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TT&C over S-Band with CubeL: Finding a Middle Way Between CSP, CCSDS and ECSS

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Abstract

Since early 2021, the German Space Operations Center (GSOC) of DLR with Weilheim Ground Station operates its first COTS CubeSat: CubeL, also known as PIXL-1. Besides the main objective of validating a miniaturized space-to-ground optical communication terminal developed by DLR-IKN and Tesat-Spacecom, CubeL shall demonstrate the execution of Telemetry, Tracking & Command (TT&C) operations between a modern CubeSat and a classical multi-mission (MUM) environment with the help of a S-band communication link.

CubeL, on the one side, relies like many other CubeSats on the CubeSat Space Protocol (CSP), a well-established delivery protocol whose layering corresponds to the TCP/IP model. The advantages of CSP are its simplified structure, modularity, easy deployment, and free availability under the LGPL license. GSOC and Weilheim Ground Station (WHM), on the other side, have a long history in the operation of all types of space missions, manned or unmanned - near earth or deep space. MUM operations can only exist with the help of highly standardized communications. This is the reason why the core mission operations systems at GSOC and the ground station equipment rely on standards and recommendations like CCSDS 132.0-B-2 (TM Space Data Link Protocol, linked to ISO 22645:2016), CCSDS 133.0-B-1 (Space Packet Protocol, linked to ISO 22646:2005) and ECSS E-ST-70-41C (telemetry and telecommand packet utilization). This approach allows GSOC to support a large number of space missions and increases reliability while simplifying the integration of other stations to existing ground station networks.

In this paper, we present CubeL, the involved S-band communication systems and the employed protocols. We detail the plan to integrate CubeL into GSOC mission operations, followed by the description of the journey towards operational TT&C using the GSOC S-band link. We conclude with some lessons learnt and suggest improvements for future integrations of CubeSat missions into multi-mission operations centers.

Keywords: DLR, GSOC, Weilheim, CCSDS, CSP, S-Band, TT&C

1. Introduction

The CubeL mission, also known as PIXL-1 is a joint CubeSat mission of the Institute of Communications and Navigation at DLR and Tesat-Spacecom launched in January 2021. The primary mission objective of CubeL is an in-orbit demonstration (IOD) of the capabilities and reliability of the primary payload, which is a miniaturized laser terminal called *OSIRIS4CubeSat*. The secondary mission objective is to integrate CubeL into the existing MUM command and control infrastructure of GSOC. GSOC will take over routine operations with the satellite manufacturer GomSpace performing the Launch and Early Orbit phase (LEOP) including the In-Orbit-Testing (IOT).

The mission, designed for a duration of three years, was planned to be divided into two phases *E2a* and *E2b*. In phase *E2a*, the spacecraft (S/C) was to be operated by GSOC via UHF, using a toolkit provided by the satellite manufacturer GomSpace. In phase *E2b*, the space segment would be integrated with the GSOC MUM environment for S-Band operations. CubeSat missions in general are simple and low-cost platforms for experimentation in space. As such, the *E2b* phase can be seen as an experiment for GSOC to assess the challenges of integrating a CSP based mission into its highly standardized CCSDS-based operations environment. However, due to limitations introduced in 2019 by the International Telecommunication Union (ITU) for UHF operations [1], S-Band has become primary mode used by GSOC to operate CubeL.

In the following, we present how CubeL was integrated into the GSOC MUM environment and describe the challenges that were encountered. Section 2 gives an overview of the involved systems. In Section 3, the integration of CubeL is described in detail. Section 4 contains some lessons learned. Section 5 concludes this paper.

2. System Overview

This section gives an overview of the systems described in this paper. This includes a system overview of CubeL, followed by a description of the differences between the CubeL mission operations environment and the MUM environment at GSOC. Finally, Weilheim Ground Station is introduced, which supports the GSOC TT&C test campaign for CubeL.

2.1 CubeL System Overview

CubeL was launched in January 2021 as part of a SpaceX launch into a Sun-Synchronous Orbit (SSO) at an altitude of 560 km and an inclination of 97.6°. The satellite is built on top of a *3U* CubeSat platform, which hosts the payload as well as necessary space to ground interface infrastructure. An overview of the satellite's subsystems is shown in Fig. 1 [2]. The primary payload of the satellite is a miniaturized laser terminal called *OSIRIS4CubeSat*. Additional payload consists of the components required for the S-Band link. This is described in more detail in Section 3.1.

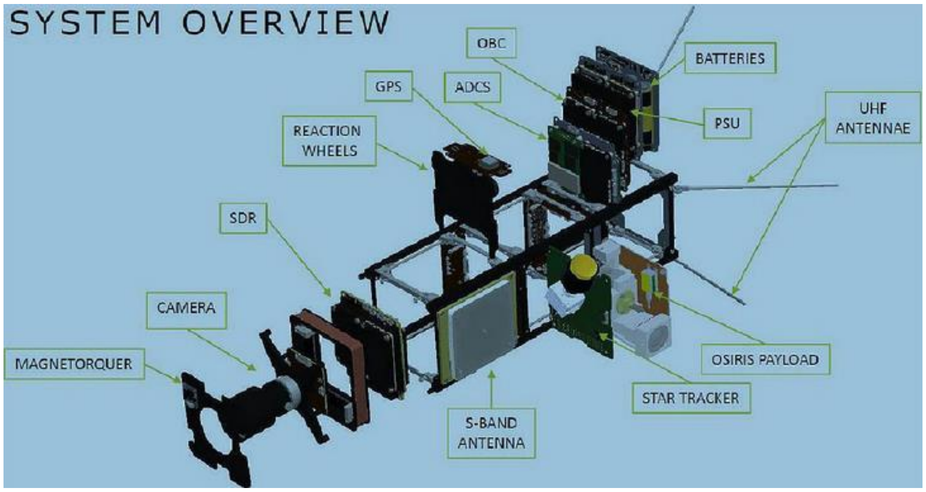

Fig. 1. CubeL System Overview [2]

2.2 GSOC Multi-Mission Operations vs. CSP

The operational segment for the CubeL mission is based on the CSP standard and is shown in simplified form in Fig. 2. The core component of the ground segment is the Monitoring and Control System (MCS) *CSP-Term* on the MS100 server. The *Beacon Parser* and the *GSWeb*, which can be used to process, store and visualize offline TM, are

