SSC24-IX-05

Assessing the results of a space-to-ground data transfer link of a 1U laser communication terminal for SmallSats

Johan du Plooy (1), Jacob Hejderup (1), Steven Engelen (1), Tushar Goyal (1), Gert Witvoet(2), Rodof Herfst(2), Dick de Bruin(2), Stefano Redi(2), Floris van Kempen(2)

1. AAC Hyperion, Vlinderweg 2, 2623AX, Delft, The Netherlands, +31 155160905,
johan.duplooy@aac-clydespace.com

2. TNO, Stieltjesweg 1, 2628CK, Delft, The Netherlands, +31 888661346,
floris.vankempen@tno.nl

ABSTRACT

As advancements in small satellite technologies continue to improve in precision and functionality, the volume of data produced has grown exponentially. The existing balance of size, weight, and power (SWaP) in radio frequency (RF) systems is unable to keep up with these advancements, necessitating a new medium for data transfer. Laser-based communications represent the future of data transmission technology, promising to increase bandwidths into the tens to hundreds of gigabits per second and facilitate larger data transmissions to earth. This enhances the versatility, functionality, and significance of SmallSats in data collection missions.

AAC Clyde Space's subsidiary, AAC Hyperion, in collaboration with their partner TNO from the Netherlands, have developed the CubeCAT Laser Communications Terminal (LCT). CubeCAT is a compact, high-performance LCT designed for use in CubeSat and SmallSat systems. The LCT establishes a two-way space-to-ground communication link between the spacecraft and an optical ground station, offering downlink speeds of up to 1 Gbps and an uplink data rate of 200 kbps.

As part of the innovative in-orbit demonstration mission, NorSat-TD, the CubeCAT LCT was launched on the SpaceX Transporter 7 mission in April 2023. The configuration used for this mission was named SmallCAT. Utilizing the TNO GoCAT ground station in The Hague, The Netherlands, the SmallCAT has successfully established a link and testing is in progress to refine and develop the overall communication chain. The consortium, which is already developing a coarse pointing assembly (CPA) as part of the TNO HemiCAT project, will use these examples and others from our in-orbit demonstration to guide the development of future iterations.

This paper will provide a summarized overview of the technology developed to enable the demonstration of data transfer from space to ground via free space optical link. The results from the IOD mission will be presented. Details such as overall performance, mission profiles, light received at the Optical Ground Station (OGS), free space channel conditions, orbital parameters and throughput will be discussed.

Additional experiments are planned to test the boundaries of the system. These results and insights will be used as building blocks for enhancing the LCT's performance in line with the development projects mentioned above. All significant results and findings will be presented with comments on outlook and further development.

INTRODUCTION

The advantages of implementing laser communication technologies as part of space missions featuring high data generation payloads has been well documented. In order to address this opportunity, AAC Hyperion along with its partner TNO have developed and demonstrated a compact laser communication terminal in orbit.

For this technology to be practical for Small Satellites and CubeSATs, form factor is crucial. This requirement posed several challenges during the design and development phase, which were addressed by co-aligning optical paths and employing compact optical layouts. Additionally, the early integration of electronic subsystems contributed to achieving a compact form factor.

This paper provides a high-level summary of the in-orbit terminal that was developed, an overview of the OGS that was used to do the Direct to Earth (DTE) link from satellite to ground as well as the results generated. This was one of the first small form factor terminals to achieve this.

Additionally, the position of the terminal in the communication systems product market is also presented and discussed.

ARCHITECTURE AND DESIGN

The CubeCAT LCT terminal, developed by TNO and AAC Hyperion, is a 1U Laser Communication Terminal (LCT) for CubeSats featuring a novel architecture due to its small form factor, see Figure 1. TNO led the optomechanical, systems design, and algorithm development, while AAC Hyperion developed the electronics, software, and firmware. The terminal's architecture uses a single detector for both communication and tracking, controlled by a Fine Steering Mirror (FSM) to correct spacecraft microvibrations and optimize performance while maintaining energy efficiency in a compact volume.

The terminal's structure is optimized for optical performance under thermal load, supporting the terminal and meeting CubeSat standards from a physical perspective. It interfaces with both the spacecraft and optomechanical assembly, managing deformation and stress to avoid misalignment and distortions through careful material and geometry selection.

