GEFÖRDERT VOM
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Development of laser terminals for satellite-based QKD on CubeSat platforms

Deutsches Zentrum für Luft- und Raumfahrt
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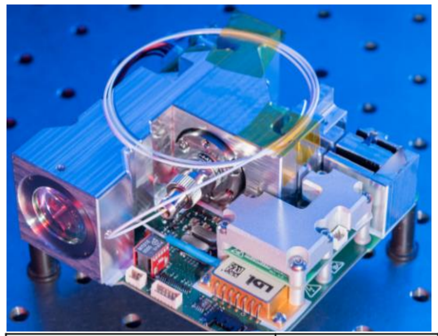
Introduction

For more than 15 years, DLR´s Institute of Communications and Navigation (DLR IKN) researches in the field of free space laser communication covering channel simulation- and measurements, the development and operation of ground-, air- and space-terminals for data links as well as Quantum Key Distribution (QKD). Based on the OSIRIS4CubeSat terminal DLR IKN is currently developing three laser terminals for satellite-based QKD on CubeSat platforms.

Osiris4CubeSat

The development of the CubeSat standard has helped to significantly decrease the cost per mass of launching payloads. Many companies offer modular systems for building a CubeSat and launch providers take care of the complete launch process. As many of these satellites generate high amounts of data to be downloaded to a ground station, there is a demand for compact and power-efficient downlink systems. Therefore, DLR IKN developed in cooperation with Tesat-Spacecom Osiris4CubeSat (O4C) – a CubeSat based laser communication terminal, using wavelengths in C- and L-Band. O4C is part of DLR´s "CubeL" satellite and was launched in January 2021 [1].



Size	1/3U
Peak Power Consumption	8.5 W
Data Rate	100 Mbit/s
Wavelength Downlink	C-Band
Wavelength Beacon Uplink	L-Band

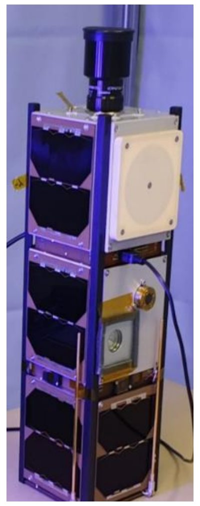


Figure 1: O4C terminal before and after integration into CubeL [1].

After LEOP and manual correction of the satellite pointing error over the last 2 ½ years, DLR IKN was able to transmit a picture taken by the CubeL satellite over the optical link to the ground station on September 15th. Figure 2 shows telemetry data from the fine steering mirror (FSM) during the pointing, acquisition and tracking process and the transfer of data through the optical downlink.

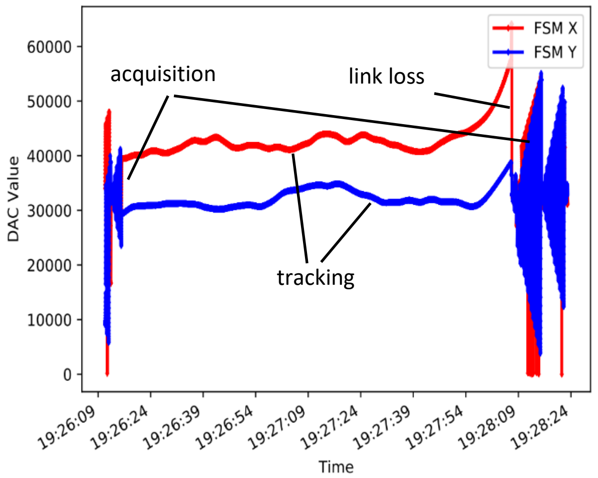


Figure 2: Telemetry of the FSM during the stable link.

With the successful transfer of an image from a CubeSat to an optical ground station (OGS) through the optical link, DLR IKN has demonstrated a fully functional laser terminal for high bandwidth optical communication from a CubeSat.

QUBE

Based on O4C, DLR IKN further developed the laser terminal OSIRIS4QUBE (O4Q) within the "Quantum Key Distribution with CubeSat (QUBE)" consortium. The aim of QUBE is to conduct experiments for QKD on a 3U+ CubeSat [2]. Besides the subsystems for commanding, controlling and distributing the power, it consists of two payloads for testing different approaches for QKD and DLR IKN´s laser terminal which is used to combine the emitted optical signals of both QKD-payloads as well as a laser signal from O4Q itself from three optical fibers into one. The output is connected to the laser terminal of O4Q, where it is coupled into a free space achromatic optical system shown in Figure 3. This cross-sectional view shows the transmitter beam path with blue rays and the receiver beam path for the tracking system with red rays.

