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Advancing Resilient Operations in Responsive Space Missions with Mobile-Based Architectures for the OTTER follow-on Project

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Abstract

The OTTER (Optical Traffic Tracking Experiment for Responsive Space) mission, initiated by the Responsive Space Cluster Competence Center (RSC³), will use a 3U CubeSat and shall undergo the complete satellite planning and development process led by the industry. There, RSC³ analyzes the potential of small satellites regarding their flexibility, cost, and production timeline and finds capability gaps where further research will be required to establish an Initial Operational Capability (IOC) for Responsive Space Capabilities. In its second phase, during the operations of the satellite in space, the mission aims to extend these capabilities into a multi-year mission focused on optical imaging, AIS (Automatic Identification System) for maritime domain awareness, and electric propulsion maneuvers.

For this second phase, which is the focus of this publication, the mission architecture is being significantly adapted to meet evolving requirements of operational objectives potentially relevant to allied responsive space capabilities. For this purpose, a robust and distributed mission control system that supports resilience and flexibility has been developed at DLR RSC³. This system utilizes virtual machines on portable devices, providing a scalable and secure environment that adapts to various scenarios and ensures operational continuity.

Operational enhancements for OTTER will include revising protocols to manage a complex data environment and integrating data fusion algorithms to improve maritime situational awareness. The mission will span two years, allowing for continuous evolution following an initial six-month plan.

OTTER's second phase aims to establish a sustainable and responsive operation model to serve as a blueprint for future responsive space missions. Lessons learned from the OTTER mission will be instrumental in designing an adaptable and resilient system for future missions, contributing significantly to Germany's maritime domain awareness in cooperation with allied partners.

This article will demonstrate the implementation of a resilient mission operations concept relying essentially on mobile devices.

Keywords: Responsive Space Operations, Mobile Device Integration, Resilient Mission Operations, Maritime Domain Awareness, Mission Control Systems Architecture

Acronyms/Abbreviations

ADCS: Attitude Determination & Control System
AIS: Automatic Identification System
BPSK: Binary Phase Shift Keying
CAT: Computer Aided Tuning
CCSDS: Consultative Committee for Space Data Systems
COVID: Definition not found
CSP: CubeSat Space Protocol
DLR: German Aerospace Center
ESA: European Space Agency
FEEP: Field Emission Electric Propulsion
FH: German: Fach-Hochschule i.e. University of Applied Sciences
FHASOF: FH Aachen Space Operations Facility
FSK: Frequency Shift Keying
GMSK: Gaussian Minimum Shift Keying
GOS: German Orbital Systems GmbH
GPS: Global Positioning System
GSE: Ground Support Engine
GSOC: German Space Operations Center
GUI: Graphical User Interface
IOC: Initial Operational Capability
ISS: International Space Station
IT: Information Technology
IUU: Illegal, Unreported, and Unregulated
KISS: Keep It Simple, Stupid
KVM: Kernel-based Virtual Machine
LEOP: Launch and Early Orbit Phase
LXC: Linux Containers
MDA: Maritime Domain Awareness
OPS: Abbreviation for Operations
ORR: Operations Readiness Review
OSI: Open Systems Interconnection, is a conceptual framework of **seven layers** that standardizes the functions of a telecommunication or computing system without regard to its underlying internal structure
OTTER: Optical Traffic Tracking Experiment for Responsive Space
PUS: Packet Utilization Standard
QPSK: Quadrature Phase Shift Keying
RDP: Remote Desktop Protocol
RF: Radio Frequency
RSLV: Reusable Suborbital Launch Vehicle
SDR: Software-Defined Radio
SSH: Secure Shell
SSL: Secure Sockets Layer
SSO: Sun-Synchronous Orbit
SVT: System Validation Test
TC: Telecommand
TCP/IP: Transmission Control Protocol / Internet Protocol
TLE: Two-Line Element
TLS: Transport Layer Security
TM: Telemetry
TMTC: Telemetry and Telecommand
UART: Universal Asynchronous Receiver-Transmitter
UHF: Ultra High Frequency
VE: Virtual Environment
VLAN: Virtual Local Area Network
VNC: Virtual Network Computing
VPN: Virtual Private Network
WOD: Whole Orbit Data
XTCE: XML Telemetric and Command Exchange
YAMCS: Yet Another Mission Control System
ZMQ: ZeroMQ

1. Introduction

Modern space missions are increasingly shaped by the need for flexibility, agility, and operational resilience, especially within the context of small satellite programs. The OTTER (Optical Traffic Tracking Experiment for Responsive Space) CubeSat mission, developed by German Orbital Systems and supported by the Responsive Space Cluster Competence Centre (RSC³) of the German Aerospace Center (DLR), was initially conceived as a short-duration demonstrator in low Earth orbit. However, alterations in mission parameters, including a new launch opportunity with Isar Aerospace's Spectrum 2 and an increase in operational altitude to 500 km in a sun-synchronous orbit, allowed to extend the planned mission duration significantly beyond the initially intended six months.

These updated parameters presented challenges in both mission planning and execution. Given budget and personnel constraints, a conventional ground-segment approach was found to be unfeasible for long-term support. Furthermore, the transition of the mission from commercial to institutional operations, led by RSC³, necessitated a mission control strategy that was more flexible and required less space, allowing for prolonged operations while encouraging academic partnerships and remote accessibility.

Creating a robust, browser-based mission operations platform surfaced as a resolution to these limitations. Initially born out of necessity during the COVID-19 pandemic, when lockdown made the FH Aachen Space Operations Facility (FHASOF) student mission control rooms inaccessible, this architecture has since evolved and been adopted as a core element of the OTTER follow-on mission concept. The approach emphasizes clientless access, open-source tools, and integration with educational partners, aiming to support responsive space operations with minimal resources.

