# A Holistic Control Center for the Operation of PUS-Based Optical Communication CubeSat Technology Demonstration Missions at the German Aerospace Center

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## CONFERENCE PAPER

CubeSats have evolved from simple technology demonstrators to important assets for space utilization to fulfill a myriad of complex goals. In contrast to small launch expenses, CubeSat operation costs are often higher due to their limited space-to-ground communication capabilities.

The recent emergence of European Committee Space Standards - Packet Utilization Standard (ECSS PUS) compliant CubeSat platforms allows the use of traditional ground segment infrastructure rather than adding dedicated mission control software for each new CubeSat. Apart from the idea of saving operations costs, these systems are, however, often overloaded with features, many of which are not applicable to CubeSat operations.

Modern nanosatellite missions tend to carry numerous increasingly complex scientific and commercial payloads to be operated by various research and commercial entities that wish to operate them from their own premises.

However, today's mission control systems require much effort to deploy network infrastructure and adapt operational software to the needs of such missions. Serious drawbacks during operations preparation, planning, and AIT (Assembly, Integration, and Testing in the context of operations) and operation execution, such as delocalized operations in-situ, limited interoperability- and multi-user/client capabilities, to name just a few, take ample time to meet the desired requirements of the stakeholders and customers of such missions.

CubeSats, relying on optical space-to-ground communication systems, are particularly susceptible to cloudy weather conditions. This susceptibility brings up the need for a flexible and resilient mission control system to change the optical teleport quickly.

Yet, current operation systems also do not have enough automation capabilities to operate single optical communication CubeSats or CubeSat fleets cost-efficiently with only few personnel. As a result, the operational costs tend to be at least as high as those of conventional satellites, which is out of proportion compared to their low launch costs. In those regards, a more flexible system is needed, which would be better suited for proper mission operations of optical communication CubeSats.

In the following, we propose a system architecture to allow reconfiguration of established operational technologies and infrastructures to better fit into the active context of state-of-the-art optical communication CubeSat mission design, planning, and operational execution. The proposed architecture outfits the design of a Holistic CubeSat Control

Centre (HC3), developed as a scalable service-based ground segment for the preparation and execution of CubeSat operations using established operation services and ground segment infrastructure from the German Space Operations Center (GSOC) but utilized in a delocalized fashion that enables multiple missions to be operated by multiple operating entities. Also, multiple entities can simultaneously cooperate on the same mission in that same delocalized frame, using newly developed software and existing software solutions running on virtual machines inside a virtual network in a cloud. This operational concept is most likely to become the new operation standard at GSOC shortly.

The proposed Holistic CubeSat Control Centre will be applied in a simplified setup onto a German CubeSat Technology Demonstration Mission, intended to be launched in Spring 2024. Three different operations centers will operate this CubeSat: The German Space Operations Center (GSOC); the FH Aachen Space Operations Facility (FHASOF); German Orbital Systems (GOS) on behalf of the Responsive Space Cluster Competence Center (RSC³), and the Institute of Communication and Navigation (DLR-KN) as the principal investigator. All operation entities will operate within the HC3 frame from their respective locations. This use case will be used as a risk mitigation and validation tool of the proposed system for the operation of the CubeISL Mission, which is intended to be launched in winter 2025. CubeISL consists of two 6U-CubeSats which will be used to investigate the performance of space-to-ground and inter-satellite laser link of an optical communication terminal subsystem (D.N. Amanor, 2018), developed at the Institute of Communication and Navigation (DLR-KN) in close cooperation with the company TESAT.

## 1. INTRODUCTION

### 1.1 The evolution of CubeSats and their growing significance in space missions.

CubeSats have become a popular and cost-effective tool for private companies, government agencies, and research institutions due to their diversified applications and advancements in miniaturization technologies. (R. Rose, 2012).

As the ambitions of the CubeSats grew, so did the complexity of their missions. With the advent of responsive space (Ince, 2005) and the growing trend toward satellite constellations (C. Manderino, 2018), simultaneous mission control from multiple control centers has become paramount (M. M. Fernandez, 2017). In this dynamic environment, where scientists, platform-, military- and payload operators, need to work in tandem, developing a robust infrastructure enabling decentralized operations is beneficial and essential (N. Rubab, 2015). Today, as CubeSats perform increasingly complex and intertwined missions, the challenges and intricacies of their operation are coming to the fore and require innovative solutions to ensure their efficient and effective operation in space (K. Hughes, 2021).

### 1.2 Problem Statement:

The proliferation of CubeSats in space exploration has presented challenges beyond their original goals. Foremost among these are operational costs, exacerbated by constraints on space-to-Earth communications. As satellite constellations become commonplace, the need for streamlined, simultaneous operations increase for various stakeholders: mission operators, payload users, and scientists.

While space operations have broadly adopted standardized communication protocols such as the Packet Utilization Standard (PUS) (L. Stöcken, 2018), supported by major players such as CNES (Centre National Espace), ESA (European Space Agency), and DLR, specific challenges remain for CubeSats. Many CubeSat mission control systems require extensive infrastructure and software customization, leading to issues such as limited interoperability and limited multi-user capabilities, and increasing operational complexity to meet stakeholder needs.

Further difficulties arise for CubeSats that use optical space-to-ground communications. Their operation is susceptible to weather conditions, limited power, pointing inaccuracy, and limited optical aperture, particularly in cloudy conditions, requiring flexible control systems. However, existing control systems are not yet sophisticated enough to efficiently monitor CubeSats individually or in fleets. This inefficiency often drives operating costs to levels comparable to conventional satellites and undermines the advantage of low-cost launch.

## 2. BACKGROUND AND RELATED WORK

### 2.1 The rise and evolution of CubeSats.

The field of CubeSats has progressed from basic communication systems to advanced optical communication terminals. Due to the need for faster data rates and secure communication, the CubeSat community has adopted optical communication, ushering in a new age of inter-satellite and space-to-ground connectivity.

The CubeSat concept, synonymous with small satellite innovation, originated in the late 1990s. At that time, professors Bob Twiggs of Stanford University and Jordi Puig-Suari of California Polytechnic State University thought of finding a new way to access space (Twiggs R. H., 2000). Their vision was to create a standardized satellite platform that was both affordable and accessible and could be used primarily for educational purposes (Heidt, 1999). The result was a novel design measuring 10 $cm^3$ and the Poly-Picosatellite Orbital Deployer (P-POD), which ensures uniform distribution in space (Twiggs R. P.-S., 2002)

By 2003, the fundamental theories had been translated into actual space missions. Early CubeSats such as QuakeSat (Long, 2003), CUTE-I (Nakaya, 2003), and AAU CubeSat (L. Alminde, 2003) flew into low Earth orbit. These first forays into space primarily used amateur radio frequencies for communications. The reasons for this decision were many: ease of licensing, the fundamental goals of educational missions, and the unwavering support of the Amateur Radio community. The operations of this era were characterized by their simplicity, often involving a single ground station, rudimentary command and control systems, and modest data rates (Amateur radio satellite, 2016).

