

IMPROVING RELIABILITY OF LASER COMMUNICATION ON CUBESATS – LESSONS LEARNED FROM PIXL-1 TO QUBE

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ABSTRACT

Free Space Optical Communications is gaining ground in several fields of satellite communication. The German Aerospace Center developed with OSIRIS4CubeSat a highly compact, efficient laser communication terminal, that serves as a technology base for future applications. The first evolution of this terminal is OSIRIS4QUBE to enable preparing technologies for quantum key distribution. OSIRIS4CubeSat was demonstrated in the PIXL-1 mission with the goal to verify an end-to-end data transmission. This mission was carried out on a 3U CubeSat. Even though the mission was successful, it took quite some effort to ensure the required conditions to close an optical link between the laser communication terminal and the optical ground station. This led to relatively low percentage of successful optical experiments. The lessons learned of the PIXL-1 mission were analyzed and discussed with Center for Telematics in preparation of the QUBE mission, where OSIRIS4QUBE is part of the demonstration mission. This paper shows the insights of the PIXL-1 mission and explains the following actions and improvements taken for the QUBE mission. These findings lead the way for upcoming mission concepts to increase the availability and reliability of laser communication in the future.

1 INTRODUCTION

With the increasing number of satellites and the development of new use cases in space, the data volume generated in space increases constantly. Thus, for nearly every space mission it is intended to maximize the data throughput from the spacecraft to the ground. The data throughput depends mainly on three factors, the data rate of the transmission channel, the link duration and the number of connections. Free Space Optical Communication (FSOC) can improve the data throughput with its very high data rates [1]. Classical Radio-Frequency (RF) channels on the other hand, are very robust against atmospheric and weather effects and are established for decades in space. Their benefit is a very high connection availability and reliability. The ideal communication system would transmit data at a speed like provided by FSOC, but has the same availability and reliability as RF.

To make use of the benefits of FSOC, it is the goal of research and industry to achieve sufficient availability and reliability of laser communication. The availability of FSOC is mainly driven by a blocked line of sight due to weather effects and the high pointing requirements of the laser beam. The high data rates of FSOC result from its capability of generated laser beams with extremely low divergence. This increases the power density at the receiver and with that, the achievable data rate. The divergences of such laser beams are much lower than the capabilities of common Attitude and Orbit Control Systems (AOCS) [2][3]. Thus, the satellite's residual pointing error must be compensated.

Therefore, common laser communication terminals (LCT) use closed-loop tracking with a Coarse Pointing Assembly (CPA) and/or a Fine Pointing Assembly (FPA). Regardless of whether a CPA or an FPA is used, the system relies on the satellite's Absolute Pointing Knowledge (APK). Hence, highly precise and accurate attitude sensors are required. On the other hand, the systems must be very well aligned mechanically to each other. If the pointing system's coordinate system is not aligned to the AOCS's coordinate system (which includes the attitude sensor), a pointing error offset will remain. Especially small satellites with limited space, cost-efficient concepts and short development times can suffer from inaccurate and unreliable subsystems. This can decrease the reliability of laser communication on small spacecrafts like CubeSats. Additionally, the pointing system inside the LCT orientates itself on a laser beacon sent from the receiver, in direct-to-Earth applications the Optical Ground Station (OGS). The OGS must ensure that the satellite is within the beacon's cone to illuminate the spacecraft. Therefore, an OGS needs also an accurate and precise pointing which is based on a mount model and the orbit files of the satellite.

The German Aerospace Center (DLR) has many years of experience in laser communication in space on small satellites. In every subsequent mission, it was intended to improve the number and the duration of the optical links in future missions. Therefore, the root causes for these performance losses in running and previous missions had to be identified and potential improvement topics were analyzed. Especially the experiences from the first CubeSat mission PIXL-1 (Photo Images Cross Laser 1) led to the necessity of improvements in the availability and reliability of laser downlinks. The lessons from PIXL-1 could directly be transferred in the following mission QUBE (Quantum Experiments on CubeSat). Both missions were carried out on a 3U CubeSat with a mostly identical LCT and used the same OGS, so that QUBE could immediately benefit from DLR's experiences.

In particular three topics were identified as main tasks that could potentially increase the availability and reliability of laser links:

1. Minimize mechanical offsets between the systems
2. Design and operation of the Attitude Determination and Control System (ADCS)
3. Highly accurate orbit predictions for OGS

This paper analyses the findings of PIXL-1 and describes the measures taken in preparation for and during the first phase of mission operation in QUBE.

1.1 Missions PIXL-1 and QUBE

PIXL-1 was the first CubeSat mission carried out by DLR. The goal of the mission was to demonstrate the world's smallest LCT OSIRIS4CubeSat [4]. Its capabilities were demonstrated by closing an end-to-end data transmission chain of operational data (images) to the OGS at the DLR site in Oberpfaffenhofen [5]. The platform was a 3U CubeSat with the name CubeL built by GomSpace A/S. CubeL used a star tracker as the most precise absolute attitude sensor. The operations concept foresaw that CubeL did the coarse pointing with a precision of minimum 1° and the fine pointing was done by OSIRIS4CubeSat internally. OSIRIS4CubeSat was equipped with an FPA to compensate residual pointing inaccuracies of up to 1° deviation from the target.

