FORESAIL-1 CubeSat mission to measure radiation belt losses and demonstrate de-orbit technology

Petri Niemelä[1], Kirill Cheremetiev [1], Bruce Clayhills[1], Ville Lundèn[1], Markus Hiltunen[1], Ville-Valtteri Kettunen[1], Marius Anger[1], Bagus Riwanto[1], Nemanja Jovanovic[1], Minna Palmroth[2], Rami Vainio[3], Pekka Janhunen[4], Jaan Praks[1]

(1) Aalto University, Maarintie 8, Espoo, Finland petri.niemela@aalto.fi,
(2) University of Helsinki, Helsinki, Finland,
(3) University of Turku, Turku, Finland,
(4) Finnish Meteorological Institute, Helsinki, Finland

Abstract: FORESAIL-1 satellite is the first small satellite mission in the series of scientific small satellite missions developed by the Finnish Center of Excellence Research in Sustainable Space. The development of the satellite started in 2018 and it is expected to be launched in June 2022. The satellite's primary payload is a scanning dual sensor Particle Telescope, PATE, which scientific objective is to measure the energy and flux of energetic particle loss to the atmosphere with a representative energy and pitch angle resolution. In the later phases of the mission, a second shorter telescope is used to measure Energetic Neutral Atoms originating from the Sun. The satellite's secondary payload is a Plasma Brake de-orbiting experiment. In the experiment the Plasma Brake payload is used to reel out a 60 meter long tether out utilizing the satellite's spin motion. After deployment the tether is charged by high voltage to measure tether's interaction with the plasma environment and later to demonstrate the existence of the plasma brake effect by lowering the orbit and eventually de-orbiting the satellite. The satellite's avionics platform has been designed to be a precursor platform for the following beyond the LEO missions to the solar wind. Thus, the avionics system has been designed for high reliability and radiation tolerance in focus. The complete avionics system has been designed and tested in Aalto University, allowing greater flexibility on satellite's system design and component selection.

1. INTRODUCTION

FORESAIL-1 satellite is the first small satellite mission in the series of scientific small satellite missions developed by the Finnish Center of Excellence Research in Sustainable Space. The consortium if formed by Aalto University, University of Helsinki, University of Turku and Finnish Meteorological Institute and funded by the Academy of Finland.

The FORESAIL-1 satellite follows 3U CubeSat form factor and weight around 4 kg. The satellite has two main payloads; Particle Telescope (PATE) and Plasma Brake (PB) build by University of Turku and Finnish Meteorological Institute (FMI) respectively. The satellite platform, consisting Attitude Determination and Control System, Electrical Power System, On-board Computer and UHF-band radio subsystem, is designed by Aalto University. Aalto University also is the responsible operator for the satellite. As an experimental payload, the satellite hosts also an Raspberry Pi based camera, commercial off-the-shelf (COTS) AMR sensor based magnetometer experiment MATTI, and six retroreflectors for laser based optical tracking. Satellite's structure and its subsystems are illustrated in Figure 2.

The development of the satellite started in 2018 and it passed its CDR in November 2019. After the delays due to the pandemic and component shortage. the satellite was finally delivered to the launch broker in April 2022 and it is expected to be launched during June 2022 on a Falcon 9 rocket as part of Transporter-5 mission.

1.1 Mission Objectives

The high-level mission objectives are the following: [1]

1. Radiation measurements with PATE instrument
    - Measure the flux of precipitating electrons at LEO
    - Measure the (possible) solar energetic neutral atom (ENA) flux at LEO
2. Deorbit experiment
    - Tether deployment demonstration
    - Lowering the satellite orbit with plasma brake tether
3. Technology demonstration of platform capabilities
    - Support and carry out the mission of two payloads for designated mission time
    - Increased radiation tolerant avionics platform
    - Improved reliable magnetorquer attitude system
    - Demonstration of new radiation tolerance technologies (Precursor to FORESAIL-2 mission)
    - Make platform trackable by laser ranger from ground

