EXPERIMENT FOR PRECISE ORBIT DETERMINATION ON INNOCUBE

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Abstract

Computing platforms, such as FPGAs and SoCs, are delivering high performance systems in a form factor suitable for small satellites. By offering system-on-modules, technology entry has been drastically lowered. A first step to achieve these higher processing capabilities in orbit is envisioned in the EPISODE payload of the 3U InnoCube satellite, set to be launched in 2024, in an effort to contribute to a safer low earth orbit environment. EPISODE is a payload mainly developed by students at TU Berlin, using commercial off the shelf hardware to develop a GNSS receiver, which is based on a software-defined radio receiver. EPISODE aims to use open-source software to calculate its position in orbit in realtime. 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, which is a universal GNSS receiver. Two commercial antennas are used to determine the position in orbit, mounted on the zenith facing cover of the satellite, with one being active and one being passive.

For orbit determination, open-source software is being used with the highly flexible software of GNSS-SDR. GNSS-SDR is providing a full navigational solution and is based on GNURadio. As an embedded operating system, the Yocto based PetaLinux project is being implemented on the payload. A system control with latchup-detection and redundancy concept with multiple memory devices is used as a precaution against radiation effects. To optimize the determination algorithm, GNSS-SDR is assisted by an algorithm, comparable to A GNSS on ground. As the motion of a satellite in orbit is highly deterministic and regularly captured by ground-based tracking, TLEs are sent via Telecommand along to provide a position estimate for the acquisition phase, along with a reference time. GNSS satellites in sight are being calculated to filter the list of PRN codes in the search space. Additionally, EPISODE-Assisted-GNSS calculates their respective doppler shift, which should improve the acquisition time even further. Time to first fix with EPISODE assisted GNSS is assumed to be less than 30 s, dramatically reducing the energy and time required to first fix. Additionally, a miniaturized laser ranging retroreflector is mounted on the satellite. In combination with laser ranging experiments, onboard calculated GNSS positions are verified with ground based measurements. Different experiment campaigns are carried out, with the goal of optimizing energy consumption and accuracy of the orbit determination.

Finally, EPISODE aims to pave the way for more sophisticated embedded platforms in orbit with high processing capabilities. Further missions may include GNSS reflectometry and radio occultation in a Cubesat.

Keywords

Technology demonstration; Cubesat; embedded systems; software-defined radio; orbit determination; space safety

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1. INTRODUCTION

Cubesats offer platforms for development of new technologies and research. At the Chair of Space Technology, the performance of small satellites shall be further increased to execute even higher level tasks such as active debris removal or scientific missions. The project combines two award-winning technologies of the InnoSpace masters program, Skith and Wall#E. The winning partners of 2016, the Chair of Computer Science VIII, Aerospace Information Technology of University of Wuerzburg and 2017, the Institute of Space Systems of TU Braunschweig, executed by the Chair of Space Technology of TU Berlin, since 2021, are combining their knowledge in a shared project [1]. InnoCube aims to demonstrate three new technologies in a 3U Cubesat, which is set to be launched in late 2024 in a 500 – 550 km sun-synchronous orbit. Skith is a concept of a wireless satellite bus, replacing cabled data connections with a wireless communication network, which is also used as a system controller of each subsystem. Energy distribution is implemented with a backplane design. Wall-E is an experimental carbon-fiber reinforced plastics based battery, which through its strength may be used as satellite structure, replacing traditional aluminium structures and thus saving mass. As a third payload, which is not particularly funded, Experiment for Precise Orbit Determination(EPISODE) is included. The development of the payload is mainly driven by students in bachelor and masters theses.

1.1. EPISODE

EPISODE is an independent payload developed at TU Berlin combining a GNSS receiver with a laser ranging retroreflector. Onboard GNSS processing is combined with laser ranging measurements to verify its determined positions. The payload aims to enable a safer operational environment with more accurate conjunction assessments by providing more precise positions compared to conventional ground based tracking. By achieving a higher accuracy in orbit determination compared to TLE, the uncertainty of the risk for a collision with a catalogued object is lowered, as the covariance matrix for one object is significantly smaller. Onboard position determination may reduce the number of high-risk encounters with other objects and thereby the amount of manoeuvres necessary, increasing the operational life of a satellite. EPISODE is using commercially available hardware for a software-based GNSS receiver. Results from the mission may then be used in a following mission to launch a GNSS receiver laboratory including multiple antennas and frequencies, enabling more scientific usage of GNSS signals.
Challenges are particular given by the power constraints and efficient use of the hardware. Additionally, the design of the communication between ground station and payload shall be designed for handling the data amounts accumulating in such a laboratory.