The goal of the QUBE mission was to verify technologies for Quantum Key Distribution (QKD) in space [6]. Low-power laser pulses and defined polarization signals, generated by experimental payloads¹ should be transmitted from a CubeSat to the ground. Therefore, DLR adapted the technology of OSIRIS4CubeSat to a bi-chromatic system to transmit these experimental signals [7]. The modular approach allowed to reuse the technology of OSIRIS4CubeSat, especially the FPA, so that the entire

¹ The experimental payloads were built and developed by Ludwig-Maximilians University in Munich and Friedrich-Alexander University in Erlangen.

link establishment concept could be taken over. Center for Telematics (ZfT) built and operated the satellite platform. Figure 1 shows both satellites with the two LCTs.

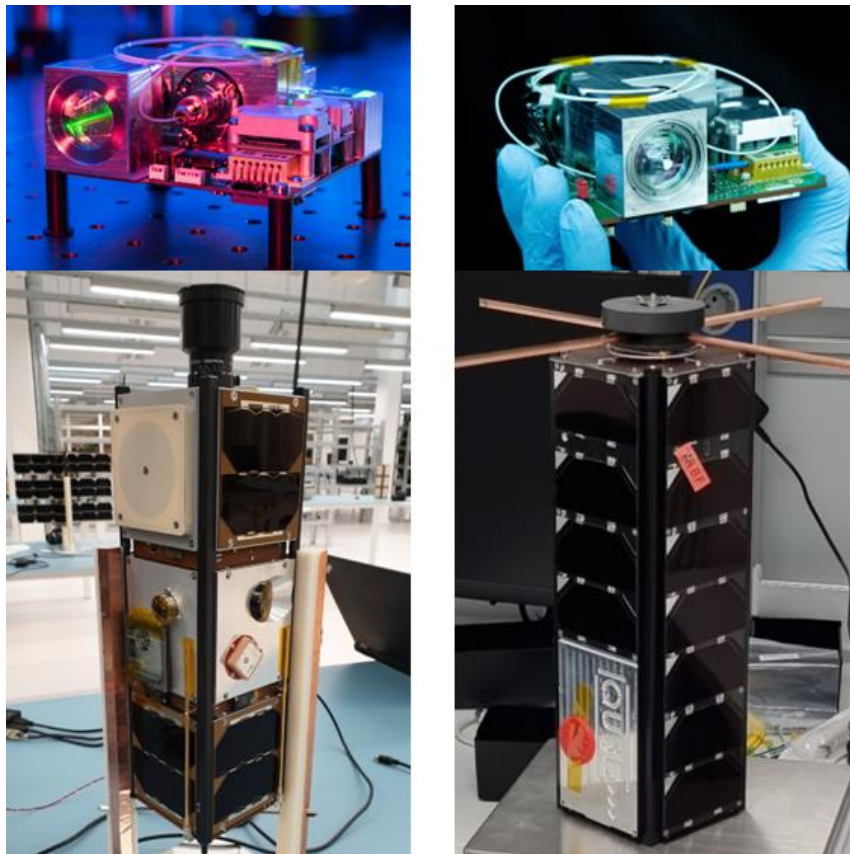


Figure 1. Left: CubeL with OSIRIS4CubeSat, right: QUBE with OSIRIS4QUBE

Both missions, PIXL-1 and QUBE, were carried out on very similar platforms so that their behavior was assumed to be comparable. The satellite QUBE used the same absolute sensor as CubeL and the counterpart, the OGS, was also identical. These similarities between the missions allowed to use the lessons learned from PIXL-1 and transfer them directly to QUBE. The operational goals were to achieve first light earlier in the mission, increase the number of successful laser links and increase the duration of the optical connection.

2 IMPROVEMENT POTENTIAL

The PIXL-1 mission started on the 24th of January 2021. First light was received on the 20th of August later that year with the 18th attempt. The first stable tracking was achieved on the 13th of June 2023. The longest permanent optical link between OSIRIS4CubeSat and the OGS lasted 275 s. To this day, it can be said, that in 11.6% of the links a signal was received and in 3.2% of the links tracking could be achieved.²

To transfer optical communication technology into operational use cases, the mission time until optical links can be established reliably must be reduced, the number of available links must be increased and the duration of the links must be increased. DLR identified three major root causes that led to the presented outcome of the PIXL-1 mission. This chapter describes these three causes, analyzes the reasons and explains the countermeasures taken for the QUBE mission.

² The numbers refer only to the links where the laser downlinks were commanded successfully. Links that were cancelled in advance were not included.

