DOI: 10.13009/EUCASS2019-779

8TH EUROPEAN CONFERENCE FOR AERONAUTICS AND AEROSPACE SCIENCES (EUCASS)

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TUPEX-7: Expanding CubeSat Capability

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Abstract

TU Berlin Picosatellite EXperiment 7 (TUPEX-7) is a student driven project, scheduled to fly on the 28th REXUS mission, as part of the German-Swedish student programme Rocket/Balloon Experiments for University Students (REXUS/BEXUS). TUPEX-7 aims to develop and demonstrate miniaturized technologies for a 1U CubeSat. This paper describes the mission objectives and novel technologies demonstrated on the mission. This includes an examination of the interfaces between the subsystems of the free-falling unit (FFU), the rocket-borne equipment (RBE) and the rexus service module (RXSM). Expected results are outlined as well as the remaining engineering & design work required to make the bus space-ready.

1. Introduction

A directional shift in modern satellite technology is emphasized by the increase of nano- and micro-satellite launches in recent years as shown in analyses by Kulu,[1] Williams, Doncaster, and Shulman.[2] The ever-increasing growth in the development, use, and capability of small satellites is both a driver and a result of the miniaturization of space technologies. Such advancement has allowed for pico-, nano-, and CubeSats to conduct meaningful science and technology development through their payloads, as explored in Selva and Krejci's survey[3] and the study by Poghosyan and Golkar.[4] However, the payloads, such as Earth observation cameras or technology demonstrators, are often constrained by the volume required for the various subsystems necessary for base-level satellite operation; therefore, the demand for volume-efficient and highly-integrated small satellite components has accelerated.[5]

Research in the area of miniaturization of such components is a focus of the Chair of Space Technology at technische universität berlin (TU Berlin), as outlined by Department Head Prof. Dr.-Ing. Klaus Brieß.[6] The ongoing research has strong momentum from a rich history of small satellite missions and suborbital missions, such as those of the TUPEX family. The latest member, TUPEX-7, is a student-led project taking part in the German-Swedish student programme Rocket/Balloon Experiments for University Students (REXUS/BEXUS). Through the project, technology researched at technische universität berlin (TU Berlin) to enable on-board payload expansion of CubeSats will be developed, integrated, and tested. If successful, TUPEX-7 will serve as a model not only for development of a potential future university CubeSat bus, but also for the unique integration of CubeSat technologies enabling payload expansion.

2. Background

Ongoing research into the miniaturization of satellite components at TU Berlin has produced advances in the state of the art in the field of attitude determination and control systems (ADCS), namely a novel type of attitude control actuator known as the fluid-dynamic actuator (FDA). The novel actuator's principle of operation is the same as reaction wheels, namely the exchange of angular momentum between the satellite and actuator. The torque is produced by accelerating a volume of liquid metal within a closed channel using an electromagnetic pump. Noack[7] has illuminated the potential application of fluid-dynamic attitude control in CubeSats, complemented by his laboratory investigation of an actuator design.[8] The application of fluid-dynamic actuator (FDA)s can offer several benefits–the increase in reliability due to the lack of mechanically moving parts, and greater flexibility in attitude control maneuvers due to the very rapid torque they generate.[9]

DOI: 10.13009/EUCASS2019-779

Grau has developed a miniaturized version of these fluid-dynamic actuators, known as pico-fluid dynamic actuators (pFDAs).[10] In addition to the benefits given by FDAs, pFDAs can be shaped in a variety of ways depending on the mission requirements, with planar-shaped channels offering maximal volume efficiency. One type of rendition detailed by Grau et al.[11] entails integrating the planar pFDAs and components of standard satellite subsystems - parts of the ADCS, the communications system (COMMS), the electric power system (EPS), and the structures and mechanisms system (SMS) - onto the satellite's side panels, such that so-called highly-integrated cubesat side panels (HISPs) are created. With the synthesis of these subsystems and the components therein, Grau[10] shows the potential for HISPs to provide a payload-to-volume ratio up to 60%, whereas traditional 1U CubeSat buses tend to achieve a much smaller ratio, as low as 20% in an example commercial platform.[12]

TUPEX-7 seeks to integrate HISPs alongside another volume-efficient subsystem technology, the software defined radio (SDR), into a 1U CubeSat bus to demonstrate maximal payload expansion and system flexibility. Traditionally designed CubeSats contain a dedicated hardware transceiver for each frequency band.[13] The SDR, with software-adjustable frequency and modulation, allows for flexible communication between ground and satellite, only requiring power- and low-noise-amplifiers for the frequencies used by the satellite.

