SpaceOps-2025, ID # 124

V3C: Mobile Control Center for Autonomous Satellite Operations

Stefan A. Gärtner[1], Robert T. Schwarz[2], Julien Grönitz[3], and Andreas Knopp[4]
[1]*German Space Operations Center GSOC, DLR Oberpfaffenhofen, 82234 Weßling, Germany,* `Stefan.Gaertner@dlr.de`, *ORCID:* `https://orcid.org/0000-0002-4077-9851`
[2]*Space Research Center, University of the Bundeswehr Munich, Neubiberg, Germany,* `Robert.Schwarz@unibw.de`
[3]*secunet Security Networks AG, 45138 Essen, Germany,* `Julien.Groenitz@secunet.com`
[4]*Space Research Center, University of the Bundeswehr Munich, Neubiberg, Germany,* `Andreas.Knopp@unibw.de`

The "Verlegefähiges Compact Control Center" (V3C) is a mobile and autonomous ground control segment developed as part of Germany's national Responsive Space capability. Responsive Space is dedicated to enable rapid deployment and operation of low earth orbit (LEO) satellites within just a few days. V3C enhances mission flexibility and resilience by allowing secure, automated satellite operations from virtually any location, complementing conventional fixed control center infrastructure. This paper presents a fully autonomous field deployment of the V3C system. The setup demonstrates complete independence from centralized control facilities, enabling mission operations directly at remote sites. To support truly mobile operations, a SATCOM on-the-move (SOTM) terminal was used for the demonstration. This terminal established a geostationary relay link to a fixed very small aperture terminal (VSAT), which in turn connected to a ground-based S-band antenna. The S-band antenna established the final space link to the LEO satellite BIROS for Earth observation tasks. The entire communication path was secured using the SINA solution by secunet, allowing the secure handling of classified data over public or insecure networks. The V3C control system, including the full Mission Operations System (MOS), was deployed on a standard laptop using multiple cryptographically separated virtual machines on a SINA workstation. Automated deployment ensured minimal setup time and operational readiness in the field. This paper describes the technical design, implementation, and results of the successful demonstration campaign. It highlights the ability to securely conduct satellite bus and payload operations from remote locations using a GEO relay link. The demonstration included the complete task cycle: satellite planning, command uplink, payload data acquisition, downlink via geostationary relay, local processing, and image display. Additionally, telemetry was processed by an integrated Flight Dynamics System to update orbital data for subsequent satellite contacts and observation tasks.

Abbreviations

BER	Bit Error Rate
CCSDS	Consultative Committee for Space Data Systems
CI/CD	Continuous Integration/Continuous Deployment
COTS	Commercial Off-The-Shelf
DLR	German Aerospace Center/Deutsches Zentrum für Luft- und Raumfahrt
DMZ	Demilitarized Zone
EIRP	Effective Isotropic Radiated Power
GEO	Geostationary Earth Orbit
GSOC	German Space Operations Center
ICD	Interface Control Document
LEO	Low Earth Orbit
MOS	Mission Operations System
PSE	Project System Engineer
SATCOM	Satellite Communications

SLE	Space Link Extension
SOTM	SATCOM On-The-Move
TC	Telecommand
TCP/IP	Transmission Control Protocol/Internet Protocol
TLE	Two-Line Elements
TM	Telemetry
TPC	Turbo Production Code
V3C	"Verlegefähiges" (mobile) Compact Control Center
VM	Virtual Machine
VPN	Virtual Private Network
VSAT	Very Small Aperture Terminal

1. Introduction

The "Verlegefähiges"[1] Compact Control Center (V3C) is a compact and mobile Mission Operations System for operating spacecraft independently of ground infrastructure except for some means to establish a communication link with the satellite. In particular, it comprises all components typically needed for spacecraft operations, i. e. a Mission Planning System, a Monitoring and Control System, a Flight Dynamics System and a Payload Processing System and integrates them on mobile COTS hardware. Its purpose is to complement a regular Mission Control Center for added resiliency in case of unavailability of the stationary main and/or backup control centers. Owing to its mobility and its flexible and responsive deployment options on COTS hardware V3C fits well into solutions for "Responsive Space" architectures. Compared to a regular Mission Control Center V3C lends itself predominantly to single or few operator routine and emergency operations. Figure 1 shows V3C running on COTS reference hardware.

Fig. 1 V3C as a mobile solution for satellite operations independent of ground infrastructure except for some means to establish a communication link with the spacecraft (symbolized by the 3d-printed antenna), runnable on mobile COTS hardware.

