TRANSFORMATION OF DLR'S LASER COMMUNICATION TERMINALS FOR CUBESATS TOWARDS NEW APPLICATION SCENARIOS

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ABSTRACT

Modern solutions for secure, robust and high-speed satellite communication rely on free-space optical communication in addition to classical radio-frequency channels. The major challenge for laser communication is the precise pointing and the dependency on high precision attitude determination and control systems, because of the lasers' narrow beam divergences. This restricts the use cases and application areas for laser communication to mainly point-to-point connections and reduces the beam steering agility.

Thus, German Aerospace Center (DLR) develops pointing concepts, independent from the carrier's attitude to open new fields for laser communication. DLR has already developed several systems of coarse pointing assemblies in different projects for various scenarios. The next step is to refine the existing systems to provide solutions for CubeSats.

The majority of the developed laser communication terminals intends to be transferred to a commercial market. Thus, the interests and the demands of possible customers are already considered during the terminals design. Furthermore, the payloads follow a modular approach to easily adapt and extend the payloads, to react on changing market demands in a short time. This paper describes the transformation from a point-to-point optical transmitter (OSIRIS4CubeSat) to an orientation independent terminal, ready to serve applications in mega-constellations (Cube1G).

1 INTRODUCTION

Optical communication terminals offer benefits in many different mission scenarios. Especially missions with demanding requirements for higher data rates to transmit the mission data from earth observation cameras or other sensor, face limitations due to traditional radio-frequency (RF) communication with limited available bands and bandwidth. Free-space optical (FSO) communication provides certain advantages for the mission:

- High data rates
- No spectrum regulation required
- High power efficiency (power/bit) compared to RF due to narrow divergence angles

The narrow divergence angles, which lead to a higher efficiency since more energy can be received on ground station side, also comes with the disadvantage of a smaller footprint on ground and with that an increased pointing requirement. While traditional RF systems have large opening angles that only require a pointing in the degree-range, optical communication terminals without pointing assembly (like OSIRISv1 on Flying Laptop (FLP) [1]) require a pointing in the range far below one degree. While this missing pointing assembly keeps the optical terminal simple and robust, the complexity is moved into the satellite's attitude determination and control system (ADCS).

Reducing the pointing requirement for the satellite has two major advantages: first, the ADCS is less complex and second, the sensor payloads (like earth observation cameras) can be operated more independent from the laser terminals since the orientation is no longer strictly coupled. Therefore, the beam pointing uses two different stages: a fine pointing assembly (FPA) which compensates small but fast disturbances in the orientation and a coarse pointing assembly (CPA) which moves slower but can cover large angular ranges up to hemispherical movement.

Besides the parameters and the dynamic of the communication link, optical terminals mainly consist of similar components in different application scenarios – of course scaled to the mission requirements. This allows to follow a modular approach in the development: by reusing qualified and tested components with flight heritage, the mission risk as well as the development time can be reduced significantly. This is a huge benefit in scientific missions, since the “time to space” is a relevant factor. To reuse and combine modules, DLR’s optical communication terminals rely on standard interfaces. In addition to the mentioned advantages, modular designs are also ideal for a technology transfer to industry and allow the handover from scientific demonstration into a serial manufacturing.

Besides all similarities, the operational scenario is usually very different: from low earth orbit (LEO) downlinks over inter-satellite links (ISL) to aircraft downlinks, the dynamic in the link changes and requires to point the transmission beam accordingly. Therefore, different CPA concepts have been investigated over the past decades that can be used in different mission scenarios, enabling new use cases with existing terminal technology. This paper gives an overview of different CPA and FPA concepts in different missions.

2 POINTING CONCEPTS FOR DLR’S OPTICAL TERMINALS

The narrow beam divergences of DLR’s optical communication terminals require a beam steering from the transmitter to the receiver, independent of the scenario (aircraft to ground, satellite to satellite, satellite to ground, etc.). The simplest realization is a hard mounting of the laser collimator on the satellite platform in combination with a pure body-pointing of the satellite. In this configuration, as demonstrated in the OSIRISv1 (optical space infrared downlink system version 1) mission on the FLP, the advantage is a very simple and robust optical terminal but with high demands on the satellite’s ADCS [2].

