SpaceOps-2023, ID # 443

InnoCube CONOPS - Concept of operations to demonstrate payloads within a wireless small satellite bus

Grzesik B. [a*], Gläsner S. [a], Walter T. [b], Baumann T. [b], Sittner F. [b], Dilger E. [b],
Montenegro S. [b], Stoll E [a]
[a] *Chair of Space Technology, Technische Universität Berlin, Marchstr. 12-14, 10587 Berlin, Germany*
Phone: +49 30 314 21339, {e.stoll, b.grzesik}@tu-berlin.de
[b] *Chair of Computer Science VIII, Aerospace Information Technology, University Würzburg, Emil-Fischer-Str. 70, 97074 Würzburg, Germany Phone: +49 931 31 83715, montenegro@informatik.uni-wuerzburg.de*
** Corresponding Author*

Abstract

This paper depicts the concept of operations (CONOPS) for the InnoCube (Innovative CubeSat for Education), a joint small satellite mission of the Chair of Information Technology for Aerospace at University of Würzburg and the Chair of Space Technology at Technische Universität Berlin. The 3U+ CubeSat is a technology demonstration of two innovative technologies: SKITH (SKIpTheHarness), a wireless satellite bus technology and Wall#E, a carbon fiber-reinforced plastic solid-state battery. Additionally, an Experiment for Precise Orbit Determination (EPISODE) is included. The CONOPS needs to account for the wireless data exchange between all satellite modules, i.e., the onboard computer (OBC), ADCS, power distribution and conditioning unit (PCDU), up-/downlink transceiver and the payloads. Having a modular design of the SKITH hardware, different modules for different tasks are utilized. For the software, the same modularity is used, and each module runs software with common tasks (e.g., housekeeping) and module-specific tasks. An app-centric approach addresses this modularity in the software and enables the implementation of automation as well as fault detection and isolation (FDIR) procedures. To verify the experimental structural battery subsystem WallE2Space and the secondary payload EPISODE several operational mission modes are defined. The dependencies and interactions of payloads, wireless bus and system constraints must be carefully considered. EPISODE consisting of two main components, a custom Global Navigation Satellite System (GNSS) software-defined receiver and a Laser Ranging Experiment (CubeLRR) several operational mission modes are defined. The laser ranging experiment is used to verify the GNSS positions. This scenario consists of four phases. At first, nadir pointing is established to align the retroreflector with the laser ranging ground station. When a connection is achieved, a parallel position determination via laser ranging and the GNSS receiver is executed. After the pass is over, the GNSS measurements are processed in the third phase, and finally the attitude control system is desaturated. The aim of the Walle2Space payload is to characterize cell performance of the experimental structural battery and lifetime-cycles within relevant environment. Battery data of charge and discharge behavior is recorded and evaluated at different temperatures and load cases. In several defined load cycles, e.g. 10% of the battery capacity or simulated adjusted varying load spectrums, information on battery significant performance metrics is collected. This is done successively with varying constant loads. After a successful constant dis-/charge cycles, the nominal operation is simulated with varying loads. The paper discusses the CONOPS, payload operations, considerations, interaction and constraints affecting the operations, the ground system setup and adaptions and procedures using wireless bus system.

Keywords: CubeSat CONOPS; wireless bus; payload operations; CubeSat GNSS; satellite laser ranging; structural battery

Acronyms/Abbreviations

Attitude Determination and Control System (ADCS),
carbon fiber-reinforced plastic (CFRP)
Chair of Space Technology at Technische Universität Berlin (RFT)
Chair of Information Technology for Aerospace at University of Würzburg (UWU)
Command and Data Management System (CDMS)
concept of operations (CONOPS)
CubeSat Laser Ranging Experiment, (CubeLRR)
Experiment for Precise Orbit Determination (EPISODE)
fault detection and isolation (FDIR)
Global Navigation Satellite System (GNSS)
InnoCube (Innovative CubeSat for Education)

lithium bis(trifluoromethylsulfonyl)imide (LiTFSI)
onboard computer (OBC),
on-board software (OBSW)
power distribution and conditioning unit (PCDU),
Satellite laser ranging (SLR)
SKITH (SKIpTheHarness)
State of Charge (SoD)
Telecommands (TC)
Telemetry (TM)
Telemetry and Telecommand (TT&C)

1. Introduction

The CubeSat presented in this project 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 and the Chair of Space Technology at the Technische Universität Berlin. The 3U+ CubeSat InnoCube is a technology demonstration of two innovative technologies: SKITH, a wireless satellite bus technology, and Wall#E [1], a carbon fiber-reinforced plastic solid-state battery [2].

The field of structural battery composites has seen significant progress, particularly at the Army Research Laboratory (ARL) [3,4,5,6,7]. In early efforts, carbon fibers were used as the negative electrode and lithium iron phosphate was coated on a stainless steel mesh for the positive electrode, separated by a glass fiber ply and infused with a solid state electrolyte. However, the lack of proper electrical insulation prevented electrochemical cycling [4]. Another approach was undertaken by Ekstedt et al.[8], using aluminum mesh coated with LFP, carbon fibers as the anode, and a glass fiber separator. However, no cycling data was presented. Moyer et al. presented structural batteries made from carbon fiber weaves coated with LFP as the cathode and graphite as the anode, using a commercial separator and liquid electrolyte [9,10,]. This resulted in a specific energy of more than 35 Whkg^{-1}. Asp et al. also prepared structural batteries, using a carbon fiber anode, glass fiber separator, and a commercial LFP cathode coated on aluminum foil [11]. The assembled electrodes were infused with a bicontinuous electrolyte, resulting in a specific energy of 24 Whkg^{-1} after electrochemical cycling.

