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TUBIN End-of-Life Operations: It's getting hot in here

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Abstract

The End of Life (EoL) phase of a satellite offers unique opportunities to monitor its final days in orbit in the Very Low Earth Orbit (VLEO) environment. However, the same physical effects that are interesting to observe also make operations increasingly challenging as re-entry approaches. These effects include increased atmospheric drag, rapidly deteriorating orbital elements and reduced ground station contact time. Based on experience gained from the EoL operations of past CubeSat missions at the Chair of Space Technology [1] [2], an operations strategy is developed that scales up to the microsatellite TUBIN. This strategy addresses challenges in mission planning and orbit determination during rapidly changing timelines and conditions. This includes technical adjustments in the ground and space segment, a comprehensive plan for EoL experiments for payload and bus, and well-defined procedures for the difficult-to-schedule final orbits. A key component of this strategy is the use of GPS data and Doppler shift evaluations to update the rapidly out dating Two-Line elements (TLEs) frequently. These updates are especially important for Doppler shift correction in the ground segment, but also crucial for the spacecraft's pointing maneuvers. To maximize the downlink capacities and mission return during EoL, several features need to be implemented in to the satellite's onboard Software via a software update. These features enable a higher degree of automation for the downlink of telemetry and methods to drastically reduce the needed command quantity for a drag reduction campaign.This approach carries certain risks, including the potential for data loss, which are acceptable in the prospect of the opportunity to gain valuable knowledge. The primary objective is to maximize data acquisition and downlink in VLEO. Several specific effects will be investigated. Operating the visual and infrared payloads as long as possible is of special interest, among others to evaluate the influence of improved ground sampling distance (GSD) on the detection of thermal anomalies. The impact of higher drag on the attitude determination and control system will be monitored, especially the influence on attitude stability and torque needed for attitude maneuvers. Since the downlink via S and X band requires target pointing, the ADCS performance is examined, as it requires ever higher angular rates from the satellite. These also affect the communication system in terms of signal strength under these rapidly changing conditions. In the final re-entry moments of TUBIN the focus will be monitoring temperature variations throughout the satellite caused by increased atmospheric friction. Applying expertise of previous satellite re-entries, the EoL phase of TUBIN presents a valuable opportunity to gather critical data about VLEO environment and dynamics. The comprehensive approach outlined in this strategy aims to maximize the scientific return from the increasingly relevant final operational period.

Keywords: End-of-Life Operations, Re-Entry, Small Satellite, Satellite Operations, VLEO, microsatellite, modular, software

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1. Introduction

The academic microsatellite TU Berlin Infrared Nanosatellite (TUBIN) (see fig. 1), developed and operated by Technische Universität Berlin, is based on the modular TUBiX20 satellite bus [3], first demonstrated in the TechnoSat mission launched in 2017 [4]. While TechnoSat focused on validating the satellite bus system, the TUBIN mission expanded its objectives to include the demonstration of its primary payload: two uncooled microbolometer cameras. These infrared sensors, with a spatial resolution of approximately 150 meters per pixel, have proven their ability to reliably detect high-temperature events, such as wildfires, from orbit [5]. Complementing the infrared cameras is a VIS CMOS camera, which enhances data processing and supports image registration for the TIR sensors. TUBIN was launched in 2021 into a 530-km Sun-synchronous orbit (SSO). The satellite has gradually been losing altitude due to atmospheric drag and is predicted to re-enter Earth's atmosphere in early autumn 2025. Its re-entry offers a unique opportunity to study satellite behavior during the final phase of its lifecycle. Thus, careful planning is essential to maximize the scientific and engineering value of this rare event [1] [2].

