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Confronting or linking CSP and CCSDS? A view on how to operate small satellites today

Pierre-Alexis Lagadrillière[a]*, Tobias Brügge[b], Kay Müller[c]

[a] *Communication and Ground Stations, German Space Operations Center, German Aerospace Center (DLR), Oberpfaffenhofen, 82234 Wessling, Germany, pierre.lagadrilliere@dlr.de*
[b] *Mission Operations, German Space Operations Center, German Aerospace Center (DLR), Oberpfaffenhofen, 82234 Wessling, Germany, tobias.bruegge@dlr.de*
[c] *Mission Operations, German Space Operations Center, German Aerospace Center (DLR), Oberpfaffenhofen, 82234 Wessling, Germany, kay.mueller@dlr.de*
* Corresponding Author

Abstract

CubeL was launched early 2021 and is the first COTS cubesat which the German Space Operations Center (GSOC) of DLR is operating. It carries 3 of the most typical space-to-ground communication systems with its UHF transceiver, its S-band transceiver and its laser terminal. Main aim is to demonstrate the capabilities of the miniaturized laser terminal for high speed communications up to 100Mbps. The second aim of this cubesat is to test operations between the on-board S-band transceiver with its native CSP and GSOC's multi-mission environment based on CCSDS and ECSS protocols and standards, e.g. the CCSDS space packet protocols.

In this paper we will dive into this second aim. More specifically we will propose an evaluation of the 3 types of operations for small satellites: CCSDS and ECSS based operations, CSP based operations, and GSOC's concept adapting CCSDS on CSP which is currently being used with CubeL. To do so, we will first describe the UHF and S-band communication systems both on ground and on-board. We will detail the CSP and CCSDS protocols. Then we will review DLR's initial approach from 2020 described in "Integrating the Cubesat Space Protocol into GSOC's Multi-Mission Environment", from Lukas Grillmayer and Saskia Arnold and presented at SSC20. We will investigate how this integration of CubeL into GSOC's multimission environment eventually happened and what are the pros and cons of this method, specifically for small satellites. Based on our experience gained with CubeL and with other missions supported by GSOC, we will end with a comparison of the operations using CSP to CCSDS adapters on both end with CSP-based UHF operations and with classical CCSDS S-band operations which are run otherwise at GSOC.

Keywords: DLR, GSOC, CubeL, CCSDS, ECSS, CSP

Acronyms/Abbreviations

Cubesat Space Protocol (CSP)
German Aerospace Center (DLR)
German Space Operations Center (GSOC)
In-Orbit-Testing (IOT)
Institute of Communications and Navigation (IKN)
Launch and Early Orbit Phase (LEOP)
Mission Information Base (MIB)
Monitoring and Control System (MCS)
Multi-mission environment (MUM)
Telecommands (TC)
Telemetry (TM)
Ultra High Frequencies (UHF)

1. Introduction

The CubeL mission, also known as PIXL-1, is a cooperation between the Institute of Communications and Navigation (IKN) of the German Aerospace Center (DLR) and Tesat-Spacecom, where the DLR German Space Operations Center (GSOC) performs the spacecraft operations. Numerous Cubesat missions rely on Ultra High Frequency (UHF) communications and the Cubesat Space Protocol (CSP). This is also the case for CubeL, which uses UHF and CSP for its main communication link. CubeL carries also an S-band transceiver (secondary payload) to test and validate the usage of CCSDS protocols over S-band.

The main component of the GSOC Multi-mission environment (MUM) is GECCOS, a SCOS-2000 based Monitoring and Control System (MCS). Prior to the launch of CubeL in early 2021, the GSOC MUM environment, consisting among others of GECCOS and of multi-mission infrastructure like the DLR satellite ground station Weilheim, was only being used for telecommunications with spacecraft using CCSDS protocols and ECSS standards. To integrate the CubeL operational segment into the GSOC MUM environment meant to find a way to link CSP and CCSDS/ECSS standards. Thus, a strategy had to be developed and tested, based on two approaches: translation and encapsulation. We will come back to this strategy, present its implementation and review the 3 types of satellite operations: CSP based, CCSDS/ECSS based, and CSP over CCSDS/ECSS.

2. CubeL mission

CubeL was launched on a SpaceX rocket in January 2021. It is located in a Sun-Synchronous Orbit (SSO) at an altitude of 560 km and an inclination of 97.6°. The mission is designed for a duration of 3 years. The satellite uses a 3U CubeSat platform, which hosts payloads and necessary space to ground interface infrastructure. The satellite's subsystems are shown in Fig. 1. The primary payload of the satellite is a miniaturized laser terminal *OSIRIS4CubeSat*. Additional payload consists of components required for the S-Band link.