2. MAIN PAYLOADS

2.1 Particle Telescope

The primary payload of the satellite is a Particle Telescope (PATE) designed and build by the University of Turku. The scientific objective of the PATE instrument is to measure the energy and flux of energetic particle loss to the atmosphere with a representative energy and pitch angle resolution over a wide range of magnetic local times utilizing a telescope and satellite's spinning motion. In the later phases of the mission, a second telescope is used to measure Energetic Neutral Atoms originating from the Sun. [1] [2]

The instrument consists two particle telescopes having identical stacks of silicon detectors equipped with readout electronics. Independently for both telescopes, the detectors' nominal energy range for electrons from 80 to 800 keV is divided in seven energy channels for and energetic protons at 0.3–10 MeV in ten channels. In addition, particles penetrating the whole telescope at higher energies will be measured in three channels. The two telescopes are have collimator tubes (long and short) for narrowing the directions of incoming measured particles.

During the nominal mission, the long telescope is directed along the long Z-axis of the spacecraft perpendicular to the rotation axis, telescope scans the directions in a plane perpendicular to the

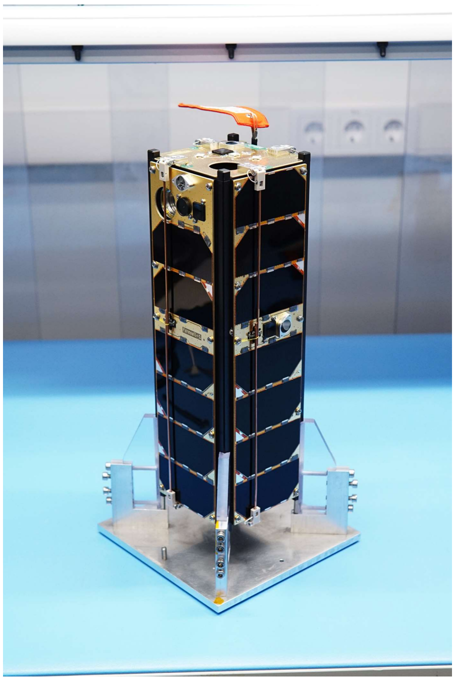

Fig. 1: FORESAIL-1 flight model in stowed configuration

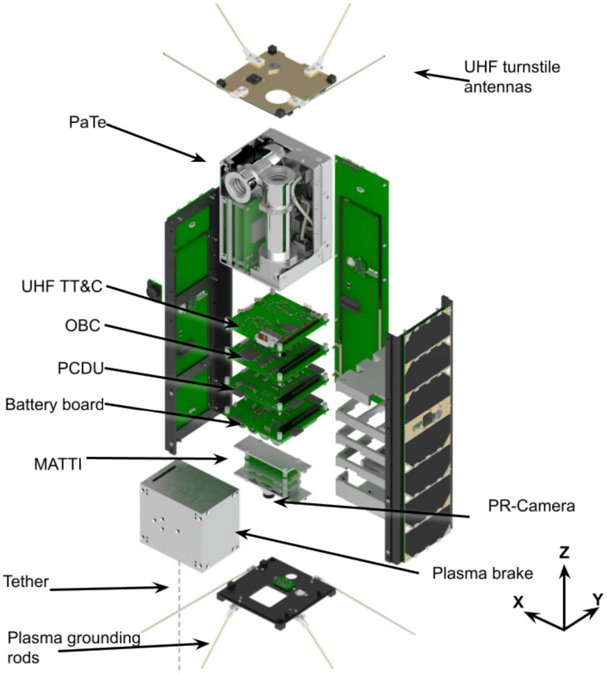

Fig. 2: Exploded view of the satellite

rotation axis of the spacecraft. By using the scanning motion the instrument provides the angular distributions of protons and electrons, at 11.25-degree clock-angle resolution. The short telescope is directed along the rotation axis to maintain constant pointing to wanted direction. The short tube is inertially pointed toward toward the Sun under the limitations of the orbital configuration and spin axis. [1] [2]