This Wall#E research focuses on the development of a new type of structural battery composite that utilizes an all-solid-state electrolyte instead of the traditional liquid electrolyte found in other studies. The structural anode, cathode, and separator are made using a slurry casting process and made from materials such as carbon fiber, poly(ethylene oxide), lithium bis(trifluoromethanesulfonyl)imide, lithium iron phosphate, carbon black, and glass fiber. The performance of the structural electrodes is tested in both half cells against lithium metal and full cells with the structural anode and cathode. The results of these tests will be used to demonstrate the viability of this all-solid-state approach to structural battery composite technology [12].

With the development of space technology, wireless communications technology in the spacecraft plays an increasingly important and even irreplaceable role to meet the networking, modular and cableless requirements and other new demands [13]. Wireless communications technology gets more and more attention. The CCSDS (The Consultative Committee for Space Data Systems) has accelerated the research on wirelesscommunications technology in recent years on the basis of years of wireless communications study and tracking. At present, several wireless communications standards have been developed for the application field of aerospace [14,15,16]. For spacecraft environmental monitoring and control, CCSDS recommends the use of the wireless sensor networks standard IEEE 802.15.4 [17]. IEEE 802.15.4 standard is intended to be used in low-speed wireless personal area networks (PAN). The key objectives are to achieve low power consumption and low cost. The CCSDS has defined the MAC (Medium Access Control) layer and PHY (Physical layer) layer protocol, but the network layer and higher layer are not defined. There have already been some missions which tested single components that communicate with the main satellite bus using a wireless connection [18]. The Defli-C3 mission for example tested an autonomous wireless sun sensor, but only one of two units remained functional and the main satellite bus used conventional data harness [19]. Other examples of wireless subsystems are the wireless digital sun sensor developed by TNO [19]and EADS Micropack wireless temperature transducers [20]. In addition, a complete fly-by-wirelessUnmanned Aerial Vehicle (UAV) platform was developed in Portugal [21]. Another form of wireless intrasatellite communication is Optical Wireless Links for Intra-Satellite Communications (OWLS) [22]. OWLS got in orbit experience on OPTOS launched by INTA in November 2013 that makes intensive use of optical wireless links, being an all-optical satellite no data wires and all the units are communicated through a Wireless-CAN [23]. In InnoCube, the main satellite data-bus will rely solely on wireless data connections. SKITH is a wireless infrastructure for satellites. By combining wireless standards currently being developed for the Internet of Things and Industry 4.0 with fault-tolerant and robust software, a system is created that can compete with cable connections in the satellite and offers many advantages. Eliminating wiring in the satellite reduces the weight and complexity of the spacecraft. This allows for smaller and more flexible systems. A modular satellite can be built by bolting components together without having to consider cabling for data exchange. The project will develop programmable radio modules, which provides a typical bus structure. These front-end modules will perform all necessary protocol conversions to provide a wireless interface for all subsystems. This results in a data management system completely independent of the interfaces of the sensors and actuators used. Replacing a device within the satellite after integration involves high effort and is to be highly avoided. The system achieves these capabilities with the necessary flexibility as a result of the channel structure. An advantage of this structure is monitoring, which is easily performed after integration, without needing a cabled interface for external devices. Sensor data can be accessed and analysed by receivers outside the satellite, which is also fed into the avionics network by a transmitter outside the satellite. The capability of hardware- and software-in-the-loop tests on an integrated satellite is achieved, which is associated with extensive effort in conventional satellites.

In the InnoCube-SKITH project [24], a satellite bus that wirelessly connects all components of the satellite is implemented using SKITH technology. This includes communications, on-board computer (OBC), attitude determination and control system (ADCS), payload, and power control and distribution unit (PCDU).

The on-board computer network consists of multiple nodes and serves as the Command and Data Management System (CDMS). A power-efficient radio interface will be utilized, which will be real-time, fail-safe, and as simple as possible.

A dedicated SKITH protocol [25] is used for full control of redundancy and message timing, with all nodes based on a Silicon Labs Flex Gecko microcontroller (EFR32FG12)[26] and similar circuitry.

Wall#E technology integrates energy storage functions into the spacecrafts supporting structure, referred to as “structural battery”. Fiber composites are equipped with novel nano- and micro-scale solid-state battery materials. Suitable materials and processes for manufacturing a structural battery from electrochemically active fiber composite components are investigated. A functional battery is fabricated by partially replacing the matrix polymer with active anode and cathode material, solid electrolyte, and conductivity additive to provide both storage and electron transport. The payload for the CubeSat mission, named Wall#E-2-Space, is used as an experimental battery. Therefore, a conventional power system will also be used on the satellite. The InnoCube payload development aims to transfer previous Wall#E research to the technology test of Wall#E2Space. The focus is on evaluating its function and operation in relevant space conditions. Experimental structural batteries will be placed on the satellite's outer wall and inside for performance evaluation under space conditions, including degradation behavior and long-term influences. The charging parameters such as charge/discharge current under thermal conditions will also be investigated. A study in a laboratory can only provide results to a limited extent. To comply with the CubeSat standard, the satellite structure will be made of aluminum.

In addition to the primary payloads, the mission includes the *Experiment for Precise Orbit Determination - EPISODE*. EPISODE is an independent payload consisting of a GNSS solution and a miniaturized laser retroreflector [27]. It is being developed through coursework and student research and will provide accurate position data of the InnoCube, which will contribute to a safe space environment by allowing collision warnings to be evaluated and assessed more accurately. The goal of EPISODE is to test commercially available hardware for a software based GNSS receiver and to verify newly developed satellite receiver algorithms in orbit. EPISODE uses off-the-shelf components to provide tracking solutions and measurement data to the ground station at regular intervals. There are several methods for measuring and determining the orbit of low-Earth orbiting (LEO) satellites. EPISODE will also facilitate the use of laser ranging for orbit determination, which offers high accuracy and unambiguous measurements related to the terrestrial reference system. This knowledge allows independent calibration and validation of the on-board GNSS hardware. A fundamental requirement of a laser ranging reflector is to enable observation by the global SLR station network with both high accuracy and sufficient signal strength. Improvements in laser ranging technology make it possible to produce a laser ranging reflector (LRR) of a size suitable for a CubeSat, even for centimeter-level measurements[28].