1.1 BIROS Demonstration Operations at GSOC

Detailed design, implementation and integration of V3C into existing infrastructure at the German Space Operations Center (GSOC) with the goal of demonstration operations using the BIROS satellite [1] has been described in [2]. Due to a spacecraft outage the demonstration campaign had to be conducted at a later point in time and is described in detail in [3]. It took place successfully over the course of two days from one of GSOC's control rooms, see Figure 2, and included a typical routine Earth observation task: selection of a target area, calculation of data take possibilities, timeline generation and commanding, satellite health assessment, orbit determination, payload data downlink, processing and display. One of the acquired images can be seen in Figure 3. V3C has been deployed on COTS reference hardware, which is a powerful laptop, and integrated into GSOC control room infrastructure. This campaign showed the compactness of the system but not yet its mobility. In this paper we demonstrate its mobility by preparing and executing two different remote operations concepts, which will be detailed in the next section.

[1]German expression for a system that is mobile in the sense that it can be deployed at different places

Fig. 2 Setup of V3C (laptop on the left) in one of GSOC's control rooms during the first demonstration campaign. V3C is accessed from the console via remote desktop connections, no other infrastructure except connection to the ground station is used.

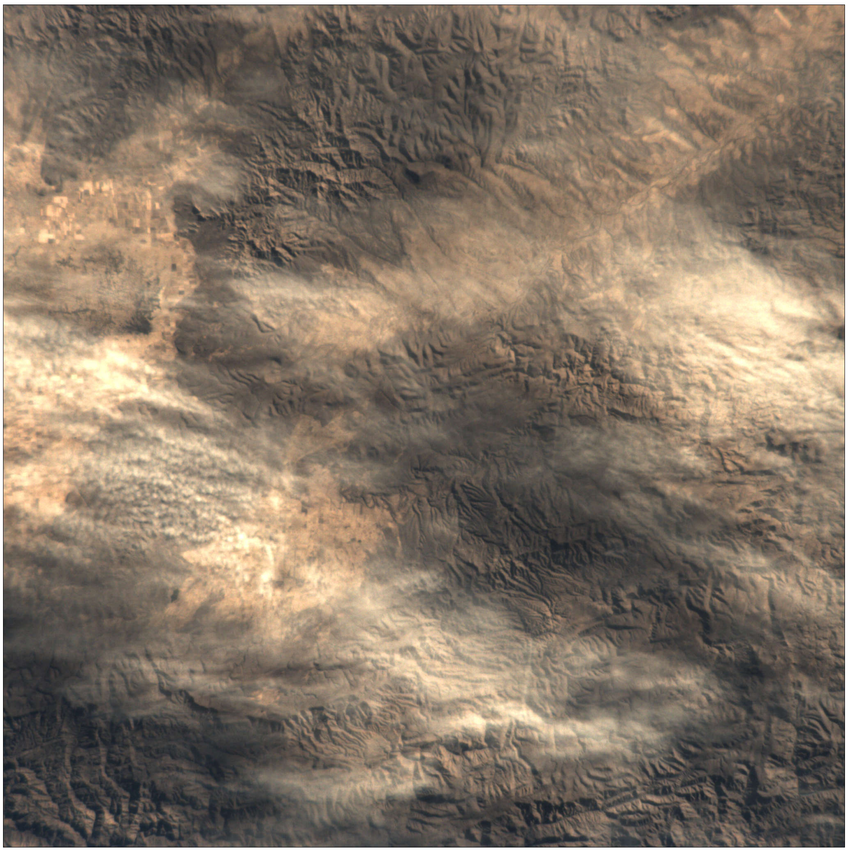

Fig. 3 Data take of the area around Truth or Consequences, New Mexico, USA, during the first V3C demonstration campaign.

2. Remote Operations Concepts

Multiple concepts for remote operations have been identified, designed and implemented: An obvious concept is coupling V3C directly to an external tracking antenna that establishes the satellite link. This approach is similar to the one already demonstrated but without resorting to any control center infrastructure. Another concept is relaying the link from V3C to a tracking antenna via some kind of communication network, preferably one that does not rely on ground infrastructure like Internet access or dedicated communication lines. The *direct* concept is less mobile than the *relay* concept, because tracking antennas are either stationary or bulky. The relay concept can possibly make use of several stationary tracking antennas depending on availability and setup of relay endpoints. It is much more mobile due to the mobility of terminals for accessing the relay. However, its setup is more complex and the relay might introduce additional latencies as well as more challenges regarding secure connections.