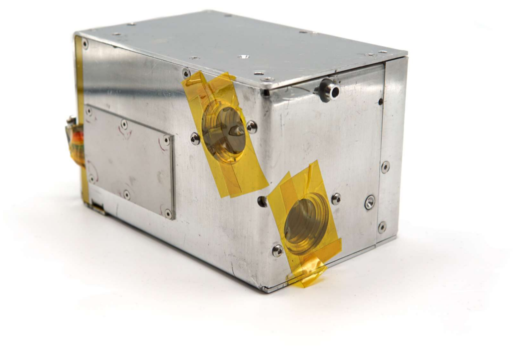

Fig. 3: Flight model of the Particle Telescope

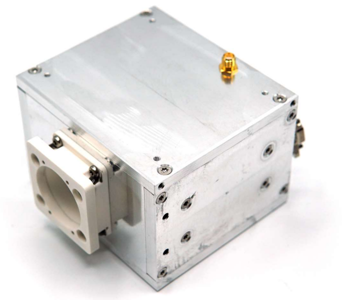

Fig. 4: Flight model of the Plasma Brake

2.2 Plasma Brake

The second payload on-board is a Plasma Brake (PB) experiment developed by the Finnish Meteorological Institute. The plasma brake experiment is based on charged solar sail concept by Pekka Janhunen [3]. In the experiment the Plasma Brake is used to reel out a 60 meter long tether out utilizing the satellite's spin motion. When deployed, the tether is charged with -1 kV potential to interact with the plasma environment in the outer ionosphere to create a braking force by electrostatic interaction with plasma particles. Because the plasma particles have average relative speed in respect to the satellite, the force can be used to accelerate or decelerate satellite's angular motion or to decrease its orbital velocity lower the satellite's orbital altitude. The experiment's objectives are to demonstrate the existence of the plasma brake effect by lowering the orbit during the mission and eventually demonstrate propellantless de-orbit capability at the end of the mission. [1]

Previously, similar experiment has flown board on ESTCube-1 (2013) and Aalto-1 (2017) satellites [4]. Both satellites failed to deploy the tether, and consequently measure braking force and deorbiting. The problem was located to mechanical failure of the tether reeling mechanism. In FORESAIL-1 the Plasma Brake has redesigned reeling mechanism, utilizing stepper motor instead of piezo electric motor along with improved mechanical design and diagnostic sensors. Similar Plasma Brake experiment also build by FMI is planned to fly on-board on ESTCube-2 3U CubeSat satellite later in 2022. [5]

3. AVIONICS PLATFORM

The satellite's avionics platform has been completely designed and build by Aalto University to meet the needs of this scientific mission. The platform has been also designed to be a precursor platform for the following beyond the LEO missions with harsh radiation environment. Therefore, the electronics are shielded by vault design and in most critical places radiation tolerant components are used. Avionics include On-board Computer, Electrical Power system and UHF-band TT&C system and Attitude Determination and Control System. The satellite mechanical design is also made specifically for this mission but can be reused due to high modularity.

3.1 On-board Computer

The On-board computer is satellite's central Command and Data handling system. The architecture of the OBC is based on Texas Instruments Hercules RM48 ARM Cortex-R4 microcontroller which have been designed for safety critical application. Each microcontroller has dual core architecture where both cores execute same program code in lock step to implement fault detection. Microprocessor's internal RAM and program flash memory have automatic error correction coding. Additionally, to processor level hot redundancy the OBC board has two identical cold redundant sides. Each redundancy side has external 2x512 kBytes FRAM and 128 MBytes NAND flash memory. FRAM memories are used for bootloading, configuration and housekeeping data and NAND flash for storing science data. The redundancy selection is performed by a MSP430 microcontroller which runs arbitration logic. The OBC software is build on top of FreeRTOS operating system. The OBC communicates to other subsystems and payloads using three shared cold redundant RS-485 busses.