The RFT’s ground station at TU Berlin is used to control the satellite. It is located on the roof of the building and is equipped with a UHF transmitter and receiver that operates in the frequency range of 430 – 440 MHz. The ground station uses two types of antennas: a double X-quad antenna with a gain of about 17 dBi and a crossed Yagi antenna with a gain of about 22 dBi. The antennas have a rotor system to align and track the satellite with an accuracy of +-4%, sufficient for a 600 km orbit.

2. Mission Concept of Operations

The mission objectives are focused on technology demonstration the capabilities of the payloads and wireless bus. The operational concept is focused on achieving the mission objectives and is subdivided into a launch and early orbit phase (LEOP), including a full functional test of all subsystems and verification of the satellite bus. The most crucial part of this phase is the location of the satellite and establishing radio communication. After deployment, InnoCube is initially booted into a safe configuration with active housekeeping. In this state, it is programmed to transmit a beacon signal and waits for commands. Upon first contact, InnoCube transmits its history and housekeeping data to provide a general overview of the spacecrafts status and wether corrective actions are necessary. Within five days, the orbit should be well known and InnoCube should be in a stable state to survive indefinitely without operator intervention. During this phase, the attitude will be stabilized, all subsystems will be powered up and tested. Once the satellite is in a power-positive state and the main systems are confirmed to be operating, the payloads will be calibrated and commissioned. EPISODE and WallE2Space checkout will be performed. Following the checkout of the payloads, the collection of scientific data and further verification of the payloads will be conducted during nominal operations. The mission is expected to last for one year, after which the mission will be considered successful. A secondary objective of the mission is to continue operating the position science payloads for as long as technically possible after a successful mission, as they can provide valuable information for end-of-life collision avoidance analysis, albeit the satellite does not include active or passive deorbiting capabilities.

3. Validation of Wireless satellite Bus

The operation of the InnoCube platform, including its payloads, is based on SKITH technology. During LEOP, an established radio link with InnoCube confirms SKITH working in practice. To assess long-term performance of SKITH, the quality of data transmission will be monitored. SKITH records statistics during normal operations, such as number of communication nodes, number of messages, lost messages, corrupted messages, field strength, and real-time performance. During commissioning, these statistics will be requested as extended and historical telemetry and evaluated, comparing to expectations established during development. In the operational phased, these SKITH telemetry will be periodically requested for continued evaluation. InnoCubes on-board communication architecture is revolutionary compared to traditional satellites, as it does not feature a single central on-board computer and transmits data wirelessly.

3.1. Satellite Bus Topology

Conventional satellite concepts are based on a central on-board computer as a control system, which is responsible for controlling application tasks as well as data management, leading to higher performance requirements for the CPU and complexity of the on-board software. In contrast, the InnoCube mission uses a decentralized network of distributed on-board computers (nodes) to control the individual subsystems. The nodes are based on a standard architecture that includes a microprocessor, a data memory and a radio interface for connection to the wireless satellite bus (SKITH bus). The individual on-board computers are configured by software for their specific tasks. These nodes are based on a standard architecture with a microprocessor, data memory and radio interface, and are assigned to specific tasks by software.

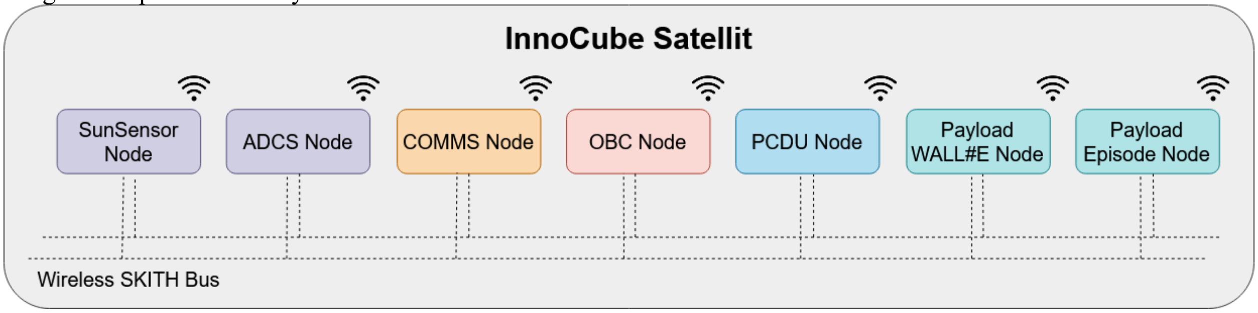

Figure 1: System overview of InnoCube satellites nodes.

All nodes are connected in the Skith network(Figure 1). Telemetry data is transmitted to the ground station through the COMMS node. Similarly, received telecommands are processed through the COMMS node and distributed to individual nodes.

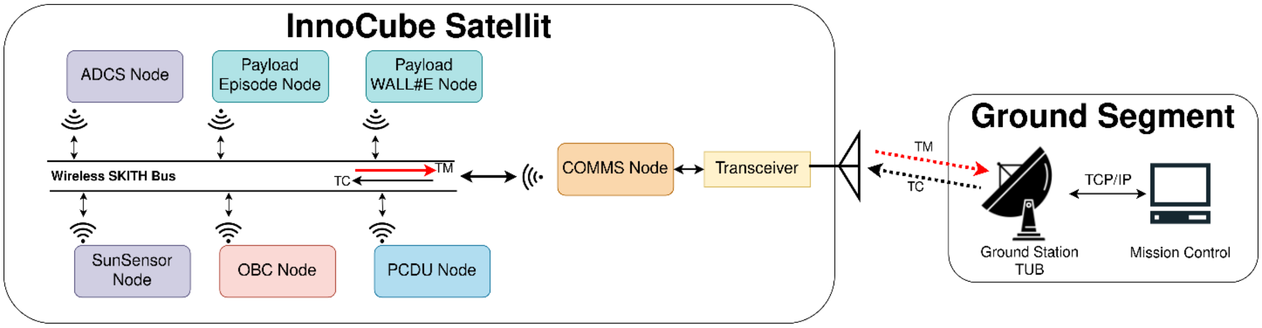

Figure 2: TT&C flow of the InnoCube mission

3.2. Data Management

For the mission, various data types (Figure 3) are defined for the bus system(Figure 4).