Both concepts were realized and demonstrated successfully. For the direct concept an antenna at Weilheim ground station was chosen as stationary tracking antenna and V3C was brought directly there. The relay concept was also realized with a tracking antenna of Weilheim ground station with the relay being a geostationary military communications satellite. The next section describes the GEO relay architecture, Section 4 shows demonstration operations via the GEO relay. We leveraged synergies between both concepts and already prepared the direct concept in a way that later would allow easy introduction of a relay. In particular this means that the security and communications solution of the relay concept was already put in place for the direct concept, although this was not strictly necessary. Due to handling the direct concept merely as a stripped-down version of the relay concept—the relay is simply replaced by a direct wired connection—we only present the more challenging architecture and demonstration operations of the relay concept.

2.1 GEO Relay Architecture

The GEO relay architecture builds upon the integration concept presented in [2] and also contains fallback mechanisms to resume operations from the regular Mission Operations System in order to ensure satellite safety in case of outages or after conclusion of the demonstration campaign. Figure 4 shows a schematic of the GEO relay architecture: The regular Mission Operations System is depicted in the upper right (green background) and does not have any direct connection to V3C, except for some data exchange for initialization at the beginning and for synchronization at the end of the campaign (dotted arrows with USB stick). Facilities located at Weilheim ground station are depicted in the left part with three different networks separated by firewalls (gradient strip). V3C is shown on the right (blue background) connected to the network of a relay communication van (orange background). Blue background networks are considered secure, orange background networks and connections between them are considered potentially insecure and/or public. The actual GEO relay is shown in the center of the schematic, with

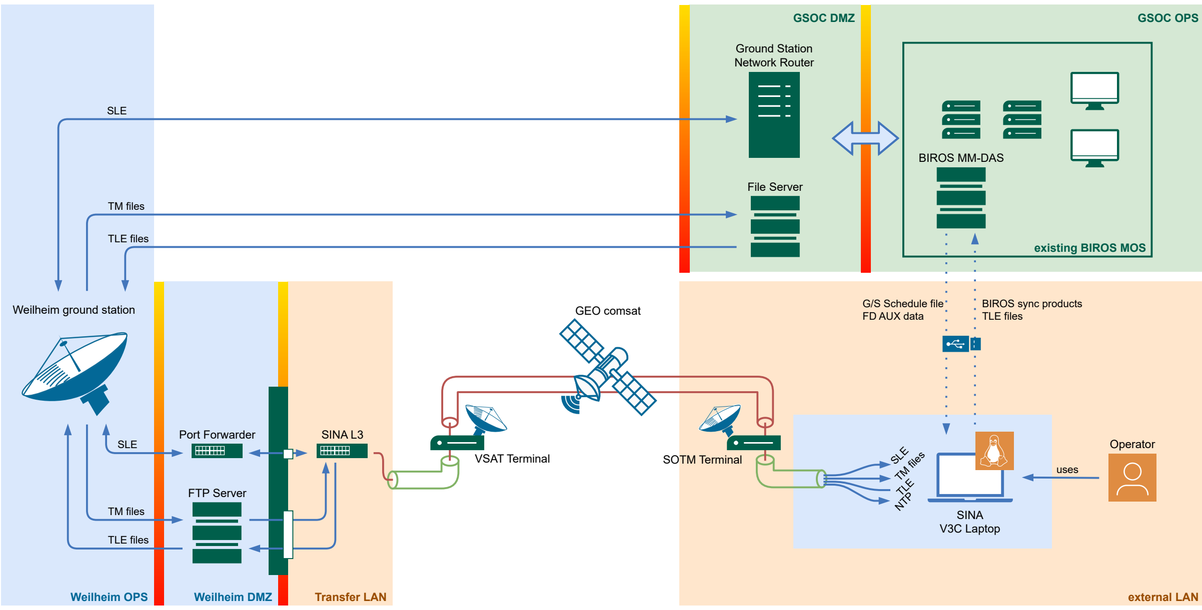

Fig. 4 Geostationary relay architecture diagram with simplified network structure. Networks are shown as colored background boxes with firewalls as gradient strips. Orange boxes and the relay in the center are considered insecure. The upper right shows the regular Mission Operations system with green background. V3C is located on the lower right as a secure enclave inside a potentially insecure network.

terminals on either side. Section 2.2 provides details about connection security, Section 4.1 about the geostationary communications link. The orange background box on the right is physically realized as a communication van provided by the University of the Bundeswehr Munich and as such is highly mobile.

