ACQUISITION CONCEPT FOR OPTICAL INTER-SATELLITE COMMUNICATION TERMINALS ON CUBESATS

Benjamin Rödiger [(1)], René Rüddenklau [(1)], Christopher Schmidt [(1)], Marc Lehmann [(2)]

[(1)] *German Aerospace Center (DLR), Institute of Communications and Navigation, Muenchener Strasse 20, 82234 Wessling, GERMANY, +498153282944, benjamin.roediger@dlr.de*

[(2)] *German Aerospace Center (DLR), Responsive Space Cluster Space Competence Center (RSC³), Rutherfordstrasse 2, 12489 Berlin, GERMANY, +493067055104, marc.lehmann@dlr.de*

ABSTRACT

Free Space Optical (FSO) communication is gaining ground in satellite industry and an ideal supplement to classical radio data transmission. It offers solutions for global, high-rate and secure communication channels with compact designs and high cost- and performance-efficiency. Thus, German Aerospace Center (DLR) develops laser communication terminals for CubeSats and small satellites.

DLR has a long heritage in developing FSO terminals for Low Earth Orbit (LEO) satellites in the Direct To Earth (DTE) scenario. The next step is to transfer this technology to Inter-Satellite Links (ISL). This paper presents DLR's current development of an ISL laser communication terminal for CubeSats "CubeISL". The optical terminal of CubeISL relies on the basic development of the "OSIRIS4CubeSat" (O4C) payload. To establish a link between the corresponding CubeISL-terminals, DLR developed a search algorithm to acquire the laser of the partner terminal on the other satellite. The paper discusses the possibilities of different concepts based on the current design.
CubeISL will be demonstrated in a mission with two 6U CubeSats. Beside the technical description of the payload design and the search and acquisition algorithm, the paper will also give an overview and an outlook to this demonstrator mission.

1 INTRODUCTION

Free-Space Optical (FSO) communication has the potential to overcome the limitations in data rate of classical Radio-Frequency (RF) communication. Especially on small satellite platforms with tight resources for size, weight and power (SWaP), efficient communication systems are key for mission success. The narrow beam divergence of optical communication systems allows to increase the data rate by orders of magnitude with the same power consumption as seen in the RF domain. Optical communication is therefore seen as an ideal supplement of classical RF communication which is a very robust and proven technology.

Besides the demonstrated Direct-To-Earth (DTE) FSO, also optical Inter-Satellite Links (ISL) come into play with the launch of large constellations. The large number of satellites required to provide seamless services around the globe, requires a significant decrease in cost per satellite and launch. Key to this decrease is a reduction of size and mass of the spacecraft as well as the approach during development: New Space has found its way into the current developments of satellites and payloads.

The narrow divergence angle also comes with a disadvantage: the acquisition concept of the laser terminal needs to be revised for ISL applications. While DTE links use beacon laser with a large divergence, which covers the uncertainty area of the position of the satellite, and high power on ground, the CubeSat scale terminal doesn't provide this option due to power limitations. Therefore, the acquisition concept between the two ISL terminals needs to be optimized for this scenario. The approach and suggested solution for the first demonstration mission will be presented in this paper.

2 BASIC TECHNOLOGY OSIRIS4CUBESAT

2.1 Overview

OSIRIS4CubeSat (O4C) is the world's smallest laser communication terminal. It was developed in close collaboration with Tesat Spacecom GmbH as DLR's industrialization partner. With its compact design, low power consumption and comparable high data-rate it overcomes the abilities of comparable RF-communication terminals on CubeSats by far. Table 1 sums up the technical parameter of the O4C payload.

Table 1. Parameters OSIRIS4CubeSat

Size	1/3 U
Weight	395 g
Peak Power Consumption	8.5 W
Data rate	100 Mbps

This performance can be achieved, because the laser is diffraction limited, means it is narrowed down to the physically possible limit, which allows the highest power density on ground. The divergence of the transmission beam is 192.8 µrad ($1/e^2$, full angle). Common CubeSat buses can achieve a pointing accuracy of ±1° in target pointing mode. Thus, O4C is equipped with a Fine Pointing Assembly (FPA) to compensate this discrepancy. Figure 1 shows the flight model of O4C.

