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Compact laser communication terminal architecture and in-orbit demonstration

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ABSTRACT

Satellites are generating more data than ever due to more demanding payloads, although communications Down To Earth (DTE) have not experienced the same growth in data rates. Compact Laser Communication Terminals are a promising technology that will increase bandwidths (10 Gbit+) and pave the way for larger data volumes to be transmitted which will increase the relevance of small and CubeSats in space data as service offerings. The in-orbit demonstrator is targeting a downlink data rate of 1 Gbit/s with a range of up to 1000km. A downlink wavelength of 1545nm is used while 1590nm is used for the ground station beacon. PRBS23 sequences will be transmitted from the in-orbit terminal to a ground station in the Netherlands. During in-orbit experimentation, attempts will be made to acquire payload data from other onboard payloads and to forward this data down to earth. This will provide valuable insight into possible future enhancements.

The goal is to use the lessons learned from the in-orbit demonstration and results to drive the development of future iterations of the terminal. Lessons learned during the development phase, market feedback and test results are already being used to shape the architecture and design of the system. The following learnings are anticipated: robust fast data storage does add value; higher down and upload speeds are required; throughput enhancement using adjustable data rates will be worth the investment and enhancing error correction allows for more efficient transfers.

INTRODUCTION

The recent advances in high data volume payloads such as Earth Observation (EO) payloads for CubeSats and SmallSats have highlighted the need for improved downlink capability in small form factors. A 1- 1.5U optical payload can easily generate 100's of Gbits per orbit. Downlinking this data to ground has been and will continue to be a major bottleneck in the data chain.

Direct to Earth (DTE) Laser Communication Terminals (LCT) will be playing an important role in elevating the pressure on the current bottlenecks in the data chain of small satellites. Increased bandwidths will pave the way for larger data volumes to be transmitted, increasing the relevance of SmallSats and CubeSats in space data as service offerings. This in-orbit demonstration (IOD) of this small and compact laser communication terminal CubeCAT aims to prove this capability and act as a foundation for the development of future terminals.

Unlike traditional Radio Frequency (RF) communication laser communication uses much more narrow beam widths and smaller divergence angles. This allows for much higher data throughput, in the order of 1Gbit/s.

Naturally the factors that lead to enhanced downlink performance (narrow beam width and small divergence angles) come at the expense of increased accuracy and pointing stability. To ease the impact on the satellite operations the pointing requirements must be taken into account for the terminal itself. Having integrated pointing mechanisms are critical in achieving the required pointing performance.

ARCHITECTURE

The CubeCAT LCT, developed by AAC Hyperion in collaboration with the Dutch applied research institute TNO, is a CubeSat form factor compatible 1U LCT. The relatively small form factor necessitated the implementation of a novel architecture for the system. The optomechanical design, systems design and algorithm development of the CubeCAT was led by TNO while AAC Hyperion was responsible for the development of its electronics and software. Figure 1 shows a high-level breakdown of the architecture. The DTE laser communication terminal's architecture can be broken into these main subassemblies.

- Structure
- Fine Pointing System
- Optomechanical Assembly
- Laser
- Detector

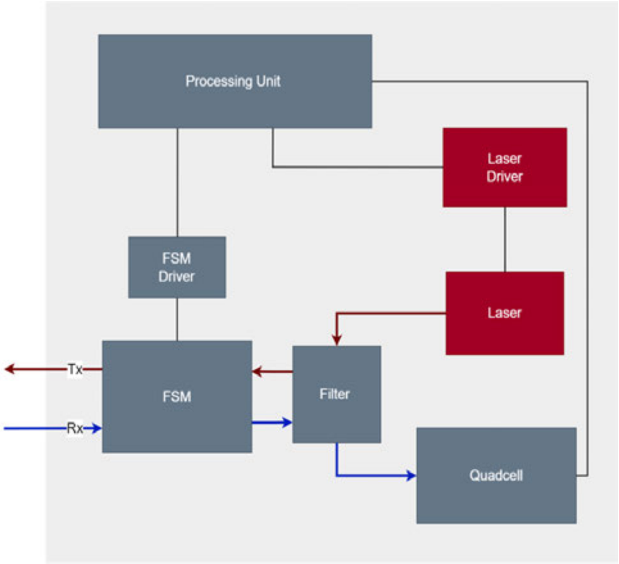

Figure 1: Basic Architecture of the CubeCAT

Structure

The structure's main function is to enclose and support the terminal while also providing mechanical mounting interfaces in line with CubeSat standards. This poses considerable design challenges since the structure interfaces both with the spacecraft structure as well as the optomechanical assembly. Controlling deformation and stress due to thermal cycling to prevent misalignment and distortions in the optomechanical assembly was critical. In the end that was achieved with the selection of the correct material and geometry combinations. The terminal with the top and side panels removed is shown in Figure 2.

