Publ. Astron. Obs. Belgrade No. 101 (2021), 173 – 187 *Contributed Paper*
DOI: 10.5281/zenodo.5645486

ASTER: DEVELOPING A FREE FALLING PLATFORM FOR ATTITUDE CONTROLLED EXPERIMENTS

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Abstract: The verification of a spacecraft component's functionality under microgravity conditions is an important topic for the low-cost development of CubeSat components. The testing and verification of new components is often carried out on technological demonstration missions. To reduce the cost and time required, the verification process can also be undertaken on sounding rockets. To achieve best microgravity conditions, a testing platform must be entirely stabilised. Most sounding rockets are spin stabilised and, therefore, a centrifugal force acting upon the components remains. This force can be eliminated by ejecting the testing platform on a fully stabilised Free Falling Unit. Available attitude control systems are targeted at orbital flights, and therefore act slowly. Such systems measure their attitude control manoeuvres in significantly longer times, which is suboptimal as experiments conducted on Free Falling Units are highly constrained by flight time. Taking these requirements into account, the objective of Project ASTER is to design and test a low-cost, fast acting solution, to stabilise and orientate a free-falling platform in a reduced gravity environment. The results of the project will be published as open source to ensure its future availability to student and low budget research projects.

Keywords: Attitude Control, Attitude Stabilisation, Free Falling Unit, REXUS/BEXUS, Microgravity Experiment

1. INTRODUCTION

In recent years, the amount of space related activities has been constantly increasing. This can be partially attributed to improvements in technology, resulting in the budgetary requirements of such missions to also decrease along with external support therefor. This has subsequently allowed for projects to be undertaken by teams and organisations which would usually not have been able to pursue such opportunities. The complexity of these projects has however not decreased and continues to be a hinderance for many of these aspiring projects (see Berk et al. 2013, Cho 2020, Dubourg et al. 2006, Schmierer et al. 2019).

The Attitude Control System (ACS) of a spacecraft is often one of the most intricate subsystems, requiring significant resources to develop and integrate. As such, this still presents a significant barrier, preventing potential experiments from being pursued by smaller teams (Fasoulas et al. 2017).

ACSs that are currently on the market are mostly targeted at orbital vehicles, which allow slow-operating solutions due to their inherent nature of returning to the same orientation each orbit. Consequently, such systems typically measure their attitude control manoeuvres in much larger timeframes (Cordeau & Laporte 2004). However, experiments conducted on sounding rockets, including those ejected as a Free Falling Unit (FFU), are usually highly constrained by their flight time. Thus, these experiments require a high-performance solution for them to perform desirably in their expedited experiment timeline. Furthermore, current ACSs are usually aimed at projects with extensive funding, ruling out a large portion of student and low-budget experiments, which operate on a limited budget. Therefore, a high performing, low-cost ACS would greatly benefit future sounding rocket experiments with suitable stabilisation and pointing needs.

Project ASTER is a student project which began in the autumn of 2019 at the Luleå University of Technology's Space Campus in Kiruna, Sweden. The project is comprised of Master's students on the various Space engineering programs that are offered by the University. The ASTER mission is undertaken as part of the REXUS/BEXUS (Rocket and Balloon Experiment for University Students) programme which aims to demonstrate a high-performance, low-cost, compact, and easy to integrate ACS platform for FFUs, to be ejected from sounding rockets, and aims to launch in March 2022. It shall be capable of stabilising a FFU after ejection and subsequently performing slewing manoeuvres by means of three reaction wheels. The performance of the ACS will be recorded throughout the mission and will later be analysed to compare the expected performance with the flight data. The developed platform should allow for follow-on missions requiring attitude stabilization, to be easily integrated on the FFU, allowing such missions to concentrate on the experimental payload instead of the ACS. For this reason, the design and findings will be published as an open-source design upon completion, to aid any future experiments.

The REXUS/BEXUS programme is performed under a bilateral Agency Agreement between the *Deutsches Zentrum für Luft und Raumfahrt*[1] (DLR) and the Swedish National Space Agency (SNSA). The Swedish share of the payload has been made available to students from other European countries through a collaboration with the European Space Agency (ESA). Experts from DLR, Swedish Space Corporation (SSC), *Zentrum für angewandte Raumfahrttechnologie und Mikrogravitation* (ZARM)[2], and ESA provide technical support to the student teams throughout the project, to ensure its success. EuroLaunch, the cooperation between the Esrange Space Centre of SSC and the Mobile Rocket Base

[1] The German Aerospace Centre
[2] Centre of Applied Space Technology and Microgravity

(MORABA) of the DLR, is responsible for the campaign management and operations of the launch vehicles[3].

2. EXPERIMENT DESCRIPTION

The ASTER experiment is comprised of three main segments: Free Falling Unit, Rocket Mounted Unit (RMU), and Ground Station (GS).

The main part of the experiment is carried by the FFU. Inside the rocket, the RMU secures the FFU during as-cent and ensures the safe ejection. Additionally, it provides the electrical and communication interfaces to the REXUS Service Module (RXSM). The Ground Station includes the necessary equipment to communicate with the FFU throughout the whole mission profile and to successfully recover the experiment.