In the mid to late 2000s, CubeSats began to shed their simple shells. CubeSat Missions such as FH Aachen COMPASS-1 integrated more complex payloads such as Phoenix GPS receiver from DLR (A. Aydinlioglu, 2005). At the same time, advances in attitude control systems, as demonstrated by satellites such as CanX-2, underscored the increasing complexity of CubeSat missions (E. Kahr, 2011). While academia continued to be the focus of CubeSat development, the commercial sector began to notice. The potential of CubeSats beyond purely educational purposes was recognized (C. Rodriguez, 2016).

The mid-2010s marked a new era for CubeSats. Commercial companies such as Planet Labs (eoPortal, 2014) and Spire Global began using CubeSats for real commercial applications (Global, 2018). Planet Labs, for example, aims to provide consistent and comprehensive Earth observation, while Spire Global focuses on signal detection. This commercial influx has required an evolution in operational paradigms. CubeSat operations have left their academic roots and require distributed ground stations, increased automation, centralized monitoring, and advanced data processing capabilities.

Data needs and growing commercial interests led to a shift from amateur bands to commercial frequencies, particularly the S and X bands. In a landmark event in 2018, the CubeSat platform demonstrated its versatility. The MarCO CubeSats that accompanied NASA's InSight mission to Mars (K. Oudrhiri et al., 2020) and, the LICIACube that monitored the impact of the Double Asteroid Redirection Test (DART) mission on the asteroid Dimorphos (Tana, 2019), demonstrated that CubeSats could also have interplanetary capabilities.

As the 2010s transition into the 2020s, CubeSats have emerged as versatile platforms for various applications. They play a central role in Earth observation, communications, scientific research, and interplanetary missions (R. De, 2022). Their concept of operations has also matured into active de-orbiting capabilities (eoPortal, 2016), and inter-satellite communication links (Weilian Su, 2017), and sophisticated collision avoidance maneuvers (O. Sanny, 2020).

Consistent with the responsive space paradigm, the U.S. Defense Advanced Research Projects Agency (DARPA) has envisioned CubeSats through partnerships with the U.S. Space Force. In this context, the BlackJack Mandrake 1 CubeSat has a supercomputing chip as a payload to rapidly process and analyze real-time imagery on demand (Erwin, 2021). The Space Test Program (STP) is another initiative to provide access to space for experiments from the DOD in a Responsive Space frame (H. Borowski, 2010).

2012 saw the first experimental optical communications missions on CubeSats. FITSAT-1 was the first CubeSat to perform downlink optical communications using high-power light-emitting diodes (LEDs) (T. Tanaka, 2013). A major milestone in laser-based space-to-ground communication was the Optical Communication and Sensor Demonstration mission (OCSD) from Aerospace Corporation. Launched in 2017, the OCSD CubeSats were designed to demonstrate high-speed optical data transmission, achieving higher data rates than conventional RF communication systems (S. Janson, 2016). The development of high data rates would eventually culminate in the Pathfinder Technology Demonstrator PTD-3 CubeSat, which in June 2022 carried TBIRD (TeraByte InfraRed Delivery), an optical communications payload that achieved downlink rates of up to 200 Gb/s (Schieler, 2022). This mission demonstrated the feasibility of optical communications from a CubeSat and illustrated the potential of CubeSats for advanced scientific and commercial missions.

In July 2022, NASA's CLICK-A mission added another feather to the cap of demonstrating optical communications technologies. Led by NASA's Goddard Space Flight Center, the mission focused on free-space optical communications between CubeSats in low-Earth orbit. The significance of this mission lies in the demonstration of optical communications between satellites (space-to-space) and space-to-ground, highlighting the versatility and potential of Laser-Com technology for CubeSat platforms (K. Cahoy, 2019).

Optical communications in CubeSats have expanded the possibilities for more advanced missions like Earth observation using high-resolution sensors, scientific data transfer from space, and secure military communications. As data demands increase, optical communications will become even more crucial for future space missions, leading to greater challenges for mission operations. Optical communication offers benefits such as compactness, superior power efficiency, and a heightened security profile, making eavesdropping almost impossible. However, other challenges exist, while weather vulnerability and the limited power of CubeSats can cause communication difficulties (M. Motzigemba, 2019).

On the German side, an important mission to test and validate a laser-based communications terminal in space with the CubeSats, was the PIXL-1 mission from the German Aerospace Center's (DLR) (C. Schmidt, 2022). PIXL-1 carried the laser communications terminal OSIRIS (Optical High-Speed Infrared Link System). This mission, conducted in collaboration with DLR-KN and TESAT, demonstrated Germany's potential for CubeSat-based laser communications to transmit data from low Earth orbit to the ground.

DLR will soon feature an innovative mission spearheading two CubeSats outfitted with cutting-edge optical communication terminals to establish a space-to-space inter-satellite link using modulated laser. The CubeISL Mission is planned to be launched in 2025 (B. Rödiger, 2021).

Multiple institutions with different objectives must operate the satellite simultaneously. Flight operations teams from various institutions must handle the core operations of the satellite, while payload operators, including scientists, want to control specific experiments and data collection. In addition, payload developers focus on testing and validating their payloads. This diverse operational environment requires advanced protocols, coordination, planning, and management to ensure the CubeISL mission success.

As a result, an extensive, distributed ground station network is critical to ensure consistent space-to-ground communications and operational efficiency while meeting the diverse needs of all entities to operate future Cube-Sats, including CubeISL.

## 2.2 The Packet Utilization Standard (PUS)

PUS is embodied in the European Cooperation for Space Standardization ECSS-E-70-41C (ECSS, 2016) and is inherently service-oriented, modeled by design and implementation. This approach provides a structured method for spacecraft operations by standardizing the interactions between ground systems and onboard software. PUS establishes several service categories, each targeting specific operational domains, such as time management, onboard monitoring, or event reporting.

The service-oriented paradigm of PUS provides a structured approach to spacecraft operations, ensuring consistency in telecommands and telemetry (R. Arias, 2008). This standardization ensures that the structure and meaning of these interactions remain consistent regardless of spacecraft or mission. Each PUS service has predefined parameters that provide essential details for the execution of the service. These can be distinct service types that correspond to tasks such as resetting an onboard system or switching the operating mode of a piece of equipment. Each PUS service has predefined parameters that provide essential details for the execution of the service. It is designed for application in all space missions, supplementing other standards meant for mission-specific operations, communications, or file transfers. PUS users are encouraged to tailor the services by selecting relevant sections for each mission just as required (Masutti, 2017) (TEB, 2016).

