CubeCAT: In-Orbit Results and the Future of DTE LCT

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ABSTRACT

As small sat technologies advance in accuracy and performance, the magnitude of data generated has grown exponentially. The current radio frequency (RF) system size, weight, and power (SWaP) and difficulties of obtaining RF spectrum licenses cannot keep pace with this progress and a new medium for data transfer is needed. Laser-based communication is an alternative data transmission technology, that is inherently well suited for large volume data transfer with a low SWaP system from space to Earth. It opens the door for larger data transmission down to Earth starting at speeds in the Gbit/s range, in a small and energy efficient form factor. Laser Communications increase the scope, functionality, and relevance of SmallSats in data-gathering missions by reducing the compression or even culling of valuable data.

AAC Clyde Space's subsidiary, AAC Hyperion, and TNO, the Netherlands Organisation for Applied Scientific Research have developed the CubeCAT Laser Communications Terminal (LCT). CubeCAT is a compact, high-performance LCT for use in CubeSat and SmallSat systems optimized for downlinking large data volumes. The LCT enables a bidirectional space-to-ground communication link between the spacecraft and an optical ground station, with current downlink speeds of up to 1 Gbps and uplink data rate of 200 Kbps.

As part of Norwegian NorSat Technology Demonstrator (NorSat-TD), a demonstrator version of CubeCAT was launched on the SpaceX Transporter 7 mission in April 2023, called SmallCAT. SmallCAT successfully achieved optical links with TNO's GoCAT ground station in The Hague, Netherlands, and with ESA's ground station in Tenerife, Spain. It also successfully transferred data at 1Gbit/s from a 500km SSO orbit to the ground station in The Netherlands. Currently further testing is underway to finetune and develop the overall communication chain as well as understand detailed performance.

This paper details the technology and the primary results from the IOD mission, a brief look will be taken at the architecture and building blocks of the terminal itself, the path to launch and the initial in-orbit testing and results. Finally, an indication is given of what is next for this exciting technology.

1 INTRODUCTION

The space sector is no different to other industries; just as seen elsewhere, data generation is increasing at a rapid rate. This is largely due to the advancements made in the development of optical payloads and their reduced form factors. The increase in data generation and reduction of satellite form factors have led to a significant bottleneck in the data chain for small satellites. The laser communication terminal and in-orbit demonstration presented in this paper aims to address this bottleneck by leveraging free-space optical communication techniques.

To ensure that the technology is usable on Small Satellites and CubeSATs the form factor plays a critical role. This posed challenges during the design and development phase which were overcome by techniques such as co-aligning optical paths and using compact optical layouts. Early integration of electronic subsystems also helps in achieving a compact form factor.

This led to the development of the CubeCAT terminal which has been launched and tested in-orbit. The initial results for the in-orbit testing are presented in this paper.

2 DESIGN AND DEVELOPMENT

Although the focus of this publication is the in-orbit demonstration of the terminal in question, in order to give the proper context of this achievement this section will serve as an introduction and background information to the development of the terminal in question.

2.1 In-orbit Terminal

The CubeCAT LCT, developed by the Dutch applied research institute TNO and AAC Hyperion, is a CubeSat form factor compatible 1U Laser Communication terminal (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 and firmware. Figure 1 shows a high-level breakdown of the architecture. The Direct to Earth (DTE) laser communication terminal's architecture is based on a single detector that captures both the communication signal and tracks the direction of the incoming light. The tracking signal is used to control a Fine Steering Mirror (FSM) to correct Spacecraft microvibrations and optimize pointing performance. This enables a small, energy efficient and cost-effective system, at the cost of a relatively low Rx data rate, from ground towards CubeCAT.