Figure 2: A Render of the CubeCAT Lasercom Terminal, Fitting in a 1U Standard Volume

The material of the structure of the CubeCAT terminal is Al 6061 and has a coefficient of thermal expansion (CTE) of 23+/-1 µm/m/k. Ideally, the spacecraft interface should be matched as closely as possible to prevent warping due to thermal expansion.

Fine Pointing System and Optomechanical Assembly

To accommodate the fine pointing system in the volume available it was decided to utilise a single optical path for both uplink and downlink. To make sure the correct link enters the correct direction a dichroic mirror was used which filters out light of a particular wavelength. In this case it allows only the uplink wavelength of 1590nm to reach the quad cell and filters out any outgoing wavelength of 1545nm from the quad cell. This is represented in Figure 3.

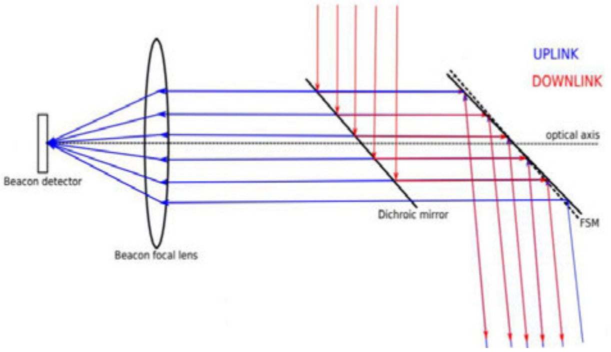

Figure 3: Diagram of the CubeCAT fine pointing system

In order to solve the pointing challenge within the volume requirements whilst adhering to pointing stability and accuracy requirements decision was taken to rely on the spacecraft for coarse pointing. Current ADCS technology is capable of achieving pointing accuracies below 0.5 deg. This is well within the requirements to be able to close the link [1].

In combination with coarse pointing (provided by the satellite bus) a fine steering mechanism had to be incorporated into the architecture. The development of this Fine Steering Mirror (FSM) was done in parallel to this project. The FSM is shown in Figure 4 and has an optical range of +/-2 degrees which means that the FSM has more than enough range to correct for the coarse pointing error introduced by the bus.

The Fine Steering Mirror has been developed by Demcon Focal to be utilised in the optical terminals of satellites, airplanes and ground stations to facilitate the accurate alignment of transmitter and receiver. They are able to filter out faults caused by high-frequency disturbances. The small mirror (20-millimeter diameter; flatness within 12 nm rms) must be able to move at a

1kHz bandwidth. The bearing with leaf springs provides for high linearity and prevents wear making the design both light weight and space compatible [2].

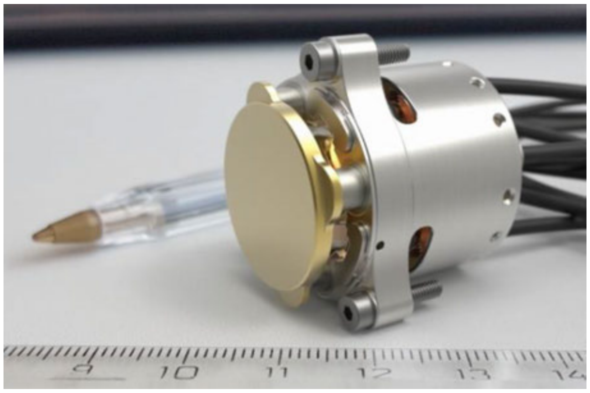

Figure 4: Render of Fine Steering Mirror with pen for reference.

Laser

At the core of the terminal is the laser transmitter, which generates the laser beam used for communication. The system makes use of a 300mW laser for the downlink beam. The laser which operates at 1545 nm was developed by the UK company Gooch & Housego.