The re-entry phase of the TUBIN mission offers a unique opportunity to gather valuable data and operational experience in the Very Low Earth Orbit (VLEO) environment, an increasingly significant region for future satellite missions [6]. By contributing to the re-entry datasets of similar missions, such as the Berlin Experimental and Educational Satellites (BEESATs) and European Space Agency (ESA)'s Ops-Sat, TUBIN adds valuable insights for understanding satellite behavior and operations during this critical phase. This phase allows for observing atmospheric drag effects, including the resulting temperatures and orbit degradation, which are essential for assessing satellite performance in the lower reaches of Earth's atmosphere [7]. By monitoring the impact on the Attitude Determination and Control System (ADCS), the mission provides insights into how these systems perform under increasing aerodynamic and thermal stress, offering guidance for optimizing satellite design and operation in VLEO, where maintaining orbit stability requires efficient propulsion or drag-compensation systems. Collecting end-of-life data from all subsystems enables a detailed evaluation of performance degradation, laying the groundwork for more accurate lifetime estimations and improved designs for future missions. Furthermore, studying the early stages of re-entry offers a valuable opportunity to better understand the operational challenges during re-entry, allowing to integrate these insights into future End of Life (EoL) phases to further extend the gathered data.

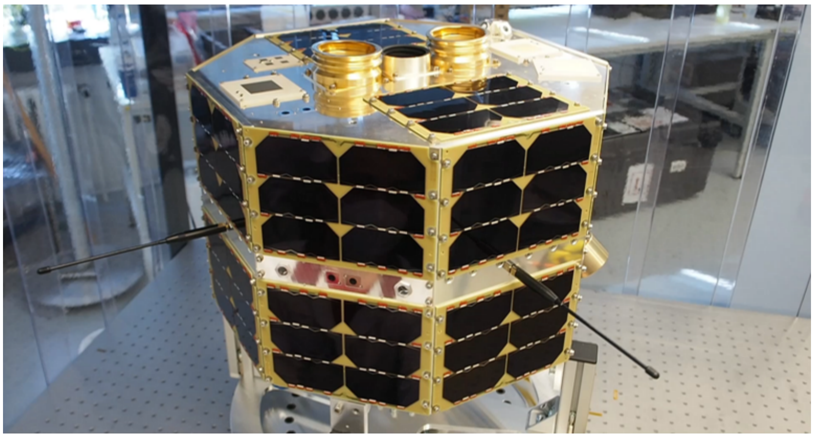

Figure 1: TUBIN flight model Prior to launch in the integration laboratory

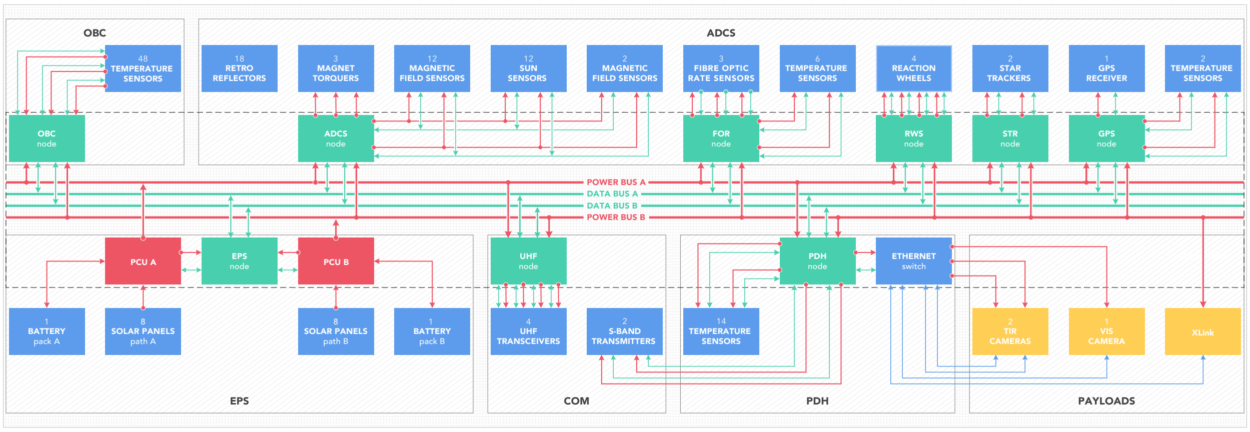

Figure 2: System architecture of the TUBIN spacecraft. Green tiles represent TUBiX20 nodes while blue tiles are components connected to them. Payloads are shown in yellow, power buses in red, and data buses in green. Multiple components are summarized as part of one subsystem denoted by shaded boxes.

