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Real Space, Real Skills: Immersive Satellite Operations Training

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Abstract

As space technology advances, the training of future space engineers must adapt to prepare students for complex, real-world missions. The Chair of Space Technology at Technische Universität Berlin has introduced an innovative educational model in which students gain practical experience by operating a satellite that is already in orbit. This study examines the structure, execution, and outcomes of this approach, emphasizing spacecraft operations. Students begin the semester with the task of managing a satellite, presented as yet to be launched, though it has been in orbit for several years. The initial six-week period involves familiarization with mission objectives, satellite subsystems, and operational procedures through lectures, hands-on workshops, and simulator exercises. A comprehensive Flight Readiness Review follows, ensuring students' preparedness for satellite operations, mimicking real-world mission evaluations. Mid-semester, a simulated launch event using recorded video footage of the satellite's actual launch and separation provides an authentic immersion. During the Launch and Early Orbit Phase, students establish communications and verify critical on-board systems, gaining real-world operational experience. In the commissioning and nominal phase, students conduct health checks, data collection, and specific mission tasks, focusing on subsystem functionality, decision-making, and real-time problem-solving. Students delve into Guidance, Navigation, and Control, validating the satellite's attitude using custom imagery-based verification methods. They also addressed a non-functioning star tracker. This hands-on experience is crucial for understanding and managing the complexities of satellite operations. Another aspect of the course is the post-processing and analysis of the self-recorded earth observation data. The results of the course demonstrate the effectiveness of the practical training. Performance data, operational and experimental results show that students develop a critical understanding of the complexities of satellite operations and acquire essential skills such as teamwork, communication and technical proficiency. The integration of real satellite operations into the curriculum bridges the gap between theoretical knowledge and practical application. In conclusion, this educational model of the Technische Universität Berlin represents a significant advancement in space engineering education and can serve as a blueprint for other institutions. It equips students with the necessary skills and experience to tackle future space mission challenges, contributing to the global space industry's growth and success.

Keywords: Satellite Operations, Hands-On Training, Education, LEOP, Commissioning, Nominal Operations

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1. Introduction

Traditional aerospace engineering programs emphasize system design and pre-launch development. However, real-world satellite missions demand a comprehensive understanding of post-launch operations. These include maintaining spacecraft health, performing anomaly detection and recovery, coordinating ground segment logistics, and adapting to unpredictable in-orbit conditions. Despite its importance, satellite operations often receive minimal attention in university curricula. Graduates enter the workforce having never interpreted live telemetry, constructed a command sequence, or navigated the constraints of ground station availability and communications bottlenecks. Recognizing this need, the Chair of Space Technology at Technische Universität Berlin (TU Berlin) has developed innovative educational programs that immerses students in basic satellite operations [1] and additionally in the full lifecycle of satellite operations using a satellite already in orbit. The latter course presents a unique pedagogical model: students assume responsibility for a satellite mission under the pretense that the spacecraft is yet to launch, despite having been in orbit for several years. This narrative supports immersion and encourages responsibility from the outset.

2. Technical Framework

To support immersive and authentic spacecraft operations training, the course is built around a technically mature satellite platform and a fully operational ground segment. The infrastructure at TU Berlin enables students to interact with real spacecraft systems using professional-grade tools and procedures. This section introduces the satellite used in the course, the associated ground station network, and the software environment through which students carry out planning, commanding, and data analysis.

2.1. Satellite TUBIN

The academic microsatellite TU Berlin Infrared Nanosatellite (TUBIN), developed and operated by TU Berlin, is based on the modular TUBiX20 satellite bus [2]. It was launched in 2021 into a 530 km sun-synchronous orbit and continues to operate in support of both scientific and educational objectives.

The primary mission goal is the in-orbit demonstration of two uncooled microbolometer cameras, forming the satellite's thermal infrared payload. These sensors have proven effective for detecting high-temperature events such as wildfires and urban heat sources from space [3]. To support these observations, a visible-spectrum CMOS camera is also integrated. This camera aids in data registration, image alignment, and visual verification of infrared data products.