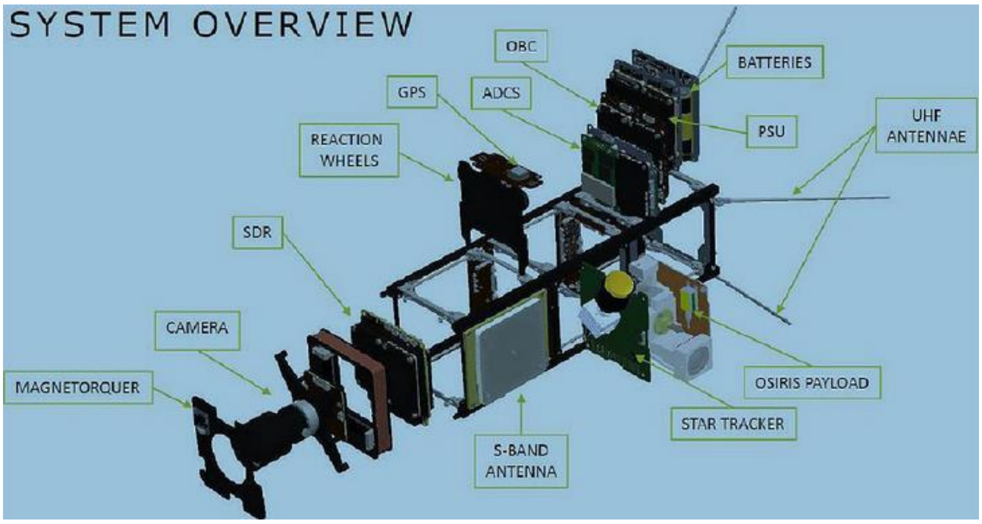

Fig. 1 CubeL System Overview [1]

The primary mission objective of CubeL "is the successful in-orbit demonstration (IOD) of the OSIRIS4CubeSat module's downlink capabilities and reliability" [1]. The secondary mission objective is to integrate CubeL into the existing multi mission command and control infrastructure of GSOC. GSOC will take over routine operations with the satellite manufacturer performing the Launch and Early Orbit phase (LEOP) including the In-Orbit-Testing (IOT).

On-board UHF

The UHF communication system of CubeL consists of a COTS UHF miniaturised transceiver from GOMSpace: the NanoCom AX100 [2]. The AX100 is connected to 4 antennas located on each sides of the satellite. On the other end, this transceiver is connected with the CAN bus of the spacecraft, on which all other components are also connected. CubeL is operated over UHF using the CSP protocol. CSP functions as an interface between multiple nodes which can be on-board or on the ground (e.g. on-board ADCS or ground transceiver). With this protocol, each node is theoretically capable of communicating with each other node. Commanding is done from a terminal (csp-term) using a shared set of commands that are understood by each node [3].

On-board S-band

The S-band communication system of CubeL is structured in a similar way as the UHF system. In this case, the transceiver is the SR2000 [4], also a COTS SDR based component from GOMspace. A difference is the single patch antenna NanoCom ANT2000 [5] to establish up- and downlink with Earth.
The SR2000 is connected to the spacecraft CAN bus and uses CSP with other on-board nodes. To support communication with the GSOC MUM infrastructure, the SR2000 software is capable of encapsulating CSP Telemetry (TM) into CCSDS/ECSS TM frames and decapsulating CSP Telecommands (TC) from CCSDS/ECSS TC frames. These functionalities allow the SR2000 to transmit and receive CCSDS/ECSS packets with the ground station while carrying CSP packets.

3. Protocols

3.1 CSP

The CubeSat Space Protocol (CSP) is a network and transport protocol specially designed for embedded systems such as 32bit AVR microprocessors, as can be found on the CubeL on-board computer (NanoMind A3200 [6]). This protocol, initially developed by Aarlborg University, is simple, lean, and well suited for low bandwidth, low latency systems as it is often the case for cubesats.