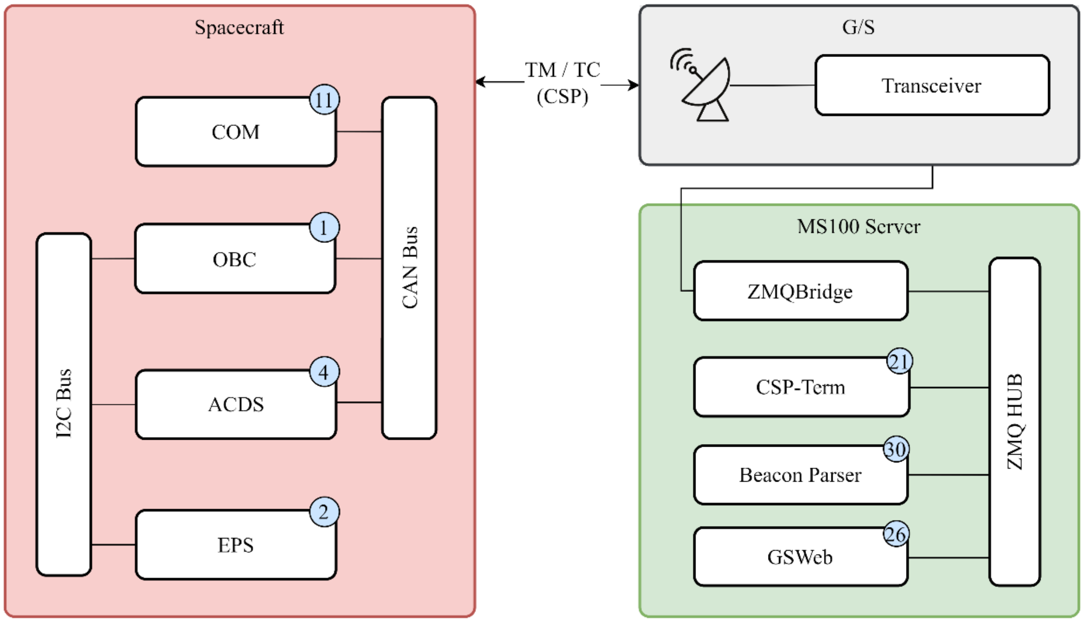

Fig. 2. CubeL Operational Segment (simplified)

also shown as examples for other components in the ground segment. The CSP-Term communicates with the other components in the ground segment using the *ZeroMQ* (ZMQ) messaging framework [3]. Each component is assigned a node for this purpose. For example, the CSP-Term is assigned the node 21, as shown in Fig. 2. The components in the space segment can be addressed using the same node system, but use different bus systems for communication.

Fig. 3 shows a typical Mission Operation Segment (MOS) in the GSOC MUM environment [4], which is based on CCSDS/ECSS standards. The core component in the MOS is the SCOS-2000 based MCS *GECCOS*, which handles the real-time (R/T) TM/TC. GECCOS uses an NCTRS interface to connect to different G/S via the SLE protocol. Several client tools are connected to the GECCOS server, in particular the SATMON tool used for monitoring R/T TM, the MOPS tool used for processing offline TM and a Procedure Converter used for instantiating procedures recommended by the subsystem engineers.

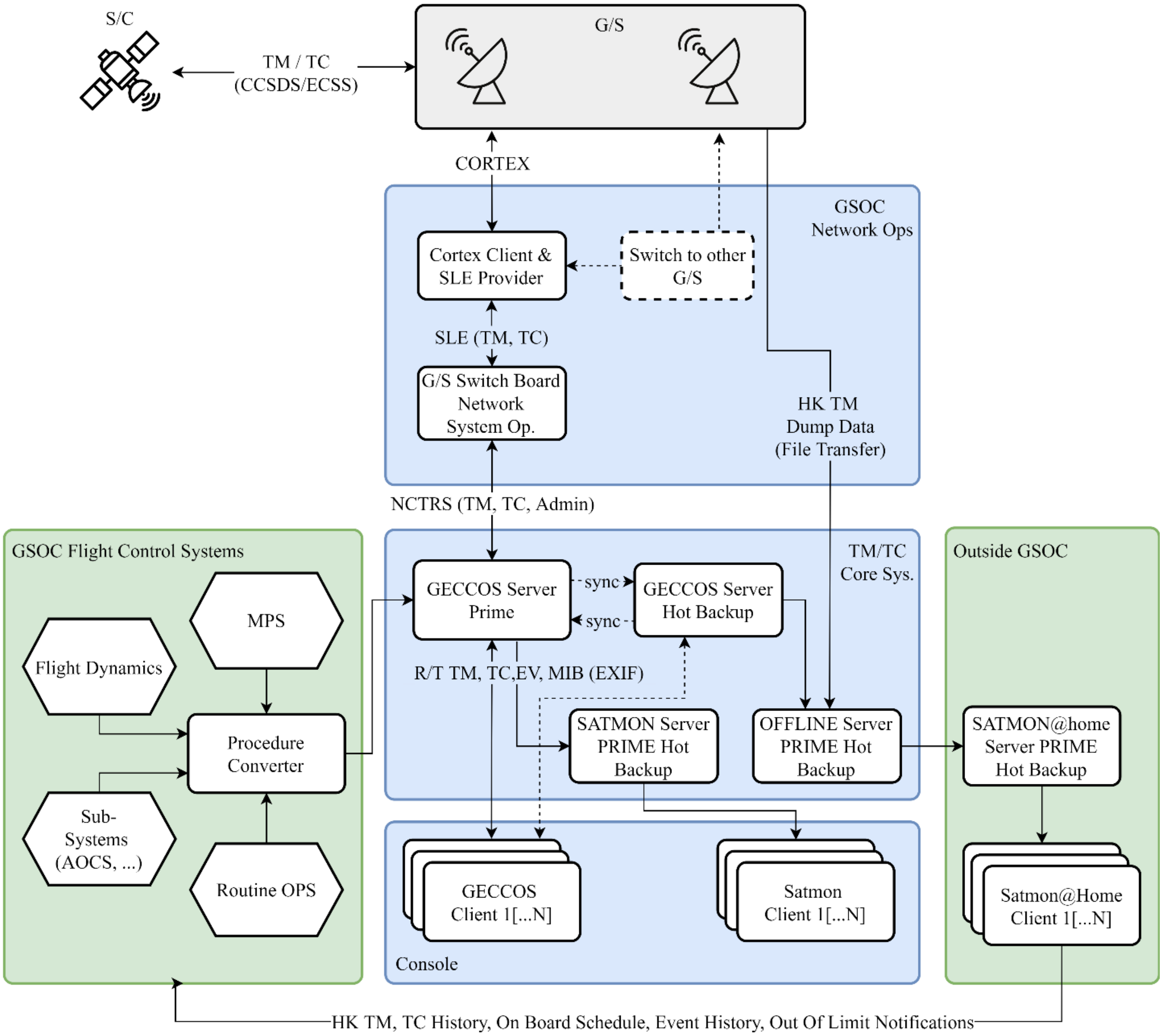

Fig. 3. GSOC Multi-Mission Environment [4]

In order to integrate the CubeL mission with the GSOC MUM environment, the main challenge was to integrate these two incompatible operational segments – the CSP based CubeL operational segment and the CCSDS/ECSS based GSOC MOS. Section 3.2 describes the approach that was taken to solve this problem.