Different ground systems can work seamlessly with distinct spacecraft, eliminating the need for a separate interface for each mission. This flexibility ensures scalability, making PUS suitable for missions initially ranging from larger space systems, downscaled to CubeSats, and improving interoperability and robustness by facilitating event-driven operations (L. Stöcken, 2018).

Historically, large satellites with proprietary communications protocols dominated space operations, posing compatibility challenges for ground stations and mission centers. That's where PUS came in. Initially designed for larger spacecraft, PUS has become increasingly relevant to the burgeoning CubeSat space.

The European Space Operations Center (ESOC), the German Space Operations Center(GSOC), and the Centre Spatial de Toulouse (CNES/CST) (C. Laroque, 2018), have adopted early on PUS (M. Pecchioli, 2010) . While CubeSat platform providers with extensive flight heritage still use individual variants of CubeSat Space Protocol (CSP) (Wikipedia, 2023) , integration into these centers would require extensive customization of their implemented systems, extensive training of personnel, and rigorous testing to ensure seamless integration of these protocols while maintaining the integrity and operability of existing missions (L. Grillmayer, 2020). Given the PUS heritage and widespread acceptance, this protocol would dramatically simplify the integration of CubeSats into these and similar multi-mission environments.

Already in early 2010, CNES has been driving the development of PUS-compatible CubeSats through Project Janus and outfitted highly successful CubeSat missions such as Angels (S. Salas, 2018), EyeSat (F. Apper, 2019), and Kinéis (Wikipedia, 2023). ESA has also supported developing PUS-compatible small satellites around the same time, first with Proba One (S. Ilsen, 2016) and later with the OPS-SAT mission (D. Evans, 2014). The system-wide implementation of the PUS protocol at GSOC required software interpreters to translate CSP to PUS for the PIXL-1 CubeSat operation, with moderate success. With the CubeSat market predicted to decline by 2025 (New Space Ecomomy, 2023), it is doubtful that major space centers would benefit from implementing proprietary CubeSat protocols like CSP. This led to the inference that the CubeISL space mission will likely be PUS compatible.

In conclusion, PUS reduces overhead, minimizes system modifications and personnel training. Moreover, it enhances interoperability - a critical advantage in the increasingly collaborative space arena. While the CubeSat Space Protocol has its niche, the overarching benefits of PUS indicate a promising path forward. As space missions become more integrated, protocols like PUS, simplifying operations and improving compatibility will likely become standard at established European agencies for future CubeSat missions. Consequently, several new space start-ups already offer PUS-compatible multi-purpose CubeSat platforms (A.J. Lago, 2019) .

## 3. CHALLENGES IN CURRENT CUBESAT OPERATIONS

Operating CubeSats presents numerous challenges due to the inherent limitations of the platform. Limited space for solar panels and batteries requires careful power management to ensure effective operation throughout the mission. This limitation affects the amount of power available for the satellite's systems and instruments. CubeSats are limited in their capabilities and mission possibilities due to their small size and weight. They have a limited amount of space for instruments and equipment on board. Additionally, thermal management is a challenge for CubeSats due to their lack of space for insulation and potential exposure to extreme temperature changes in orbit, which can affect their lifespan.

Furthermore, onboard computers on CubeSats have limited processing power compared to larger satellites. This means CubeSats may require assistance in performing complex data processing tasks onboard and may need to transmit raw data back to Earth for processing. Selecting onboard computers and allowing service-oriented intervention in the software system is essential.

Especially in the case of CubeSats that rely on optical space-to-space and space-to-ground communications, as in the case of CubeISL, accurate attitude control can also be challenging due to the small size of the reaction wheels, the reduce aperture size for space trackers and limited power supply, making accurate pointing a problematic endeavor and prolonging operations.

In addition, the small size of CubeSats allows limited or no redundancy of critical subsystems. Typically, attitude control and the electric power system (EPS) are the first subsystems to fail. As a result, CubeSats typically have shorter mission lifespans than larger satellites, making it even more critical to achieve the primary objectives of the space mission as quickly as possible and requiring more straightforward, more flexible mission operations concepts (CONOPS) to ensure mission success.

Traditional CubeSat missions often rely on predefined schedules, fixed ground stations, and dedicated mission control systems, limiting operational flexibility. This limitation becomes particularly critical when unforeseen circumstances, such as adverse weather conditions affecting optical communications, make switching to another optical ground station necessary. In addition, traditional systems may not facilitate real-time data sharing and collaboration among the various operational entities involved, making it difficult to make quick decisions and adjustments during the mission. Moreover, traditional systems may need to provide the level of access control required for multi-party missions, leading to security risks and unauthorized access to mission-critical systems.

Managing CubeSat missions in a multi-entity operating framework can be particularly challenging, as it can be difficult to efficiently allocate resources and manage access control for different operating entities. Finally, traditional systems may require dedicated software for remote mission operations, which can be a limitation even for experienced flight operators who typically work with mission control systems on which they were trained on

## 4. THE CUBE-ISL MISSION

The CubeISL mission is an initiative of DLR to develop a German contribution to a high-rate and secure ISL laser communication terminal for CubeSats. It aims to demonstrate the potential of optical communication technology as a viable and efficient alternative to traditional radio data transmission. The CubeISL Laser Communication Terminal (LCT) is at the heart of the mission. The development of the terminal is based on the OSIRIS4CubeSat (O4C) payload, which has been demonstrated on the previously flown PIXL-1 3U CubeSat mission.

The CubeISL mission consists of a fleet of two CubeSat. Each CubeSat is equipped with an LTC. The mission will be carried out using two identical 6-unit CubeSats placed in low Earth orbit.

The mission's primary objective is to validate the CubeISL payloads and to demonstrate the functionality of the optical ISL and its interoperability with other optical ground stations (OGS).

The ISL establishment process involves a search algorithm developed by DLR to locate the partner terminal's laser on the other satellite. Enabling the optical ISL for communication is a crucial part of the mission. Additionally, the mission will gather measurement results and mission data performed during the experiments with the LTC, that can serve as valuable knowledge for the CubeISL mission and future initiatives in optical communication technology.

The high-rate experiment data will be downlinked using several OGS. The two CubeSat will also carry S-Band RF transceivers for the platform operation and should carry UHF transmitters for transmitting housekeeping telemetry data into the SatNOGS ground station network.

The mission aims to achieve these objectives within one year from launch. Since the two CubeSats rely on optical space-to-space and space-to-ground communications, accurate attitude control will be a central focus of the platform operation as there is a direct correlation between the pointing ability and mission duration.

Also, the laser-based space-to-ground communication of the two CubeSats are particularly vulnerable to bad weather conditions. Here, the performance level of the proposed virtual mission operation concept to rapidly switch between OGS has a critical impact on the time it takes to complete the downlink of the mission data.