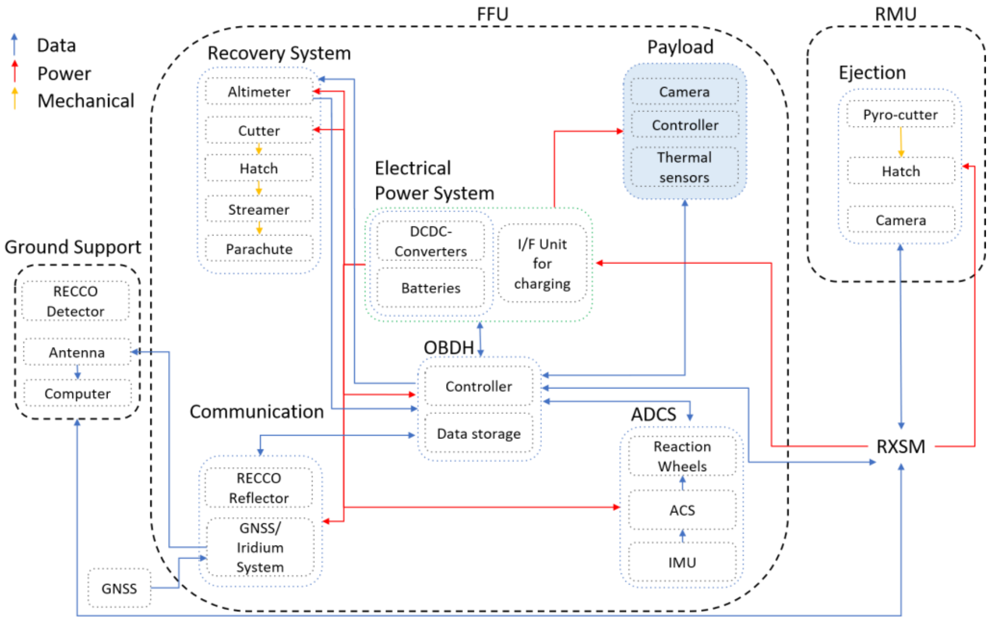

Figure 1: Overview of the Experiment's Functional and Physical Concept

Only the RMU is a subsystem by its own. The Ground Station and FFU are further separated into different subsystems. The Attitude Determination and Control System (ADCS) is the subsystem that defines the success of the mission, as it is responsible for the stabilisation of the FFU and its slewing manoeuvres. The other subsystems are the Electrical Power System (EPS), On-Board Data Handling (OBDH), Communication, Structure, Thermal and Recovery. The payload subsystems act as a demonstrator for future missions and for the verification of the system performance. In our case, it consists of a RaspberryPi Zero and a RaspberryPi fish-eye camera. The block diagram in Figure 1 shows an overview of

[3] Guidelines for Student Experiment Documentation, REXUS/BEXUS Organisers, 2018

the functional and physical concept of the experiment. It displays the three main segments of the experiment and the applicable power and data flows between them.

The FFU is defined as stable if the absolute angular velocity is less than $1°s^{-1}$ with a steady state tolerance of ±10°, while a successful slewing manoeuvre will have an accuracy of ≤10°. These values were determined analytically and are based on the available components and the performance values that can be guaranteed. Three primary and three secondary objectives are defined for the experiment:

1. Develop an attitude controlled FFU to be ejected from a sounding rocket.
2. Demonstrate that the ADCS can stabilise the FFU.
3. Recover the system after the experiment has been concluded and the FFU has landed.
4. Demonstrate that the ADCS can perform slewing manoeuvres of the FFU with the desired accuracy.
5. Design an FFU which can accommodate payloads of future experiments.
6. Design and build an FFU, including the ADCS, that is easy to integrate with future experiments.

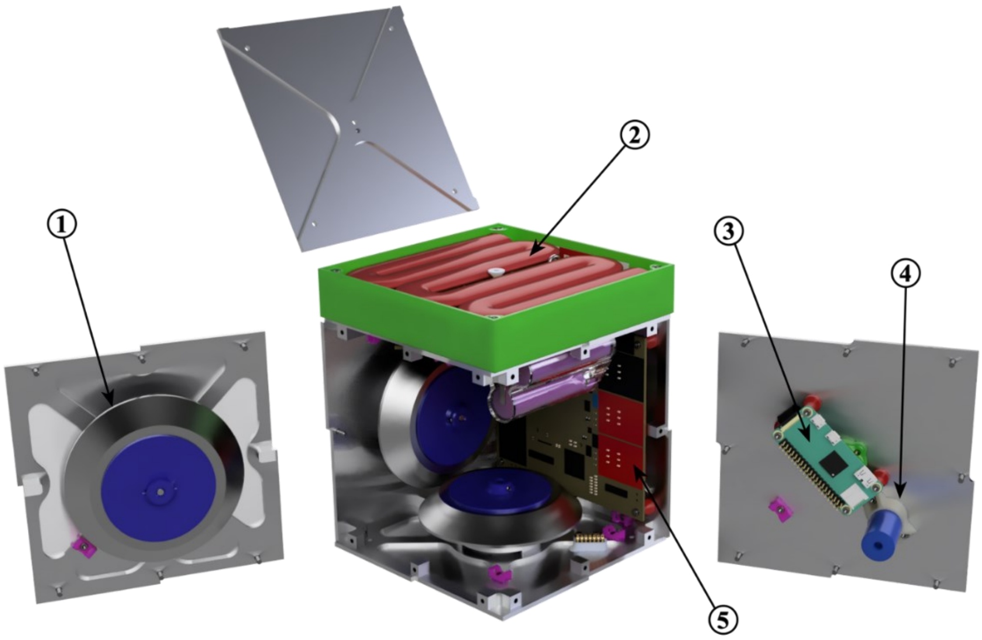

Figure 2: Open View of the Free Falling Unit: 1 – Reaction Wheel, 2 – Parachute, 3 – Payload, 4 – Iridium Antenna, 5 – Main PCB.