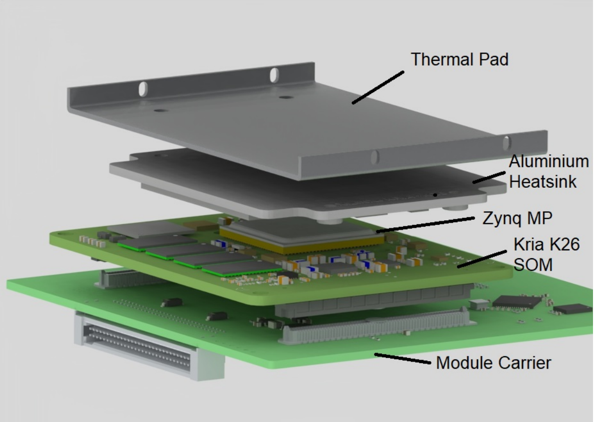

FIG 1. Payload overview

1.2. Goals

EPISODE aims to fulfill certain goals in the first on-orbit verification of the payload. Additionally, certain goals are to be achieved in ground testing prior to launch.

- Valid GNSS position with accuracy of 2 meters on ground
- Assisted GNSS capability on ground
- Unassisted GNSS position fix with less than 5 W on ground
- Valid GNSS position in orbit, using less than 5 W.
- GNSS position accuracy of less than 10 meters in orbit.
- assisted GNSS capability with EPISODE algorithm
- time to first fix cold start less than 90 s
- time to first fix warm start less than 60 s
- time to first fix hot start less than 30 s

2. HARDWARE

The hardware of the payload consists of a processing unit, the integration into the innovative satellite bus on a carrier module and GNSS antennas on the zenith lid of the satellite. Additionally, components for thermal conduction of the processing computer are provided.

2.1. Processing Unit

The processing unit of the payload is mounted separately from the carrier module. A system-on-module board of a Xilinx Kria K26I is used, using a Zynq UltraScale+ MPSoc. A proprietary xck26 processor includes a quad-core application processing unit which consists of four ARM Cortex A53 cores with a clocking frequency of up to 1.5 GHz, a dual-core realtime processing unit, consisting of two ARM Cortex R5F processors and a graphical processing unit of an ARM Mali-400 MP2. The programmable logic features 256 K logic cells and 1248 digital signal processing (DSP) slices. In EPISODE, the full capability of the processor is not nearly reached, as the graphical processing unit is not used. The main advantage of using a dedicated system-on-module (SOM) compared to a custom board is twofold, the integrated design of the SOM lowers the technology hurdle, as well as simplifies the complexity of the carrier board it is mounted on, which decreases manufacturing costs and hardware development time. A main challenge is lowering the peak power of the processing unit below 5 W as per requirement of the satellite power distribution. The module is integrated with two connectors, each featuring 240 pins for IO pins, power pins and different interfaces. The height of the SOM above the carrier module is 15.9 mm, the SOM itself has measurements of 77 x 60 mm and a mass of 58 g. A heat sink is provided by the manufacturer, which will be interfaced with another plate as a thermal and radiation shield. The module is rated from -40°C to 85°C and includes additional memory, such as a 16 Gb eMMC, a 4 GB DDR4-RAM and a QSPI Flash with a size of 512 Mb [2]. The flash memory is primarily used for configuration data. An SD - card holder is mounted on the carrier module as additional memory, which may allow last minute memory changes to the payload.

2.2. Payload control

The payload is monitored and controlled via microcontrollers of the satellite bus. Different functionalities are included in the payload with different interfaces. Firstly, the Bootmode pins are set, which initiate booting from different memory sources, such as QSPI or eMMC. Error monitoring is facilitated through Error Status and Error Flags, which are included in the payloads telemetry. Firmware updates can be set via the satellite bus. Control functions such as Enable, Reset, and Power On/Off are integrated for efficient management. The UART interface establishes communication between Skith and Zynq, while the I^2C bus is employed exclusively for power monitoring within the System Control module. The Zynq system controls the Front-End through a serial interface similar to SPI. Configuration procedures are conducted on ground through JTAG and UART interfaces, as they would be too time and data consuming once the satellite is in orbit.

