Miniaturized Optical Intersatellite Communication Terminal – CubeISL

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***Abstract*—The increasing request for higher data rates and the technical limitations of traditional radio-frequency channels in intersatellite communication requires solutions to overcome these obstacles. German Aerospace Center (DLR) has a long heritage in optical air-to-ground and space-to-ground transmission. Due to its high data rates, resistance against interferences and being free from regulations like from the International Telecommunication Union (ITU), Free Space Optical communication (FSO) provides solutions to overcome the challenges for satellite communication.**

Based on the developments in the "OSIRIS4CubeSat" project, DLR transfers the technology of laser communication on CubeSats from Direct to Earth (DTE) into the intersatellite domain. Therefore, the project "CubeISL" started with the goal to develop an optical intersatellite for CubeSats. This paper discusses possible mission scenarios where CubeISL terminals can be used, the research results of a feasibility analysis and the required technical adaptions, which will be realized in the near future.

Keywords: OSIRIS, Free-Space-Optics, Intersatellite Links, CubeSat, Laser-Communication, High data-rate, New Space

I. INTRODUCTION

Constellations of small satellites, like pico- and nanosatellites, are progressively replacing individual larger spacecraft to provide space-based services. Such fleets in evenly distributed orbits can cover larger areas in shorter times, leading to worldwide accessibility of the provided service with higher network coverage.

Ensuring robust and reliable communication between individual satellites is a key functionality in these constellations. The increasing number of small spacecraft, the bandwidth limitations in the Radio Frequency (RF) spectrum, the limited amount of available channels, and the mandatory frequency regulations pose the biggest challenges for Inter-Satellite Links (ISL).

Free Space Optical (FSO) communication provides solutions to overcome the challenges of RF-communication. Laser communication terminals are less power hungry and much more compact than RF-systems with similar data-rates. Their higher efficiency in Size, Weight, and Power (SWaP) satisfies the necessity of higher data throughput even for the smallest satellites [1].

Its emission in the (near-)infrared spectrum solves the challenges of channel crosstalk and interferences. Additionally, governments and institutions do not impose any regulations on optical data transmissions.

The Optical Communication Systems Group (OCS) in the Institute of Communications and Navigation of German Aerospace Center (DLR-IKN) has a long heritage of laser communication terminals for small satellites in Low Earth orbit (LEO). The newest development of the Optical Space Infrared Downlink (OSIRIS) program, OSIRIS4CubeSat (O4C), is a highly miniaturized optical terminal which provides a data rate up to 100 Mbps for Direct-To-Earth (DTE) communications. Using the advantages of the modular approach of O4C, OCS now aims to modify the existing payload design by changing and adding subsystems to extend the payload functionalities towards bidirectional optical ISL-communication.

This paper shows the necessary technical extensions to O4C for CubeISL. It describes the additional necessary adaptions for ISL compared to DTE and presents solutions that fulfill these requirements. Finally, the paper presents possible applications for CubeISL in different satellite constellations.

II. MISSION SCENARIO

New mission scenarios with larger numbers of satellite in a constellation require increasing data rates in the communication between the satellites. The satellites of a constellation are usually lined up in one orbital plane – larger constellations even use multiple orbital planes with numerous satellites per plane, so that all points on Earth can be covered. This is e.g. the scenario for a worldwide coverage of broadband internet access via satellite.

This creates two potential scenarios for intra-plane communication as well as inter-plane communication. In this paper, we will focus on intra-plane communication in LEO Orbit. Depending on the exact orbit and number of satellites per plane, the communication distance between two satellites is in the order of 1500 – 2000 km. Due to the small apertures on a CubeSat, the link budget is very tight and all parameters need to be optimized. CubeISL is designed for a symmetrical full-duplex communication and therefore needs a transmit and receive channel that can be operated at the same time. This requires precise separation of the paths to avoid crosstalk. To communicate not only with one satellite

A. Responsive Space

The CubeISL project will be realized through co-funding between DLR's Responsive Space Cluster Competence Centers (RSC^3) and by DLR's Space Research Program. RSC^3 is supported through funds from the German Ministry of Defense. The project lead is the DLR Institute of Communications and Navigation.

Responsive Space is understood as the ability to launch small military satellites (up to 500 kg) on-demand and on-call into near-Earth orbit and start operating in days, in order to be able to replace failed satellites rapidly. The main objective of the CubeISL mission is to demonstrate bi-directional inter-satellite laser communication between two CubeSats building on the experience of the pre-cursor mission PIXL-1 with the CubeL satellite. CubeL contains the first O4C terminal to demonstrate the capabilities of optical transmission from a CubeSat in the DTE scenario.