This paper presents the motivation, technical implementation, and operational use of this system to demonstrate how responsive missions, such as OTTER, can be sustainably operated and expanded through a hybrid academic-engineering model.

2. Background and mission context

The OTTER mission was initially conceived as a short-term technology demonstrator to validate key capabilities for responsive space applications on small satellites, particularly in the context of maritime domain awareness (MDA). Owned by the Responsive Space Cluster Competence Centre (RSC³) and developed by main contractor German Orbital Systems (GOS), the 3U CubeSat was designed to integrate and test an AIS receiver and optical payload in combination for identifying and verifying cooperative maritime targets. At first, the mission aimed to collect AIS signals and optical images separately; however, OTTER now enables the integration of spaceborne data onboard, connecting AIS signals with synchronized images using a built-in GPS module. This enhancement significantly improves OTTER's role in maritime situational awareness, allowing for the identification of spoofed signals, hidden targets, and illegal, unreported, and unregulated (IUU) fishing activities.

The original plan was to launch the satellite into a low circular orbit at 240 km on Isar Aerospace's inaugural Spectrum flight, with an anticipated operational lifespan of just six months. During this period, GOS was engaged to handle the launch and early operations (LEOP), commissioning, and deorbiting. However, the mission parameters changed when the launch was moved to Spectrum 2, aiming for a 500 km sun-synchronous orbit (SSO). This alteration in orbit extended the expected mission length to several years and necessitated a thorough reassessment of operational and technical approaches. RSC³ reacted by taking on the responsibility of the long-term operations and setting up its mission control facilities in Trauen, Germany.

Due to evolving ground station service limitations, the OTTER satellite platform's communication infrastructure was also modernized to replace UHF. While UHF was initially planned for all mission phases, it is now reserved for LEOP and early commissioning (e.g., for ADCS sun-pointing), with routine operations switching to S-band to leverage a broader network of high-capacity ground stations. Additionally, the OTTER satellite's system functionality has been expanded with a GPS receiver for precise timestamping, and a Field Emission Electric Propulsion (FEEP) unit was added for orbital adjustments and deorbiting. The external hardware can be seen in Figure 1 below [1].

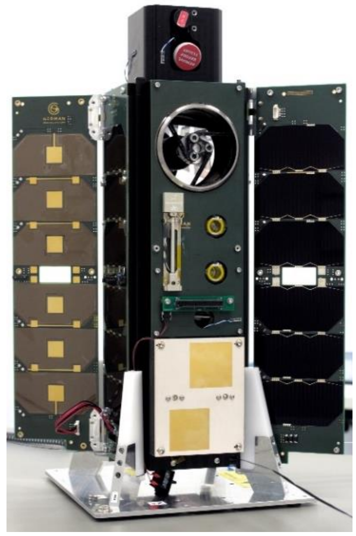

Fig. 1: OTTER 3U CubeSat flight hardware.

Owing to OTTER's non-standard firmware, a custom software layer was also developed to generate compliant telecommand frames. Additionally, the mission's proprietary TMTC database was migrated to the open-source YAMCS format, with a custom tool to export to XTCE, ensuring compatibility with the procedure development tool ProToS [4] and future missions.

This transition brought both opportunities and constraints. On the one hand, it allowed OTTER to serve as a prototype for low-cost, agile satellite operations under the responsive space paradigm. On the other hand, the original budget – planned for a short demonstration – was insufficient for extended activities. To address this, RSC³ adopted an innovative academic-partnered operational model to support mission resilience and align with evolving operational demands.

Flight operations include several educational training campaigns with stakeholder involvement. In the first scenario, after subsystem commissioning, a cooperative maritime target – provided by an external user –is located and verified using AIS and optical data. This involves synchronized pass planning, duty cycle management, satellite scheduling, ground station access, downlinking, and data fusion – activities that require tight coordination among users, the client (DLR), the integrator (GOS), and participating institutions (e.g., FHASOF). This hands-on structure also prepares the RSC³ to train personnel and establish a national responsive space capability (Fig. 2).

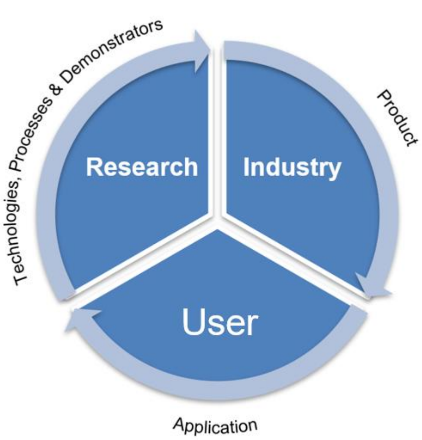

Fig. 2: The envisioned operational environment cycle of the RSC³ to achieve the national Responsive Space Capability

Additional scenarios will include detecting non-cooperative targets with their AIS turned off (illegal fishing activities), localizing targets through coastal lines based on optical image data, and assessing the saturation limits of the AIS antenna in areas with high maritime traffic.

These requirements and shifts in operational scope and system architecture set the stage for an innovative approach to CubeSat mission control, emphasizing modularity, security, remote accessibility, and integration with academic partners.