The packaging of the laser module into the tight volume while adhering to performance and environmental requirements was critical. Close collaboration with the supplier was instrumental in achieving the required power output.

The laser is driven by a laser driver developed by AAC Hyperion. Details on the laser driver are presented in the Electronics subsystem section.

Quadrant detector

In order to establish a link, a beacon light is transmitted from the ground station. The light coming from the ground station beacon signal is captured using the quad cell. The readout from the quad cell can be used to obtain tip/tilt knowledge of the pointing error of the spacecraft. From this information the required corrections the FSM has to make can be calculated. This is done in the processing unit. The FSM is then used to make corrections using this tip/tilt information obtained from the Rx beam. The design leverages a paired common path for the Tx and Rx beams, meaning that corrections made for the Rx beam led to corrections for the Tx beam as well [3].

The beacon detector is the opto-electronic sensor of which the output is fed back to the fine pointing system controller. Its normalized two-dimensional (X,Y) spot location output represents the location of the guidance beacon`s spot in the focal plane, where the quad cell is mounted. This is the controlled quantity in order to maintain alignment of the downlink Tx with the uplink Rx beam. This is because the spot locations are a direct measure of the uplink beacon angle with respect to the principal optical axis after reflection by the FSM. The accuracy and precision of the read-out electronics have been optimized during design, in particular the noise of the readout circuit, as any noise content that has a sufficiently low frequency (i.e. lower than the closed-loop bandwidth of the fine pointing system) will directly propagate to the system`s eventual pointing error performance.

A quad cell photodiode configuration is positioned in the focal plane, as illustrated in Figure 3. The centre location of the beacon’s spot is proportional to the beacon angle after reflection by the FSM and to the focal distance of the optics.

The modulated nature of the uplink beacon is exploited by the spot location sensor, as it allows to reject low-frequent parasitic light sources (sun/moon) and electronic flicker noise. This could otherwise jeopardize the quality of the measured quad intensities and thus the spot location output. An electronic high-pass filter is used for this purpose.

Processing Unit

The processing unit (CP400.85) has several tasks in the context of CubeCAT. The first task is to manage power rails for the other subsystems. If a unit operates outside its bound, the processing unit will shut that unit down to prevent damage. Other tasks include interfacing with the satellite OBC, housekeeping of the system, performing firmware updates of the system and computing the point-ahead angle(s). During a transmission, a set of commands will be sent to the processing unit, which will then further delegate those tasks to other subsystems. With one main node, it simplifies synchronisation and also the collection of logs and telemetry data [3].

ELECTRONIC SUBSYSTEMS OF CUBECAT

FSM Control and Driver Electronics

The FSM Control and Driver are responsible for actuating the mirror such that the CubeCAT can acquire and track the ground station incoming laser. To achieve this objective, an MCU takes incoming data from the quad cell and adjust the mirror according to a control algorithm. The MCU controls the two axis of the mirror via a DAC. The DAC output voltage is converted to a current which actuates the mirror to move.

During a pass the FSM Control and Driver will try to start acquiring the incoming laser beam in the acquisition phase. The mirror will move according to a defined pattern and search for the highest intensity. There is also a spiral mode which can further help acquisition under certain circumstances. Once the uplink laser signal has been acquired the FSM controller goes into a closed control loop and maintains tracking of the signal. To account for delays, there is a point ahead angle which provided by the processing unit. The FSM control and driver electronics are shown in Figure 5.

For optimizing and debugging the FSM controller performance, a tracing file is logged during operation and can be used to fine tune parameters.

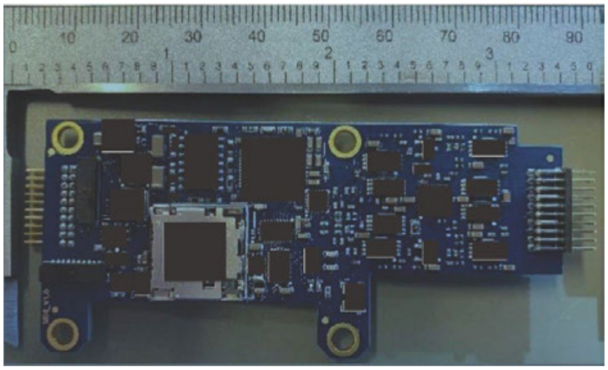

Figure 5: FSM Control and Driver Electronics

Modem

The modem's role is to packetize transmission data and send it via the laser. To ensure high utilization of transmission time an FPGA was selected. The firmware for the FPGA can be easily customized to support different protocols. The modem takes data from the Processing Unit via either a high speed serial link or a high throughput parallel link. The data gets wrapped around Space Packets and those packets get put in CCSDS Transfer Frames. These Frames are then passed through a TNO O3K encoder and finally fed through a SERDES peripheral on the FPGA. On the demonstrator a PRBS stream will be used to evaluate the bit-error rate.