Inside the REXUS rocket, the ASTER experiment is located directly underneath the nose cone in a 270 mm high module with a diameter of 350 mm. Three other experiments are accommodated in the rocket, μMoon above ASTER and IMFEX and B2D2 below. The FFU is comprised of a 150 mm cube with an additional 30 mm high recovery module which houses the streamer and the parachute. This configuration can be seen Figure 2. The mass of the FFU is expected to be around

3 kg which will result in a total experiment mass of 13.7 kg, including the module and RMU. The structural integrity of the FFU is provided by 6 5754 aluminium plates with a nominal thickness of 3 mm. Depending on the components mounted to each plate, different cut-outs with a depth of 2.5 mm were added for weight reduction.

2.1. ROCKET MOUNTED UNIT

The RMU is the mechanical and electrical interface between the FFU and the REXUS rocket. The primary task of the RMU is the housing and ejection of the FFU prior to reaching the apogee of the trajectory. The retention mechanism keeps the hatch and FFU in the module via three steel cables. At ejection, four pyro-cutters are activated by the RXSM, which will cut both steel cables holding the hatch, with two pyros cutting each cable to ensure the uniform release of the hatch.

Subsequently, a fifth pyro-cutter separates the retention cable attached to the FFU and a spring ejects the FFU with a velocity of around 1.5 m/s, and a maximum tumbling rate of 0.08 Hz (which is the angular velocity of the de-spun rocket). During the ascent of the rocket, the FFU is connected with the RXSM via pogo pins, which are also used to charge the batteries prior to launch. Once the pogo pins are disconnected during ejection, the free-falling phase begins where power is provided by the batteries. A camera, mounted behind the FFU within the RMU, will record and confirm the ejection process, transmitting a live feed to the Ground Station via the RXSM.

The mechanical design of the RMU is based on a heritage design from the previous REXUS mission Tupex-6 (Sullivan et al. 2018), which was a pico-satellite experiment from the *Technische Universität Berlin* that was launched in March 2019. A render of the module with a removed hatch and the RMU inside can be seen in Figure 3.

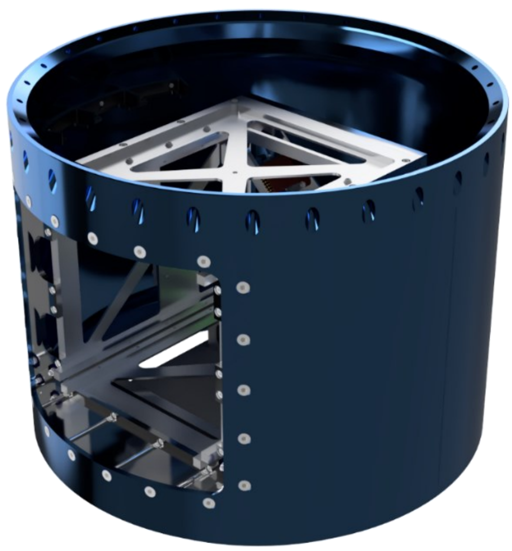

Figure 3: The Rocket Mounted Unit, without the Hatch.

2.2. ATTITUDE DETERMINATION AND CONTROL SYSTEM

This core subsystem of the ASTER experiment can be divided into three parts: the Attitude Determination System (ADS), the ACS and the Reaction Wheels.

The ADS utilises two 9-axis Inertial Measurement Units (IMUs) manufactured by Bosch. These sensors have already been used and tested by MIRKA2-RX (Ehresmann et al. 2016) a previous REXUS experiment of the *Universität Stuttgart*, Germany, which flew in 2016. The block diagram of the electronics design of the ADS is shown in Figure 4.

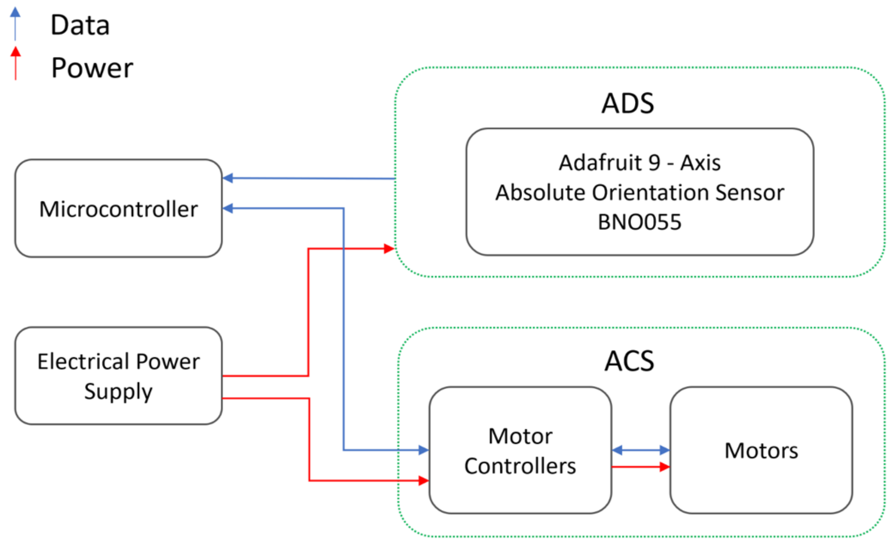

Figure 4: Schematics of the Attitude Determination and Control System Electronic Design.