The external interfaces of V3C that are relayed via the GEO link are typically realized as TCP/IP connections, possibly mediated via an IPSec VPN (Virtual Private Network) provided by the SINA architecture. It is well known [4, 5] how long-delay environments affect the performance of TCP which was designed with terrestrial networks in mind. In particular, two TCP features play a major role: the TCP receive window size which describes the maximum number of bytes in flight before acknowledgment is needed, and TCP flow control techniques. These effects were evaluated in a test setup using a channel emulator and a ground station and spacecraft mock-up. Real-time commanding and telemetry monitoring were not affected except by the expected latencies between telecommand release and its acknowledge by the spacecraft mock. The situation is different for "offline" telemetry transfer. Typically, only a subset of all satellite telemetry is forwarded from ground station to control center during real time contacts in a timely manner, whereas the whole telemetry set is stored at the ground station and delivered after the contact, this time with focus on completeness rather than on timeliness. The offline data transfer was notably affected by long-delay effects with very different performance figures depending on the operating system running the client that requested the data transfer. On Linux (SuSE Linux Server 15) a maximum throughput of $\approx 1\,\mathrm{MB\,s^{-1}}$ was measured, on Microsoft Windows it was $\approx 120\,\mathrm{kbit\,s^{-1}}$. Because the offline data transfer is not time critical both performance figures were acceptable for demonstration operations and no further optimization was attempted. It is likely that the TCP stacks of both operating systems are configured differently and that reconfiguration could enhance performance.

2.2 Secure Operations

The integration of secunet's SINA technology enables the V3C system to carry out satellite operations securely and reliably, regardless of location. At the heart of this solution is the SINA Workstation S, which allows national data up to classified level (German classification "VS-NfD") and international classified information up to EU-RESTRICTED and NATO-RESTRICTED to be processed and transmitted on standard laptops.

The SINA architecture is based on highly secure end-to-end encryption and uses cryptographically secured virtual sessions, each of which represents its own security domain. These sessions are strictly isolated from each other in the network, thus ensuring uncompromising separation of different security levels and operational tasks. For example, this allows assigning different security levels to satellite bus operations, payload operations, or payload processing. In addition, SINA L3 boxes are used to provide secure IPsec VPN tunnels, enabling a secure and protected connection across potentially insecure networks.

This architecture ensures that mission planning, satellite control, telemetry monitoring and payload data processing can be carried out in parallel and securely. This technology offers decisive advantages, particularly in deployment scenarios that require mobility and self-sufficiency, for example during operations in remote regions or in critical security situations. The rapid deployment of the system corresponds to the concept of Responsive Space and supports the ability to react quickly and flexibly to unforeseen requirements.

3. Deployment Concept

The deployment concept, i. e. how the systems comprising the ground segment are rolled out on physical or virtual hardware and how they connect to each other, is described in detail in Section 3 of [2]. This process is highly automated by leveraging so-called "infrastructure as code" techniques. These techniques are the basis for deploying the system to all kinds of targets and into all kinds of environments. A "deployment target" is a specific physical or virtual hardware setup that runs a V3C instance. Such an instance needs some well-defined interfaces to external systems, most notably to ground station equipment, see Section 2.5 of [2] for details. A concrete configuration of those interfaces makes up an "operation environment", i. e. how a V3C instance embeds into a larger system. Typically, different targets can be put into different environments, although not all combinations are sensible or possible. See Figure 5 for an overview of deployment targets, operation environments and which combinations of both are usable.

3.1 Deployment Targets

Originally, only one deployment target was planned: the reference hardware. During project progress it became clear quickly that there are more diverse requirements regarding deployment targets than originally assumed. Currently, following deployment targets are supported:

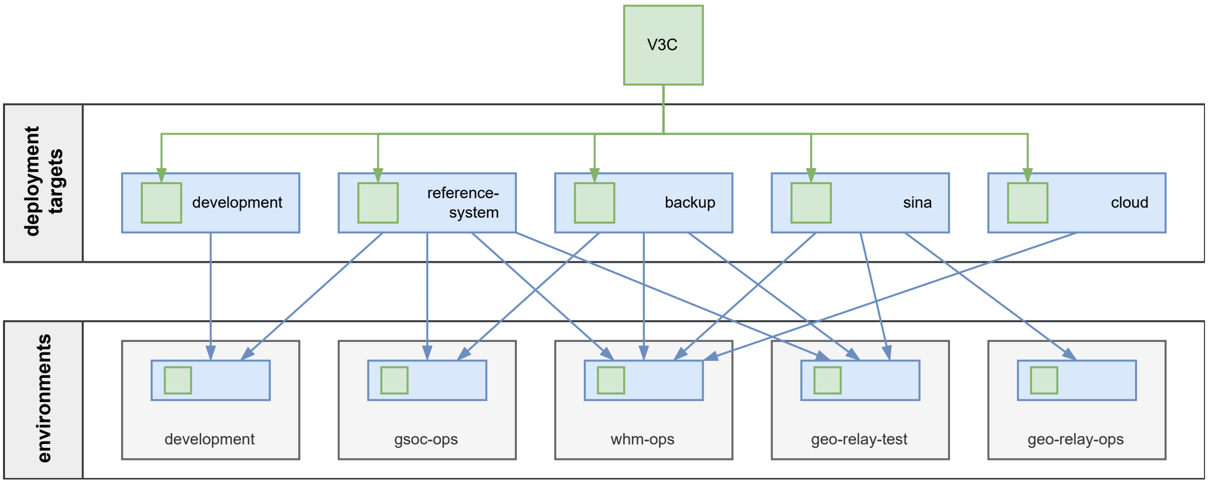

Fig. 5 Diagram of deployment targets and execution environments.

development: This target describes the diverse hardware and software of the V3C developers, e. g. different operating systems like Linux or Microsoft Windows. It enables full or partial execution of the V3C system locally on these computers.

reference-system: This target represents the reference hardware procured for this project, which is running a Linux operating system. It is a powerful laptop capable of executing several V3C instances in parallel, possibly in different versions, where each instance gets assigned its own network and IP addresses. It is the main target for use in operations but it is also used for CI/CD pipelines during development as presented in detail in [2], Section 3.4.

backup: In case of a malfunction of the reference hardware a backup system for use in operations has been set up. The same deployment as for the reference system is used, just with less powerful hardware such that parallel execution of several V3C instances is not possible.

sina: This target represents SINA hardware, specifically secure SINA workstations by secunet. Refer to Section 2.2 for more details.

cloud: This target is designed for deployment in cloud infrastructure, decoupled from laptop hardware. Currently, we support private cloud deployments using Proxmox VE. More details can be found in [6].

3.2 Operation Environments

Hallmark of a mobile Mission Operations System is the ability to be used in different operation environments. An operation environment is characterized by the accessible services (like a ground station network) and the network infrastructure (e. g. addressing of services) in which the system needs to be embedded. Because adaptions to different operation environments are served by the same deployment processes as the initial system setup they can be executed in an automated manner and most notably with quick response times. V3C has been prepared for deployment into the following operation environments:

development: This is the default environment, which serves as baseline if nothing else is configured. Its purpose is development of the system and local testing without resorting to external infrastructure or services. This is also the environment used for the CI/CD pipelines as detailed in [2].

gsoc-ops: This is an environment with full operational capability and is used for deployment in GSOC control rooms. V3C was validated in this environment which was used for first demonstration with the BIROS satellite.

whm-ops: This is an environment with full operational capability and is used for deployment on site of Weilheim ground station. It is the foundation for operations which are completely decoupled from control room infrastructure. This environment was used for validating the *direct* remote operations concept as described in Section 2.

geo-relay-test: This environment builds upon `whm-ops` and is used for laboratory testing of GEO relay links using channel emulator and ground station mock-up.

geo-relay-ops: This environment builds upon `geo-relay-test` and provides full operational capability from remote sites using a GEO relay link for connection to Weilheim ground station and was used for validating the "relay" remote operations concept.

3.3 Infrastructure as Code

In order for the deployment to support different targets and environments the provisioning process pictured in Figure 12 of [2] has been extended. The extension is shown in Figure 6 and directly connects to the "Provision VMs" step of the previously presented workflow. Because some deployment targets do not provide any automatable interface this process supports both automatic and manual target roll-outs. The process provisions a system for a baseline deployment target in a baseline environment by default. Baseline target is developer hardware and baseline environment is a typical, self-contained development environment. Other targets and environments build upon the baseline. Depending on the type of deployment target the next step is either a manual roll-out on the target or an automated roll-out governed by the same automation tool already used for the rest of the system, namely Red Hat Ansible. The environment integration, which typically covers setting e. g. IP addresses of external systems, configurations of SLE providers or mounting of network shares, is automated with Ansible again. Each environment is represented by a so-called "playbook". In case the environment needs to be changed, e. g. when V3C is moved to a different operations site, the system is quickly adapted by executing the respective environment integration playbook.