A secondary payload, an X-band transceiver, is included to enable high-rate data downlink capability. The platform's onboard systems are designed to support advanced imaging and orientation requirements.

The satellite is equipped with a comprehensive attitude determination and control system. This includes four reaction wheels and three-axis magnetorquers, supported by two star trackers, inertial measurement units (IMUs), sun sensors, fibre optic rate sensors, and magnetic field sensors. Redundant communication systems operate via Ultra High Frequency (UHF) for command and telemetry and S-band for telemetry and data downlink. Together, these components enable flexible mission operations and provide a reliable platform for hands-on academic training in real spacecraft operations. An image of the TUBIN flight model is shown in fig. 1a. In addition to the Flight Model (FM) in space, there is also an almost identical Engineering Qualification Model (EQM) in the laboratory.

2.2. Ground Station Infrastructure

TU Berlin operates a global network of ground stations to support its satellite missions. The main hub is located in Berlin and includes multiple UHF ground stations, as well as a combined S- and X-band ground station for comparatively high-data-rate downlink. These facilities are complemented by two UHF polar ground stations located in Svalbard and Antarctica, which extend pass opportunities. All telemetry and image data received from the satellite are automatically processed and stored in dedicated databases.

This back-end infrastructure ensures that students can focus on planning, commanding, and analysis, without needing to handle low-level data acquisition and decoding processes.

(a) TUBIN FM in laboratory (b) TU Berlin ground station in Berlin (c) VTS-timeloop visualization tool

Figure 1: Technical Framework

2.3. Software Tools

Students work with a suite of open-source and in-house tools tailored to academic operations. Pass planning is supported by *Gpredict* [4], which provides visibility forecasts and pass timing for all ground stations in the network. To visualize the satellite's 2D and 3D orientation and orbital path, the open-source tool *VTS-timeloop* [5] is used for historical and live satellite data. For imaging campaign design, students utilize an internal tool called *PycturePlanner* [6], which provides an interface to VTS-timeloop to simulate the attitude of the satellite, for example to plan satellite pictures, offering functionality comparable to commercial tools like Analytical Graphics Inc.'s Systems Tool Kit (STK). Sending telecommands and telemetry visualization are conducted via TU Berlin's in-house operations software. All downloaded telemetry is stored in databases that can be accessed via an own telemetry viewer or *JupyterLab*, using Python scripts to query and analyze mission data. In addition, premade basic *Grafana* dashboards [7] are provided to give students a rapid overview of historical telemetry trends, including power and satellite status. These tools ensure that both real-time and long-term spacecraft behaviour can be efficiently monitored and interpreted.

3. Educational Framework

Building on the technical infrastructure described in the previous section, the educational model at TU Berlin transforms the operational satellite environment into a semester-long, immersive training scenario. Students are placed in a mission-like setting where they gradually take on the responsibilities of a satellite operations team. The course structure is aligned with the real-world mission lifecycle, simulating the sequence of operational phases from pre-launch preparation to nominal mission execution. By integrating academic instruction with real-time system interaction, the course bridges the gap between theoretical understanding and applied expertise in spacecraft operations.

The educational approach is built around an immersive learning environment, in which students are not passive recipients of instruction, but active participants in a simulated mission with real consequences. In this context, *immersion* refers to the realistic conditions, responsibilities, and decision-making pressures experienced by students as they take on the role of an operations team managing a live spacecraft. Unlike traditional courses that rely on hypothetical case studies or idealized simulations, this format leverages real mission hardware, ground systems, and telemetry to bridge the gap between academic training and professional practice. The immersion begins on the first day of the course, when students are taken to the laboratory housing the EQM of the TUBIN satellite. There, the instructors announce that short-notice funding has become available to launch this satellite. The launch is scheduled in six weeks. Due to a lack of personnel funding, it is up to the students to prepare and operate the mission from that moment forward. This scenario establishes immediate responsibility and simulates the time pressure and uncertainty often faced in real mission campaigns.