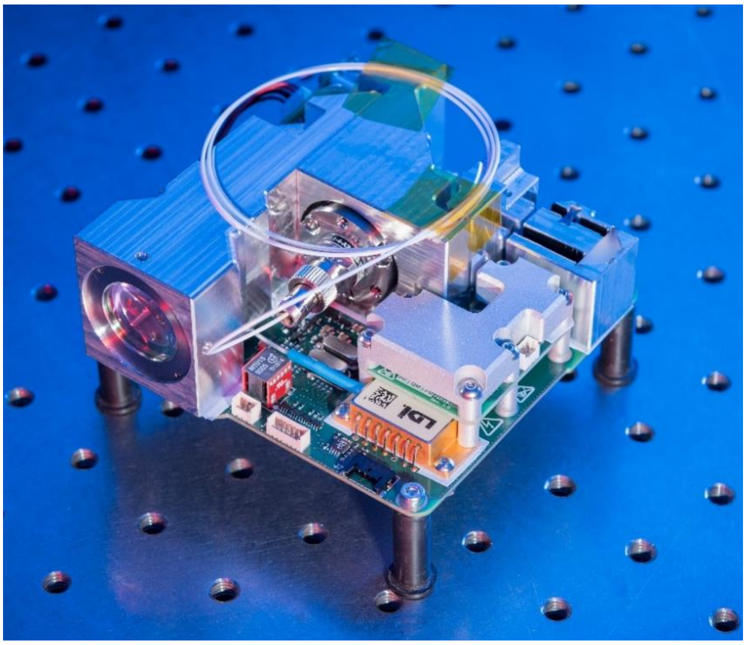

Figure 1. OSIRIS4CubeSat Flight Model

2.2 Link Setup

To establish a link in O4C, the Pointing Acquisition and Tracking (PAT) system is used. Therefore, an Optical Ground Station (OGS) points to the satellite and sends relatively wide laser beacons to the spacecraft and illuminates it. The OGS is equipped with two beacons, to achieve transmitter diversity and each has a divergence of 0.5 mrad [1]. With the general pointing accuracy of the OGS of better than 0.1 mrad and the precision of common orbit files like Two Line Elements (TLE) it is guaranteed that the beacons always hit the satellite [2]. In parallel the satellites Attitude and Orbit Control System (AOCS) points the spacecraft to the OGS and keeps the pointing stable within its ±1° window during the entire flyover. The compensation of the inaccuracy is done by the FPA as it is sketched in Figure 2 and described below.

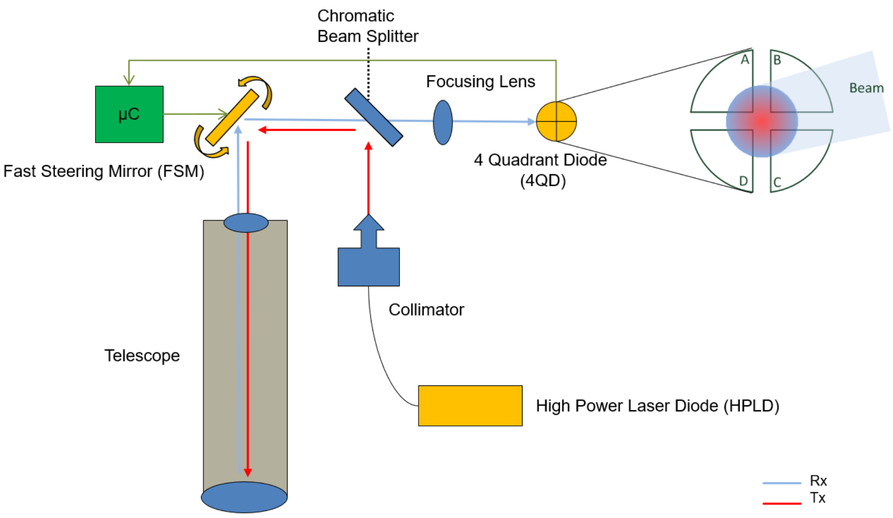

Figure 2. Block diagram of O4C including FPA

The FPA consists mainly of a 4-Quadrant Diode (4QD) to acquire the beacon and measure the angular offset, a Fast Steering Mirror (FSM) to correct the measured error and a Microcontroller (µC) to process the control loop. The Field of View (FoV) of the 4QD is limited to 3.14 mrad (ex-aperture). To acquire the beacon the FSM scans its whole Field of Regard (FoR) with a spiral. The FoR of the FSM covers the inaccuracy window of ±1° of the satellite. As soon as the 4QD receives light from the beacons, the power value summed over all four quadrants exceeds a defined threshold and the FPA switches from “acquisition” into “tracking” mode. While tracking the 4QD measures the angular offset in X- and Y-direction, calculated with equations 1 and 2:

$$X_{err} = \frac{(A+D)-(B+C)}{A+B+C+D} \tag{1}$$

$$Y_{err} = \frac{(A+B)-(C+D)}{A+B+C+D} \tag{2}$$

The µC processes the error and controls the FSM in the opposite direction to correct the offset. In a closed loop with 200 Hz update rate the beacons beam is kept in the center of the 4QD. Afterwards the transmission laser is coupled into the exact same optical path where the received beam comes from. This can also be seen in Figure 2 and guarantees that the transmission beam hits the OGS.

Receiving and transmission beams are separated by wavelength. The transmission laser emits in C-band (1550 nm) while the beacon operates in L-band (1590 nm).

2.3 Demonstrator Mission

The first payload of O4C is demonstrated in the "PIXL-1" mission, flying on a 3U CubeSat from GomSpace "CubeL". The major goal is to demonstrate the transmission of a picture, taken by a camera on the satellite to an OGS. CubeL started on the 24th of January 2021 into a Sun Synchronous Orbit (SSO) and after Launch and Early Orbit Phase (LEOP) the commissioning of the laser communication terminal began. First laser experiments were done with DLR's Transportable Optical Ground Station (TOGS) at Oberpfaffenhofen with first light received on the 20th of August 2021 as it can be seen in Figure 3. The beacons were included after the first successful experiments and a successful tracking lock, over a longer period, could be achieved on the 8th of September 2021.