The IMUs calculate the attitude expressing them as quaternions, which are subsequently used for system verification after flight with all measurements being saved on-board, on redundant SD cards for post-flight analysis of the FFU's behaviour. Since it was not possible to verify the functionality of the IMUs fusion algorithm in reduced gravity, the attitude will not be used for the system's ACS. Nevertheless, the attitude and all other IMU measurements will be logged and analysed after flight to learn more about the inflight behaviour. In combination with the payload camera data, it will be attempted to verify IMU's attitude determination for future uses. Only the gyroscope measurements will be used as input for the ACS control loop. A microcontroller calculates the necessary rotational velocity for the reaction wheels to stabilise the FFU or perform slewing manoeuvres. Different operational modes for different mission phases are utilised by the ACS. This modular approach allows a step-by-step integration and verification of the functionalities and therefore a more rapid development as concurrent engineering techniques are utilised. The different modes are summarised in Table 1. The control parameter's values are obtained through simulations and the tuning of the actual system during the testing process.

Table 1: Attitude Control Modes

Mode	Definition
OFF	Attitude- and angular velocity signal is measured but no signal is sent to the motor controller.
PASSIVE – Constant RPM	Attitude signal is measured but has no effect on control signal. The motor is run at a constant RPM for which a signal is sent to the motor controller
PASSIVE – RPM Sequence	The motor RPM is changed according to a timing sequence. Attitude signal is measured but not used.
ACTIVE – Stability Control	The angular velocity signal is fed to the inner P-controller which produces an angular acceleration. The system will aim to stabilise and achieve zero angular velocity.
ACTIVE – Stability Control with Slewing Manoeuvre	The slewing manoeuvre can start after the stability controller has de-tumbled the FFU. Angular velocity controller setpoint is adjusted to achieve a relative rotation of a certain angle and direction from the current attitude of the FFU.

The three identical Reaction Wheel setups are designed by team ASTER. They consist of the motor, mounting bracket and rotor. Two roller bearings protect the motor axis during launch from the high radial loads. The steel rotor is connected to the motor axis via a 3D printed disc, glued to the front face of the rotor, and two grub-screws. Table 2 gives the rotor properties, while Figure 5 shows an exploded view of the reaction wheel setup. The motor is an EC45 flat brushless DC motor from Maxon with a maximum power of 30 W.

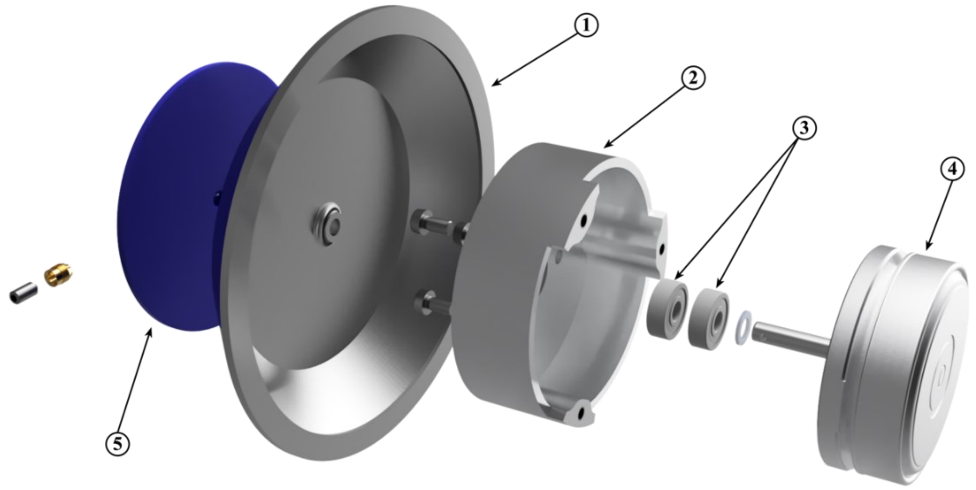

Figure 5: Exploded View of the Reaction Wheel Assembly: 1 – Rotor, 2 – Mounting Bracket, 3 – Bearings, 4 – Motor, 5 – Adapter Disk

Table 2: Rotor Properties

Property	Value
Mass	0.232 kg
Axial inertial moment	$3.841 \cdot 10^{-4}$ kgm^2
Planar inertial moment	$1.972 \cdot 10^{-4}$ kgm^2
Eigenfrequency, first mode	229.4 Hz

2.3. RECOVERY & COMMUNICATION

The purpose of the recovery subsystem along with the communication subsystem is to ensure a safe landing and retrieval of the FFU after completion of the mission. The three main parts are: the parachute, the top plate ejection system, and the communication system.

During descent, the recovery system will be triggered by a signal from an altimeter when the FFU approaches an altitude of 6 km. A secondary trigger is provided by a Global Navigation Satellite System (GNSS) altitude reading of 5.5 km and a tertiary by a timer, set to expire at around 5 km. When this system is activated, a pyro-cutter is used to cut a cord fixed to the retention bracket, releasing the top plate of the recovery compartment. A spark cover protects the electronics inside the FFU from any potential damage which may occur during the firing of the pyro-cuter. The top plate is preloaded using springs, and when ejected exposes the parachute and the streamer to free air. The recovery compartment and its main parts are shown in Figure 6. Once the parachute is completely deployed, the descent velocity of the FFU will be decreased to a velocity of less than 8 ms^{-1}.