3.2 Tracking, Telemetry & Commanding

Satellite's main communication system is UHF-band radio which operates on 70 cm radio amateur band. The radio subsystem has a central radiation hardened Vorago VA10820 ARM Cortex-M0 microcontroller with FRAM boot and configuration memory and two identical cold-redundant half-duplex transceiver and RF chains. The radio subsystem supports GMSK-modulation at 9600, 19200 and 38400 bits/s symbol rates. The transmission power of the system is 31 dBm. [6]

As the physical and link layer protocol the communication link uses the Aalto Skylink protocol which was developed for the platform. The physical layer protocol is based on well established Golay24 + RS(223,255) framing used by many small satellites. The link level protocol provides features such as windowed Time Division Duplexing (TDD) for medium access controlling, virtual channel multiplexing and Automatic Retransmit Requesting (ARQ) logic. On the application layer the communication link utilizes ECSS/CCSDS Packet Utilization Standard (PUS) for satellite telecommanding and telemetry. One of the virtual channels is reserved for radio amateur packet repeater functionalities using AX.25/APRS protocol.

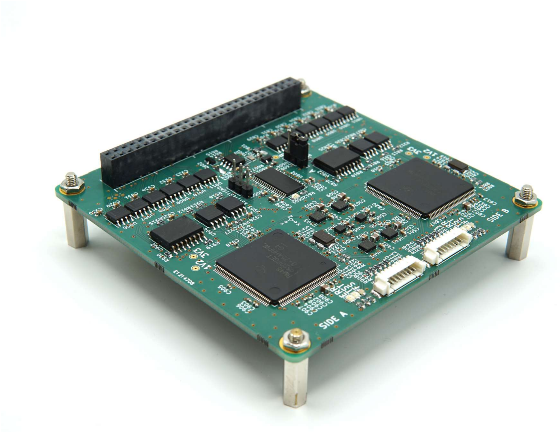

Fig. 5: Cold redundant On-board Computer

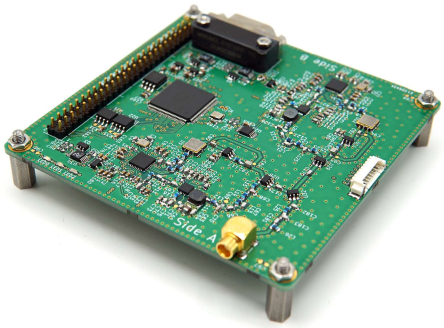

Fig. 6: UHF-band Tracking, Telemetry & Commanding subsystem

3.3 Electrical Power System

Satellite's Electrical Power System (EPS) consists two separate boards: Power Conditioning and Delivery Unit (PCDU) board and Battery Board (BATT). The PCDU board (in Figure 7) performs the input power regulation from solar panels, battery charging, output regulation and power distribution. PCDU has radiation hardened Vorago VA10820 ARM Cortex-M0 microcontroller with FRAM boot and configuration memory. The input regulation with Maximum Power Point tracking and battery charging is performer by manually driven buck converters using "perturb and observe" algorithm. PCDU and Battery board connect directly to solar panels using spring loaded pogo pin connector which make contact on mating connectors soldered behind the solar panels. Usage of pogo pin connector simplifies significantly the integration process. [7] [8]

The battery board (Figure 8) has four Panasonic 18650 cells in 2S2P configuration mounted on PTFE supports and soldered on the PCB. The cells were qualified and selected from a bigger patch. The board has a housekeeping microcontroller which performs cell monitoring, balancing and heating. Additionally, the board accommodates also the magnetorquer driver and Z-axis torquer coils and connections to solar panels other payloads.

The solar panels for this satellite were also designed and manufactured specifically for this satellite. Additionally to the high efficiency solar cells, the panels feature magnetorquer coils, retroreflectors, Sun sensors and antenna deployment mechanism.

