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Optical Satellite Communication Space Terminal Technology at TNO

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ABSTRACT

Optical communications will complement radio frequency (RF) communications in the coming decades to enhance throughput, power efficiency and link security of satellite communication links. To enable optical communications technology for intersatellite links and (bi-directional) ground to satellite links, TNO develops a suite of technologies in collaboration with industry, which comprises of terminals with different aperture sizes, coarse pointing assemblies and fast steering mirrors. This paper presents the current state of the development of TNO technology for optical space communications. It mainly focuses on the development of an optical head with an entrance aperture of 70 mm, an optical bench for CubeSats and coarse pointing assemblies (CPAs). By continuing these steps, world wide web based on satellite communications will come closer.

Keywords: Optical Satellite Communications, Optical Space Terminals, Coarse Pointing Assemblies

1. INTRODUCTION

Optical satellite communication already is complementing satellite communications based on radio frequencies (RF). Although high throughput is a very prominent advantage, also the advantage of low-power, low interference and high security for optical wavelengths, e.g. 1064 or 1550 nm. These advantages serve several business opportunities, such large-scale communication via satellites and quantum key distribution (QKD) channels. Since optical communications technology has been proven to be a technical viable solution, the road has been paved for broad applications [1]–[3].

In this perspective, the European data relay system [4], [5] is currently effectively in use, mainly to transport data from scientific missions toward ground based systems. On the EDRS, TESAT provided high end versatile technology [6]. This technology is able to establish intersatellite links, e.g. LEO-LEO and LEO-GEO, but also satellite to ground communication [7]. The work that has been done to persistently perform optical communication links, brought the confidence that optical satellite communications could be used for other business cases [5].

Other attractive business opportunities serve the communication between people, for instance to transfer confidential data, or encryption keys. The inherent security of optical links, due to the limited beam divergence provide the confidence in such business applications. To enable wide usage of optical satellite communication, e.g. to provide massive LEO constellations with optical terminals, still work has to be done to provide commercially attractive laser communication terminals. Furthermore, there is also a clear trend towards smaller and smaller satellites for various earth observation and science tasks [8].

To realize massive satellite constellations using optical communications technology, the following key requirements are identified:

- **Low Size, Weight and Power (SWaP):** Compared to RF-terminals, optical communication terminals inherently support low SWaP, which is key for cost effective satellite payloads.
- **Low Recurring cost terminals** is key for commercial exploitation, and is mainly realized at the start of the design process.
- **Low latency, high reliability and security** optimally uses the advantages optical communications have compared to RF terminals.

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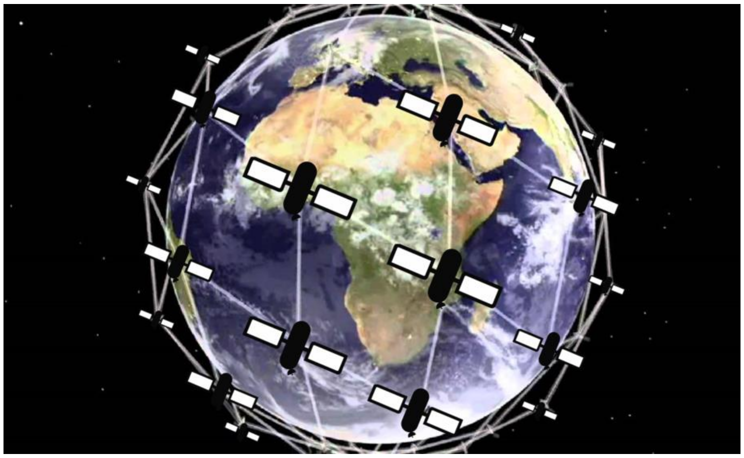
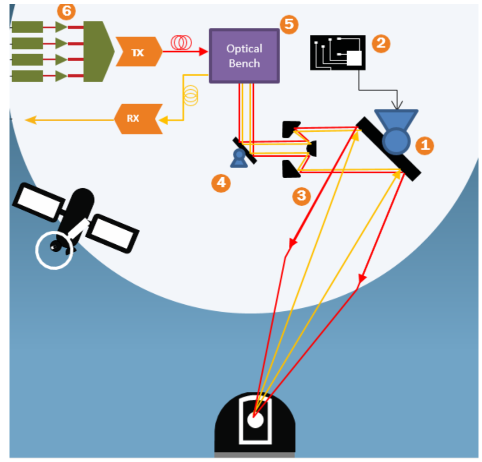


(a)



(b)

Figure 1 (a) Massive satellite constellation to connect people everywhere at every time at a reliable and secure way, with low latency. (b) Optical terminal system architecture, with (1) CPA, (2) Controller, (3) Telescope, (4) FSM, (5) Optical Bench, (6) Photonics.