2.1 Mechanical Structure

The optical experiments with CubeL started in July 2021 after the Launch and Early Orbit Phase (LEOP) was successfully finished. During the first experiments no signal was received at the OGS. The evaluation of the telemetry afterwards showed, that, whenever the star tracker had a valid signal, the ADCS of CubeL was able to keep the boresight pointing error below the required 1° for the FPA. This led to the conclusion, that the two coordinate systems of the ADCS sensor (i.e. the star tracker) and OSIRIS4CubeSat were not sufficiently aligned to each other. As described in [5], after several experiments, a total offset 1.636° around the X- an 1.066° around the Y-axis could be measured. That the mechanical offset was larger than the field of regard of the FPA explains why no signal was received at the OGS even though the pointing was assumed to be sufficient, according to the ADCS error estimation.

These identified offsets were compensated in the recommendation of the downlinks during the PIXL-1 mission. Therefore, the mechanical offsets were added as initial pointing offsets to the commanded pointing target – the OGS. As the mechanical offset is static with regard to the satellite's body frame, it ensures that the pointing offsets compensate the mechanical offset independent from the satellite's attitude or the specific flyover.

For future missions or operational use cases, such sophisticated search algorithms or lengthy offset compensations have to be avoided. Thus, these insights were shared with ZfT during the design phase of the QUBE satellite.

The structural and electrical framework of the QUBE satellite was engineered for high-precision alignment and rapid system integration, adhering to the UNISEC-Europe standard. This modular approach ensures that the mechanical dimensions of the subsystems as well as the payloads are well-defined, utilizing standardized mounting hole positions and attachment schemes to maintain structural rigidity and interface compatibility across the bus [8].

To minimize complexity and potential points of failure, the QUBE architecture replaces traditional wiring harnesses with a sophisticated backplane and front access board system. All primary electrical interfaces, including power distribution and data lines, are consolidated within the UNISEC connector. This cableless design not only streamlines the assembly process but also enhances reliability during high-vibration launch environments. The only exceptions to this integrated approach are the optical fibers required to route quantum signals from the experimental payloads to the laser terminal, and a dedicated cable for the star tracker.

To achieve the required 1° margin of pointing error, the mechanical design prioritizes the co-location of the star tracker and the laser terminal. By mounting both components to a shared, rigid mass, the design minimizes thermal expansion differentials and structural flexing that could lead to boresight drift. Figure 2 depicts the mounting of the star tracker and the laser terminal within the satellite.

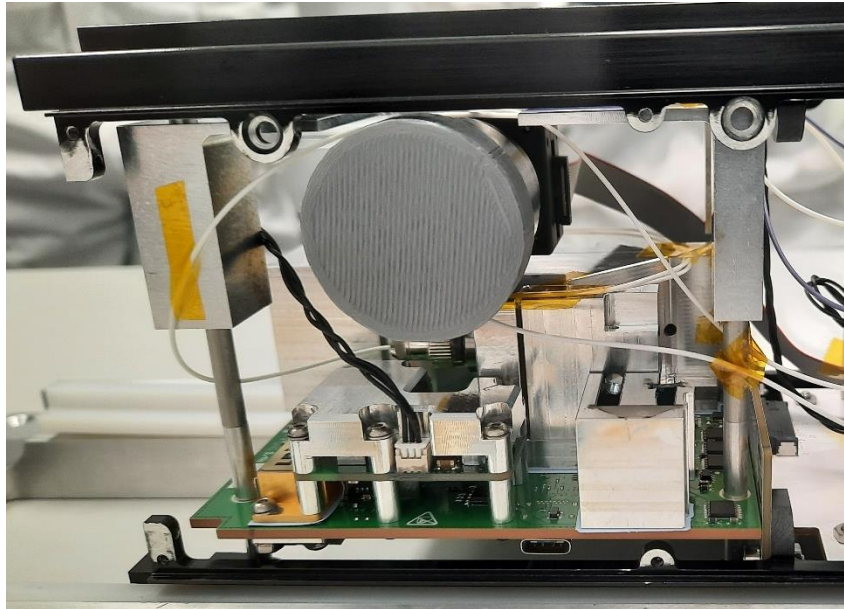


Figure 2. Mounting of star tracker and OSIRIS4QUBE on a shared structural mass

Furthermore, to eliminate any risk of magnetic interference with the attitude control system, the assembly is secured exclusively with titanium screws. This avoids potential magnetization issues associated with standard steel fasteners, ensuring that the attitude information remains pure and the pointing vectors stay true to the mission's high-precision requirements.

2.2 Attitude Determination and Control System

In general, the PIXL-1 mission showed a significant low reliability of the star tracker. In only 22.1% of all attempts, the ADCS could at least partly rely on valid quaternions from the star tracker. After several discussions and workshops with the satellite and the star tracker manufacturer, it turned out that software updates could potentially mitigate some of the issues. Unfortunately, the device was not able to receive software updates in space, so that DLR had to accept the limited availability. QUBE used the same star tracker as CubeL. The insights of the PIXL-1 mission were shared with the ZfT team so that necessary software updates could be performed in advanced and the device could be fully tested and prepared on ground before the launch.