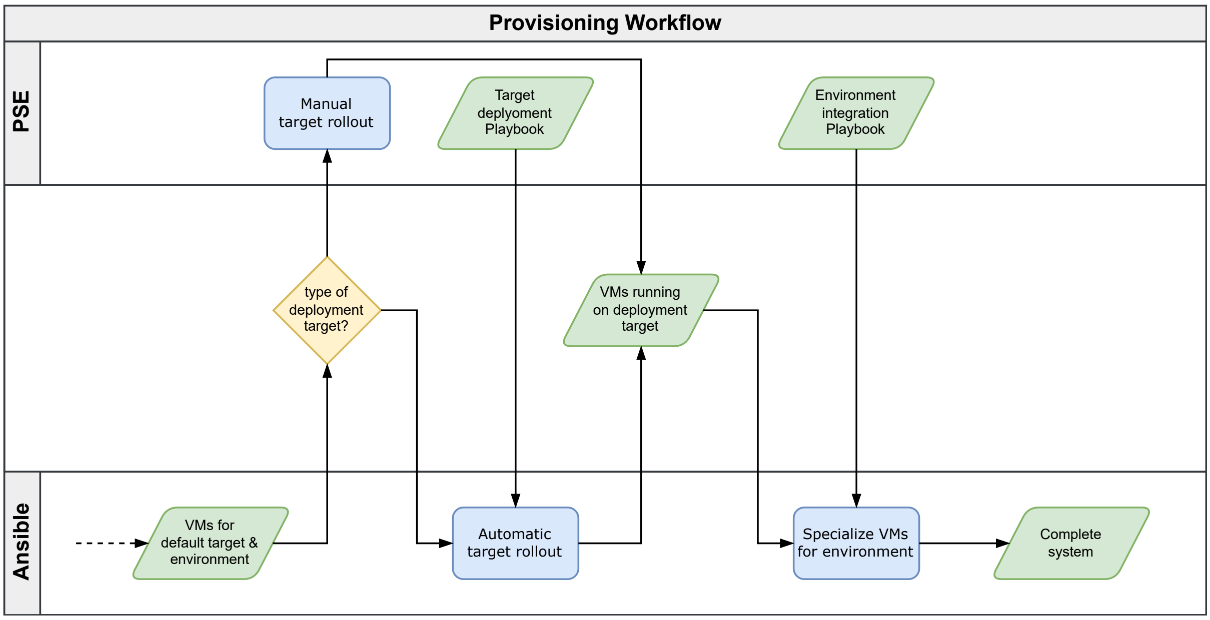

Fig. 6 Extension of the provisioning workflow of Figure 12 in [2] for roll-out of V3C on different deployment targets in different operation environments. "PSE" is the Project System Engineer.

4. GEO Relay Demonstration

All components of the V3C system that had previously been tested and validated individually—including the Mission Operations System, the hardware and network configuration involving SINA workstations and secure connections, as well as the simulated geostationary relay link—were integrated for a "GEO Relay Demonstration Campaign". The objective of the campaign was to validate the complete system in an end-to-end scenario, using secure communication channels via a geostationary satellite. This was achieved by performing a typical Earth observation task with the BIROS satellite. As in previous demonstrations, the task included selecting an observation target, calculating data acquisition opportunities, generating and uplinking a mission timeline, monitoring its execution, assessing satellite health, determining the orbit parameters, and downlinking, processing, and displaying the payload data.

Table 1 Technical data of the VSAT terminal.

Parameter	Value
Antenna diameter	1.5 m
Maximum EIRP	55 dB W
G/T	$18\,\mathrm{dB\,K^{-1}}$

Table 2 Technical data of the SOTM antenna.

Parameter	Value
Antenna diameter	45 cm
Maximum EIRP	40 dB W
G/T	$8\,\mathrm{dB\,K^{-1}}$

4.1 Communication Van, Link Characteristics and Budget

For the geostationary relay test setup, a bidirectional satellite communications (SATCOM) link was established between a VSAT and a mobile SOTM terminal via a geostationary earth orbit (GEO) satellite operating in the X-band. The configuration included a forward link from the VSAT to the SOTM terminal, and a return link in the opposite direction, enabling full-duplex communication over the satellite channel. Due to the mobility of the scenario and the requirement of controlling the space segment while on the move, a small SOTM antenna is necessary at the mobile end of the link. Phased array flat panel or conventional parabolic reflector antennas are market available and could be deployed for these scenarios. In our case, we used a parabolic reflector having a diameter of 45 cm on the roof top of a van (see Figure 7). The technical characteristics of the VSAT are detailed in Table 1, while the specifications of the SOTM terminal are provided in Table 2. At both ends of the communication link, Q-Flex modems from Paradise Datacom were deployed to handle modulation, coding, and demodulation tasks.