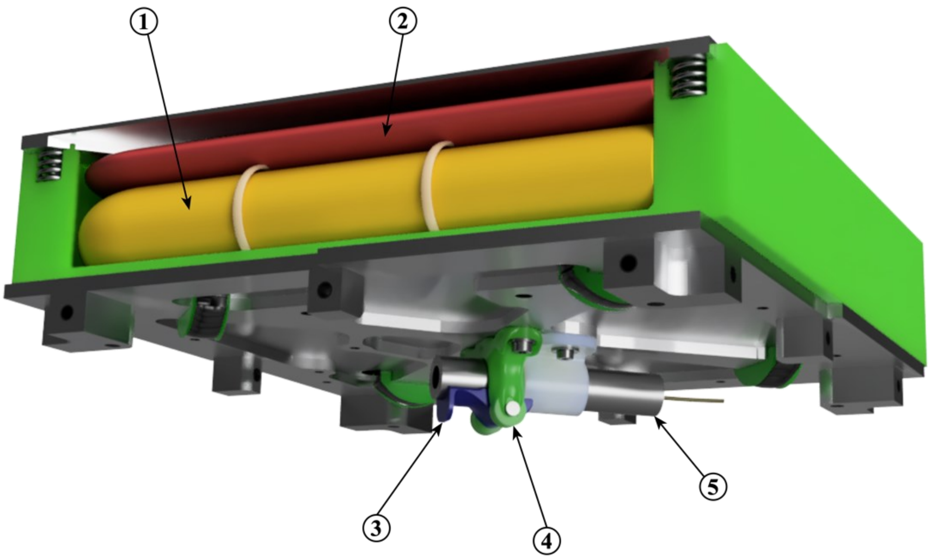

Figure 6: Recovery Compartment: 1 – Parachute, 2 – Streamer, 3 – Spark Cover, 4 – Retention Bracket, 5 – Pyro Cutter

The location of the FFU during the descent is determined using the GNSS data. This location data is then transmitted via the Iridium satellite network to the GS. Measurement data from the IMU will be used for landing confirmation. The location data will continue to be transmitted for around 2 h after landing, and afterwards the communication system will be powered down. This time frame is limited by the battery capacity but is sufficient to validate the final location of the FFU, to ensure it is not being moved by external factors such as wind dragging by the parachute.

Furthermore, the parachute and streamer will be equipped with RECCO reflectors, which are normally used in avalanche rescue operations, to allow the recovery team with its corresponding detectors, to precisely locate the FFU upon arrival in the landing area that is indicated by the transmitted location data.

Along with the location information, attitude and other platform data is sent periodically to the GS to allow basic monitoring during the mission and to provide the team with minimum data in case of a failed recovery.

2.4. ELECTRICAL POWER SYSTEM

The power requirements for the experiment are shared by the RXSM and the internal batteries on-board the FFU, with the source depending on the stage of the experiment. The OBDH system and a MOSFET control the switching between these two sources. The EPS setup is shown in the block diagram in Figure 7.

This switching capability will also be used to comply with the radio silence and payload-off states requirements stipulated by the REXUS/BEXUS programme. This ensures that the ESU and the FFU are switched off during the launch phase using a signal from the On-Board Computer (OBC). After those states are over, external power will be used to turn the microcontroller on again.

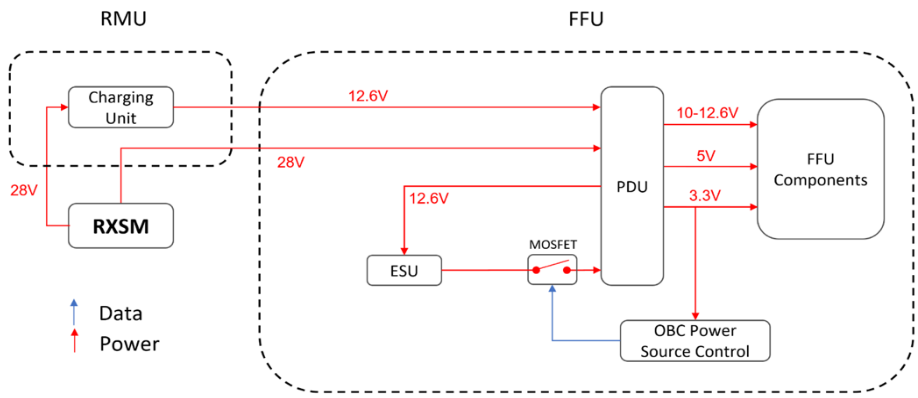

Figure 7: EPS Block Diagram

The internal power is provided by the Energy Storage Unit (ESU). Three Lithium-ion batteries are connected in series and placed within a separate 3D printed compartment in the FFU. Each battery has a nominal voltage of 3.7V and a capacity of 2600mAh. This configuration provides a nominal voltage of 11.1V, which is within the power supply range of the motor controllers, and, therefore, allows to directly supply the voltage from the ESU to the motor controllers.

In order to activate the system on-board the FFU, an external power supply will be required, which prevents any loss of power during transport. Prior to ejection, the RXSM will provide the power to spin up the reaction wheels and the ESU will receive a top-up charge.

Since the power supply to the recovery system is essential for the success of the experiment, a stop-power command from the OBC is implemented for the other subsystems after landing, thereby ensuring that enough power capacity is reserved to power the recovery system for the required period of time.