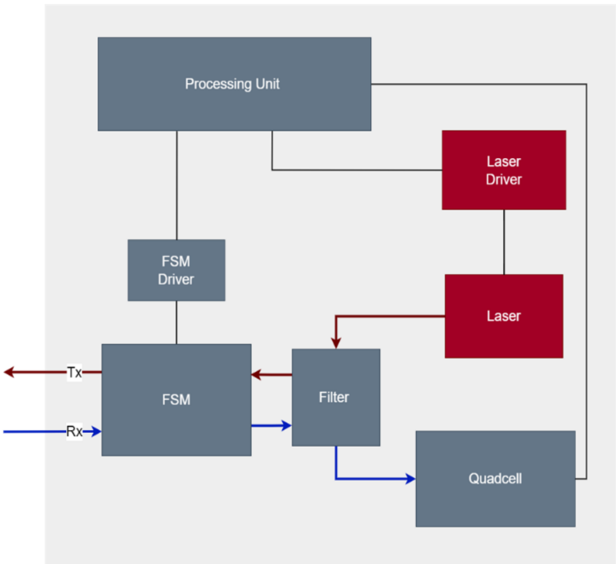

Figure 1: Basic Architecture of the CubeCAT

2.1.1 Structure

The structure encloses and supports the terminal, meeting CubeSat standards and is optimized for optical performance under thermal load. It faces design challenges by interfacing with both the spacecraft and optomechanical assembly, necessitating control of deformation and stress to avoid misalignment and distortions. This was achieved through careful selection of materials and geometry. See Figure 2 for the terminal without top and side panels and Figure 3 for a picture of an assembled CubeCAT.

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

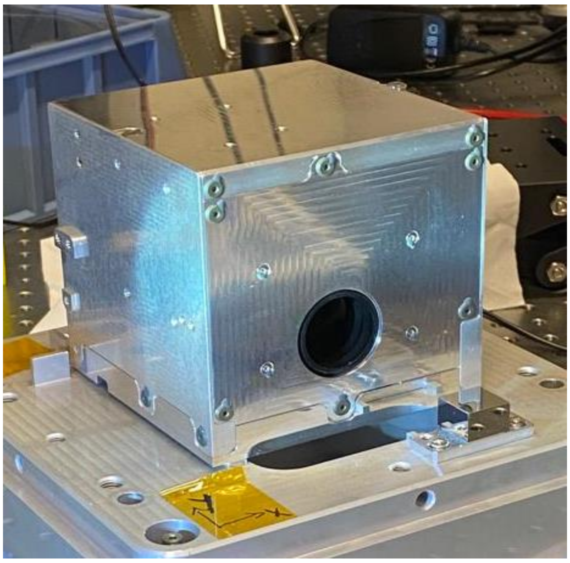

Figure 3: A picture taken early 2022 of an assembled CubeCAT.

2.1.2 Fine Pointing System and Optomechanical Assembly

To accommodate the fine-pointing system, within the available volume, a single optical path was utilized for both uplink and downlink. This decision was made to optimize space usage. A crucial component of this setup was the use of a dichroic mirror, which ensured that the correct link direction was maintained. Specifically, the dichroic mirror filters out light of a particular wavelength, allowing only the uplink wavelength (1590nm) to reach the quad cell while effectively blocking the outgoing wavelength (1545nm). Other wavelengths, in or near the optical C-band, are possible by exchanging filters during the manufacturing process. This configuration was illustrated in Figure 4.