2.3 WHM Antennas

WHM Ground Station, located in Weilheim, Germany, is owned by DLR and is one of the main G/S used by GSOC for MUM operations. In the ongoing campaign to establish TT&C operations of CubeL via S-Band, WHM plays a key role for establishing the S-Band link with the S/C. The block diagram in Fig. 4 describes the design of the station. WHM operates, among others, two 15 m diameter S-Band antennas for TT&C. These antennas, S69 and S67, are mechanically identical (size of reflector, sub-reflector, feed and wave-guide are the same) but have slightly different RF receiver performances. S69 has about 1 dB better reception performance, G/T (antenna gain over system noise temperature) is 1 dB higher than S67 in downlink S-Band frequency range (2200 – 2290 MHz). Table 1 and Table 2 show the key parameters of the S67 and S69 antennas.

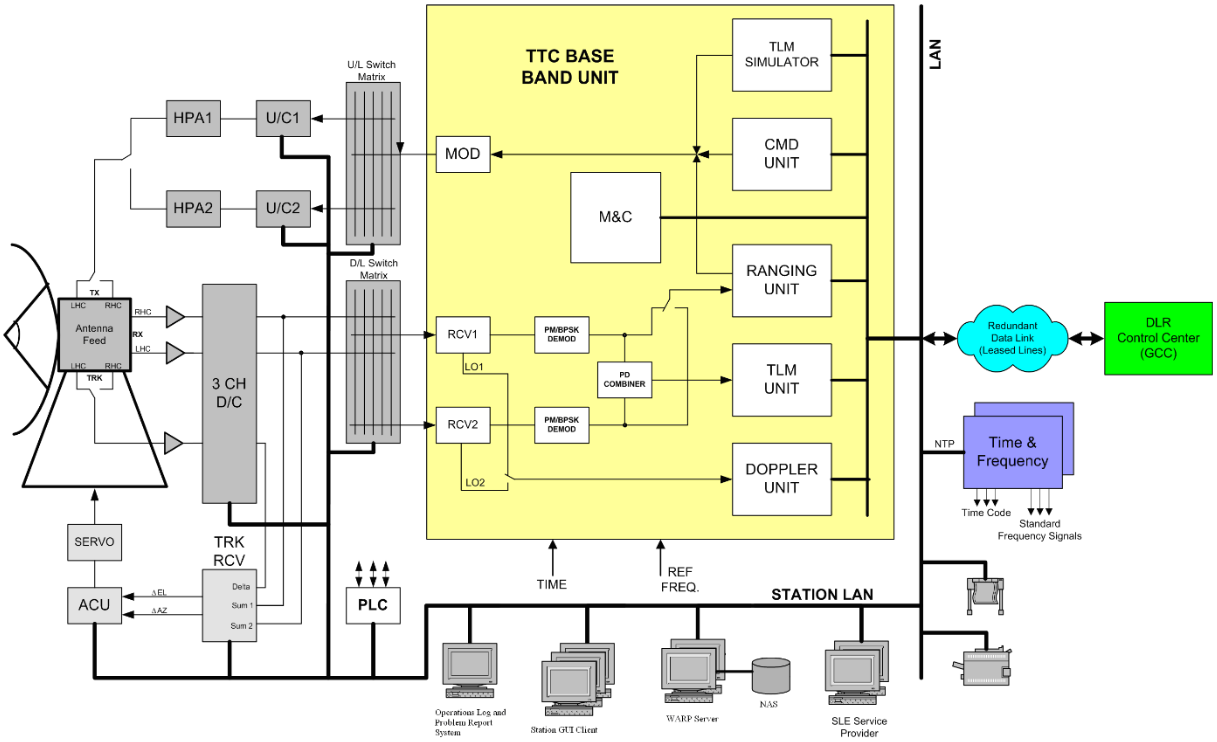

Fig. 4. Functional block diagram of the S-Band TT&C station in WHM

Table 1. Downlink S-Band Parameters of WHM G/S

Parameter	**Station**	**Characteristics**
Frequency Range	S67, S69	2200 to 2300 MHz
Polarization	S67, S69	RHC and LHC simultaneously in DL
Antenna Gain	S67	47.8dBi @ 2250MHz
	S69	48.3dBi @ 2250MHz
G/T	S67	26.7dB/K @ 5° elevation
		27.8dB/K @ 90° elevation
	S69	27.8dB/K @ 5° elevation
		28.8dB/K @ 90° elevation
Beamwidth	S67	0.66°
	S69	0.66°

Table 2. Uplink S-Band Parameters of WHM G/S

Parameter	**Station**	**Characteristics**
Frequency Range	S67, S69	2025 to 2120MHz
Polarization	S67, S69	RHC and LHC
Antenna Gain	S67	46.4dBi @ 2075MHz
	S69	47.2dBi @ 2075MHz
EIRP	S67	58 to 78dBW @ 2075MHz
	S69	59 to 79dBW @ 2075MHz
Beamwidth	S67	0.66°
	S69	0.66°

3. System Integration

This section describes the approach that was taken to integrate the CubeL into the GSOC MUM environment, in order to meet the mission objective. Section 3.1 contains a description of the on-board communications system. This is followed by Sections 3.2 and 3.3, which describe the chosen approach and its implementation.

3.1 On-Board S-Band Communications System

The on-board component used for S-Band communications is the *NanoCom SR2000*, a high-speed S-Band radio transceiver customized for the CubeL mission. A high-level system overview of the S-Band antenna and modem is shown in Fig. 5. The transceiver connects to the CAN bus of the S/C and uses the on-board S-Band antenna for ground communications. The S-Band transceiver includes closed-source custom firmware by GomSpace, which enables the encapsulation of CSP packets in CCSDS/ECSS frames. This functionality is central to integrating the CubeL mission into the GSOC MOS, using the GSOC S-Band link, as is described in Section 3.2. Selected parameters of the on-board S-Band configuration are shown in Table 3 and Table 4.