In the future the goal is to enhance this and work towards full compliance with the applicable CCSDS, O3K and SDA standards. Intercepting data transferred using laser communication methods is inherently difficult due to the low beam divergence. It is however still necessary to incorporate encryption techniques such as commercial standards like AES. This system also supports tailored encryption methods.

Laser Driver

The laser driver subsystem is responsible for turning the laser on or off, controlling the Thermoelectric Cooler (TEC), adjust parameters related to the laser behaviour, and ensuring the laser operates within its safety limits. The processing unit sends commands to the laser driver, which the laser driver will parse and execute.

To ensure that the laser does not get damaged during operation, the laser driver has a set of safety parameters. These parameters are compared to measured values. If the measured values are out of bound from the safety values, then the laser driver will enter an error mode and turn the laser off to ensure no damage will occur either to the laser or the TEC.

Detector Electronics

The detector electronics subsystem's purpose is to receive and decode the incoming laser beam and derive the horizontal and vertical position, as well as the intensity of the laser beam, and the binary data encoded in the beam. The quad cell detector has four quadrants which are amplified and filtered before it they are converted to the digital domain via Analogue-to-digital converters (ADCs). An FPGA then computes the position and intensity of the four quadrants, as well as the binary data in the beam. The positions and intensity are sent to the FSM & Control Subsystem via a serial link. Here the FPGA is the master transmitter, which interrupts the FSM & Control Subsystem to ensure that control algorithms on the FSM & Control Subsystem are always using the latest sample. The decoded binary data of the incoming beam is then sent to the processing unit for further handling. The detector electronics are shown in Figure 6.

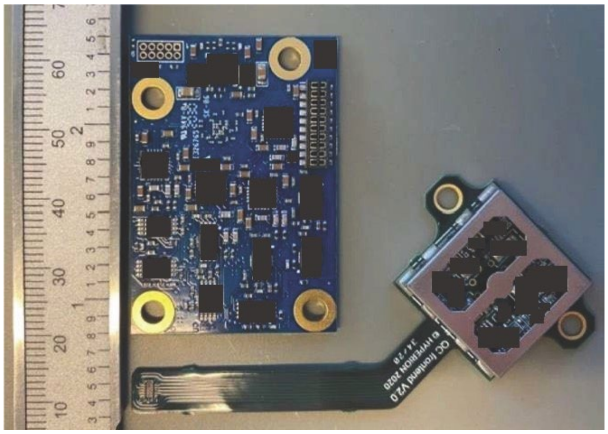

Figure 6: Detector Electronics

Processing Unit

The Processing Unit (CP400.85) is responsible for accepting commands from the satellite and housekeeping the whole system. The heart of the Processing Unit is an MPU running Linux. The MPU receives commands from the satellite and executes them or forwards the messages to different subsystems.

To ensure smooth operation, there are several modes implemented on the Processing Unit. The modes range from idle, collecting telemetry data, turning laser, to acquisition and transmission. These modes are requested by the satellites via an RS422 channel. The Processing Unit will then configure and command all subcomponents accordingly.

PATH TO LAUNCH

Functional Testing

A series of functional tests were conducted throughout the design and development phases of the terminal.

TNO developed a test bench which was utilized to perform on-ground verification testing of the control algorithms, end-to-end link testing and other parameter testing. This was a critical building block for the development of the terminal. Details of these tests and the results will be available in future publications.

Environmental Testing

Like all satellite subsystems, the CubeCAT terminal had to be space qualified before the IOD. To achieve this a typical environmental testing campaign was conducted.

Thermal Vacuum Testing

Thermal Vacuum (TVAC) Testing was conducted at terminal level. This included the suspension system for a laser communication terminal, this test is critical, as subsystems like the laser are temperature sensitive and proper thermal management of these subsystems is critical. The terminal is designed to withstand a temperature range of -30°C to 60°C and was qualified as such during the TVAC campaign.