3. Initial challenges in remote operations

The groundwork for OTTER's remote operations concept was laid during the COVID-19 pandemic when the academic partner FHASOF faced access restrictions due to university lockdown policies. At that time, the FHASOF was engaged in a collaborative experiment with ESA's OPS-SAT mission, focusing on the real-time control of a planetary rover via the OPS-SAT satellite, which acted as a relay service provider. However, strict university lockdown measures prevented access to on-campus control rooms and ground infrastructure. Moreover, the home computing environments of team members were not sufficiently powerful to support traditional mission operations software stacks. Consult Fig. 3:

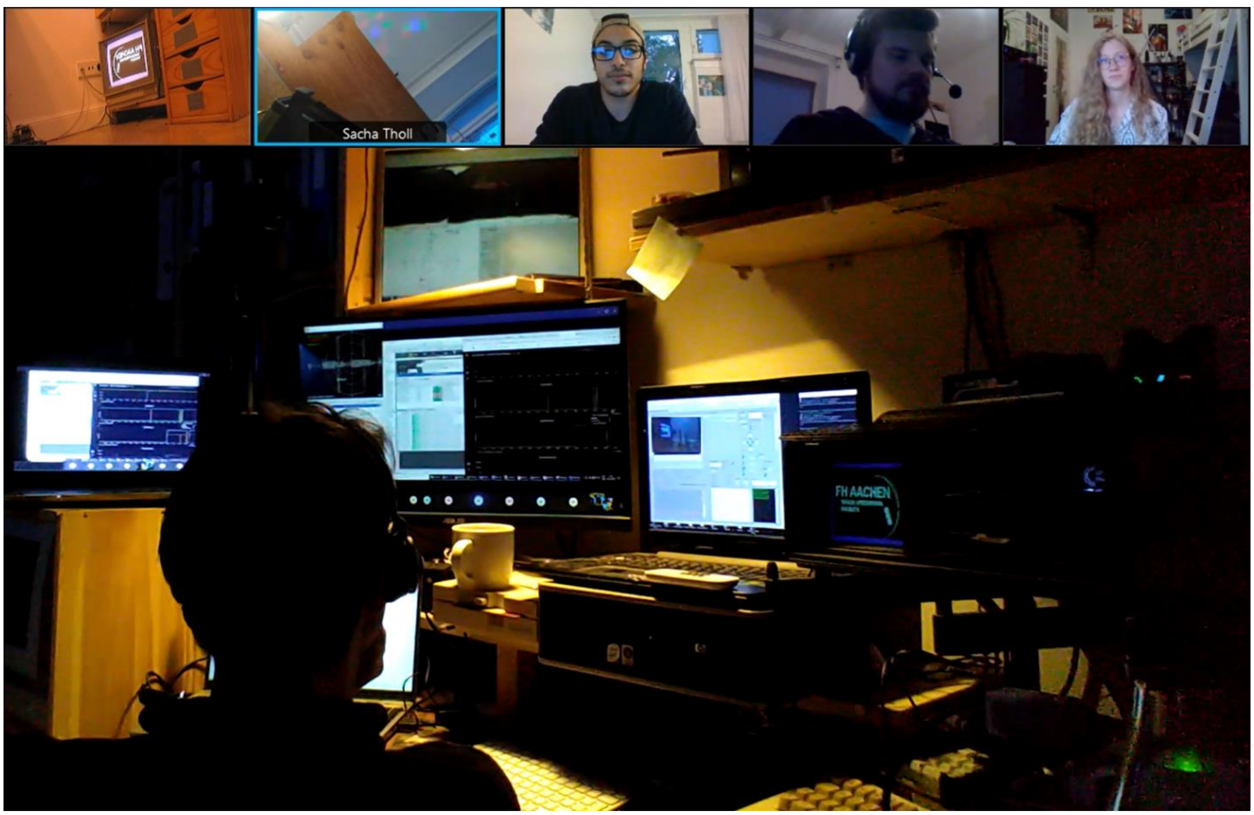

Fig. 3: Planetary Rover operations via OPS-SAT relay service provider experiment 123 during first pandemic lockdown. The mission control server infrastructure and the ground station infrastructure stood at university's control room and the rover operations team performed operations from their home. Running the many mission operations clients on private laptops, connection to the servers were established using reversed SSH-port forwarding connections using Putty Terminals.

This situation necessitated the creation of a lightweight, browser-accessible mission operations environment that could remotely control core mission control and ground station components. The system had to include tools for orbit propagation (SGP4), ground station scheduling, rotor and radio control, and the satellite consoles – packaged to be securely accessed and used across different computer operating systems without requiring local installation or computational overhead.

Initial network solutions relied on reverse SSH port forwarding to access control systems remotely. While functionally effective, this setup posed significant cybersecurity risks and was difficult to justify within university IT policies. As an interim solution, FHASOF transitioned to a VPN-based architecture with two-factor authentication while maintaining SSH tunnels for specific services [3].

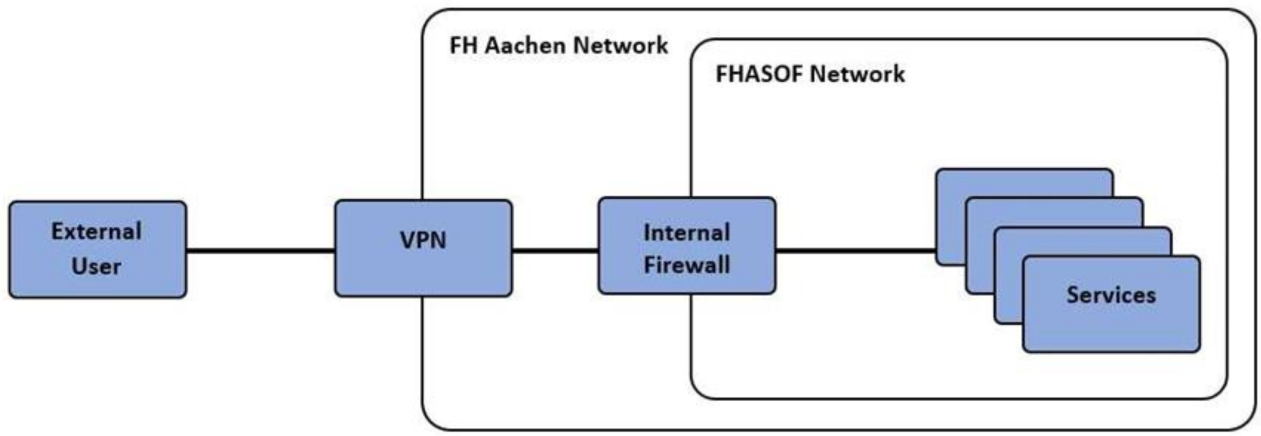

Fig. 4: Modernized Ground Station Setup.