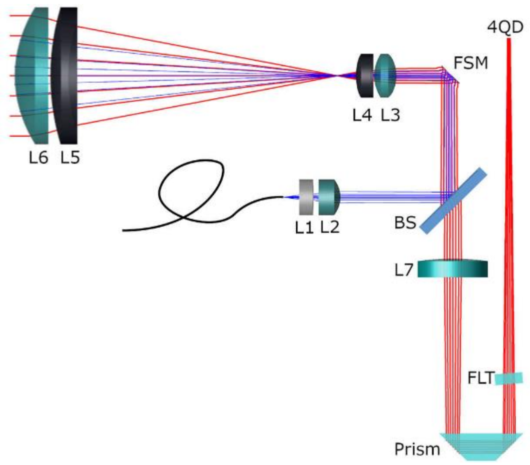


Figure 3: Cross-sectional view of the optical system of QUBE. The transmitter beam path consists of lenses L1&L2 for fiber collimation, a beam splitter (BS), fine steering mirror (FSM) and lenses L3 to L6 for beam expansion. The receiver optical path consists of lenses L6 to L3 for beam shrinking, FSM, BS, lens L7 for focusing, a prism, a laser line filter (FLT) and a four-quadrant diode (4QD). 4QD and FSM are used in a closed loop tracking system [4].

A major challenge was the transformation of the single wavelength optical system of O4C to an achromatic system needed for O4Q in the same form factor (C/L-Band wavelengths and 850 nm). Especially the performance of the telescope (L3-L6) is of importance for the tracking- and pointing behavior as the divergence of the transmitted beam depends on wavelength and magnification. Three scenarios of different pointing are visualized in Figure 4. Scenario ***a*** shows a perfect achromatic system where two laser beams of different wavelengths are perfectly pointing on one center axis to the ground station at heir minimum divergence. In scenario ***b*** both beams still have their minimum divergence, but due to residual chromatic errors in the telescope, they have an angular offset to each other. Taking dimensional constraints to the optical system and the manufacturability of lenses into account, a compromise between divergence and angular offset is necessary, ending up in the more realistic scenario ***c***.

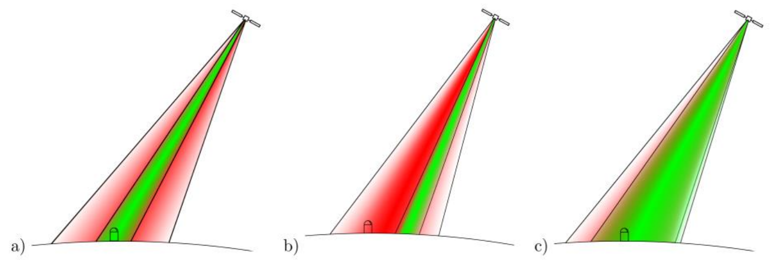


Figure 4: Three different scenarios of pointing from satellite to an OGS using two wavelengths: a) Divergences are optimal and beams are concentric. b) Divergences are optimal, but beams have an angular offset. c) Divergences and angular offsets are mutually adapted *[4]*.

QUBE II

The aim of the consortium "Quantum Key Distribution from a CubeSat to Ground" (QUBE-II) is to develop a CubeSat based system, which is able to perform a complete quantum key exchange. For the necessary post-processing steps, the laser terminal in QUBE II will provide a bidirectional optical data link (up- and downlink). The optical system of its predecessor QUBE is therefore modified to reduce the channel loss. This is done by using a larger exit aperture supporting also a larger transmitter beam diameter and hence a smaller beam divergence. Figure 5 shows the optical system of QUBE II in a) the top view and b) the side view, which fits into 2U of a CubeSat. The additional focusing telescope with a diameter of 85 mm is not shown in the picture. In contrast to QUBE, one collimator is used to couple the QKD- and the classical signal in C-Band (Collimator C1) into one free space path and a second to couple the QKD signal at 850 nm (Collimator C2) into a second free space path. Through a chromatic beam splitter BS2 both paths are combined. Lenses L1-L4 are used to expand (Tx) and shrink (Rx) the beam and additionally compensate aberrations introduced by the focusing telescope. FSM and 4QD form the closed loop tracking system. Beam splitter BS1 separates Tx and Rx beam, while beam splitter BS3 separates the uplink data signal at 1605 nm, which is focused onto the APD, from the beacon signal at 1590 nm, which is focused onto the 4QD.

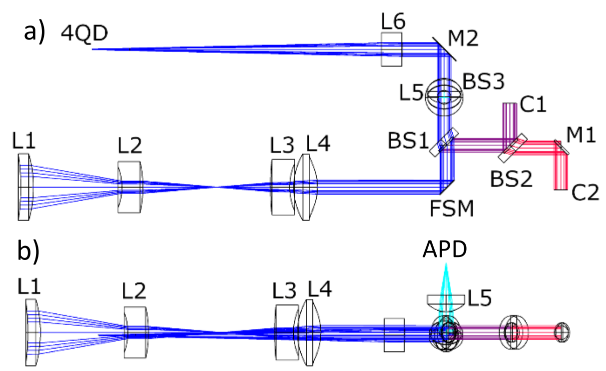


Figure 5: a) Top- and b) side view of the optical system of the QUBE II terminal.

