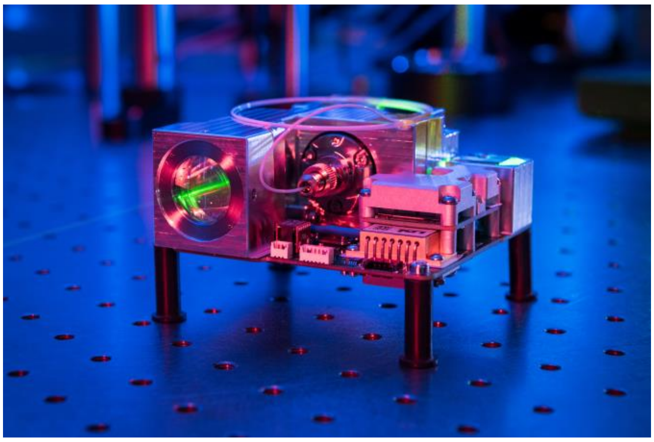

Figure 1: O4C flight model

The selection of common interfaces allows the integration of the payload in different types of satellites. O4C has standard interfaces for data transfer and Telemetry and Telecommand (TM/TC) to enable easy adaptions to nearly every satellite and CubeSat bus. This includes the electrical, software as well as the mechanical interfaces.

B. *Demonstrator Mission*

O4C is demonstrated in the “PIXL-1” mission. The goal is to transmit pictures, taken by an onboard camera via O4C to an OGS. Thus, the first O4C payload is flying on the “CubeL” satellite, a 3U CubeSat from GomSpace which started in January 2021 onboard a Falcon 9 into a Sun Synchronous Orbit (SSO). Figure 2 shows the fully integrated satellite CubeL.

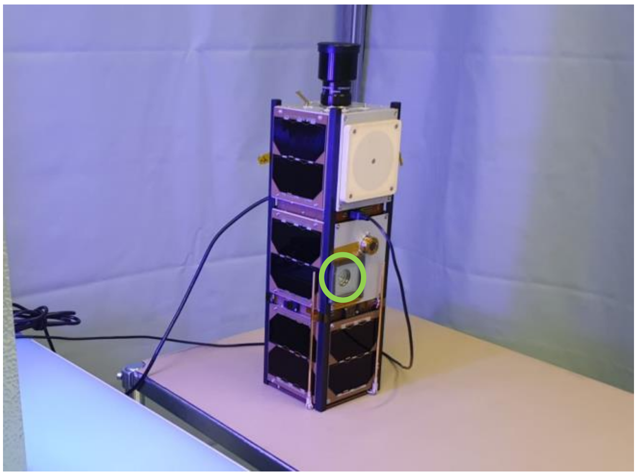

Figure 2: CubeL finally integrated (O4C aperture marked in green)

After Launch and Early Orbit Phase (LEOP) and commissioning of the satellite, the focus was to stabilize the Attitude and Orbit Control System (AOCS). During this phase DLR started with laser experiments in parallel. The first measurements were performed with DLR’s Transportable Optical Ground Station (TOGS). The TOGS is designed for the operational use with the focus on data transmission. It is equipped with a 60 cm telescope.

The first task was to determine the satellites AOCS and its pointing accuracy. Therefore, the FSM of O4C was driving spirals to cover the whole field of regard which could be seen as flashes at the TOGS. Figure 3 shows the first flash of the O4C laser from CubeL, measured with the TOGS.

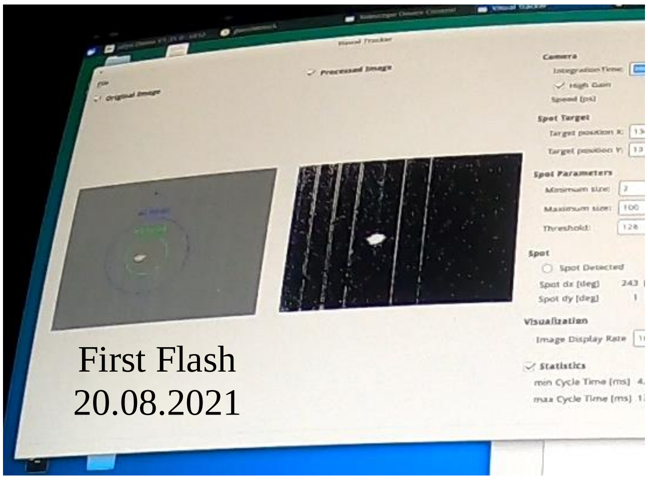

Figure 3: First flash of O4C received by TOGS

After the first results, the beacons of the TOGS were included into the operation. On the September 8th 2021 an experiment demonstrated a successful tracking.