Although this improved security, the architecture remained complex, fragile, and unsuitable for long-term mission operations, as it still relied on several bare-metal components [7].

Despite these challenges, the system completed rover operations experiments with ESA from the students' home offices. This experience laid the foundation for our current work: designing a more scalable and secure virtualized mission control architecture suitable for responsive space missions, such as OTTER, where mobility, remote access, and operational resilience and robustness are critical from the outset.

4. System architecture and implementation

To meet the operational demands of the extended OTTER mission and maintain a high level of flexibility with constrained resources, RSC³, together with FHASOF, implemented a mission control environment based on the V3C architecture – a mobile, cloud-capable, and virtualized system developed by the German Space Operations Center (GSOC) in close collaboration with RSC³ [5]. The architecture is purpose-built for resilient and scalable small satellite operations and has been adapted at FH Aachen's Space Operations Facility (FHASOF) to support responsive missions such as OTTER.

4.1. System architecture of secure remote access

Remote access incorporates a proxy server accessible through DLR's VPN, facilitating remote access to virtual machines outside the RSC³ ground station network. The VPN establishes a secure, encrypted tunnel, ensuring the confidentiality and integrity of data transmitted between the user's endpoint device and the network, safeguarding against interception. Upon establishing a connection to the DLR network via the VPN, a reverse proxy functions as an intermediary, receiving user requests and routing them to the appropriate backend servers or services. Unlike a traditional forward proxy, which operates on behalf of the client to forward requests to external servers, the reverse proxy operates on behalf of the servers, managing incoming requests and directing them to the relevant internal services. This configuration ensures that only authenticated VPN users can access internal services, enhancing security by controlling traffic flow and reducing the direct exposure of backend servers to the internet.

The Transport Layer Security (TLS) protocol is employed to encrypt communication between the user's endpoint and the reverse proxy, ensuring the security and confidentiality of data exchange. Secure Sockets Layer (SSL) certificates authenticate the proxy and user identities, establishing a trusted and secure connection. This authentication process prevents unauthorized access and mitigates the risk of man-in-the-middle attacks, thereby protecting sensitive information exchanged between the client and the network. Furthermore, TLS ensures that all interactions with the reverse proxy remain encrypted, reinforcing the security of the VPN connection and the internal network services accessed through the reverse proxy. The SSL certificates are issued with expiration dates, enabling control throughout user access. However, such certificates can be manually revoked if required, providing an extra layer of security management and control [2].

4.2. Multi-Mission virtualization and cloud architecture

The ground segment architecture of the Responsive Space Cluster Competence Centre (RSC^3) is implemented on Proxmox VE. This open-source virtualization platform integrates KVM (Kernel-based Virtual Machine) and LXC containers into a unified, centrally managed environment accessible through a comprehensive web interface. At its core, KVM is a Linux kernel module that transitions the host operating system into a Type 1 hypervisor, enabling virtual machines to run directly on hardware with minimal overhead and robust isolation between virtualized systems. Proxmox VE supports a wide range of advanced features, including live migration, high availability clustering, snapshotting, automated backup scheduling, and native support for VLAN-based networking, making it ideal for mission-critical and research-intensive applications.

The architecture extensively uses Virtual Local Area Networks (VLANs) to logically isolate network domains at the data link layer (OSI Layer 2), so that traffic between systems that physically share the same hardware is separated. This ensures that their communications are kept strictly separate at the switch level, before Layer 3 (IP routing) even gets involved. This enables concurrent operation of multiple satellite missions within a shared physical infrastructure. Within this framework, each satellite mission is assigned a unique VLAN identifier, and all mission-specific virtual machines (such as YAMCS servers, telemetry processors, and ground station interfaces) are connected to dedicated VLAN-tagged virtual bridges. This configuration ensures strict traffic isolation, effectively mitigating the risk of cross-contamination or data leakage between coexisting mission environments.

In addition to logical segmentation, VLANs enable efficient allocation of shared computing resources and centralized hardware management. Granular Proxmox firewall rules can be enforced at the level of individual virtual machines or entire VLANs to maintain strict security boundaries. Shared services – including user authentication (e.g., via LDAP), remote desktop access (e.g., Apache Guacamole), and centralized telemetry logging – can be hosted in a separate management VLAN and made selectively accessible to mission VLANs through well-defined firewall exceptions. This modular architecture is inherently scalable; new satellite missions can be added quickly by provisioning additional VLANs and virtual machines without reconfiguring the existing operational environment. This underlines true multi-mission capability, allowing multiple satellite operations to be run independently, securely, and concurrently on a single infrastructure.

4.3. Mission control and operations systems architecture

The mission control and operations systems architecture of the OTTER project is designed to support distributed, secure, and scalable satellite operations. It integrates remote access capabilities and a fully modular mission control system to enable flexible operator workflows and multi-mission compatibility. The following sections describe the architecture of the remote mission portal and the integration of the mission control system, which together form the digital backbone of OTTER's ground segment.

4.3.1. Architecture of the remote mission operations portal

To enable secure and flexible remote access to the mission control environment, the OTTER project uses Apache Guacamole. This clientless remote gateway allows operators to access a desktop environment via any modern web browser supporting HTML5 and JavaScript. This architecture combines the benefits of browser-based access (eliminating the need for local software installation) with the ability to get access to corresponding mission control desktops and services. As a result, several satellite missions can coexist and can be operated in parallel, having their operations personnel grouped in categories based on security levels, roles, and levels of responsibility, where each operator can intuitively configure their workspace by combining telemetry displays, documentation, and operational procedures on a single screen – even in mobile setups with limited display space.

