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InnoCube – Final design of the wireless satellite technology demonstration

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Abstract

The Innovative CubeSat for Education (InnoCube) represents a collaborative effort between the University of Würzburg's Information Technology for Aerospace chair and the Technische Universität Berlin's Chair of Space Technology. The 3U+ CubeSat is scheduled for launch in October 2024 serving as a technology demonstration for two innovations: SKITH (SKIpTheHarness), a wireless satellite bus technology, and Wall#E, a carbon fiber-reinforced plastic solid-state battery. Additionally, the satellite incorporates an Experiment for Precise Orbit Determination (EPISODE). To showcase the SKITH concept, the InnoCube enables wireless data exchange among all satellite modules, including the onboard computer (OBC), ADCS, power distribution and conditioning unit (PCDU), and up-/downlink transceiver, facilitating seamless communication with the payloads. The satellite's wall between the solar panels accommodates experimental Wall#E structural batteries, emulating their intended use as satellite structure, as well as interior mounted batteries for reference. This developmental phase is crucial to elevate the Technology Readiness Level (TRL) of Wall#E, paving the way for a subsequent experimental satellite application, WallE2Space. Given that Wall#E, as a structural battery, deviates from the properties of conventional polymer composites or Li-polymer batteries, a separate conventional power system is essential for satellite operations and experimental payload activities. The EPISODE, serving as a secondary payload, aligns with the educational strategy of the university and is primarily developed through student projects and theses. Comprising a custom Global Navigation Satellite System (GNSS) receiver and a Laser Ranging Experiment (CubeLRR), EPISODE is designed for versatility, supporting multiple GNSS signals on the L1 frequency, including GPS, Galileo, and others. CubeLRR, a miniaturized four-prism pyramid-shaped Laser Retro Reflector, adheres to CubeSat size constraints and aims to verify GNSS measurements.

This paper provides an overview of the final design of InnoCube, researching into system details and technical aspects of the mission design. It will highlight the critical development aspects and final developments to bring the system into orbit with an emphasis placed on the assembly and testing of engineering model.

Keywords: CubeSat; wireless bus; data harness free satellite; satellite

1 MISSION OVERVIEW

The InnoCube (Innovative CubeSat for Education) mission is developed by students and scientific staff as a joint small satellite mission of the Chair of Information Technology for Aerospace at the University of Würzburg (UWU) and the Chair of Space Technology at the Technische Universität Berlin (RFT). The mission aims to test innovative and advanced technologies: SKITH, a wireless satellite bus technology, and WallE, a carbon fiber-reinforced plastic solid-state battery, on a 3U+ CubeSat. The CubeSat bus is based on a novel technological wireless bus technology – SKITH - from the Chair of Computer Science VIII at UWU. The project is supplied by the Avionic Department of the Institute of Space Systems in Bremen and is supported by the Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag. The project includes the qualification of the system all the way to the flight model. Generally, InnoCube is developed according to the prototype model philosophy, in which a prototype (here the Engineering Qualification Model - EQM) and a flight model (Flight Model - FM) will be available. For intensive electrical or software tests during development, the combination of individual Demonstrator Models (DMs) results in an Electrical and Functional Model (EFM). This model is used to test the most important bus functions and the power distribution via the PCDU. The estimated launch with SpaceX transporter-12 mission will put the satellite in a SSO of approx. 510 km.

The primary mission objectives of the InnoCube mission are as follows:

1. **SKITH Wireless Bus demonstration:** Development and flight testing of a wireless Data Bus system for internal subsystem data communication.
2. On-orbit hard- and software demonstration:
    1) WallE2Space a novel carbon fiber-reinforced plastic solid-state battery
    2) EPISODE a SDR based GNSS orbit determination system and determination algorithms.
    3) CubeLRR Laser ranging retroreflector experiment.
    4) Amateur Radio Community Transponder Payload.
3. **Student education:** Involvement of students during the InnoCube project phases, especially in the development of EPISODE and CubeLRR.

The secondary mission objectives are:

1. Qualification and risk avoidance for the development of satellite components.
2. Public relations and utilization of mission results.
3. Improvement of education and training.

The satellite bus is based on the developed technology from the Skith project. The aim of Skith is "the wireless satellite." The entire data harness will be replaced by robust, high-speed, real-time short-range radio communication. This will make InnoCube one of the first small satellite relying solely on a wireless data bus. The second technology demonstration is the energy-storing satellite structure developed in the Wall#E project, which is envisioned to replace conventional battery technology in future. As further payload, hardware will be developed for the concept of a software-based solution for receiving signals from global navigation satellite systems (GNSS) to enable precise positioning of the CubeSat. The verification takes place during the operational years, where scientific/technological data will be collected, and simultaneously, the configurable GPS payload will be used as an experimentation platform for students. The satellite operations will be performed by researchers and students and will transition to an educational use handing the operations over to a student satellite operations team after the end of the funding period.

1.1 Space Debris Mitigation and Regulatory compliance

With the first of October 2024 the grace period for the FCC's ruling, that spacecraft must be disposed of within 5 years of the end of their mission, ends and spacecraft launched from the U.S need to comply. Since the launch of Transporter-12 is scheduled for October 2024 the InnoCube mission needs to demonstrate the fulfillment of this requirement. For the verification the Debris Risk Assessment and Mitigation Analysis (DRAMA) tool suite Version: 3.1.0 from the European Space Agency (ESA) has been used. The orbital lifetime and the assessment of post-mission disposal strategies was performed with the OSCAR – Orbital SpaceCraft Active Removal tool: Version 2.4.3.