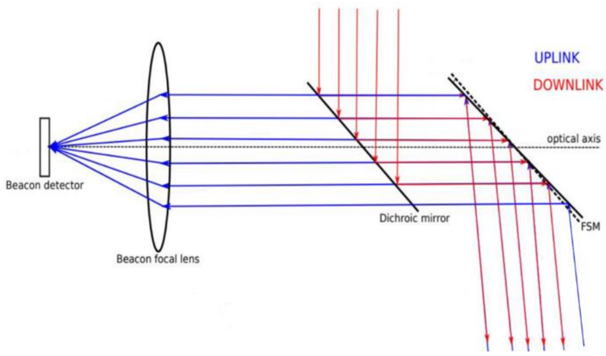

Figure 4: Diagram of the CubeCAT fine pointing system

In the in-orbit-demonstration, CubeCAT relied on coarse pointing by the spacecraft. This decision was supported by the capabilities of current ADCS (Attitude Determination and Control System) technology, which is capable of achieving accuracies below 0.5 degrees. Complementing the coarse pointing provided by the satellite bus, a Fine Steering Mirror (FSM) was integrated into the architecture. Developed by TNO, and produced by Demcon Focal, the FSM plays a crucial role in fine-tuning the pointing accuracy. With an optical range of ±2 degrees, the FSM effectively corrected for any coarse pointing errors introduced by the satellite bus. Its compact design, featuring a 20-millimeter diameter and flatness within 12 nm rms, made it particularly well-suited for space applications. Additionally, the FSM operated at a 1 kHz bandwidth, allowing for rapid adjustments to maintain precise alignment. Its lightweight construction, incorporating a bearing with leaf springs, ensured high linearity and prevented wear over extended periods of operation. These characteristics collectively made the FSM an essential component in achieving and maintaining reliable communication links in space [2].

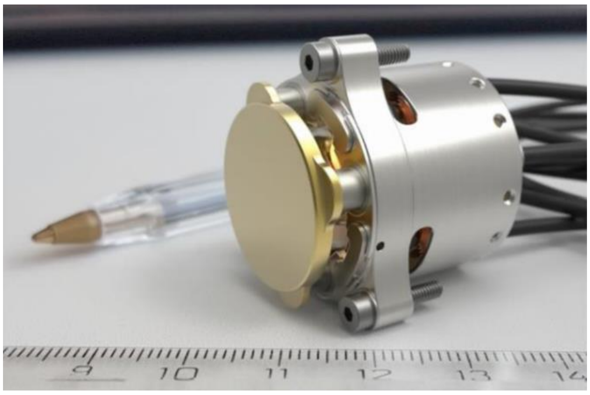

Figure 5: Render of FSM with pen for reference.

2.1.3 Laser

At the heart of the terminal lies an essential component: a 300mW laser transmitter developed by Gooch & Housego in collaboration with TNO and AAC Hyperion. This laser operates at a wavelength of 1545 nm, specifically tailored for the downlink beam. The laser was meticulously packaged to meet stringent performance and environmental standards. Complementing this intricate setup is a precision-engineered laser driver from AAC Hyperion, responsible for powering and controlling the laser.

2.1.4 Quadrant Detector

To establish a link, a beacon of light is transmitted from the ground station and captured by a quad cell. In order to make the acquisition of the first signal more robust, the FSM performs a spiral search pattern. After acquisition of the signal is complete, the Quadrant Detector provides tip/tilt knowledge of beam pointing errors, which includes spacecraft pointing errors. Corrections for the fine steering mirror (FSM) are then calculated based on this information in the processing unit. Utilizing a common path for both transmission (Tx) and reception (Rx) beams, adjustments made for the Rx beam also apply to the Tx beam.

The detector (an opto-electronic sensor, used both for beacon detection as well as receiving data), feeds its output back to the fine pointing system controller. Its two-dimensional spot location output on the focal plane indicates the guidance beacon's spot location, crucial for aligning the downlink Tx with the uplink Rx beam. Noise optimization of the read-out electronics, particularly the readout circuit, is paramount to minimize any noise that could affect pointing accuracy.

2.1.5 Processing Unit

The processing unit (the CP400 processing unit developed by AAC Hyperion) 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].

2.2 Optical Ground Station

The Optical Ground Sation that was used for the in-orbit demonstration is located in The Hague in the Netherlands. It was developed by TNO and Airbus Netherlands. It consists of a 800mm ASA telescope, and GOCAT, the Gigabit Optical Communication Active Terminal. It is capable of establishing a bi-directional communication link to a LEO satellite with a data rate up to 10 Gigabit/s.