2. The TUBiX20 Satellite Platform

TUBiX20 is a modular satellite platform for microsatellites of 20 kg and above. Satellite tasks are distributed between multiple processing units, or nodes. These nodes communicate via a central CAN bus. The software is similarly distributed, supporting modularity. This design enables high reusability of both hardware and software across missions. Subsystems can be easily extended by adding nodes with specific functions. To improve reliability, all nodes are redundant.

2.1. The TUBIN Satellite

Figure 2 shows the system architecture of TUBIN. Using the modularity of TUBiX20, each subsystem consists of one or multiple computational nodes. Each node in turn may have sensors or actuators connected to it. Namely, the ADCS subsystem consists of the main ADCS node, as well as the subordinated nodes Reaction Wheel System (RWS), Fiber Optic Rate sensor (FOR), Star Tracker (STR) and Global Positioning System (GPS). As seen in fig. 2, these subordinated nodes control four reaction wheels, two star trackers, a GPS receiver as well as a set of high-precision fiber optic rate sensors. The payload subsystem consists of the TUBiX20 Payload Data Handling (PDH) node connecting the three payload cameras and an X band transceiver via Ethernet.

3. EoL Ops strategy

This section presents the proposed EoL operations strategy for TUBIN. Initially, the EoL campaigns from the BEESAT satellites at Technische Universität Berlin (TU Berlin) in section 3.1, as well as the EoL campaign for ESA's Ops-Sat in section 3.2 are described. With the lessons learned during these campaigns, the TUBIN EoL campaign was designed and will be laid out in section 3.3.

3.1. BEESAT EoL Ops strategy

Within the BEESAT satellite series TU Berlin launched five 1U CubeSats between 2009 and 2019. As an example, BEESAT-4 can be seen in fig. 3. Over the course of nine months spanning from September 2023 to June 2024 the satellites BEESAT-2, -3, -4, and -9 re-entered Earth's atmosphere. This presented a unique opportunity to study the behavior of small satellites in VLEO and during re-entry. The lessons learned during these campaigns were extensively described in [1] and [2].

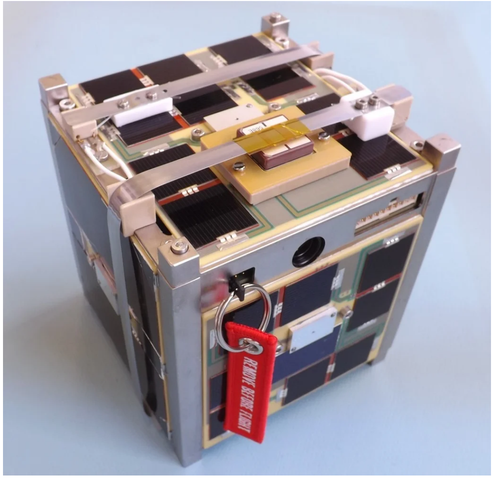

Figure 3: BEESAT-4 (Image Credits: TU Berlin)

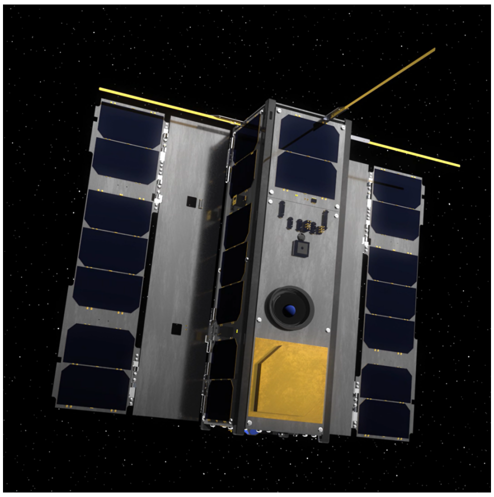

Figure 4: Ops-Sat-1 (Image Credits: ESA [9])