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

The fine-pointing system uses a single optical path for both uplink and downlink to optimize volume. A dichroic mirror filters light, allowing only the uplink wavelength to reach the Quadcell while blocking the outgoing wavelength. In orbit, CubeCAT relies on the spacecraft for coarse pointing, with the FSM correcting any errors. The FSM, developed by TNO and produced by Demcon Focal, features a 20-mm diameter and flatness within 12 nm rms, providing fine-tuning with an optical range of ±2 degrees, see Figure 2. Its lightweight, bearing-based design ensures high linearity and durability.

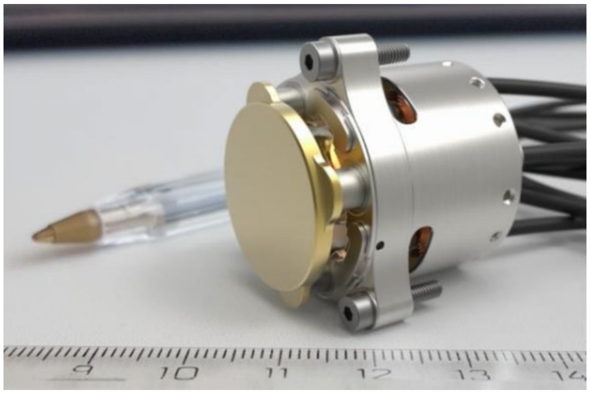

Figure 2: Render of Fine Steering Mirror with pen for reference.

At the heart of the terminal is a 300mW laser transmitter developed by Gooch & Housego with TNO and AAC Hyperion, operating at a wavelength of 1545 nm for the downlink beam. A precision-engineered laser driver from AAC Hyperion powers and controls this laser.

The beacon beam from the ground station is captured by a Quadcell detector, with the FSM performing a spiral search pattern for signal acquisition. The Quadcell detector then provides beam pointing error data, which is used to calculate FSM corrections. This common path for transmission and reception beams ensures adjustments apply to both.

The CP400 processing unit, developed by AAC Hyperion, manages power rails, interfaces with the satellite OBC, performs system housekeeping, updates firmware, and computes point-ahead angles. It synchronizes tasks and collects logs and telemetry data, simplifying system operations.

OPTICAL GROUND STATION

This in-orbit demonstration was planned to connect with TNO's optical ground station located in the Hague, The Netherlands. The OGS consists of an 800mm ASA telescope, and an optical bench developed by TNO and Airbus known as GOCAT, the Gigabit Optical Communication Active Terminal. This Ritchey-Chrétien telescope with f6.85 combined with the GOCAT has the capability of establishing a 10 Gigabit/s bi-directional link to a LEO satellite.

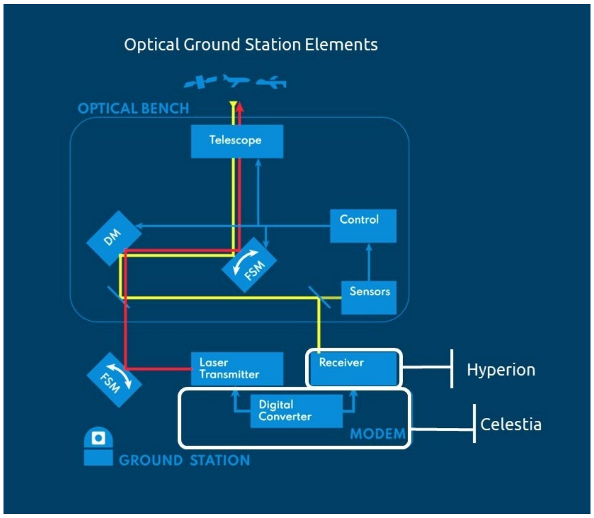

Figure 3: Functional Break Down of Optical Ground Station [5]

Telescope subsystem

To realize reliable optical links with satellites there is a requirement for ground terminals with high pointing accuracy in contrast to traditional RF antennae. This key challenge is addressed utilizing an on-axis optical tube assembly (OTA) telescope with an active tracking mount and a control system as a key subsystem of the ground station.

This telescope system addresses the coarse pointing requirements for tracking a moving target based on orbit predictions of the satellite. The remaining tracking error for fine pointing is amended by the GOCAT Fine Steering Mirror (FSM).

Optical Bench subsystem

This optomechanical system is designed to relay the satellite laser beam to the detectors and to transmit free space data while also launching the beacon laser beams.