3.2.1. Telemetry/Housekeeping Data

Telemetry (TM) data collected from all nodes on the InnoCube satellite reflects its internal state (e.g. battery bus voltage) and is either transmitted directly to the ground station or stored and transmitted only when requested. The Telemetry page provides an overview of the telemetry data system. Standard telemetry provides periodic summaries of key data from each node, while Extended telemetry is used to provide more detailed data on request through telecommand in a more flexible way to collect data. Payload systems data is transmitted using extended telemetry.

3.2.2. Historic Telemetry

Historic Telemetry is not a separate telemetry data type, but is stored standard telemetry or extended telemetry data. It is temporalily saved in a ring buffer in the OBC node and is transmitted to the ground station on demand. Historic telemetry is marked with a special flag for identification.

3.2.3. Telecommand Data

Telecommands (TC) are issued from the ground station through the uplink channel and received by the transceiver (TRX), which forwards the data to the COMMS node (see Communication Architecture Figure 2). Immediate Telecommands are instantly published on the SKITH bus and executed by the receiving node. Temporary Telecommands are temporarily stored in the OBC node after reception until specified time-tag has elapsed, after which they are published on the SKITH bus and executed by the designated node.

3.2.4. Data Files

In addition to telemetry and telecommand data, larger data files may be uploaded to the satellite, like data file segments or boot images.

3.2.5. Data Processing

The InnoCube data processing software is based on the RODOS real-time operating system [29], which has been extended with the Corfu framework [30] to create a configurable and reusable on-board software for InnoCube.

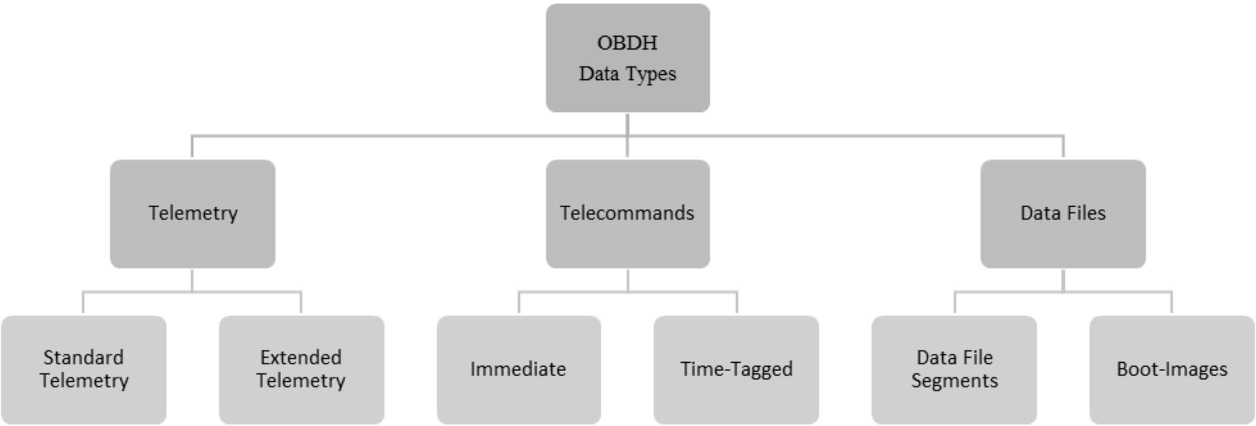

Figure 3: OBDH Data Type Structure

3.3. Redundancy Concepts

The redundancy concept is a key aspect to ensure the reliability of the OBDH system. It includes appropriate protection of all subsystems, both hot redundancy of particularly critical components and cold redundant systems. In general, the computing nodes for each subsystem are designed to have at least two (cold) redundancies.

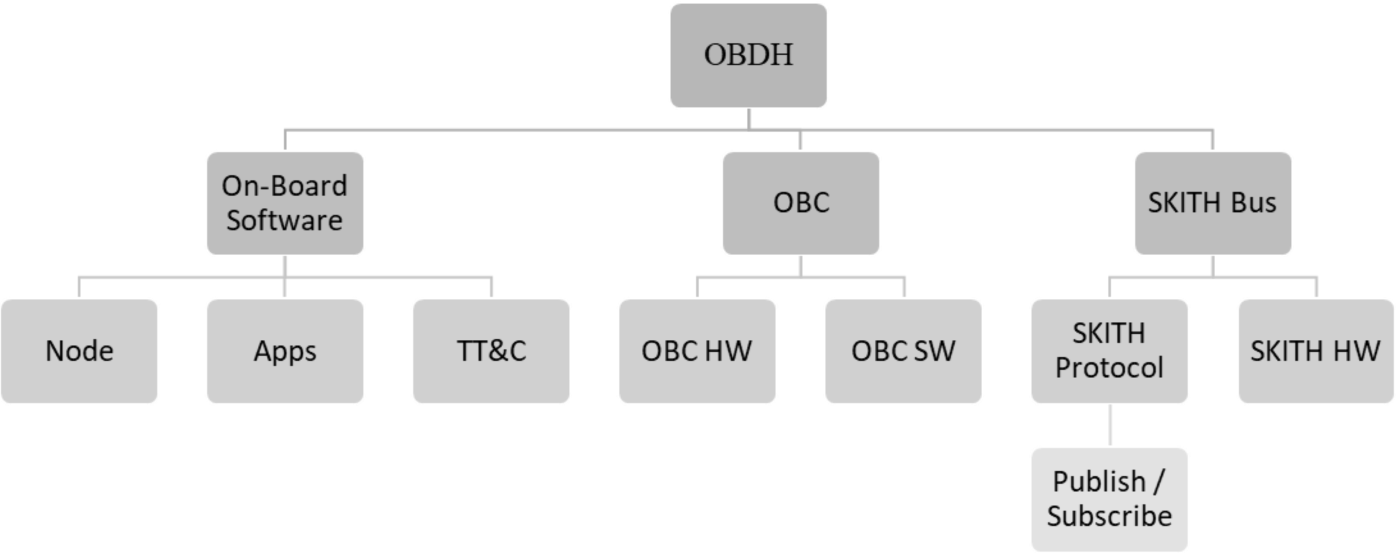

Figure 4: OBDH System Overview

For reliable operation, only one coordinator is powered at a time. If both are powered on, they would both send out uncoordinated sync frames and it would be unclear which one the other modules would follow.