C. *Outlook*

The next steps in the PIXL-1 mission are to increase the stability of the AOCS of CubeL and further laser experiments to verify the data transmission between O4C and the TOGS.

III. QUBE

A. *Project overview*

As described in II.A the modular approach of O4C allows easy technology transfer into other use segments beyond classical communication. One upcoming and interesting field in the CubeSat sector is Quantum Key Distribution (QKD). The goals in the project “QUBE” (founded by the German Federal Ministry of Education and Research, BMBF with the indication 16KIS0769) are to develop and demonstrate technologies in preparation for QKD on CubeSats. The in QUBE involved partners are Max Planck Institute for the Science of Light (MPL) and Ludwig-Maximilian-University in Munich (LMU), who develop experimental CubeSat payloads for QKD experiments. DLR provides a modified version of an O4C payload to establish the optical link between the satellite and the Optical Ground Station (OGS). The scenario will be demonstrated on a 3U CubeSat of Center for Telematics (ZfT). OHB completes the consortium as the industrialization partner for the QKD payloads.

B. *Payload adaptions*

The major challenge for DLR was to adapt the optical system to the wavelengths of the partner payloads. O4C uses C- and L-band (1550 nm and 1590 nm) laser for transmission and tracking. MPL also emits their signals in C-band. The LMU payload transmits light with 850 nm. Thus, the optical system had to be replaced by an achromatic system. The divergence must be similar for all wavelengths and narrow down the angular offset, over the full Field of Regard of the FPA (< ±1°). Figure 4 shows different scenarios of the implementation of the optical system and explains the challenges and solution afterwards.

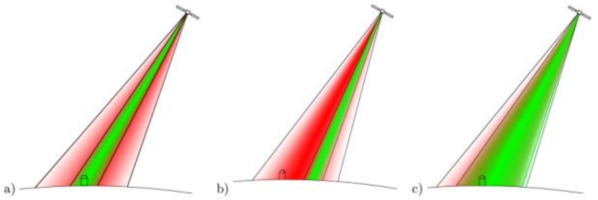

Figure 4: Pointing scenarios from satellite to OGS using two different wavelengths: a) Optimal divergences, without offset, b) Optimal divergences, angular offset and c) Angular offset with adapted divergences.

Scenario a) shows the optimal setup. The divergences of all beams are at their physical minimum which leads to the highest possible power density on ground. As described in II.A the FPA can compensate an inaccuracy of the satellite of up to ±1°. In a non-achromatic system, the beams get refracted under different angles, due to the different wavelengths. This leads to an angular offset which can be seen in Figure 4 b). In this scenario the narrower beam does not hit the OGS anymore. Scenario c) shows the compromise which is used in QUBE. The 850 nm signal is not diffraction-limited anymore, its divergence is increased by the system to match the divergence of DLR’s and MPL’s lasers.

The different signals are coupled fiber based into the system. Therefore, a triplexer is used which combines the three input signals into one fiber. Figure 5 shows the flight models of the adapted O4C payload for QUBE and the triplexer below.