The main goal of the BEESAT EoL campaigns was to receive telemetry as long as possible during their descents. Thereby, increasing angular rates were observed with BEESAT-2 and -4 below an altitude of 300 km, but it was possible to dampen them through the usage of their magnetorquers. BEESAT-9 was the only satellite that also showed an increase in temperatures within its last 3 orbits up to 25 °C/min in the last frames at an altitude of only 97.6 km above the mean earth radius, which was measured by BEESAT-9's Global Navigation Satellite System (GNSS) receiver. For all BEESAT campaigns the tracking and thereby communication became difficult in the last 36 hours as the provided Two-Line-Elementss (TLEs) became quickly outdated, as the SGP-4 algorithm does not account for the denser atmosphere of lower altitudes well. However, utilizing Satellite Networked Open Ground Station (SatNOGS) and an own Software Defined Radio (SDR) ground station, it was possible to derive custom TLEs from Doppler shift curve fitting with the help of the satellite tracking toolkit for radio observations (STRF) software [8]. Therefore, a telemetry beacon was activated over SatNOGS ground stations during the final orbits. Post-flight these observations were decoded yielding additional telemetry that was transmitted outside of TU Berlin ground station passes.

3.2. Ops-Sat EoL Ops strategy

Ops-Sat, shown in fig. 4, was a 3U CubeSat operated by ESA and reentered on May 22, 2024. The Ops-Sat team conducted an extensive EoL campaign of which the operational aspects and results are published by Frederik et al. in [7]. These include: conducting third-party experiments in the final days of the mission, reducing atmospheric drag extending the mission lifetime as well as overcoming challenges in communicating with the spacecraft as TLEs deteriorate. For atmospheric drag reduction, the spacecraft's nominal attitude was switched from tumbling to near-constant three-axis attitude control in a newly implemented dedicated pointing mode that minimized the area facing the flight direction [7]. Potential communication challenges were addressed by a Ultra High Frequency (UHF) campaign. This UHF campaign, similar to the ones conducted during the BEESAT re-entries, involved the international amateur radio community and SatNOGS by continuously transmitting telemetry beacons around the world. These received telemetry beacons were decoded live and shared by ESA allowing the amateur radio community and the general public to track the spacecraft until its final demise [7].

3.3. TUBIN EoL Ops strategy

The TUBIN EoL operations strategy is mainly based on the BEESAT EoL strategy laid out in section 3.1 and builds on some important inspirations and lessons learned from the Ops-Sat EoL campaign. However, as TUBIN is a larger and more capable spacecraft compared to the BEESATs some important adaptations of the EoL operations concept are necessary to fully utilize the additional capabilities.

3.3.1. Communication

TUBIN uses half-duplex UHF communication for telecommanding and transmission of live telemetry. Additionally, TUBIN features two S band transmitters with a maximum data rate of 1 Mbit/s each that can be used to download payload data and telemetry recorded outside of ground station contacts. TUBIN's payload also features an X band transmitter with a maximum data rate of 12 Mbit/s that can be used to download payload data. This high bandwidth communication is an especially useful capability for the EoL phase as it enables the download of much larger data volumes compared to UHF, as long as the orbit determination and ADCS performance in VLEO are sufficient to maintain alignment between the antennas in the space and ground segment. This allows the recording and downloading of more telemetry data from VLEO compared to BEESATs. However, since a reliable S band and especially X band link cannot be guaranteed in the final passes, a UHF telemetry beacon similar to the one used in the BEESAT and Ops-Sat campaigns is utilized to broadcast the most crucial telemetry to be revived by SatNOGS stations. The implementation of these is further discussed in section 4.

3.3.2. Orbit determination

Precision orbit determination onboard TUBIN is performed using GPS when required, with baseline orbit information being available from regularly uploaded TLEs at all time. In addition to various onboard tasks, good orbit determination is vital for mission planning and especially for performing Doppler shift correction and antenna pointing to maintain communication as discussed in section 3.3.1. As this has proven very effective for EoL orbit determination during the BEESAT EoL campaigns, the TUBIN EoL campaign additionally will make use of STRF based orbit determination. In addition to STRF, the TUBIN EoL campaign also incorporates GPS data. Therefore, GPS telemetry is recorded continuously in 30 s intervals. This continuous recording has already been started in February 2025 so that at least 6 months of continuous GPS data will become available from VLEO for trajectory analysis.