3.4 Attitude Determination and Control System

The main missions for PATE and plasma brake requires satellite spinning motion up to 40°/s. The spinning motion is achieved using magnetorquer based attitude control integrated to the avionics platform. The attitude determination two cold redundant magnetometer and MEMS gyroscopes located on the OBC board and fine Sun sensors located on satellite's surface. The attitude estimation based on Unscented Kalman Filter (UKF). For controlling the attitude and spin motion, detumbling, 3-axis pointing and spin control algorithms were implemented. Attitude determination and control algorithms are executed on the OBC as part of the flight software.

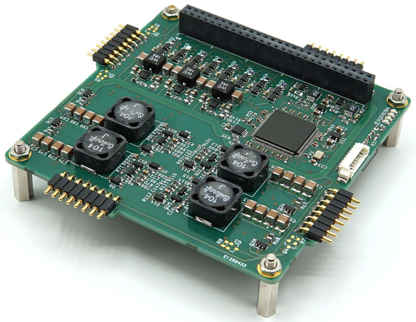

Fig. 7: Power Conditioning and Delivery Subsystem (PCDU)

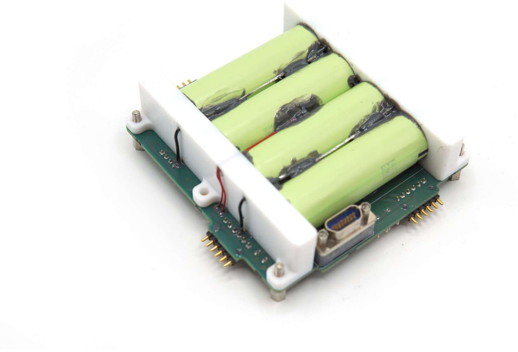

Fig. 8: Battery Pack flight model

The Foresail-1 satellite has six PSD (Position Sensitive Device) based sun sensors located on satellite's each face. Each sensor covers 100°Field of View cone. The combined sun vector estimate covers the complete sphere and can resolve the sun vector in better than 1.5°accuracy. Each sensor has four integrated transimpedance amplifiers for current to voltage conversion and a low-power MSP430 microcontroller for signal digitization, point estimation and I2C communication. The mass of single sensor is 4 grams and per sensor power consumption is less than 4 mW when active. The flight model of the PSD sun sensor is shown in Figure 9.

As an secondary experimental sun sensor design, the satellite has a digital imaging profile sensor based sun sensor located on the the satellite's Y+ sun pointing side. The sensor has an imaging profile sensor by Hamamatsu which captures the profile light spot image projected by a pin hole structure. The pin hole structure is formed by and ND-filter on top of the sensor which has pinhole mask 100 µm using optical lithography. The sensors purpose is provide more accurate sun vector measurements in the sun pointing modes. By using subpixel-level peak finding algorithm sensor can achieve better resolutions than 0.2° in Field of View cone of 50°. The mass of the sensor assembly is 6 grams and it consumes 100 mW when active. The flight model of the digital sun sensor is shown in Figure 10.

For the actuation, satellite has 5 air core magnetorquer coil located behind the solar panel PCBs and on the battery board. The torquer coils are driven by an integrated driver circuit located on the battery board. [9]