It is through this effective integration of the subsystems of satellites that the TUPEX-7 student team, together with TU Berlin Chair of Space Technology research staff, will demonstrate impactful expansion of payload volume in CubeSats–more payload for more return from educational, technology demonstration, and scientific CubeSat missions.

3. Mission Objectives

The overarching objective of the TUPEX-7 mission is to develop a free-falling unit (FFU) as the foundation for a volume-optimized TU Berlin educational CubeSat bus, to test the bus in a space-analogous environment, and to recover the data contained in the FFU after the flight. More specifically, the bus is to include the TU Berlin-developed HISPs and low-cost SDR transceiver. The HISP's suite of pFDAs and attitude sensors are to be tested and characterized in the milli-gravity environment (within thousandths of Earth's surface gravity) by attempting three-axis attitude control. The application of the team-developed SDR transceiver will be demonstrated through simplex communication with a ground station. Also captured in the mission objectives are the passing of the qualification campaign, launch, and ultimate recovery of the FFU. The definitive mission objectives are listed in Table 1.

Table 1: TUPEX-7 mission objectives

ID	Objective	%
MO1	Development of FFU bus including low-cost HISPs.	15
MO2	Development of a low-cost SDR transmitter.	15
MO3	Pass qualification campaign.	15
MO4	Launch of TUPEX-7 hardware.	10
MO5	Demonstration of the capabilities of HISPs in an operational environment.	10
MO5.1	Demonstration of three-axis ADCS	5
MO5.2	Characterization of actuators and sensors in a space-like environment.	5
MO6	Demonstration of simplex communication using an SDR transmitter.	10
MO7	Recovery of FFU data storage	25

4. Experiment Concept

As can be seen in Figure 1, the experiment is split into four phases: rocket ascent, milli-gravity and the ADCS experiment, free-fall and the communications experiment, and the parachute descent. After the rocket ascent, an FFU will be ejected from the rocket and it will then perform a pre-programmed sequence of experiments. Immediately after ejection, the FFU will determine its angular rate and commence a maneuver to reduce its angular momentum using the pFDAs. Then, the pFDAs will be de-saturated using the magnetic coils incorporated in the HISPs. Afterwards, it will perform a slew angle maneuver using the pFDAs, and again, magnetic coils for desaturation.

After the ADCS experiment, the communications experiment will begin. During this phase, the FFU will transmit a fixed data payload that is known ahead of time to the ground station (GS). This exchange of information will allow an assessment of bit error rate of the communications system. Additionally, the FFU will transmit housekeeping

DOI: 10.13009/EUCASS2019-779

data and a fraction of the payload data acquired during the milli-gravity phase of the experiment to the GS in order to demonstrate that the SDR transmitter can be used in an operational scenario.

Finally, the parachute will deploy according to a time- and pressure-based triggering system, and, when the FFU is close to the ground, the global positioning service (GPS) recovery system will be enabled, which will transmit the location of the FFU to the GlobalStar simplex network. The location will be received by the TUPEX-7 team, which will subsequently direct the recovery personnel to the landing area. Performance data will be measured throughout both experiments and stored in nonvolatile memory within the FFU and GS, which will be retrieved and analyzed after a successful recovery campaign.