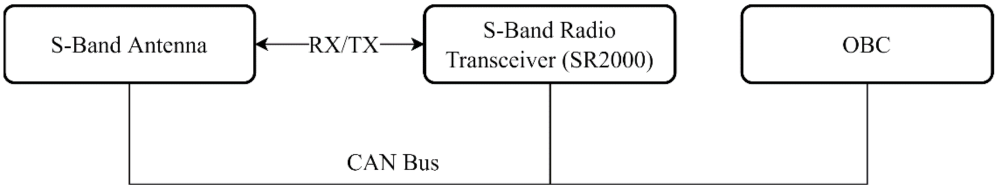

Fig. 5. CubeL Satellite Layout with S-Band Radio (high-level)

Table 3. Uplink S-Band Parameters of On-Board Antenna

Parameter	**Value**
Uplink / Forward Frequency	2083.38 MHz
EIRP	58 dBW
Doppler offset	± 65 kHz
Doppler Rate	< 1kHz/s
CCSDS TC Protocol	TC Packet / TC Transfer Frame / CLTU
PLOP mode	PLOP-2

Table 4. Uplink S-Band Parameters of On-Board Antenna

Parameter	**Value**
Downlink / Return Frequency	2262.5 MHz
S/C EIRP	3.5 dBW
Bandwidth	< 4 MHz
Polarization	RHC, near omnidirectional coverage
Modulation	BPSK
Randomization	Pseudo Randomization (CCSDS compatible)
Reed Solomon Coding	Default enabled
Convolutional Coding	Rate ½
CCSDS Transfer Frame FEC	CRC (CCSDS 131.0-B-3)
CCSDS Transfer Frame CLCW	Yes

3.2 Integrating CubeL into the GSOC MUM Environment

To achieve the GSOC mission goal, the operational segment for CubeL needed to be integrated with the GSOC MOS. As described in Section 2.2, the two segments are not compatible. The CubeL operational segment is based on the CSP standard while the GSOC MOS is based on CCSDS/ECSS standards. We considered two approaches to integrate the two segments. They are described in the following. The first approach makes use of the Mission Information Base (MIB). The second approach is to use packet encapsulation.

3.2.1 TM/TC Definition in MIB

The MIB is the database standard for S/C operated with ESA SCOS-2000 based systems, implemented as a relational database in plain-text format. By defining the structure of TM and TC in the appropriate MIB tables, a SCOS-2000 based system such as GECCOS will be able to parse TM in CCSDS/ECSS format from the S/C and transmit TC to the S/C in the form of Command Link Transmission Units (CLTU). Hence, by translating the CubeL TM/TC structure in CSP format into the according definitions in the MIB, it would be possible to operate the S/C using only the GSOC MUM environment. This requires detailed knowledge of the CSP TM/TC structure.

It was fairly straightforward to implement the TM structure for CubeL in a MIB, because TM descriptions were provided by the satellite manufacturer in the form of so-called beacon definitions. However, determining the TC structures proved more challenging. Knowledge about the TC structure can mostly be attained by analysis of the CSP source code and of the mission-specific GomSpace libraries containing the command implementations. Other available documentation derives mostly from the CSP project [5], which contains information about general CSP concepts and a description of the CSP API.

Thus, it was possible to implement the structure of simple TCs, as for example a *ping* command, into the MIB, by using a CAN sniffer to isolate the command in a test environment and parse the encoded command, consulting the available CSP source code and documentation for reference. However, it was much more challenging to deduce the structure and implementation of more complex commands, which require a dynamic interaction between S/C and G/S with a sequence of multiple requests and responses[1]. For this reason, it was decided to follow a second approach to send TC to the S/C.

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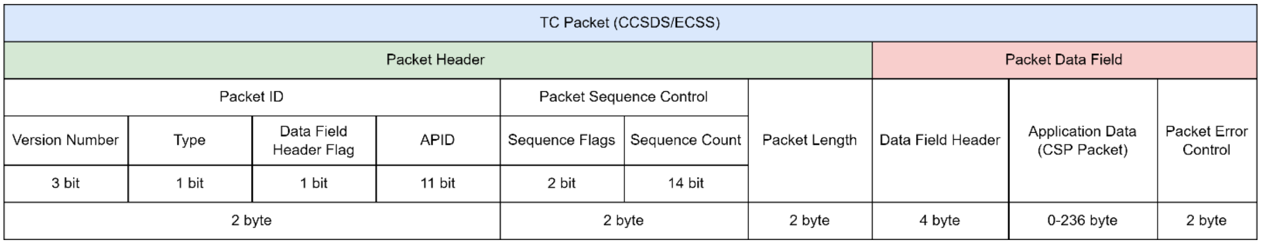
[1] An example for this is the *ftp download* command

3.2.2 Using CCSDS Encapsulation

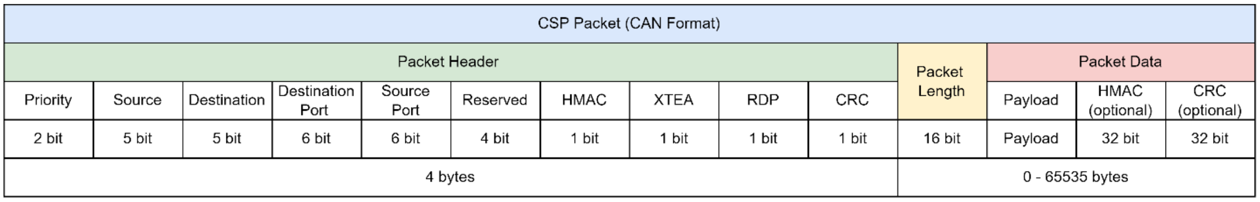
In the packet encapsulation approach, the CSP packets are encapsulated in CCSDS packets on the ground and uplinked to the S/C. When the transporting frame has been received by the S/C, the CSP packets are extracted from the encapsulating packet. They can then be processed on-board as a regular CSP packet. Fig. 6 shows the structure of such an encapsulating CCSDS TC packet. As can be seen, the packet consists of a CCSDS-compliant Packet Header, followed by the Packet Data Field. The Packet Data Field contains a ECSS-compliant Data Field Header, followed by a field containing the Application Data and finally a field for Packet Error Control. The Application Data Field can be utilized to transport a CSP TC packet as shown in Fig. 7. In other words, the TC packet encapsulates the CSP packet.