Similarly, any failure of the active coordinator must be detected in order to switch to the other. This requires both software and radio hardware to be functioning correctly (Figure 5).

The two redundant modules of the PCDU serve as radio coordinators, a switch to the other module is facilitated by keep-off switches.

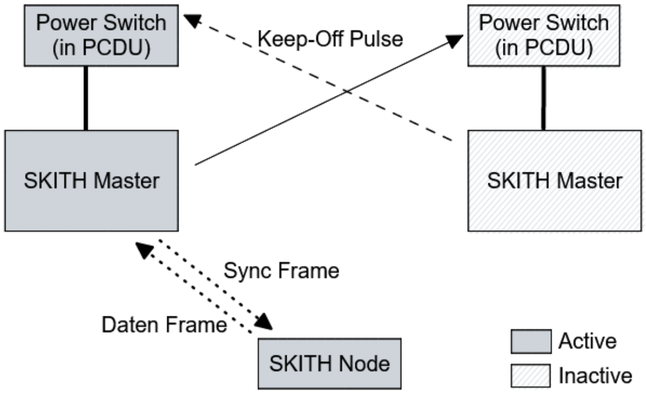

Figure 5: Redundancy and powering concept SKITH master module

These switches remain off as long as periodic pulses are applied to the control input at intervals every second. If these pulses stop, the switches turn on. One coordinator controls the switch of the other and vice versa. The active coordinator sends keep-off pulses as long as it functioning properly. This is verified by essential threads sending "I am alive" messages and regularly receiving radio messages from other modules.

The design ensures that at least one COMMS module is always on to receive sync frames from the coordinator. If a failure occurs, the keep-off pulses stop, and the other coordinator module starts, generating its own keep-off pulses and turning off the first module.

3.4. Fault detection and isolation

All applications in the network communicate using a publish/subscribe mechanism, with the middleware RODOS providing several topics. Each application has a defined set of topics it subscribes to and is allowed to publish messages specified in its Corfu configuration. Certain topics are predefined as part of the on-board-software system, which is the anomaly report, I am Alive, Telemetry Real Time, Telemetry History and Telecommands. An anomaly watchdog is implemented. All applications of a node publish I am Alive messages with a valid time counter in the App-is-Alive topic, which is stored by the local watchdog and periodically checked for timeout violations.

The local hardware watchdog is triggered if all timeouts are in the future, a node-is-alive message is published via the node-is-alive topic. If a timeout is exceeded, the corresponding app is marked as failed and the local watchdog stops publishing node-is-alive message. If automatic restart is enabled, the node restarts.

Failure scenarios such as SKITH transmitter/receiver failure, radiation-induced bit flip, or software errors are anticipated. Keep-off pulses are generated only when frames are received from other modules, ensuring established communication. Any loss of radio communication caused by one of the above (or other) errors is thus secured. To protect against the case that the coordinator keeps the radio communication active due to an error, but can no longer be commanded, the keep-off pulses are also disabled, when a number of commands have not been processed for a longer period of time.

4. Payload operations

Payload operations are managed from the ground station using predefined modes, such as GNSS, laser ranging or Wall#E charge/discharge scenarios. They are executed via command scripts with some able to be run simultaneously. The power consumption scenario accommodates parallel GNSS SLR operation while charging of the experimental batteries at a low current. During the commissioning phase, more controlled operations will be performed and more telemetry will be collected to evaluate the payload operation. Subsequently, scientific experiments are planned as part of nominal operations. The operational concept of the EPISODE and WallE2Space payloads is described in more detail in the subsections below.

4.1.1. WallE2Space payload operations

The basis of the Wall#E technology are carbon fiber reinforced plastics (CFRP) structural batteries with slightly varying layer structures. Four types were investigated in the original project. Type I is a layered structure based on carbon fiber based graphite anodes, carbon fiber based cathodes and a commercial separator based on polyethylene oxide (PEO). Type II consists of a layered structure of a carbon fiber-based cathode, the commercial separator, and a lithium metal anode. Type III and IV use a glass fiber-based separator impregnated with electrolyte solution of PEO, lithium salts and a solvent. The basis weights of these two types differ, with Type IV having a basis weight of 105 g/m^{-2} and Type III only having a basis weight of 25 g/m-2, which is expected to improve performance.

The WallE2Space payload consists of three experimental structural batteries on the outer wall of the satellite and in three module carrier slots inside the satellite () for a total of six batteries. The battery management system is using commercial linear charging ICs with adjustable charging currents and monitoring as well as heating circuits for each battery. The power is provided by the backplane. The SKITH microcontrollers are used to control and configure the payload.

The batteries are charged and discharged with varying currents. Previous laboratory battery samples showed strong dependencies in discharge capacity and discharge rate in relation to its capacity. A drop-off of 50% in battery capacity was observed when charged at a rate of 0.1C compared to a rate of 0.05C. This is an indication of diffusive limitation of the anodes. Although the improved version under development shows a more stable behavior, the system is designed for very low charge and discharge rates down to 0.025 C to 10 C to characterize the battery performance. A strong dependencies between battery temperature and overall performance is expected, as the battery samples in laboratory tests have been most efficient at higher temperatures. This will be investigated in later tests.