It was considered in PIXL-1 from the beginning on, that the star tracker loses its lock at higher slew rates of the satellite. These were assumed to exceed the limits at elevations above 35° . The concept foresaw that in these cases, the ADCS switched to the secondary absolute attitude sensor, the magnetometer. The telemetry later showed that, as soon as the star tracker lost the lock, the control error in the ADCS increased instantaneously. Figure 3 shows this behavior.

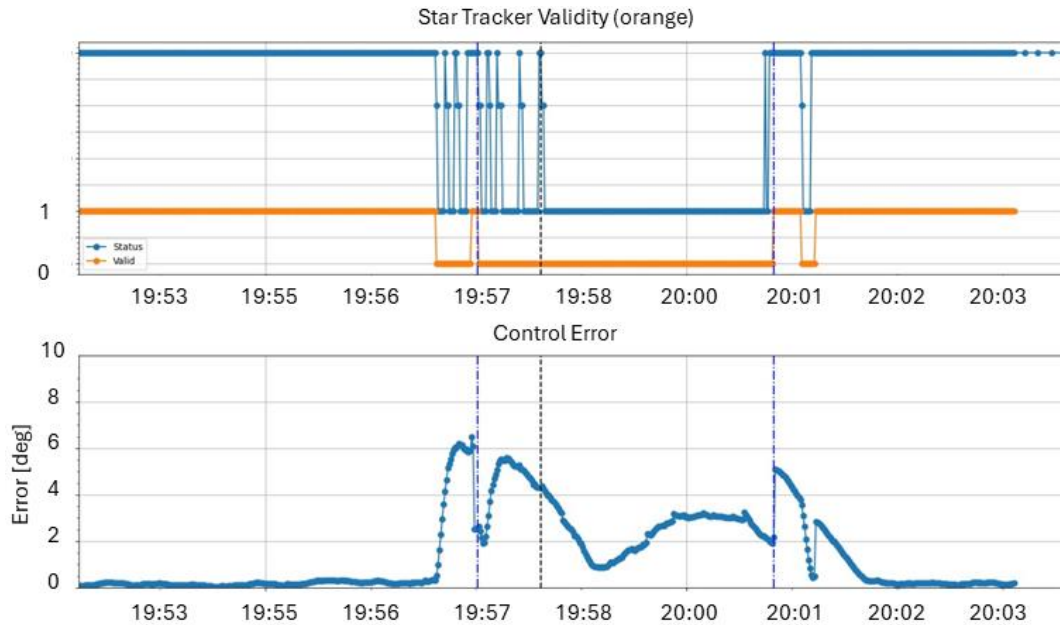


Figure 3. Telemetry of CubeL during laser experiment. Star tracker lost the lock at 19:56:37

The picture shows the star tracker validity (orange) in the upper plot and the control error in the lower plot. The error increased as soon as the star tracker did not deliver valid quaternions anymore. The error jumped immediately from $<0.3^\circ$ to $>6^\circ$ and exceeded the required 1° pointing accuracy by far. This led to the assumption that the magnetometer and the star tracker were not sufficiently well aligned to each other so that the magnetometer could not be used for the target pointing during laser experiments. Unfortunately, it was not possible to exclude the magnetometer out of the Kalman-filter so that optical links were only possible when the star tracker signal was valid. These insights were discussed with ZfT during the design phase of the ADCS of QUBE.

The ADCS of QUBE was designed to provide the pointing accuracy required for optical communication experiments within the constraints of a 3U CubeSat platform [9]. The system enables three-axis stabilized operation and supports multiple operational modes ranging from safety mode, detumbling and Sun pointing to fine pointing for optical payload operations [10]. The control software runs on a microcontroller with a real-time operating system-based flight software stack [11].

The ADCS architecture consists of a guidance module, an attitude estimation unit, and a control system using reaction wheels and magnetorquers for actuation. A functional overview of the system is shown in Figure 4. During optical communication experiments, the spacecraft operates in fine pointing mode in which the optical payload is directed toward the OGS. The guidance module generates the reference attitude for optical link experiments based on GNSS-derived orbit information and the known location of the OGS. Using the predicted spacecraft trajectory, the module computes a time-dependent target quaternion for target tracking. Field of view constraints are applied to prevent bright objects, such as the Moon or Earth limb, from entering the star tracker field of view during optical operations. Precise attitude determination is primarily based on a star tracker providing absolute inertial attitude measurements, supported by gyroscopes for angular rate sensing and state propagation. When the star tracker temporarily cannot provide valid measurements, the attitude estimate is propagated using gyroscope data. For precise attitude control, the spacecraft is equipped with a redundant reaction wheel configuration that enables fine torque control around all three axes.