The RSC^3 considers the implementation of a third nanosatellite that could perform various technology tests that are key for a national Responsive Space Capability (RSC), without compromising the primary mission objectives. All three laser communication terminals should be able to communicate with each other in all conceivable combinations to simulate a possible (temporary) failure of a satellite. The implementation of a camera, as an additional payload in the third CubeSat will be useful to represent an inspection mission by having the approaching satellite capture images and relay them to the optical ground station. A triangular satellite constellation also extends operations time as the additional satellite can be used as a movable relay station. Other payload concepts include testing autonomous collision avoidance and decentralized mission planning using a deployable, compact control center and mobile optical ground station build with COTS components. A de-orbiting maneuver is foreseen at the end of the mission.

III. OSIRIS4CUBESAT

The goal of CubeISL is to transfer the advanced functionalities of Optical Communication, from Direct-To-Earth (DTE) to bidirectional Inter-Satellite (ISL) Communication. The increasing number of small satellites and constellations leads to challenges for satellite communication in many aspects like interferences, channel crosstalk and bandwidth. The capabilities of Free Space Optical Communication (FSO) were already demonstrated in former projects with satellite downlinks. These advanced technologies provide solutions also for the challenges in ISL communication.

The base for the development of CubeISL is DLR's smallest laser communication terminal "OSIRIS4CubeSat" (O4C). This highly miniaturized and compact payload is designed for high rated data transmission from CubeSats. With an electrical power consumption of less than 8.5W and a size of 1/3U it can transmit data with a data-rate of up to 100 Mbit/s to the ground. Figure 1 shows the Flight Model of O4C.

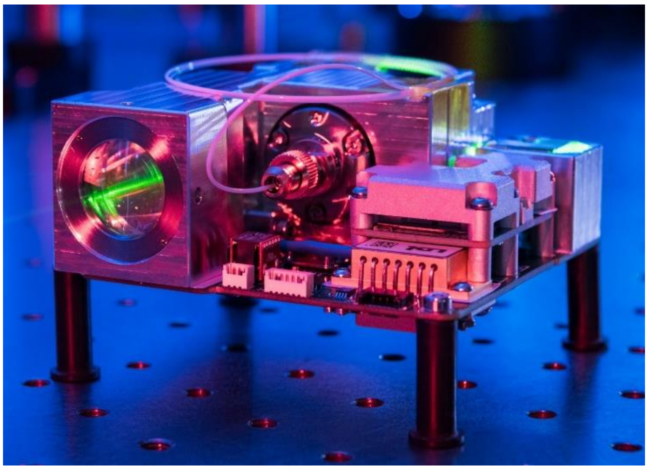

Fig. 1. OSIRIS4CubeSat Flight Model

To increase the pointing accuracy and compensate inaccuracies by the satellites Attitude and Orbit Control System (AOCS), O4C is equipped with a Fine Pointing Assembly (FPA). A 4-Quadrant PIN Diode (4QD) measures the angular offset of a beacon sent by the optical ground station and a Fast Steering Mirror (FSM) compensates this offset inside the system. The transmission beam is coupled into the same path to guarantee that it hits the ground station.

O4C has a modular design where subsystems can easily be replaced or extended. Standard Interfaces and the use of Commercials Off-The-Shelf (COTS) components are compatible with a variety of market available technologies. Furthermore, this concept allows quick reactions to non-conformances during tests and qualifications. Thus, the systems Engineering can directly be transferred to current and future developments like CubeISL.

IV. CUBEISL

To identify the necessary adaptions of O4C a link budget for CubeISL was calculated. Compared to O4C the transmission channel and with this the physical conditions change significantly. Major differences between DTE and ISL are the higher distance, the smaller receiver aperture and the missing atmosphere. These parameters have an effect on the single factors of the link budget. Based on this link budget possible adaptions were evaluated to increase the link margin to fulfil the requirements of optical ISL communication. This chapter explains the base parameters of the link budget and discusses the derived technical adaptions.

A. Link Budget

The performance of an ISL depends on internal and external parameters that affect the quality of the transmission. Amongst the system-specific internal parameters, we considered emitted power, data rate, laser wavelength, modulation losses, amplifier gain, optical losses at the transmitting and receiving components, system aperture at both terminals, beam splitting, coupling losses, and detector sensitivity. On the other hand, the external parameters are pointing losses, tracking losses, and link distance [2]. The link budget weights together these parameters to determine the quality of the transmission at varying distances. Increasing the achievable link distance requires improvements in the coding gain, the emitted power and the receiver sensitivity and will be discussed in the following.

CubeISL distinguishes between two separated link budgets. On the one hand, the link budget has to be calculated for the tracking, which describes the maximum distance until where the terminals are able to establish a stable connection. This can be seen in figure 2 in blue. On the other hand, a second link budget is calculated for the communication channel, which describes maximum distance for data transmission, depending on the data-rate and the used code-schemes. The suggested modifications improve the link distance up to 650 km at 100 Mbit/s for an uncoded signal (figure 2 in red). Using an error correction coding leads to additional improvements in the transmission quality and hence, the link distance. The following section describes different options for the coding choice.