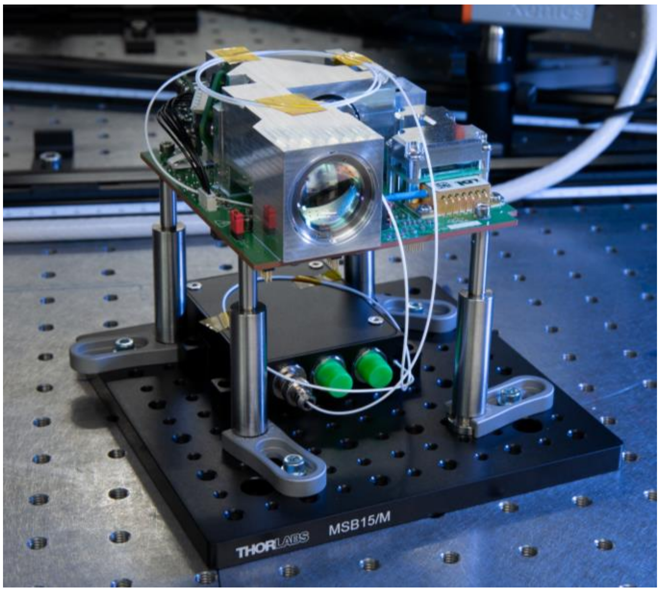

Figure 5: QUBE flight model (top) and triplexer flight model (bottom)

QUBE will fly on a different type of CubeSat than O4C does. Due to its flexible design, the electrical and mechanical interfaces could easily be adapted to the satellite bus of ZfT, which applies the UNISEC standard. The shape of the mainboard, including the mechanical mounting holes could be changed without changing the electronics on it.

C. *Qualification and testing*

The payload is fully qualified and tested. As it was also done with O4C, an end-to-end test was performed to recreate the scenario of the final mission. On an FSO track of 3 km the QUBE payload established a link to the TOGS. Both systems were running in their final mission configuration and the lasers were attenuated to have representative power to a link between an OGS and a satellite at 10° elevation. Figure 6 shows the results of the tracking tests.

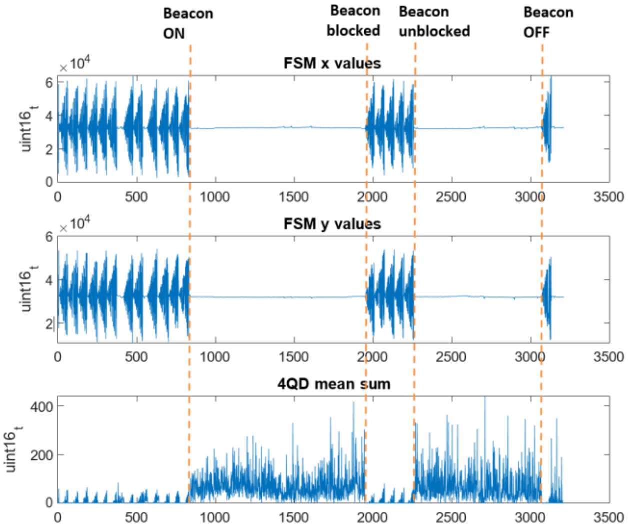

Figure 6: Tracking results of end-to-end test with QUBE

To search for the beacon, the FSM starts driving spirals, which can be seen in the triangles in x- and y-axis in the figure above. If the 4QD sum value over the four quadrants rises above a certain threshold due to the beacon of the TOGS, the FSM stops the spiral and starts closed loop tracking. In Figure 6 it can be seen that the terminal acquires the beacon as soon as the beacon is turned on and re-acquires after the beacon was blocked. The results of this end-to-end test show that the tracking will be stable above an elevation of 10° in the final mission.

D. *Outlook*

After the test and qualification campaign the flight models were delivered to the satellite manufacturer ZfT and integrated into the satellite bus. Figure 7 shows the satellite “QUBE”. The satellite undergoes the last acceptance tests and the launch is targeted for the end of 2022.

Figure 7: QUBE satellite finally integrated

IV. CubeISL

A. *Overview*

CubeISL is DLR’s newest development based on the O4C optical terminal. It aims to achieve optical ISL communication at a rate of 100 Mbps and DTE links at 1 Gbps with the same terminal. Similar to O4C, CubeISL has been developed with a compact design to fit standard CubeSat buses. The whole system presents a Size, Weight, and Power (SWaP) of just 1 U, 1 kg, and 35 W.