Along with these challenges which must be met to support commercial exploitation, few other technical challenges have to be met. Due to the limited beam divergence the line of sight between the partnering terminals needs to be controlled within several microradians. This requires highly accurate beam-steering control to enable acquisition between two different terminals. Because of the leap in technology from RF to optical wavelengths, technical solutions that are viable to support laser satellite communication, have never been used in space. In order to gain confidence in the technology, technology has to be proven in space.

TNO works together with a broad range of industrial partners, research institutes, universities and service provides to roll out this technology [9]. In this paper several projects and technologies that TNO is working on. In particular, this paper presents a telescope with an aperture of 70 mm diameter.

2. SYSTEM ARCHITECTURE

Satellite communication systems, as referred to in the introduction typically consists of multiple LEO satellites, and ground terminals. Most viable option for optical satellite communications technology is intersatellite links, as no atmospheric influences, such as clouds and atmospheric turbulence can occur. The intersatellite links account for the majority of the data-relay system. In addition, the connection with the ground station has to be established, where optical communications can complement the RF communications technology.

Optical communication systems are composed of several generic building blocks, which can be used throughout several applications of optical communications. Hence they can be shared between the several different applications, which helps to realize a low recurrent cost. For the hardware described in this paper, also several modes of operation are important to establish and maintain the optical link. The acquisition mode is needed to acquire the link, i.e. find the partnering terminal. The tracking mode is needed to determine the handshake and maintain the optical link. And communication mode is do the actual communication. The building blocks are described below.

2.1 Optical bench function

The optical bench combines the functionality of all building blocks. It forms the physical and functional connection of all optical and opto-mechatronic components. To accommodate this function, it provides beam conditioning, splitting and shaping directing the optical beams towards the targeted components. The key requirements and functions are:

- **Separating the receive and transmit beam** to avoid high optical power from the transmit beam to the receive beam and pointing detectors.
- **Splitting and combining the optical channels** for multiplexed data-communication.

- **Filtering out-of-band light** originating from scattering and background radiation, improving the signal to noise ratio of detection.
- **Provide stability** against the effects of the launch and operational environments, such as vibrations and temperature fluctuations.

2.2 Telescope function

The telescope expands and decreases the beam size from the entrance pupil to the optical bench. As sufficient area is needed to collect sufficient amount of light, it determines the antenna gain for both transmit and receive beam. The optical quality of the telescope determines partly the transmission of the optical system, since transmission can be degraded by wave front errors. This is especially relevant, when the optical beam is coupled into a single mode fiber. Since a telescope consists of multiple optical elements, it requires quite some design effort to keep it low SWaP.

2.3 Coarse pointing function

Coarse alignment of the optical terminal is done via the coarse pointing assembly (CPA), which steers and aligns the optical beam for both the receive and transmit beam. This is used to provide the basic angular motion of the laser beam needed for acquisition mode and to anticipate on the relative motion between the optical terminals. To realize this the key requirements and functions are:

- **Large angular range:** to establish and maintain the optical link, partnering optical satellites to accommodate for the large relative motion between two neighboring satellites or satellite and ground station, with minimal impact on beam quality and transmission.
- **Coarse open-loop positioning resolution:** In combination of the FSM, the CPA can be tailored to work in a proper precision regime, without over-requiring the mechanical aspects.
- **Low angular uncertainty,** to minimize the required acquisition time between two terminals.

2.4 FSM function

Complementary to the coarse steering function of the CPA, the fast, fine steering mirror (FSM+) provides the fine resolution steering, which is required for both the received and transmitted laser beam. The received laser beam needs to be pointed onto a photodetector, or into a single mode fiber to demodulate the data from the optical beam. Since the divergence of the optical beam is small due to high antenna gains for optical communications systems, it is required to steer the transmit beam with micrometer accuracy. Pointing errors will lead to reduced optical power at the receiving end of the optical communication channel.