3.3.3. Drag reduction

As mentioned in section 2.1, TUBIN features a sophisticated ADCS, capable of precise 3 axis attitude control. Up until now, whenever TUBIN is idle in between experiments, imaging campaigns or ground station passes, the ADCS was also left idle, reducing power consumption and operational complexity. Therefore, like many small satellites, TUBIN is tumbling at a very low angular rate below 1 °/s for the majority of the time. However, since TUBIN needs to perform daily target pointing for S and X band operations, leaving the ADCS idle to observe spin up by increasing disturbance torques as done during several BEESAT campaigns is not feasible. Instead, the TUBIN EoL operations strategy includes a drag reduction campaign similar to the one conducted by Ops-Sat [7]. However, as the differences in cross-section from the nominal idle attitude of tumbling to the minimal drag attitude in nadir pointing mode is smaller for TUBIN compared to Ops-Sat a smaller effect on orbital decay rate is expected. The expected decay of TUBIN with and without the drag reduction campaign as predicted by a Debris Risk Assessment and Mitigation Analysis tool (DRAMA) analysis is shown in fig. 5. For this DRAMA analysis, the operational constraints identified by Traub et al. in [10] are taken into consideration as they apply to the TUBIN spacecraft. Since TUBIN features star trackers, is capable of damping angular momentum during three-axis attitude control, has margin in the power budget, and the TUBiX20 platform overall proved to be very stable, the main limitations for the drag reduction campaign are spacecraft availability as well as uplink of necessary commands via UHF. As observation campaigns and downlink activities dictate TUBIN's attitude for up to 20 % of the time, the spacecraft availability for the drag reduction campaign is estimated at 80 % of the overall time. To address the uplink bottleneck identified in [10], the automatic execution of the drag reduction campaign was implemented in the onboard software. This is further discussed in section 4. To evaluate the effectiveness of the drag reduction campaign, TUBIN as usual was left tumbling when idle through February of 2025 while already continuously recording GPS data to serve as a baseline measurement. The continuous drag reduction campaign started in April 2025 and will be continued until EoL.

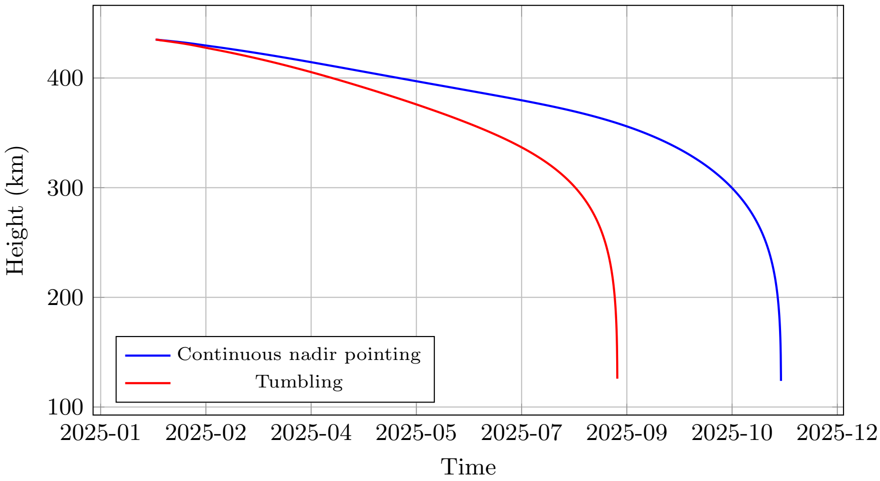

Figure 5: ESA DRAMA analysis for TUBIN decay in different idle attitudes

3.3.4. Data of interest

In the final days of the TUBIN mission, special emphasis will be on recording and downloading data from the following subsystems:

- **GPS** as this data is needed during the EoL campaign for orbit determination as well as post-flight for VLEO trajectory analysis
- **ADCS** as the dynamics of this subsystem change significantly from Low Earth Orbit (LEO) to VLEO due to increased drag and changed target pointing geometry at lower altitudes.
- **Thermal** telemetry is of increasing interest the closer the re-entry approaches as very little in-flight thermal behavior data of spacecraft during early re-entry exists. BEESAT-9 has shown that in principle it is possible to receive telemetry during early re-entry, when it happens to occur over a ground station.
- **Electrical Power System (EPS)** telemetry is of interest, as the drag reduction campaign and the transmission of UHF telemetry beacons increase energy consumption compared to the nominal mission configuration. Additionally, the solar input is to be monitored for efficiency decreases in solar cell performance due to atmospheric heating.
- **Communications** was shown to be a major challenge during EoL operations during previous campaigns. On the one hand, orbital elements needed for Doppler shift correction and antenna tracking outdate quickly make communication challenging, while on the other hand theoretically, the link budget should improve due to the lower slant ranges involved, lowering the free-space loss. To observe any possible changes, data from the communication subsystem regarding signal strength is recorded. Additionally, the radio spectrum observed at TU Berlin ground stations is recorded during the final passes.

This data will be recorded and downloaded as part of regular S band telemetry dumps. As these cannot be guaranteed until the very last second, close to EoL this data will be continuously transmitted via UHF telemetry beacons discussed in section 3.3.1.

3.3.5. Operational risks

The BEESAT and Ops-Sat EoL campaigns have shown that operations until shortly before re-entry are possible. However, the operations during the last hand full of days are very different from nominal spacecraft operations. Especially, the amount of acceptable operational risk grows drastically in comparison as the

EoL approaches, representing a stark contrast to the otherwise very risk-averse procedures for spacecraft operations. This includes blind commanding of the spacecraft as described in [2], risking data loss or battery drainage. Additionally, thresholds for safe mode activation are examined in regards to possibly triggering in the VLEO environment. Also, the definition of the safe mode itself is critically examined as a "safe" configuration of the spacecraft in EoL leans more towards ensuring mission return than spacecraft health. For example, the continuous transmission of the telemetry beacons discussed in section 3.3.1 is absolutely critical to ensure mission success in EoL and needs to be continued no matter what, regardless of critical battery state, failing devices, high spin rate or any other critical anomaly. A trade-off, that during regular operations would be resolved more in favor of preserving spacecraft health.

3.4. Wrapping up operations

As the re-entering spacecraft will (obviously) no longer be available after re-entry, all nominal operations need to be wrapped up before EoL. This includes downloading any remaining payload data and making sure all information needed from the flight model for post-flight analysis is well saved, as after EoL, it can no longer be accessed from the satellite!

Additionally, as the spacecraft has reached EoL, there is the opportunity to test all spacecraft systems to measure any changes in the performance of certain subsystems or components during the mission's lifetime. However, most importantly, there is the opportunity to check out any backup or redundant equipment and redundant node sides on board; this previously was not needed and therefore preserved in case it ever becomes necessary. This information can be of great value for the development of future satellites as well as the operations of already flying spacecraft that may be using the same components.

On TUBIN, one piece of backup equipment is an SD card in each of the three cameras serving as a backup to their usually used internal flash storage. Using these SD cards has so far been omitted as they are expected to significantly deteriorate once in use due to solar radiation. Hence, booting the cameras from their SD cards near EoL would be of great value.

3.4.1. TUBIN EoL Ops Preparations

As a critical and unique mission phase EoL requires, similar to Launch and Early Orbit Phase (LEOP), careful planning and preparation. A crucial step is the formation of an operations plan, such as the one formulated in this paper. However, other crucial steps must not be missed. This includes:

- **Testing** of all involved procedures, both, on the ground using development hardware, and crucially also in space well before they become critical for mission operations. This is especially important for the newly developed features discussed in section 4.
- **Training** of the individuals involved to ensure they are familiar with all procedures that need to be conducted during EoL. This is especially important for systems and procedures that are never or only rarely used in nominal operations. In this case, this would be orbit determination using STRF, swapping out the TLEs used in the ground segment for antenna tracking and Doppler shift correction between passes as well as automatic telemetry transmissions and SatNOGS operations.
- **Monitoring** of all ground and space station systems is of utmost importance as the passive re-entry will proceed no matter what. Therefore, issues must be identified and addressed early to enable the EoL campaign. An important part of this is the monitoring of the Radio frequency (RF) spectrum, increasing situational awareness during passes with potentially subpar link quality. To accommodate this increased monitoring demand, the EoL ops are executed by a larger team compared to nominal operations; and similar to LEOP, EoL operations are operated from the TU Berlin main control room.