CubeISL’s main goal is achieving an ISL at 100 Mbps with a receiving aperture at the satellite of only 2 cm. For comparison, the 60 cm telescope of the TOGS is used in the PIXL-1 mission to achieve the same data throughput. To make this possible, CubeISL includes an Erbium-Doped Fiber Amplifier (EDFA) capable of achieving an output power of 1 W. Moreover, the terminal also incorporates a Data Handling Unit (DHU) to make it more independent from the satellite. The DHU also allows the terminal to process information at the required data rate of 1 Gbps, and encode and decode the exchanged data which requires a large computational power. Contrary to O4C, which was a pure emitter, CubeISL will now have to simultaneously receive and transmit data. For this task, an additional receiver with enough sensitivity will be used to read the high-speed data. This leads to the payload design for CubeISL as shown in Figure 8 which consists of three sub-payloads: Transmitter System, Optical Terminal and Data Handling Unit (DHU).

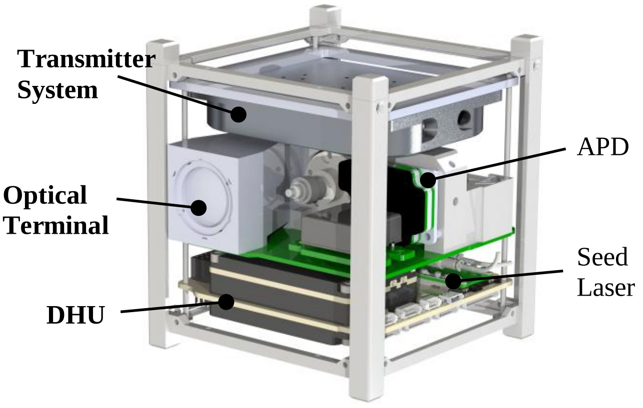

Figure 8: CubeISL payload concept

B. *Transmitter System*

The transmitter system consists of a laser source and its amplifier. CubeISL uses Commercial Off The Shelf (COTS) optical transceiver as laser source, which already include an electronics board for their modulation and monitoring. On each satellite, the laser will be tuned to its respective wavelength. The output power of the laser will be amplified to the desired 1 W intensity by the amplifier. For the amplifier, the EDFA technology was chosen due to their high saturation power and lower pump power as compared to Raman amplifiers; as keeping a low power consumption is critical on CubeSats. At its highest output power of 1 W, the system will be tenfold the optical output of O4C.

C. *Optical Terminal*

The Optical Terminal, based on the O4C payload, uses spectral isolation to distinguish the incoming data from its own emitted signal. Each terminal emits a beam in C-band, at different wavelengths (i.e., 1537 nm and 1553 nm) and receives the respective counter wavelength of the other terminal. The tracking path for DTE stays with 1590 nm in the L-band. The transmission wavelength range has been chosen due to the larger availability of COTS EDFAs at the C-band, as compared to the L-band, and will serve for both, tracking and data reception during ISL. Figure 9 shows the schematics of the optical terminal. Here, the emitted wavelength is marked with red arrows and the received beam, with blue arrows. The diagram also shows the addition of an amplifier after the laser source and the highly sensitive Avalanche PhotoDiode (APD) detector for the data reception, which is described below. The extension of O4C to CubeISL has only been possible thanks to its modular design and COTS components. These allow a simple exchange and addition of new subsystems to the current design.

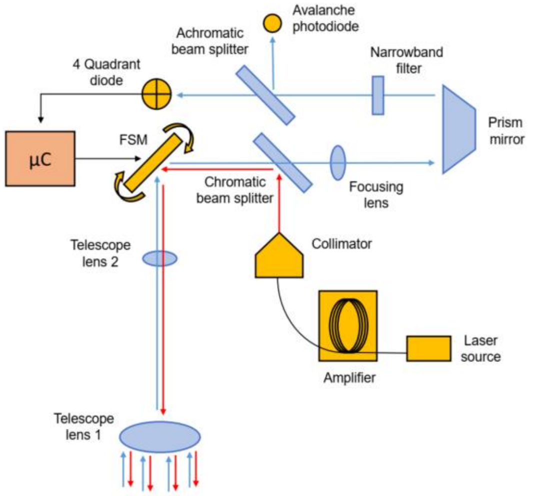

Figure 9: Diagram of the CubeISL optical terminal

D. *Receiver*

On CubeISL, the receiver splits the incoming light between two detectors (4QD and APD), as described in Figure 9. The 4QD is used to track the received signal so that the emitted beam becomes perfectly aligned with the receiving beam. The second path is used for the actual data reception. It uses an APD detector, which has a much higher gain than its PIN photodiode counterpart at the 4QD. These detectors require typically as little as 500 ppb to achieve a BER of 10^{-9} [1]. With a sensitivity of 500 ppb, the system can achieve data rates of 100 Mbps at a link distance of ~1000 km. With a Forward Error Correction (FEC) coding scheme, even fewer ppb would be required [2].