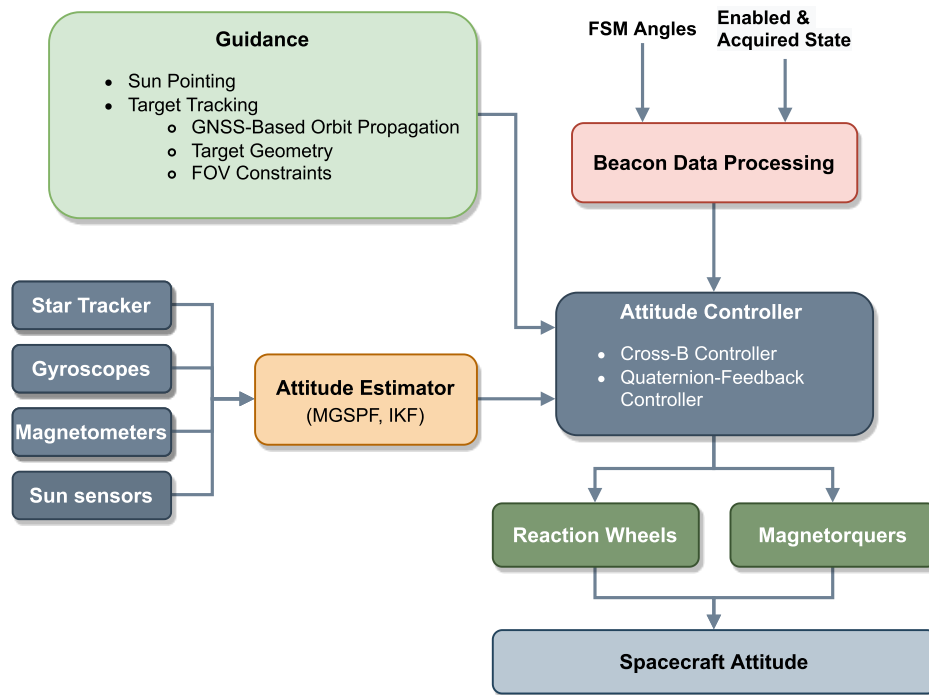


Figure 4. Overview of QUBE's ADCS architecture

Magnetometers in nanosatellites are challenged by locally induced disturbances from onboard components and their angular accuracy depends inversely on the magnitude of the Earth's magnetic field, making them less reliable for high accuracy fine-pointing control. These architectural choices enhance operational robustness for optical link experiments while maintaining system simplicity and flexibility. Besides, the control mode was extensively tested on ground before launch [10][13].

Compared to the prior mission PIXL-1, the QUBE system relies solely on star tracker and gyroscope fusion. By excluding magnetometer data, the filter focuses on high-rate gyroscope propagation between absolute star tracker updates, providing continuous attitude knowledge and fine-pointing capability during periods when absolute measurements are temporarily unavailable. The advantage of the attitude estimation of QUBE's ADCS is illustrated in Figure 5, which shows the control error over time.

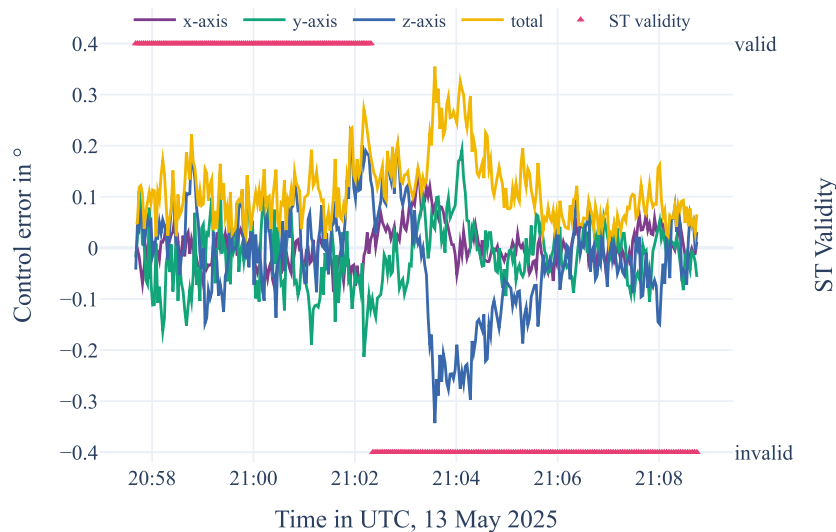


Figure 5. Control error response after star tracker loss during laser experiments [12]

The QUBE data show no comparable discontinuity at the time of star tracker loss. The control error remains at a consistently low level, and no noticeable change in the error curve is observed. This behavior reflects the continuous gyro-based state propagation used in the QUBE attitude filter, which avoids abrupt estimation transitions and enables stable pointing performance even during extended periods without valid star tracker measurements.

Overall, this comparison highlights the benefit of relying on gyro-based attitude propagation without incorporating magnetometer measurements into the attitude estimation filter. The QUBE ADCS architecture demonstrates significantly improved robustness in maintaining optical link performance under poor star tracker performance.