Vibration

The terminal was subjected to random and sine vibration loads. A proto-flight approach was used and the vibration levels for both random and sine were defined by the launch vehicle and spacecraft combination. The specific bus on which the terminal is used has a resonant frequency in a domain which adversely affects the terminal. In order to address this a suspension system was added in order to damp the critical frequencies. See Figure 7.

Figure 7: SmallCAT (i.e. CubeCAT with an added suspension system)

The modified mounting for this mission to accommodate environmental loads specific to the satellite bus of the NorSat-TD and shows the versatility achievable with this laser communication terminal [4].

The terminal was shown to withstand the following Random Vibration loads:

X Direction	Y Direction	Z Direction
23 G_{rms}	8.0 G_{rms}	9.9 G_{rms}

Radiation Testing

In order to ensure that the electronic subassemblies will withstand the targeted lifetime in LEO Total Ionizing Dose (TID) Testing was done. The tests we conducted at ESA ESTEC's radiation test facility in Noordwijk in The Netherlands.

The items under test were exposed to a Total Ionizing Dose in excess of 20krad. It should be noted that testing was conducted without any additional shielding on chip level, ergo the results are valid at silicon level.

EMC/EMI

A radiated emissions test was conducted at ESA ESTEC in Noordwijk in the Netherlands. This was done to ensure the terminal's emissions will not impact other satellite systems adversely. The test was split into 2 parts. Emissions below 1 GHz and emission between 1 GHz and 18 GHz. The maximum emission levels prescribed by the satellite integrator were not exceeded.

Satellite Stability

Since the terminal is reliant on coarse pointing being provided by the satellite bus the following stability requirements need to be adhered to as described in Table 2.

Table 1: Satellite Requirements

Parameter	Value	Units
Low Frequency Vibration Velocity (<20Hz)	<2.445	mrad/sec
High Frequency Vibration/Jitter Amplitude (>20Hz)	<15/0.86	µrad/mdeg
Time Accuracy	50ms or better	wrt UTC
Pointing Accuracy	<8.7/0.5	mrad/deg

OPTICAL GROUND STATION REQUIREMENTS FOR CONNECTING WITH CUBECAT

The link needs to be planned prior to the moment of the link. Ground station operator requests a link at mission control. Each link request contains:

- Latitude
- Longitude
- Altitude of the OGS in WGS84
- Start time T0 (UTC)
- Link window duration (s)

Table 2: Ground Station Requirements in line with CCSDS O3K standard

Optical Path	Wavelength	Tolerance
Data	1545 nm	± 0.4 nm
Beacon	1590 nm	± 0.4 nm

A number of links can be bundled into a single request. There are 2-4 link opportunities out of ~15 orbits per day for the latitude of the Netherlands. This increases with increasing latitude for a sun-synchronous orbit at an altitude of 500 – 600 km [4]. For in-orbit Rx/Tx calibration the optical ground station shall have:

- Step time as configurable parameter
- 1ms accuracy w.r.t to UTC.
- Lowest elevation is 25 degrees

FLIGHT DEMONSTRATION

The CubeCAT laser terminal was launched on Transporter-7 on 15th April 2023 onboard the NorSat-TD (Figure 8) as SmallCAT.

The NorSat Technology Demonstrator (NorSat-TD) is a technology demonstrator mission developed by the Space Flight Laboratory (SFL) at the University of Toronto's Institute for Aerospace Studies (UTIAS) in collaboration with the Norwegian Space Agency (NOSA). The NorSat-TD mission aims to validate and test novel payloads and concepts from multiple European countries. The objective of NorSat-TD is to demonstrate the viability of optical laser communication using the experimental CubeSat terminal (CubeCAT). Additionally, the mission aims to validate various other technologies, including maritime communication, satellite navigation, collision avoidance, satellite operations, and satellite laser ranging. The mission also seeks to verify sub-decimetre augmented GPS positioning in real-time using a CubeSat receiver [5].

Figure 8: NorSat-TD Satellite [5]

The in-orbit testing is ongoing at the time of publication. A systematic approach has been used, where subsystems are activated one by one, and their performance is tracked under overpass conditions. This approach ensures a comprehensive evaluation of the mission's capabilities and functionality.

The health and sanity check of CubeCAT have been successfully completed on orbit, yielding positive results. This milestone confirms the operational readiness of the CubeCAT subsystem.

