Qualification of Inter-Satellite Link Laser Communication Terminals on CubeSats - CubeISL

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ABSTRACT

Free Space Optical (FSO) communications on the rise to replace classic Radio-Frequency (RF) systems in many sectors of satellite communication. DLR has a long heritage in developing Laser Communication Terminals (LCT's) for LEO satellites. Major requirement for the design of the terminals is the optical characterization. Beside the verification in the laboratory, the terminals must withstand the harsh conditions of launch and space and fulfil all functionalities.

To characterize the LCT's optical properties, DLR developed and built an Optical Ground Support Equipment (OGSE) which mirrors the functionalities of an Optical Ground Station (OGS), in a small scale, to test and adjust the LCT's. This paper describes the setup of the OGSE and its capabilities.

The success of the New Space move is based on short qualification and development times. Thus, DLR tailors common standards to the needs of the final mission. The paper describes the qualification approach with the example of the world's smallest LCT OSIRIS4CubeSat (O4C).

The next step is to transfer the technology from Direct-To-Earth (DTE) into the Inter-Satellite Link (ISL) domain in the CubeISL project. To reduce time and cost efforts for development and qualification, subsystems and processes were reused from O4C.

INTRODUCTION

Laser Communication is key for higher data rates on small satellites. The high efficiency of the communication allows to use limited optical output power for a significant increase in data rate compared to Radio-Frequency (RF) systems.

DLR's Institute of Communications and Navigation is active in the field of Free Space Optical (FSO) communication on small satellites for more than 20 years. Starting on satellites with a total mass of about 120 kg like the Flying Laptop satellite of University of Stuttgart, the size of the satellites decreased in the meantime and with it also the size of the laser communication terminal. With the development of OSIRIS4CubeSat, the limits of miniaturization have been approached.

CubeSats do not only play an increasing role in space industry, they also bring challenges on the technical side with low size, weight and power but also on organizational as well as financial side. While the technical aspects have been covered, the focus of this paper will be on the qualification process.

Using fully space-qualified components like in traditional space allows to apply all standards developed and applied over many years. On a CubeSat, fully space qualified components are not only behind the state of the art but also budget wise unlikely to be an optimal choice based on the requirements of a comparably short mission duration of typically 5 years in LEO orbit. The OSIRIS developments (Optical Space Infrared Downlink System) are based on Commercial-off-the-Shelf (COTS) components in combination with an individual qualification campaign for each mission.

Therefore, DLR developed a qualification process for COTS-based missions on CubeSats with a lifetime of minimum 5 years in a LEO orbit. This qualification process consists of classical qualification tests like vibration, thermal-vacuum and radiation testing but optimized for the mission needs. This allows to keep the balance between a minimum technical risk in combination with short development times and an attractive budget for the development as well as a later technology transfer in a mass manufacturing.

OSIRIS4CubeSat

With the upcoming New Space move DLR saw the necessity for miniaturized Laser Communication Terminals (LCT), especially designed for CubeSats. Together with its industrialization partner Tesat Spacecom GmbH, DLR developed OSIRIS4CubeSat (O4C), the world's smallest LCT, which is marketed under the name CubeLCT by Tesat.[1] Figure 1 shows the first Flight Model (FM) of O4C.

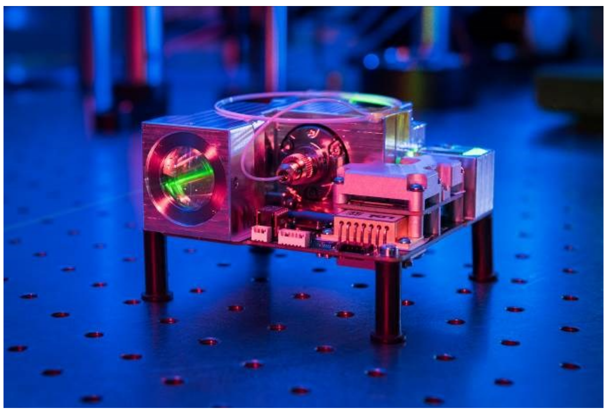

Figure 1: OSIRIS4CubeSat Flight Model

O4C can transmit data at 100 Mbps via laser to an Optical Ground Station (OGS). To establish a connection, O4C uses the Pointing, Acquisition and Tracking (PAT) system, where a beacon from the OGS illuminates the satellite, O4C acquires the beacon and tracks it in a closed loop. This so-called Fine Pointing Assembly (FPA) consists of a 4-Quadrant Detector (4QD), to measure the angular offset, a microcontroller (µC) to calculate the control variable and a Fast Steering Mirror (FSM) to correct the measured offset. With this FPA, the terminal can compensate for inaccuracies of the satellites AOCS of up to ±1° (ex-aperture). The transmission beam is coupled into the exact same optical path as the incoming signal to guarantee that it hits the OGS.