Apache Guacamole provides access over standard TCP/IP networks, particularly advantageous for decentralized or mobile operations. It enables engineers and operators to run mission-critical software remotely while maintaining central security and control. By interfacing through Guacamole, the team achieves a hardware-agnostic access layer, making the environment portable and easy to scale across institutions or distributed ground stations.

Additionally, Guacamole integrates cleanly with other tools and protocols (e.g., SSH, VNC, RDP), offering flexibility for diverse visualization needs. Its centralized access control and logging capabilities align well with mission security requirements while providing a seamless operator experience.

4.3.2. Mission control system integration

The mission control system for OTTER is based on YAMCS, an open-source, web-based mission control suite that serves as the operational backbone of the ground segment. It is tightly integrated with ProToS, DLR's next-generation Flight Control Procedure (FCP) environment. It supports distributed procedure development, version control, execution monitoring, and automation—features well-suited to responsive and academic-integrated satellite missions.

Real-time operations are supported through YAMCS Studio, a desktop application that connects to the YAMCS server and provides operators with interactive GUI interfaces. These interfaces allow for tasks such as loading command stacks, monitoring telemetry and telecommand (TMTC) links, and executing ProToS-generated procedures. YAMCS Studio supports dynamic, software-generated displays, including dashboards, graphs, and telemetry validators aligned with specific flight activities. This drastically reduces manual display setup and enables customized operator views based on the mission phase.

Whole Orbit Data (WOD) and long-term telemetry trends are visualized using Grafana dashboards, complementing YAMCS's real-time telemetry handling. Furthermore, YAMCS Studio supports script embedding, including real-time update indicators and context-aware telemetry logic directly in operator displays. This reduces the need to switch interfaces and speeds up decision-making.

Fig. 5: Customized YAMCS Studio Mission Operations System.

The mission control system supports multi-user operations, with each operator accessing the same telemetry stream while customizing their visual environment. Combined with the ProToS workflow and the flexibility of YAMCS

Studio, this architecture ensures OTTER's control system remains modular, scalable, and adaptable to evolving mission needs.

4.4. Ground station system architecture

Real-time operations such as pass prediction and antenna pointing are also embedded in dedicated VMs. Importantly, this architecture supports integration with physical ground station hardware (e.g., TMTC modems, antenna rotors) via USB, RS232, and IP interfaces, making it deployable in fixed and mobile scenarios. Setting up an integrated team, German Orbital Systems, RSC³ and the FHASOF perform operations and contribute to software configuration, system hardening, and feature extension, bridging the gap between mission engineering and applied education in a real-world, responsive space environment.

4.4.1. UHF-Ground system architecture

The UHF ground system architecture for the OTTER mission processes and transmits telecommands through a modular pipeline tailored for responsive space applications. Telecommands originate from the YAMCS mission control system as PUS (Packet Utilization Standard) packets. These are parsed by the GSE Bridge, which extracts key fields such as source, destination, and message ID. The extracted data is encapsulated into OTTER's internal Protoplexer format and then wrapped into a CSP (CubeSat Space Protocol) packet. This CSP packet is transmitted over a ZMQ (ZeroMQ) socket interface to the next system component, enabling low-latency, modular message passing. ZMQ is a high-performance asynchronous messaging library that enables fast and flexible communication between software components using sockets, like a lightweight, embeddable alternative to traditional message brokers.

Before transmission, the data is encapsulated using the KISS (Keep It Simple, Stupid) protocol – a lightweight framing method for serial communication like UART. It is then sent via UART to the UHF software-defined modem, which de-frames the packet and modulates the signal – typically using GMSK (Gaussian Minimum Shift Keying), a bandwidth-efficient modulation that smooths frequency transitions with a Gaussian filter, or FSK (Frequency Shift Keying), which encodes data by shifting the carrier frequency. The modulated RF signal is then transmitted through the UHF-crossed Yagi antenna. This architecture allows efficient handling of telecommands from high-level mission control down to the physical RF layer, leveraging modern networking tools and embedded standards. A visualization of the UHF workflow is shown in Fig. 6.

4.4.2. S-Band ground system architecture

The OTTER mission's S-band ground system architecture for TMTC (Telemetry and Telecommand) is designed around direct support for standardized CCSDS protocols, removing the need for intermediary framing or protocol bridges. YAMCS, the mission control software, outputs telecommands in the form of CCSDS-compliant transfer frames, which are passed directly to the S-band modem, as the S-band system natively handles CCSDS Telecommand (TC) and Telemetry (TM) frames. The modem modulates outgoing TC frames (typically using Binary Phase Shift Keying (BPSK) or Quadrature Phase Shift Keying (QPSK) for uplink transmission. It demodulates incoming TM frames received from the satellite. These signals are transmitted and received via a high-gain, directional S-band dish antenna. The resulting architecture ensures high data-rate communication for payload and system telemetry while complying with international space communication standards. A visual overview is shown in Fig. 6.