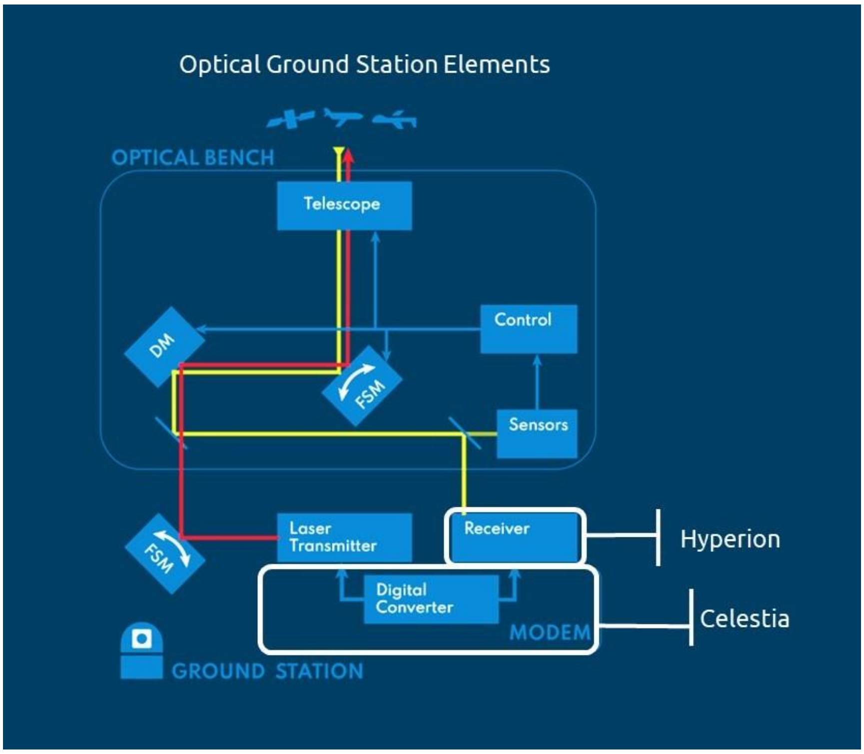

Figure 6: Functional Break Down of Optical Ground Station [5]

Telescope subsystem

Compared to RF antennae, the high pointing accuracy required of ground terminals is one of the challenges that need to be addressed to realize reliable optical links with satellites. A telescope, consisting of an on-axis optical tube assembly (OTA), an active tracking mount and a control system, is a key subsystem of a ground station.

The telescope will provide the coarse pointing whereas the remaining tracking error will be corrected for by the GOCAT Fine Steering Mirror. The telescope will point towards a (moving) target in the sky based on orbit predictions of the satellite.

Optical Bench subsystem

The Optical Bench is an optomechanical system that is connected to the telescope subsystem to relay the satellite laser beam to the detectors and to launch free space data and beacon laser beams.

The received light needs to be focussed on the detectors. The detectors consist of free space photodiodes a physical size of typically less than 30µm, which requires accurate pointing. The remaining telescope tracking error and angle-of-arrival errors due to Earth's atmosphere are corrected by the Fine Steering Mirror (FSM).

For the FSM to perform the fine pointing on the detector, a small portion of the satellite's received beam is diverted to an Acquisition and Tracking Sensor (ATS). This ATS allows GOCAT to acquire an active link with the satellite and track the satellite by measuring the fine tip/tilt errors of the received light. The sensor's output signals are used as input to a real-time controller that drives the FSM.

The transmit laser beam will be coupled into the Optical Bench's common path. In order to achieve the challenging link budget of up to 10 Gbit/s uplink towards satellites, it is important that this beam has low optical aberrations and that the pointing is controlled with high accuracy. The pointing is achieved by both a point-ahead mirror (PAM) to correct for static errors (e.g. the point-ahead angle to correct for the momentum of the satellite during time-of-flight of transmitted photons) and a fine steering mirror (FSM) to compensate for dynamic errors (e.g. ground vibrations and the errors induced by earth's atmosphere).