The first O4C payload flies on the 3U CubeSat CubeL of the PIXL-1 mission. It started on the 24th of January 2021 with the goal to demonstrate a picture transfer via an optical link from space to the ground.

CubeISL

In CubeISL the technology of laser communication is transferred from Direct-To-Earth (DTE) into the Inter-Satellite Link (ISL) domain. The goal is to extend O4C towards a bidirectional connection between two satellites with a data rate of 100 Mbps over a distance of up to 1.500 km. DLR uses O4C as a base technology for future developments. The modular approach enables reusing many subsystems and components, and leads to time and cost reduction in the development and qualification.

Figure 2 shows the first prototype of the CubeISL payload. In CubeISL, O4C is extended by an optical amplifier, to overcome the power loss in the link budget, due to the smaller receiver size. The receiver is no longer a 60 cm or 80 cm mirror at an OGS, it is the 20 mm aperture of the partner terminal. Furthermore, the terminal is extended by a Data Handling Unit (DHU) to compute high processing tasks like en- and decoding of the transmit data.[2]

Figure 2: CubeISL Prototype

The CubeISL payload is divided into three major sections. The Transmitter System is located on the top layer and consists of the optical amplifier and the laser source. The DHU sits on the bottom layer of the payload. The middle layer shows the adapted O4C terminal, the so-called Optical Terminal of CubeISL. The optical path is extended by a data receiver, while the tracking and transmission paths remained unchanged. This allows the reuse of the known test equipment and procedures developed during O4C.

CubeISL uses the PAT system as well. The difference to O4C is that no longer a beacon from an OGS is used for acquisition and tracking. The terminal uses the transmission laser of the partner terminal to establish and keep the connection.

OPTICAL VERIFICATION

The key to success is the optical design of the terminal. The optical system is diffraction limited, which means the divergence of the transmission beam is at the physically possible minimum. Thus, the highest possible optical power density can be achieved and leads to the high efficiency of the terminal.

Beside the transmission beam, also the receiving beam must be characterized. The tracking abilities are mainly driven by the spot size and form at the 4QD inside the terminal.

Transmission (Tx) and Receiving (Rx) beam must be perfectly aligned to each other. The tolerance of the Tx-/Rx-alignment is driven by the smallest divergence, in that case the one of the Tx-beam.

The verification measurements and adjustment methods of these key requirements are described in the following.

OGSE

The beacon sent from an OGS hits the satellite in orbit with an almost flat wave front and overfills the aperture. This causes diffraction effects inside the terminal and affects the beam shape on the 4QD for which the optical system was designed. However, in order to adjust and verify the optical performance of the terminal, an Optical Ground Support Equipment (OGSE) was developed. Its purpose is to simulate the beacon hitting the terminal in orbit and monitor the Tx beam at the same time to use it for the alignment of the Tx and Rx system.

Figure 3 shows a schematic of the OGSE with the terminal aligned to it. A fiber collimator (not depicted) collimates the light at the beacon wavelength which is transmitted through a beam splitter and expanded afterward (red rays). In reverse direction, light entering the telescope is shrunk and hits the beam splitter (green and blue rays). The transmitted part is not used, but the reflected part is focused by a lens onto a camera. In this configuration, the OGSE can transmit the beacon signal and receive the Tx beam of the terminal. In order to reference the optical axis of the OGSE for adjustments of the terminal, a retroreflector is used in front of the beam expander creating an optical feedback at the camera (blue rays).

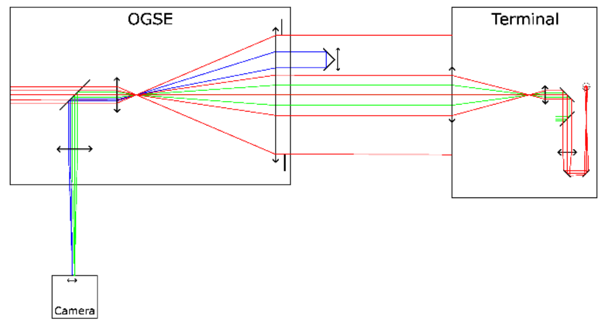

Figure 3: OGSE set up for terminal characterization and adjustments

Divergence

The divergence of the Tx beam path of the terminal is adjusted by the fiber collimator and the aperture lens of the telescope. Since the collimator is a COTS component which can be used for a certain range of near infrared wavelengths and different fibers, the distance of the lens to the fiber tip can be adjusted. This is done using the central wavelength of the High-Power Laser Diode (HPLD), but with a benchtop laser which has a narrow linewidth. A shearing interferometer and a camera are used for collimation. After the integration of the collimator, the access for tools needed to the collimation is blocked, hence it cannot be used as to compensate for any mismatches of the telescope without disassembling the system.