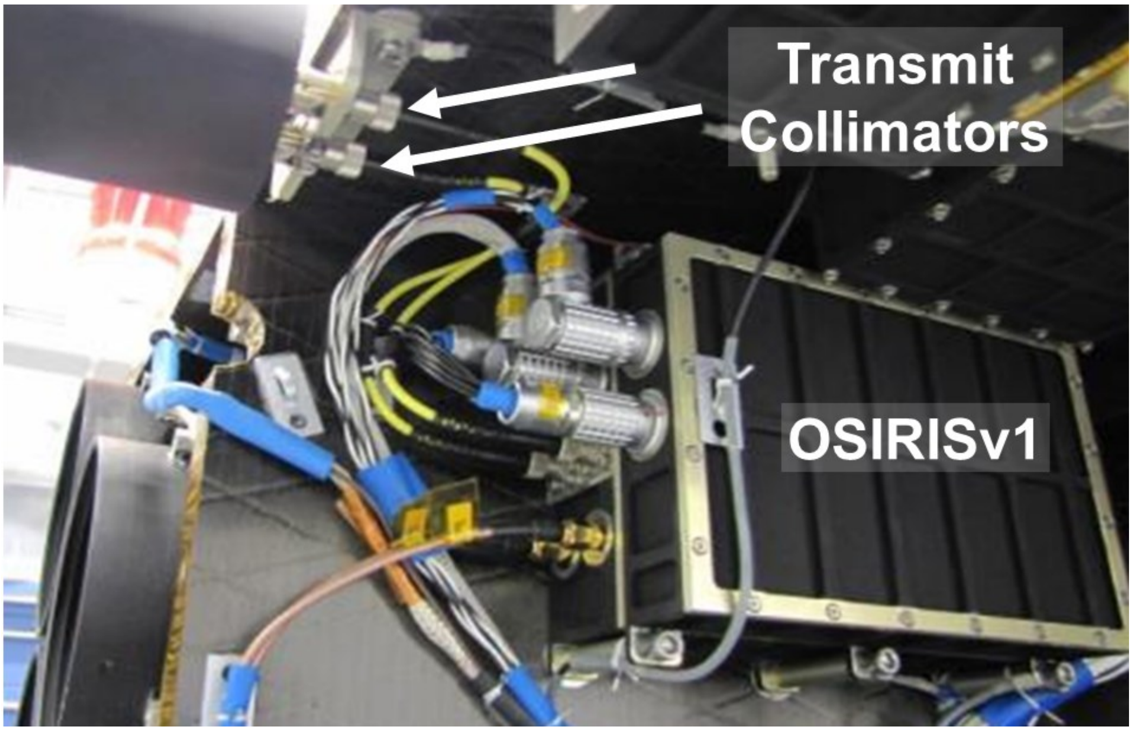

Figure 1. OSIRISv1 integrated in small satellite Flying Laptop (FLP) [1] [2]

OSIRIS4CubeSat (O4C) marks the basis of DLR's laser communication terminals (LCT) especially designed for CubeSats [3]. The purpose of O4C is to serve a high-speed connection from smallest spacecrafts to earth using the advantages of FSO communication. The LCT development philosophy is a step-by-step approach which starts with use cases where DLR has the most experiences with. During the OSIRISv1 mission on the Flying Laptop satellite, DLR could already gain knowledge in a point-to-point scenario from LEO. With the miniaturized OSIRIS technology, O4C can provide communication solutions for common CubeSat missions like earth observation or remote sensing.

O4C is a pure data transmitter with no receiver onboard. This limits the use case to direct to earth (DTE) communication. To establish a connection, it uses a closed loop tracking system in combination with body pointing of the satellite. The fine pointing assembly (FPA) can compensate inaccuracies of the satellite pointing by up to 1°. That reduces the flexibility of the satellites attitude during transmission. During a data downlink the satellite must point to the correct destination (usually an optical ground station, OGS) and can rotate only around the optical axis. This limits the flexibility of the satellite during communication. Furthermore, it increases the mission risks as a connection can only be established if the satellite points within an absolute pointing error (APE) of ±1°. Deviations caused by misbehaving sensors, misalignment or launch effects can lead to mission delays, reduced performances or even to a complete mission failure. An illustration of the DTE concept is shown in Figure 2.