The course follows a complete Phase E operations cycle and is supported by a structured curriculum of lectures, simulator exercises, and operational workshops. Beginning with platform familiarization, students progress through simulated launch, early orbit activities, commissioning, and nominal operations. Throughout the semester, they work with live spacecraft telemetry and telecommands, making decisions that directly affect satellite operations and health status. This pedagogical model emphasizes not only technical proficiency but also situational awareness and team coordination. Students are responsible for operational planning, diagnosing unexpected behaviour, and applying their engineering knowledge to maintain spacecraft functionality. In doing so, they develop an operational mindset and gain hands-on experience in making time-sensitive and consequence-bearing decisions. The structure of the course enables students to learn progressively while increasing their autonomy. From initial simulation exercises to live mission execution, each phase builds on the last, reinforcing knowledge through practice. The activities conducted during the 2024 summer semester are illustrated in fig. 2, which provides an overview of the key mission phases, reviews, and campaign periods. The following section outlines the course structure phase by phase, highlighting how each segment contributes to developing operational competencies.

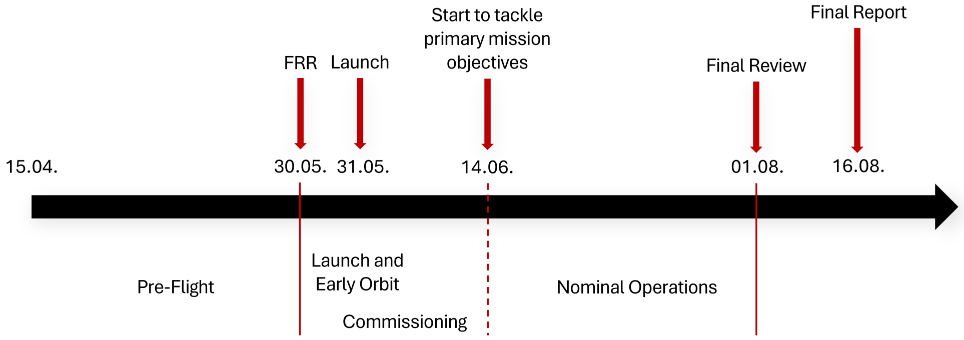


Figure 2: Course timeline of summer term 2024

4. Phase-by-Phase Breakdown

With the fundamental training, system knowledge and operating procedures, the students were ready to take responsibility for operating the satellite as a mission team. The course proceeds by simulating the operational aspects of the pre- and post-launch mission, divided into realistic phases. Each phase presents new technical challenges, shifting priorities, and decision-making opportunities, allowing students to progressively build their confidence, autonomy, and spacecraft expertise. The following section outlines this progression in detail—highlighting how students planned, rehearsed, and executed each step of the mission from pre-launch to routine operations.

4.1. Pre-Launch and Flight Readiness Review

The Pre-Launch Phase, which spans the first six weeks of the course, focuses on developing a comprehensive understanding of the spacecraft's systems and mission goals. Participants are assigned to subsystem teams like Attitude and Orbit Control System (AOCS), Electrical Power System (EPS), Payload and Project Management, ensuring that each student works across at least two focus areas to develop system-level awareness. Additionally every participant is assigned to the operations team. To prepare for the upcoming tasks, students engage in lectures, simulator exercises, and rehearsals. The TUBIN EQM serves as a live training platform throughout this phase. Telemetry is actively generated through EQM operations, allowing participants to analyze real subsystem responses.

Students investigate power draw characteristics of individual components under different operating conditions, estimate battery capacity and solar power input under varying illumination, and evaluate how long subsystems can safely remain active during eclipse periods. These findings feed into the creation of a power budget calculator and are documented in technical notes for operational reference.

In parallel, students examine how to configure housekeeping rates, manage data limits, and retrieve recorded telemetry effectively. They study the logic and transitions of the satellite's operational modes [8], as well as gaining insight into the interactions between sensors and actuators within the Attitude Determination and Control System (ADCS). Typical topics include interpreting magnetometer data, validating sun sensor inputs, and understanding actuator command hierarchies. A series of analytical and procedural exercises support the development of system awareness. Students calculate a preliminary orbit using a state vector provided by the fictional launch provider to compute contact times and evaluate downlink capacities. Payload-related training includes interpreting camera telemetry, tracking and cataloguing image data, and establishing initial calibration parameters. All major tasks are accompanied by written documentation, with subsystem teams producing technical notes that contribute to a shared knowledge base.