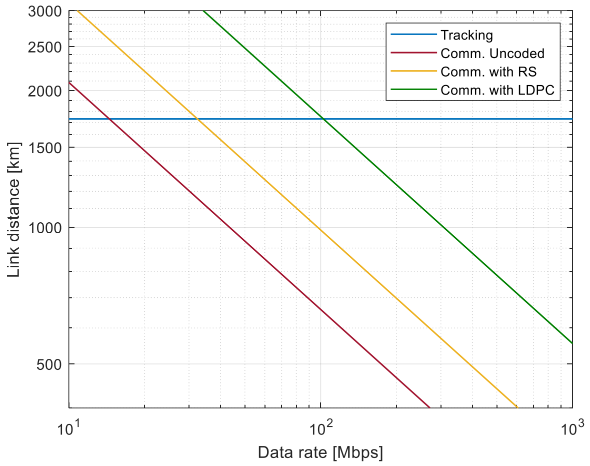

Fig. 2. Maximum achievable link distance over data rate for the tracking and communication channel and comparison between selected FEC codes.

B. Channel Coding

Forward Error Correction (FEC) allows further improvements to the link performance by adding redundant parity bits to the information bits, thus decreasing the user data rate. Same Bit Error Rates (BER) can be achieved with a lower Signal-to-Noise-Ratio (SNR), reducing the required power for the data transmission channel [3]. Furthermore, in the presence of burst errors, adding an interleaving on top of the FEC code helps prevent the loss of whole codewords at the cost of an added delay.

Low complexity, fast decoding, and high data rates make Reed-Solomon (RS) FECs the most suitable block codes for ISL between small-sized spacecraft. RS codes are often used to improve FSO communications [3]. O4C uses an RS FEC scheme, requiring three times less received power than an uncoded channel [4]. Implementing this scheme on CubeISL leads to significant increases in the link distance of up to 1000 km at 100 Mbit/s.

Compared to RS, Low-density parity-check (LDPC) FECs offer higher performance and more flexibility in code rates at the expense of added decoding complexity [3]. Despite being mainly used for space-to-ground links, improvements in decoding algorithms are making LDPC more accessible for ISL with small satellites [5]. With LDPC, the link distance can further be increased up to 1750 km, as seen in figure 2 [3].

C. Technical adaptions

To achieve the results of the link budget shown above, several technical adaptions of the optical payload are necessary. The required optical output power of 1W cannot be achieved with the laser source used in O4C.

O4C is equipped with an optical sensor to acquire the beacon sent by the optical ground station. This sensor is theoretically able to receive data at relatively low data-rates. To achieve the capability of receiving high data-rates like 100 Mbit/s, CubeISL has to be extended by an additional receiver.

As shown in subchapter IV.B. special coding schemes are necessary to increase the data throughput. These en- and decoding procedures require a lot of computational power. O4C is equipped with a microcontroller with limited processing power. CubeISL will be equipped with an own Data Handling Unit (DHU) to provide the necessary calculation capabilities and handle the high amounts of data, transmitted via the optical link.

These major adaptions are described in detail below.

Transmitter

Bidirectional ISLs require isolating the low-power received signal from the high-power transmitter signal. Possible techniques to separate transmitted and received signal are wavelength, polarization, spatial or temporal isolation [6]. Like O4C, CubeISL will use wavelength differentiation between emitted and received carrier waves. However, it will require two different terminals. Terminal A will emit at one wavelength in the near-infrared spectrum, while Terminal B will do it at a slightly different wavelength of the same spectrum.

Instead of one high-power laser diode, each terminal will use the same sort of laser diode and an optical amplifier, optimized at their respective wavelength to generate an average output power of 1 W. High bandwidth Distributed FeedBack (DFB) lasers can be optimized over a wide range of wavelengths, efficiently modulated at 100 Mbit/s, encased in a compact butterfly packaging, and have a narrow spectral linewidth, making them excellent candidates as emitters. Its output signal will be boosted by the amplifier to the final output power.

Receiver

The incoming beam is compressed at the aperture by an optical system and focused on the detector. Simultaneous tracking and data readout are necessary on ISL and require either two photodiodes or one detector array.

In the first case, a 4-Quadrant PIN Diode (4QD) usually performs the position sensing, and an additional receiver diode performs the information processing. The optical signal is forked with a beam splitter and focused independently on each detector. This solution requires a higher number of optical elements, larger volumes, and a precise optomechanical assembly to focus the spot on each sensor in case of thermal expansion or pointing errors.