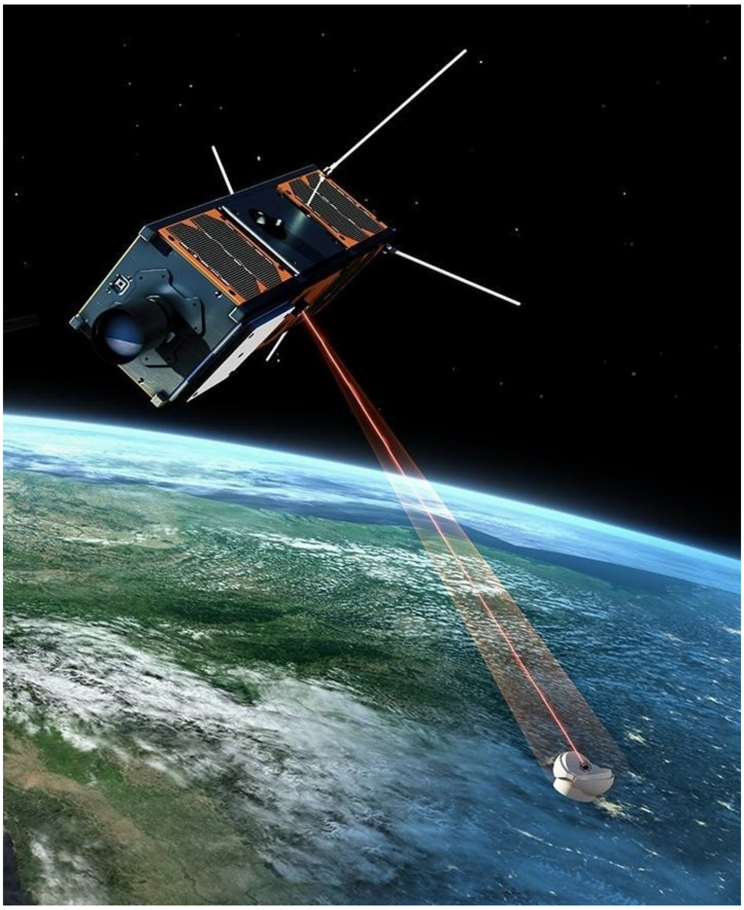

Figure 2. Illustration of direct to earth laser communication

To further reduce the pointing requirements of the host platform, the optical terminal can be equipped with a CPA that is adapted to the mission needs. The CPA can cover large angular ranges up to hemispherical beam pointing but also smaller ranges if sufficient (e.g. in intra-plane ISL missions 7° - 20 ° are sufficient). The following section will present two fundamental CPA concepts with first a periscope configuration and second a prism configuration.

2.1 Example periscope CPA on aircraft

The first realization of a hemispherical CPA is shown in Figure 3, installed in DLR's Dornier Do-228 research aircraft (Figure 4). Since the aircraft can move freely in respect to the ground station, the CPA needs to cover the full hemispheric range in combination with an FPA on the optical bench within the aircraft to compensate for channel effects as well as vibrations due to the turboprop engines [4]. The setup is a coudé-path with two turning axis, as it can be seen in Figure 3.

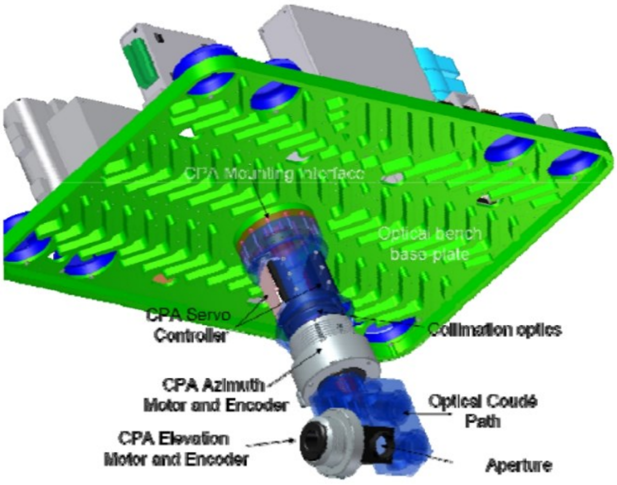

Figure 3. Coudé-path of periscope CPA [4]

Figure 4. Periscope CPA integrated in aircraft

The drawing in Figure 3 shows the setup of the CPA: the light on receive but also transmit path is guided through the CPA via four mirrors that can rotate around the elevation as well as azimuth axis and therefore reach hemispheric angles. The disadvantage is certainly the comparably large system and a changing distance between CPA lens and the protective dome which leads to deviations in the optical behavior depending on the direction of the communication.

2.2 Example Prism-CPA

To reach more compact system designs, the number of reflective surfaces can be reduced. In a very simple approach, one mirror is used in front of the primary lens which can be tilted in two axes. This configuration allows for large angular ranges with an agile movement but with the disadvantage of a blind cone in nadir direction [5]. Figure 5 shows the same configuration but with a prism instead of a mirror.

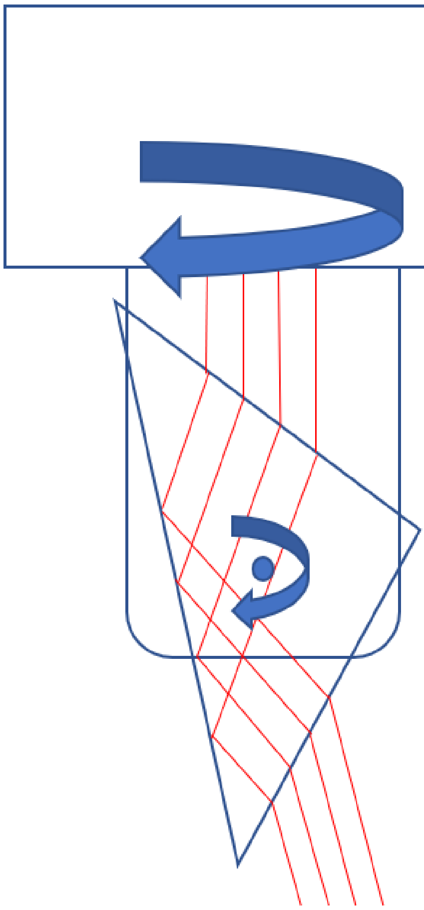

Figure 5. Prism-CPA used in the DODFast project [5]

The replacement of the mirror with a prism comes with the advantage, that a blind cone in nadir direction can be avoided and guarantees for a hemispheric pointing. Nevertheless, the prism comes with a higher weight and reduced dynamic behavior. Furthermore, it is not really scalable since the prism grows in all directions and gains additional weight with disadvantages also in vibration domain.