The Power Distribution Unit (PDU) uses three lines to distribute the power at the required voltages to all the components and to switch between power sources. Using DC-DC converters, the power provided by the ESU, as well as the external power, are converted to 3.3V and 5V. The total power required by the FFU is approximately 14Wh, which is provided by the ESU. An additional 5Wh margin is reserved for the payload. Figure 8 shows the power consumption profile of the FFU over the complete mission phase.

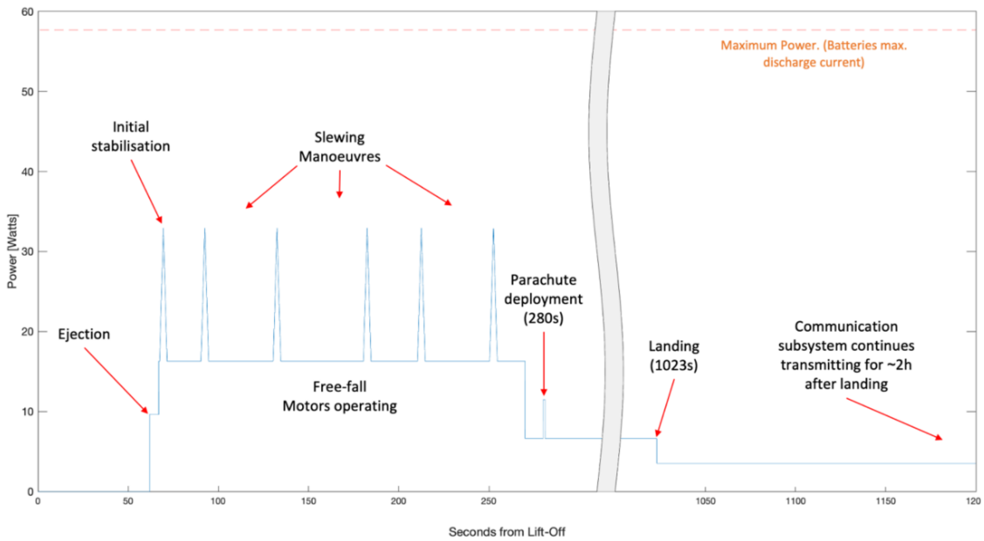

Figure 8: Power Consumption Diagram

2.5. THERMAL SUBSYSTEM

The experiment is expected to experience a broad environmental thermal profile, ranging from +50 °C inside the rocket to -30 °C after landing. These conditions need to be considered as they present a significant challenge to the nominal functionality of the experiment.

The environment is however not the only source of thermal disturbance, with the batteries and reaction wheel motors being identified as the largest thermal disturbances. The batteries generate a significant amount of heat during discharge, which is why the battery compartment consist of an insulated enclosure, shielding the rest of the FFU from the potential heat source. This is additionally done to protect the batteries from the sub-zero temperatures experienced after landing which may reduce the battery capacity, resulting in the FFU potentially not being able to transmit its location for recovery. The motors of the reaction wheels also prove a significant heat source due to their performance and high RPM use. To negate this and prevent overheating, the motors are positioned with the stator housing against the mounting bracket which subsequently act as heat bridges to dissipate the resulting heat to the FFU wall plate.

In order to ensure that the experiment functions as intended when being influenced by the various heat sources and the environment, extensive verification will need to be performed. This includes analytical testing methods such as performing a Finite Element Analysis (FEA) to obtain a model of the thermal distribution, and extends to subsystem, and subsequently system level tests of the experiment in nominal and sub-zero temperatures. An example is shown Figure 9. To obtain a comprehensive overview of the internal temperature distribution, six temperature sensors will be placed throughout the FFU which continuously take measurements. These sensors will additionally be used to provide the temperature profile of the actual mission for the post-flight analysis. This will all be done to verify the experiment and to qualify it for flight on board the REXUS rocket.

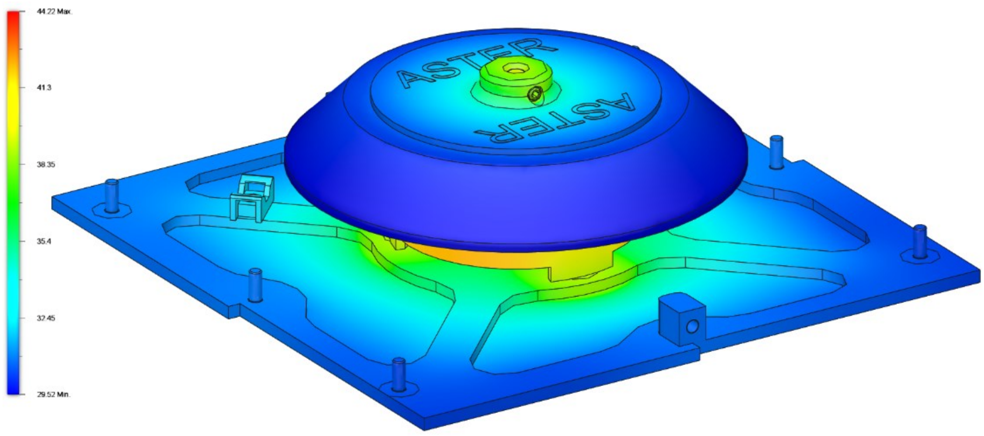

Figure 9: FEA of Reaction wheel showing temperature distribution.