The fine pointing functionality of the FSM is also used to mitigate high frequency disturbances in the common optical path. These disturbances generally originate from various vibration sources on the satellite platform. And for ground based terminals, atmospheric turbulence need to be corrected [10]. The key requirements and functions of the FSM are:

- **Small tip-tilt range,** compatible with the coarse resolution of the CPA, with minimal impact on beam quality and transmission.
- **Low closed-loop positioning resolution** to correct for the satellite orientation disturbance and the atmospheric turbulence induced tip-tilt.
- **High closed loop bandwidth** to provide sufficient attenuation of the high frequency disturbances.

2.5 Controller function

The control system ties the electronic part of all subsystems together. It is responsible to drive the CPA, the FSM, the transmit laser and the modulation mechanism to realize tracking and communication in all operational modes. It collects the several sensor inputs, such as the orientation of the satellite from the inertial measurement unit IMU, the positions of the CPA and FSM and the pointing sensor. It drives the CPA and the FSM based on the sensor inputs and their setpoints. The setpoint trajectory is generated using knowledge of the position and orientation of the satellite and the orbital information of the neighboring satellite or position of the ground terminal. As the FSM and CPA work realize pointing together, the controller must be able to schedule tasks and combine position feedback control.

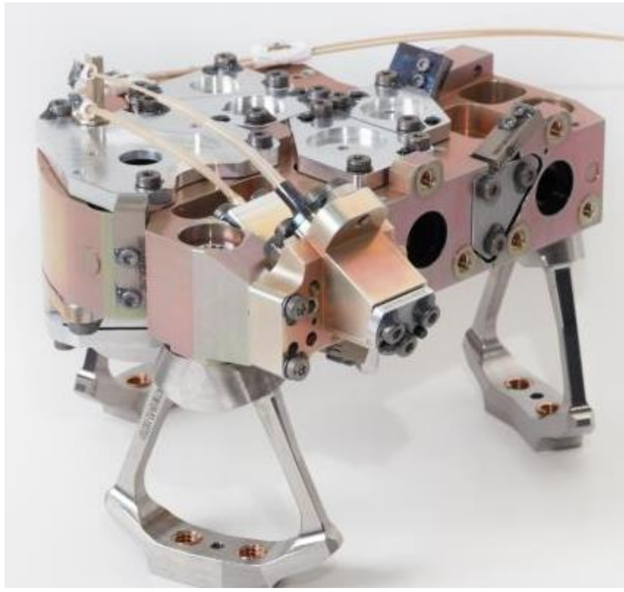


Figure 2 TESLA-C optical bench

3. SUBSYSTEMS STATUS AND PERFORMANCE

3.1 Tesla status

TNO successfully designed, integrated, tested and qualified for flight the optical bench for the Optel-μ terminal in the TESLA-C Project (primed by TAS-CH), for direct to ground laser downlinks from LEO satellites. The emphasis was a compact and robust terminal that mainly addresses the needs of the emerging market of small satellites to increase data download capabilities with higher security, at comparable on-board resource constraints. In this project, TNO achieved the following results:

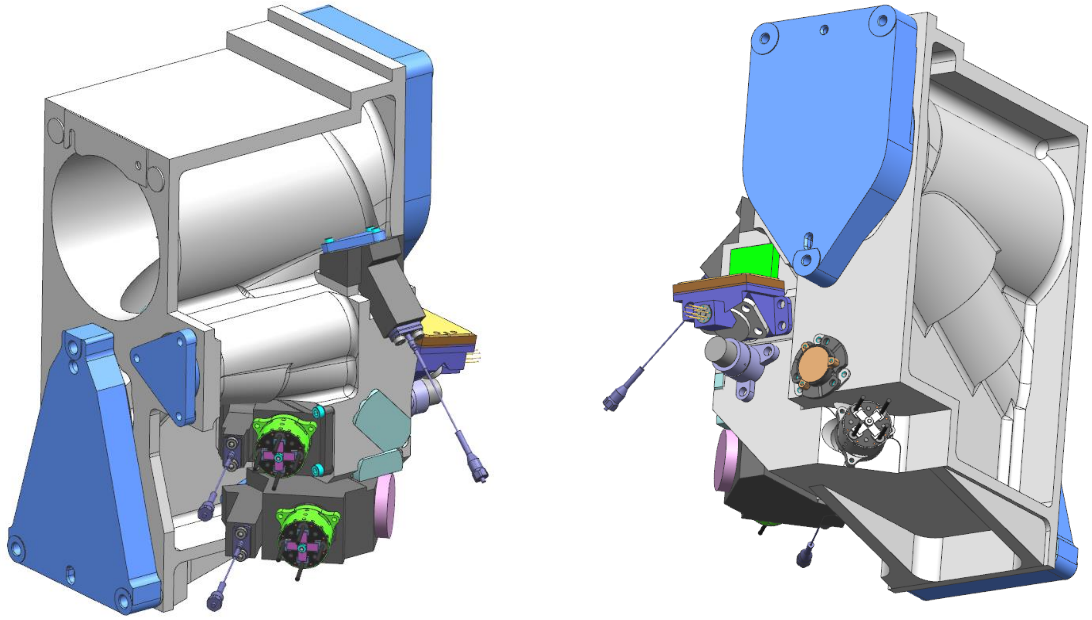
- The optical bench is tested to withstand worst case launching conditions.
- It has μrad stability between the optical channels.
- Its Pointing stability is verified in thermal vacuum.
- It is qualified for space environment