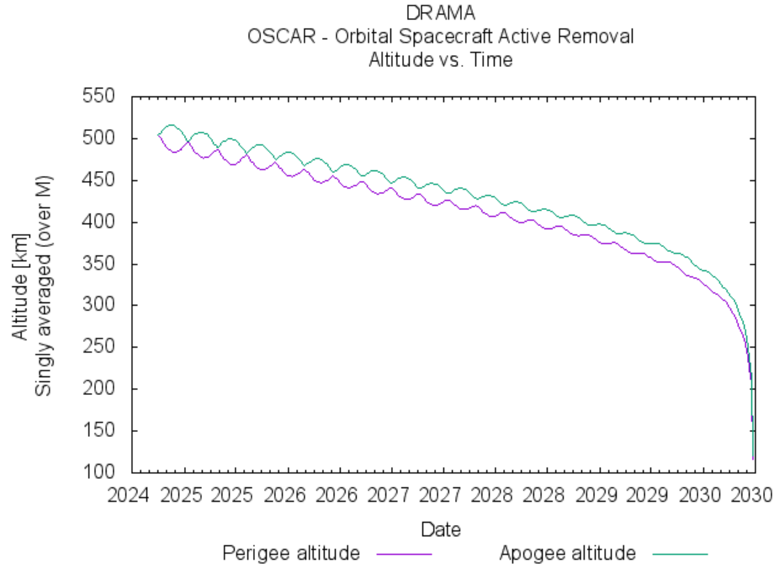
DRAMA
OSCAR - Orbital Spacecraft Active Removal
Altitude vs. Time

Figure 1: DRAMA OSCAR Result compliant with ESA SDM requirements: SSO 510 km reentry: 6.008 yr.

The earliest launch window has been chosen as start of the Simulation and a circular target orbit of 510 km SSO. The spacecraft was modelled with a cross-sectional area of 0.041 m^2 and a mass of 4.8 kg with a drag coefficient of 2.2 and a reflectivity coefficient of 1.3. For the solar and geomagnetic activity latest prediction of ESA (from: 2024-03-28) has been used.

Due to the lack of orbit control on InnoCube, no post-mission disposal maneuvers can be performed.

The following mission operations and activities will be realized:

I. LEOP Phase: T0 – T + 1 month
  - First Contact
  - Telemetry download (EPS/OBC) Analysis of historical TM, temperatures, and bus voltages/currents.

II. Scientific data download: T + 1 month – T + 11 month
  - WallE Experiments, SKITH Assessment, EPISODE Experimentation data download.

III. Educational Operational Time: T + 12 Month – T+ 24 Month
  - Operations to StudOps and Educational use
  - T-24 Month: Assessment of Time for additional experiments

IV. Orbital decay
  - Spacecraft is disposed during re-entry.

OSCAR provides a diagram for each orbit, which plots the apogee (blue) and perigee (purple) trend for the orbital lifetime of the satellite (see Figure 1). Due to atmospheric drag and perturbation forces acting on the satellite will cause InnoCube to re-enter the Earth's atmosphere within 6.008 years (incl. margin of 5.00 % according to ISO 27852:2011.) after launch.

With the mission operations and activities of 24 month and an On-Orbit Lifetime of 6.008 years the satellite will reenter far within the required 5 years after operation. InnoCube will be reenter within 4 years after End of Operations.

2 INNOCUBE OVERVIEW

The InnoCube satellite is designed as 3U+ to comply with the CubeSat standard [1] and provide some radiation shielding for the Skith satellite bus, the basic structure is made of aluminum. Therefore, due to the experimental nature of the payload, the use of the Wall#E structural battery [2], [3] as a load-bearing structure was deliberately avoided. The following are the key design decisions summarized for the 3U+ format of InnoCube:

- Although the advantages of Skith technology [4] scale with s/c size and becomes more profitable for larger satellites [5], saving more cables, a 3U+ CubeSat can demonstrate the application. As a first step it can show that that the radio bus works reliable and at distances up to at least 30 cm and is ready to use in larger satellites in future.
- 3U+ satellites have larger solar panels, providing sufficient energy to demonstrate Wall#E. The generated energy supports conventional energy storage and for Wall#E.
- With the provided energy (3U+), more Skith modules can be operated. With the aim to demonstrate a network with at least 8 modules that can run permanently and demonstrate hot redundancy with Skith.
- In a 3U+ there is enough energy to operate the EPISODE payload and provide the necessary attitude control for the SLR. The Tuna Can provides volume for the retroreflector.

2.1 InnoCube Subsystem design description

The InnoCube satellite consists of an aluminum profile frame that consists of a top cover accommodating the GNSS Antenna and amateur payload antenna, the main communication UHF antenna as a bottom cover, two side walls, a front wall, and rear wall which feature the rails as the contact area with the P-Pod. The side panels have a slotted structure to insert and clamp the module carriers into the structure like a CD rack. The module carriers all have the same dimensions and feature a uniform connector at the rear edge, which connects to a backplane board. The backplane board is responsible for distributing power within the satellite. The primary communication with the satellite bus is conducted via the wireless SKITH bus.

In Figure 2, the key components and their positions inside the InnoCube satellite are depicted. A total of 10 module carriers with 12 modules are integrated. In the following, the essential components from top to bottom will be briefly introduced. Later the paper will depict the design of the technology demonstration and payloads in more detail.