TC Packet (CCSDS/ECSS)									
Packet Header							Packet Data Field		
Packet ID				Packet Sequence Control		Packet Length	Data Field Header	Application Data (CSP Packet)	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				
2 byte				2 byte		2 byte	4 byte	0-236 byte	2 byte

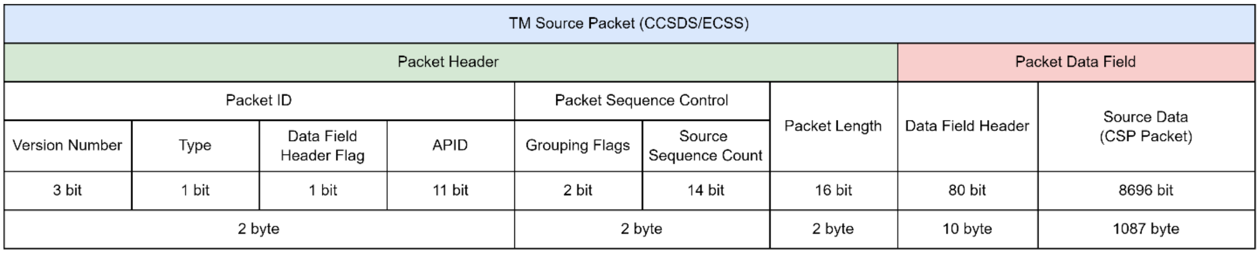
Fig. 6. Encapsulating CCSDS TC Packet Structure

The same approach can also be used for TM packets. Fig. 8 shows the structure of a CCSDS TM packet, which encapsulates CSP TM packets.



CSP Packet (CAN Format)													
Packet Header										Packet Length	Packet Data		
Priority	Source	Destination	Destination Port	Source Port	Reserved	HMAC	XTEA	RDP	CRC		Payload	HMAC (optional)	CRC (optional)
2 bit	5 bit	5 bit	6 bit	6 bit	4 bit	1 bit	1 bit	1 bit	1 bit	16 bit	Payload	32 bit	32 bit
4 bytes										0 - 65535 bytes			

Fig. 7. CSP Packet Structure (CAN Format)



TM Source Packet (CCSDS/ECSS)								
Packet Header							Packet Data Field	
Packet ID				Packet Sequence Control		Packet Length	Data Field Header	Source Data (CSP Packet)
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	8696 bit
2 byte				2 byte		2 byte	10 byte	1087 byte

Fig. 8. Encapsulating CCSDS TM Packet Structure

The advantage of using packet encapsulation is that the contents of the CSP packets can be treated as a black box. It is not required to use to define the TC structures for the CSP commands into the MIB at significant resource cost. Furthermore, the S/C can be operated using the toolkit provided by the satellite manufacturer GomSpace.

CSP packets are sent and received using the CSP-Term and are used for internal communication of the on-board subsystems. However, the CSP packets are transported over the S-Band link of the GSOC MOS in encapsulating CCSDS TM/TC packets. This allows the GSOC S-Band link to be used for communicating with the S/C. Encapsulation of the CSP packets on-board is done by the S-Band transceiver firmware. As stated in Section 3.1, the firmware of the transceiver on the S/C is closed source, so that details about the framing and deframing process on board the S/C are not known.

3.2.3 Hybrid Solution

It was decided to implement a hybrid solution using both approaches. The TM structure for the mission was implemented in the MIB, as specifications for the TM structure were provided by the satellite manufacturer. This enabled the integration with the GSOC MOS for the purpose of monitoring and analyzing TM using SATMON (see

Section 2.2). A number of simple TC were also implemented in the MIB for testing purposes. For the remainder of the commands, it was decided to use packet encapsulation.

To implement the packet encapsulation approach, a new software component was developed, which has been called the ZMQ-Connector. The design of the ZMQ-Connector is shown in Fig. 9. The ZMQ-Connector integrates the CubeL ground segment with GSOC MOS by linking together the CSP-Term with GECCOS. On the side of the CubeL ground segment, the ZMQ-Connector connects to the ZMQ-HUB, over which the other components in the CubeL operational segment also communicate. The ZMQ-Connector is also assigned its own node, following the methodology of the CubeL ground segment (see Fig. 2). This allows the CSP-Term to communicate with the connector as with any other