To further increase link robustness, the ADCS architecture includes the capability to incorporate measurements from the LCT into the control loop. The optical terminal provides incident angle information (Fast Steering Mirror (FSM) angles) describing the deviation between the optical boresight and the received signal direction. These measurements can be used as a feedback signal, fed into the controller for relative pointing. Ground-based experiments have validated the feasibility of this approach [12], while full in-orbit validation is still pending. Nevertheless, the FSM angles can already be used as a more precise pointing knowledge source. The angles show the exact orientation to the OGS beacon and therefore represent the satellite's residual error around the optical axis. In Figure 6, the FSM tilt angles are shown over time during representative laser communication experiments.

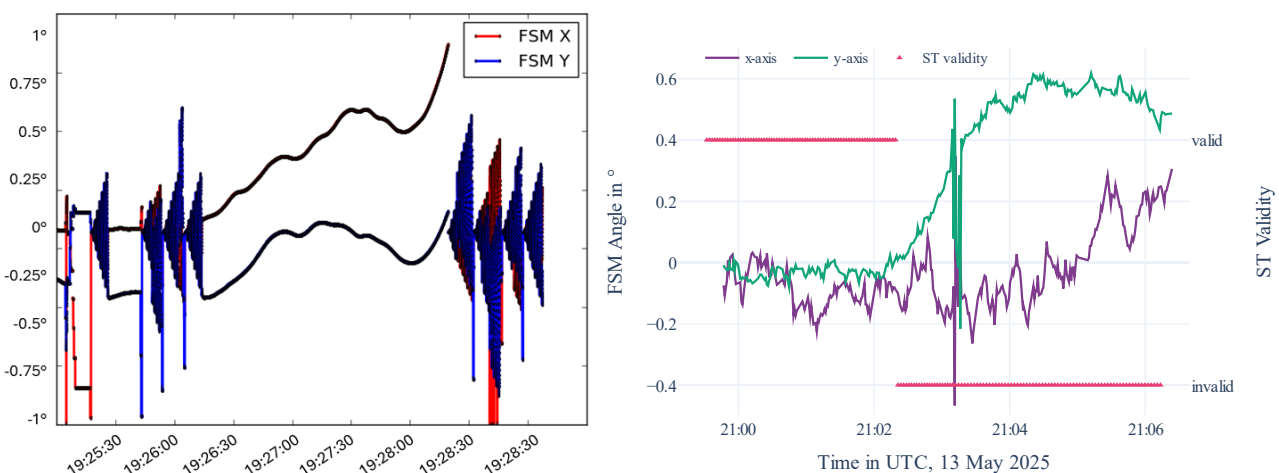


Figure 6. FSM angles over time for PIXL-1 link with 30° max elevation (left) and an exemplary QUBE link with 48° max elevation (right), illustrating link maintenance performance during attitude propagation without valid star tracker measurements. For the right plot data from [9] and [12] was used

The left plot corresponds to an experiment conducted with PIXL-1, while the right plot shows results from QUBE. In the PIXL-1 case (left), the star tracker lost tracking at approximately 19:28:04 UTC. Following this event, the FSM angles started to increase, indicating a growing pointing error due to the satellite's change in attitude. Despite this, the optical link could be maintained for additional ~ 20 s until the FSM reached its mechanical limits. Afterwards the link interrupted and the FSM started driving search spirals again.

In contrast, during the QUBE experiment (right), the star tracker was lost at approximately 21:02:20 UTC and did not reacquire tracking for the rest of the pass. Here as well, an increase in FSM angles is visible after the loss of star tracker measurements, reflecting the transition to gyroscope-based state propagation. However, the growth of the FSM tilt angles is significantly slower compared to PIXL-1,

indicating a much more stable attitude propagation during star tracker outages. As a result, the optical link remained operational for almost the entire overpass. A short outage shortly after 21:03 UTC was attributed to excessive received power on the OSIRIS4QUBE sensor during peak elevation rather than to pointing degradation. Overall, the optical link was maintained for approximately ~240 s after the loss of the star tracker, effectively until the end of the pass.

2.3 Orbit Files

To close the optical link between the OGS and the LCT, a high pointing accuracy of the OGS is needed. Only when the OGS' pointing error to the satellite is smaller than the beacons' divergence half angle, the beacon illuminates the satellite. This is the precondition for the FPA in the LCT to acquire the beacon and close the link. If this is not the case, the OGS has to compensate for the correct alignment which results in a delayed acquisition and therefore in a reduced total link time. While the accurate celestial pointing of the OGS can be ensured with a proper star-calibration in advance, the main source of pointing error remains a proper determination and description of the satellite's celestial position based on the orbit predictions.