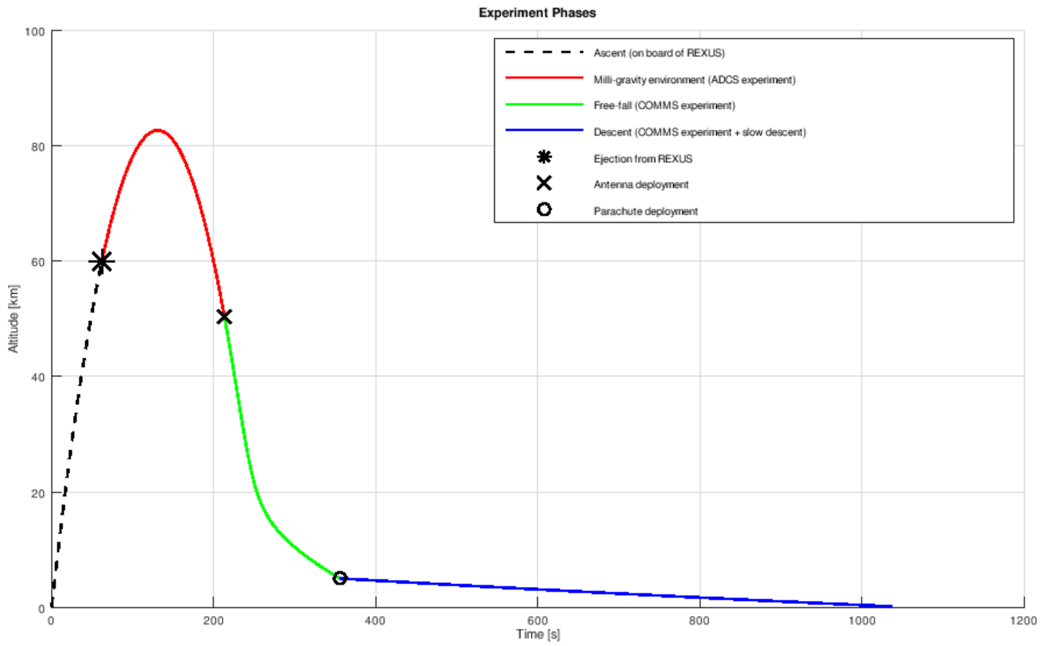

Figure 1: Phases of the flight

The TUPEX-7 mission is structured into three segments: the launch segment, offered and operated by REXUS; the space segment, containing the RBE and FFU developed by the TUPEX-7 team as well as the RXSM; and the ground segment, which is operated by TUPEX-7 in cooperation with ZARM/DLR. Each segment is described in the following subsections.

4.1 Launch Segment

The Launch Segment consists of the REXUS rocket and associated electrical ground support equipment (EGSE) and mechanical ground support equipment (MGSE). This segment is operated exclusively by the EuroLaunch cooperation. By participating in the REXUS/BEXUS campaign, the TUPEX-7 team obtains a "ticket" to fly the experiment to the edge of space on a REXUS rocket.

> The REXUS/BEXUS programme is realised under a bilateral Agency Agreement between the German Aerospace Center (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). EuroLaunch, a cooperation between the Esrange Space Center of SSC and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles. Experts from DLR, SSC, ZARM and ESA provide technical support to the student teams throughout the project. REXUS and BEXUS are launched from SSC, Esrange Space Center in northern Sweden. ([14]Section 1. Introduction.)

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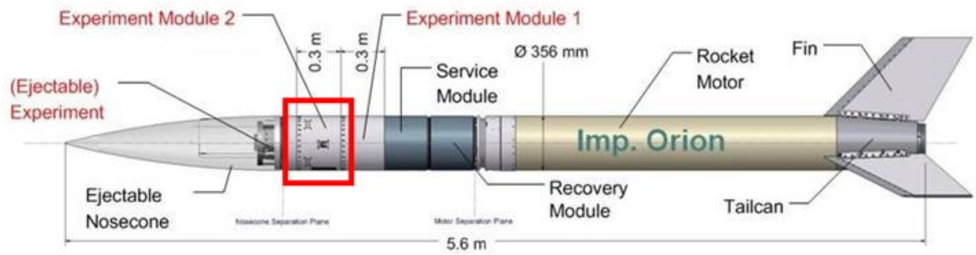


Figure 2: Representative image of the REXUS launch vehicle.[15] The location of the TUPEX-7 Experiment Module (next to the nosecone) is highlighted in red.

The launch vehicle uses an Improved Orion motor, as shown in Figure 2, which is attached to the RXSM. Above the RXSM, the student Experiment Modules can be found, and finally the nosecone. In some REXUS configurations, the nosecone can also house an experiment. But most importantly, it contains the parachute used to recover the experiments at the end of the flight.