The mission objectives and the short operations period present challenges, requiring concurrent operations of multiple entities: the LCT developers, scientists, and the platform operators on CubeISL. With the proposed system architecture, we aim to operate the CubeISL mission in a decentralized fashion, enabling the different operation entities to fulfill their duty on the mission.

## 5. THE FHASOF GROUND SEGMENT AND ITS GROUND STATIONS

The FH Aachen can reflect on an extensive ground segment tradition. Since 2008, CubeSats have been actively operated and tracked here. Finally, in August 2018, the ground station eventually became the FH Aachen Space Operations Facility (FHASOF), is a multi-mission ground segment for educational purposes. It has been founded in august 2018 as a permanent facility at the department of Aerospace Engineering of the University of Applied Sciences of Aachen. The goal was to set up a ground station where students could operate and shadow-track small amateur radio satellites for educational purposes. The first CubeSat that has been operated at FHASOF was the Compass-1. Since then, the FHASOF has been actively engaged in first-level support of non-commercial, amateur radio and university satellite missions, mostly CubeSats, and served several times as a secondary amateur radio satellite ground station.

Over time, the FHASOF cooperated with several universities, agencies, and international partners. Among these cooperations were the DLR with the Phoenix GPS receiver, the Dragsail for actively deorbiting CubeSats, a simultaneous operations campaign with ESOC/SMILE to operate a small planetary rover demonstrator via the OPS-SAT satellite, and payload downlink operations of the DSLWP-B amateur radio transmitter onboard the Long Jiang II Lunar orbiter (T. J. Dijkema, 2019). Recently we performed an official space-to-ground ARISS-call (Amateur Radio International Space Station) with astronaut Mattias Maurer and children which asked him questions (N. E. Schreyer, 2022).

For the operation of these amateur radio satellites, the FHASOF ground segment has a multitude of different antennas. Among them, a VHF and UHF right-hand-circular-polarized Cross-Yagi antenna arrays (RHCP-Yagi-array), one quadrifilar VHF, and one downlink S-Band antenna. A second S-Band Dish antenna will be added by mid-2024.

The ground segment has two ground stations, outfitting several dedicated analog amateur radio transceivers for VHF, UHF, and L-Band. Since 2018, radio up- and downlinking have mainly been performed using software-designed-radio (SDR) such as the HackRF, ADALM-Pluto, and Ettus N210 (A. Csete, 2020). These SRDs are operated using GNU Radio companion, which enables the usage and development of CCSDS-compliant radio gears and modems, facilitating participation in cutting-edge CubeSats missions (M. A. Boettcher, 2016) (D. Estevez, 2023).

The FHASOF will perform first-level routine operations during several campaigns of the CubeISL mission. DLR has chosen this ground station as a test pilot of the holistic control center implementation and the proposed virtual ground segment system architecture.

## 6. PROPOSED SYSTEM ARCHITECTURE

To be able to execute routine operations of the CubeISL CubeSats within the Ground segment of the FH Aachen Space Operations Facility, we are implementing the operation of our ground station and the mission control system through a service-based infrastructure. This service-based software infrastructure will enable the flight operators to execute operations outside the open hours of the University and enable the GSOC flight operators to give support in critical situations.

Before this mission is to be supported, we will utilize another DLR CubeSat Mission, OTTER, to validate our approach. OTTEROTTER is equipped with an amateur radio-compatible UHF transceiver that can be addressed by typical amateur radio satellite mission control software. OTTER is a CubeSat mission that aims to provide maritime situational awareness using an onboard AIS transponder (Automatic Identification System). Since it is intended to be operated in a short campaign of one week to validate the proposed system architecture, we decided ahead of time to implement this amateur radio compatible software. This has already allowed us to perform a feasibility analysis by performing APRS (Amateur Packet Radio System) contacts over the International Space Station (ISS) amateur radio repeater as an end-to-end test set in anticipation of the start of the OTTER mission. APRS stands for Automatic Packet Reporting System. It is a digital communication system that uses packet radio protocol AX.25 to exchange information between amateur radio stations.

At DLR-GSOC, the development of the Holistic Control Center (HCC) has been initiated a few years ago (A. Hauke, 2018). At the basis of the system architecture, we use the Data transport layer of HCC (HCC-DT) (Hauke, 2023), which is a highly secured data-bus, allowing the transportation of data over the local area network or the internet between HCC-Nodes.

HCC-DT will be used to separate the physical ground segment infrastructure of the FH Aachen (Radio equipment, Antenna systems, Modems) from the mission operations consoles and front ends. These front ends are consolidated on virtual machines, so called virtual cockpits that are running behind a virtual router and forwarder of a commercial

Infrastructure as a Service (IaaS) provider. The connection between the cockpits and the physical ground station servers is done using an additional virtual machine where an HCC-DT-Node is running. This node performs the wide area network (WAN) connection to the HCC-DT-Node which is running at the physical ground segment of the FHASOF.

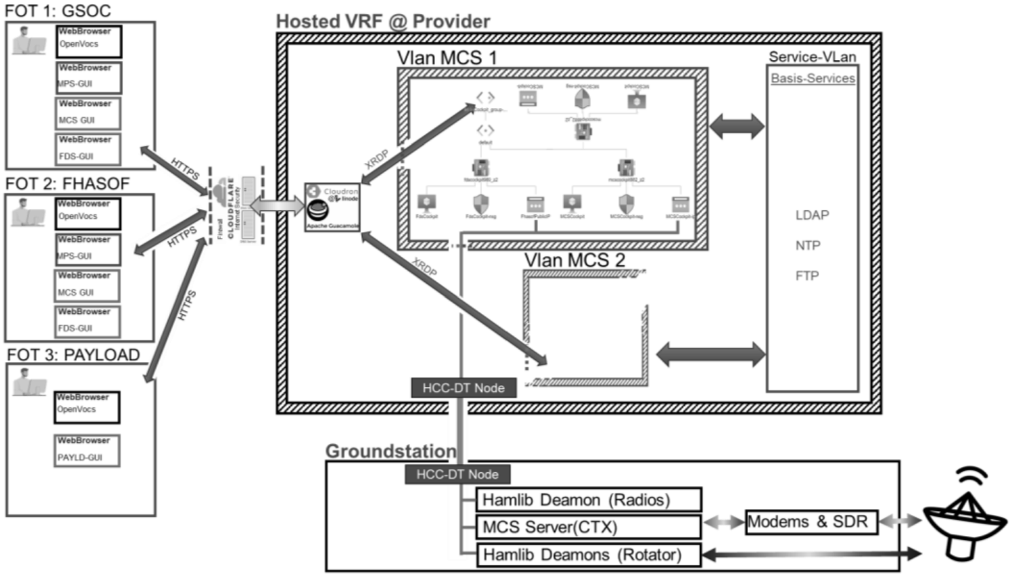

FIG. 1 The proposed system architecture of the Holistic CubeSat Control Center

To allow access to the virtual cockpits, an Ubuntu Linux virtual machine has been implemented, that outfits a Guacamole server. Apache Guacamole is a clientless remote desktop gateway. This platform enables remote access using common protocols such as VNC, RDP and SSH. It is clientless, which means there is no need to install additional software on the client machine or the virtual cockpits.