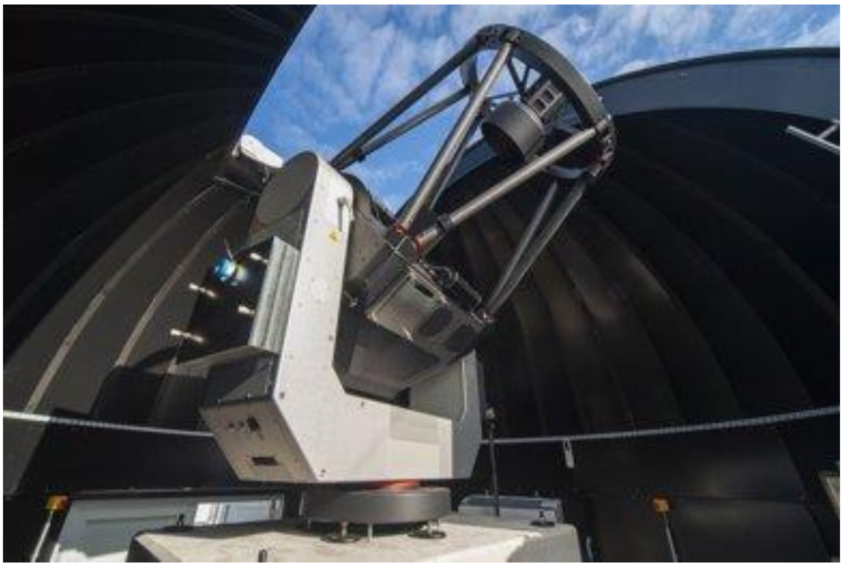

Figure 7: OGS Telescope [6]

Figure 8: TNO OGS Tower

3 APPLICATION

As mentioned earlier, the laser communication terminal (LCT) was developed to tackle the issue of data congestion often encountered with data-rich payloads on small satellites. A key part of solving this problem involves shortening the data path during transmission, and onboard storage on the CubeCAT terminal plays a crucial role in making this happen.

In Low Earth Orbit (LEO) at about 500km altitude, satellites complete an orbit in about 90 minutes. With advancements in payload technology, the amount of data collected during each orbit has been increasing rapidly. This can lead to a significant amount of data—potentially hundreds of gigabits—accumulating with each pass.

Having onboard storage on the CubeCAT terminal allows for a more manageable approach to handling this data influx. By providing a slower data interface, the terminal can store data until there's a better opportunity for transmission. This not only helps optimize bandwidth but also ensures smoother data management and transfer, ultimately improving the efficiency of satellite communication systems in LEO.

To put this into perspective a typical downlink scenario is described below.

- Forward payload data to the CubeCAT, as it is acquired during orbit, no need to store it on the satellite. A low-power mode is used on the CubeCAT terminal to receive and store data.
- Utilize RF link to send orbital parameters to ground, this information will be used for tracking and pointing by the OGS.
- Turn on the CubeCAT Unit when the Satellite is approaching the OGS and point the CubeCAT to the OGS
- In parallel the OGS beacon must be activated and tracking of the satellite from ground must start
- Acquisition and transmission mode can now be initialized on the CubeCAT, once this is done the following steps are taken to down link the data, see Figure 9.