4.2 Space Segment

The Space Segment is where the bulk of the experiment happens, see Figure 3 for an overview. The RXSM is responsible for providing power to the experiments while on the launchpad and in flight; providing a video downlink which can be switched between a number of cameras onboard the rocket; providing a data downlink from the experiments; and controlling pyrotechnic elements, such as the ejection mechanism used for TUPEX-7. The RBE retains the FFU prior to ejection and provides a power and data interface.

The FFU, in turn, is the heart of the experiment. It is ejected from the rocket by the RBE and begins an automated sequence of actions (performing data collection throughout), which are intended to fulfill the mission objectives in Table 1.

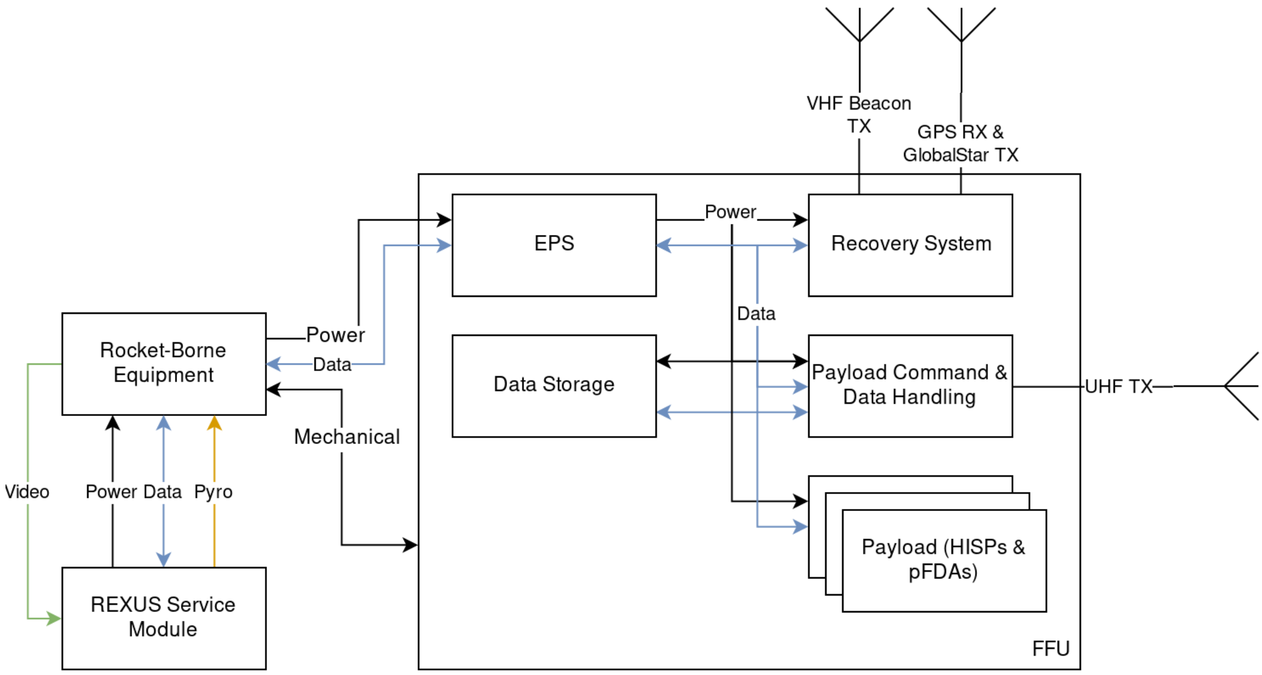


Figure 3: Schematic diagram of the components of the Space Segment.