The light received in the telescope needs to be focused by the connected optical bench on to the detectors. These free space photodiode detectors have an active diameter of 75 µm, which imposes precise pointing requirements. The Fine Steering Mirror (FSM) compensates for the telescope tracking error and angle-of-arrival errors due to Earth's atmosphere.

An Acquisition and Tracking Sensor (ATS) utilizes a small portion of the satellite's received beam to feed the FSM to perform the fine pointing on the detector. The sensor's output signals are used as input to a real-time controller that drives the FSM. 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 OGS utilized for this IOD is designed to accommodate up to 4x 10W(each) transmit laser beams which is coupled into the Optical Bench's common path. For initial links the Tx beam was only used as a beacon at 6W power per beam.

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 4: TNO OGS Tower

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 5.

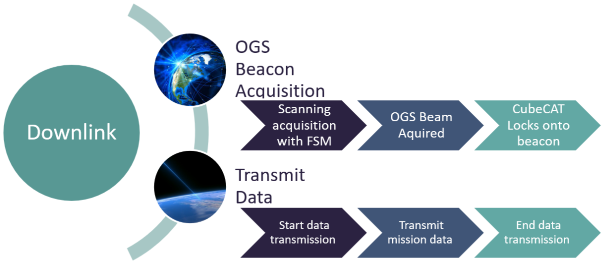

Figure 5: Transmission Steps

In order to execute the transmission as described in Figure 5 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)
Pointing Knowledge and Stability	<0.49	mrad (1 σ)
Low-Frequency Vibration Velocity (<120 Hz)	< 1.9	mrad/s rms

Parameter	Value	Unit
High-Frequency Vibration/Jitter Amplitude (>120Hz)	< 2.5	µrad rms
Time accuracy	50	ms wrt UTC or better

IN-ORBIT DEMONSTRATION

The unit utilized for the in-orbit demonstration is called the SmallCAT. This SmallCAT unit features an additional suspension system, required due to the dynamic interaction between CubeCAT and the satellite bus structure's mounting panel. The SmallCAT unit is shown in Figure 6.

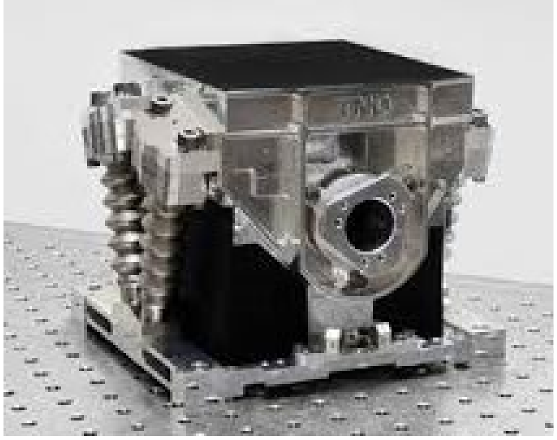

Figure 6: SmallCAT IOD Terminal

The SmallCAT terminal is included in the NorSAT-TD mission, a technology demonstration initiative created by Space Flight Laboratories (SFL) in Canada, in partnership with the Norwegian Space Agency. NorSAT-TD is a microsatellite intended for the validation and testing of payloads and technologies from the Netherlands, Italy, and France.

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 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/EMCF
- 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

In addition to functional and performance testing environmental testing was done as well. Vibration and Thermal Vacuum Testing was conducted at proto-flight levels to qualify the unit for spaceflight. Additional radiation testing was done as well. Acceptance testing was done on the spacecraft level

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

The process followed to achieve the results presented above is discussed in the following paragraphs. It has been broken down into 4 different milestones.

Milestone 1

In order to successfully detect the OGS beacon laser on the SmallCAT detector the OGS beacon laser was activated, and the OGS was set to track the satellite. In orbit the satellite was tasked to track the OGS while making pass. This resulted in the successful readout of intensity and spot location on the SmallCAT detector.

Milestone 2

The first light from the SmallCAT was received by the OGS on 11 September 2023. To achieve this the OGS had to successfully track the satellite, the satellite had to successfully track the OGS and the control loop on SmallCAT had to be closed. The light was captured using the OGS's tracking sensor.

Milestone 3

The next milestone achieved was receiving the SmallCAT laser beam on the communication detector at the OGS. All of the steps described above had to be repeated as well as closing the control loop at the OGS. While the light was detected the communications detector no modem or oscilloscope was attached at this point therefore no postprocessing could be done to demodulate the PRBS23 signal.