With CubeL, the accuracy of the orbit data – given in a description of Two-Line Element (TLE) sets – was often insufficient for immediate acquisition. The solution was the so-called “blip-tracking”. The laser of the LCT swipes during its spirals over the OGS which can be registered as very short flashes. The blip-tracking recognizes these flashes and compensates the OGS' pointing error so that the link can be acquired within the next spiral. This prolongs the acquisition time but still enables an optical connection. Thus, a call for the usage of Consolidated Prediction Format (CPF) files for the orbit description of QUBE had been raised. The assumption was, that the highly sampled description of the satellite position within the CPF format would outperform the approximated description of the TLE data format.

While several contacts with QUBE showed an increased initial pointing accuracy and an immediate link acquisition under usage of a CPF orbit description, the link operations with QUBE also revealed contacts, in which the pure orbit data description through the CPF data format would not have been sufficient for immediate reacquisition at any time of the overpass. At the same time, tests with orbit data described as TLE sets showed a sufficient performance for fast link-acquisition on the optical channel with QUBE. In addition, with the improved attitude control of QUBE, the necessity of a frequent reacquisition during an overpass has drastically reduced.

In total, the learning from operations with QUBE is that the expected improvement of initial telescope pointing is not necessarily dependent on the orbit data format. As such, the small improvement of using a CPF file-based pointing does not balance the necessary effort to create these files and the usage of TLE-format orbit information is sufficient for most operations with QUBE. The observations during the PIXL-1 mission, that the OGS pointing was insufficient could have had two root causes. First assumption was that, the source of the TLE file was different. While the CubeL TLE files were provided by the German Space Operation Center (GSOC), the TLEs for QUBE were directly downloaded from an online source. This could have resulted in different times when the files were generated. Older files could have led to more inaccurate predictions. The second possible cause could have been the further improvement of the OGS. The OGS underlays a constant improvement process in technical aspects to reduce tolerances and improved software like mount models and star calibration. These improved accuracy and precision could have led to the improved results as they were seen during the QUBE mission. As the system showed absolute reliable performance during the ongoing QUBE campaign, further investigations in the root causes of the lower performance during the PIXL-1 mission are not considered.

3 LINK AVAILABILITY AND RELIABILITY

The described countermeasures led to an improved reliability and availability of laser links. Figure 7 summarizes the link statistics of the PIXL-1 and the QUBE mission for all link attempts conducted from 2021 to 2026 for OSIRIS4CubeSat and for 2025 to 2026 for OSIRIS4QUBE. The bar plot provides a categorical breakdown of total link attempts and their respective outcomes.

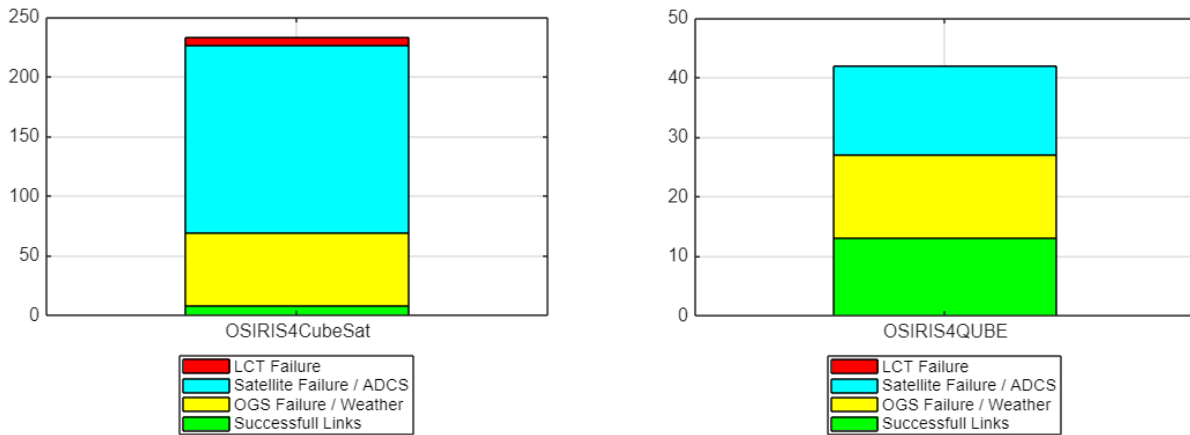


Figure 7. Statistics of PIXL-1 (left) and QUBE (right) optical links from 2021 to 2026

A total of 295 link attempts were performed with both satellites to optical ground stations. Of these, 41 resulted in successful optical links with constant tracking over at least several seconds, corresponding to a success rate of approximately 13.9%. The remaining 254 attempts were unsuccessful and are attributed to three principal causes: OGS failure (74 cases) and satellite failures (173 cases). The LCT failed in only 7 cases which corresponds to a success rate of 97.6%.

The link availability, illustrated by the success rate could be increased from 3.2% (OSIRIS4CubeSat) to 31.0% (OSIRIS4QUBE).³ The number of outages due to the LCT could be reduced to zero. Nevertheless, the root causes for the failed attempts were discussed in comparison.