The link budget for the demonstration setup considered a required data rate of at least $150\,\mathrm{kbit\,s^{-1}}$ for the forward link and $50\,\mathrm{kbit\,s^{-1}}$ for the return link as demanded by the space-to-ground ICD of the BIROS satellite. To ensure reliable communication, the bit error rate (BER) was specified to be at least 10^{-6}, which, based on the modulation and coding scheme described in Table 3, required a minimum E_b/N_0 of 1.3 dB. A key limiting factor in the forward link performance is the low receive system gain-to-noise temperature ratio (G/T) of the SOTM terminal, which was $8\,\mathrm{dB\,K^{-1}}$ in our case. This value could be increased, but with the expense of a larger physical dimension of the antenna. Consequently, the achievable carrier-to-noise ratio (C/N) for the forward link was constrained by the downlink segment. Despite this limitation, the link performance was adequate, achieving an overall C/N of −1.3 dB for the forward link and 6.4 dB for the return link. These values resulted in positive link margins of 2.5 dB and 10.2 dB for the forward and return links, respectively. Further details on the link performance are provided in Table 3.

4.2 Detailed Sequence of Events

Table 4 provides an overview of the sequence of events for the GEO relay demonstration campaign, which took place over the course of three days. The first day was dedicated to the set-up of VSAT, SOTM, SINA L3 box and V3C, as well as initialization of the system with up-to-date data like current orbit parameters, ground station schedule or atmospheric conditions. We decided to place both endpoints of the relay line close to each other for easier access in case problems were encountered, see Figure 7 for a photo of the setup. In general, SOTM and V3C, which is placed in the van's trunk compartment, see Figure 8, may be located several hundreds to thousands of

Table 3 Link budget parameters for the forward and return links.

Parameter	Forward Link (VSAT to SOTM)	Return Link (SOTM to VSAT)
Modulation and coding	BPSK, turbo production code (TPC) with code rate 5/16	
Data rate	$150\,\mathrm{kbit\,s^{-1}}$	$50\,\mathrm{kbit\,s^{-1}}$
Symbol rate	480 kSym/s	160 kSym/s
Occupied bandwidth	648 kHz	216 kHz
Uplink carrier frequency	8223.1 MHz	8225.2 MHz
Downlink carrier frequency	7573.1 MHz	7575.2 MHz
Achieved C/N	−1.3 dB	6.4 dB
Resulting E_b/N_0	3.8 dB	11.5 dB
Required E_b/N_0 for BER of 10^{-6}	1.3 dB	
Link margin	2.5 dB	10.2 dB

Fig. 7 Photo of communication van (center) with SOTM antenna (on the van's roof top), S-band tracking antenna (left) and VSAT antenna (right) during GEO relay demonstrations.

Table 4 Simplified sequence of events for the GEO relay demonstration campaign.

UTC		2024-07-23
08:30	Preparation	set-up of VSAT, SINA L3, SOTM and V3C
08:30	Preparation	transfer of initialization data to V3C
		2024-07-24
05:30	Pre-pass #1	selection of data take opportunity
06:48	Pass #1	spacecraft health assessment and timeline uplink
07:00	Post-pass #1	transfer of recorded telemetry from ground station → V3C
07:05	Post-pass #1	orbit determination calculation and transfer of TLE → ground station
08:27	Pass #2	spare – monitoring pass
		2024-07-25
06:13	Pass #3	spacecraft health and data take success assessment
06:25	Post-pass #3	transfer of recorded telemetry from ground station → V3C
06:30	Post-pass #3	orbit determination calculation and transfer of TLE → ground station
06:30	Post-pass #3	payload data processing and display
07:45	Pass #4	spare – monitoring pass
08:30	Wrap-up	dismantling of VSAT, SOTM and V3C

Fig. 8 Photo of V3C in trunk compartment of van during GEO relay demonstrations. The laptop shows visualizations of various satellite telemetry parameters, the connected monitor shows successfully uplinked telecommands. Some communication equipment for the relay link can be seen in the background.