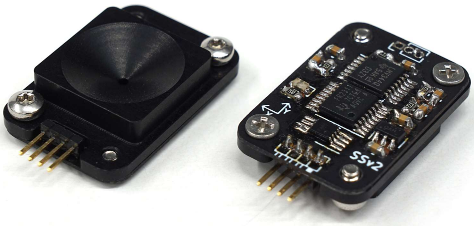

Fig. 9: PSD Sun Sensor

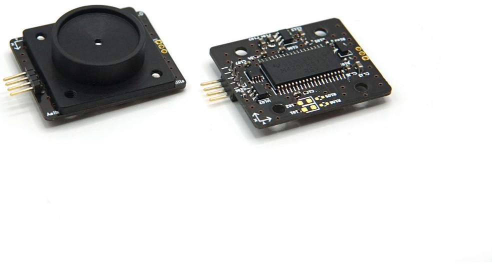

Fig. 10: Digital Sun Sensor

4. EXPERIMENTAL PAYLOADS

4.1 Camera

As tertiary experimental payload, the satellite has a visible camera. The main mission of the camera payload provide additional confirmation of the deployment of the plasma brake tether by imaging the tether's end mass. The camera is based on commercial-off-the-shelf Raspberry Pi Zero single board computer and its camera module. The stock camera module is modified to receive S-mount wide angle lens mounted on supporting aluminium structure. The Raspberry Pi runs a minimal DietPi Linux distribution which can operate on fully read-only file system and use second data partition for storing the image data. On top of the operating system a lightweight RS-485 commanding utility was built. The software contain utilities for bus communication and various imaging scripts for normal/quick mode, sequence mode and HDR and panorama modes written in Python. The flight model of the camera payload is shown in Figure 11.

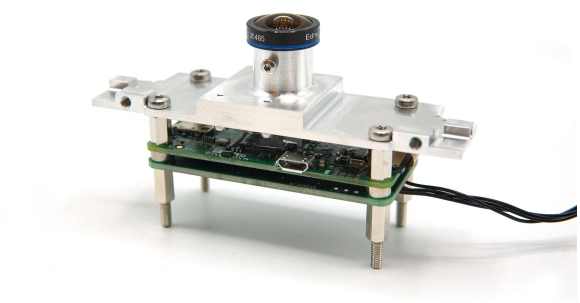

Fig. 11: RaspberryPi Zero based camera payload

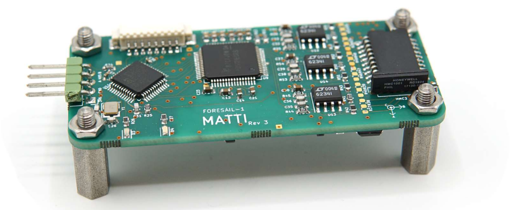

Fig. 12: Flight model of the MATTI magnetometer

4.2 MATTI magnetometer

As an experimental payload, a Magnetometer Technology Test Instrument (MATTI) was developed as a precursor instrument for the further magnetometer instruments and missions. The instrument is based on Honeywell HMC1001/1002 AMR sensors with required set/reset pulse driving circuit. The data collection and processing is performed by STM32L432 microcontroller which can readout the up to 30Hz rate. [10]

5. Conclusion

The presented Foresail-1 satellite design is an attempt to improve university CubeSat and extend the usage of the form factor to science missions. The satellite design is largely based on heritage and lessons learned from Aalto-1 and Aalto-2 missions. One of the radically improved areas was reliability and ease of use of the communication link and modularity of the design. Well defined and simple interfaces allow easier payload development. The develeoped avionic system can be adapted for various future missions and will be used as a baseline for Foresail-2 mission to higher orbits.

References

1. M. Palmroth, J. Praks, R. Vainio, P. Janhunen, E. K. J. Kilpua, N. Y. Ganushkina, A. Afanasiev, M. Ala-Lahti, A. Alho, T. Asikainen, E. Asvestari, M. Battarbee, A. Binios, A. Bosser, T. Brito, J. Envall,

U. Ganse, H. George, J. Gieseler, S. Good, M. Grandin, S. Haslam, H.-P. Hedman, H. Hietala, N. Jovanovic, S. Kakakhel, M. Kalliokoski, V.-V. Kettunen, T. Koskela, E. Lumme, M. Meskanen, D. Morosan, M. R. Mughal, P. Niemelä, S. Nyman, P. Oleynik, A. Osmane, E. Palmerio, Y. Pfau-Kempf, J. Peltonen, J. Plosila, J. Polkko, S. Poluianov, J. Pomoell, D. Price, A. Punkkinen, R. Punkkinen, B. Riwanto, L. Salomaa, A. Slavinskis, T. Säntti, J. Tammi, H. Tenhunen, P. Toivanen, J. Tuominen, L. Turc, E. Valtonen, P. Virtanen, and T. Westerlund, "Foresail-1 cubesat mission to measure radiation belt losses and demonstrate de-orbiting," *Journal of Geophysical Research: Space Physics*, 05 2019.