The major driver for failed attempts lies in the reliability of the satellites. CubeL suffered mainly from the very limited reliability of the star tracker. Also, the misalignment between the ADCS sensors and the LCT required a high number of pointing correction measures which caused a high number of failed experiments. On the other hand, CubeL was commanded by GSOC which used automated recommendation processes, that ensured a high reliability in the commanding chain. QUBE on this regard, had to be commanded manually in the beginning. Automated processes were developed during the mission. Thus, in QUBE, satellite-related failures mainly occurred due to failures in the commanding pipeline, which were due to non-standardized processes. Furthermore, high solar activity during the mission's campaign caused several outages in the commanding of the laser experiments.

For the OGS-related failures, adverse weather represents the dominant external limiting factor. Internal technical issues are comparatively less frequent but should still be considered. Technical OGS failures arose mainly from outages in the beacon system or human errors. Here, a major improvement could be observed since PIXL-1 as none of the QUBE downlinks failed completely due to technical issues at the OGS. These results indicate that environmental conditions remain the primary constraint on operational availability.

³ Only links with stable tracking and a constant connection over several seconds were considered as successful.

The link availability balanced distribution between successful and unsuccessful attempts highlights both the increased maturity of the system and the operational challenges inherent to optical downlinks. Given that most failures are weather-driven rather than hardware-related, improvements in site diversity or predictive scheduling could substantially increase the effective link yield.

Besides the availability, the reliability could also be improved from PIXL-1 to QUBE. This is presented by the links' duration. Table 1 compares the active tracking time to the total scheduled operation duration for example link attempts. The total operation duration of OSIRIS4QUBE during the links varied from 279 s to 456 s with a maximum absolute tracking duration of 445 s on the 13th of May. In several cases, tracking time closely approaches the total scheduled duration, demonstrating stable and sustained terminal pointing performance once acquisition is achieved. In contrast, other attempts show a marked discrepancy between tracking and total overpass duration. This is due to several reasons. The total time accounts for the entire period during which the OSIRIS4QUBE terminal was turned on. Therefore, time below 5° elevation is also included in the statistics. Additionally, the signal was partially obstructed by clouds. For example, on May 2nd, it was primarily cloudy. On October 14th, the 30.7% pass result is due to tests of reducing the beacon power on the OGS to measure the minimum requirements.

Table 1. Tracking time in percent with respect to total available link time for overpasses in 2025.

Date	02.05.	13.05.	22.07.	12.08.	13.08.	13.08.	02.10.	02.10.	14.10.
AOS Time (UTC)	21:09	20:58	23:34	20:56	20:27	22:00	20:43	22:14	22:13
Max. Elev., deg	68	48	65	40	20	32	25	69	56
Direction	East	East	West	East	East	West	East	West	East
Tracking, %	53.9	97.6	67.0	91.2	93.2	65.2	64.7	77.1	30.7

These results indicate a significant increase in link reliability compared to the predecessor mission PIXL-1 which yielded a smaller maximum total tracking time of 275 s [14].

4 CONCLUSION

This paper showed three example countermeasures to increase the availability and reliability of laser communication from CubeSats. Explicitly the mechanical interfaces of the relevant systems, an improved ADCS and an improved OGS pointing led to significant improvements.

The synergy between the UNISEC-compliant mechanical structure and the integrated electrical backplane facilitated rapid integration and system-level testing. The standardized interfaces allowed for a plug-and-play workflow, enabling the team to transition from individual component verification to full system testing with minimal lead time, ensuring QUBE was flight-ready and optically aligned for its LEO mission. The rigid integration of the star tracker and the laser onto a shared structural mass was fundamental to achieving the necessary pointing accuracy, as it minimizes mechanical drift and structural flexure between the attitude reference and the pointing device. This could be proven as sophisticated search algorithms had to be developed during PIXL-1 to measure and correct the target pointing. In the QUBE mission, first light was achieved during the first downlink attempt (with good

weather conditions). No target offset and no search algorithms were needed. This is a major improvement which reduces the commissioning time of LCTs significantly.

The preparations of the star tracker in QUBE improved the number of available links significantly. While the star tracker was available during the PIXL-1 mission in less than one quarter of the link attempts, the star tracker was nearly always available during QUBE downlinks (if the respective commanding was successful). Furthermore, the improved ADCS concept without the magnetometer led to a stable tracking, even after the star tracker dropped out. This increased the number of usable links and the link duration significantly and enabled with that links over the entire duration of a flyover.

Even though the root causes of the lower performance of the OGS during the PIXL-1 could not be analyzed in detail, it could be shown that the measures led to an improved reliability of the link. In the QUBE mission, no search algorithms or offset corrections had to be used for the acquisition which increased the link duration and with that the reliability of the laser links.

Overall, the comparison of both campaign results proofed that the LCT itself performs absolutely reliably once the required boundary conditions are fulfilled, with sustained tracking durations approaching the full scheduled overpass time in multiple cases. However, environmental constraints – particularly weather and satellite pointing – remain the principal factors limiting overall link efficiency.

5 ACKNOWLEDGMENTS

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