The virtual cockpits can be accessed from any computer using a web browser. In-fact, Guacamole-server can be regarded as the Lobby of the virtual holistic control center, see Fig 2. The decision to use Guacamole was the fact that there is no need to invest in the development of expensive dedicated clients and facilitating the maintenance of the cockpits to a minimum. Also with its several remote access protocols, guacamole provides a robust platform agnostic way of operation.

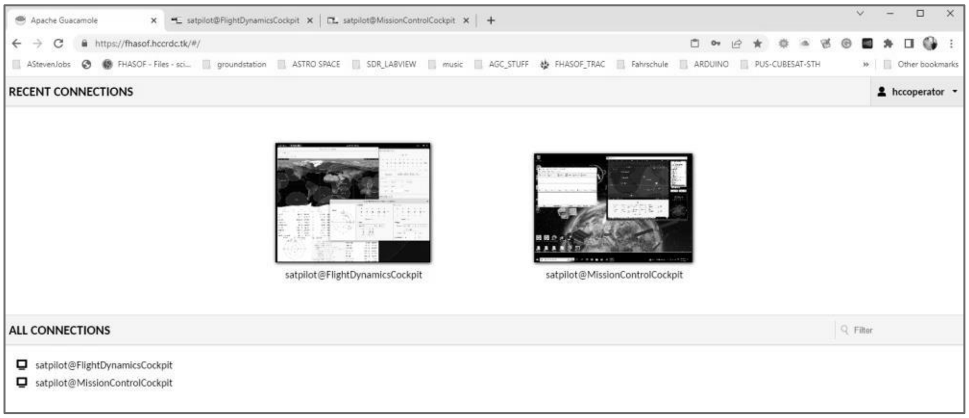

FIG. 2 The digital lobby of a mission's virtual operations facility. From here, the flight operator gains access to the mission's virtual cockpits of the mission. In the lobby, he only sees the cockpits and VMs to which he has access rights.

While the HCC-DT-Nodes handle the connection between the virtualized mission control center and the physical ground segment over the WAN, data, like Telecommand (TC), Telemetry (TM) and ground station control commands need first to be fed-in into the HCC-DT-Nodes before they can be transported. As most of these devices cannot be modified so easily, a piece of software needs to translate this data into a suitable format for HCC-DT. For this purpose, we developed the HCC-Bridge.

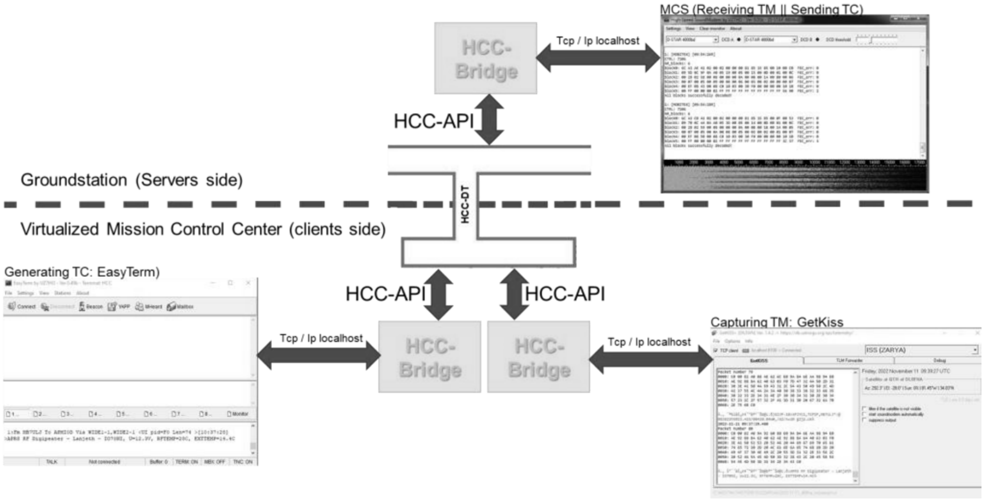

FIG. 3 The HCC-Bridge helps connecting subscribes to the HCC-DT-Network

It acts as a TCP/IP bridge between software, services, devices, and the HCC-DT-Nodes, facilitating the transfer of data between these applications and the HCC-DT system. This setup ensures the seamless integration and communication of each subscriber with the HCC-DT-Nodes, each subscriber being located at the different cockpit virtual machines. Currently two different types of virtual cockpits are implemented in individual virtual machines as follows:

### A) Virtual Ground Station Operation Cockpit (vC-GS)

The first virtual cockpit, called “vC-GS”, is for ground station operations and includes several front-end interfaces for radio control, modem configuration, and satellite tracking via Gpredict, an open-source application (About Gpredict, 2020).

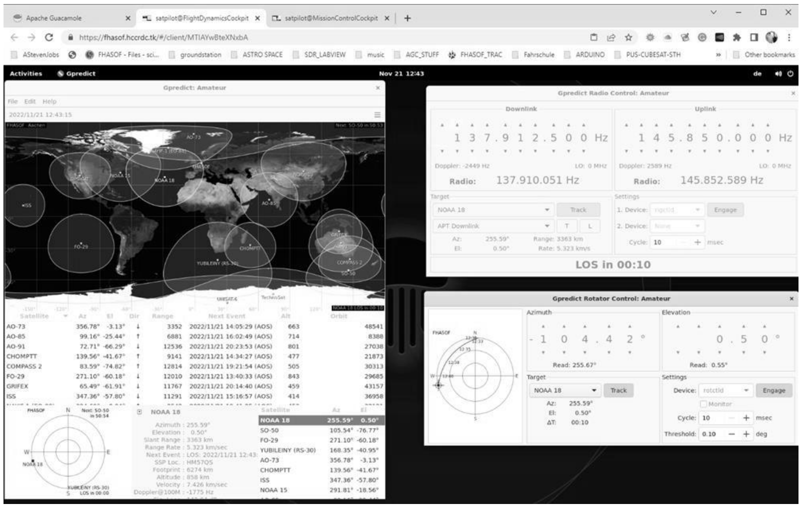

FIG. 4 vC-GS: The virtual ground station cockpit

The connection between the satellite tracker, the robotic rotators, and the radio transceivers is facilitated by two instances of HCC-Bridges. The first HCC-Bridge instance translates the pointing coordinates from Gpredict and enters them into the HCC-DT node. The data is then transmitted over a WAN to the HCC-DT Node of the physical ground segment. Upon receipt, the secondary HCC-Bridge instance at the physical ground segment forwards the data to the appropriate ground station device drivers, which may include the Rotctld Hamlib daemon for antenna pointing devices and the Rigctld Hamlib daemon for Doppler shift corrected uplink and downlink frequencies. Hamlib is a software library that provides a standardized interface for controlling robotic rotators, radio transceivers, and receivers, thereby streamlining the development of amateur radio applications and promoting interoperability between different software applications and various radio hardware (Bargmann, 2021).