QuNET

QuNET is an initiative funded by the German Federal Ministry of Education and Research with the goal to develop technologies for a quantum secure communication network within Germany [3]. Those technologies are then demonstrated in three key experiments that simulate real life scenarios in which future quantum secure networks will be essential to Germany's IT sovereignty and security. Within this framework, DLR IKN is developing a laser terminal for ground-to-ground QKD experiments, while keeping size, weight and power consumption (SWaP) within typical CubeSat boundaries. Figure 6 shows a ray trace image of the terminal developed in QuNET. It is based on the O4C terminal with a few significant adaptions. The focusing telescope to the left increases the optical diameter for the transmitted beam to 85 mm reducing the divergence and by that the channel loss in the quantum channel. The focusing telescope alone takes up one CubeSat unit. Lenses L1 to L3 collimate the focused beam and compensate aberrations introduced by the telescope. A second movable mirror, here called the MPA (Mid Pointing Assembly), is placed in the pupil of both telescopes. Fine steering mirror (FSM) and mid pointing assembly (MPA) mirror form together with the 4QD the closed loop tracking system. The additional mirror is introduced since through increasing the exit aperture of the terminal, its field of view (FOV) is reduced from 1° (O4C) to approximately 0.1°. A pointing accuracy of 0.1° is very demanding for the AOCS of a CubeSat. Through the combined control loop of FSM and MPA mirror the field of view of the terminal can be increased to 3°, significantly relieving the requirement towards pointing accuracy of the satellite. QKD signals in C-Band are coupled together with the classical optical data signal into the free space path and sent towards the ground station through the telescope. Additionally, the terminal also incorporates a data receiver, enabling a bidirectional, optical communication at 1Gbit/s.

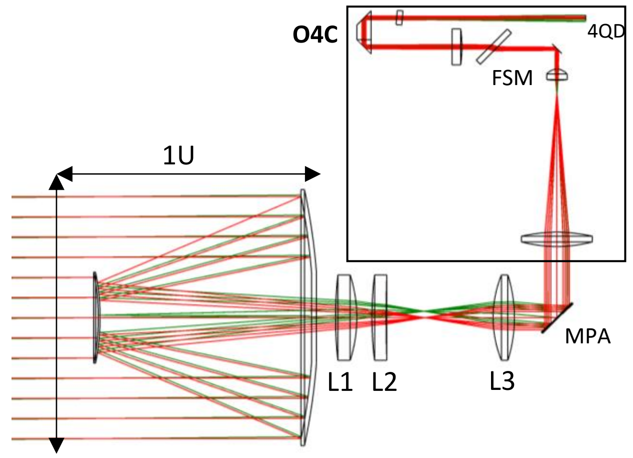


Figure 6: Ray trace of the QuNET terminal for ground-to-ground QKD experiments.

Key Experiment 2 (SE2)

The developed terminal will be demonstrated in key experiment 2, where a quantum network connects multiple users in two far distant cities. Figure 7 shows schematically a possible network architecture. The network will be mainly fiber based with at least one free space link of 10 km distance, emulating the connection of a satellite to the quantum network.

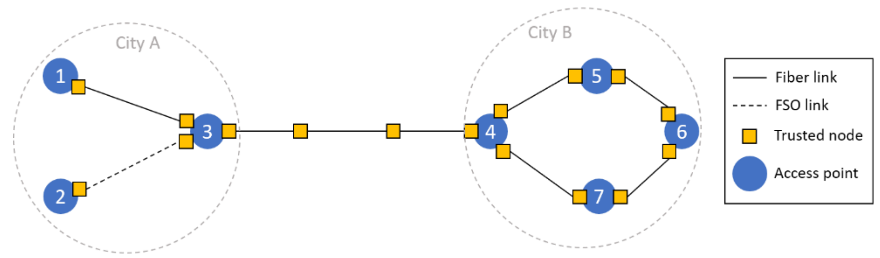


Figure 7: Schematic architecture of the intercity quantum network with multiple access points/End-Users and at least one FSO link.

Acknowledgements:

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[1] B. Roediger, M. Hahn, C. Schmidt and C. Fuchs, *OSIRIS4CUBESAT – SYSTEM ENGINEERING WITH NEW SPACE APPROACH,* 2020.

[2] R. Haber and W. Rosenfeld, *QUBE - A CubeSat for Quantum Key Distribution Experiments.*

[3] B. f. B. u. Forschung, "QuNET-Initiative," [Online]. Available: https://qunet-initiative.de/.

[4] C. Roubal, F. Moll and B. Rödiger, *Dual Wavelength Optical System for Multi Quantum Communication Transmitters in CubeSat Platform.*