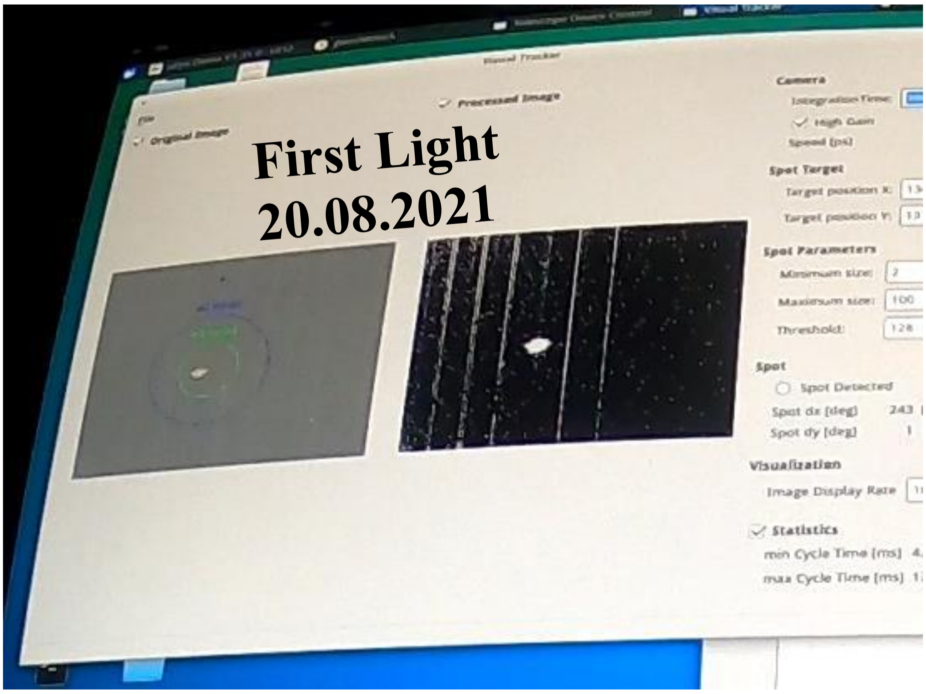

Figure 3. First light of O4C received by TOGS

During the bad weather period in winter 2021 DLR and GomSpace worked on improving the pointing stability of CubeL and the performance of the FPA. The next steps are to include the data receiver systems towards final demonstration of data transmission.

3 PAYLOAD DESIGN CUBEISL

3.1 Motivation

O4C follows the modular design approach. Even though the payload is highly integrated, it consists of separated subsystems which can be handled independently. Standard interfaces allow easy extensions and compatibility to other satellite busses or systems. Therefore, O4C represents the basic technology for further developments. The next step for DLR is to transfer the technology of optical communication from the Direct To Earth (DTE) into the Inter-satellite Link (ISL) domain. Following the New Space approach in the CubeSat market, short development and qualification times are highly appreciated. With the modular design of O4C many subsystems are already qualified and can easily be re-used in upcoming projects. Thus, the project "CubeISL" was started to develop a laser communication terminal for ISL on CubeSats, based on the O4C technology.

3.2 Payload

The design goal of the CubeISL payload is to reuse as many systems as possible from O4C, especially the optomechanics and the FPA, with a minimum of adaptions. O4C is a pure transmitter and can transmit data in one direction. To establish bi-directional data transfer in ISL, the payload needs an additional receiver, as the 4QD is not capable of receiving high data rates. Avalanche Photo Diodes (APD) are already used in DLR's Ground Stations, so that this technology will now be adapted for a usage in CubeISL and integrated as an additional subsystem.
In the ISL scenario the receiving aperture is not any longer an OGS with a 60 cm telescope like it is in DTE. In ISL it is the aperture of its corresponding terminal. As the technology of O4C, including the optomechanics is reused, the receiving diameter is limited to 2 cm. To overcome the lack of received power, each CubeISL terminal is equipped with an optical amplifier to tenfold the output power compared to O4C.
In the PIXL-1 mission high processing tasks like channel coding or forward error correction are outsourced to the satellite bus. To be more independent from the spacecraft CubeISL will have its own onboard computer acting as a Data Handling Unit (DHU).

The described adaptions and extensions lead to the terminal design shown in Figure 4.