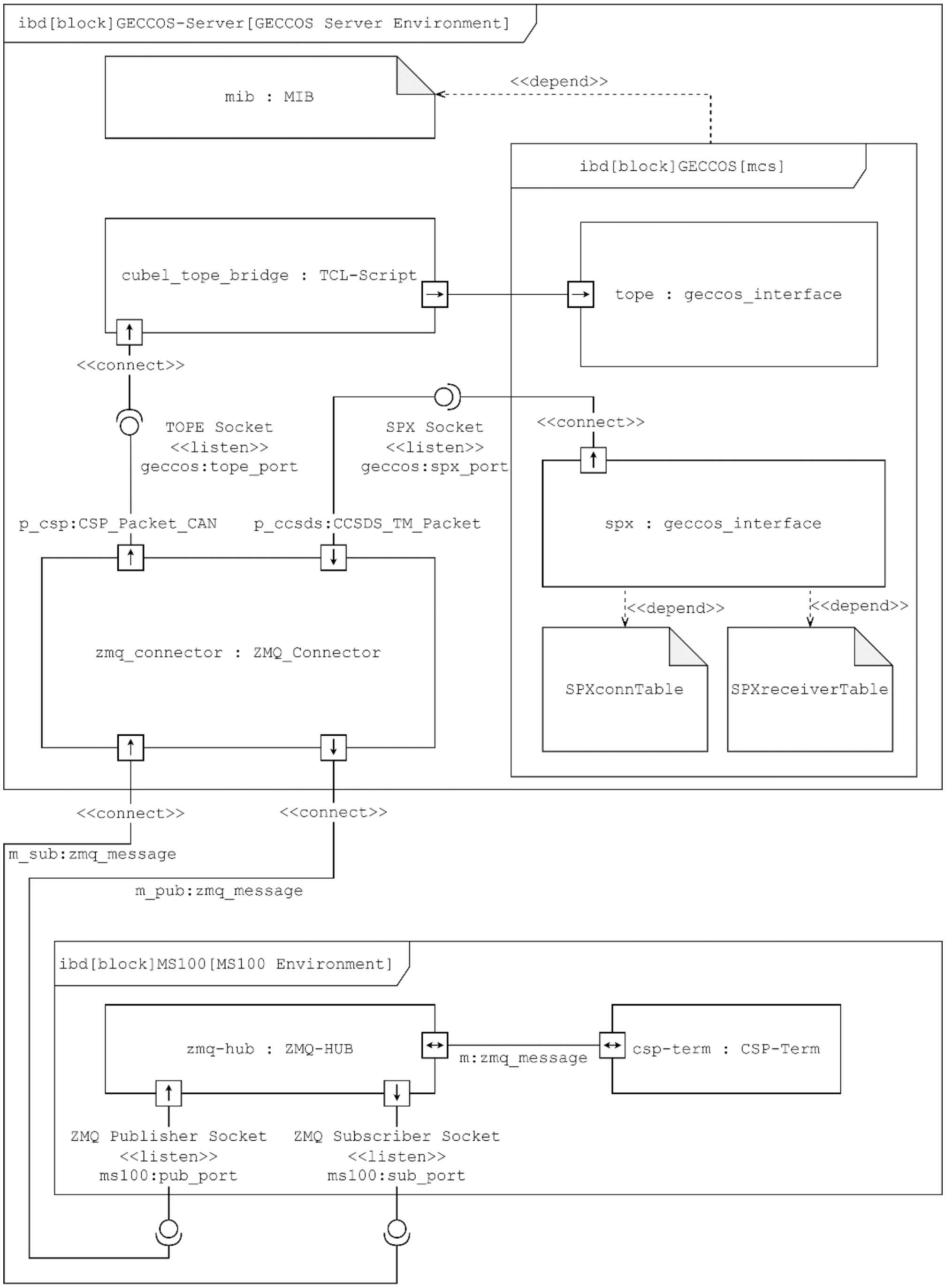


Fig. 9. Design of the ZMQ-Connector

node[2]. On the side of the GSOC MOS, the ZMQ-Connector connects to two interfaces provided by GECCOS – the *TOPE* interface, which GECCOS uses for sending TCs, and the *SPX* interface, which GECCOS uses for exporting incoming TM packets.

The ZMQ-Connector handles incoming TM by extracting the CSP packet payload from the encapsulating CCSDS/ECSS TM packets received via SPX and forwarding the CSP packets to CSP-Term via the ZMQ-Publisher Socket of the ZMQ Hub. It should be noted that GECCOS requires the size of the Packet Data Field of CCSDS TM packets to be exactly 1103 bytes[3] (see Fig. 8). Depending on the configured buffer size, the CSP packet size may not entirely fill the Source Data Field of the encapsulating TM packet, whereas the S-Band transceiver firmware on-board the S/C is only capable of encapsulating a single CSP packet in a CCSDS TM packet. For this reason, the S-Band transceiver firmware on-board the S/C needed to be patched to completely fill encapsulating TM packets with zero-padding when the length of the transported CSP packet is smaller than 1087 bytes. This means that the full payload capacity of the encapsulating TM packets will not always be utilized.

The ZMQ-Connector handles TC by listening for any messages received from CSP-Term via the ZMQ-Subscriber Socket and forwarding them to the TOPE-Bridge. CSP packets are sent between S/C and G/S in the CSP CAN packet format (see Fig. 7), whereas the components in the CubeL ground segment (see Fig. 2) send data in the form of ZMQ messages. For this reason, the ZMQ-Connector has to convert between CSP packets in CAN format and the corresponding ZMQ messages. This can be achieved by restructuring the information contained in the CSP packet header and the packet length field. Using the TOPE interface, the TOPE-Bridge instructs GECCOS to insert the CSP packet received from the ZMQ-Connector as a variable length parameter into an encapsulating CCSDS/ECSS TC defined in the MIB. This TC is then sent over the S-Band link of the GSOC MOS.

It should be noted that SCOS-2000 based systems like GECCOS typically track the execution stages of a TC in several stages – TC release by GECCOS (R), G/S acceptance (G), G/S transmission (T), on-board reception (O), on-board acceptance (A), start of on-board execution (S) and completion of on-board execution (C).The first three stages R, G and T are based on the NCTRS and SLE protocols and can therefore be tracked in the GSOC MOS for CubeL. However, the stages O, A, S and C, which are based on the frame layer (COP-1 [6]) and on the packet layer (PUS services [7]), are not implemented in CubeL.

3.3 On-Going Operational Activities

In February 2022, a test campaign was initiated at GSOC, supported by WHM G/S. The objectives of the campaign were to establish TT&C operations of the S/C using the S-Band link of the GSOC MOS and to perform a system validation test of the space and ground segment. As described in Section 3.2.3, the TM communications were based on TM structures defined in the MIB. For TC communications, only simple ping commands defined in the MIB were sent to the S/C in the first phase of the test campaign while the ZMQ-Connector (see Section 3.2.3) was developed in parallel. Once a first prototype of the ZMQ-Connector was implemented, the tests were continued using the integrated CubeL operational segment with GSOC MOS. This made it possible to send more complex commands to the S/C via CSP-Term and fully test the involved systems. Table 5 highlights several milestones from the test campaign that have been achieved so far. The campaign is still on-going and the integration between the CubeL operational segment and the GSOC MOS continues to be developed based on the results from the tests. Several problems were encountered that posed challenges to accomplishing the milestones. Together with the manufacturer, the reasons for these problems were identified and solutions or workarounds were proposed, which are described in Sections 3.3.1 and 3.3.2.

3.3.1 Establishing TM communications

The initial tests to establish a TM link over S-Band failed due to difficulties in achieving frame lock on the TM link and problems with the format of the incoming TM packets. The first steps to identify the origin of the problems in achieving frame lock were to compare in detail the on-board and ground configurations. Parameters like frequencies, modulation type, sample rates and coding settings were verified and discrepancies were eliminated.

Following this, the first milestone was achieved in test 19 with the successful reception of real-time TM in GECCOS. There was also a second issue due to a bug in the on-board S-band transceiver firmware. This had the effect that every well-formatted encapsulating CCSDS/ECCSS packet (see Fig. 8) received from the S/C was followed by a high-frequency burst of encapsulating packets with empty Packet Data Fields. These empty packets were incorrectly interpreted by GECCOS, causing a high system load and heavily delayed packet processing on the GECCOS server. Our analysis indicated that there was no buffering of TM data anywhere between the G/S antenna and GECCOS, thus

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[2] Of course, the appropriate responses to any requests from the CSP-Term need to be implemented in the ZMQ-Connector

[3] 6 bytes + 10 bytes + 1087 bytes = 1103 bytes

hinting at a problem generated by the S/C. Indeed, a patch of the S-Bank modem link firmware by the manufacturer solved this issue. As a temporary workaround, processing the incorrectly formatted packets was disabled in GECCOS.