Milestone 4

After all the building blocks for the various testing were verified data transmission was successfully achieved from the SmallCAT to the OGS in The Hague in The Netherlands.

Figure 7 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 8 shows the Eye Diagram of the received signal at 23:21:01 on 19/01/2024, which is the eye diagram after the photo-current is amplified to a voltage by the trans-impedance amplifier and converted to a digital signal by the limiting amplifier.

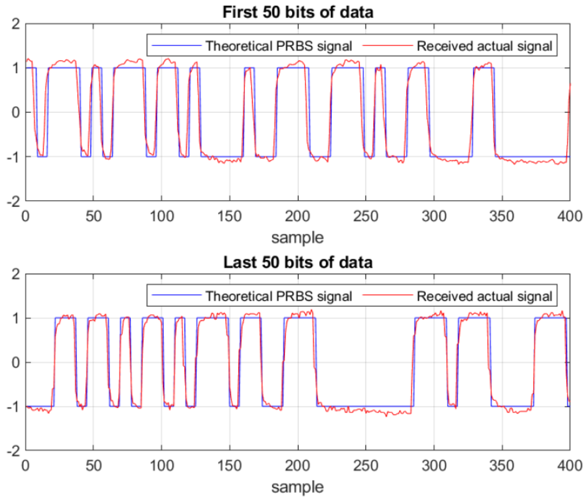

Figure 7: Example of received signal measured by the Oscilloscope and comparison with PRBS sequence.

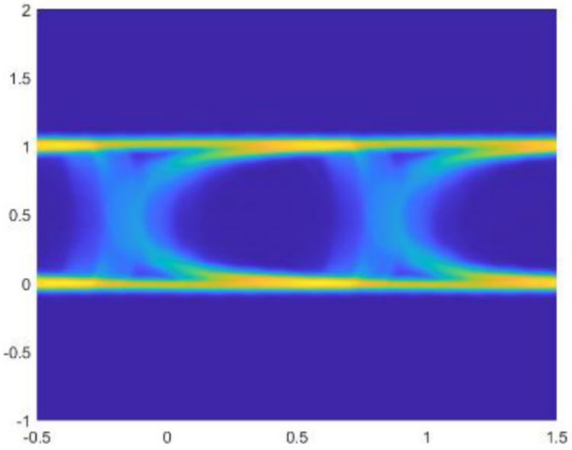

Figure 8: Eye diagram of received SmallCAT laser by GOCAT, as measured after the limiting amplifier.

Bit Error Rates (BER) are shown 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.

IMPACT ON MARKET

One of the objectives of this IOD was to break the so-called chicken and egg problem, where LCT providers suffered a lack of OGS to establish a link and vice versa. This experiment was planned for development of the LCT and the OGS to prove the complete chain. It has shown that reliable links can be made with a SmallSat from LEO to an OGS paving the way for the market to open for future demonstrations and commercialization.

To establish 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.

Currently, X-band technology offers a 1 Gbps bandwidth with comparable power consumption to the laser terminals available on the market. Furthermore, X-band technology is proven, reliable, cost-effective and most importantly the ground infrastructure required is less complex and is currently readily available as a service. This makes 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 10 Gbps. The chart presented below in Figure 9 compares the CubeCAT LCT with X-band solutions commercially available on the market. This chart compares the power consumption per Mbps with volume per Mbps of the LCT and the X-band systems. With the first generation of 1Gbps, CubeCAT already stands out from most X-band systems.

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. The chart presented in Figure 10 below compares the CubeCAT LCT with other successfully in-orbit demonstrated LCTs. Some versions of these LCTs are commercially available and others are only developed for experimentation. This chart compares the power consumption per Mbps for downlink with mass per Mbps of different LCTs with the CubeCAT. The SWaP of the CubeCAT due to its compact size puts it ahead of most of the other demonstrated LCTs providing opportunities for early market capture.

This IOD has enabled sales of the first commercial versions of this LCT, pushing satellite integrators to start looking to integrate this technology early into their platforms. This will enable offerings for high-speed data downlinking satellite platforms to be commercially and readily available. 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.

One of the critical factors mentioned earlier in the commercialization of laser communication terminals is the development of the ground infrastructure. OGSs are essential components but currently remain limited in availability. Furthermore, only a limited number of OGSs have 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.

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.