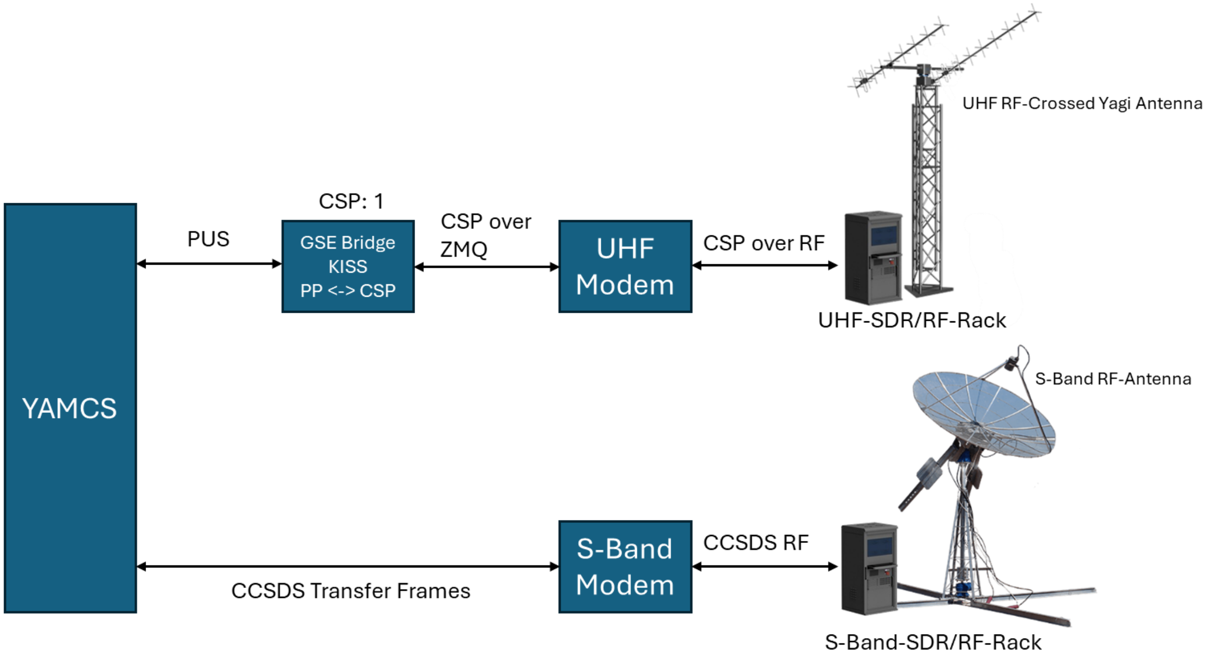

Fig. 6: RF path from mission control system YAMCS to corresponding RF antennas.

4.4.3. Satellite tracking and antenna control architecture

The satellite tracking system developed for the OTTER mission is designed around a custom-built ground station automation suite "LabTrack" tailored for lightweight and mobile ground stations and has been implemented in LabVIEW. LabTrack integrates with the SatNOGS database to automatically retrieve satellite-specific metadata, including operating frequencies, modulation schemes, and other essential communication parameters.

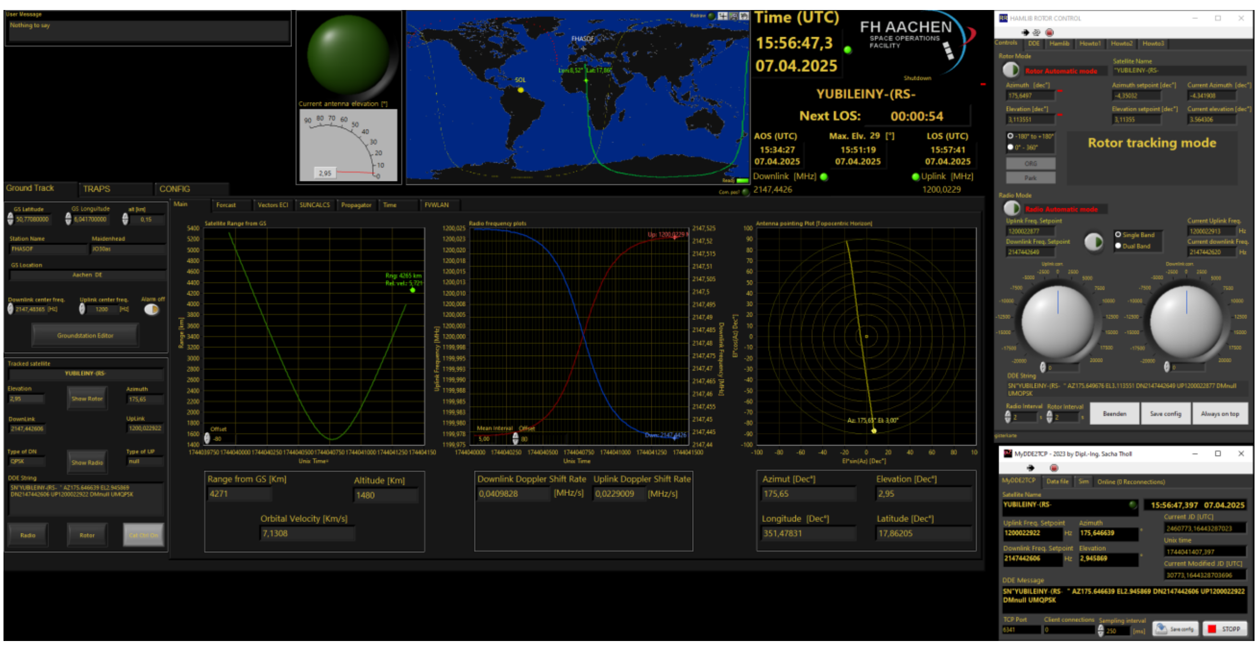

Fig. 7: LabTrack ground station automation and tracking software suite

This metadata-driven architecture allows LabTrack to dynamically select and initialize the appropriate terminal node controller (TNC) or software modem as a plugin, automating the processes of telemetry decoding and telecommand frame encoding. A distinctive feature of LabTrack is its wide area network (WAN) capability, which facilitates simultaneous coordination and control of multiple geographically distributed ground stations.

Using SGP4 orbital propagation model, LabTrack processes standard two-line element (TLE) data to provide real-time satellite position predictions in topocentric local horizon-based coordinate frame at epoch, and AOS/LOS scheduler events. and calculates frequency doppler shift for CAT-control of the transceivers. LabTrack interfaces seamlessly with the Hamlib library, an open-source library that supports a wide range of communication equipment to control radios and robotic antenna positioners. Hamlib provides two key daemons: Rigctld, which handles radio (SDR) control, and Rotctld, which manages the antenna rotor. Both daemons abstract away hardware-specific control commands and expose a TCP/IP interface. This allows the mission control software to be run remotely while radios and antenna systems can be deployed at a distant ground station. This architecture provides high flexibility and vendor independence, a significant advantage considering the OTTER mission uses both UHF and S-band radios from different manufacturers.