As part of mission infrastructure familiarization, students coordinate with operators of other ongoing missions to negotiate time slots within the shared TU Berlin ground station network. They are also responsible for drafting detailed procedures for the Launch and Early Orbit Phase (LEOP) and Commissioning Phase, which are rehearsed in the Mission Control Centre (MCC) using the EQM. Each procedure is refined over multiple iterations to build team-wide system expertise and eliminate operational ambiguities. Redmine [9] serves as the central platform for task distribution and project documentation, with work packages, milestones, and system knowledge organized in its ticket and wiki structure. Weekly team meetings and daily use of a TU Berlin chat platform ensure consistent communication and operational alignment across all groups.

The pre-launch phase culminates in a tailored Flight Readiness Review (FRR), held approximately six weeks after course start. Each team is responsible for presenting the status of their subsystem, operational procedures, identified risks, and planned LEOP actions. Only upon successful completion of the tailored FRR are students permitted to proceed to on-orbit operations, marking the symbolic launch of the satellite.

4.2. Simulated Launch and Early Orbit Phase

The transition from preparation to operations begins with a ceremonial launch event. The symbolic launch of the TUBIN satellite is performed using original SpaceX' Transporter-2 Mission footage from the spacecraft's actual launch and orbital deployment in 2021 [10]. This event marks the beginning of the LEOP, during which students assume responsibility for the live flight model of the satellite.

Outside of the course structure, the satellite was configured to simulate a realistic post-deployment state. A small rotation rate was induced to mimic conditions immediately after separation from the launcher. Battery levels were partially depleted to simulate initial power constraints, and all telemetry history and anomaly logs were cleared at the time of virtual separation. The satellite was placed in LEOP mode, where it began transmitting its unique beacon signal, replicating the configuration it had during its actual deployment in 2021.

To enhance the realism of the experience, the course hosted a public livestream [11] of the simulated launch event in the MCC, including commentary, satellite and subsystem introductions, as well as establishing first contact, see figure 3. This created a ceremonial and professional atmosphere that underscored the operational significance of the weekend to follow.

Figure 3: Mission Control Centre - Establishing first contact during live stream

LEOP operations were conducted intensively over a full weekend, spanning from Friday to Sunday night. Students organized themselves into rotating shifts, including overnight coverage, to ensure continuous situational monitoring during the critical initial contact windows. Each shift included the full stack of engineers to operate and monitor the satellites health and ground systems, including flight director, operator, telemetry analysts for each subsystem like EPS, ADCS, thermal, communications. Teams were tasked with acquiring the satellite signal, verifying the satellites health, and assessing system status via telemetry received from UHF passes. During these shifts, the spacecraft was transitioned from LEOP mode with its beacon turned on into *suspend mode* to conserve power. The status of all subsystems was analyzed in detail, and the first command sequences were prepared and uploaded in response to real system conditions. Automated telemetry downloads during overnight passes were made available each morning, enabling timely analysis of battery performance, thermal behaviour, and attitude estimates. Shift handovers, mission logs, and analysis findings were shared using standardized documentation and team communication tools.

4.3. Commissioning Phase

Following successful initial acquisition and stabilization of the spacecraft during LEOP, the focus shifts toward bringing all satellite subsystems into full operational status. The Commissioning Phase is structured to validate core functionalities of the platform and establish readiness for nominal mission operations. Each commissioning activity is planned using operational timelines and rehearsed prior to execution. Procedures are documented and reviewed by supervisors to ensure clarity and safety. They are first rehearsed on the EQM to mitigate risks before uplinking to the flight model. Execution takes place during live passes, and telemetry is closely monitored for anomalies or unexpected system behaviour. In case of ambiguous results, students simulate subsystems offline using the EQM or analyze historical telemetry to refine their understanding. They monitor trends using Grafana dashboards, paying special attention to battery state-of-charge, power generation and consumption, temperature evolution, and the telemetry rates and fill levels. Students begin by activating components in a step-by-step process. One of the earlier goals is to enable the onboard GPS receiver to improve orbit determination, followed by evaluating the performance of ADCS sensors and actuators and culminating in testing the S-band transceiver. This allows for more efficient downlinking of payload data and reduces reliance on the lower-bandwidth UHF system.