With the collimator, beam splitter and Fast Steering Mirror (FSM) integrated, the telescope can then be adjusted. The aperture lens shell is mounted inside a fine-pitched thread in the telescope block, so that the distance between the two lenses is precisely adjusted by rotating the shell along the thread.

After collimation of the Tx system, the beam size at the position of the 4QD is verified with a camera. If the size does not match the design and tracking performance is reduced, the aperture lens can be readjusted during a tracking test. This will influence the divergence, but the change in beam size is more sensitive than the change in Tx divergence and within the tolerance.

Before the FM is integrated into the satellite, the aperture lens has to be readjusted for use in vacuum. An optics simulation showed negligible influence of the collimator to the divergence, but the telescope has a high impact on the divergence and tracking performance. Due to different refraction indices between glass to air and glass to vacuum, the focal lengths of the lenses get smaller. Therefore, the distance between the two telescope lenses for compensation of the change in refractive index is determined using an optics design software. From the already adjusted optimal position for use in air, the aperture lens is turned clockwise for this compensation.

Tracking

One of the main functionalities of the terminal is to detect attitude errors with respect to the pointing target and hence correct for it. The OGSE helps to set up a testbed that not only meets the high requirements for angular alignment accuracy, but also provides a high degree of reproducibility for individual sequentially performed tests.

To characterize the tracking behavior of the terminal, the OGSE, the terminal itself and an actuator such as a hexapod are required. A minimum incremental step size should be chosen that equals at least the precision of the FSM itself at ex-aperture. Repeatability that lies within the divergence of the transmitter is additionally desirable for terminal manipulation. In contrast, the linear displacement actuation can be chosen coarser. In a first step, the terminal is aligned with linear movements such that the terminals aperture is placed as centrally as possible in the beam of the OGSE. This ensures that, even with small distances between OGSE and Terminal and angular movements that do not pivot around the optical pupil, no translational effects due to beam truncation are present. In a second step, the terminal is aligned with rotational movements in an iterative process such that the power intensities on all four quadrants of the 4QD are equally distributed. This procedure is described below in detail. All further tests are performed with respect to this orientation.

To verify the functionality of the acquisition and control algorithm, the Field of Regard (FoR) ±1° ex-aperture is traversed by the hexapod to ensure that tracking is achieved and maintained over the full operating range.

The camera can be used in the receiving path of the OGSE to measure the remaining jitter in closed loop mode. For example, a camera with 30 µm pixel pitch and a focus lens at a focal length of 500 mm can be used for this purpose to achieve precision in the order of microradians. A sufficiently large integration time should be selected to allow the deviations of the spot to be represented as an increase in diameter. At this step, both the repeatability and the absolute maximum deviation can be measured with the appropriate camera software.

Tx-/Rx-Alignment

During a flyover, the terminal is spiraling the FSM in a loop until the beacon from the OGS is acquired and afterwards tracks constantly. In order to guarantee precise pointing of the Tx beam to the OGS, the Tx- and Rx optical system have to be aligned to each other with minimum angular offset.

Three main steps are needed to perform the Tx/Rx alignment after the system’s divergence has been adjusted and tracking could be verified:

Step 1 involves the OGSE with an attached camera and a retroreflector as schematically shown in Figure 4. The red rays indicate the beacon signal coming from a fiber collimator on the left (not depicted) which is transmitted through the beam splitter and expanded with the telescope. The retroflector is positioned in front of the telescope, so that the exiting light of the OGSE is reflected back (cf. blue rays in the schematics). After partial reflection at the beam splitter, the light is focused by a lens onto a camera sensor. The camera is correctly aligned to the OGSE if the sensor is placed precisely at the focal plane. This can be adjusted by moving the retro reflector on one axis over the whole aperture of the telescope. If the spot on the sensor moves as well, the camera is not in the focal plane and has to be readjusted. At the focal plane, the spot will stay constant, while the retro reflector is moving, but it might change its shape. Therefore, it is practical to use a software showing and marking the Center Of Gravity (COG) of the spot in order to use coordinate values for the reference point.