An IOD of the Optel-μ terminal is planned shortly with the aim of demonstrating the functionality of the system, and in doing so also demonstrating the performance of the TESLA-C optical bench.

TNO have been keen to build upon this achievement, spinning off the developed technology towards other applications such as:

- Optical Heads for Intersatellite Links (LEOCAT) – Aimed at the emerging LEO constellation market where high through bi-direction links are required with very challenging recurring cost targets.
- CubeSAT laser communication terminal (CubeCAT) – a very cost effective terminal aimed at the direct to ground laser downlinks from LEO satellites.

This paper reports on the status of these developments at TNO.



(a) (b)

Figure 3 Preliminary design of a LEO communication terminal with 70 mm entrance aperture front side (a) and back side (b).

3.2 LEOCAT optical communications head for intersatellite links

For the mentioned massive LEO constellations, TNO is developing a compact LEO communication optical head for intersatellite links (LEOCAT). An CAD drawing of the LEOCAT optical head is depicted in Figure 3. The optical head has a 70 mm entrance aperture and a telescope field of view (FOV) of ±0.25°, which is a good compromise between directivity of the optical beam and the achievable pointing precision [11], [12]. In order to be compact, the optical design has been optimized, so the global outside dimensions of the terminal fits in a volume of 190x190x250mm. The optical head contains the following functionalities:

- The optical design features a telescope with a 70 mm entrance aperture, a FOV of ±0.25°, a magnification of 1/8, and a WFE by design < 10 nm RMS over the complete FOV.
- The optical head comprises of 3 optical channels. An Rx channel is included to receiving the data of the optical beam. A Tx channel is included to transmit an optical beam. In addition, a separate quantum key distribution (QKD) channel is added. In terms of data communication possibilities it provides versatility.
- The optical head contains several FSMs. One FSM compensates for the rotational motion of the optical head for both the Rx and Tx path. A second FSM is used as point ahead mirror (PAM), to compensate for the point ahead angle (PAA) in the transmit beam. This is a similar mechanism compared to the FSM. A third FSM is integrated as PAM for the quantum key distribution (QKD) channel.
- For pointing and tracking two sensors are used which are included in the pointing and tracking channel. For the acquisition strategy a CMOS camera is included for coarse acquisition, i.e. detecting the rotational position of the optical head with respect to the neighboring satellite before handshake. In addition, a quad cell for fine tracking is included which provides feedback to the FSM.
- In the presence of temperature gradients, the several channels may exhibit thermal drift. Hence, the positions of the CMOS camera, the quad sensor, the Rx and Tx channel may not be co-aligned [13]. In order to mitigate this effect, calibration functionality to properly couple these channels is added.