The ongoing work focuses on the fine-tuning of the attitude determination and control system. This crucial aspect of the mission is still in progress to optimize the satellite's orientation and stability.

SmallCAT will communicate with the TNO GoCAT gigabit class optical ground station demonstrator that has been installed by TNO. The optical ground station (OGS) located in The Hague, The Netherlands, is undergoing calibration and preparations to establish a link with the CubeCAT. This step ensures the interoperability and compatibility of the CubeCAT laser communication technology with European optical ground stations [5].

The completion of subsystem testing is a prerequisite for the initial link attempt with the CubeCAT. Once all subsystems have been thoroughly tested, the mission will proceed to establish the first link, marking a significant milestone in the NorSat-TD mission.

INTENDED MODES OF OPERATION

Acquisition mode

To establish initial link the FSM will be set in open loop which will switch to closed loop autonomously when the quad cell detects light from OGS beacon above a set threshold. There is a backup strategy applied as well, the FSM performs open loop scans repeatedly within the uncertainty cone of 0.5 degree which should be the maximum attitude error of the satellite the CubeCAT is mounted on. This mitigates risk of the misalignments of the FSM, CubeCAT, and the star tracker and compensates for errors in the attitude update interface.

In-orbit calibration modes

The optical range of the FSM is +/-2 degrees or +/-35 mrad and the quad cell field of view is +/- 6 mrad whereas the required satellite pointing accuracy is +/-0.5 degrees or +/-8.7 mrad. During the acquisition mode or nominal operation, the CubeCAT is provided with attitude knowledge from the satellite star tracker and then the FSM corrects for the pointing error of the satellite. The FSM should be aligned with the CubeCAT optical coordinate system in order to achieve nominal operation. Similarly, when the FSM is properly calibrated, there is a known FSM zero current (2 DOF) that aligns the outgoing Tx beam of CubeCAT with the +z axis of the CubeCAT optical frame [4].

The FSM zero current setting can change due to launch vibrations or thermal effects. Also, the nominal acquisition strategy maybe at a risk of failing for a number of other reasons:

- Error in the interface by which the satellite provides attitude data to CubeCAT
- Calibration error
- Misalignment in CubeCAT or the satellite.

The FSM zero current calibration can be used if the CubeCAT does not detect light from the beacon on the first attempt. The zero current scan needs to have shorter period than the step time of the OGS beacon.

The quad cell set point determines whether Tx and Rx are aligned during the closed loop operation of the FSM. To achieve Rx/Tx alignment we must use a calibrated (non-zero) quad cell set point which is optimally calibrated on ground. Ideally the set point should not change but due to number of reasons listed above there is a risk that the optimum setpoint is different in orbit.

Point ahead angle (PAA) correction

The effect of the point ahead angle arises due to the travel time of light between the terminal and the OGS. The PAA is approximately 50 µrad for low earth orbit which is not a negligible value. The implementation of PAA correction changes the quad cell setpoint to be used in the closed loop as the Tx and Rx no longer align. The PAA changes during a link and impacts measurement and the analysis of the Rx/Tx calibration. Therefore, it is important to correct each result by PAA contribution to perform multiple measurements during a link after which the results can be averaged.

The in-orbit calibration modes are set up to account for these and many other scenarios and should allow the CubeCAT to establish a link by mitigating them.

PRODUCTIZATION AND COMMERCIALIZATION CHALLENGES

Commercialization and productization of laser communication terminals for CubeSats involves several crucial steps in order to establish the reliability and market presence of this cutting-edge technology. A key aspect is the need for a successful proof of concept, which serves to demonstrate the system's capabilities and reliability in space. Space data service providers and space mission operators require proven systems that have been validated in orbit.

Currently, x-band technology offers a 1Gbps bandwidth with comparable power consumption to the laser terminals available on the market. Furthermore, x-band technology is proven, reliable, and cost-effective, making it the preferred option for current missions despite the associated licensing processes and costs. Laser communication terminals, on the other hand, provide a secure link and have the potential to offer higher data rates exceeding 10Gbps. However, their true commercial viability will only be realized once they have been proven in orbit.