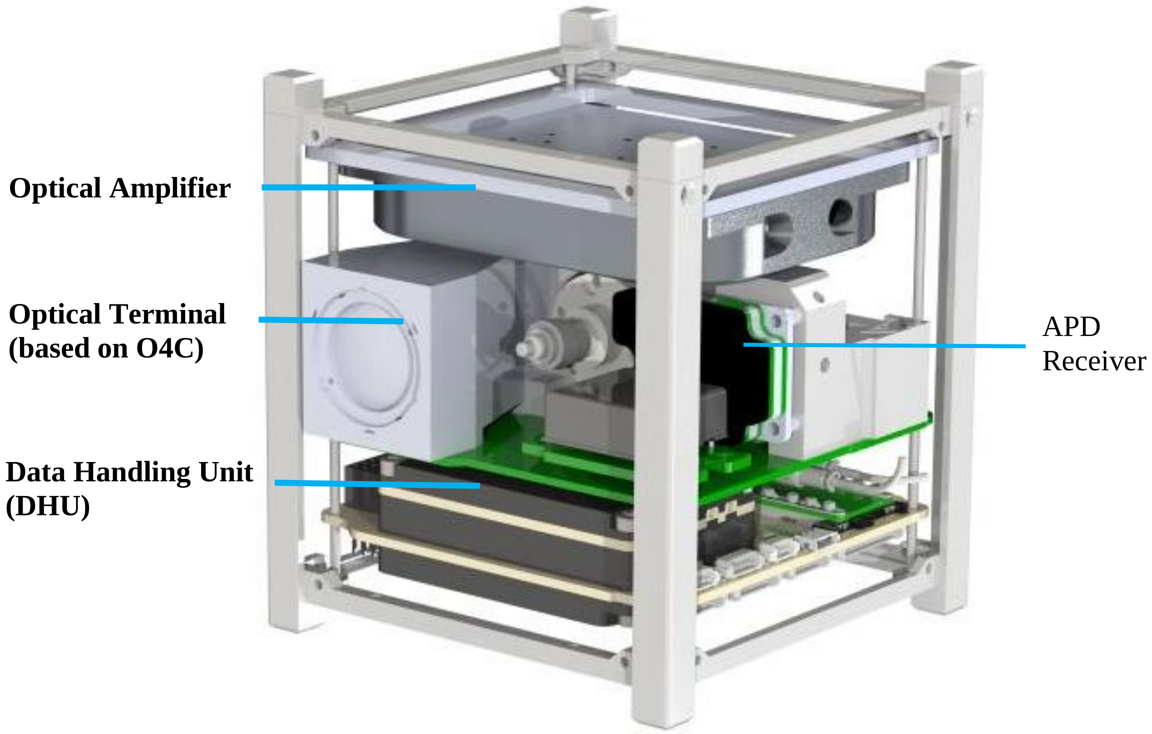

Figure 4. CubeISL payload design

In this configuration CubeISL can establish a bi-directional data transmission with 100 Mbps, over up to 1500 km distance between two terminals. Beside the ISL, it is also capable of transmitting data to the ground with 1 Gbps in DTE. Transmission and receiving beam for ISL are separated by wavelength. This leads to two different configurations for CubeISL, Terminal A and Terminal B, where the transmission wavelength of Terminal A is the receiving wavelength of Terminal B and vice versa. Both wavelengths (1536.6 nm and 1553.3 nm) are still in the C-band so that the beacon for DTE communication can still operate in L-band (1590 nm) thus the ground segment can serve CubeISL and O4C with the same setup. The link establishment is discussed in detail in the following chapter 4.

4 LINK ESTABLISHMENT

Compared to the DTE scenario the transmitted beam does not only serve the purpose to send data but is also the only optical reference for the opposing tracking sensor. A beaconless acquisition was shown before i.e. in [3]. The approach shown consists of a multistage actuator and sensor concept which leads the beam from a coarse to a fine alignment procedure. However, in CubeISL limited capacities in terms of the available space and power have to be considered.

The goal was to develop an acquisition scheme which works with the hardware being already available, is not dependent on a secondary communication channel (for time synchronization, for example) and most important, reduces the time for establishing a link. The challenge is to align a beam with a small divergence of 192.8 µrad (0.011°) to a sensor FoV of 3.14 mrad (0.180°), as described in chapter 2.

First of all, the duration of the search pattern was investigated. This is essentially dependent on the size of the uncertainty range of the overlying attitude control system, in this case the satellite, and the speed at which the pattern is traversed (see also Figure 7). Following this approach, the actuation frequency of the mirror at which new search points are being commanded was increased leading to a shorter full spiral period of about 2 s (compared to 8 s in O4C). This has the following two effects. The search pattern is executed more quickly in time when using a constant number of discrete points and, due to the fact that the FSM does not have an angle measurement system in the considered case, the specified trajectory has to be adapted with respect to the open loop bandwidth of the mirror which otherwise leads to a mismatch between the desired pointing and the actual angle. As a direct consequence, the sampling time of the partner terminal must also be increased to ensure that the 4QD is read out at the time it is hit by the beam. This event can then be used to activate the interrupt routine of the tracking controller such that it can run independently at any other desired frequency. As mentioned in chapter 2 the control loop update frequency was and is still set to 200 Hz whereas the new acquisition sampling and scan algorithm will run at about 1 kHz based on simulation results.

Up to this point, the two search patterns have been considered separately. It can be seen though that identical search patterns lead to a temporal dependency between the two. In an illustrative example, two spirals could therefore end up following each other indefinitely. Inverting one search pattern is also unreliable in most scenarios, since both terminals would have to steer towards each other at the exact same time. The solution is to desynchronize both search patterns from each other. This is achieved by using different repetition periods. The procedure becomes more efficient the further apart the two repetition rates are and the faster the slower pattern needs for one complete run. One example of an acquisition concept is depicted in Figure 5.