2.3. Front End

A commercial front-end receiving chip is used for signal reception and analog-digital conversion. The MAXIM2769 universal GNSS receiver is the main element of the front-end. It covers GPS, GLONASS and Galileo satellite navigation services [3]. The analytic signal, consisting of the In-Phase and Quadrature components, is forwarded to the programmable logic of the MPSoC using four signal lines. Additionally, the crystal oscillator for GNSS processing is contained inside the Front End. A TXC oscillator with a clock frequency of 16.368 MHz with a clock stability of 0.5 ppm is used. The receiving chip uses an ADC with a sample rate of 50 Msps. The proposed receiver bandwidth is 4.092 MHz. However, the chip features a serial interface, which uses different states to configure.

The signal high for a logic high is 3 V. As a result, the signals are connected to a high density bank of the programmable logic block of the ZynqMP.

2.4. Antennas

EPISODE is using two different commercial GNSS antennas, which are both mounted on the zenith pointing lid. Opposed to common connectors on GNSS antennas, using flat MHF connectors, EPISODE will be using MMCX connectors, which are less prone to detaching during the high vibrations experienced during launch.

An active antenna is used, which is powered by the antenna bias output of the MAXIM2769 chip. Additionally, a passive GNSS antenna will be used, to assess the performance requirements in orbit. Both antennas are SMT ceramic patch antennas by Taoglas, with a surface area of about 25 x 25 mm. The antennas are mounted on a carrier printed circuit board with a ground plane of about 65 x 65 mm and impedance matching traces of 50 Ohm.

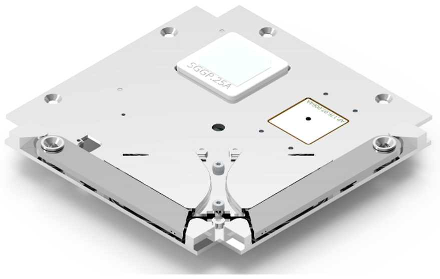

FIG 2. Antennas on the nadir pointing lid

2.5. Thermal

The payload computer is consuming up to 5 W continuously during operations. Tests in a simulation environment have shown the temperature of the Zynq MPSoC to be rising up to 60 °C. To conduct the excess heat into the structure, two thermal heat sinks are used. First, the heat sink, which is provided by the manufacturer is used. This is a aluminium heatsink, which covers the most heat generating components, such as the Zynq IC, the RAM and power solution. The heatsink is delivered with thermal paste, which is cleaned off for the use in orbit and substituted by graphite foil. The second heatsink is custom made and is placed on top of the aluminium heatsink, where usually a fan can be mounted. Both surfaces are polished and are using graphite foil as a conductor similarly. The second heatsink is made out of wolfram, as it is highly conductive and has the function of a radiation shield for the electronics in one direction as well. It is connected to the structure side walls.

3. SOFTWARE

The software consists of three main parts, which have to be developed. Firstly, a software stack has to be selected and implemented on the processing unit. Secondly, a navigational solution is needed for position de-

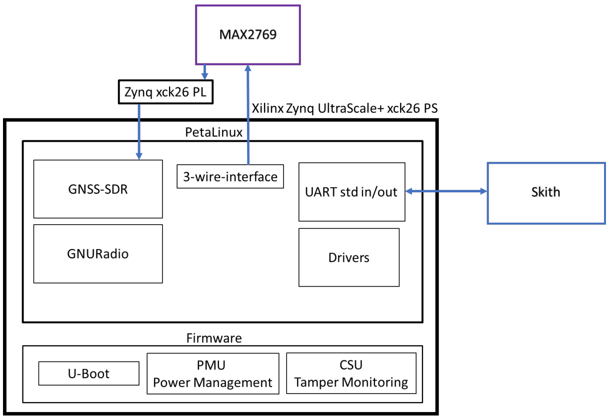

FIG 3. Platform Design

termination. This includes the operation of the front-end receiving chip and its interface to the processing computer. Additionally, experiments have to be considered and designed in the scope of the mission constraints of orbit and communication link. Lastly, a system control monitoring the payload computer, using a set of sensors and actuators, has to be included. The system control shall also be monitoring all possible effects due to the space environment.