3 CUBEISL

The modular approach is used for the first time during the CubeISL development. The goal of the project is to design a payload that can serve optical inter-satellite links (OISL), with 100 Mbps, over a distance of up to 1,500 km. Base for CubeISL is O4C which is reused as the optical terminal, while the transmitter system was replaced by an erbium doped fiber amplifier (EDFA) and got extended by a data handling unit (DHU) [6]. Figure 6 depicts the design of the three major subsystems of CubeISL.

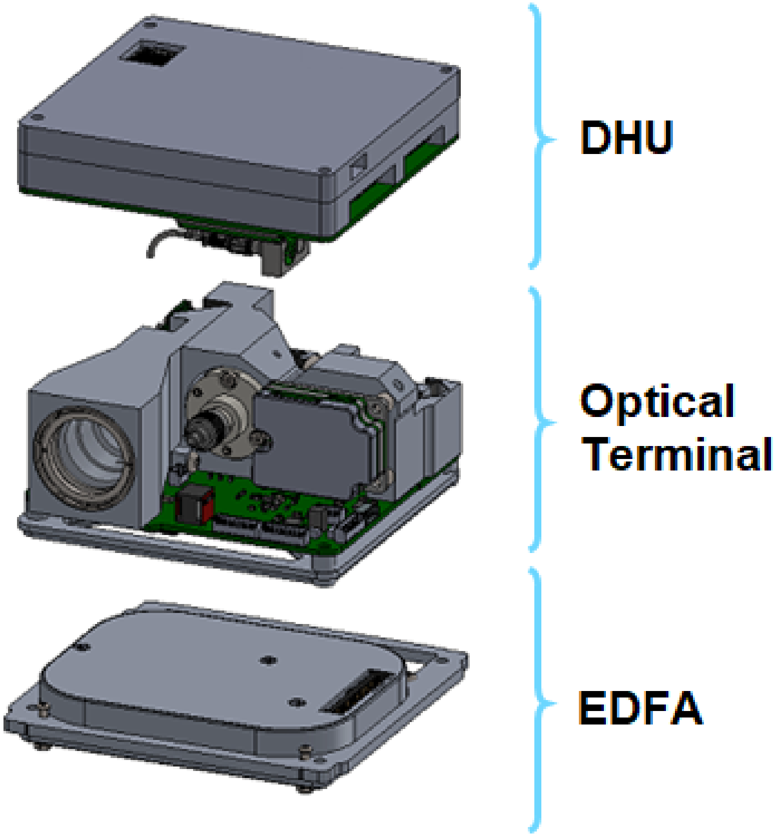

Figure 6. System design CubeISL

As CubeISL will demonstrate a bidirectional data transfer between two terminals, the optical terminal includes an additional data receiver, which is placed at the position of the former transmitter system of O4C.

3.1 New use cases in ISL

The extensions and adaptions compared to O4C allow to transfer the technology from DTE into OISL for the first time. It opens new use cases for customers and can provide the advantages of laser communication also in the data transfer between satellites. O4C is a pure transmitter, which means for CubeISL a concept had to be found how to separate transmission (Tx) and receiving (Rx) beam. Thus, CubeISL separates the channels by selected wavelengths defined in the international telecommunication union (ITU) standard ITU-T G.694 [7]. The selected EDFA was already used during the OSIRISv1 mission on the Flying Laptop satellite, so the wavelengths for CubeISL were selected in the C-band that the same EDFA could be used. The concept foresees that there are two types of terminals where the Tx-wavelength of terminal A is the Rx-wavelength of terminal B and vice versa. The channel concept can be seen in Figure 7.