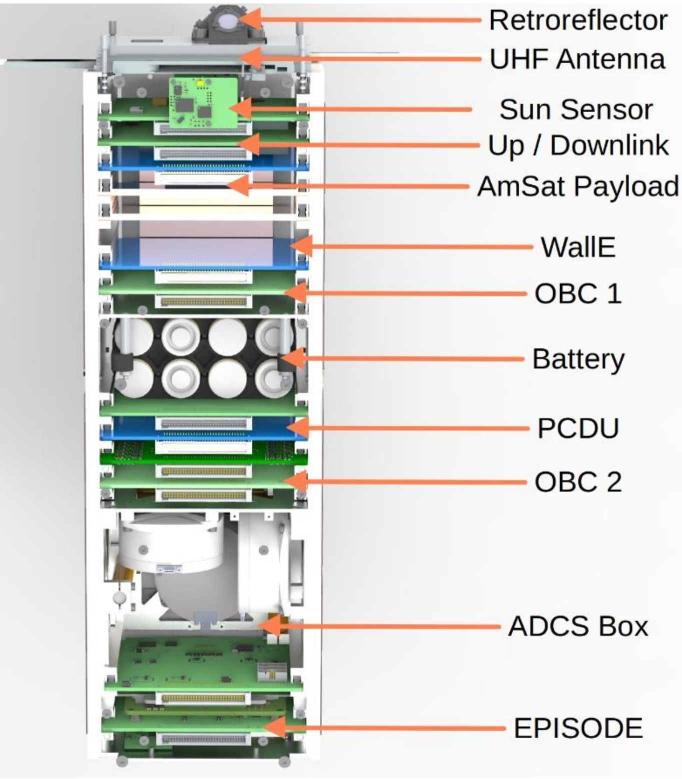

Figure 2: InnoCube system overview [1]

The retroreflector is part one of the Episode Payload and is necessary for laser-ranging measurements. It consists of four prisms arranged in a mechanical holder to reflect incoming light over a large solid angle. SLR where a laser beam is directed from Earth to the satellite and reflected back by the retroreflector allows for precise satellite positioning. The determined satellite position serves as a reference for the onboard position estimation by the Episode GNSS payload.

As mentioned above, the UHF Antenna III model from Endurosat [6] serves also as cover structure part. The cross-dipole antenna is designed for frequencies in the range of 435 to 438MHz and has an omnidirectional radiation pattern. It features a redundant deployment mechanism and is qualified by the manufacturer according to ECSS-E-ST-10-03C. To keep necessary RF cables short below the antenna are the Up/Downlink modules located. There are two up/downlink module carriers in the satellite, containing the communication module. The core of the communication module comprises two NanoCom AX100 transceivers from GomSpace. The transceivers are connected to the antenna via an RF switch, ensuring that only one transceiver is connected to the antenna at any given time. The satellite's communication system serves as the interface between the ground segment and the satellite to telecommand, software and data up/downlink and to receive satellite telemetry. As the satellite is operating on frequencies of the amateur spectrum, an amateur radio payload is included. The amateur payload consists of a hybrid system. One part of the payload is an experimental beacon, which is based on Spacecraft Identification and Localization developed by LibreSpaceFoundation to track and identify InnoCube using a low-power spread-spectrum transmission during LEOP [7]. The second part is a reconfigurable amateur experimental platform by TU Berlin Amateur Club to receive text messages and transmit them via Slow Scan Television QSLs (SSTV QSLs).

WALL#E-2-Space Payload or short Wall#E is a payload developed by Technische Universität Berlin. It consists of structural elements that can also be used for storing electrical energy. Control electronics are used to investigate properties such as charging and discharging behavior, cycle duration, or temperatures. The goal is to demonstrate and characterize the fusion of electrical energy storage and structural elements in a satellite application. More details are provided in chapter 4.

OBDH (On-Board Data Handling)

The On-Board Computer is part of the On-Board Data Handling (OBDH) subsystem. Instead of a single central onboard computer, InnoCube uses a network of distributed onboard computers (nodes). Each

Figure 3: Redundant Skith implementation on a module board.

node is based on a microcontroller. Data communication between all nodes occurs via the SKITH bus (Figure 3). The On-Board Computer node plays a significant role in the OBDH subsystem as it can control the timing of commands on other nodes and monitor them if necessary. The OBDH manages all data on the satellite, including sensor data, housekeeping, control, and command data. Beside the batteries of the WallE payload there is a conventional power subsystem that consist of a battery, power generation and the charge regulation and power distribution electronics. As battery a Nano Power BPX lithium-ion battery pack in a 2S-4P configuration from GomSpace [8] is used as the battery. It contains 18650 cells with a capacity of 3000 mAh and total capacity of 86 Wh at a nominal voltage of 7.4V. The Electronic Power Supply (EPS) system on InnoCube is divided into energy generation, storage, and distribution. Its task is to supply all modules with the necessary energy and simultaneously disconnect faulty modules from the network. The control of the EPS system is distributed across two module carriers. To charge the battery with maximum efficiency from solar cells the PCDU Battery/Solar Panels module carrier features a Maximum Power Point Tracker (MPPT) for the solar cells [9] and a battery charger. For supplying all subsystems with energy and monitoring output currents the second module the Power Conditioning and Distribution Unit (PCDU) and the backplane are responsible. The PCDU provides three different voltage levels (3.7V, 5V, and battery voltage) for the subsystems. As part of the Attitude Determination and Control System (ADCS) subsystem six sun sensors developed by the University of Würzburg are placed on each side of the satellite for attitude determination. The collected data is transmitted to the ADCS via the SKITH bus. Each sun sensor can determine the relative direction to the sun and with the known installation position, the ADCS can determine the solar vector. The rest of the ADCS system is implemented in a substructure, called ADCS-Box, in the satellite and can be easily removed and integrated as whole. The box contains three reaction wheels, three double-wound magneto torquers, and the ADCS module carrier. One advantage of this substructure is the simplified testability of the correct functioning of the ADCS utilizing the advantages of the SKITH radio bus. The box can be effortless operated on an air bearing table to test the interaction of torquers, reaction wheels, and attitude determination. The second part of the EPISODE payload besides the retroreflector is a software-defined radio (SDR) GNSS receiver that uses open-source software to calculate its position in orbit in real time. For this mission, an embedded system of a Xilinx Zynq UltraScale+ multiprocessor system-on-a-chip (MPSoC) is used, mounted on a Xilinx Kria K26I system-on-module. The module is paired with a commercial front-end receiving chip, MAXIM2769 and two commercial antennas, an active and a passive, mounted on the zenith facing cover of the satellite. More details are provided in chapter 5.