3.1. Platform Design

For the custom carrier card including the system-on-module, a platform design is created. The design of the payload consists in principle of an interface between the processing unit and the Skith satellite bus node, an interface to the front-end receiver, as well as interfaces to the memory devices and debugging equipment. The platform design is created using Xilinx propietary software suite Vivado for high-level synthesis and analysis. The Skith modules are used for controlling the processing unit. As a data interface, a UART interface is used. Additionally, the Skith controller is using different IOs for controlling the system, such as errors, control signals and bootmode pins. The front-end sends the in-phase and quadrature signals to the programmable logic (PL) of the Zynq MP with a frequency of 4.092 MHz. Additionally, the processing system is controlling the MAX2769 with a 3-wire-interface, to set modes, frequencies and antenna selection. An overview of the platform design is given in 3.

3.2. Software Stack

For software development on an embedded system such as the Xilinx Zynq MP, different operation systems are possible.

- PetaLinux, which is an embedded linux distribution based on the Yocto Project, created and maintained by AMD. PetaLinux includes different board support packages, which accelerates software development with preconfigured boot-loader, optimized kernel and linux applications and libraries. This software stack was chosen, because it is the most common stack and offers the most support with official guides as well as its wide spread among users in different forums, such as the xilinx-wiki. Additionally, PetaLinux can be tailored best for the custom operation in orbit, especially with the constraints of power usage and safety measures.
- Another option is GeniuX, which is an embedded distribution for running GNSS-SDR on embedded devices. This stack is also based on Yocto Project and is widely used, however it does not feature the same level of support, which is especially important for beginner-level designs. Additionally, it has less flexibility than using PetaLinux.

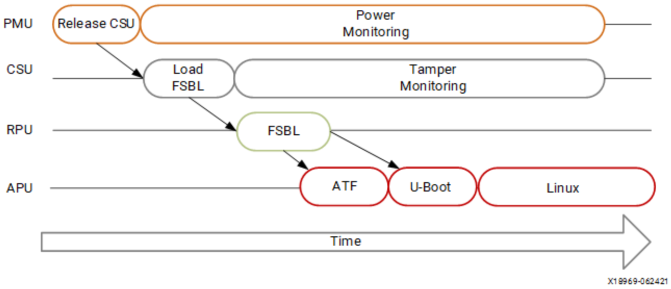

FIG 4. Boot Flow

3.2.1. Boot Flow

Using PetaLinux as an embedded linux distribution marks the last layer to be booted in the software stack. Before booting, different elements to the boot flow have to be considered. These include a first stage boot loader (FSBL), as well as a universal boot loader, called U-Boot. The first stage boot loader loads u-boot into the RAM. It is stored in the QSPI Flash and sets up the hardware to load and execute the linux kernel. The linux kernel is also stored in the QSPI Flash. The boot flow is shown in Figure 4. When booting the linux kernel, the applications which are defined start running immediately. Working with a UART interface in a development environment, Linux can be used in a terminal. The custom software stack is consisting in total of six layers.

- Bootloader: uboot is used for initializing the hardware and loading the linux kernel
- Linux kernel: core component, customized PetaLinux kernel optimized for Xilinx platforms
- root filesystem: Busy box is used as the base for the root filesystem
- Device drivers: Xilinx IP drivers specific to Xilinx' IP cores are used, allowing software to communicate with and control various peripherals and interfaces provided by Xilinx
- User space libraries and tools: GNU C Library (glibc) is used as a standard C library required by user applications. PetaLinux provides development tools, including compilers (GCC), debugging tools (gdb), and profiling tools (perf).
- User applications: GNSS-SDR, system-control, EPISODE experiment, EPISODE propagator.

The whole software stack is to be loaded onto the memory of the payload prior to launch, with additional images for redundancy. In orbit, the change of the software stack is limited to configuration data, consisting of less than 100 kB each.