4. Onboard Software adjustments

In contrast to nominal operations, requirements and necessary features for the onboard software are different during the spacecraft's EoL. This section introduces the changes implemented for TUBIN.

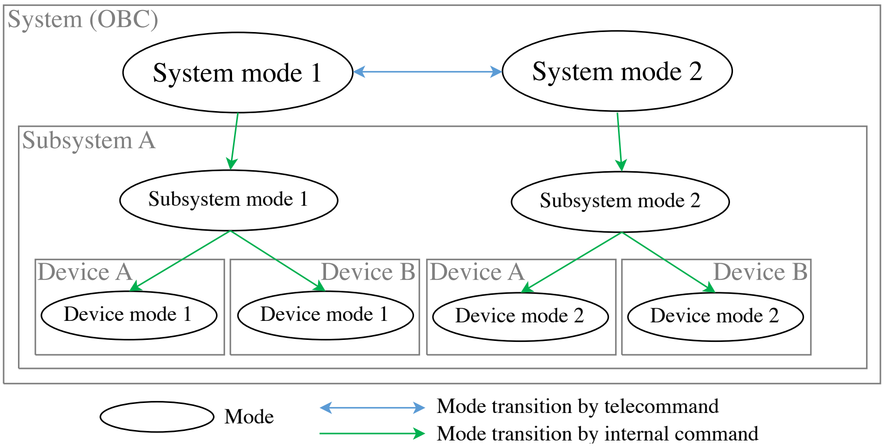

Figure 6: The hierarchical mode concept operates as follows: When an operator sends a system mode command to the OBC, it automatically propagates the corresponding child mode to all subsystems. Each subsystem then sets the required child modes on its devices, which may be distributed across different nodes. Devices can be powered on or off during this transition. (from [11])

4.1. Utilized Features of the Modular Onboard Software

As the satellite bus, the TUBiX20 software is also built in a modular way. Each node in the system has several applications that run in parallel and perform specific tasks. The proposed EoL procedures make use of several software features that are briefly introduced in the following.

Hierarchical Modes. To minimize the complexity of manual satellite operations and as a first step towards autonomy, TUBiX20 features a hierarchical mode concept [11]. The concept is based on the fact that every satellite is built hierarchically. The system (the parent) consists of subsystems (the children) which in turn consist of nodes that consist of components. In every operational situation, all layers and thus the whole satellite have a well-defined state. This is what we call a mode. Consequently, when commanding a mode to the system (OBC) the system in turn commands its subsystems to a certain mode. The subsystems then command their nodes to enter a certain mode. Finally, the nodes command their components to enter a mode by enabling and configuring them. Figure 6 shows this hierarchy of modes. Any deviation from the commanded state is considered a fault and is handled on the layer on which it was detected. Only in case it could not be handled the layer above is informed. During a mission's lifetime, especially in the EoL scenario, new operational states may become necessary. Instead of going through a full release and software upload cycle, the TUBiX20 software allows for modifying or adding new modes via a few telecommands. In these telecommands so called parameter sets are uploaded to the spacecraft, immediately allowing it to enter these new modes.

Automation. Building on modes as the foundational infrastructure, automatic mode transitions based on specific triggers may be initiated. These triggers include factors such as time, spacecraft position, or illumination levels. TUBIN's OBC implements this kind of automation as part of its *OpsBot* application. The OpsBot consists of several modules. Each module listens for one of the mentioned triggers and executes defined automations. For instance, this system allows the satellite to autonomously capture images of a designated target on Earth whenever it passes within a defined region at a specified elevation, or to initiate automatic downlinks when passing over ground stations. Another module triggers on occultation changes of the satellite. This way, an arbitrary mode may be issued when entering or leaving Earth's eclipse. While all modules are always listening for their triggers in the background, only one module can execute an automation at a time. Module execution is priority-based, i.e. lower priority modules are preempted by higher ones. Depending on the module, preemption leads to either abortion of the module or suspension. Suspended modules may immediately continue again as soon as the higher priority one is done.