3 WIRELESS SATELLITE BUS SKITH

The satellite bus is based on the developed Skith technology, and the entire data harness is replaced by robust, high-speed, real-time short-range radio communication. The entire software runs on Skith nodes, which are on the respective module carriers. Typically, there are two nodes on each module carrier, which are powered via the backplane. All nodes are based on the same hardware components, as depicted in the **Fehler! Verweisquelle konnte nicht gefunden werden.**. The Gecko microcontroller (EFR32FG12) [10]. serves as the platform for the node software and provides the functional interface for integration into the SKITH bus.

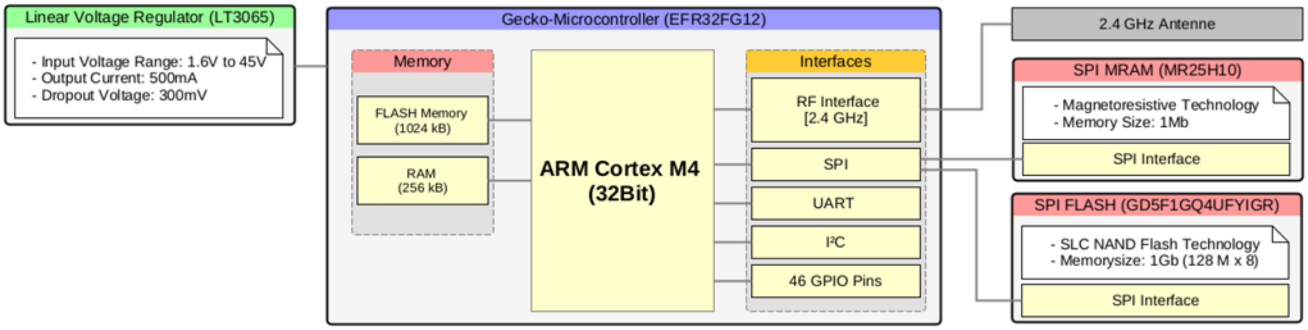

Figure 4: Component overview of Skith node.

The Gecko microcontroller has an integrated 2.4 GHz radio interface. This allows for the transmission and reception of arbitrary data without a fixed protocol in the 2.4 GHz band, with up to 19 dBm transmission power, 2 Mbit/s data rate, and various modulations. Investigations for InnoCube have shown that communication between all nodes can occur with a transmission power of 9 mW. Configuring the transmission power to 10 mW gives a sufficient link margin taking the maximum allowed transmitting power of 14 dBm (25 mW) EIRP, that wouldn't cause any interference with terrestrial, or space born application. With 14 dBm power and 6 dB bandwidth of the transmission a resulting power flux density (PFD) at the Earth's surface from a 500 km orbit is approximately -164 dBW/m2/4 kHz. This will neither increase the background noise nor negatively affect terrestrial applications (e.g., RLAN, SRD, Bluetooth, RFID). To avoid in theory possible potential interference with receivers on board other LEO satellites, a frequency band with enough distance to the MSS band (2483.5-2500 MHz) should be used. A band typically used for terrestrial applications with higher powers between 2446-2454 MHz would be particularly favorable. For this reason, to avoid any in-orbit interference, the internal Skith radio will use 2448 MHz with Gaussian Frequency Shift Keying (GFSK) modulation and +/- 1 MHz frequency deviation at a 1Mbit/s data rate. Thus, the bandwidth twice as large as necessary for the data rate because there have enough spectrum available which provides more reliable stability in data transmission. Figure 5 shows the OBC module carrier with the two OBC nodes, the two Skith nodes are placed side by side on the module carrier and are not interconnected. On top side the SKITH Node 1, the Gecko SoC and the antenna are visible. On the backside of the module carrier the components are mirrored for SKITH Node 0. The InnoCube data processing software is based on the RODOS real-time operating system [11], which has been extended with the Corfu framework [12] to create a configurable and reusable on-board software for InnoCube. The various active nodes communicate wirelessly via the SKITH protocol [13].

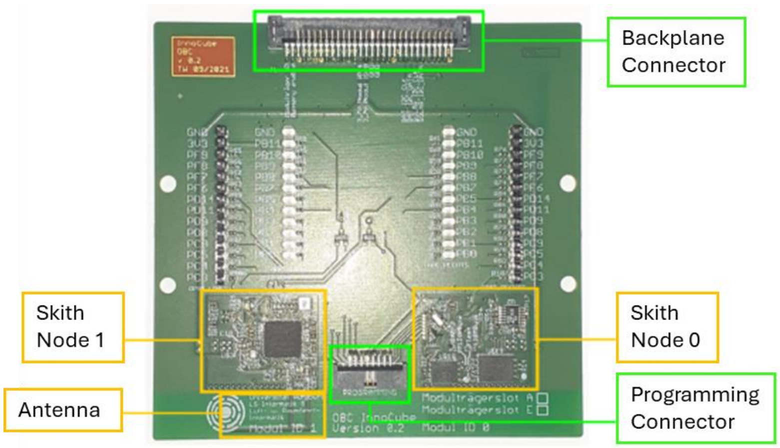

Figure 5: OBC module board showcasing Skith node design.