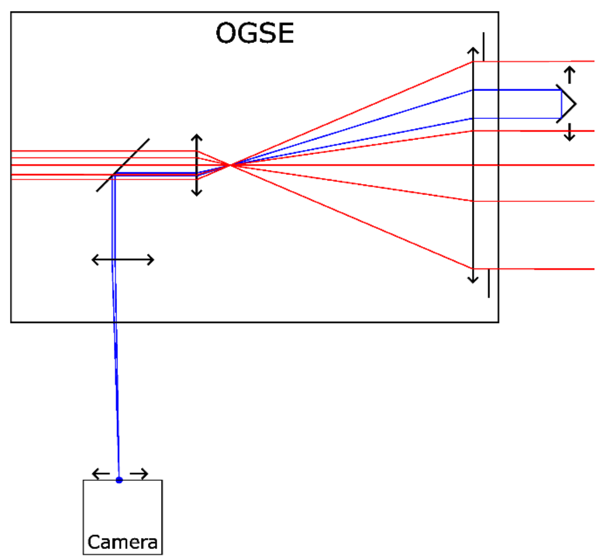

Figure 4: Step 1: Adjustment of the OGSE for setting the reference point.

Step 2 involves the OGSE and the terminal placed in front of it as shown in Figure 5. The terminal is placed onto a hexapod to align the Rx-system of the terminal to the optical axis of the OGSE. If the tracking of the PAT system is active, the optical axis of the OGSE needs to be at least in the FoR of the terminal's Rx-system. The FSM compensates eventual inaccuracies.

If the tracking system is not active, the alignment needs to be more precise, so that the beacon light hits the center of the 4QD. Only a rotation around pitch and yaw axis influence the position of the spot at the 4QD. Therefore, the translational alignment of the terminal is checked with another camera imaging the aperture of the terminal and closing the iris of the OGSE until the shadow can be observed at the aperture lens shell.

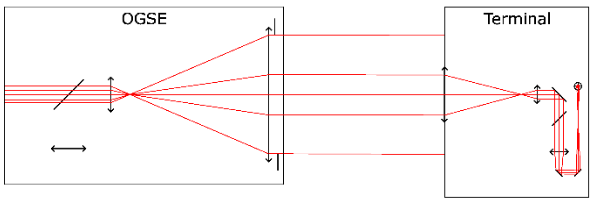

Figure 5: Step 2: Alignment of the terminal to the OGSE.

Step 3 is the final alignment of the terminal's Tx-system. As indicated by green rays in Figure 6, the Tx-beam forms a spot on the camera sensor of the OGSE whose position is dependent on the angle of the Tx-beam. While keeping the terminal constantly aligned to the OGSE by either using active tracking or readjustment with the hexapod, the collimator of the terminal is adjusted until the COG of the Tx-beam matches the COG of the reference point.

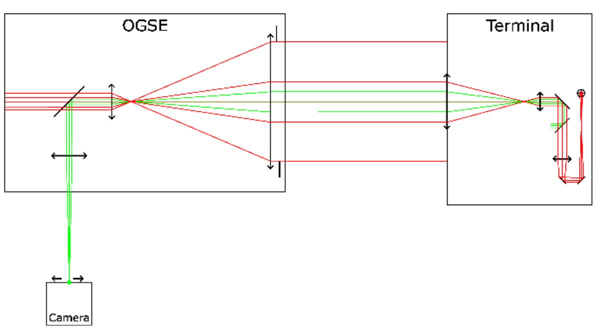

Figure 6: Step 3: Adjustment of the terminals Tx system to the reference point from step 1.

QUALIFICATION OF OSIRIS4CUBESAT

DLR follows the New Space approach to reduce costs and effort for the qualification of the LCT's. Standards are tailored to the specific needs of the final mission. In general, the qualification can be separated into three parts:

- Vibration
- Thermal-Vacuum
- Radiation

The whole qualification is done on payload level, which means the entire terminal is tested, after it is fully assembled. This enables reductions in qualification time compared to tests on subsystem or parts level.

Vibration

The first version of O4C started on a 3U satellite CubeL with a Falcon 9 from SpaceX. The launcher was fixed before the final qualification. The National Aeronautics and Space Administration (NASA) defines the General Environmental Verification Standard (GEVS) load specifications for canisterized launches such as in CubeSats. GEVS lays an envelope over the loads of all known launch vehicles. This means, that the GEVS are always higher than every single launcher. Figure 7 compares random vibration loads for Falcon 9 and GEVS as an example. As the Falcon 9 was already fixed as a launcher for O4C, the payload was qualified only for the loads of the SpaceX launcher.