3.3. System Control

A system control is included as a monitoring program for the health of the payload. The focus on the system control is to ensure the safety for the payload and the satellite, especially the power consumption. To achieve this task, an application is developed inside of the linux kernel, which is monitoring different sensor data and is sending signals to the Skith satellite bus, which acts on the data accordingly. System control resides in the realtime processing unit(RPU) of the Zynq UltraScale+. The RPU includes two ARM Cortex R5F processors, which are able to run in lock-step mode, enabling a higher safety due to redundancy. Additionally, the RPU is connected to the platform management unit (PMU), which includes dedicated SOM power and subsystem management functions. Using the RPU and PMU, the system control can be operated in a lower power mode compared to the APU. The system control has different functions, which include three main areas:

- memory integrity: To avoid corrupt images due to bitflips, different and redundant firmware images are used. These are stored in different memory units, using the eMMC and QSPI Flash memory. As the communication link is slow, complete images can not be sent to the satellite and have to be implemented before launch. A complete linux image has a size of rougly 20 MB.
- latchup detection: The ZynqMP is prone to latchups due to heavy ions in HD IO banks [4]. These states have to be detected by the system control, which in results shuts down the device. After detecting a latchup, the system is booted into a secure state, in which the domains are checked. When cleared, the nominal operation is resumed. For monitoring, the voltages of each bank of the processing system and programmable logic, as well as used I/O banks are observed. Banks which are not used, are pulled to ground in the hardware design.
- power and temperature monitoring: the health of the payload is constantly monitored and sent to the satellite bus as extended telemetry. The device houses temperature and supply sensors, which are read out during operation. The PS temperature as well as V_{CCINT} and voltages for auxiliary, low-power and full-power domain are monitored by the system monitor [5]. These integrated sensors are mainly used, with further sensors on the custom board. Additionally, different power modes are set as part of power and temperature monitoring.

3.4. GNSS-SDR

GNSS-SDR is used as the navigational solution. It is an open-source software-defined radio receiver developed by the Centre Tecnològic de Telecomunicacions de Catalunya. It is written in C++ and is utilized for its flexibility and multi-system capabilities [6]. In EPISODE, GNSS-SDR is implemented for the digital part of the GNSS signal processing chain. For a SDR, a heterogeneous system has to be used, the digital signal processing is shifted to the programmable logic of the ZynqMP, the control plane of the SDR receiver is implemented in the processing system of the chip. GNSS-SDR requires GNURadio for its signal processing framework and therefore has to be included in the linux kernel as well. The operation of GNSS-SDR is achieved using different operations, in which each parameter for signal processing is defined. These parameters include Doppler step, Doppler range as well as sampling frequencies, filter settings. The Doppler range has to be extended for a spaceborne GNSS receiver in 600 km LEO to about 45 kHz [7].

4. OPERATIONAL CONCEPT

4.1. Challenges

For a GNSS receiver in a LEO satellite, different challenges are present in comparison to a GNSS receiver on earth's surface.

- Doppler shift and search space: in ground applications, the highest occuring Doppler shift is approximately ± 20 kHz in airborne systems. For space applications, the relative velocity between a navigation satellite and a receiver can amass to up to 11 km/s, hence the Doppler shift can amount to ± 45 kHz [7]. A usual Doppler step is defined to 500 Hz, as a result, the search space for identifying a GNSS signal increases from a maximum of 41 steps in a terrestrial receiver to 91 steps. This larger search space increases the time to first fix drastically.
- Turnover: the time, in which a GNSS satellite is visible for a terrestrial receiver is very high, as the receiver moves much slower than the satellite. For these quasi static operations, the turnover of different GNSS satellites is usually very low, hence only a small number of acquisition phases have to be considered after the first fix. In a LEO satellite, the maximum contact window to a single GNSS satellite is around 50 minutes, therefore the high turnover of GNSS satellites has to be considered with many additional GNSS satellites to be acquired during operation.

4.2. Chances

Beside the challenges, certain aspects of the position of the receiver improves signal processing and position determination.