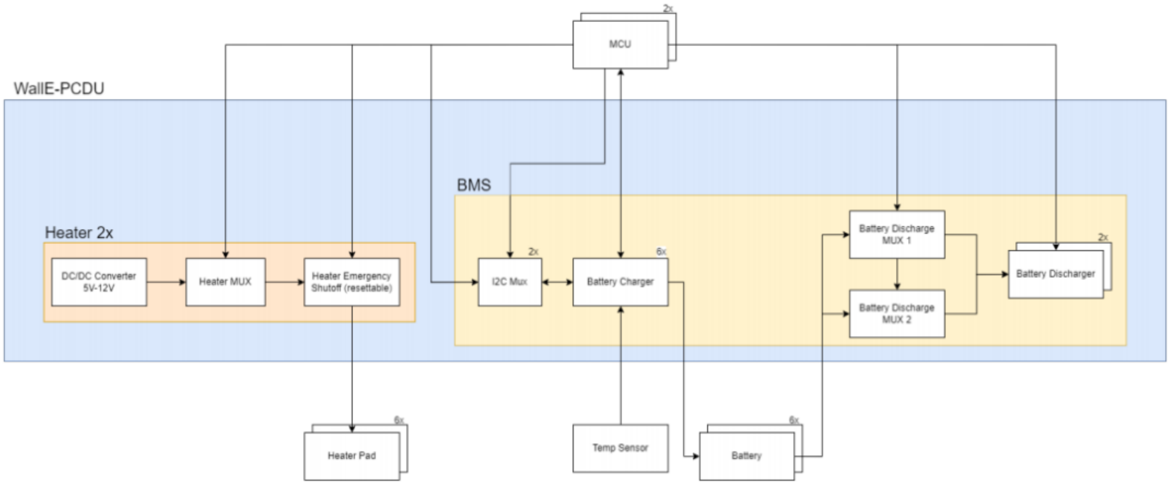

Figure 6: Overview WallE2Space subsystem.

The goal of the in-orbit technology demonstration is to characterize cell performance and capacity data and lifecycles under real-world conditions.

Battery charging and discharging data will be recorded and evaluated at different temperatures and load cases. Different load cycles with constant C and adjusted varying load spectra based on satellite telemetry are used to gain information on battery power density, cycle stability, long term stability and degradation. These information will be derived on sensor data of the battery management system which includes voltage, current, temperatures and charge/discharge rate.

Initially, the parameters of the laboratory experiments will be used to have comparable data from in-orbit and ground tests. A typical charging/discharging experiment will consist of the following steps:

1. Powering up BMS
2. Check system status via TM.
3. Set experiment parameters: Operating battery [1...6], operating temperature [°C], charge/discharge rate [mA], set cut-off voltage [mV], number of cycles [n], enable experiment protocol.
4. Enable Heater to specified temperature.
5. Start charging/discharging cycle(s).
6. End experiment. Secure data for transfer.
7. Stop experiment – disable heating, monitor temperature.

During commissioning, several initial checks are performed to obtain basic characteristics and comparable statistics of the batteries as a starting point (P_0) in orbit. In an initial test the battery is first charged at the minimum charge rate (0.025 C) to see changes with ground measurements. In a subsequent test, a self-discharge test is performed. Then a minimum load (0.025 C) is set for discharge (after full SOC) while monitoring until approximately SoD=0.75. While positive, similar tests are performed down to 0.5 until the full cycling of the battery. Nominal operation will be reflected on the battery for a few orbits. Real-time telemetry of the satellite will be used and scaled down to the capacity of the experimental batteries to verify their suitability for future use in orbit.

4.1.2. EPISODE operations

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. However for simultaneous operation, ADCS modes have to be considered, as laser ranging is the most demanding mode for the ADCS system.

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 [31].

The active payload consists of a software-defined GNSS receiver, based on a commercial front-end, a MAXIM2769, and a multiprocessor system, a Xilinx Zynq Ultrascale+ on a Kria K26I module. The system uses embedded Linux with the open-source positioning tool GNSS-SDR. The main challenge to achieve a positional solution is power supply, as the system can not exceed 5 W of peak power.

During commissioning, the first step is to ensure a valid GNSS solution. For verification, firstly GPS signals will be the main source, with extending capabilities and optimization later in the operation. The goal is to be able to produce use captured ephemerides data, while an initial almanac will be provided on ground.

Processing is tested both in orbit and on ground to optimize the navigational algorithms. At first, the processing system will handle the main workload of signal processing, with a plan of shifting capabilities to the programmable logic of the chip.

In simultaneous operation of position determination and laser ranging, the accuracy of the GNSS receiver can be compared to the determination on ground via SLR.

Based on this, errors are calculated and orbit determination algorithms can be updated. For simultaneous operation, time tagged command scripts are used. In later stages, an optimization in power consumption and time of acquisition is targeted, while providing a reasonable accuracy improvement to TLEs.

4.1.3. Satellite laser ranging

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 analyzed 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.

For simultaneous operation, a higher demand in power is expected, as the attitude control requires the highest precision in the mission. Successive measurements of the GNSS receiver and SLR may be used as well. An analysis using orbit propagators provides a basis for the operational scenario and for estimating the times and number of contacts between the satellite and the sample ground station. Basic scenarios are projected using an approximately circular 580 km SSO of InnoCube and position data of the SLR station of GFZ Potsdam. The laser range measurement is divided into the following measurement phases: calibration and alignment of the satellite and ground station (GN), range measurements (laser ranging) and acquisition and processing of GNSS data, slew mode of the S/C and tracking of the laser for the subsequent measurement (laser ranging pointing), and the desaturation phase. In the first phase, GNSS data from the satellite will be used for initial tracking. The second phase is the laser range measurement. A maximum number of pulses are sent to the satellite to achieve the highest number of range measurements. For the experiment, an accuracy of the ADCS of 17° is required. After the satellite has left the contact window, the reaction wheels are desaturated, and nominal operation is resumed.