To verify the satellite's pointing capabilities, students assess the functionality and accuracy of the attitude control system components. This ranges from switching individual devices on and off to reading and verifying telemetry output; for example, comparing sun sensor values with solar cell currents under known illumination conditions. In an extensive analysis, students investigated the time required for the satellite to reduce its angular error to below 2° from different initial offset angles, drawn from several maneuver sequences. The results, shown in Figure 4, provide valuable insight into system performance and actuator efficiency during detumbling and pointing.

Imagery from the visible and infrared spectrum payload is used to visually assess satellite orientation and cross-check expected versus actual pointing. To support this analysis, students also implemented the Moon and Earth horizon constellation method described by Koßack et al. [12], enabling angular verification based on image content and spacecraft geometry. An example of this approach is shown in Figure 5.

During the commissioning process, students discovered that one of the two onboard star trackers was not delivering valid data. After sampling more telemetry and conducting dedicated tests, they confirmed the anomaly and documented it as a single-point failure. However, thanks to redundancy in the ADCS and the availability of a second star tracker and complementary sensors, this impairment had no significant impact on operational performance. The system was reconfigured accordingly, and all subsequent attitude tasks were carried out using the remaining sensors.

Payload commissioning included evaluating the functionality and performance of the infrared and visible cameras. Students downlink calibration frames, adjust image acquisition settings, and confirm timestamp alignment and telemetry consistency. They also begin implementing cataloguing routines to track imagery and associate it with observation campaigns. The end of this phase is a fluid transition to the Nominal Operations. Most of the satellite components and modes are analyzed and fully operational. The first visual image was captured and downloaded on the fourth day after the launch as shown in figure 6.

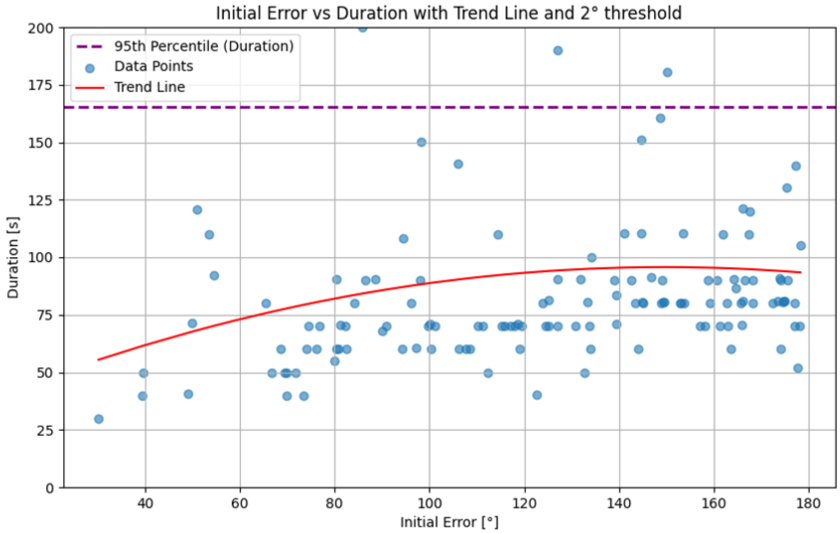


Figure 4: Time required to reduce the angular error below 2° at different initial error angles

All core systems are functional, imaging pipelines are verified, and campaign planning can begin. Students demonstrate autonomy in decision-making and show a clear understanding of how spacecraft components behave and interact under real conditions.

4.4. Nominal Operations

The nominal phase lasted for 33 operational days and introduced structured routine management protocols. Each day began with a review of the previous night's passes and image data. Operators prepared new time-tagged command sequences, updated TLEs, and executed tasks such as health checks, telemetry downloads, and campaign uploads. Operations were carried out in shifts, with a supervisor and two operators per day.