The radio protocol coordinates the communication among the modules to prevent transmission interference from multiple modules transmitting simultaneously. For this purpose, a central, predefined coordinator is used, which regularly assigns time slots to each module during which they are allowed to transmit. For redundancy reasons, two independent coordinators are implemented, which are integrated into the two modules of the PCDU (Power Conditioning and Distribution Unit). Only one of the two coordinators may be active at a time (active coordinator), as otherwise undefined behavior may occur due to uncoordinated transmission of sync frames. This is realized through "Keep-Off" switches. These switches remain in the off state as long as periodic pulses are applied to the control input at intervals of up to 1 second. If these pulses are absent, the switches turn on. One coordinator controls the switch of the other, and vice versa. As long as the active coordinator detects that it is functioning, it continuously sends "Keep-Off" impulses to the switch of the other coordinator. This ensures that only one of the modules is powered on at any given time. These impulses are only generated if all essential threads regularly send "I am alive" messages and regularly receive radio messages from other modules. This ensures the functioning of both the transmission and reception direction of the coordinator because other modules can only respond if they have previously received a sync frame from the coordinator. For this, at least one other module must always be powered on. The design ensures that this is always the case for at least one of the comms modules. In case of errors, the "Keep-Off" impulses are absent, and the other coordinator module starts. This now generates "Keep-Off" impulses itself and switches off the first module. When the power supply is turned on, for example, after separation, both coordinator modules start simultaneously. The first "Keep-Off" impulse is randomly delayed by a few milliseconds to randomly determine one of the two modules and not to favor any of them.

4 WALL#E-2-SPACE OVERVIEW

Wall#E represents a technology integrating energy storage functionalities into spacecraft support structures. This involves equipping fiber composites with solid-state battery materials at nano- and microscales. The research aims to explore suitable solid-state battery materials and processes for creating a structural battery from electrochemically active fiber composite components. Additionally, it seeks potential processes to fabricate a functional battery providing storage function and electron transport by partially replacing the matrix polymer with active material for anode, cathode, solid electrolyte, and conductivity additive. Laboratory prototypes were developed and the functional principle was demonstrated during the research phase. In the ongoing InnoCube project, it is essential to adapt this technology as a payload, under the project named Wall#E-2-Space (W2S). Despite being a structural battery, W2S does not serve as a load-bearing structure to adhere to CubeSat standards, simplify design, mitigate risks, provide shielding for the wireless bus, and focus on the electrochemical and mechanical aspects of the payload's development.

The objective of the Wall#E-2-Space initiative is to transition the previous Wall#E research into a technical application for CubeSats, emphasizing functionality and operation in a relevant environment. Structural battery application is intentionally omitted due to the need for shielding from radiation for the second, operationally critical technology test of the Skith satellite bus, which has not been tested for Wall#E. To meet CubeSat standards, the basic structure will be constructed from aluminium. Multiple experimental structural batteries will be placed on the satellite's outer wall, with some reference cells inside the satellite. The research will investigate performance parameters of the structural batteries, including various charging parameters such as charge/discharge current as a function of in-orbit thermal conditions, degradation behaviour, and long-term influences of the space environment. Real charge-discharge curves from InnoCube will be adapted to simulate real operational cycles and monitor battery behavior. For the technical application of the technology, the following requirements are outlined:

- W2S payload is considered a consumer and receives charging current from the power management system during experiments.

- W2S has its own Power Conditioning and Distribution Unit (PCDU) for experiments and distributes the received current from the Electrical Power System (EPS).
- At least one side wall (1U) of the Wall#E structural battery should be present.
- W2S must record and store charge and discharge currents, temperatures, and voltages.
- Payload data should be stored and recorded.
- Experimental batteries must be capable of controlled discharge.
- During experimental charging, a current of 1-100 mA (at 3.7V) is required for approximately 100-1 hour per cycle, followed by an identical discharge cycle (data acquisition only).

4.1 Wall#E-2-Space *payload design*

The system comprises three experimental structural batteries mounted on the satellite's exterior wall and batteries housed within three module slots inside the satellite. A module board incorporates the control and charging electronics for each battery along with Skith nodes. The overall design of the payload system is depicted in the block diagram (Figure 6). The electronics board integrates two Skith wireless radio modules and interfaces with the backplane to deliver power and charging current to the payload. Microcontrollers are employed to manage and configure the payload. Additionally, the board includes integrated charge controller circuits for each battery cell. These circuits facilitate voltage, temperature, and current measurements, crucial for charge control. The batteries can be charged and discharged with configurable currents. The Skith node running the payload application can change the charging parameters such as battery control voltage and charging current and retrieve detailed information about the device status and errors via the I2C interface. Additionally integrated sensors can measure the charge current, battery thermistor, battery, input, and system voltages. The heater can heat the area of the functional layers of the batteries and is designed for aerospace applications where low outgassing is required. The supply voltage of 5 V is regulated up to 12 V by using a voltage converter on the board.