One of the prominent risks for this optical head is the challengingly low required wave front error (WFE) of less than 30 nm RMS, while remaining a low recurrent cost price. To mitigate this risk, TNO manufactured a prototype of the

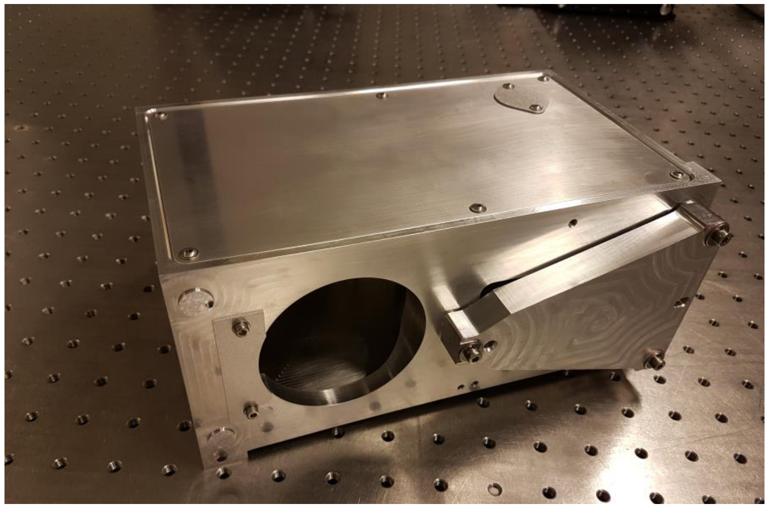


Figure 4 Picture of prototype telescope.

telescope, shown in Figure 4. Focus of this risk mitigation comprises the manufacturing of the mirrors, but also the effort required to assemble and align the optical system, since it also has a major impact on recurrent price.

The telescope mirrors and the structure are all made from the same type of aluminum, to reduce thermal stresses due to material differences. For this sake, the telescope mirrors where not NiP (Nickel-Phosphor) plated. Instead, TNO has the unique possibility to achieve excellent optical performance, using only diamond turning, so no form of polishing is applied after the diamond turning. The achieved results are shown in Figure 5. The measured WFE is 24 nm RMS, which is well within the targeted WFE of <30 nm RMS. Also the surface roughness of the mirrors is between 2 and 4 nm RMS, which is beneficial for improving the transmissivity of the system and to reduce scattering of the Tx beam into the Rx channel.

With the obtained results of the prototype telescope, TNO concluded, that it should be feasible to manufacture these telescopes, with high optical quality, for a low recurring cost price. An engineering model of the optical head, with the full functionality as described above is planned to be realized before the end of 2019.

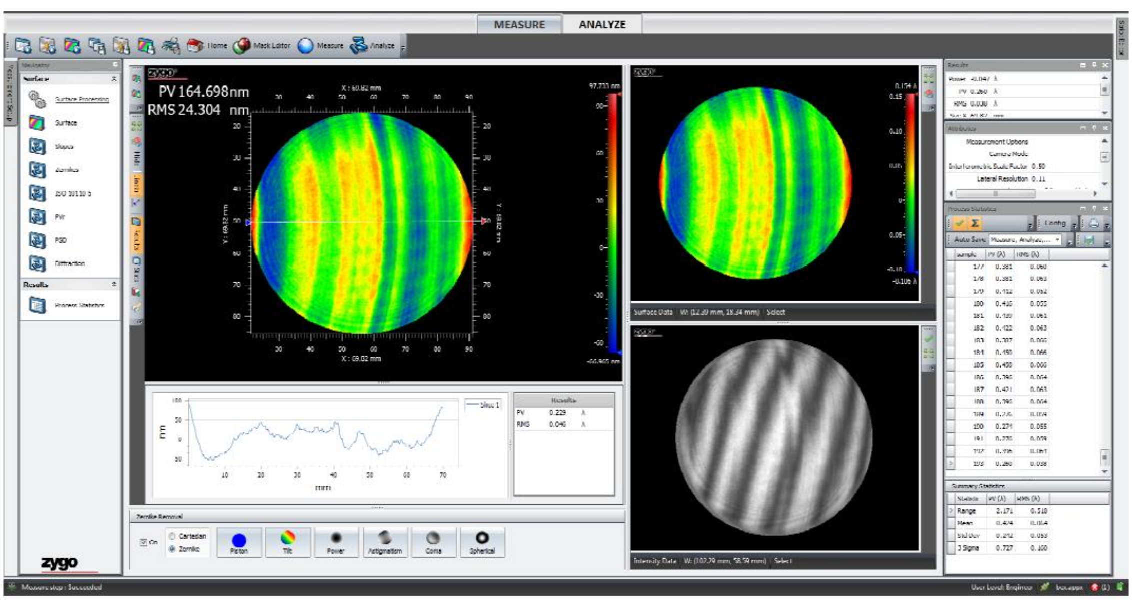
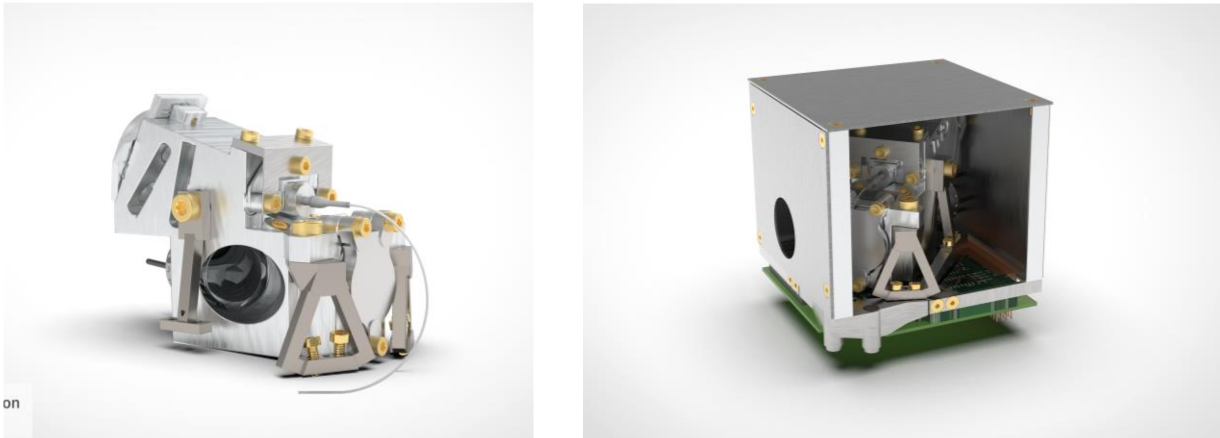