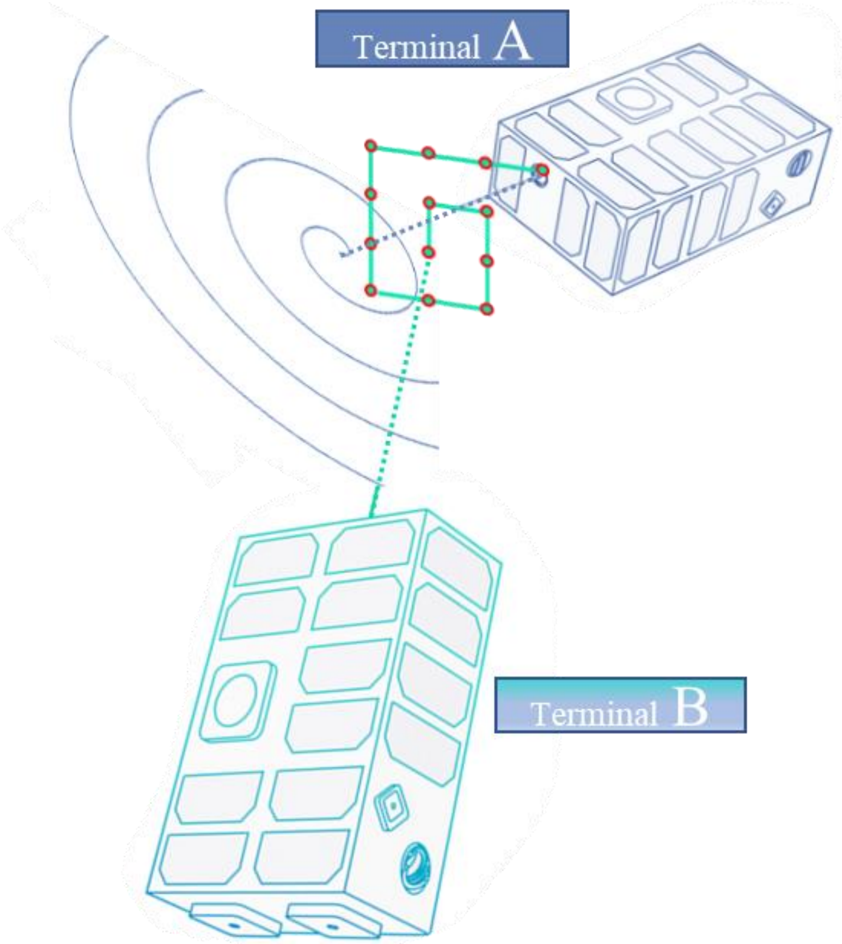

Figure 5. Example acquisition patterns. A slow grid (cyan), where each step (red marks) will be hold for 2 seconds and a fast scanning spiral (blue), which uses the same amount of time for a full period.

The only limitations are the maximum bandwidth of the sensor and the inertia of the actuator. In this particular application, a slower search pattern than the spiral was chosen to achieve those requirements. The terminal with the slower search pattern is referred to as Terminal B and the other as Terminal A. Terminal B passes through individual points that are laid out in a grid whose spacing is smaller than the FoV of the 4QD and is dependent among other disturbances on the jitter resulting from micro vibrations. At each point, at least the time period is waited that Terminal A needs for a single search run.
This results in the following sequence for the two terminals respectively (see Figure 6).

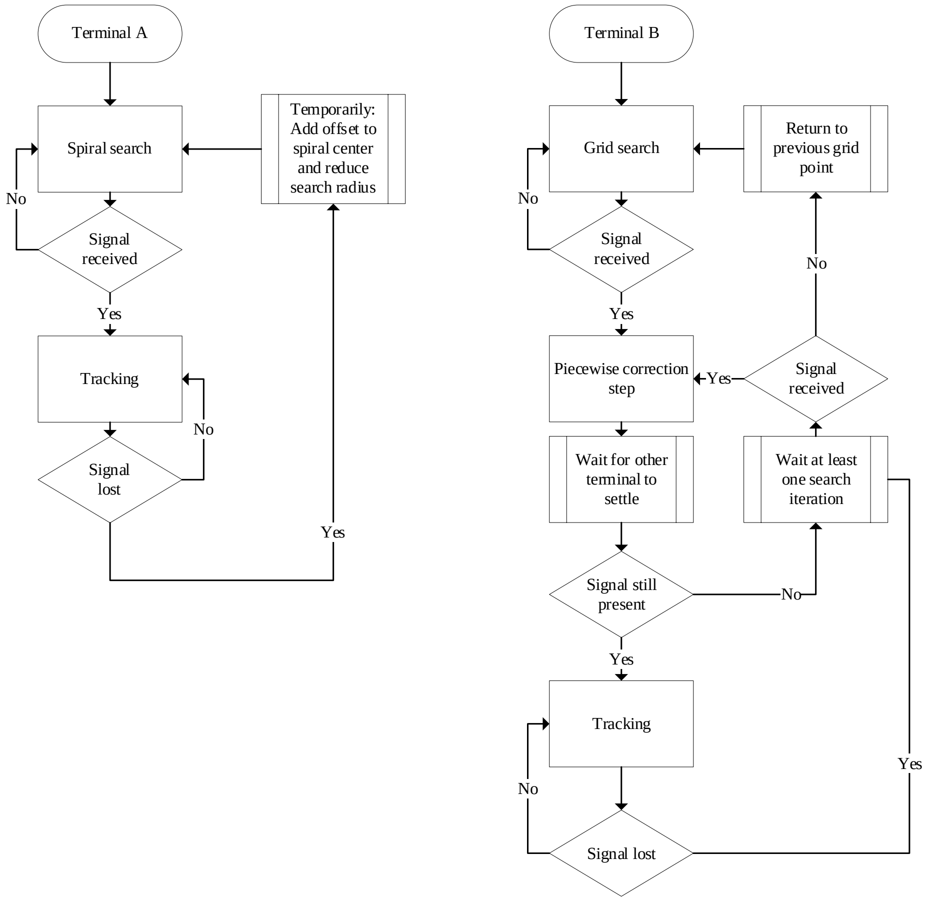

Figure 6. Flowchart of the acquisition scheme

An acquisition can be performed by switching to active tracking at the moment when both terminals receive a signal. In theory this can happen simultaneously when both terminals acquire each other at the same time. In the more general case, it is more likely that Terminal B will receive light on the 4QD first as its grid is optimized to its receiver FoV. A piecewise correction and wait step will be applied which either leads to an acquisition on both ends or otherwise will be repeated until both terminals are aligned to the precision of the transmitting beam divergence angle. The robustness can be further improved by one of the two terminals, for example Terminal B, which readjusts with a lower frequency (<200 Hz) in the early tracking phase until a stable link has been established. If the signal is lost, Terminal B returns to the last point in the grid with the now known offset and Terminal A starts its search pattern at the angle of the last contact with reduced spiral radius. If no signal was acquired after a determined time, both terminals will return to the predefined pattern.