### B) Satellite Operations Cockpits (vC-MCS)

The second cockpit, called “vC-MCS”, is dedicated to implementing mission control software front ends, which could be for example the GECCOS, ProToS or a SATMON front end (M. Hobsch, 2022), NASA's OpenMCT (NASA), or similar. To perform the end-to-end test of our cloud-based mission control setup, we used EasyTerm to generate APRS messages to uplink the APRS repeater of the ISS. EasyTerm, developed by UZ7HO, is a terminal program designed to communicate with Terminal Node Controllers (TNCs) such as soundmodem, via TCP/IP using the KISS (Keep It Simple and Stupid) protocol, a standard protocol in amateur radio. Soundmodem by UZ7HO is a software based TNC that enables the transmission and reception of digital signals (such as packet radio) over radio frequencies commonly used in amateur radio applications. To archive the received APRS messages from the ISS amateur radio APRS repeater and the telemetry from amateur radio CubeSats, we used the ONLINEKISS application, a compact software utility for storing KISS frames into a file.

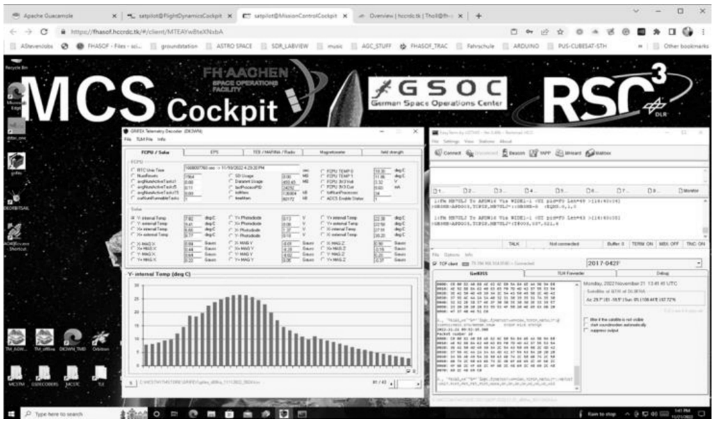

FIG. 5 vC-MCS: The virtual mission control cockpit

These files can later be read using GETKISS, a generic file-based KISS frames reader, or the corresponding file-based satellite telemetry interpreter application. Two instances of HCC-Bridges facilitate the connection between EasyTerm, ONLINEKISS, and the TNC. The first HCC-Bridge instance enters the KISS frames of EasyTerm into the HCC-DT-Node, from which the data is transmitted over a WAN to the HCC-DT-Node of the physical ground segment. Upon receipt at the ground segment, the secondary HCC-Bridge instance retrieves the KISS frames from the node and forwards them to the corresponding TNC. A similar process is used for the telemetry backchannels: the KISS frames containing telemetry are inserted from the TNC into the HCC-DT-Node of the physical ground segment and then transported over the WAN to the HCC-DT-Node of the virtualized Mission Control Center. At the satellite operations cockpit, another HCC-Bridge instance retrieves the KISS frames from the node and forwards them to the ONLINEKISS telemetry storage application.

## 6.1 Connection to a worldwide available ground station network

The CubeISL mission is not designed for 24/7 multi-mission operation. This places special requirements on the CubeSat platform, such as the ability to self-diagnose (FDIR; Fault Detection and Isolation) and, if necessary, automatically switch to a safe mode until the first or second-level flight operations crew is available. In addition, the platform should be able to autonomously broadcast periodic auto-beacons with reduced housekeeping information over the UHF amateur radio band.

The system architecture proposed in this article is intended to interface with the SatNOGS ground segment. SatNOGS (Satellite Networked Open Ground Stations) is a global decentralized network of ground stations based on open-source principles. It consists of a global community of participants that make their own ground stations available to the SatNOGS network and exchange telemetry data received from the satellites through a common telemetry database called the SatNOGS DB (J. Nicolas, 2021). Telemetry data received by CubeISL worldwide can thus be retrieved from this database 24 hours a day. The prerequisite is that the CubeISL satellites transmit amateur radio compatible and open transmission protocols approved for amateur radio in the UHF band (IARU, 2023).

SatNOGS uses GNU-Radio as a generic receive modem for decoding satellite data. The integration of GNU-Radio ensures that various satellite radio signals, including signals from the two CubeISL satellites, can be accurately acquired and decoded. This eliminates the costly acquisition of a Cortex modem but does not preclude its use if required.

Over the course of the mission, the SatNOGS telemetry database will have accumulated an extensive and global collection of telemetry data on the CubeISL mission. This wealth of information can be critical to understanding the behavior of both satellites under different conditions and provide invaluable insights for optimizing day-to-day mission planning.

For the proposed system architecture, this means increased reliability and flexibility in mission operations. The integration of GNU Radio and the SatNOGS network not only extends the operational capabilities of the proposed system architecture, but also embeds it in a global collaborative ecosystem, setting a new paradigm for the operation of German CubeSat missions at DLR.

### 6.2 Quick adaptation and reconfiguration for CubeSat that rely on optical communications.

Current meteorological conditions, especially cloud cover, can change for the worse very quickly and at short notice. We currently have access to three OGS. In case of bad weather conditions, we could switch to an OGS where the current weather conditions would allow an optical space-to-ground link. The first OGS is located in Munich, the second near Hamburg, and the third in Almeria, Spain.. The ability to quickly switch to an alternate ground station in a clear sky region is necessary to maintain a reliable communications link. The centralized access of the proposed system architecture facilitates the reconfiguration of the satellite operating parameters. The Apache Guacamole server allows reconfiguration of user permissions and user groups, essential for tasks requiring collaboration between multiple mission operations entities and tight access control. The HCC-DT nodes and HCC bridges provide a secure data transmission infrastructure that can be expanded or modified as operational conditions change. Within the mission's VLAN, the system promotes collaboration and real-time data exchange between the various mission operations entities, which may be in different geographic locations. The flexibility of the virtual cockpits and service-based infrastructure also allows for easy updating and reconfiguration of operational technologies as mission requirements change.