Figure 5 RMS WFE of prototype telescope.



(a) (b)

Figure 6 (a) CAD render of the optical bench (b) cad rendering of the optical bench in an cubecat structure

3.3 CubeCat architecture

Small satellites, also known as CubeSats could provide an excellent opportunity for cost-effective satellite communications services. Due to the advantages of optical satellite communications, their small size is suited very well suited towards the low SWaP requirements, with still a high data rate. Hence, it provides a good alternative for large, but cost effective LEO constellations, or for smaller experimental satellite missions or for surveillance.

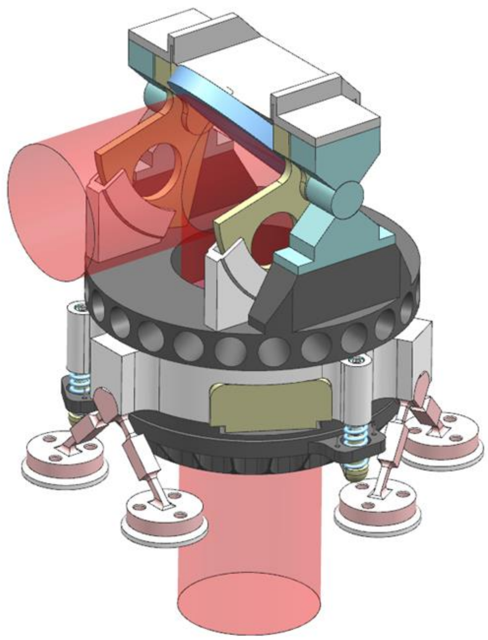
As it is predicted that satellite services need to increase in the coming future, e.g. by SpaceX or Morgan Stanley, more and more companies are available that can make small CubeSats. In order to use this opportunity, TNO is developing CubeCat, a communication terminal suited towards a CubeSat in collaboration with industrial partners. As shown in Figure 6, the design is already in an advances stage; the preliminary design phase (PDR) has already been closed, and at the end of this year there should be hardware on the table.