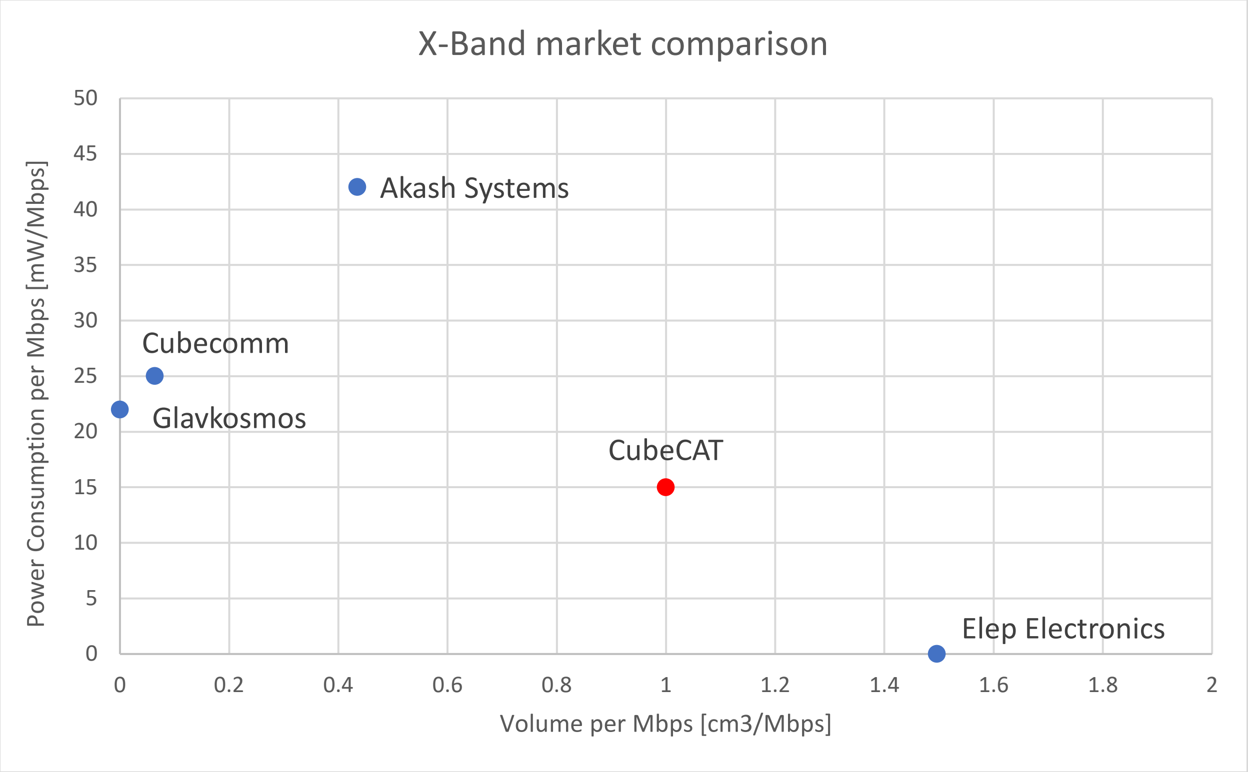

Figure 9: CubeCAT (1Gbps) compared with commercially available X-band radio

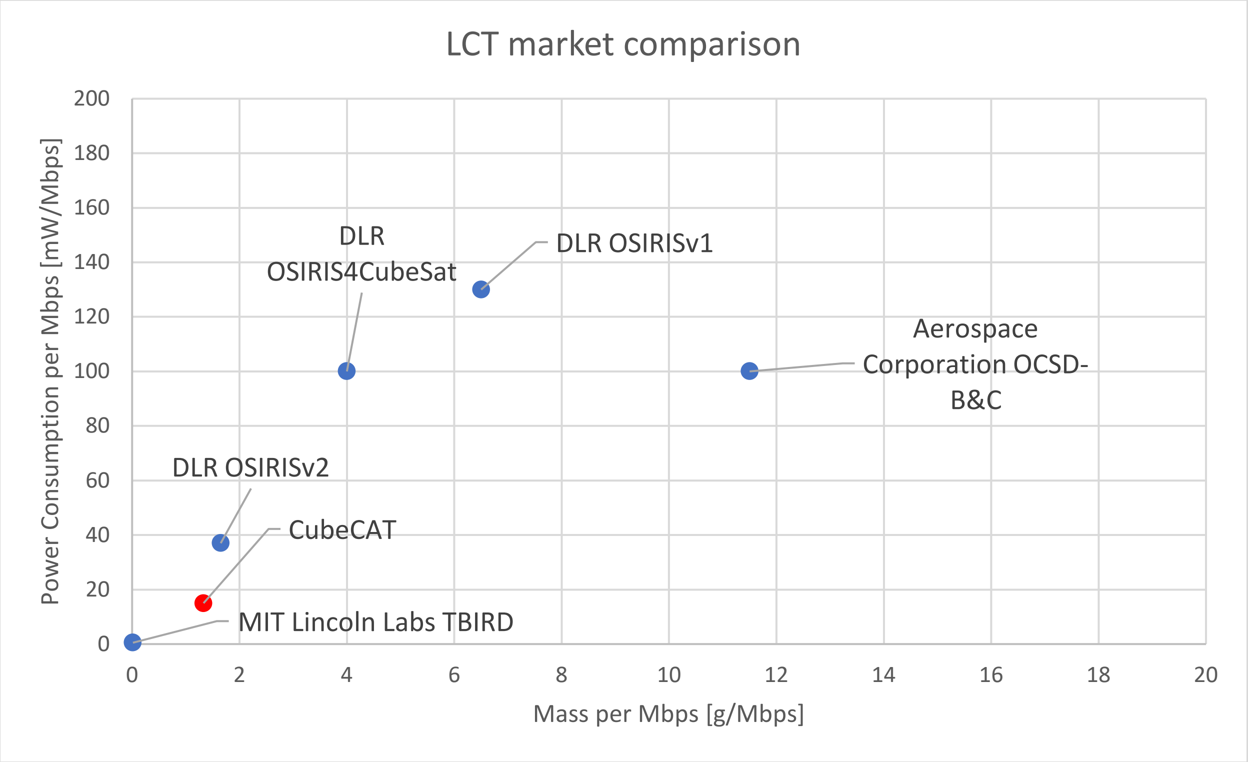

Figure 10: CubeCAT (1Gbps) compared with other successfully in-orbit demonstrated LCTs [6]

OUTLOOK

This IOD has provided some valuable lessons which are being implemented to further improve the technology and has paved the way for future developments. Apart from the ongoing in-orbit testing, the consortium has sanctioned two future developments which have been approved and funded. First is development of a coarse pointing assembly (CPA) for the HemiCAT project which will adapt the technology developed for the CubeCAT for a CPA enabled LCT downlinking at 1 Gbps, which is scheduled for IOD at the end of 2025. The second project is to develop a 10Gbps version of the CubeCAT maintaining the same 1U form factor.

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 and encryption techniques. 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. As mentioned previously a development project aiming to address this is by incorporating a CPA is already underway with TNO taking the lead and AAC Hyperion supporting the development with electronic and software development.

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 enable platform users to dynamically adjust protocols before transmission, facilitating seamless integration of new protocols as they develop.

CONCLUSION