2.6. ON-BOARD SOFTWARE

After launch, the experiment will operate in a fully autonomous manner. The on-board software is therefore responsible for ensuring continued operations of the various subsystems throughout the duration of the entire mission. Additionally, the system needs to be capable of maintaining operations even when confronted with non-nominal conditions and resolving such scenarios as they arise.

To fulfil these tasks the STM microcontroller which acts as the on-board computer, will run the real-time operating system FreeRTOS, with all the on-board software written in C. This allows the system to operate with defined runtimes while ensuring that the system can handle all system interrupts and tasks in time. Furthermore, the on-board software is responsible for maintaining communication with the ground and enables the experiment to respond to telecommands prior to launch. Prior to ejection, the information is transmitted to the Ground Station via the RXSM, whereas after ejection, it is transmitted via the Iridium Satellite network. A copy of all measurement and system data is stored on-board using two redundant SD cards for subsequent analysis following recovery.

For extended functionalities during integration, testing, and verification a test jumper pin is integrated in the system. If this jumper is recognized by the software, it will have more functionalities and more data is available via telemetry. To ensure functionality during flight this jumper is removed and only required commands and telemetry are available.

2.7. GROUND SUPPORT SOFTWARE

The Ground Support Software consists of two components, which are the Ground Station software and the Test Environment Software. During the initial phases following the launch, the Ground Station Software will receive information from the RXSM via the REXUS downlink. Following ejection of the FFU, this information will be transmitted via the Iridium network. The Ground Station Software will be developed by the team through the help of tolls such as Grafana and will be able to decode and display the incoming data in real-time.

The Test Environment Software will be used to test and analyse the system during the testing phase and will be able to send commands and initial test conditions to the FFU while simultaneously receiving measurement data from the on-board sensors. This will allow for any issues that may arise to be identified, rectified, and will permit fine tuning of system parameters such as the controller values in the ADCS.

3. TIMELINE

Through the REXUS/BEXUS programme, students experience all the phases of a space project. Additionally, they are introduced to the redaction of proposals and documentation, as before each review, the teams must submit an updated version of their documentation, the so-called Student Experiment Documentation (SED).

After the acceptance of the project in November 2019, team ASTER successfully passed the Preliminary De-sign Review (PDR) in February 2020. This first review took place during the Student Training Week at the Esrange Space Centre in Kiruna, Sweden, where all the teams participated in workshops and received input from various experts on the projects. The final design of the experiment was approved at the Critical Design Review (CDR) in June 2020. At the end of August 2020, an expert from the REXUS/BEXUS committee visited the team in Kiruna for the Integration Progress Review (IPR) which prompted the approval of all changes pro-posed since CDR.

Due to the COVID-19 situation, the whole REXUS/BEXUS cycle 13 was delayed by a year, including the relevant reviews. The Experiment Acceptance Review (EAR) will now take place in September 2021, along with additional progress reviews happening throughout Q1 and Q2 of 2021, where REXUS/BEXUS experts will verify that the teams are progressing as intended. The integration week at the ZARM facilities in Bremen, Germany, consisting of ejection and vibration tests, will take place in December 2021, while the final tests will be run during the Bench Test week at DLR Oberpfaffenhofen, Germany in January 2022. At this point the project will be fully verified and no further modifications will be allowed.

The launch campaign will take place at the Esrange Space Centre in Kiruna, Sweden during March 2022. After the flight and recovery of the experiment, the team will be given two months to analyse the data and submit the final reports in June 2022, which consist primarily of the final version of the SED with its findings. Figure 10 shows the updated timeline of the project with the key milestones.

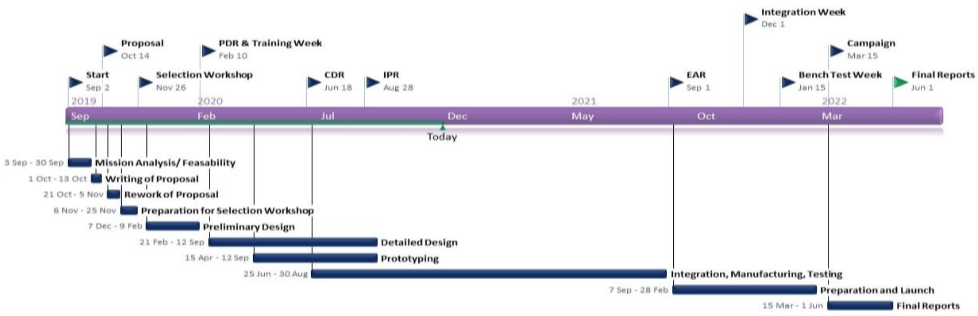

Figure 10: Project Time Schedule

4. CONCLUSION

Having received the bulk of our components, assembly, integration, and testing will become our main priority. The manufactured FFU and RMU as well as the experiment module can be seen in Figure 11. Most of the system verification should be concluded at the end of February and we will have our internal EAR.

The project is therefore well on its way towards being completed in early 2021. The COVID-19 health crisis has resulted in a significant delay of the project and launch schedule, but the team is confident in the given launch timeframe in March 2022 and that the project will be fully verified for its flight by then. The launch will mark the end of the development and testing period and the team will thenceforth focus on the analysis of the gathered data to verify whether all mission objectives were met, and to ultimately validate whether the ASTER platform proves a suitable platform for future free-falling experiments.