This procedure leads to stricter requirements for the satellites Attitude and Orbit Control System (AOCS). In the PIXL-1 mission an accuracy of ±1° was sufficient to establish a link. One spiral takes 8 s so that the maximum time to establish a link would be 8 s, if the beacon is acquired at the outer edge of the FOR of O4C. With the acquisition concept described above the duration is depending on the total pointing accuracy of the satellites. The total error of this pointing accuracy is a combination of the angular pointing error and the knowledge error of the own angular attitude and the knowledge error of the lateral displacements of both satellites to each other. As the search pattern has to cover both axis the duration increases exponentially with the total pointing error as seen in Figure 7.

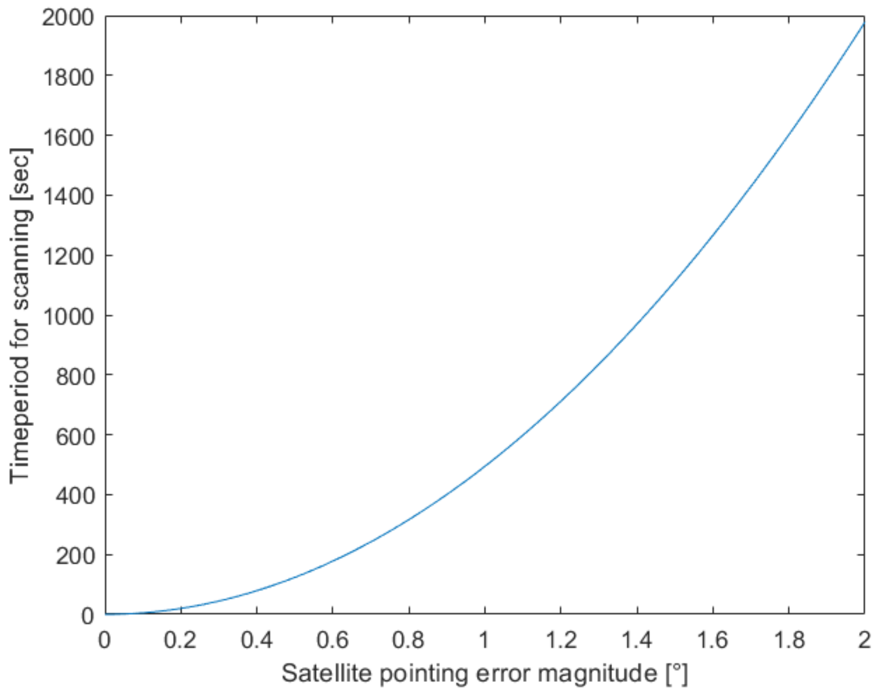

Figure 7. Acquisition duration over total pointing error

That means for example with a total pointing error of ±0.1° it would take up to 20 s to acquire the transmission beam of the other terminal and establish a connection. With a total pointing accuracy ±0.3° it would take up to 181 s. Experiments with CubeL showed that a total pointing accuracy of better than ±0.3° is possible, even with a 3U CubeSat. To measure the pointing accuracy multiple overexposed pictures of the moon were taken to calculate the optical center of gravity. The offsets between the center of gravity and the assumed target pointing were measured for each picture. The maximum measured boresight error was below 0.3° (0.292° to be precise) which can also be seen in Figure 8.