4.2. Required Adjustments for EoL

To support the EoL campaign, new OBC modes were introduced via parameter set upload. Also via parameter sets, these new modes were then integrated into the OpsBot's occultation modules – with low priority to ensure that nominal operations such as downlinks and imaging are not disturbed.

Continuous GPS Logging - All of the newly introduced OBC modes and respective OpsBot modules ensure continuous GPS data recording. For the acquisition of baseline measurements for the upcoming drag reduction campaign (see section 3.3.3), the newly added OrbitDetDamping mode is entered in the first few weeks after the software adjustment.

Drag reduction - To minimize drag, nadir pointing mode is entered on the ADCS. During eclipse phases, star trackers are activated to compensate for the absence of sun sensor data (mode OrbitDetNadirNight), while keeping energy consumption low during the longer illuminated phase of the orbit (mode OrbitDet-NadirDay). An overview for naming and specifications of these modes is portrayed in Table 1.

OBC Mode	**GPS Logging**	**ADCS Mode**	**Star Trackers**
OrbitDetDamping	✓	Damping	–
OrbitDetNadirDay	✓	Nadir Pointing	–
OrbitDetNadirNight	✓	Nadir Pointing	✓

Table 1: Overview of features for new OBC modes for GPS and ADCS adjustments during the EoL phase.

AutoSend - Another feature introduced for the EoL campaign is the AutoSend functionality, which enables periodic transmission of telemetry frames as telemetry beacons. This feature is particularly beneficial for ensuring the continuous reception of telemetry from the satellite, even in cases where telecommands cannot be received by the spacecraft. By using global tracking networks such as SatNOGS AutoSend allows for widespread data reception. Furthermore, regular transmissions enable orbit determination through STRF (see section 3.1).

The implementation of the latter feature is achieved via a software update, introducing a dedicated application that periodically simulates an external telecommand to trigger the transmission of telemetry. The transmitted data is configured to include key operational parameters relevant for EoL monitoring specified in section 3.3, which can be adjusted easily via telecommand. To prevent interference with nominal satellite operations, the periodic timer for AutoSend is reset upon receiving any telecommand, as the transceiver uses simplex communication, meaning it can only receive telecommands while not actively sending. Hence, the timer reset ensures that operator interventions take priority when required.

5. Conclusion and Outlook

The EoL operations strategy for the TUBIN microsatellite presented in this paper scales up the EoL operations approach from TU Berlin's BEESATs to the larger and more capable TUBIN spacecraft. By building on lessons learned from the EoL campaigns of the BEESATs and ESA's Ops-Sat, the strategy laid out in section 3.3 aims to address the unique challenges posed during EoL operations. Previous EoL campaigns revealed these challenges to mainly consist of rapidly outdating orbital elements due to the increased atmospheric drag as well as reduced ground station contact time [1][2][7]. In addition to addressing these challenges, the presented EoL operations approach aims to maximize the scientific insights into the unique operational environment of VLEO and potentially early atmospheric re-entry. Before this, the final weeks of the mission will be utilized to access the EoL state of all systems and to test any redundant systems that have been omitted so far.

The key to this EoL operations approach is the implementation of several dedicated EoL features in the onboard software via software upload and parameter set updates as discussed in section 4. These features include a drag reduction campaign, aiming to reduce the decay rate and extend the mission's lifetime. Additionally, this campaign continually enables and records data from the GPS receiver for orbit determination purposes. A critical feature for EoL operations is the implementation of the *AutoSend* telemetry beacons, as these enable orbit determination via STRF as well as continuous acquisition of telemetry via SatNOGS during the final orbits. Both of which have been essential for previous EoL campaigns, as described in section 3. The fast implementation of these features making use of existing features in the TUBiX20 onboard software, such as the automation application *OpsBot*, is a testament to the modularity of the TUBiX20 platform.

In this paper, the importance of proper preparation of EoL operations was laid out. Special emphasis is also placed on the training of the personnel involved in the EoL procedures, as well as the close monitoring of the ground segment during EoL operations. Last but not least, this paper outlined the rapid shift in the trade-off between ensuring spacecraft health and mission return as EoL approaches, representing a stark contrast to all other phases of a spacecraft's life cycle.

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