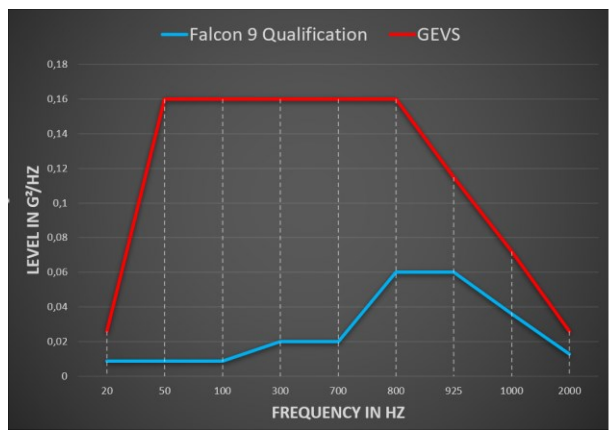

Figure 7: Comparison of random vibration loads between Falcon 9 and GEVS[3 4]

For the test procedures itself, DLR follows to the ECSS standards. One of the criteria is that none of the tests causes a shift of the first eigenfrequency by more than 10%. Thus, the resulting order of the tests is:

1. Modal
2. Sine
3. Modal
4. Random Vibration
5. Modal

These five tests have to be performed for all three axes, making 15 tests in total.[5]

Beside the shift of the eigenfrequency a functional test was performed before and after the vibration campaign, but the most important success criterion is the verification of the optical characterization. After the vibration tests divergence and the Tx-/Rx-Alignment were measured. The Link Budget includes some headroom for the optical parameters. It includes a beam quality parameter, M² value of 1.2 and a pointing loss of 3 dB due to misalignment between the tracking path and the transmission beam are considered. The vibration test is successful if the M² and pointing losses are within these tolerances and the functionality of the terminal can be verified.

Thermal-Vacuum

Deformations due to thermal effects can negatively influence the divergence and the TX-/Rx-Alignment, if single components move relatively to each other. Thus, O4C was qualified in Thermal Vacuum Chamber (TVAC).

The goal was to measure in situ the thermal effects of thermal deformation on the optical parameters. Therefore, the test was done in a TVAC which contains an optical window, to allow the OGSE to be located outside the TVAC. Figure 8 shows the setup. The EQM was placed at the bottom plate of the TVAC to maximize the heat flux into the system. A periscope was required to guide the laser through the optical windows as this height could not be adjusted. The setup allows to directly measure the divergence and the Tx-/Rx-Alignment during the temperature cycles in vacuum with the OGSE.

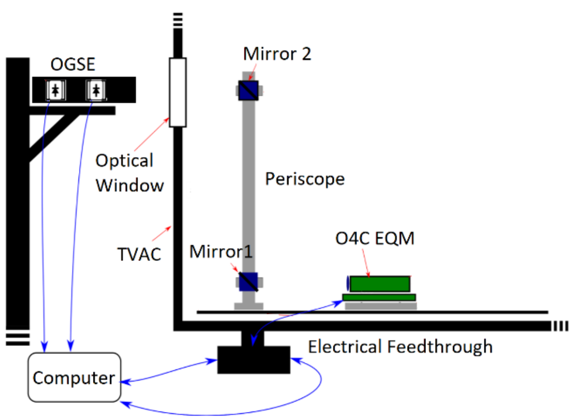

Figure 8: TVAC setup for O4C

O4C was qualified according to the ECSS standard. This means, eight cycles were run in total, one under survival (unpowered at -40 to +80°C) and seven under operational temperatures (powered at -20 to +60°C).[5]

Radiation

O4C is designed for a mission duration of five years in a 550 km Sun-Synchronous Orbit (SSO). Below the first Van Allen Belt the amount of corpuscular radiation is negligible, which is why only Total Ionizing Dose (TID) was considered for the qualification. The terminal is designed for the use inside a satellite and not for the use directly exposed to space. It can be considered that there is always the satellites shell, including solar panels or antennas around the terminal which can be understood as a shielding. With the conservative assumption that the shielding has at least a thickness of 1.5 mm (equivalent Al thickness), a maximum dose of 17 krad(Si) is expected for the described use case of a 550 km SSO and 18 krad(Si) for a 600 km SSO. This can be seen in Figure 9. The radiation modeling was performed with OMERE using the AX-9 trapped particles mean model, the ESP solar protons with 90% confidence, and the Psychic model for solar ions. The launch was chosen in 01/01/2024, which corresponds with a maximum of the 11-year solar cycle.