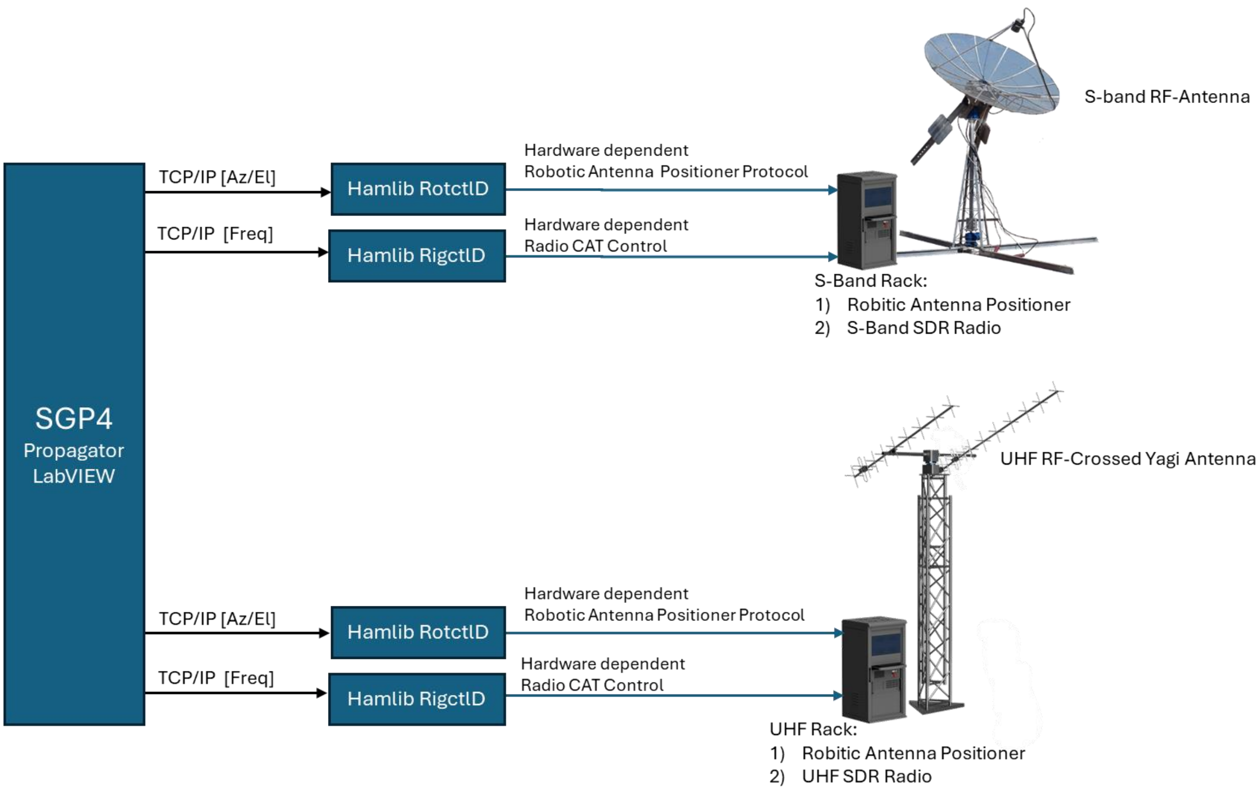

Fig. 8: Control Path for Satellite Tracking and Radio CAT-Control.

Rigctld communicates with the SDR's CAT control interface, while Rotctld connects to the rotor's proprietary driver. This modular and networked setup allowed the OTTER mission to adapt quickly to hardware variations and geographic constraints while maintaining precise satellite tracking and robust communication.

5. Applications and operational use

The OTTER mission has evolved from a short-term commercial demonstrator to a fully-fledged, long-term responsive space platform. Initially designed for a six-month lifetime in a lower orbit, the transition to a 500 km sun-synchronous orbit and an extended mission scope required a comprehensive redefinition of the operational strategy. OTTER now serves as a platform, supporting advanced maritime domain awareness (MDA) experimentation and the implementation of a resilient, decentralized satellite operations framework.

Following the planned LEOP and commissioning phase to be conducted by German Orbital Systems (GOS), operational responsibility – after approximately six months of routine operations – is scheduled to transition to the Responsive Space Cluster Competence Centre (RSC³) in collaboration with the student operations team from Aachen University of Applied Sciences. This handover reflects a reallocation of mission responsibilities: from GOS' initially planned full-lifecycle role – from LEOP through final deorbit – to a shared operational model coordinated by DLR and academic partners.

RSC³ Flight Directors will oversee mission operations, while students will perform routine operations, gaining hands-on experience in spacecraft control and system evolution—a proper integration of mission engineering and applied education.

6. Key outcomes and lessons learned.

The preparation of the OTTER mission has yielded valuable insights into both technical and organizational aspects of responsive space operations. Conceived initially as a short-term experiment with GOS being the essential mission operations provider, the mission's transformation into a long-term, academically supported operational platform has surfaced several essential lessons for the design, preparation, execution, and sustainability of small satellite missions.

6.1.1. Responsive space in practice

A key outcome is the successful demonstration of responsive space principles: rapid adaptation to new mission conditions, modular upgrades to satellite hardware and software, and the integration of new objectives mid-mission. The ability to retrofit the propulsion system for collision avoidance and deorbiting, expand the communications subsystem from UHF to S-band, and reframe the payload use case from simple reception to sensor fusion demonstrates an elevated level of mission agility.

The mission also confirmed that responsive satellites benefit from DevOps-driven ground segments, where operational tools, visualizations, and mission-specific utilities continuously improve in sync with evolving goals. In this regard, integrating students into the development and operations preparation loop proved essential.