- Signal strength: due to less interference and no atmosphere to weaken the signal, the signal strength is expected to be much higher.
- Geometry: the receiver in space is in range to a higher amount satellites compared to ground. The L1 beam can even reach the receiver through the

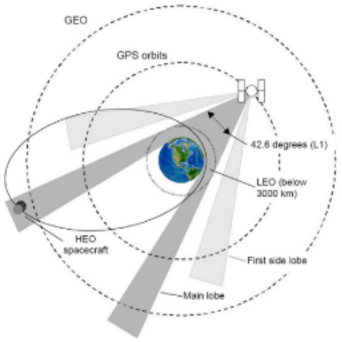

FIG 5. Orbit reception for a LEO satellite to MEO [8]

atmosphere at time. This increased availibility is shown in figure 5.

- Deterministic motion: all objects in space are on highly predictable paths, determined by keplerian motions and pertubations. With TLE data and propagators, an accuracy error of less than 10^3 m can be achieved. For InnoCube, the receiver and the transmitting satellites are all tracked, while the tracking data for InnoCube is TLE data, the data for the GNSS satellites is being transmitted as ephemeris in the subframe of the navigational message. Therefore, each source in view can be calculated along with its unique PRN code and relative velocity to the receiver.

4.3. Assisted GNSS

In applications, in which GNSS reception is limited, methods to assist the position determination are used. These methods are providing supporting data by a different transmission channel from GNSS. A common method for Assisted GNSS, or A-GNSS / A-GPS, is widely used in mobile phones. If a location is requested by the phone, the cell tower which the phone is connected to provides the phone with current almanac data, a position estimation and reference time. By using multiple cell towers, the position estimation may be increased by measuring signal runtime and trilateration. In urban environments with multiple cell towers in range, a position determination with a high accuracy can be achieved in seconds. As the peak power consumption of a GNSS receiver is highest during acquisition, an optimization is aimed for. Beside reducing the peak power, the time to acquire a satellite shall be reduced, optimizing the energy to first fix. Similar to A-GNSS, the receiver shall receive supporting data. This supporting data may be supplied via telecommand, in which case a valid ephemeris, almanac and reference time is given. As the satellite travels with roughly 7 km/s, a position estimate can not be given. Receiving the data via telecommand equals a a warm start of the GNSS receiver. Another mode, equal to a hot start, shall be implemented, reducing the energy and time to first fix even further. By calculating the position of the receiver with TLE data and a propagator onboard, a position estimation is given. Additionally, the search space is reduced due to the knowledge of ephemeris data with the last set of satellites in view and a coarse estimation of their respective doppler rates. Energy consumption will be decreased by reducing the time, in which Linux is running on the APU. To provide the assistance to the navigational solution, the telecommand interface of GNSS-SDR is used. The data is provided using extensible Markup Language (XML). The propagator is a linux application and runs parallel to the navigational solution. The reference clock is updated regularly via Telecommand and provided by the satellite bus. It is the highest uncertainty in the process of assisting GNSS with a clock inaccuracy of several seconds per day.

4.4. Experimental workflow

The automated workflow, as depicted in Figure 1, is composed of multiple phases that seamlessly integrate software-defined radio (SDR) and GNSS signal processing.

- The workflow commences with the activation of the payload, initiating the boot process. System control components are loaded, and integrity checks are performed to ensure the system's stability and readiness for operation.
- Subsequently, time information is retrieved from the bus, serving as a reference for the TLE based propagator. The EPISODE propagator module is engaged to calculate positional coordinates and reference time information. This critical data is stored in XML format, as a set of longitude, latitude, altitude and time.
- GNSS-SDR is then launched with predefined parameters and the reference position in a warm start configuration. Different configurations may include cold and hot start capabilities.
- The acqusition phase is then initiated, during which GNSS satellites are identified and pseudorange being calculated. Times are continuously processed, with the TTFF being the interval between the start of the acquisition phase and the first entry with positional data. All data is stored in a GPX format. Additionally, measurement data may be included in the GPX file as part of extended telemetry. This data may contain power consumption and number of satellites among others.

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- After an experiment is concluded, the GPX file is stored to the root file system. The GNSS data is sent to ground as files with a size of approximately

30 to 100 kB, depending on the duration of the experiment.
- Configuration data can be provided via uplink, with a file size of approximately 5 kB.