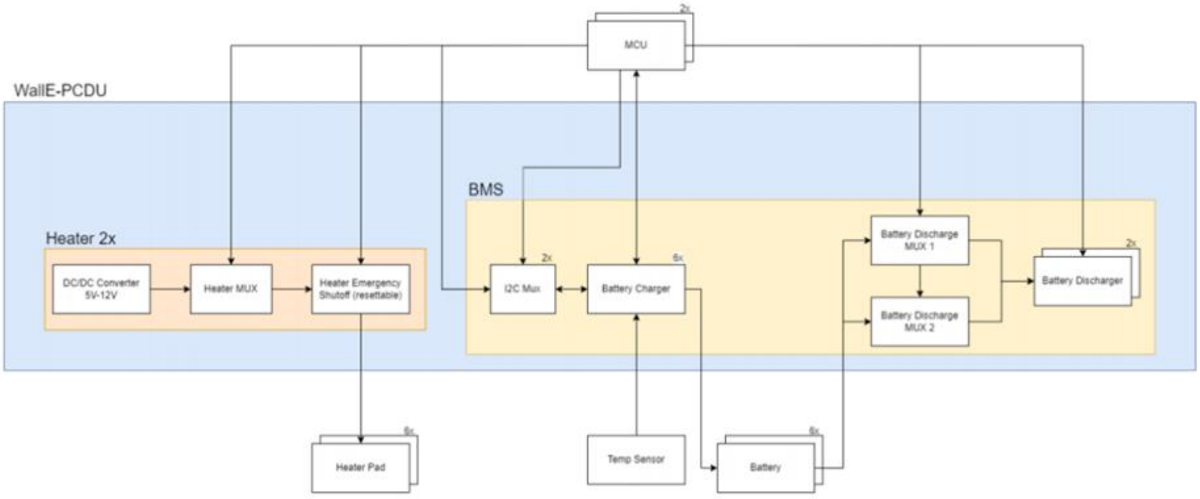

Figure 6: Wall#E-2-Space system diagram.

4.2 Experimental battery

The structural batteries utilized in Wall#E-2-Space employs functional layers comprising a carbon fiber-based cathode containing lithium iron phosphate (LFP) as the active material, carbon black as a conductivity additive, and a polyethylene oxide (PEO) separator. The anode consists of lithium metal, and the separator is made of glass fiber coated with PEO and LiTFSi [14]. These functional layers are encapsulated within a layer of glass fiber reinforced plastic (GFRP) made from prepreg. Like standard pouch cells, the cell is contacted via a metal braid that extends to the exterior.

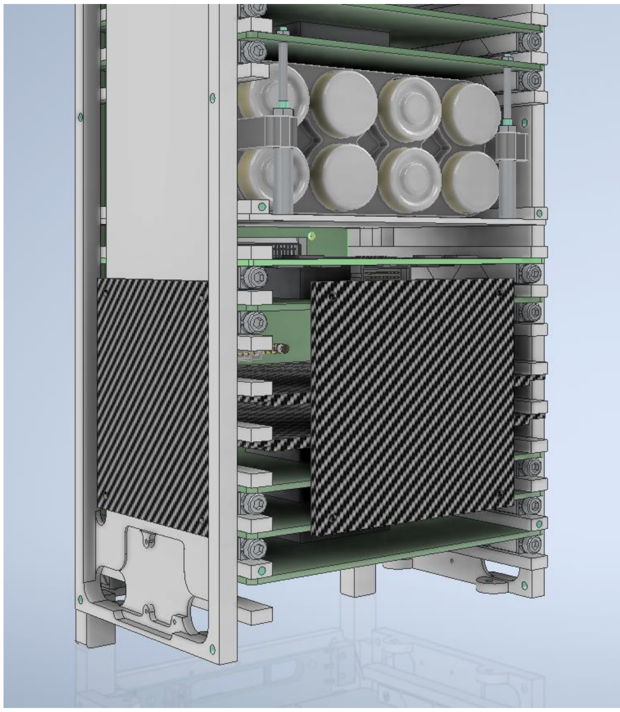

Figure 7: Integration of W2S

Each battery measures approximately 70 mm by 65 mm by approx. 3 mm and has a storage capacity of about 80 mAh. With a density of approximately 2 g/cm³, the weight of the battery is approximately 30 g. Additionally, a 2W heating foil is affixed on top of the structural battery to operate at various temperature points, adding an additional five grams. The experimental batteries for W2S are mounted on the outer wall using four screws (Figure 7), and four slots are available for integrating the electronic board and batteries within the satellite. Each slot provides an installation space of 11.4 mm.

5 EPISODE

The payload consists of two separate systems. An active payload is used for GNSS position determination, while the passive payload is the laser ranging retroreflector. The challenges of a device for determining position based on GNSS are diverse compared to a terrestrial device. Firstly, a high relative velocity between the navigation satellites and the receiver has to be considered. Due to orbital velocities exceeding 7 km/s, Doppler shifts of up to 45 kHz occur. Additionally, the satellite orbits the Earth approximately every 100 minutes, resulting in higher satellite fluctuation compared to terrestrial receivers, necessitating a fast algorithm for GNSS satellite acquisition. Due to coverage ([15], [16]), it's possible to simultaneously receive a high number of satellites, allowing for precise positioning if utilized. Commercial products are not feasible due to the high relative velocities, covering only a range of up to 10 kHz. Military GNSS applications achieve 20 kHz, but this is still insufficient for an orbital receiver. As a result of these difficulties, a dedicated high-frequency frontend for the L1 band (1.6 GHz) must be designed, which outputs the signals of the navigation satellites in raw data form, allowing for the detection of higher Doppler shifts. This processing will be carried out using an FPGA and includes resolving the signals into the following information during acquisition:

- Identification of the satellite based on the unique PRN code and the position of the code phase match.
- Determination of the Doppler shift of the signal with an accuracy of 500 Hz, sufficient for tracking
- Continuous tracking of the signal based on the provided information, tracking the PRN code and frequency change.
- Decryption of the navigation data

- Calculation of the distance between the transmitter and the receiver based on time-of-flight measurement, also known as pseudorange. Using pseudoranges, the payload computer can determine a position.
- The data is stored and transmitted to the ground station.