Imaging campaigns became the central focus of nominal operations. Students proposed and evaluated observation campaigns targeting high-temperature events and urban heat patterns, as illustrated in Figure 7. They used tools such as *PycturePlanner*, *Gpredict*, NASAs *Fire Information for Resource Management System (FIRMS)*, and *Windy.com* to schedule observations based on maximum elevations, cloud coverage, lighting conditions, and thermal signatures.

Downlinked images were analyzed for quality and thermal relevance, often requiring post-processing and calibration. Students adjusted exposure parameters, planned re-observations, and compared infrared imagery with publicly available datasets to validate performance. Acquired images were catalogued using internal routines that linked visual data with relevant telemetry context. Processed data products were reviewed, shared, and interpreted throughout the course.

In parallel, students maintained responsibility for system health. This included daily health checks, power budget monitoring, trend analysis of battery and temperature behaviour, and validation of TLEs. Grafana dashboards were used to visualize historical telemetry trends. Subsystem teams documented anomalies, proposed hypotheses, and rehearsed recovery procedures in simulation before applying them on the flight model.

As the phase progressed, operational workflows shifted from guided response to autonomous mission execution. Students made independent decisions and justified them based on telemetry trends, sensor behaviour, and operational context. By the end of this phase, students demonstrated full operational competence, capable of planning, commanding, and analyzing spacecraft behaviour with the confidence and fluency of a professional small satellite operations team.

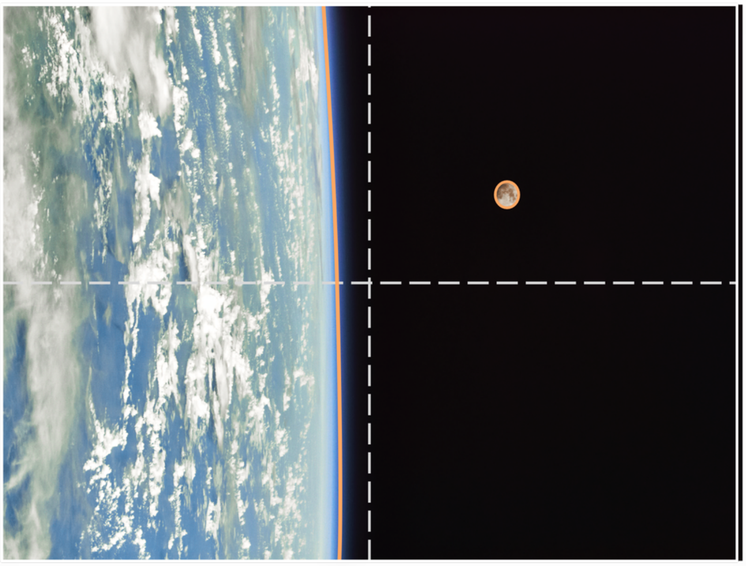


Figure 5: Using Moon and Earth horizon constellation for attitude verification

5. Evaluation and Educational Outcomes

The structure and execution of the course not only provide students with valuable hands-on experience but also support the development of core competencies essential for careers in the space sector. As the semester progresses, students transition from guided instruction to independent mission operation, gradually building confidence in handling the responsibilities of a flight operations team.

Throughout the course, participants gain technical fluency in interpreting live telemetry, configuring command sequences, managing subsystem behaviour, and validating satellite pointing and imaging performance. Subsystem-specific knowledge, such as power modelling, thermal trend evaluation, and attitude control logic, is acquired through repeated interaction with real satellite data.

The use of professional tools and workflows, such as time-tagged command stacks, shift handovers, and mission logging, helps students develop a practical understanding of how satellite missions are executed in operational environments. Tools like Grafana, JupyterLab, and the internal telemetry viewer enable flexible, data-driven analysis and support a wide range of technical investigations. In addition to technical skills, students gain experience in mission planning, time management, and decision-making under uncertainty. Team-based activities such as subsystem coordination, procedure development, and campaign implementation foster collaboration, communication, and shared responsibility. The rotating shift structure ensures that each participant takes ownership of both routine tasks and critical decisions, further reinforcing the operational mindset.