## 7. OPERATIONAL CONCEPT

### 7.1 System overview

The proposed system architecture consists of a minimum of three components per CubeSat mission which are living behind a virtual local area network appliance: The virtual machine of the HCC-DT-Node, the ground station- and the satellite operations cockpit. These components interact through a service-based infrastructure, HCC-DT nodes, and HCC-bridges, enabling data transfer between the virtualized mission control center and the corresponding physical ground stations. The Apache Guacamole Server provides centralized, clientless, controlled access to the virtual cockpits.

### 7.2 Multiple missions and operation entities

The system is designed to support multiple missions and operation entities simultaneously. Virtualized cockpits are implemented, with each operation entity having its own virtual machine via a service-based infrastructure. This virtual cockpit runs behind a virtual local area network within the virtual router and forwarder provided by the commercial IaaS provider. These virtual cockpits house the front ends of the mission control software and other necessary applications that may be specific to each mission and operating entity.

### 7.3 Data transfer and communications

The HCC-bridge instances facilitate data transfer between the mission control system front ends, endpoint devices, and HCC-DT-Nodes. The HCC-DT-Nodes of the virtualized mission control center can be connected to available physical ground stations, by the mission's designated ground data network administrator in charge, providing seamless communication and operation of the entire system of the mission.

### 7.4 Real-time collaboration

Multiple entities can work simultaneously on the same mission by sharing data and resources in real-time using data transfer over the virtual local area network within the mission. The flexible remote access protocols enable work on a single cockpit per operation entity or collaboration between multiple entities on a single cockpit, depending on the nature of the operations session. Collaboration between operation entities can occur in real time, even when separated at different geographical locations, which is especially useful for flight controller training sessions, LEOP or contingency operations. To be able to communicate also verbally between operation entities, we will use the OPENVOCS voice communication system, developed at DLR (M. E. Reichardt, 2019).

### 7.5 Centralized Access

The Apache Guacamole server provides centralized, clientless access to all virtual cockpits through a standard Web browser. With Guacamole, administrators can assign specific connections or groups to different users to control and authorize access. Centralized access is especially beneficial in a multi-mission virtual control center where additional system administrators must manage many servers and virtual machines.

### 7.6 Security considerations

The HCC-DT is a highly secure data bus that ensures that data transmitted between the virtualized mission control center and the various physical ground segments is secure and protected from unauthorized access. Additional security measures can be implemented using an external web infrastructure provider to enhance the secure internet connection between the controller's local digital operational environment and the distant virtualized control center if required.

### 7.7 Flexibility design

The system is designed to be flexible in its deployment. In the case of the FHASOF flight operations team, student flight operators could establish APRS contacts with the ISS outside the open hours of the university since it was not mandatory to be in the control room inside the university building. In addition, GSOC flight operators could assist student flight operators in emergency CubeSat situations.

The System’s flexibility is also beneficial for the CubeISL Mission, in that during bad weather conditions, the connection between different HCC-DT-Nodes would allow for quick switching from one optical ground station to another available one, where the current weather conditions would be more favorable to the space-to-ground link to be optically performed.

## 8. VIRTUAL CONTROL CENTER TEST CAMPAIGN

To fundamentally evaluate the operational concept with the virtualized mission control system and its architecture presented here, a test campaign was conducted with the ISS APRS repeater using the Virtual Control Center in anticipation of CubeISL. It was previously (January 2023) deployed at an IaaS service provider.

Since it was still interesting to test how operations would look outside the usual control rooms with only a few laptops and a mission control cockpit used from a web browser, it was decided to conduct a continuous test campaign with the ISS APRS repeater before the end of the test phase. Without an HCC-DT, the connection between the virtual control center and the physical ground station was established via remote SSH port forwarding.

For over two decades, the International Space Station (ISS) is orbiting the Earth and serves as a laboratory for various experiments. Among these experiments, is ARISS (Amateur Radio on the International Space Station), which allows communications between the ISS and amateur radio on the VHF Band. APRS is a digital communications system that uses the AX.25 packet radio protocol to exchange information between amateur radio stations.

This study selected the International Space Station (ISS) as the test object The ground segment is an approved Amateur Radio station with licensed radio amateurs, allowing a quick start of the test implementation process without additional authorizations. First, however, the network robustness of the proposed system architecture was quantitatively evaluated.

### 8.1 Preparation of the Virtual Control Center and the Ground Station

The test campaign took place during the cost-neutral test phase of the IaaS provider. During this time, the system architecture and functionality were tested. A dedicated VLAN was set up so that this test could be considered a stand-alone mission. Two VMs were set up for operations, one for the ground station and one for the satellite operations. The cockpits were set up using an amateur radio satellite toolkit as described in Section 6 under vC-GS and vC-MCS.

Next, the physical ground station was prepared. First, a WebSDR station from Goonhilly (UK) was opened in the web browser. WebSDR is an online platform that allows you to receive radio sources from an SDR receiver via a web browser. WebSDR cannot transmit radio signals, but it does allow "CAT control". CAT Control (Computer Aided Transceiver Control) allows you to control and configure radios from a computer. It is an interface that allows you to switch transmission modes and change frequencies, for example, to correct the Doppler shift of the incoming signal from the ISS. For this purpose, the author developed an application to translate the Rigctld control commands for WebSDR (S. Tholl, Hamlib2WebSDR).

Following, the soundmodem was started. The virtual audio driver Virtual Cable (vbCable) was used to send the demodulated radio signals received by WebSDR to the sound modem as audio signals. Virtual Cable is a free virtual audio driver that routes audio signals between different applications on a computer. It behaves like a physical audio cable but emulates audio transmission without real hardware connections. Here it was used to connect the digital audio output of the WebSDR to the digital audio input of the soundmodem and to enable decoding of AFSK signals.

A Linux VM was then started using the Hamlib daemon Rotctld. Rotctld was configured to interact with a dummy antenna rotor, since WebSDR does not provide antenna rotor control. This was done to test the possibility of remote controlling the antenna rotor using the Virtual Control Center.

Since the final release of HCC-DT was not available at the time, the network connection between the Virtual Control Center and the physical ground station was implemented using remote SSH port forwarding. This method generally allows a local port on a computer to be redirected to a port on a remote server using SSH as a tunnel, allowing secure access to services on the remote server as if they were available locally. Using SSH port forwarding, secure tunnel connections were established, allowing EasyTerm and ONLINEKISS to communicate over the WAN with the soundmodem on the physical computer at the FHASOF ground station. Gpredict was also connected to Hamlib over the WAN.

To analyze the packet transmission quality from the physical ground station to the virtual control station, the APRS packets decoded by the soundmodem were stored both at the ground station and in the virtual control station.