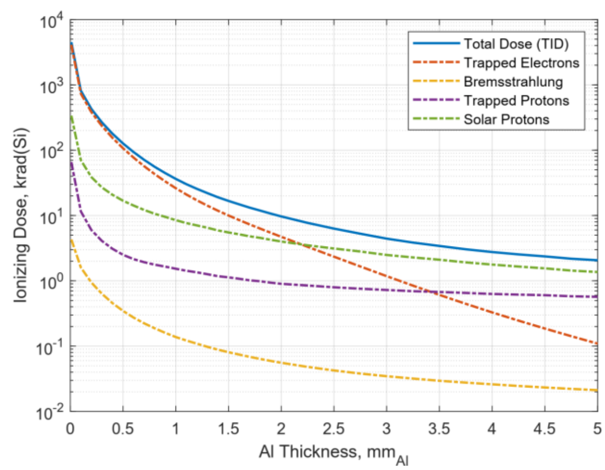

Figure 9: Ionizing dose over shielding on a 5-year SSO mission at 550 km altitude

For the qualification of O4C, the terminal was radiated over two days with a Cobalt-60 source at the Helmholtz Center for Materials and Energy (HZB) in Berlin. On the first day the radiation dose was reduced to 0.5 krad/h, to avoid saturation effects and increased to 3 krad/h on the second day. The dose was adjusted by the distance between the source and the EQM. After a TID of 20 krad(Si) the terminal was tested, all parameters were measured and deviations were evaluated.

QUALIFICATION PHILOSOPHY OF CUBEISL

The goal of the qualification of CubeISL is to minimize costs, effort and duration of the qualification campaign, based on known procedures. Many parts and subsystems are reused from O4C, so the qualification does not have to be performed with the whole payload. The modular approach allows to qualify single subsystems while others can be developed in parallel. Some parts need a reduced delta-qualification, other do not have to be qualified at all, as they were already qualified during O4C. The differences and advantages for the three qualification processes are discussed in the following.

Vibration

Overqualification can easily lead to extended development times and an oversized system design and cost. Accurate modeling and qualification of the CubeSat payload are critical to minimize the risk of failure during launch, deployment, and operations in space. CubeISL takes advantage of prior system qualifications on O4C, where it could be shown that the Fine Steering Mirror (FSM) poses the biggest challenge under mechanical vibration loads.

The goal for the CubeISL payload design was to shift the eigenfrequency of the terminal by a safety factor of 2 higher than the mirror's eigenfrequency. Lessons learned from O4C showed that realistic models that include the CubeSat structure lead to higher eigenfrequencies than when the subsystem or payload is attached directly to the vibration table. Initial Ansys models showed that with the CubeSat frame, the eigenfrequencies of the payload already increased by a factor of 1.3 on CubeISL. To verify the accuracy of the mechanical models, they were first adapted to match the behavior of the mirror and optical terminal from previous shaker tests. The models were then extended with the remaining components (e.g., EDFA, DHU, and structure).

The analysis of different CubeSat structures with varying rail thickness, materials, and profiles did not lead to significant variations in the eigenfrequency. The mainboard Printed Circuit Board (PCB) of the Optical Terminal acts as a membrane attached to its corners that can swing in the center. Additional protective measures, such as different materials (FR4 and Al) for the PCB, were considered to minimize this effect. The widest frequency shifts were achieved using a cross-shaped Al bracket structure underneath the PCB to provide an additional fixation at its center, shown in Figure 10. The new eigenfrequency of the terminal was increased by a factor of 1.7 in a worst-case scenario analysis. Further tests will be performed on the EQM to verify the Ansys models.

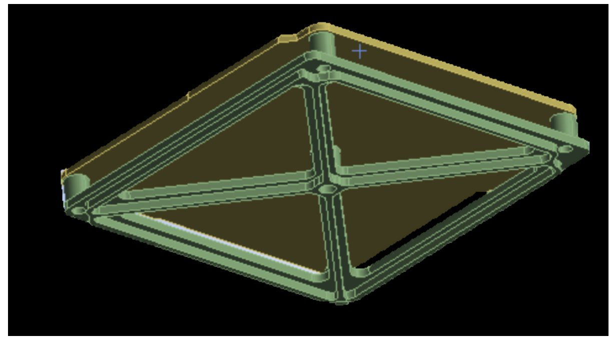

Figure 10: CubeISL Optical Terminal mainboard with vibration-dampening bracket

Additional measures to shift the eigenfrequency will be discussed with the satellite manufacturer. A careful design of the satellite structure will allow tuning of the transfer function of the vibration spectrum. The material and size of the CubeSat bus rails can be adapted to improve vibration dampening. At the time of writing this paper, the final CubeSat manufacturer has not been selected.