Evaluation of participants is based on participation, technical notes, presentation-reviews, campaign reports, performance during live shifts, and final report. The final presentation at the end of the semester provides an opportunity to reflect on lessons learned and to communicate results to peers and instructors. Feedback collected from participants highlights the authenticity and challenge of the course experience. Students consistently report improved confidence in applying their knowledge and a greater understanding of the complexities of satellite operations. Several graduates from previous cohorts have since joined space companies or research institutions in roles directly related to mission operations, systems engineering, or ground segment development. Shortly after completing the module in the summer 2024, one participant was hired as flight director for another satellite project at the university.

The course proves that when students are placed in realistic and accountable roles, they not only meet

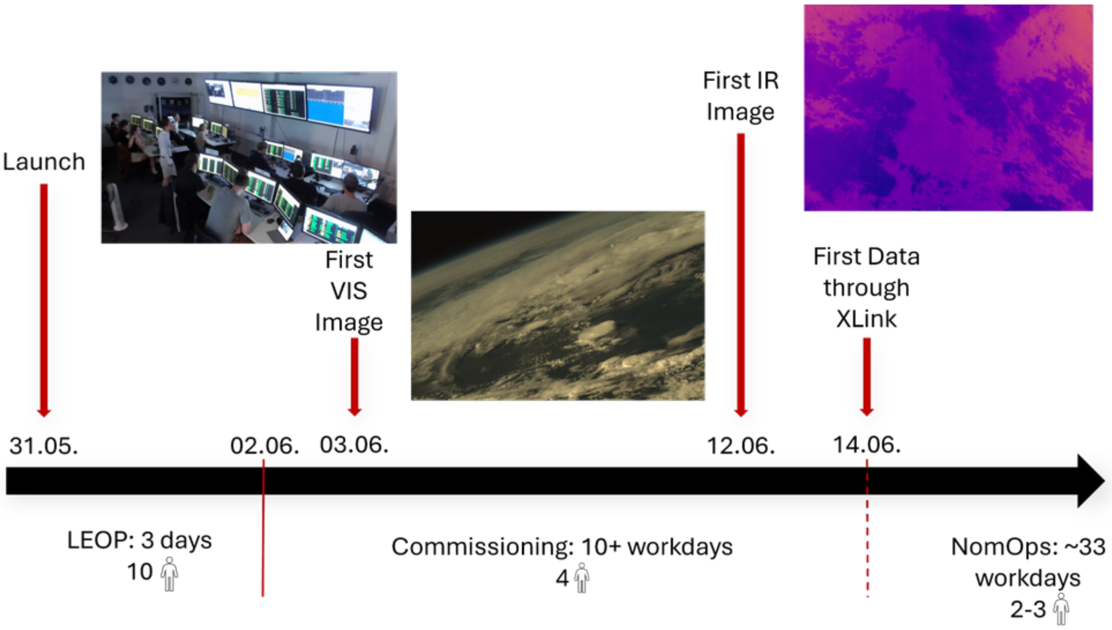


Figure 6: Timeline with achievements until Nominal Operations. Number of student operators per satellite pass shown below each bar.

expectations but often exceed them, demonstrating that immersive operational training is an effective and scalable model for future space education.

6. Comparative Analysis

While satellite design and development are increasingly part of university curricula, hands-on operations training with real spacecraft remains rare. Most academic programs focus on theoretical modeling, systems engineering, or hardware integration prior to launch, but few provide students with the opportunity to interact with an in-orbit satellite during its operational lifetime.