<table>
<tr><td>Bit Offset</td><td>31</td><td>30</td><td>29</td><td>28</td><td>27</td><td>26</td><td>25</td><td>24</td><td>23</td><td>22</td><td>21</td><td>20</td><td>19</td><td>18</td><td>17</td><td>16</td><td>15</td><td>14</td><td>13</td><td>12</td><td>11</td><td>10</td><td>9</td><td>8</td><td>7</td><td>6</td><td>5</td><td>4</td><td>3</td><td>2</td><td>1</td><td>0</td></tr>
<tr><td>0</td><td colspan="2">Priority</td><td colspan="5">Source</td><td colspan="5">Destination</td><td colspan="6">Destination Port</td><td colspan="6">Source Port</td><td colspan="4">Reserved</td><td>HMAC</td><td>XTEA</td><td>RDF</td><td>CRC</td></tr>
<tr><td>32</td><td colspan="32">Data (0 - 65 535 bytes)</td></tr>
</table>

Table 1: Cubesat Space Protocol (Version 1) in use with CubeL

The CSP header shown in Table 1 features among others the necessary connection information along with additional optional authentication and encryption features. In addition to its simplicity, the protocol library and source code are freely available on GitHub under an LGPL license [7].

3.2 CCSDS and ECSS standards

Uplink protocol stack

For uplink 4 layers are identified between the physical channel and the application data, each of them supporting integrity checks:

1. Physical layer, as defined in CCSDS 231.0-B-4 [8]
   This layer consists of start sequence, CLTUs (communications link transmission unit), and idle sequences The CLTUs contain start sequence, codeblocks and tail sequence, where codeblocks carry the information (and an error control field).

2. Frame layer, as defined in CCSDS 232.0-B-4 [9]
   This layer consists of TC transfer frames which are the information carried by the CLTU codeblocks. TC transfer frames carry 3 types of information: frame header, frame data field, and frame error control.

3. Segment layer, also defined in CCSDS 232.0-B-4 [9]
   The segment layer consists of TC segments which are the frame data fields from the TC transfer frames. These TC segments contain a segment header and source packets.

4. Packet layer (see Table 2), as defined in CCSDS 133.0-B-2 [10] and using the PUS (Packet Utilisation Service) defined in ECSS-E-ST-70-41C [11]
   These TC packets are the TC segment source packets. Each TC packet carries among others an APID (application process identifier) and a packet data field along with a packet data field header.
   The APID serves as destination for the telecommand. The data field header contains the source ID. And the application data is the information itself (telecommand)

CCSDS TC packet										
Packet Header							Packet Data Field			
Packet ID				Packet Sequence Control		Packet Length	Data Field Header	Application Data	Packet Error Control
Version number	Type	Data Field Header Flag	APID	Sequence Flags	Sequence Count				
3 bit	1 bit	1 bit	11 bit	2 bit	14 bit	16 bit	32 bit		16 bit
2 byte				2 byte		2 byte	4 byte	0 - 236 byte	2 byte
12 - 248 byte									

Table 2: CCSDS Telecommand packet layer

For a typical spacecraft operated at DLR/GSOC, the content of the TC packet application data is documented inside mission-specific Mission Information Base (MIB) tables. MIB is the database standard for S/C operated with ESA SCOS-2000 based systems and contains definitions of TM and TC structures, which allow to parse TM and transmit TC using the CCSDS and ECSS formats.

Downlink protocol stack

For downlink the layering is similar to the uplink stack. Between the physical channel and the source data, we observe the following layers:

1. Physical layer, as defined in CCSDS 131.0-B-4 [12]
   This layer consists of attached sync marker, transfer frame and R/S check symbols, also known as CADU (Channel Access Data Unit)

2. Frame layer, as defined in CCSDS 132.0-B-4 [13]
   This layer consists of TM transfer frames which are the information carried by the CADUs transfer frames. The TM transfer frames carry 3 types of information: frame header, frame data field, and frame trailer.

3. Packet layer (see Table 3), as defined in CCSDS 133.0-B-2 [10] and using the PUS (Packet Utilisation Service) defined in ECSS-E-ST-70-41C [11]
   These TM source packets are the TM transfer frame data fields. Each TM source packet consists of a packet header (with the APID) and packet source data field along with a packet data field header.
   The data field header contains the destination ID. And the packet source data is the information itself (telemetry).

CCSDS TM source packet								
Packet Header							Packet Data Field	
Packet ID				Packet Sequence Control		Packet Length	Data Field Header	Source data
Version number	Type	Data Field Header Flag	APID	Grouping Flags	Source Sequence Count			
3 bit	1 bit	1 bit	11 bit	2 bit	14 bit	16 bit	80 bit	0 - 8240 bit
2 byte				2 byte		2 byte	10 byte	0 - 1030 byte
16 - 1046 byte								

Table 3: CCSDS telemetry source packet [14]

As described for the uplink protocol stack, for each spacecraft the structure and content of TM packet source data is also stored in MIB tables, allowing correct interpretation of TM by GSOC MUM systems.