Table 1 Specifications of the CubeCat terminal for CubeSats

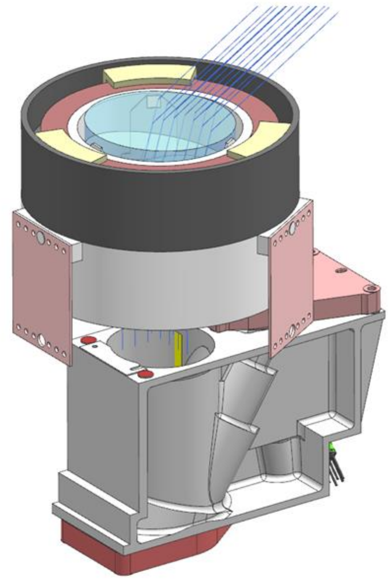
Property	Specification
Data rate down	1Gbit/s, 1545 nm OOK modulation
Data rate up	100 kb/s, 1590 nm, OOK modulation
Data storage	128 GByte
Volume	1U
Mass	1 kg
Power consumption	10 W peak power during communication

The entire CubeSat optical terminal fits in a 1U standard CubeSat volume (1dm^3), including all parts, such as the control electronics. The downlink data rate is 1 Gbit/s at 1545 with an on and off keying (OOK) modulation scheme. For the uplink channel, a data rate of 100 kbit/s is foreseen at 1590 nm, with an OOK modulated beam. The uplink beam is also used as beacon for the CubeSat for coarse orientation of the CubeSat and to correct the optical beam with an FSM, for frequencies below 10 Hz.

At the end of 2018 the integration phase of the CubeCat should be finished. As it is important that the technology gain space heritage, it is planned to launch the CubeCat during 2020, for in orbit demonstration. In orbit tests of the CubeCat will not only promote confidence for this specific type of technology, but will also demonstrate the subsystems, such as the onboard detector technology and control system.



(a)



(b)

Figure 7 Two coarse pointing assembly (CPA) architectures TNO is currently developing. (a) A mirror-based configuration targeted for LEO-LEO use-cases. (b) A CPA architecture based on prisms following the Risley-principle which is targeted for LEO-Ground use cases.

3.4 Course Pointing Assembly status

Course pointing assemblies (CPAs) are very application specific components of optical communication terminals, as the optimal CPA-architecture is strongly determined by the required field of regard (FOR). TNO is developing a mirror based and a Risley prism based CPA as shown in Figure 7 (a) and (b) respectively.

LEO constellations have their satellites typically on orbits with the same altitude. For inter-satellite communications between two LEO satellites, the CPA is mainly pointing at satellites with the same altitude. For this reason, a relatively large azimuth angle is needed to be able to point in all direction, but only a small elevation angle to anticipate on the exact deviation from this orbital planes. The targeted azimuth range is ±180º and the elevation range is from -5º up to around +20º. This architecture is shown in Figure 7 (a).

For LEO-Ground use cases, the azimuth and elevation angles should be equal, to target a conical FOR. By using the Risley architecture with two counter rotating prisms, this can be achieved, while using the advantages of high compactness and low mechanical complexity. Under an ESA Artes program, TNO is also developing an CPA based on this Risley principle. The Risley architecture as shown in Figure 7 (b), allows for a conical FOR with a range of ±60º. The main advantage of the Risley architecture is the compactness and low mechanical complexity. For bi-directional communications over single channels low complexity singlet prisms suffice. To utilize the Risley architecture in combination with wavelength division multiplexing (WDM), i.e. using multiple wavelengths, the dispersion of the prisms need to be compensated in order to ensure that all communication channels are pointed towards the same direction. To achieve this, TNO is investigating the use of diffraction gratings etched on one side of the prisms. This architecture is also referred to as Grism's.

The heart of the both CPA's is a motorization axis, consisting of a bearing, motor and encoder, which can be strong cost drivers of the overall CPA-system. TNO is developing a cost-effective solution for the motorization axis, based on an integrated motor and encoder concept. This motorization solution is applicable for both CPA-architectures and has the potential of low-recurring cost for small series.

4. CONCLUSIONS

In order to enable a true world-wide internet, where everyone is connected everywhere, optical satellite communications technology is needed to complement radio frequency communications technology. TNO is developing technologies to support this development. The technologies supported cover a broad range: optical heads, optical benches, coarse pointing assemblies (CPAs), a fast and fine steering (FSM+), and a control system. This paper shows the state of their development. Three main development branches have been highlighted in this paper, the LEOCAT optical head, the CubeCat optical bench and the CPA development. A prototype of the LEOCAT telescope has been manufactured to demonstrate feasibility having less than 30 nm RMS WFE, with a system architecture that would enable low recurrent costs. The design of CubeCat, an optical bench to support optical communications on CubeSats is completed and a first prototype is expected before the end of 2018. Also the status of a mirror based and a Risley prism based CPA are presented in this paper. By continuing this development, a true world-wide web is coming closer.

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