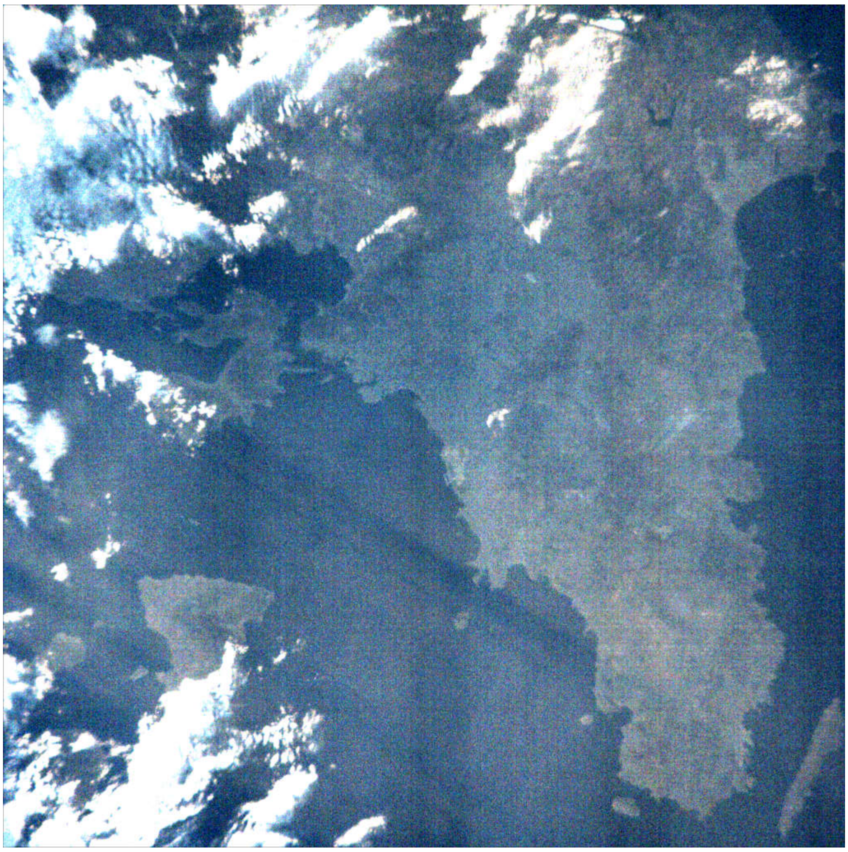

Fig. 9 Data take of Attic peninsula, Greece, during the GEO relay demonstration campaign.

kilometers away from VSAT, SINA L3 and tracking antenna, provided both sides have line-of-sight to the relay satellite.

The communication van was kept in active operation mode during the night, however was found dead on day two due to a faulty power converter. The van was made operational again using the van's alternator instead of an external power supply shortly before the first satellite pass. A backup V3C instance was made ready with direct connection to the tracking antenna, but was not needed after all. The pass could be supported successfully and a timeline that was generated prior with a selected data take opportunity of the Attic peninsula was uplinked to the BIROS satellite. Latencies due to the relay line were noticeable during the contact but did not affect operations negatively. The whole set of telemetry was recorded at the ground station and transferred to V3C after the contact, using the same relay link. Based on the telemetry, new orbit parameters were calculated and transferred to the ground station in form of a two-line element (TLE) file, also using the same relay link. A second pass the same day was planned as a spare pass and used for monitoring purposes. During the first pass on day three success of the data take could be confirmed. The recorded telemetry also contained the payload data, which was processed on V3C after transfer via the relay link. The acquired image was displayed and can be seen in Figure 9. The second pass of the day was planned as spare pass and only used for monitoring. The whole setup was dismantled in roughly one hour after the second pass and the demonstration was declared a success.

5. Conclusion and Outlook

We have shown how to perform satellite operations outside of control centers while being on the move with minimal reliance on ground based infrastructure. We coupled a compact, yet fully functional, Mission Operations System, runnable on COTS hardware and quickly deployable in an automated fashion, to the BIROS satellite using several solutions for the communication links: using control center infrastructure, direct connection to the tracking antenna, and relay connection via a geostationary communications satellite. We successfully performed routine Earth observation tasks using any of these communication methods, showing how V3C can be used flexibly in changing environments, while still providing robust and secure operations capabilities. By leveraging industry standard security solutions we were able to perform secure satellite operations via possibly insecure communication links. In future, such a system becomes a building block for providing more resiliency to space missions. Using the same technological foundations also allows us to build the basis for cloud-based mission control.

Acknowledgments

Our special thanks go to Martin Wickler for initiating this project, providing core ideas and ensuring initial funding through DLR's German Space Operations Center GSOC. We sincerely appreciate project funding provided by Wolfgang Jung through the DLR Responsive Space Cluster Competence Center RSC^3 with support by the German Federal Ministry of Defence. We thank the University of the Bundeswehr Munich for providing the geostationary terminals, communication van and personnel and we thank the Bundeswehr for providing communication capacity. Appreciation goes to secunet AG for providing the security solution and support. Finally, we thank the team members and supporting staff bringing this project to life.

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