Thermal-Vacuum

To model the thermal conditions under vacuum and define the thermal interfaces, it is first necessary to finalize the component selection and the design of the terminal. On CubeISL, the two critical components that generate the most heat are the DHU and the Transmitter System. These two subsystems are placed on each side of the 1U CubeSat structure to allow easier heat dissipation toward the satellite. The optomechanical block lies in between, as the optical alignment has already been verified on O4C for operational temperatures between -20 and 60ºC and survival temperature -40 to 80ºC as described above for O4C. The aluminum blocks on which the optical components are fixed, have been designed massive enough to avoid significant deformation in this temperature range. The transmitter system and DHU include a heat sink and mechanical Al structure to dissipate the excess heat and connect them to the satellite structure. The concept will be tested in a hot and cold case in a TVAC to verify the design of the thermal interfaces in an ultra-high vacuum (i.e., $<1 \cdot 10^{-6}$ mbar).

In-orbit temperature data of the 3U CubeSat CubeL has shown that the temperature of O4C fluctuates between 0 and 23ºC for all measurements performed during a timeframe of 30 days. The temperature results over time can be seen in Figure 11. Temperature measurements of the O4C payload over two months vary from -5 to 25ºC.

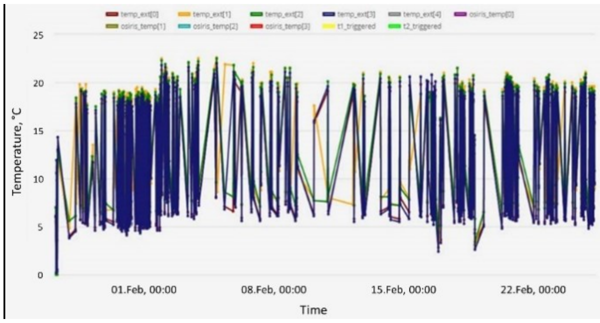

Figure 11: In-orbit temperature measurements of O4C inside the 3U CubeSat CubeL

To avoid an overqualification, CubeISL will only be tested between -10 and 40ºC in a TVAC, as its orbit will be comparable to the one in the PIXL-1 mission. This allows a significant reduction of the qualification duration. Main time driver is heating up and cooling down the terminal. The subsystems of CubeISL are mounted in the CubeSat rail-system. These mechanical interfaces between the subsystems and the rails have very small contact surfaces which act as thermal resistors for heat transfer. Thus, simplifying the qualification requirements reduces the booking time of the TVAC accordingly and with it the cost of the qualification campaign.

Radiation

The influence of radiation on the performance of the newly introduced amplifier and receiver components has to be evaluated, as these affect directly the power budget. Apart from them, all other components of the LCT have been previously tested either within the scope of O4C or are radiation-hardened by design (e.g., the DHU), so no further tests were deemed necessary.

One way to reduce the time and cost effort of testing is to outsource the irradiation procedure. This was feasible as only the effect of TID was of concern, and neither transient effects such as those caused by Single Event Effects (SEEs) nor in-between measurements at intermediate radiation levels had to be done. Since the evaluated components need to remain within the performance margins of the link budget and power consumption at their End Of Life (EOL), they were only tested before and after being irradiated. Naturally, an alternative part or new radiation mitigation techniques would have been required if one part shows degraded performance outside the margins or in case of device failure.

The transmitter components under test were the EDFA with its external input and output fibers (see Figure 12). It has to be investigated whether the maximum optical transmit power can be maintained and which decrease in power conversion efficiency has to be expected as a consequence of Radiation Induced Attenuation (RIA). Treating the EDFA and optical fiber as a unit also facilitates the test itself, since fibers are often directly spliced to the amplifier, and removing them pre- and post-irradiation can be a cumbersome procedure.

Concerning the receiver, ionizing radiation leads to a higher dark current I_{dark} of the Avalanche Photodiode (APD) and thus a higher receiver noise floor, which manifests itself in the form of a reduced detector sensitivity. The influence of TID on the rest of the receiver signal chain (i.e., amplifier and filter stages) is negligible in comparison and will not be covered.

To determine the dark current characteristic of the APD, the voltage drop is measured over a series shunt resistor. This is necessary because the APD's high interelectrode resistance (which is voltage dependent and lies in the order of 100 MΩ) makes a current measurement difficult. The shunt resistor also clamps the current at high bias voltages, which prevents the APD from thermal runaway (see Figure 12).