E. *Data Handling Unit*

CubeISL remains as independent as possible from the satellite bus thanks to the addition of a COTS Field Programmable Gate Array (FPGA). During transmission, it processes and forwards data to the laser at a high speed of 100 Mbps in ISL or 1 Gbps in DTE. Furthermore, it encodes the transmission data with the FEC. For the received data, it performs the computationally demanding task of decoding the transmission's FEC scheme and storing the information for post-processing. The link distance can be increased to up to 1500 km with different coding schemes (i.e., Reed Solomon or LDPC). However, implementing FEC increases the overhead and decreases the user data rate.

F. *Outlook*

CubeISL will be demonstrated on two 6U CubeSats. The mission will show the exchange of operational data via bidirectional optical link, between two satellites over 1500 km, with 100 Mbps and a data downlink of 1 Gbps to an OGS. The satellites will start in 2023 to a Sun Synchronous Orbit (SSO) in Low Earth Orbit (LEO). The two satellites will fly along the same orbital plane to demonstrate intraplane scenario, which is a first step towards constellations and mega-constellations. The mission and the operation will be done by DLR's Responsive Space Cluster Competence Center (RSC^3).

V. QUBE-II

A. *Project overview*

QUBE-II is the follow-up project of QUBE, with the goal to demonstrate a full QKD implementation with a demonstration mission in the same round of partners. QUBE-II is founded by the German Federal Ministry of Education and Research, BMBF with the indication 16KISQ051.

B. *Payload development*

The challenging goals of QUBE-II put additional requirements on the capabilities of the satellite and its latest terminal. For the postprocessing steps of a QKD protocol a bi-directional classical link between the two partners, that seek to establish a key, is necessary. In QUBE an optical downlink from the satellite to the ground station has already been implemented. Therefore, an additional uplink from the ground station to the satellite is one of the key features that needs to be developed and implemented in QUBE-II. Another, crucial property of the QKD system is the quantum link efficiency. The vast majority of DV-QKD protocols work in the single photon regime, either utilizing single photon sources or weak coherent laser pulses to realize the qubits. Increasing the transmitted power to compensate for the losses is therefore not possible, without reducing the security of the process. A valid measure to increase the efficiency, or reduce the channel losses, is to reduce the geometric losses, more precisely, the losses due to the divergence of the laser beam. This is achieved by increasing the aperture of the laser terminal by equipping the optical terminal with a telescope with a diameter of more than 80 mm.

Altering the laser terminal’s optical system has an impact on the entire system. The larger aperture puts higher constrains on the tracking system and the pointing accuracy of the satellite. While for QUBE a pointing accuracy of 1° was sufficient, QUBE-II demands a pointing accuracy of 0.1° because of the decreased divergence of the laser beam. This needs to go hand in hand with the extension towards a dual-wavelength operation of the optical system. Finally, the required space of the laser terminal with the new telescope and possibly additional components for beam guidance, increases as well. As a result, QUBE-II will likely be demonstrated on a 6-U CubeSat.

VI. CONCLUSIONS

DLR developed a laser communication terminal for CubeSat applications in different missions. The first measurement results have been achieved with the PIXL-1 mission in 2021. Based on this development and the parallel volume manufacturing with Tesat, the optical terminal is adapted for scientific missions with quantum experiments in QUBE and a full QKD implementation in QUBE-II.

With an extension of the terminal with a receive channel, also intra-plane communication can be supported in large constellations of CubeSats.

Future developments will also target higher link efficiencies and hence larger distances or higher data rates in ISL applications.

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