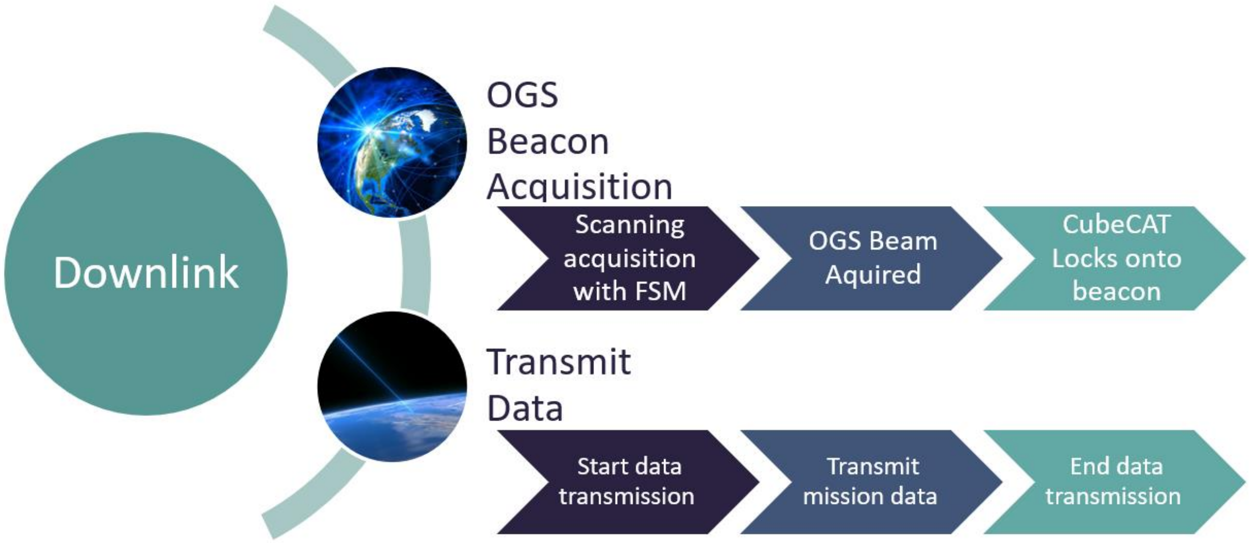

Figure 9: Transmission Steps

In order to execute the transmission as described in Figure 9 the satellite platform has to provide a level of stability to ensure that the link can successfully be established. The key parameters that the satellite needs to achieve are listed in Table 1 below.

Table 1: Satellite Stability Requirements

Parameter	Value	Unit
Pointing Accuracy	< 0.5	deg (2σ)
Low-Frequency Vibration Velocity (<20 Hz)	< 0.6	mrad/s rms
High-Frequency Vibration/Jitter Amplitude (>20Hz)	< 2.5	µrad rms
Time accuracy	50	ms wrt UTC or better

4 IN-ORBIT DEMONSTRATION

The unit that was used for the in-orbit demonstration is named the SmallCAT. The SmallCAT unit has an additional suspension system which was necessitated by dynamic interaction between CubeCAT and the mounting panel of the satellite bus structure. The SmallCAT unit is shown in Figure 10.

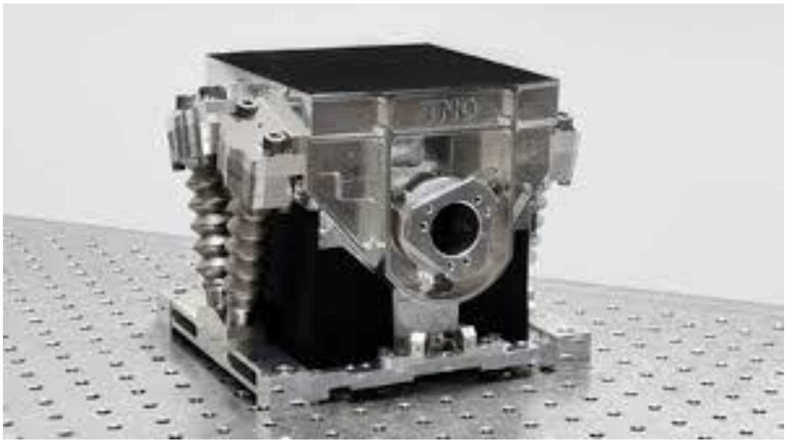

Figure 10: SmallCAT IOD Terminal

The SmallCAT terminal is part of the NorSAT-TD mission, a technology demonstrator mission developed by Space Flight Laboratories (SFL) in Canada through the Norwegian Space Agency. NorSAT-TD is designed as a microsatellite aimed at the validation and testing of payloads and technologies from the Netherlands, Italy, and France.

4.1 On-Ground Testing

The SmallCAT terminal is a proto-flight unit and was therefore subjected to a test campaign in line with proto-flight test requirements. High-level details of the testing are presented in the subsequent paragraphs.