4. Combining CSP with CCSDS and ECSS

The GSOC approach was to use its MUM environment for CubeL operations over S-band. The main interest is to operate CubeL like any other mission at GSOC. The resulting challenge is that the GSOC environment is developed around CCSDS and ECSS recommendations and protocols while CubeL uses CSP. In order to integrate CubeL S-band operations into the GSOC environment, the strategy developed at DLR consists in a combination of three approaches:

- **Use the CSP-Terminal**
  The client-server design of CSP and its features are difficult or impossible to replicate in the classical SCOS/GECCOS setup. Thus, the CSP-Terminal is used as a source of commands and command responses are routed back to it. It remains the actual mission control system. The GSOC MUM

environment serves as the CCSDS/ECSS backbone to which CSP connects for the purpose of en- and decapsulation.

- **Implement the CSP TM (and commands) structure in the MIB**
  The structure of CSP TM is translated into appropriate MIB tables.
  With CubeL, this approach was applied to the entire TM because the TM structure documentation is readily available and detailed enough.
  The same was applied only to a limited amount of simple CSP commands. However, we decided against translating the full set of CSP commands into the MIB database for the following reasons. First, limited budget was available for integrating CubeL into the GSOC MUM environment. The definition of a MIB requires significant resources in any space mission. This holds especially, if only little documentation about the TM / TC structure is available (keyword reverse engineering). A second reason was different design philosophies behind CCSDS/ECSS based and CSP based communications. While traditional operations with CCSDS/ECSS based communication clearly differentiates between a TM and a TC channel, the approach taken in CSP is instead based around the concept of client-server connection between nodes in the space and ground segment.

- **Encapsulate CSP packets**
  For uplink this means that the CCSDS/ECSS TC packet application data is a CSP command packet. Once reaching the spacecraft, the CSP command packets are extracted and processed like any other CSP command packet.
  For downlink this means that each Source Data field from the CCSDS/ECSS TM source packet is a CSP TM packet. On ground, the CSP TM packets are extracted and sent to a CSP terminal system.
  This approach is used for CubeL with most of the CSP commands.

There are limitations and necessary adjustments which are not described in this summary. For example, the TC frame length must be set to a fixed value. Please refer to [14] and to [15] for a detailed description of the strategy, preliminary validation, implementation and integration into the operational environment.

5. Review of the 3 types of operations

5.1 CCSDS/ECSS based operations

Let us start with the type of operations in place at GSOC for decades. 76 years of space missions showed that cooperation is a major key to access Space and that limited budgets imply the reuse of previously developed technologies and systems. These in turn foster interoperability between missions and between space operations assets. CCSDS and ECSS are the results of these needs, with the aims to unify and standardise spacecraft operations. And DLR, which is strongly involved at CCSDS and ECSS due to its major participation in exploration and research in Space, developed and uses CCSDS and ECSS compliant satellite ground operations systems like GECCOS and the Weilheim station. Not only the GSOC MUM environment is compliant with the standards and recommendations mentioned in chapter 3.2 it is also the perfect example of intercompatibility (e.g. to other ground stations) and reuse, with several dozens of missions supported using GECCOS for monitoring and controlling the spacecrafts.

It is important to mention that the CCSDS and ECSS publications are results of consensus between the partners, and that the publications are exhaustive since they need to cover all the partners' needs. It is then left to each one to decide on the degree of compliance, as "tailoring" is an option, if not an obligation. The intercompatibility is in any case achieved with CCSDS which defines standard frames and layers, and with ECSS which defines standard content within these frames.

A consequence and major benefit is that entities having the same compliances, are interoperable, and that companies and organizations can identify quickly which entities will be compatible with their spacecraft.

Another major advantage is that the different layers, headers and parameters offer a large panel of verifications (e.g. execution stages of a TC), integrity checks, encryptions.

The counterpart of CCSDS and ECSS is the need to understand the full collection of publications before being able to tailor the compliance degree. Only then can the implementation begin. Tailoring and implementing consume a large amount of resources, which might be critical especially for newcomers and young companies working with Space operations.

5.2 CSP based operations

CSP is in some extent the opposite of CCSDS/ECSS. The author of CSP is a single entity (Aalborg University). It has a lean and efficient protocol. It follows the well-known layering of TCP/IP and the client-server architecture. And the availability of the CSP libraries eases the process of implementing CSP in new systems and infrastructures, while involving other potential partners to cooperate on further development of this protocol and enhancing flexibility of the protocol.

As a result, operations are simplified, not only because of the simplicity of this protocol but also because of the simple hardware required to run CSP operating tools. Also, it is worth mentioning that the communication bus is the interface to all subsystems (including ground and space subsystems), which reduces complexity of the topology.