Figure 8: Engineering model of CubeLRR.

The principle of SLR is based on the emission of a laser pulse from an optical ground station to the satellite. The reflected pulse is registered, amplified, and analysed by the ground station's receiving optics. The transit time of the laser pulse, which is derived from the registered time interval, is used to determine the distance to the satellite. Three consecutive data points are necessary for orbit propagation, while additional points improve the solution. To achieve results, measurements during night are considered. Modern stations use highly focused laser, which can also provide measurement data during daylight, however the reflecting prisms of the satellite are relatively small [17]. The main limitation of SLR is the poor spatial and temporal coverage, but SLR measurements are free of ambiguities and can be directly related to the terrestrial reference system. This method is used within the CubeSat project for external calibration and validation of the GNSS receiver. A fundamental requirement of EPISODE is to enable observation of the satellite by the global network of SLR stations with both high accuracy and sufficient signal strength [18]. The development of the payload is conducted with the aid of students, using theses and coursework. The corresponding hardware is derived from commercial-off-the-shelf components, which are tested and verified for operating in the space environment. The focus of the payload is adaption and flexibility. The software of the system shall be configurable and updatable in orbit via telecommand. During operations in orbit, different navigational solutions shall be implemented. This way, algorithms can be tested on their performance both in resource utilization and position accuracy.

5.1 Hardware

The miniaturized laser retro reflector, which is mounted on the nadir pointing cover of the satellite has an edge length of 34 mm and a height of 15.5 mm, shown in Figure 8. The body is made of Titanium grade 2 to minimize the influence of the thermal stress on the structure. Four coated 10 mm prisms with flight experience are used. For EPISODE-GNSS a commercial high-frequency receiver frontend with a heterogeneous processing unit comprising an FPGA and an ARM Cortex processor. This blend of parallel hardware processing and software adaptability maximizes the strengths of each technology. To maintain payload affordability, no specialized space-grade hardware is utilized. The GNSS receiver employs the MAXIM2769 universal frontend receiving chip, which has been utilized in previous academic missions. The design is derived from student work based on the open-source design of the Portland State Aerospace Society [19]. All baseband operations are performed within the chip. The receiver is paired with two antennas, both operating within the L1 band at approximately 1.6 GHz. One antenna is passive and active, capable of receiving GPS and Galileo signals, while the other is broader, capable of receiving GLONASS signals. The MAXIM chip converts received radio waves to a lower frequency of 4.092 MHz, which is adequate for operations considering the symbol rate of the C/A code modulated onto the GPS signal is 1.023 Mchips per second. The frontend incorporates a 16.368 MHz crystal oscillator, with a frequency stability of 500 ppb. Signals are sampled into in-phase and quadrature components by an analog-digital converter before being buffered and transmitted to the processing unit. The processing unit, or payload computer, is a commercially available system-on-module heterogeneous processing unit, specifically the Xilinx Kria K26 SOM. It features a Zynq Ultrascale+ MPSoC with a low-voltage version having a Vcc of 0.72 V. The processing system includes an ARM Cortex A53 quad-core with a maximum frequency of 1.3 GHz and an ARM Cortex R5F dual-core with a frequency of 533 MHz. The board is equipped with 4 GB of 64-bit-wide DDR4-RAM and 250k logic cells in the programmable logic. Interfacing is facilitated through 127 in-out pins, and the module measures 77 by 60 mm with a mated height of 15.9 mm, featuring an aluminum heat spreader on the top. To mitigate cosmic radiation effects, particularly from heavy ions [20], the Zynq processor is enclosed by 0.5 mm tungsten on both sides (Figure 9), covering the Zynq, connectors, and SD card. Power rail monitoring is employed to promptly detect latch-ups. For system control and interfacing with the satellite bus, EFR32FG12 Flex Gecko wireless controllers are utilized, employing a SPI interface for payload data transfer and GPIOs for enabling various operational modes.

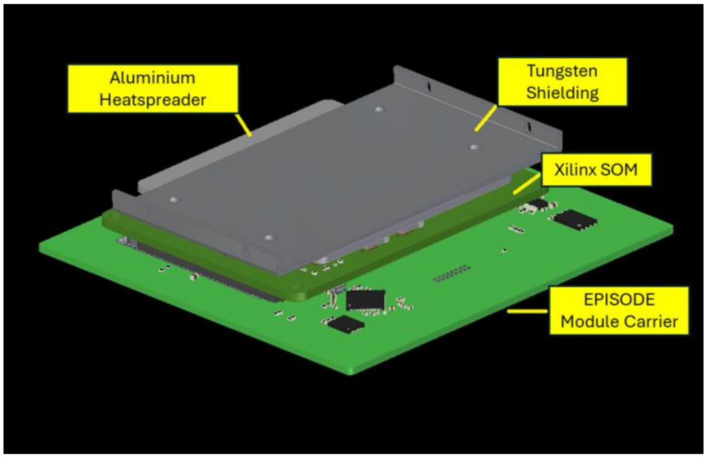

Figure 9: EPISODE module design.

5.2 Software

The payload computer Zynq Ultrascale US+ (xck26) utilizes an embedded operating system, PetaLinux, which is a Linux OS for Xilinx. PetaLinux is based on the Yocto Project, a program that allows specialized implementations of Linux that are configurable based on a modular approach. The following applications run on it:

1. GNSS-SDR
2. Telemetry and telecommand interface
3. Control of the front end
4. Experiment monitoring

To provide the possibility of existing software and simple development, the software stack (see Figure 10) is of crucial importance. In addition to the operating system, several hardware abstraction layers (HAL) need to be selected and implemented. Essentially, two levels need to be considered, which are referred to as firmware and operating system. In addition to the development and implementation of the software stack, applications need to be developed to complete the software. These applications must be created within the operating system, firmware, and Skith.