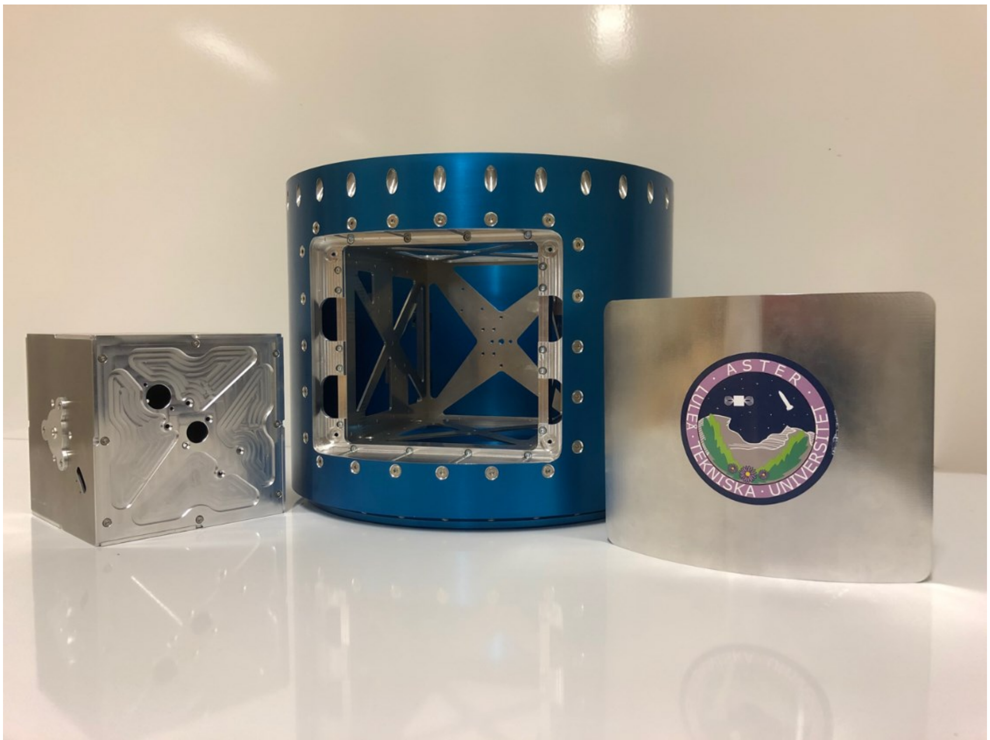

Figure 11: The FFU and the RMU inside the Experiment Module.

Project ASTER is looking forward to contributing to the space sector in the near future, by implementing a fast acting, low-cost and easy to integrate attitude control platform. This will be a viable solution for a variety of different applications and will aid future experiments in their endeavours to perform true microgravity experiments.

Acknowledgements

We would like to acknowledge and thank the various organisation which have afforded us this opportunity to pursue this project. Firstly, we would like to thank the REXUS/BEXUS organisation, which consists of experts from the DLR, SSC, ZARM and ESA, providing technical support to the student teams throughout the duration of the project. Additionally, we would like to thank EuroLaunch, the cooperation between the Esrange Space Center of the SSC and MORABA, who are responsible for the campaign management and operations of the various launch vehicles.

We would also like to thank our endorsing professor at the Luleå University of Technology, Professor Thomas Kuhn, alongside the other members of staff who are providing us with invaluable advice and guidance, namely: Olle Persson, René Laufer, Élcio Jeronimo de Oliveira, Anita Enmark, Chris Nieto, Siiri Talvistu, and Diego Oc-tavio Talavera Maya.

In particular, we would also like to thank our ESA mentor Jeroen Vandersteen who has supported us throughout this project, and continues to do so, especially with the ADCS and the implementation thereof.

Additionally, we would like to thank our various sponsors who continue to support us both financially and technically, namely: Maxon Motors AG, Rock Seven, AISLER, RECCO, RS-Components, PELI Products, and OFAB.

Lastly, we would like to thank the various members of Team ASTER: Anne Hartmann, Henning Isberg, Cornel-is Peter Hiemstra, Noel Janes, Tõnis Kull, Miguel Llamas Lanza, Erik Lindström, Flavia Pérez Cámara, Erik Samuelsson, Sebastian Scholz, and Andreas Wolnievik.

References

Berk, J., Straub, J., Whalen, D.: 2013, *The Open Prototype for Educational NanoSats: Fixing the other side of the small satellite cost equation*, IEEE.

Cho, A.: 2020, *Science*, **367**, 967.

Cordeau, J.-F., Laporte, G.: 2004, *Journal of the Operational Research Society*, **56**, 962.

Dubourg, V., Kainov, V., Thoby, M., Silkin O., Solovey, V.: 2006, *Journal of Atmospheric and Solar-Terrestrial Physics*, **37**, 754.

Ehresmann, M. et al.: 2016, *ESA/CNES Small Satellites, System & Services Symposium (4S)*.

Fasoulas, S., Herdrich, G., Schateikis, T., Martin, J.: 2017, *International Electric Propulsion Conference*.

Pérez Cámara, F., Janes, N., Lange, J.: 2020, *Proceedings of the 34th Annual Small Satellite Conference*.

Schmierer, C., Kobald, M., Tomilin, K., Fischer, U., Schlechtriem, S.: 2019, *Acta Astronautica*, **159**, 578.

Sullivan, D. A., Fürstenau, J. F., Posada Garcia, C., Grau, S., Brieß, K.: 2018, *The 4S Symposium*.