A spatial combined tracking and data-reading sensor is a simpler, more compact solution less prone to coupling losses. The idea is to use a diode array with four dedicated diodes around the center for tracking and an additional receiver diode in the middle of the array. So far, no commercial off-the-shelf (COTS) arrays are available for this purpose, but with sufficient improvements to the link margin, a 4QD could replace the array as a single-path low-bandwidth receiver [8].

Data Handling Unit

O4C outsourced processes which require high computational power to an external Field Programmable Gate Array (FPGA). To be independent of the satellite bus CubeISL will be equipped with an own FPGA which will work as a Data Handling Unit (DHU). Especially channel coding and forward error correction schemes like LDPC codes use high computational power, where the decoding is more power hungry than the encoding.

Furthermore, optical communication moves the bottleneck for data transmission from the link between the satellite and earth to the satellite bus. Transmitting data with 100 Mbit/s or more requires a data readout at the same rate. This exceeds the capability of common CubeSat busses by far. Thus, the DHU buffers, processes and transfers the data over a dedicated high-speed interface to the transmitter system. The DHU operates vice versa for the received data, which will be transferred from the receiver to the DHU, decoded and stored for the use afterwards by the satellite.

D. Payload Concept

As O4C is designed for standard CubeSat busses CubeISL will be as well. One major aspect of CubeSat payloads is its compact design. The goal of CubeISL is to fit all technical adaptions, including all additional subsystems into 1U of a CubeSat. Figure 3 shows a first concept of how the additional subsystems can be integrated into a structure of 1U. The payload consists of three layers that can be individually separated.

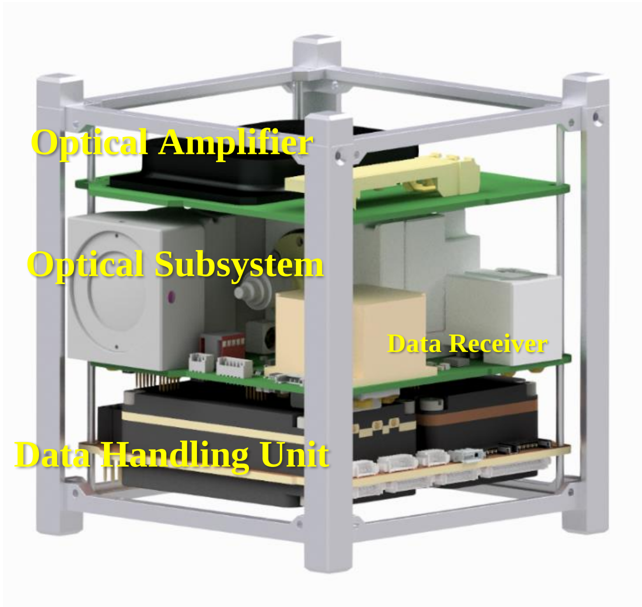

Fig. 3. CubeISL payload concept

CubeISL consists of three major subsystems the optical subsystem based on O4C, the amplifier board and the DHU. Each of these three subsystems comes with an own mainboard which provides all necessary electronic and digital functionalities for the individual subsystem. This follows the modular approach of developing, operating and testing each subsystem seperately and independently from the others.

The core of the payload is the optical subsystem which is based on O4C with slight adaptions. The transmitter system is separated on its own mainboard. The gained space can be used for an additional data receiver, which is mandatory for the bidirectional communication if a forked solution between tracker and receiver is necessary. This would require small adaptions in the optical path to split the signal for tracking and data reception. Apart from this, the payload design could be completely transferred from O4C without further significant changes.

The optical amplifier board is depicted as the top layer of CubeISL in figure 3. A single laser source as used in O4C is not powerful enough to achieve high data rates over the required distance, as described in subchapter IV.C. To achieve a compact design the payload will have an own transmitter board, which includes the laser sources and the amplifier.

The DHU board is located at the bottom level of the unit. Common processing units like FPGA's with a space heritage are commercially available. The goal is to rely on system that have already flown in several space missions. This reduces the qualification effort while retaining high reliability of this subsystem.

V. SUMMARY AND OUTLOOK

The increasing importance of small satellite constellations with high data rate requirements within the constellation raises the need for optical inter-satellite links. Based on the OSIRIS4CubeSat development launched early 2021, CubeISL extends its design with an optical amplifier to achieve an optical output power of 1W, an additional data receiver with 100 Mbit/s and a data handling unit to encode and decode the transmit and receive signal. These modifications lead to a bidirectional full-duplex data rate of 100 Mbit/s over distances of up to 1750 km. The CubeISL payload will fit into 1 Unit (1U) of a standard CubeSat and will use standard interfaces for the communication.

Based on the CubeISL development, DLR will fly a mission together with partners in 2023 to demonstrate the optical inter-satellite link in orbit.

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