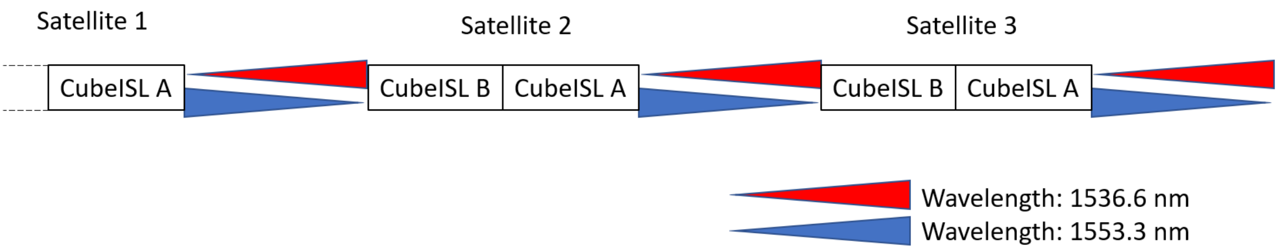

Figure 7. Channel separation concept in CubeISL

The integration of two terminals on one satellite allows not only a point-to-point connection between the satellites, on top it allows a daisy chain communication concept which is able to build up networks like mega-constellations. Furthermore, the concept can compensate outages of entire satellites. In the example of Figure 7, if satellite 2 drops out, satellite 1 and 3 are still able to communicate with each other, if the doubled distance can be bridged. This can be done by reducing the data-rate, which would result in a reduction of the throughput, but still keep up the functionality of the constellation data connection.

Beside the OISL, CubeISL is still capable of transmitting data to the Earth and even tenfold the data-rate due to the increased optical power by the EDFA. The CubeISL payload sticks to the CCSDS O3K (consultative committee for space data systems optical on-off-keying) standard which requires an L-band beacon from the optical ground station (OGS) to orientate itself and improve the tracking behavior [8]. Thus, CubeISL must still be able to receive the wavelength of 1590 nm on the tracking receiver, additionally to the Rx-wavelength from the partner terminal.

Even though it is possible to build up a daisy chain communication with multiple CubeISL terminals, the links are still depending on the satellites attitude. CubeISL uses the same fine pointing assembly (FPA) from O4C which limits the field of regard (FoR) to ±1°. To establish an OISL connection, an even more accurate pointing of the satellite of ±0.1° is required. As a consequence, CubeISL can transfer the FSO technology into the new field of inter-satellite communication but is limited to trailing constellations in intraplane scenarios.

The relative motion between the satellites and the finiteness of the speed of light lead to a point ahead angle (PAA) which might have to be compensated [9]. The PAA is illustrated in Figure 8. The time t highly depends on the relative motion which is in an intraplane scenario constant and relatively low. In these cases, the PAA is much lower than the divergence of the transmission beam and does not lead to significant power losses [10]. In interplane constellations, especially during crosslinks, the relative motion can be significantly higher and changes during the whole link.

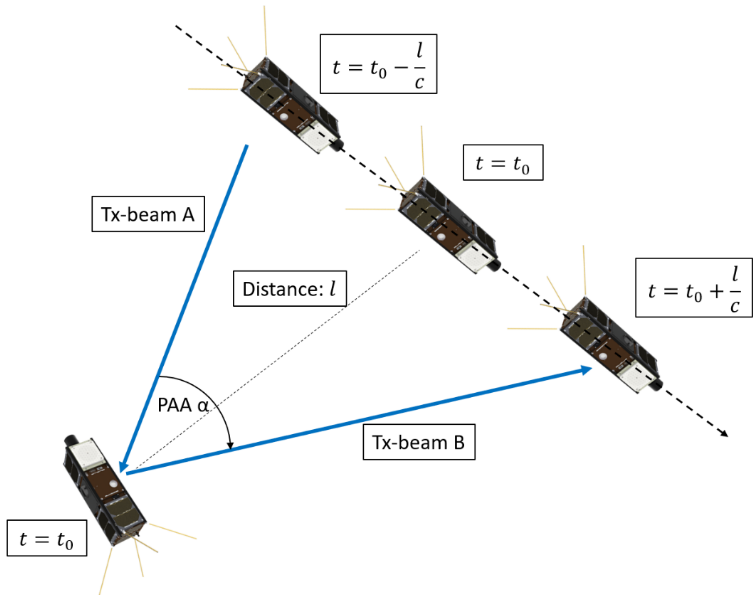

Figure 8. Point ahead angle (PAA) in an OISL scenario

DLR has already developed mitigation concepts to compensate for PAA's in other missions. Solutions for these future use cases can be an adaptive tracking correction by postprocessing the feedback of the angular tracking sensor or the integration of a compensating device like a point ahead mirror (PAM).

4 CPA REALIZATION IN CUBE1G AND OSIRISV3

The CPA enables a high flexibility of laser communication for multiple additional missions. With a movable optical head, the Cube1G terminal is not anymore depending on the satellites attitude as it can steer the laser beam to every position in the whole hemisphere. The efficient design and the prism as a relatively low mass allow high agile beam steering and accurate pointing of better than the FoR of the FPA, in the case of Cube1G ±1°. Even if Cube1G is independent from the satellites APE it still requires an accurate absolute pointing knowledge (APK) of the satellite. The CPA needs the input from the spacecraft about the orientation and the position of the satellite in relation to the earth's coordinate system. Inaccuracies of the APK of >1° can theoretically be accepted, but they would lead to longer search and acquisition periods, before the link can be established and would reduce the data throughput during the mission significantly. This requirement counts for both operation scenarios – DTE and OISL.