## 8.2 Performance of the ISS pass over Goonhilly WebSDR Station

The test was conducted using a pass of high elevation over the Goonhilly (UK) ground station with an expected maximum elevation of 82°. It was waited for the ISS to send AFSK signals over Goonhilly. The first packets arrived at 4° elevation. WebSDR demodulated the received AFSK audio signals and fed them into the soundmodem. The soundmodem decoded the APRS packets as text messages. These were fed into the appropriate remote SSH port forwarding tunnel and forwarded to the vC-MCS cockpit. The last packet was received at 7° elevation.

Remote control of the dummy antenna rotor and WebSDR worked as expected during the pass of the ISS with no noticeable delay. The WebSDR receiver always received the correct Doppler shift from the virtual control center during the pass. As a result, all AFSK radio signals clearly visible in the spectrogram could be demodulated without clipping and decoded correctly by the soundmodem.

## 8.3 Evaluation of the performance of the virtual control center during the pass of the ISS-Repeater

A post-flight analysis confirmed that all packets transmitted from the physical ground station were created in their entirety and without any alterations on the ground station computer and in the vC-MCS Cockpit archive. Unfortunately, the Amateur Radio Mission Control applications do not allow further analysis. It also turned out that the system clock of the computers in the cloud had a slight time offset compared to the system clock of the ground station computers. Finding this difference would not have been an obstacle, but the applications used do not record packet arrivals with millisecond accuracy. However, this time resolution is needed to characterize the network during the experiment.

During the post-flight review, the student flight operator, who had previously performed many ISS Automatic Packet Reporting System (APRS) passes using conventional operating methods, stated that there was no perceived difference between performing the pass using the virtual control center and performing it directly at the ground station. Despite the additional steps required to set up the software with the new component (preparing the SSH port forwarding connections minutes before the pass), there was no noticeable difference in operation. Even when the software components exchanged data indirectly, they behaved as if they were communicating directly. This was considered positive. It was also considered very positive the fact that the pass could be performed from home.

In-fact, he found it interesting that his counterpart, the student flight operator in charge of antenna control, was monitoring the dummy antenna rotor from home through the vC-GS and communicating with him through the audio flight loop, and he could imagine that using the virtual control center would allow much more complicated operations to be performed very easily.

## 9. CONCLUSION

CubeSats have become an integral part of modern spaceflight. Their low-cost function as technology demonstrators has made them indispensable. In addition, they have established themselves as a valuable tool in commercial spaceflight.

Traditional CubeSat mission operations designs can reduce mission efficiency, increase operational complexity, and pose potential safety hazards. There are several obstacles related to achieving operational flexibility, real-time collaboration, access control, managing high data rates, handling multiple CubeSat missions, and remote operations. Ultimately, the goal is to drastically reduce mission duration to achieve all intended mission objectives before the satellite decays and keeping mission operations costs as low as possible.

The problem statement of the article underlines the need for a standardized infrastructure that makes the operation of CubeSats more efficient. Especially considering the increasing popularity and diversity of CubeSat missions, the need for such an infrastructure is growing. This need is exacerbated by the increasing number of CubeSat missions and their varying requirements. This has led to the question of how best to integrate CubeSats into existing control centers.

The motivation and goal of this work was to demonstrate a solution for a more efficient and integrative operation of CubeSats, in particular using standards and protocols. The main goal is to increase CubeSat missions' efficiency and reduce operational costs. It became clear that standardized protocols such as PUS are critical to better integrate CubeSat mission operations with the existing European control center infrastructure and to simplify operations.

This article has highlighted the challenges of CubeSat operations. These include technical, organizational, and operational hurdles. Overcoming these challenges is critical to the successful deployment of CubeSats, even because the increasing complexity of the tasks to be performed may shorten the practical lifetime of CubeSats because there is virtually no redundancy where it is most needed.

For this reason, this paper proposes a solution where mission lifetime could be significantly reduced by a control center that allows simultaneous operation of the involved mission operations entities, especially when they need to cooperate far away from each other.

In this context, a novel system architecture emphasizes modularity and adaptability to meet the diverse requirements of CubeSat missions. A key element is the HCC-DT, a data bus that separates the virtual control center from the physical ground station, thus allowing essential data exchange decentralization and task distribution between the two environments. This is complemented by the HCC Bridge, which acts as a critical communication bridge between the user interfaces and the HCC-DT to ensure seamless software and hardware integration between the virtual control center and the elements of the physical ground operations facilities.

Then there are the cockpits, integrated user interfaces that provide individualized and intuitive control of the mission. Another critical step in the architecture is the integration of SatNOGS, a network of ground stations. This integration ensures that the CubeSats have extended and reliable communications coverage, especially when the satellite must be left alone for several days.

A qualitative test was conducted to verify the functionality and efficiency of the virtual control center. The system was particularly successful in passing the ISS APRS repeater.

The system architecture was tested with typical Amateur Radio satellite operations software systems. The primary goal was to try the HCC-DT with a virtual control center and a physical ground station during a three-month free subscription with an IaaS provider. Since the original goal could not be achieved, setting up a remote SSH port forwarding solution was a viable alternative. This allowed the underlying concept to be tested, although it did not have the total capacity of the real HCC-DT.

Nevertheless, the system's potential could be assessed through the successful remote performance of the ARPS ISS pass. This suggests that the system architecture proposed in this article to create a holistic virtual control center should undoubtedly be further investigated. The student flight operator in charge noted no difference from using the virtual control center operations with respect to "normal operations" performed at the ground station directly, highlighted as a positive point. The system allows for location-independent operations, which is also a significant advantage.

## 10. OUTLOOK AND FUTURE WORK

The virtual control center ran as part of a free subscription with VMs equipped with shared CPUs, where processor resources are shared with other subscribers. Shared CPUs work well for applications with low CPU utilization or sporadic workloads. While the advantage of this approach is cost efficiency, a major disadvantage is that performance can fluctuate, and maximum CPU power is rarely available, which can be problematic for time-sensitive mission-critical applications. Migrating from a free IaaS offering to a premium one will be an important adjustment.

The first version of the HCC-DT simulator was recently released. It will replace remote SSH port forwarding. The HCC-DT is the result of several years of development at DLR. It has a significantly extended feature set, optimized communication protocols, and high-security standards.

The mission control software archives its data only in the range of seconds, which does not allow a quantitative evaluation of the network during mission operation. To optimize this aspect, the next series of tests must use software that allows time recording in the millisecond range; if necessary, mission operations software must be developed for this purpose.

Soon, the project will investigate how well the presented system scales to larger CubeSat fleets or more complex missions. For the CubeISL mission, the system architecture must be ready in time. The hard work here will be the adaptation of the CubeISL MCS to fit into the virtual mission control center.

The virtual control center and the proposed architecture represent a promising approach to CubeSat operations. The tests conducted demonstrate the efficiency and effectiveness of the system. However, there is still a need for research and development to realize the system's full potential before CubeISL and the OTTER CubeSat are ready for operations.

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