Yet, the availability of the CSP libraries happens to foster also the main setback. In fact, Cubesat manufacturers and integrators have various, sometimes diverging needs, while the libraries might not cover all these needs. Thus, each of the manufacturers tends to develop their own variants of the CSP code with custom content in CSP packets which will cover their requirements, since CSP defines only a standard for the frames but not the content. If documentation is also limited, then we have suddenly the best soil to grow proprietary protocols with single-mission use. To be precise, proprietary protocols are not a drawback for mission operators working on constellations and/or having free selection in the manufacturer. But GSOC and other multi-mission environments focus mostly on IOD and other unique research missions, where interoperability is a critical requirement. Consequently, proprietary single-mission systems will consume additional resources for each integration into a multi-mission environment and will be lost once each mission ends. In addition, CSP is limited to a maximum of 32 nodes in its architecture, rendering it impracticable for larger spacecrafts and for operating constellations with overlapping contacts.

5.3 Operation with CSP within CCSDS/ECSS protocols

We will review here the implementation of CSP over CCSCS/ECSS in GECCOS, as described in chapter 4, in [14] and in [15]. Two years operating CubeL with this implementation led us to the following observations:

- It is possible to operate spacecrafts using CSP on a CCSDS/ECSS based system
- CCSDS and ECSS headers and additional fields enhance majorly the CSP packets (even if not all functionalities of the CCSDS/ECSS packets can be used). For example, it is possible to obtain the No Bit Lock Flag (NBLF) in the TM transfer frame, which is not possiblewhen using CSP alone.
- It is possible to implement some MIB tables as translators for CSP packets, but not all of them, in particular those for commands, and at significant resource cost. Condition for this implementation is sufficient documentation and resources.
- Issues were found on various layers and components for both up- and downlink. While the signal transmissions work perfectly in both directions, these issues were mostly caused by bugs on software and firmware (e.g. on the S-band modem link firmware)
- Additional components: on-board CSP “encapsulator”/wrapper and "decapsulator”, ZeroMQ connector to interface GECCOS with the CSP terminal, increase complexity and error sources
- Troubleshooting is also particularly exhausting because of the lack of proper feedback parameters on CSP
- The data rate cannot exceed 32kb/s since the TM transfer frame virtual channel identifier is set to 0
- CSP source packets shall always be inserted synchronously in transfer frames and in forward order. Segmentation of source packets is not supported
- The source packet secondary header shall indicate the usage of ECSS PUS, request no acknowledge report and have fixed PUS service type and subtype designators within the custom service range.
- Only one CSP packet is possible inside a TM packet (the bytes available are filled with zeros). Since the CSP packets might be smaller, we observe losses in the payload capacity. Note that at this point, we do not know what will happen if the size of the transported CSP packet exceeds the payload capacity of the encapsulating TM packet

6. Confronting or linking CSP with CCSDS/ECSS?

To conclude, we have seen that each type of operations has its own pros and cons. In short, CCSDS and ECSS based operations foster the reuse of existing systems between missions, even if these missions have different origins and objectives. This is a cost-effective approach on a long perspective, particularly adapted to multi-mission environments. On the other side, for short-living missions and young companies, implementing a compliance is complex and consuming resources, which drives the costs up typically at times where such companies face other important challenges. CSP operations lead to a quick and simple implementation while covering basic options for encryption and authentication. CSP is readily available and easily adaptable to the missions’ needs, which would have been perfect for larger constellations if the architecture had allowed a larger amount of nodes. And these availability and adaptability lead to the problem that “CSP might not be not the same as CSP” because cubesat manufacturers develop their own CSP variant. In addition, changes towards some sort of standardisation of CSP is not foreseen yet. As for using CSP over CCSDS/ECSS, this shows that CCSDS and ECSS can host CSP packets. Such systems allow to operate both types of spacecrafts with one single monitoring and control system. And even with limited resources, this implementation remains feasible, assuming that there is access to proper documentation of the CSP TM and TC. Yet such an implementation remains new and full of challenges. Among others, in our implementation the resulting overhead is not neglectable anymore. And at this time, we do not use all the possibilities offered by the 3 systems.

If we come back to the initial question, GECCOS is now compatible with a cubesat using CSP, which shows that linking CSP with CCSDS and ECSS is possible and brings new capabilities to CCSDS/ECSS based multi-mission systems. Part of our implementation will surely be reused for upcoming cubesat missions and this will allow us to gather more experience with this linking. Other implementations of CSP over CCSDS seem to have been tried, for example where the codeblocks from the CLTUs are the CSP packets and where the TM transfer frames are CSP packets. A comparison of these 2 approaches with ours would surely bring new insights, as would an implementation of CCSDS/ECSS packets over CSP.

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