The nascent market for laser communication terminals is evolving rapidly, with changing protocols, emerging players, and diverse use cases. Laser communication terminals can be utilized for various applications, including direct-to-earth communication, inter-satellite links, and space-to-air communication. The CubeCAT, specifically, targets the Direct-To-Earth (DTE) market, which represents a relatively small segment of the laser communications market.

Another critical factor in the commercialization of laser communication terminals is the development of the ground infrastructure. Optical ground stations (OGS) are essential components but currently remain limited in availability. Furthermore, OGSs have not yet been validated with terminals in space, particularly those operating in low-Earth orbit (LEO). The OGS market is still in its early stages and undergoing development, with new technologies emerging and existing technologies used in Astronomy being leveraged to enhance signal capture and information efficiency.

Establishing a reliable link with a laser terminal requires precise ground-level infrastructure. OGSs cannot be deployed anywhere; they require locations with favourable weather conditions, as clouds pose a significant challenge to optical communication.

The current interest in laser communication terminals for CubeSats primarily lies with organizations and entities willing to demonstrate the technology's capabilities and plan future missions based on the outcomes of the demonstrator. These stakeholders recognize the potential of laser communication terminals and their value in enabling advanced communication capabilities for CubeSats.

It is critical to work with satellite providers and SDaaS providers to make it more reliant for them.

LESSONS LEARNED

1. The development of CubeCAT demonstrator has given us valuable insights to nuances of developing laser communication terminals, such as the interdisciplinary nature of combining infrared optics, mechanics and electronics into one compact unit. These aspects make it harder to debug and find faults on system-level testing. It is therefore imperative to do extensive testing on unit level as much possible before and preferably in one domain using simulated inputs.

2. During the development of CubeCAT demonstrator an Electrical Ground support Equipment (EGSE) was used to control the CubeCAT and perform various tests. The EGSE was used with a human operator who would set and then get parameters to confirm that the updates have indeed occurred. However, the OBC uses a timetable which does not allow for the same check. Various commands had to be reworked to work with this method of interfacing, which could have been avoided if the EGSE was built differently from the start.

3. As with any product development, if the requirements are not clear and well defined from the start, and the derivative requirements are therefore also unclear, it pays to have many review cycles earlier on, in order to smoothen the development process.

4. It is also important to not underestimate the usefulness of simulation models for various subsystems. One of the issues that occurred was the delay between receiving GPS and ST data from the satellite to the CubeCAT for the Point-Ahead-Angle calculation. The delay was a higher-than-expected which led to a re-implementation of the algorithm. During this time a model was implemented to better understand which algorithm modification would best take account for the delay while being accurate.

5. It is highly beneficial to start integration testing early, as this is the phase where most faults will show up, especially given how densely integrated this product is. By doing it early and often, it gives more time for debugging and finding better solutions for any errors found. However, it puts pressure on the schedule, yet as always, errors solved early on are much cheaper than those solved near the end.

OUTLOOK

As the free space optics is still an emerging technology many new standards and protocols are created. To be able to efficiently accommodate different ground stations, a reconfigurable protocol platform is needed. This protocol platform would allow the user to change the protocol before a transmission. It would also make it easier to implement new protocols in the future.

To downlink large volumes of data, a Store and Forward functionality for large data volumes will be implemented. In this scenario, payload data can be streamed to the terminal where it will be stored until the next downlink opportunity. Using robust storage hardware is critical to ensure that no data gets lost. This setup should be able to accommodate several passes at the targeted data rate.

SUMMARY AND CONCLUSION

Commercializing and productizing LCTs for CubeSats involves overcoming various challenges, including proof of concept, competition with established technologies, evolving market dynamics, ground infrastructure requirements, and the impact of weather conditions. By addressing these challenges, LCTs can establish themselves as reliable and high-performance communication solutions, enabling advanced capabilities for CubeSats and expanding their market presence.

The CubeCAT terminal's development was a crucial step in order to move towards a reliable, repeatable terminal for use on low-earth-orbit satellites, without placing too much strain on the ADCS system of those satellites. An embedded store-and-forward function will further offload the satellite's data handling system, avoiding the need of transferring data at gigabit speeds through the satellite during a pass.

Having gone through the process of developing the system for the current IOD rendered a lot of lessons learned, and the on-orbit performance data will be used in future commercial versions to fine-tune the controllers and atmospheric models used to generate them. The upgradability of the IOD model might allow to do further testing after the primary mission phase for example data transmission instead of PRBS.

Acknowledgments

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