The modular approach allows to integrate and extend CubeISL with CPA solutions. The resulting Cube1G terminal can be divided in three main subsystems. A CPA, the CubeISL optical terminal and a periscope are all housed in a 2U+ CubeSat structure. The position of all subsystems is shown in Figure 9.

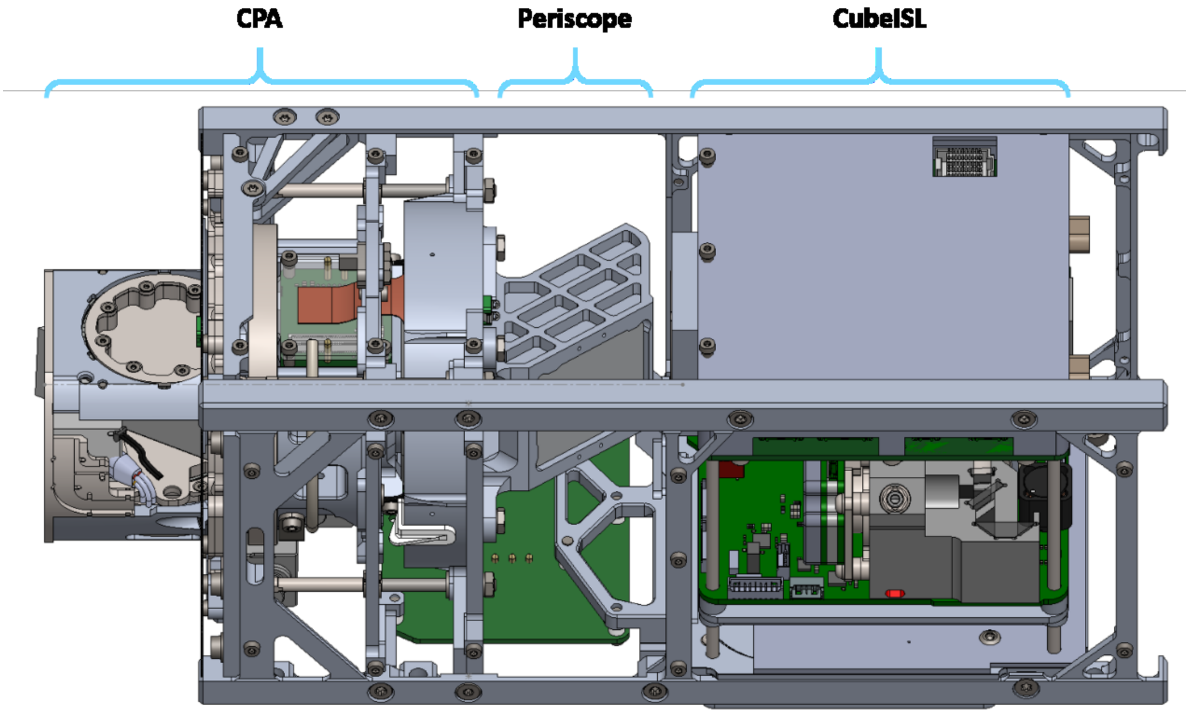

Figure 9. Overview of Cube1G payload in a 2U+ CubeSat structure

The CubeSat tuna can extra volume is utilized to house the elevation axis of the CPA including the optical prism. This location allows for a full hemispherical FoR. A periscope is necessary to align the optical axis of the CPA and the CubeISL terminal.

The Cube1G CPA redirects the communication laser beam by rotating an optical prism in two axes. The CPA can therefore be divided in three subsystems by their relative movement as it can be seen in Figure 10. The stator assembly includes the satellite structure as well as all non-rotating systems. The Azimuth assembly is capable of rotating around the Z-axis of the CubeSat. The elevation assembly is mounted to the azimuth axis and can rotate in a perpendicular axis to the azimuth assembly.