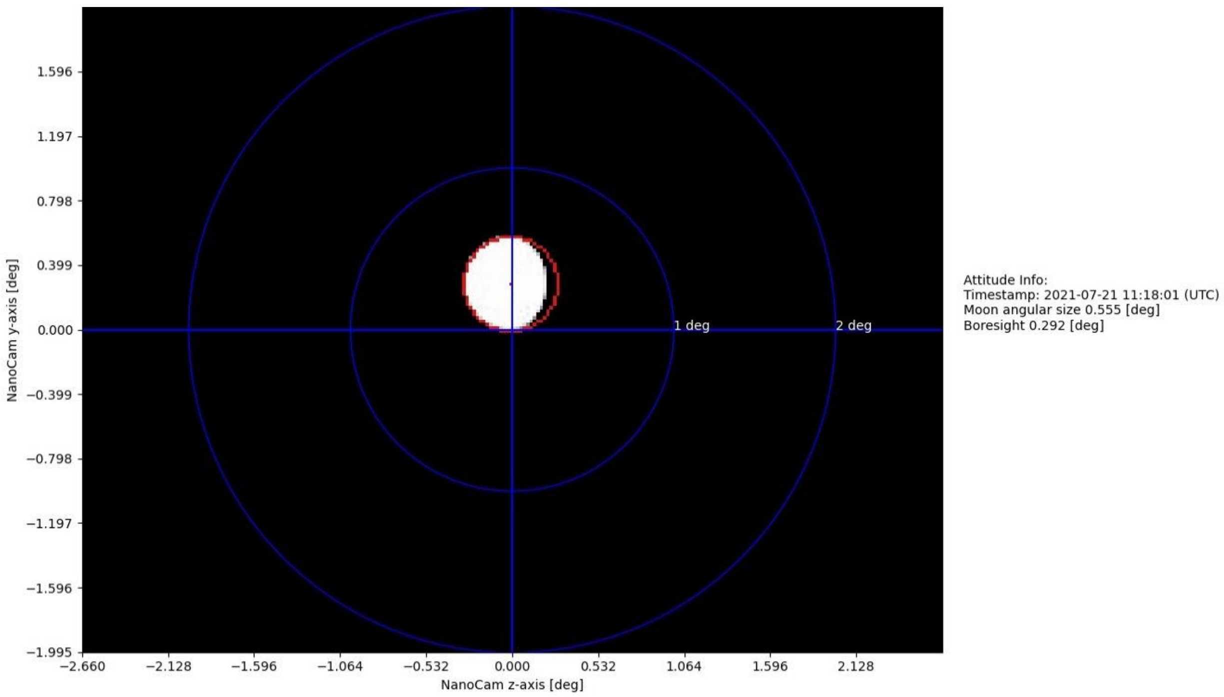

Figure 8. Maximum measured boresight error during moon calibration

This leads to a total pointing error of CubeL of maximum ±0.292°. In addition, it has to be mentioned that in all pictures an offset in the positive y-axis of minimum 0.086° was measured. That means, that for all measurements the center of gravity of the moon moved within a window of ±0.101°. With a larger CubeSat of 6U, as it is considered in the CubeISL mission and more precise sensors in the AOCS, it is assumed that a total pointing accuracy of ±0.1° can be achieved.
One further error source which contributes to the total pointing error is mechanical displacement between the CubeISL payload and the AOCS. This can occur due to mechanical tolerances in the mounting or settling effects during launch. To compensate the offset in space the mission will start with DTE downlinks. For a successful DTE connection a pointing error of ±1° is sufficient, which is easily doable with a CubeSat (as it could be shown with CubeL in PIXL-1). The telemetry of CubeISL contains the angles of the FSM. If the CubeISL payload tracks the beacon sent by the OGS, the mirror angles show the exact angular attitude of the payload with respect to the beacon. With this, the AOCS telemetry and the mirror angles can be correlated to measure the exact angular offset between the beacon and the assumed target pointing of the AOCS. With these results all mechanical offsets can be corrected between the CubeISL payload and the AOCS. This procedure can also later be used in the ISL to improve the pointing accuracy of the satellites to reduce offsets like the one described above, for example. The CubeISL sensor is the most precise sensor on board and gives, with the mirror angles, exact feedback of the pointing accuracy with respect to the incoming laser.

5 DEMONSTRATION MISSION

The CubeISL Laser Communication Terminal (LCT) will be demonstrated on the like named mission CubeISL. This mission will be realized with two identical 6-unit CubeSats on a Low Earth Orbit (LEO) in 2024. As depicted in Figure 9 the satellites will fly in a trailing constellation on the same orbital plane. To validate the LCT's parameters like acquisition time, data rate and also the maximum achievable distance, the satellites will have an orbit control system. Using this, the distance between them will be increased up to 1500 km in steps with validation experiments on each step. At the time of writing this paper, the orbit control solution is not yet finalized, thus the needed time for orbit modifications is not determined. Nevertheless, the main mission goals of validating the CubeISL payloads shall be done within one year after launch. It will contain the demonstration of the optical ISL as well as the 1 Gbps DTE to DLR's main Optical Ground Station (OGS) in Oberpfaffenhofen. Following this, there will be a secondary mission phase which focusses on demonstrating different use cases for a CubeSat based LEO formation with laser communication capabilities, for example the interoperability with other OGS'. The mission scenarios are also shown in Figure 9.

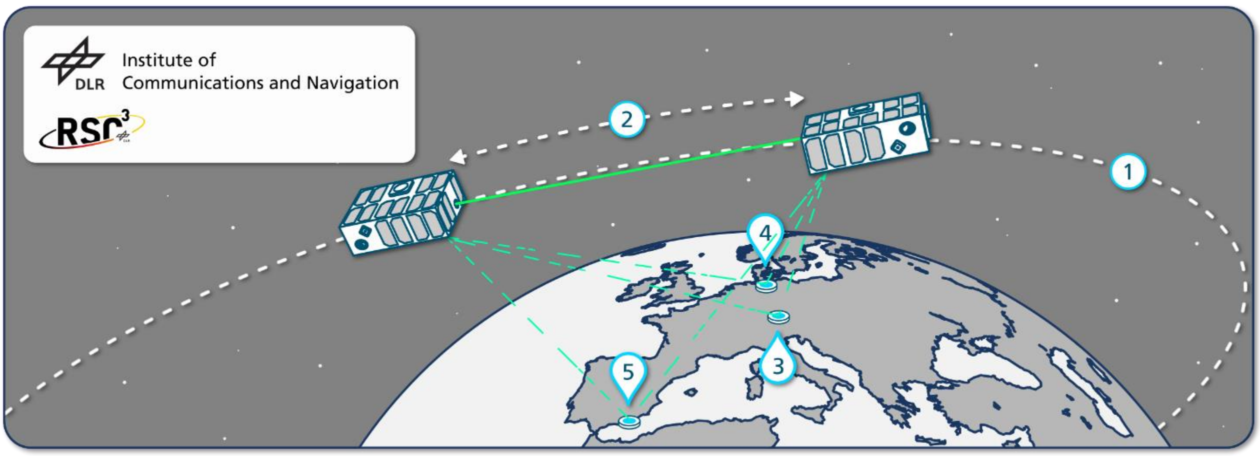

Figure 9. CubeISL concept of operations. (1) ~550 km Low Earth Orbit; (2) up to 1500 km distance between satellites; DLR's OGS' in Oberpfaffenhofen (3), Trauen (4) and Almeria (5)