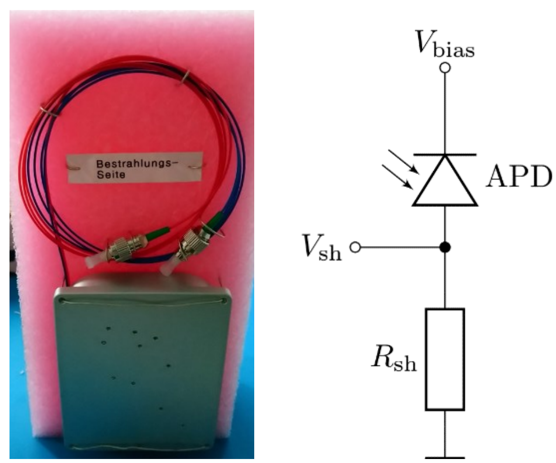

Figure 12: Radiation test setup with EDFA and fiber (left) and APD measurement circuit (right)

From Figure 13, it can be observed that while irradiation can significantly reduce the optical efficiency, a stable output power of 1 W can be maintained due to the EDFA's overhead in optical power of 25%. Its available overhead will gradually decrease over the mission lifetime. Regarding the APD, the measurements in Figure 14 show the radiation-induced increase in dark current for two relevant APDs and their high dependency on the applied bias voltage. As the APD is designed to operate only within the region of avalanche breakdown ($V@I_{\mathrm{dark}} = 100\ \mu A$), the resulting loss in sensitivity remains among margins for the tested TID.

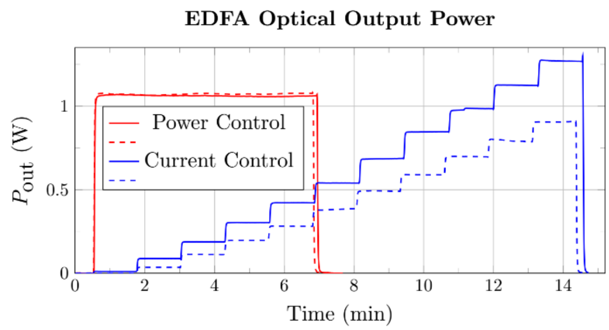

Figure 13: EDFA output power measurements in current and power control mode before (solid) and after (dashed) irradiation

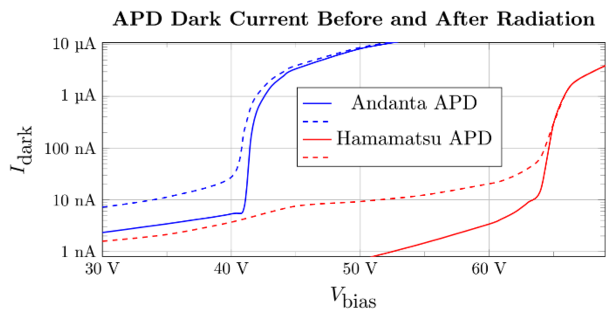

Figure 14: APD dark current before and after irradiation with applied bias voltage

All radiation tests were, as for O4C, conducted at the HZB in Berlin. The probes were subjected to a TID of 23 krad(Si), which was administered at a constant dose rate of 1krad/h. The TID has been chosen as a worst-case estimate from simulations, assuming a maximum mission duration of 5 years in an SSO orbit at 600 km, 1.5 mm aluminum shielding, and a 25% safety margin.

The TID irradiation tests have demonstrated that all components will operate within the defined specifications and margins. This can be guaranteed even for worse conditions than those expected during the mission.

SUMMARY AND OUTLOOK

This paper describes the optical and environmental qualification procedure of multiple LCT payloads developed at DLR for CubeSat missions following the New Space approach. The terminal's optical functionality (i.e., its divergence, tracking system, and Tx-/Rx-alignment procedure) can be efficiently verified with the help of a setup using an OGSE and a hexapod. The design and calibration of the OGSE are described in detail in three straightforward steps.

The shorter qualification times reduce personal costs and user fees for testing facilities. Remote tests reduce travel costs and releases resources. These free resources can then be used in other tasks and increases the efficiency of the whole development. The modular design of DLR's terminals is one of the key enablers to the effort reduction of the qualification campaigns. Tailoring the standards and qualifying and testing only for what is absolutely necessary guarantees short and efficient developments.

The O4C payload currently remains fully operational in space for over two years on the 3U CubeSat CubeL. Its environmental qualification campaign for vibration, thermal vacuum, and radiation conditions based on mission-tailored ECSS standards for LEO has been covered. The subsequent optical verification during and after the qualification is also shown.

Due to the success of the O4C campaign, DLR applies the same qualification philosophy for its subsequent CubeSat projects like CubeISL. Additionally, the new projects follow a modular design approach that allows for testing and qualifying individual subsystems as they approach design maturity. This procedure guarantees short and efficient development times despite an increased system complexity. The state-of-the-art CubeISL payload will demonstrate 1 Gbps downlinks and 100 Mbps ISLs at 1 500 km link distance between two 6U CubeSats.

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