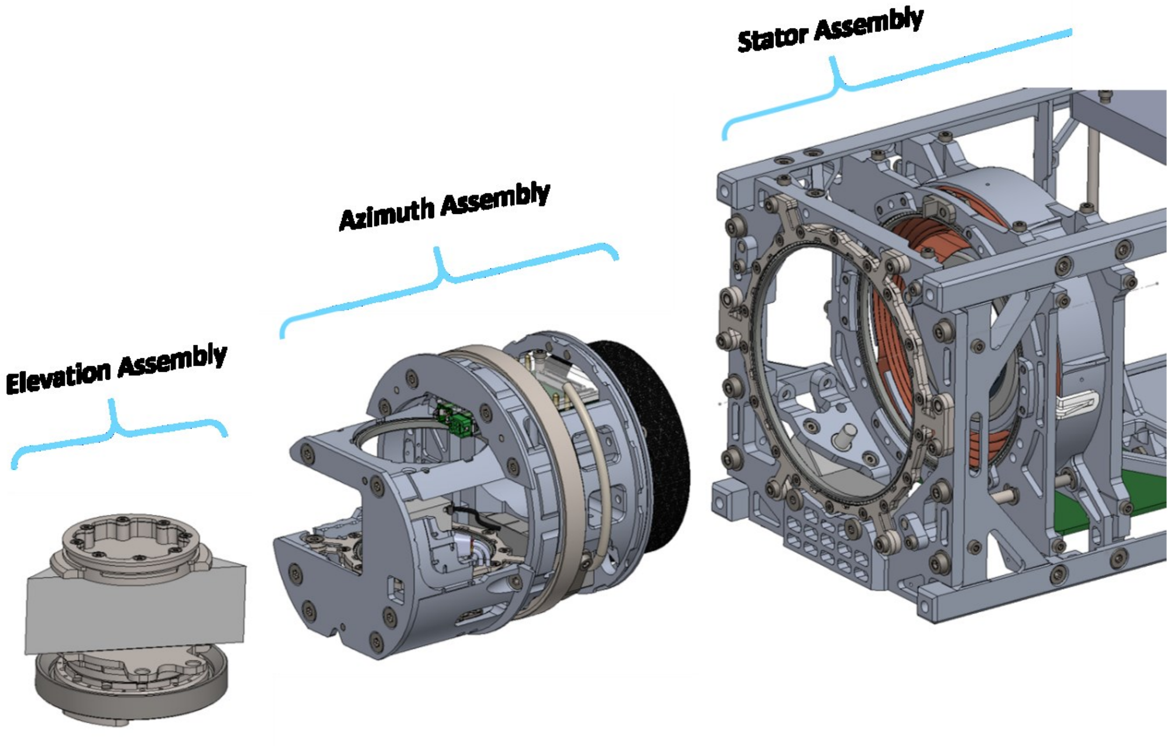

Figure 10. Overview of the Cube1G CPA with main subsystems

The streamline development takes advantage of previously developed CPAs by reusing proven concepts but also components. Like in the DODFast CPA ultra-slim thin section ball bearings are used but with a compliant mechanism to apply the correct axial bearing preload and prevent hammering damage during launch. Other commercial of the shelf (COTS) components that have previously been used and qualified in CPA projects are motors, pin pullers and rotational encoder systems.

The Cube1G CPA is the first CPA that is compliant to the CubeSat standard. By occupying a tuna can extra volume with a diameter of only 64 mm the CPA can be launched with any CubeSat deployer system. In addition, the stator assembly of the CPA has an envelope measuring 100 x 100 mm leaving room for solar panels or radiators on the side surfaces of the satellite.

4.1 OSIRISv3 CPA

OSIRISv3 is a DTE laser communication Terminal developed by DLR aiming to provide a high throughput connection from small satellites in LEO to an OGS on earth. The system provides a modular design including a CPA, FPA and point ahead assembly. The OSIRISv3 CPA has been developed at DLR in combination with an FPA for jitter and micro vibration and a point ahead assembly for PAA compensation. OSIRISv3 serves various LEO applications while being independent of the satellite's pointing.

During in-orbit lifetime, OSIRISv3 sees several environmental effects such as thermal influences, hence thermal stresses on the hardware. To minimize these effects, the environmental conditions have been considered during the design phase. To track the temperature gradient along the OSIRISv3 CPA, temperature sensors are included. The temperature information is collected and processed by OSIRISv3 and provides information on the actual temperature and if it is within its operational or non-operational temperature range. The used materials have been chosen based on their coefficient of thermal expansion (CTE) besides structural requirements. Interfaces between different material types, e.g. glass (optical elements) and metal (structural elements), have been designed as such that the CTEs match. This design method allows to reduce stress peaks on these interfaces, thus it allows to support the overall structural and functional integrity under thermal influences. Figure 11 provides the OSIRISv3 design including the main body and its CPA in front [11].