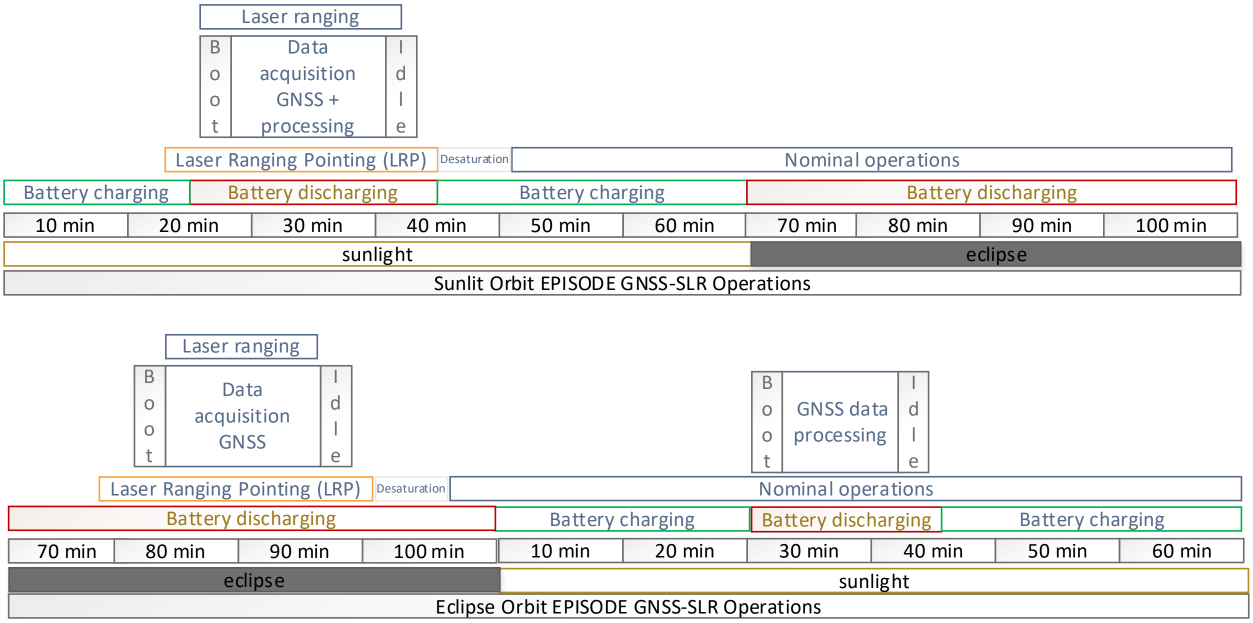

Figure 7: EPISODE operations scenarios eclipse and daylight.

5. Conclusions

The InnoCube satellite will host the first full wireless radio satellite bus using SKITH technology, which is expected to offer numerous advantages for a 3U Cubesat design. A modular hardware and software approach complements the decentralized on-board data handling system to provide flexibility and safety in verifying and flying the novel satellite bus.

The experimental structural energy storage payload, WallE2Space, will be tested in a relevant operational environment, characterized based on scaled real telemetry data, and its performance analyzed.

The operation of a software defined GNSS receiver aims to enable precise determination for more optimized orbit utilization as well as laying the foundation for more sophisticated payloads and GNSS research.

The operational concept follows a stepwise approach and is aimed at demonstrating revolutionary technologies for the advancement of small satellite missions.

Acknowledgements

InnoCubE is supported by the German Aerospace Center (DLR) - Space Management Division with funds from the German Federal Ministry for Economic Affairs and Energy. FKZ: 50 RU 2000/50 RU 2001

Thanks to the Institute for Particle Technology (iPAT) of the Technical University of Braunschweig for the previous and continuous cooperation and support at Wall#E. Furthermore, thanks to GFZ Potsdam for testing the prisms for satellite laser range finding. Further thanks go to our sponsors Valispace and ITP Engines UK Ltd. for ESATAN-TMS.

List of references

[1] B. Grzesik, G. Liao, D. Vogt, L. Froböse, A. Kwade, S. Linke and E. Stoll, “Integration of energy storage functionalities into fiber reinforced spacecraft structures,” *Acta Astronautica,* no. 166 , p. 172–179, 2020.
[2] B. Grzesik, T. Baumann, T. Walter, F. Flederer, F. Sittner, E. Dilger, S. Gläsner, J.-L. Kirchler, M. Tedsen, S. Montenegro and E. Stoll, “InnoCube—A Wireless Satellite Platform to Demonstrate Innovative Technologies,” Aerospace, vol. 5, no. 8, p. 127, 04 05 2021.
[3] Wetzel, E.D. Reducing Weight: Multifunctional Composites Integrate Power, Communications, and Structure. AMPTIAC Q. 2004, 8, 91–95.
[4] Snyder, J.F.; Carter, R.H.; Wong, E.L.; Nguyen, P.A.; Xu, K.; Ngo, E.H.; Wetzel, E.D. Multifunctional Structural Composite Batteries. In Proceedings of the Society for the Advancement of Materiel and Process Engineering (SAMPE) 2006 Fall Technical Conference, Dallas, TX, USA, 6–9 November 2006.
[5] Wong, E.L.; Baechle, D.M.; Xu, K.; Carter, R.H.; Snyder, J.F.; Wetzel, E.D. Design and Processing of

Structural Composite Batteries. In Proceedings of the Society for the Advancement of Materiel and Process Engineering (SAMPE) 2007 Symposium and Exhibition, Baltimore, MD, USA, 3–7 June 2007.

[6] Snyder, J.F.; Carter, R.H.; Wetzel, E.D. Electrochemical and Mechanical Behavior in Mechanically Robust Solid Polymer Electrolytesfor Use in Multifunctional Structural Batteries. Chem. Mater. 2007, 19, 3793–3801.