5. PERFORMANCE REFERENCES

GNSS Receivers on board satellites have been used onboard small satellites since around 20 years. While the first generation of receivers have taken around 8 to 15 minutes for a cold start with an average power of 1 to 2 W, newer generations like u-blox or warpspace receivers have improved TTFF to around 30 to 90 seconds, while using less than 200 mW. These receivers have usually a standard interface (UART) and fit as a submodule with a small size of less than 20 by 30 mm and a weight of less than 10 g. Receivers of this generation have been used by currently active missions of TU Berlin, namely BEESAT-9. Experiments have been proven to have a TTFF of less than 60 s in more than 95% of the experiments [9].

The goal of EPISODE is to match these performances. A test campaign with different amounts of a priori information to the payload is planned. As well as defining the accuracy of different configurations. In laboratory environment, cold and warm start setups with GNSS-SDR have been tested with TTFF of less than 60 s each. However, the environment and Doppler shift range is much less than compared to space operations. The focus of the payload is not to compete with available commercial hardware, but to path a way for future scientific applications. For this use, many components of the payload may be reused, such as the platform design, software stack and system control.

6. QUALIFICATIONS

For a safe and controlled operation in orbit, the payload is examined against effects of the space environment. However, due to time constraints, radiation tests are not planned. As the ZynqMP is using 16 nm FinFET technology, tests for similar hardware are sourced, especially Lange et al. In the system control section, a special attention is given to hardware latchups in high-density IO banks. A radiation shield is included to mitigate potential risks even further.

Additionally, the Zynq US+ is used in many small satellites as an onboard computer [10], and is also endorsed in the state of the art small spacecraft report, published by NASA Ames Research Center in January 2023.

7. CUBELRR

To verify the position determinations by the active payload, a laser-ranging reflector CubeLRR is included in the mission. With satellite laser-ranging (SLR), the position of an object can be measured with multiple observations with high accuracy in the centimeter range. The main limitation of such a reflector is however, poor spatial and temporal coverage. To accomplish measurements, a cooperation with the global SLR station network as well as cooperation universities is intended. The design of the retroreflector is based on the design of German Research Center for Geosciences (GFZ), consisting of four prisms in a pyramid arrangement. However, the design is scaled down to fit the measurements of fit inside of a CubeSat tuna can configuration.

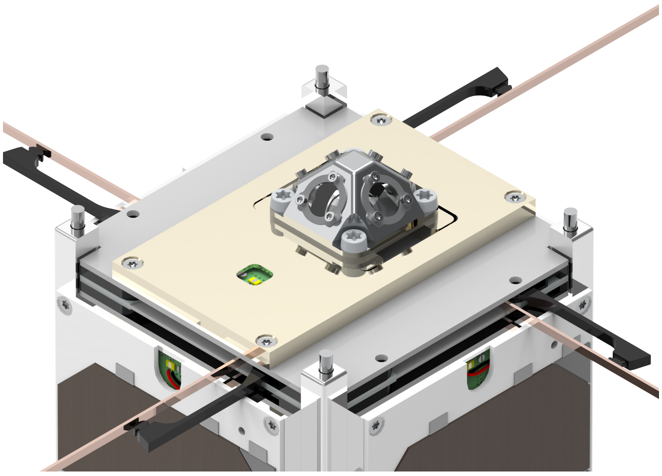

FIG 6. Laser retro-reflector on satellite top lid

The final design uses a titanium holder with an edge length of 34 mm and a height of 15.5 mm. Four coated 10 mm prisms are used, which are measured before the use in the mission.

8. CONCLUSION

EPISODE, a novel payload developed by TU Berlin under heavy influence of student work, exemplifies the convergence of advanced computing and space technology. Utilizing FPGA-based systems and open-source software, EPISODE achieves precise real-time GNSS reception in the challenging orbital environment. Its integration within the InnoCube satellite, alongside innovative technologies like Skith and Wall#E, showcases interdisciplinary collaboration. EPISODE's achievements are leading a path for future scientific applications. Beyond accurate orbit determination, its success could promote the development of advanced satellite-based GNSS-Reflectometry (GNSS-R) and Radio Occultation (GNSS-RO) techniques with onboard-processing in a CubeSat. Moreover, the commercial hardware and software designs open doors for AI-powered payloads, enabling cutting-edge research.

9. ACKNOWLEDGEMENTS

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