6.1.2. Distributed and decentralized control

The OTTER mission preparation demonstrated the feasibility of a decentralized, multi-entity mission control framework, with operational responsibilities shared among an agency research center (RSC³), a commercial provider (GOS), and an academic institution (FH Aachen). This structure leveraged tools such as Proxmox, YAMCS, ProToS, and custom-developed mission control software to achieve development at a high pace and operations preparation without the complexity, cost, and infrastructure burden typically associated with conventional mission control centers. The implementation of virtualization and browser-based control enabled secure remote access, enhancing resilience and reducing infrastructure costs while minimizing reliance on fixed control rooms, a particular advantage given post-pandemic operational constraint.

6.1.3. Educational integration

Additionally, OTTER provided an educational model involving students as active contributors to mission tooling, procedure design, and command logic development, fostering a cost-effective talent pipeline aligned with real-world space mission requirements. This approach streamlined operations preparation, reduced costs and created a valuable talent pipeline, enriching academic curricula by bridging theoretical knowledge with practical applications and real-world space mission requirements.

6.1.4. Challenges and workarounds

Several challenges emerged during implementation. Porting legacy TMTC data from proprietary systems required significant manual intervention and the development of specialized tools. The FEEP system's non-standard firmware also introduced operational complexity, requiring operator-side command assistance tools. Additionally, coordinating the use of ground stations across multiple frequency bands and institutions presented logistical challenges.

Nevertheless, these challenges were effectively addressed through close collaboration and iterative development, highlighting the importance of flexibility, rapid prototyping, and strong academic-industry partnerships in small satellite missions.

7. Conclusion

The OTTER mission exemplifies a compelling case study in the evolution of small satellite platforms, transitioning from a time-limited technology demonstrator to a robust, long-duration space capability. The mission has effectively demonstrated the feasibility of sustaining complex space activities under constrained resources and evolving mission requirements by applying modular architectures, virtualization technologies, and decentralized operations.

Transitioning from UHF to S-band communications, integrating a field emission electric propulsion (FEEP) system for active orbital management, and implementing AIS-optical data fusion for maritime domain awareness represent pivotal technical achievements. These enhancements are supported by a virtualized mission control infrastructure grounded in Proxmox, Apache Guacamole, and YAMCS, which enables secure, browser-accessible, and scalable operations. Logical isolation through VLAN segmentation, encrypted reverse proxy access, and modular service orchestration collectively provide a resilient and flexible operational environment.

Equally important is the mission's innovative organizational model. The hybrid operational framework – comprising governmental, industrial, and academic entities – has facilitated a shared responsibility structure that extended operational viability. The formal transfer of operations from commercial provider German Orbital Systems (GOS) to the Responsive Space Cluster Competence Center (RSC³) and FH Aachen marked a critical reallocation of roles, enabling sustained mission execution without reliance on monolithic control centers.

The academic integration has further underscored the mission's pedagogical value. Students at FH Aachen have been deeply involved in mission operations preparations, system configuration, and tool development. This hands-on involvement contributed materially to mission resilience and cultivated competencies essential for national capacity building in responsive space systems.

The OTTER mission validates the operationalization of responsive space principles – rapid adaptation, decentralized control, and modular design – within the constraints of a low-cost, small satellite paradigm. The successful implementation of a virtualization-based ground segment, coupled with a distributed control model and academic participation, offers a replicable framework for future missions seeking agility, robustness, and educational synergy.

As such, OTTER constitutes a benchmark for the design and execution of resilient satellite missions. Its outcomes contribute meaningfully to the discourse on responsive space and offer a concrete blueprint for allied institutions aiming to enhance situational awareness and operational readiness through innovative, distributed space system architectures.

8. Outlook

As the OTTER mission nears its launch phase, the upcoming months represent a crucial period for establishing its responsive space operations framework. Key pre-launch milestones, including the System Validation Test (SVT) and Operational Readiness Review (ORR), are scheduled for May 2025. These events will be essential for assessing the functional readiness of the satellite platform, the mission operations infrastructure, and the preparedness of the flight operations team for the upcoming phases of the mission.

The SVT will comprehensively validate the integrated system performance across all mission segments, encompassing satellite hardware and software, the mobile-based mission control architecture, and the ground station infrastructure. This test will assess whether OTTER's hardware and software components operate cohesively as a unified system under nominal and contingency conditions.

The subsequent ORR will evaluate the readiness of all mission assets and stakeholders to initiate flight operations, including a thorough examination of operational procedures, data handling workflows, communication protocols, and personnel capabilities for the Launch and Early Orbit Phase (LEOP), commissioning, and sustained operations. This review will provide a technical evaluation and a final validation of the organizational and procedural frameworks developed during the OTTER program.

Achieving both milestones is crucial to confirm the readiness of the mission's innovative, distributed, and virtualization-based control system, which RSC³, German Orbital Systems, and FH Aachen have collaboratively developed. These milestones also represent the culmination of mission preparation and establish the foundation for in-orbit validation of new operational concepts. This solidifies OTTER's position as a viable testbed for future responsive space technology demonstration missions at DLR RSC³.

With a planned launch window between July and September 2025, the OTTER mission is poised to transition from development to operational execution. After a (hopefully) successful launch, the upcoming operation execution phases present a unique opportunity to observe the system's performance under real-world constraints and to identify potential areas for refinement from the perspective of practical user interaction. Particular attention will be paid to operator workflows, system scalability, interface usability, and robustness under constrained conditions typical of responsive space missions. Adapting and optimizing the mission operations system based on user feedback during operations will be crucial for refining future resilient, decentralized space operations infrastructures at DLR RSC³. Thus, the OTTER mission stands poised to demonstrate technical feasibility, architectural agility, educational integration, and operational sustainability within the responsive space paradigm. These outcomes will significantly advance responsive space capabilities, setting a precedent for future missions prioritizing adaptability, efficiency, and collaboration.

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