[7] Snyder, J.F.; Wong, E.L.; Hubbard, C.W. Evaluation of Commercially Available Carbon Fibers, Fabrics, and Papers for Potential Use in Multifunctional Energy Storage Applications. J. Electrochem. Soc. 2009, 156, A215.

[8] Ekstedt, S.; Wysocki, M.; Asp, L.E. Structural batteries made from fibre reinforced composites. Plast. Rubber Compos. 2010, 39, 148–150.

[9] Moyer, K.; Boucherbil, N.A.; Zohair, M.; Eaves-Rathert, J.; Pint, C.L. Polymer reinforced carbon fiber interfaces for high energy density structural lithium-ion batteries. Sustain. Energy Fuels 2020, 4, 2661–2668.

[10] Moyer, K.; Boucherbil, N.A.; Zohair, M.; Eaves-Rathert, J.; Pint, C.L. Polymer reinforced carbon fiber interfaces for high energy density structural lithium-ion batteries. Sustain. Energy Fuels 2020, 4, 2661–2668.

[11] Asp, L.E.; Bouton, K.; Carlstedt, D.; Duan, S.; Harnden, R.; Johannisson, W.; Johansen, M.; Johansson, M.K.G.; Lindbergh, G.; Liu, F.; et al. A Structural Battery and its Multifunctional Performance. Adv. Energy Sustain. Res. 2021, 2, 2000093.

[12] Vogt, D.; Michalowski, P.; Kwade, A. Production and Characterisation of Fibre-Reinforced All-Solid-State Electrodes and Separator for the Application in Structural Batteries. Batteries 2022, 8, 55. https://doi.org/10.3390/batteries8060055

[13] Puschita, Emanuel; Ratiu, Ovidiu; Drobczyk, Martin; Panagiotopoulos, Nickolaos; Kirei, Botond Sándor; Vos, Stefan et al. (2020): A UWB solution for wireless intra-spacecraft transmissions of sensor and SpaceWire data. In: *Int J Satell Commun Network* 38 (1), S. 41–61. DOI: 10.1002/sat.1307.

[14] CCSDS. Wireless network communications overview for space mission operations. CCSDS 880.0-G-1. CCSDS, Washington, D.C. (2010)

[15] Zhou, Y.: Overview of standardization in CCSDS spacecraft onboard interface services. J. Spacecraft TT&C Technol. 30(z1) (2011)

[16] CCSDS. CCSDS 850.0-G-2, Spacecraft Onboard Interface Services. CCSDS, Washington, D.C., USA (2013)

[17] CCSDS. Spacecraft onboard interface systems-low data-rate wireless communications for spacecraft monitoring and control. CCSDS 882.0-M-1, Magenta Book. CCSDS, Washington, D.C. (2013)

[18] WJ Ubbels, CJM Verhoeven, RJ Hamann, EKA Gill, and J Bouwmeester, "First flight results of the delfi-c3 satellite mission," in Proceedings of Conference on small satellites, s.n., Ed., United States, 2008, pp. 1–6, American Institute of Aeronautics and Astronautics Inc. (AIAA), null ; Conference date: 11-08-2008 Through 14-08-2008.

[19] C. de Boom, J. Leijtens, L. Duivenbode, and N. van der Heiden, "Micro digital sun sensor: System in a package," in Proceedings of the 2004 International Conference on MEMS, NANO and Smart Systems (ICMENS'04), pp. 322– 328, 2004.

[20] S. Eckerley, J. Schalk, O. Coumar, and K. Haira, "The EADS micropack," in 5th round table on micro/nano technologies for space, ESA-ESTEC, 2005.5

[21] T. E. Coelho, R. Macedo, P. Carvalhal, J. A.Afonso, L. F. Silva, H. Almeida, M. J. Ferreira, and C. Santos, "A fly-by-wireless UAVplatform based on a flexible and distributed system architecture," in Proceedings of IEEE International Conference on Industrial Technology, pp. 2359–2364, 200

[22] Guerrero, Héctor. (2006). Optical Wireless Intra-Spacecraft Communications. 621. 177.

[23] Rivas Abalo, J., Martínez Oter, J., Arruego Rodríguez, I. *et al.* OWLS as platform technology in OPTOS satellite. *CEAS Space J* **9**, 543–554 (2017). https://doi.org/10.1007/s12567-017-0178-0

[24] T. Mikschl, "Skith - skip the harness : Schlussbericht," Technische Informationsbibliothek (TIB), Würzburg, 2019.

[25] T. Mikschl, R. Rauscher, S. Montenegro, K. Schilling, F. Kempf and T. Tzschichholz, "Collision free protocol for ultrawideband links in distributed satellite avionics," University of Würzburg, 2016.

[26] Silicon Labs, "EFR32FG12 Gecko Proprietary ProtocolSoC Family Data Sheet," 2021. [Online]. Available: https://www.silabs.com/documents/public/data-sheets/efr32fg12-datasheet.pdf. [Accessed 28 02 2021].

[27] L. Grunwaldt, "Basic Principles of LRR Design," in Remote Sensing and Laser Ranging, Riga, 2014.

[28] L. Grunwaldt, R. Neubert and J. Neubert, "The Retro-Reflector for the CHAMP Satellite: Final Design and

Realization," GeoForschungszentumPotsdam, Potsdam, 1997.

[29] S. Montenegro and F. Dannemann, "RODOS real time kernel design for dependability," in DASIA 2009, Istanbul, Türkei, 2009.

[30] F. Flederer, CORFU - An Extended Model-Driven Framework for Small Satellite Software with Code Feedback, Würzburg, 2021.

[31] P. C. L. Stephenson, "UNCLASSIFIED Satellite Laser Ranging Photon-Budget Calculations for a Single Satellite Cornercube Retroreflector : Attitude Control Tolerance Executive Summary.," National Security and ISR Division, 2015.