The main challenges for the CubeISL satellites are, for the above described reasons, the requirements on the attitude control precision and the knowledge, both for angular attitude and lateral orbital position. The total attitude precision must be better than ±0.3°. To decrease the acquisition time ±0.1° are wished for, as described in chapter 4. The LCT's internal fine pointing mechanism generates an attitude error data product, which can be used by the satellite's AOCS computer as a feedback to point into the direction of the beacon laser. This eases the attitude control in both modes, ISL and DTE. On the other hand, this feedback is only available after the LCT has locked onto the beacon (in ISL the transmission laser of the counterpart terminal), which in case of an ISL drives the high requirements of the reliability of the acquisition concept, depending on the AOCS. Therefore, both CubeSats will be fitted with a GNSS Receiver, to create accurate orbital models, so that each satellite can calculate the other one's correct position to point the LCT to. An RF inter-satellite link could aid by directly feeding the knowledge of the own position to the other satellite prior to the laser link acquisition, thereby bypassing the need and error of the orbital modelling through historical positioning data. The high distances that the CubeISL terminal will be validated for and the limitations of a CubeSat makes the use of an RF-ISL system complicated though. This leads to a possible satellite bus design shown in Figure 10.

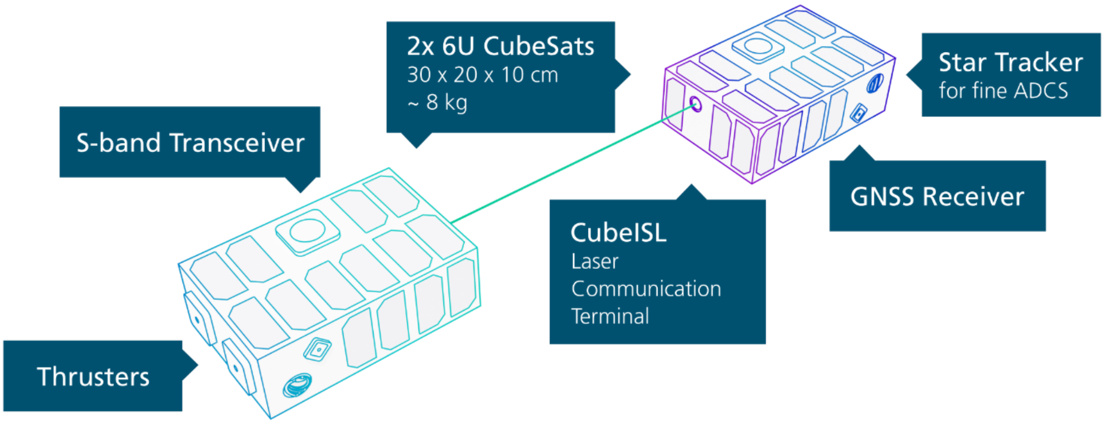

Figure 10. Key components of the CubeISL satellites

Each satellite will have one body-fixed LCT. Thus, between an optical inter-satellite link and a direct to earth link the satellites need maneuver from satellite target pointing to Earth target pointing mode. It is envisioned that these operations will be planned and controlled by DLR's German Space Operation Center (GSOC).

6 SUMMARY AND OUTLOOK

The optical terminal in CubeISL is based on the development of OSIRIS4CubeSat and extends the optical communication technology of Direct To Earth (DTE) links with the capability to serve optical Inter-Satellite Links (ISL). This paper discussed the challenges of link establishing in the ISL compared to DTE. It could be shown that an elaborated acquisition concept on both communication terminals is required. The discussed procedures show that the time of the acquisition is sufficient for operational scenarios. The duration of the acquisition is depending on the pointing knowledge and accuracy of the satellites. Results from the PIXL-1 mission have been incorporated into the development of the acquisition concept to make sure that the concept can be realized in a realistic scenario.

The next step is to prove the feasibility of the concept in a laboratory demonstration. Thus, to prototypes of the CubeISL optical terminal are assembled and the connection establishing will be demonstrated and further characterized. As a next step both terminals will be operated on two hexapods to replicate the satellites trajectory. After the final characterization, an Engineering Qualification Model (EQM) and two Flight Models (FM) will be assembled in parallel. After the following qualification with the EQM, which includes a final end-to-end test, the two FM's will be delivered to the satellite manufacturer for the final mission. In parallel further experiments in PIXL-1 will be performed to gain additional measurement results and mission data as a knowledge base for the CubeISL mission.

7 REFERENCES

[1] Fuchs, Christian, et al. *Transmitter Diversity With Phase-Division Applied to Optical GEO Feeder Links*, IEEE Photonics Technology Letters, 33 (11), 541-544, 2021

[2] Kahr, Erin, et al. *Estimation and Analysis of Two Line Elements for Small Satellites*. Journal of Spacecraft and Rockets, 50 (2), 433-439. American Institute of Aeronautics and Astronautics (AIAA), 2013

[3] Uwe Sterr, Mark Gregory, and Frank Heine. *Beaconless acquisition for isl and sgl, summary of 3 years operation in space and on ground*. In 2011 International Conference on Space Optical Systems and Applications (ICSOS), 38-43, 2011.