The in-orbit results have proven that the SmallCAT architecture is well suited to transmitting data at speeds of up to 1 Gbit/s across a free space channel from LEO to ground. To achieve this a comprehensive test campaign was conducted on the ground which covered functional, environmental and performance testing. This approach allowed for a systematic way to derisk the development.

The optical ground station development, where a similar, approach was followed, also contributed to the successful data transmission.

Although there are still steps to be taken and additional testing to be conducted such as activating Forward Error Correction (FEC) and through-put tests at very low elevation angles, the most important initial milestone have been achieved.

This has also proven that the SmallCAT architecture which will be the basis for further development is well placed in the satellite communication market when compared to commercially available X-band as well as Laser communication-based solutions.

REFERENCES

1. Du Plooy, P. D., Ackaert, G., Witvoet, G. & Crowcombe, W., 2022. *System Architecture for a CubeSat DTE Laser Communication Terminal.* Logan, Utah, Small Satellite Conference 2022, p. 1.

2. Demcon, 2023. *demcon.com/fine-steering-mirror/.* [Online] Available at: https://demcon.com/fine-steering-mirror/

3. AAC Hyperion , n.d. *AAC Hyperion Internal Documentation,* Delft: AAC Hyperion.

4. TNO, n.d. *TNO Internal Documentation ,* Delft: TNO.

5. eoPortal, 2023. *eoPortal powered by ESA.* [Online] Available at: https://www.eoportal.org/satellite-missions/norsat-td#references

6. NASA. “State-of-the-Art of Small Spacecraft Technology” [Online]. Available: State-of-the-Art of Small Spacecraft Technology - NASA