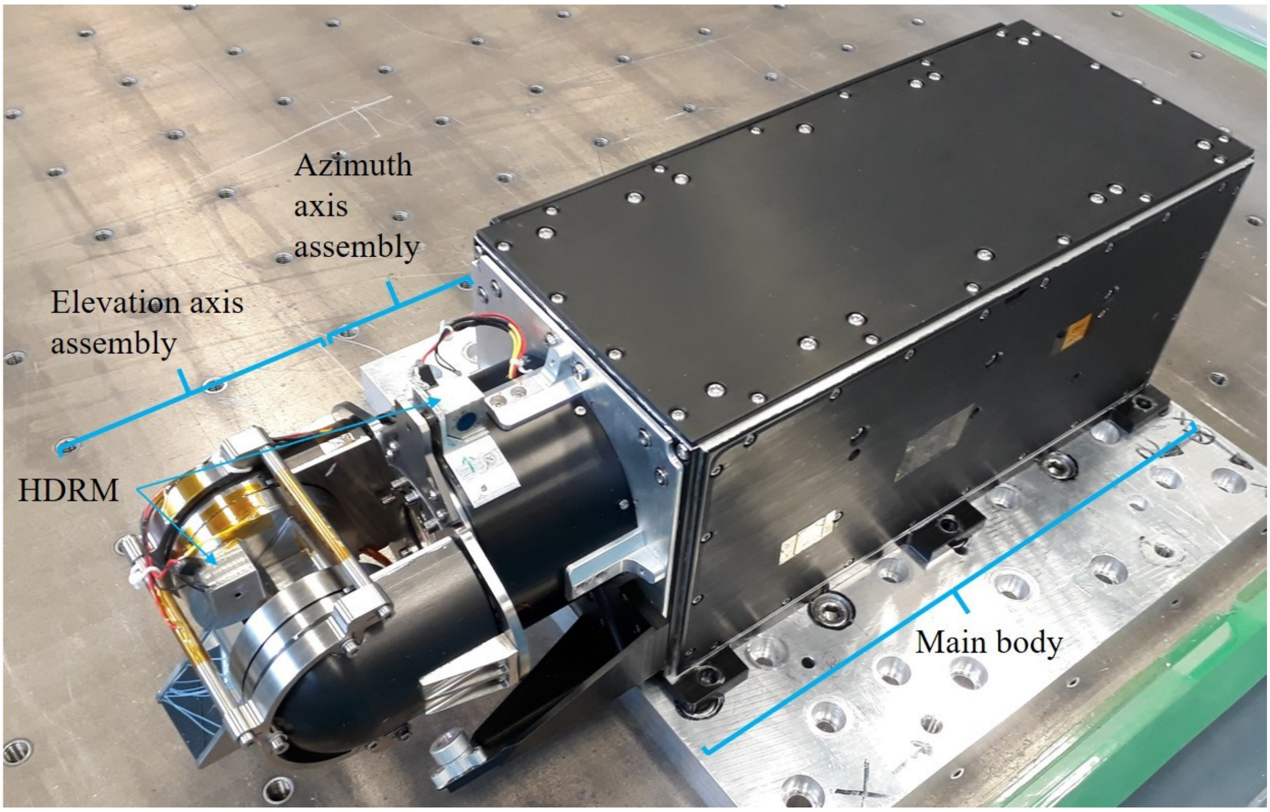

Figure 11: OSIRISv3 laser communication Terminal including CPA

The OSIRISv3 CPA design is based on DLR's previous CPA developments and adapted to the requirements of a space mission in LEO on small satellites. These requirements are split into functional and environmental ones. The OSIRISv3 CPA itself provides a hemispherical FoR. The FoR is achieved by two moving axes – elevation and azimuth – while providing an optical aperture of 30 mm.

One key aspect for a functional CPA is the APK in both axes, therefore high precision encoders are integrated into the design. The position information is fed into the motor controller unit which actively controls the motor movement in elevation and azimuth axis. For an FSO link to an OGS on earth, the OSIRISv3 CPA steers the beam during the full overflight. The motor controller unit is a separate part and accommodated in the OSIRISv3 main body.

The OSIRISv3 CPA is a mechanism to be used in space, hence design constraints caused by environmental effects and loads were considered. It requires a locking mechanism for the launch and early orbit phase to prevent it from uncontrolled movements induced by the launcher's vibration and the satellite's movement. DLR uses hold-down and release mechanisms (HDRM) to lock the two OSIRISv3 CPA axes. Without locking mechanism, the occurring uncontrolled movement would result in major damages during launch. As part of the commissioning phase the HDRMs are released to achieve full functionality.

5 CONCLUSION

The higher flexibility enables new fields in the OISL as DLR's CubeSat laser terminal is not any longer limited to intraplane communication, but can serve the technology also in crosslink or interplane scenarios instead. This allows Cube1G to build up global networks and meshes as a reliable space-based highspeed communication backbone, for example. Nevertheless, the described use cases might require further adaptions. Changing distances need adaptive laser powers or receiver gains to avoid saturation of the sensors and receivers. Suitable countermeasures can be implemented in software, based on the specific concept of operations (CONOPS) of the mission and do not require changes in hardware. Furthermore, the slew rates and the relative positions between the satellites change much faster than in a DTE or intraplane scenario. The propagation duration of the laser and the relative movement of the two targets in relation to each other result in a point ahead angle (PAA) which, as described in this paper, has to be considered or compensated for in the terminal.

But not only for OISL transmission, the CPA increases also the flexibility in the DTE. Active beam steering allows a high independency for the carrier spacecraft, that it can operate its primary activities during the laser transmission in parallel. For future missions, also the increasing demand of interoperability can be solved by swiftly changing the target, for example if an OGS is suddenly out of the line of sight due to clouds, the terminal can switch to another OGS which might be reachable during the same flyover.

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