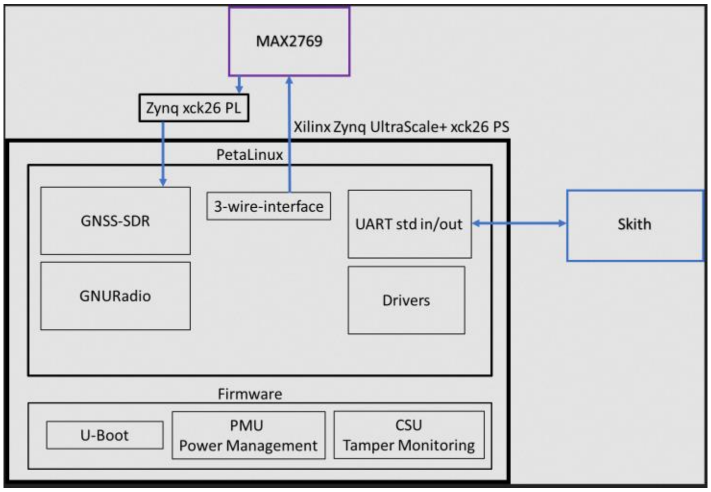

Figure 10: Overview of the EPISODE software stack.

For signal processing, the open-source program GNSS-SDR is utilized. GNSS-SDR is an open-source software program that implements a GNSS receiver based on Software-Defined Radio (SDR). It provides a complete navigation solution. Depending on the configuration, raw signals can be used, which are then processed. Multiple channels are available for determining the PRN and code phase, and tracking is also performed within these channels. The navigation solution is then calculated, and a position is output. Depending on the output format, the position is provided in latitude, longitude, and altitude or in other formats. GNSS-SDR can be fully configured to suit specific needs.

6 TESTINGS AND QUALIFICATION

The design of InnoCube is primarily verified and qualified following the "small to large" approach. Qualification progresses from component-level verification to system-level qualification. Critical components in the design were identified at the component level, necessitating specific qualification measures early in the project. This includes microcontrollers, critical switches in the PCDU, or radiation-sensitive components [21]. Individual modules or circuit parts can also undergo verification at this stage. This approach reduces the risk of component failure in later subsystem or system-level tests, aiding in the early consolidation of the design. Verification of system-level requirements through an EQM ensures the qualification of the overall system, while the FM undergoes acceptance tests to assess flight readiness. Requirements related to specific programmatic points or functions, such as software, are primarily verified through verification by design or analysis. This includes orbit selection, launch times, or individual telecommand and telemetry definitions, which are continuously verified throughout the project as the design progresses. Pre-launch tests to determine mission readiness are conducted at the system level following acceptance tests with the FM. Because the Skith hardware and other in house developed components has never been used in orbit before, it has been important to test for their resilience against radiation. The radiation test campaign is briefly described here. To simulate radiation conditions in orbit, the boards are irradiated with a cobalt-60 source, accumulating TID for the expected mission duration. For SKITH a sample of four microcontrollers have been irradiated by a Cobalt-60 source with a mission dose of 0.64 krad/h and a total ionisation dose of 10.8 krad over 20 hours. While testing, the controllers exchanged radio messages and performed memory checks. No memory errors or communication failures were detected. Thus, the Skith hardware shows a suitability for the use in space. Another critical component is the PCDU. To verify the requirements the power distribution is connected to the via the backplane and telemetry from the EGSE provides insight into the PCDU's condition throughout the entire testing period. The PCDU is monitored via telemetry, with a telecommand script commanding regular switch changes and querying telemetry data. No mission-critical errors were recorded. The same result has been observed during the test of the sun sensors and ADCS module. In WallE-2-Space, Commercial Off-The-Shelf (COTS) Texas Instrument BQ25157 charging ICs are used. These were irradiated in the same TID test, and telemetry values were queried. The charging regulators showed no degradation and functioned without errors after irradiation. Similarly, the RF switch of the communication board was irradiated and switched every two minutes during this time. Despite the increased radiation dose and the high amount switching operations, not expected in this magnitude for the mission, no significant errors were found. The successful testing of critical components reduces the mission risk and raises the confidence in the reliability of the spacecraft design.

7 CONCLUSION AND OUTLOOK

The development and application transfer of previously researched innovative technologies are outlined. Utilizing a wireless data bus, the developed satellite system showcases, verifies, and validates its usability and benefits. Leveraging Skith facilitates a modular structure that allows for easy module switching with minimal time and effort. Furthermore, the discussion involves the deployment of a payload for space application to address additional research queries regarding an experimental structural solid-state battery. This payload aims to investigate the degradation behavior and the impact of space conditions on the technology. One challenge is to devise a programmable charging solution capable of handling very small charging currents given the limited capacity of individual Wall#E batteries. Employing a commercial front-end high-frequency receiver alongside a heterogeneous processing unit comprising an FPGA and an ARM Cortex processor, the concept of an SDR GNSS receiver offers significant flexibility in selecting GNSS signal features. Additionally, an application for the system control of the payload computer has been developed, along with a multilateration algorithm that calculates the satellite's position based on pseudorange measurements from at least four satellites. To validate GNSS accuracy, a Laser Retro Reflector (LRR) has been designed and downscaled to fit within a CubeSat system. Reliability and radiation tolerance of Skith and other critical components has been verified with TiD testing. The EQM is scheduled to be integrated and qualified on a system level in May 2024. Subsequently, the FM will undergo integration testing at an acceptance level and is slated to be shipped in August for the Transporter-12 launch in October 2024.

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