Table 5. Milestones in the GSOC test campaign

Date	**Test No.**	**Milestone**	**Comment**
26.04.2022	19	Stable RT TM in GECCOS	GECCOS Bitlock Flag toggled multiple times during pass. TM Packets appeared to be arriving in bursts
05.05.2022	21	Pings sent from GECCOS received on-board the S/C	Only the second stack of pings were received by S/C, after WHM operator set the Cortex to “idle” during the pass. Commanding was not reproducible
30.05.2022	24	Pings again partially received on-board the S/C	Second stack of pings was received on-board. It is surmised that a reset on-board the spacecraft must have occurred during the pass
18.08.2022	38	Stable TM is received in GECCOS and is logged by the ZMQ-Connector prototype	Shadow operations of the first ZMQ-Connector prototype
20.10.2022	40	First operational use of ZMQ-Connector. Ping responses received from S/C in CSP-Term	First test after GomSpace patched S-Band modem firmware
04.11.2022	44	Stable ping responses received from S/C from time of maximum elevation until LOS	Reason why there are ping responses only for second half pass may be an issue with the Doppler Shift of the signal
22.11.2022	50	Successful test of more complex commands *eps hk, ftp server and ftp ls*	The command *eps hk* displays the current subsystem status of the S/C in the CSP-Term. The command *ftp ls* returns a listing of the on-board flash drive
24.11.2022	51	Partial dump of offline TM file via *ftp download*	Due to the downlink speed, the file download terminated at ca. 85 % at LOS.
14.12.2022	56	Stable ping responses from S/C over entire pass	Doppler shift compensated by applying a -10 kHz offset to the on-board receiving center frequency

3.3.2 Establishing TC Communications

Early tests to establish TC communications with the S/C revealed that there was a different understanding regarding the concept of bit lock. During test 19, it was observed that the bit lock flag in the GECCOS IMSTK, which reflects the TM *No Bit Lock Flag*, toggled multiple times during the pass. This partially prevented the transmission of TC. The No Bit Lock Flag is defined in CCSDS 232.0-B-4 [8] (CLCW bit 17) as an optional performance quality indicator. When used, “0” means the on-board receiver locks on the uplink bit stream, and “1” indicates no lock from this receiver on the uplink signal. Even if CCSDS marks this parameter as optional, most of the missions, particularly *Old Space*[4] missions, keep making use of this parameter in the way defined by CCSDS. Consequently, the GECCOS uses this indicator for its pre-transmission checks. Failing to provide a bit lock (No Bit Lock Flag = 0) leads to GECCOS blocking the transmission of TC to the S/C.

A toggling No Bit Lock Flag normally indicates that the uplink signal has difficulties to reach the S/C. The issue typically lies with the G/S, more specifically with the antenna and to the uplink signal configuration. However, analysis showed that the G/S configuration was nominal. Further investigation then showed that the root issue for the toggling was in the on-board usage of the No Bit Lock Flag. As a matter of fact, the usage of the No Bit Lock Flag described above does not necessarily apply to a New Space mission like CubeL. It appears that the S/C manufacturer uses this parameter for a purpose close to its objective defined by CCSDS, but not in the way that is expected by the G/S. This led to confusion and difficulty to identify the root of the problem. As a workaround for this issue, the dynamic pre-transmission checks of GECCOS, which contain the bit lock check, have been deactivated. This prevents GECCOS from using the event “No Bit Lock Flag”=”0” as condition sine qua non for transmitting TC. In fact, this is also the common procedure for blind acquisitions when the S/C downlink signal is not active at the time of transmitting TC (e.g. during an unplanned support).

The first major milestone in establishing TC communications was accomplished during test 21, in which pings sent with GECCOS were received and processed on-board the S/C. Unfortunately, this was not reproducible behaviour. After several repetitions of the test with unchanged configurations of the GSOC MOS and WHM G/S, it was determined that a timeout was occurring in the on-board S-Band transceiver. Analysis by the manufacturer revealed as the cause for this issue that received CSP packets were not being properly forwarded by the transceiver firmware. A patch of the S-Band transceiver firmware by the S/C manufacturer solved the issue. Another possible reason for the transceiver timeout issue was the idle configuration used by the G/S. The nominal configuration at WHM for U/L uses PLOP-2 as defined in CCSDS 231.0-B-4 [9]. This means that the physical communication channel is not deactivated after each CLTU sent over the TC link (in opposition to PLOP-1). Instead, an idle sequence is sent between each CLTU. This idle sequence is basically a high transition density bit pattern consisting of alternating “0” and “1” [9]. However, instead of an idle sequence, the S-band transceiver on-board CubeL expects idle packets as defined in CCSDS 133.0-B-2 [10]. Idle packets are fully valid space packets containing some idle data predefined by the mission. This is to maintain an active communication link between the G/S and the S/C. Should this link deactivate, e.g. if there are no valid packets arriving to the S/C for a certain amount of time (say 30 seconds), the transceiver assumes that there might be an issue and reboots after the specified timeout as a precaution. According to the satellite manufacturer, this could be a reason for the failure of the S/C to respond to pings. Usually the space packets (including the idle packets) are generated by the MCS, i.e. GECCOS. However, since the G/S Cortex demodulator is responsible for inserting the idle sequence between the CLTUs, it was decided to try a reconfiguration of the Cortex in order to insert idle packets instead of the idle sequence. To do so, the Cortex CCSDS idle sequence was replaced by a hexadecimal sequence containing a single CCSDS idle packet surrounded by CCSDS idle sequence, as shown in Fig. 10. This extended idle packet is then inserted and, if necessary, repeated for as long as there are no TC arriving from GECCOS at the Cortex.

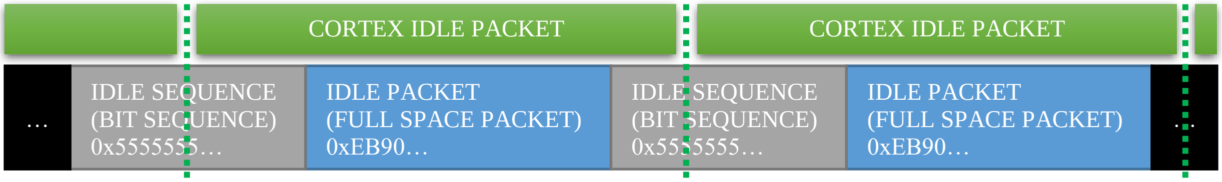

Fig. 10. Idle packet generation on Cortex demodulator

A further milestone was achieved in test 40 with the first operational use of the integrated ground segments. Using CSP-Term, a number of ping commands were successfully sent to the S/C via the ZMQ-Connector and the S-Band link of the GSOC MOS. After this success, the focus shifted to improving stable commanding over the entire duration of the passes, with the final goal of testing more complex commands using the integrated ground segments.