Functional and Performance Testing

Functional and performance testing was conducted throughout the test campaign. The main objective of these tests was to verify that the unit was still functional and performing at an adequate level. This included:

- EMI/EMC
- Sun simulator blinding
- Electrical and software interface
- Optical Rx/Tx alignment, divergence, WFE, transmission
- FSM functionality and performance
- Acquisition and Tracking scenario (open and closed loop)
- End-to-end Communication
- Magnetic dipole
- Laser safety
- Laser burn-in

Environmental Testing

Vibration and Thermal Vacuum (TVAC) testing were done at terminal level for proto-flight testing. Additional radiation test campaigns were conducted as well. The terminal was then subjected to an acceptance test campaign at satellite level.

4.2 In-orbit Testing

The in-orbit testing was done in a phased approach. First CubeCAT was carefully commissioned, in order to minimize risk of damaging the system. During multiple links with GOCAT in The Hague, The Netherlands the following results were achieved:

1. OBS Beacon laser was detected on SmallCAT Quadcell
2. FSM control loop was closed on SmallCAT
3. SmallCAT Laser was detected with in-line power monitor on SmallCAT
4. SmallCAT Laser was detected on GOCAT ATS
5. FSM control loop was closed on GOCAT
6. SmallCAT laser was detected on GOCAT Comms detector
7. SmallCAT's PRBS23 signal was recorded on a high-speed oscilloscope

Figure 11 shows an example of the received signal at a certain instance during one of the overpasses. Note that the received signal waveform was captured by the high-speed oscilloscope and then stored for offline postprocessing. A comparison to the PRBS sequence (as sent by SmallCAT) is also shown.

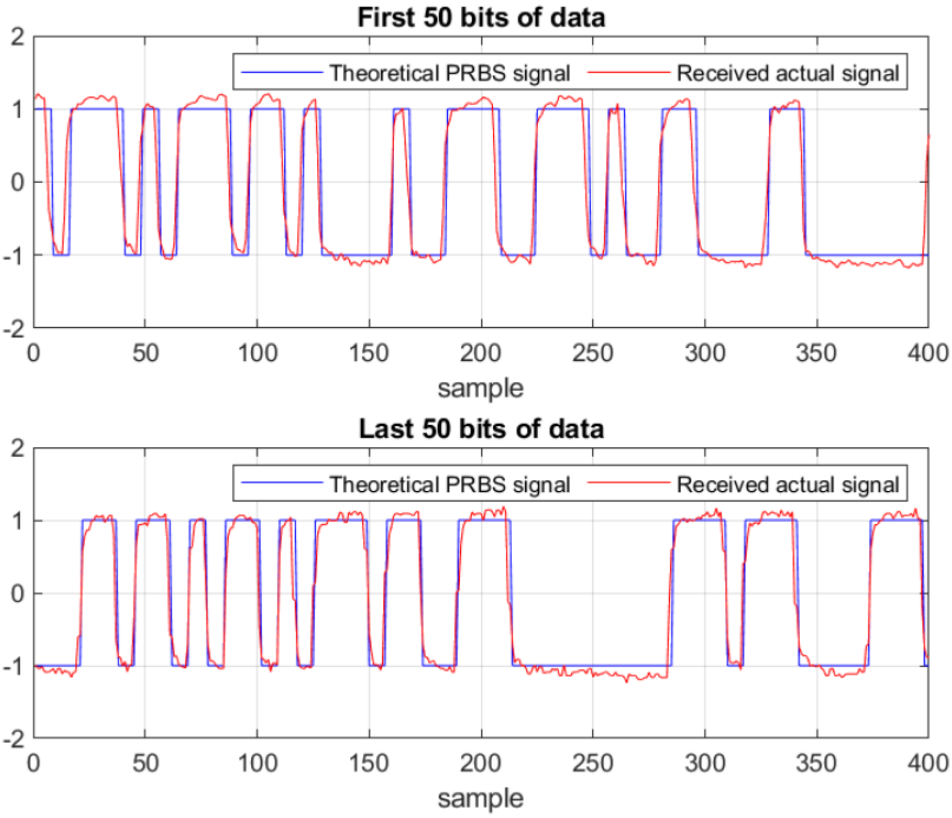

Figure 11: Example of received signal measured by the Oscilloscope and comparison with PRBS sequence.