2. P. Oleynik, R. Vainio, H.-P. Hedman, A. Punkkinen, R. Punkkinen, L. Salomaa, T. Säntti, J. Tuominen, P. Virtanen, A. Bosser, P. Janhunen, E. Kilpua, M. Palmroth, J. Praks, A. Slavinskis, S. Kakakhel, J. Peltonen, J. Plosila, J. Tammi, and T. Westerlund, "Particle telescope aboard foresail-1: simulated performances," 2019.
3. P. Janhunen, "Electrostatic plasma brake for deorbiting a satellite," *Journal Propulsion Power*, p. 370–372, 2010.
4. J. Praks, M. R. Mughal, R. Vainio, P. Janhunen, J. Envall, P. Oleynik, A. Slavinskis, P. Niemelä, J. Gieseler, P. Toivanen, H. Leppinen, T. Tikka, A. Näsilä, N. Jovanovic, B. Riwanto, T. Peltola, A. Bosser, A. Kestilä, G. Schwarzkopf, A. Punkkinen, R. Punkkinen, H.-P. Hedman, J.-O. Lill, and J. Slotte, "Aalto-1, multi-payload cubesat: In orbit results and lessons learned," *Asta Astronautica*, 11 2020.
5. I. Iakubivskyi, P. Janhunen, J. Praks, V. Allik, K. Bussov, B. Clayhills, J. Dalbins, T. Eenmäe, H. Ehrpais, J. Envall, S. Haslam, E. Ilbis, N. Jovanovic, E. Kilpua, J. Kivastik, J. Laks, P. Laufer, M. Merisalu, M. Meskanen, R. Märk, A. Nath, P. Niemelä, M. Noorma, M. R. Mughal, S. Nyman, M. Pajusalu, M. Palmroth, A. S. Paul, T. Peltola, M. Plans, J. Polkko, Q. S. Islam, A. Reinart, B. Riwanto, V. Sammelselg, J. Sate, I. Sünter, M. Tajmar, E. Tanskanen, H. Teras, P. Toivanen, R. Vainio, M. Väänänen, and A. Slavinskis, "Coulomb drag propulsion experiments of estcube-2 and foresail-1," *Acta Astronautica*, vol. 177, pp. 771–783, 2020.
6. V.-V. Kettunen, "Communications subsystem test bench and design verification for foresail-1 cubesat," 12 2021.
7. K. Cheremetiev, "Design of reliable electrical power system for foresail-1 small satellite," 2020.
8. K. Cheremetiev, P. Niemelä, V.-V. Kettunen, T. Peltola, C. Bruce, V. Lundén, M. Palmroth, E. Kilpua, R. Vainio, P. Janhunen, and J. Praks, "Design and verification of electrical power systems for foresail satellites beyond the leo," 2022.
9. N. Jovanovic, B. Riwanto, P. Niemelä, M. R. Mughal, and J. Praks, "Design of magnetorquer based attitude control subsystem for foresail-1 satellite," *IEEE Journal on Miniaturization for Air and Space Systems*, 6 2021.
10. V. Lundén, T. Peltola, P. Niemelä, K. Cheremetiev, C. Bruce, M. Palmroth, E. Kilpua, R. Vainio, P. Janhunen, and J. Praks, "Performance and design of commerical of the shelf (cots) components-based magnetometer for foresail-1 cubesat," 2022.