Starting at test 44, a recurring behaviour was observed where commands were only acknowledged by the S/C in the second half of the pass, starting at maximum elevation until LOS. It was determined that the reason for this could be an issue with the acquisition of the RF signal on board the S/C, potentially due to a frequency shift. Typical CubeSat

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[4] We understand *Old Space* as a term for describing the hierarchical, risk-averse organization that characterizes legacy missions. This stands in contrast to *New Space*, characterized by an agile and low-cost approach to space missions, which is more open to risk [11]

operations foresee that the G/S compensates automatically over each pass the Doppler effect in the uplink. This practice is uncommon for Old Space LEO missions where it is expected that the on-board transceiver is capable to cover more than the maximum Doppler shift during a pass. However, since the nominal acquisition bandwidth of CubeL should exceed the maximum expected Doppler shifts of ± 65 kHz (see Table 4) by a sufficient margin and the tracking functionality of both S67 and S69 is successfully verified several times a day in passes of other missions, the next probable cause was a shift in the actual on-board receiving center frequency. Indeed, tests with a shifted uplink frequency led to better results. The best results are obtained with a -10kHz offset from the uplink frequency specified in Table 4. This reproducibly allows ping responses from the S/C over the entire pass.

The GSOC test campaign is still ongoing at the time of writing this paper. Current efforts are focused on testing more complex commands and downloading dump files from the S/C using the integrated ground segments, with some promising results. Some of the current issues are related to downloading dump files from the S/C and are being debugged in cooperation with the satellite manufacturer.

4. Lessons Learned

Several lessons were learned in the CubeL mission so far. A lengthy test campaign has been ongoing almost a year, in order to establish TT&C operations with CubeL. Some of the issues that were encountered could have easily been identified prior to launch in an RF Compatibility Test (RFCT), which could not take place due to the ongoing Corona pandemic in 2020[5]. For example, the "idle sequence vs. idle packets" issue could have been identified beforehand. An RFCT would have also provided vital insights regarding the integration of a novel standard (CSP) into the GSOC MUM environment.

Because UHF operations in phase *E2a* were hampered due to the ITU resolutions from 2019 [1], the use of the GSOC MOS S-Band link, which was initially planned to be evaluated in phase *E2b*, became the primary mode of operating the S/C. As was described in Section 3.2.3, the solutions for S-Band operations were in part designed and implemented while the mission was already flying. This could have been avoided if a MIB containing the TM/TC structures for CCSDS/ECSS based operations would have been available prior to launch, and shows how important the availability of a mission data model such as the MIB is for a space mission. Nevertheless, it was possible to adapt to the changed circumstances by implementing a solution and solving occurring problems in an agile collaboration with the manufacturer. In the spirit of New Space [11], this shows that agile principles can be successfully applied in a space mission. As a result of the problems with UHF in phase *E2a*, activities like S/C housekeeping, flight plan uploads and on-board software patches had to be taken over by the satellite manufacturer, in close coordination with the GSOC team. This led to a situation where a number of distributed teams were working on the same system. Continuous and direct communication between the system experts from the different teams is very important in order to maintain an overview of the system. As such, it is vital to have a responsive manufacturer to accompany the operations team along the path of problem solving. Maintenance of a global system change log accessible to all involved personnel can also be beneficial.

In summary, the lessons learned from the CubeL mission are of value for any future CubeSat missions that may be operated at GSOC.

5. Conclusion

This paper described the integration of the CubeL mission into the GSOC MUM environment. After a description of the involved systems and the differences between the operational segments, approaches were discussed how the two previously incompatible architectures could be integrated. It was shown how the solution was implemented under a bilateral effort of the GSOC operations team and the satellite manufacturer GomSpace. After unforeseen issues with UHF, it was necessary to adapt to changed circumstances in which S-Band became the primary operations mode.

As such, CubeL is a good case study of the challenges of integrating a "non-standard" CubeSat mission into a CCSDS-based mission operations environment, such as the GSOC MUM environment. We hope that the lessons learned may be of use for any future CubeSat missions that face similar challenges.

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[5] Other issues, like the shift of the on-board uplink frequency might have started in space and would not have been detected during the RFCT.

Acronyms/Abbreviations

Application Programming Interface (API)
Command Link Transmission Unit (CLTU)
Communications Link Control Word (CLCW)
CubeSat Space Protocol (CSP)
German Space Operations Center (GSOC)
In-Orbit-Testing (IOT)
Integrated Manual Stack (IMSTK)
International Telecommunication Union (ITU)
Launch and Early Orbit Phase (LEOP)
Loss of Signal (LOS)
Low Earth Orbit (LEO)
Mission Information Base (MIB)
Mission Operation Segment (MOS)
Monitoring and Control System (MCS)
Multi-mission (MUM)
Network Control and Telemetry Routing System (NCTRS)
Physical Layer Operations Procedure (PLOP)
Radio Frequency (RF)
Realtime (R/T)
RF Compatibility Test (RFCT)
Space Link Extension (SLE)
Spacecraft (S/C)
Telemetry, Tracking & Command (TT&C)
Ultra High Frequency (UHF)
Weilheim Ground Station (WHM)
ZeroMQ (ZMQ)

Appendix A List of Figures

Appendix B List of Tables

References

[1] World Radiocommunication Conference 2019 (WRC-19) - Final Acts, Sharm El-Sheikh: ITU, 2019.

[2] "eoPortal - Satellite Missions Catalogue," European Space Agency, February 2021. [Online]. Available: https://www.eoportal.org/satellite-missions/pixl-1. [Accessed 16 January 2023].

[3] P. Hintjens, Code Connected Volume 1 - Learning ZeroMQ, iMatrix Corporation, 2013.

[4] C. Stangl, B. Lotko, M. P. Geyer, M. Oswald and A. Braun, "GECCOS - the new Monitoring and Control System DLR-GSOC for Space Operations, based on SCOS-2000," in *SpaceOps 2014 Conference*, Pasadena, California, 2014.

[5] "Cubsat Space Protocol Project," CSP Community, [Online]. Available: https://github.com/libcsp/libcsp. [Accessed 17 January 2023].

[6] Consultative Committee for Space Data Systems, Communications Operation Procedure 1 - Recommended Standard CCSDS 232.1-B-2, Washington: CCSDS Secretariat, 2010.

[7] European Cooperation for Space Standardization, Space Engineering - Telemetry and Telecommand Packet Utilization, Noordwijk: ESA Requirements and Standards Division, 2016.

[8] Consultative Committee for Space Data Systems, TC Space Data Link Protocol - Recommended Standard CCSDS 232.0-B-4, Washington: CCSDS Secretariat, 2021.

[9] Consultative Committee for Space Data Systems, TC Synchronization and Channel Coding - Recommended Standard CCSDS 231.0-B-4, Washington: CCSDS Secretariat, 2021.

[10] Consultative Committee for Space Data Systems, Space Packet Protocol - Recommended Standard CCSDS 133.0-B-2, Washington: CCSDS Secretariat, 2020.

[11] B. Eilertsen, "NewSpace - Forcing a Rethink of Ground Networks," in *SpaceOps 2016*, Daejeon, 2016.