Figure 12 shows the Eye Diagram of the received signal at 23:21:01, which is the eye diagram after the photo-current is amplified to a voltage by the transimpedance amplifier and converted to a digital signal by the limiting amplifier.

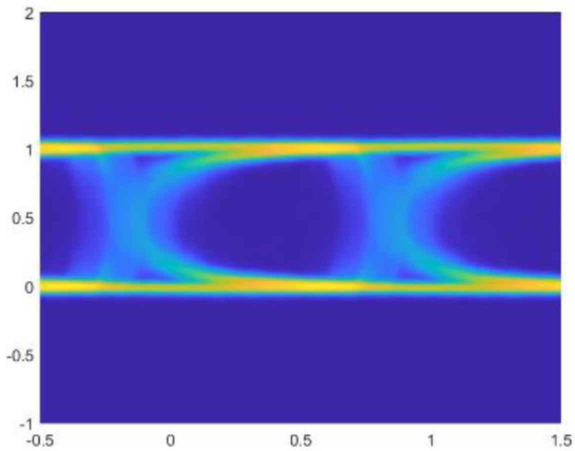

Figure 12: Eye diagram of received SmallCAT laser by GOCAT, as measured after the limiting amplifier.

Bit Error Rates (BER) show to be dependent on the overpass and test conditions, but typical BER is in the range of 10^{-4} to 10^{-6} without Error Correction.

The results presented demonstrate the implementation of the relevant functionalities on both Space (SmallCAT integrated on NorSat-TD) and Ground (GOCAT integrated on TNO-OGS) terminals. This paves the way for further test activities to fully assess the performance of the system, and in relation to the environmental conditions encountered during operations.

5 OUTLOOK

Future improvements are being considered to further enhance the CubeCAT design. These enhancements will focus on optimizing performance, expanding functionality, and ensuring compatibility with evolving industry standards.
Performance enhancements will be materialized through increased data rates. There are various approaches that can utilized to achieve this, ranging from increased laser power, smaller divergence angles or coherent modulation techniques.

Decoupling the pointing of the laser communication terminal form that of the satellite will also aid in making this technology easier to implement and to plan into various mission concepts of operations. A development project aiming to address this is already underway with TNO taking the lead and AAC Hyperion supporting the development with electronic and software development. The focus of this project is to incorporate a Coarse Pointing Assembly (CPA).

Since free space optics remains an evolving technology, various standards and protocols continue to emerge. To effectively cater to various ground stations, a platform flexible to different standards becomes essential. In future this should platform enable users to dynamically adjust protocols before transmission, facilitating seamless integration of new protocols as they develop.

6 CONCLUSION

In the paper a summary of the architecture of the CubeCAT laser communication terminal was provided along with a high-level summary of the on-ground testing that was conducted to ensure the terminal would indeed survive the environment in space and perform as intended. After successfully launching and commissioning the satellite, in-orbit testing has been conducted using the SmallCAT terminal and the Optical Ground Station in The Hague. The in-orbit testing has delivered very promising results, with the SmallCAT terminal managing to lock onto the OGS beacon and the data beam being received at the OGS. TNO also managed to demodulate the incoming PRBS23 bit stream.

Apart from in-orbit testing, the consortium is also developing a coarse pointing assembly (CPA) as part of the TNO HemiCAT project and a 10Gbit/s version of CubeCAT.

Future papers will present results from recent and on-going SmallCAT – GOCAT experiments, on Pointing, Acquisition and Tracking performance and on the quality of the optical link for data transfer.

7 ACKNOWLEDGMENTS

The SmallCAT/CubeCAT has been designed and developed by TNO and AAC Hyperion. The expertise and ingenuity of both teams have been invaluable in getting this terminal in to orbit.

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