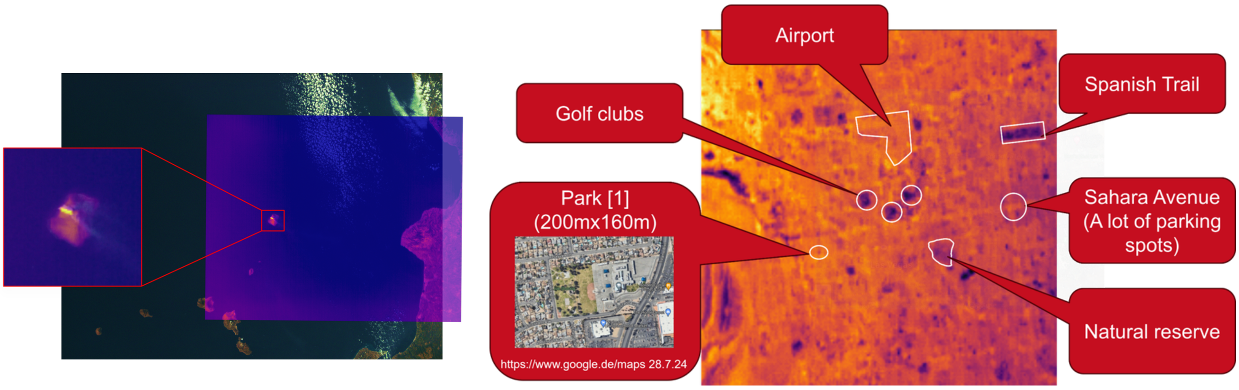
Compared to simulation-based mission exercises or lab-based mock operations, the TU Berlin model offers an authentic learning environment in which students work with real telemetry, control software, and mission data. This transition from simulation to reality creates a steep but valuable learning curve and fosters the kind of mission ownership that is difficult to replicate in abstract exercises.

A small number of international programs offer partial exposure to satellite operations. The University of Surrey and Kyutech involve students in long-term CubeSat programs [13] [14], while ESA's Academy organizes short intensive operations training [15] or the dedicated OpsSat [16] but with a focus on testing new software. However, these models often limit student involvement to specific roles or time windows, and typically do not allow for live commanding of the spacecraft.

TU Berlin's approach stands out by embedding the full Phase E operations cycle into a semester-long course, integrating real-time operations, technical documentation, shift rotations, anomaly handling, and imaging campaigns. All operational decisions ranging from mode transitions to payload tasking are executed by students, under supervision but with growing autonomy.

Another unique aspect is the deliberate use of a spacecraft that has already been in orbit for several years. By simulating a new launch and reset scenario, students are placed in a realistic post-deployment setting while still benefiting from a known and stable platform. This model balances operational risk with learning opportunity.

The structure is also designed for scalability. Universities with their own functioning satellite or with access



(a) Volcano Stromboli – visual and infrared

(b) Annotated heat map of Las Vegas - parks show noticeably lower temperatures

Figure 7: Imagery from student campaigns: volcanic thermal activity and urban heat mapping

to other satellites could adopt. TU Berlin's course provides a blueprint for immersive operations education that can be adapted to different institutional capabilities and mission profiles.

7. Conclusion and Future Outlook

This course at Technische Universität Berlin demonstrates how immersive spacecraft operations training can be fully integrated into an academic curriculum using an existing satellite platform. By simulating the full Phase E operations cycle, students engage in a mission experience that blends real-time decision-making, technical execution, and team-based responsibility. Through this hands-on format, participants not only develop proficiency in satellite systems and ground operations, but also cultivate an operational mindset — learning to plan under uncertainty, respond to anomalies, and coordinate within a team structure. They rehearse procedures, manage shift work, and work with professional tools in a mission-critical context. This progression from preparation to execution results in observable growth in confidence, fluency, and systems understanding.

The use of a real spacecraft creates a unique educational environment. Unlike traditional simulations, students are required to interpret real telemetry, upload live commands, and deal with actual spacecraft constraints. The sense of responsibility and relevance deepens their engagement and reinforces the connection between classroom knowledge and operational practice. Looking ahead, this course model offers a scalable framework for operations training. It can be adapted for different mission types, satellite platforms, and levels of complexity. Potential future directions include multi-satellite coordination, integration of autonomous tools, or extending the model to cross-institutional teams.

The model of TU Berlin demonstrates that such an evolution is not only possible but essential. *Through real space, students gain real skills* and with those skills they are nearly mission-ready space engineers; well prepared to shape the future of space exploration.

Acknowledgements

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