4.2.1 Rocket-Borne Equipment

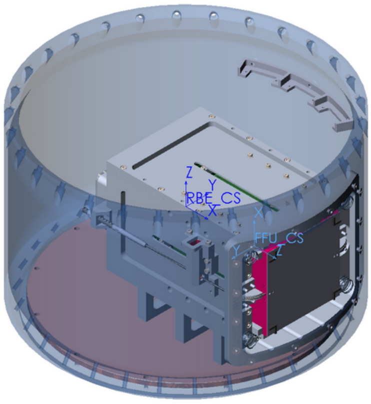
The RBE is the interface between the REXUS rocket and the TUPEX-7 FFU. As such, it provides first and foremost a mechanical interface to safely carry the FFU into the desired ejection altitude. Additionally, it provides a power and data interface (as described in Section 4.2.3), and ejects it at the desired deployment altitude. The design

DOI: 10.13009/EUCASS2019-779

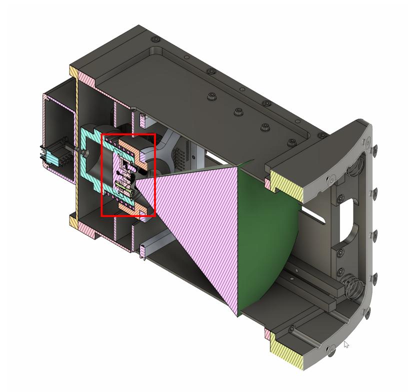
was successfully proved by the predecessor mission, TU Berlin Picosatellite EXperiment 6 (TUPEX-6),[16] and it is used mostly unaltered, except for the following modifications:

A small form-factor camera has been included in the deployer (see Figure 4.b) to observe the ejection of the FFU, and provide additional status feedback by looking at a pattern of LEDs included in the highly-integrated cubesat side panel (HISP) facing the push plate. The information encoded in the pattern of LED flashes can be used as additional input for a root cause analysis should an anomaly occur.

The number and purpose of pogo pins has been changed. On TUPEX-6, two sets of 12 pins were used to provide power, data, and a programming interface. Importantly, both sets had to be operational, i.e. there was a single point of failure. On TUPEX-7, the programming interface has been removed, and all of the functions provided by the pogo-pin interface (PPI) can be fulfilled with only one set of pins in contact with the target pads. The other set is then used for hot redundancy.



(a) Assembly view of RBE and FFU



(b) Cross section of deployer, with camera (highlighted in red) and field of view

Figure 4: CAD views of the RBE

The electronics on-board the RBE are also directly inherited from TUPEX-6, with some small modifications. The charging line for the FFU is now powered from a dedicated circuit intended for charging the batteries of experiments on the rocket, without having to wake up other experiment subsystems, and the rocket-borne equipment electronics (RBEE) also provide a power interface for the RBE camera. The printed circuit board (PCB) layout of the RBEE has also been reworked to reduce the voltage ripple fed back to the RXSM.

In addition to the interfaces with the FFU, the RBE also interfaces with the RXSM. The location of the RXSM can be seen in Figure 2.

4.2.2 Free-Falling Unit

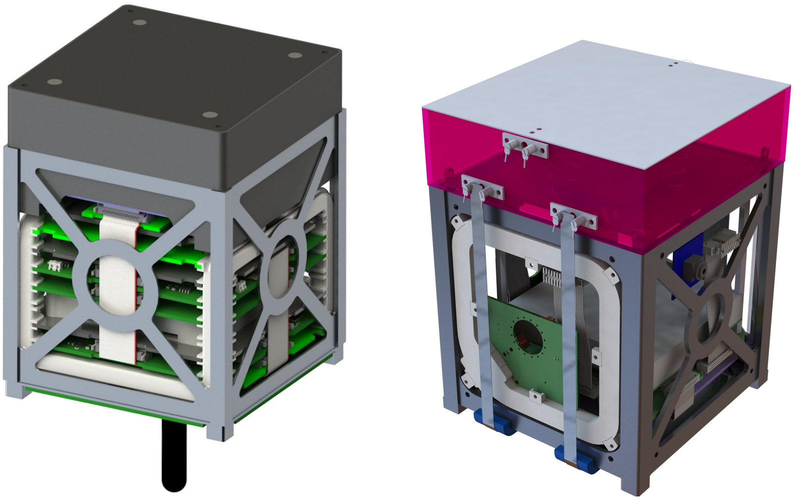
The FFU contains the subsystems seen in Figure 3, which are required to perform the experiments required by the mission objectives in Table 1:

- **Electrical Power Subsystem**: responsible for providing power and data to the rest of the subsystems in the bus. Since it acts as the master node, it also controls the flight schedule.
- **Recovery System**: responsible for a successful retrieval of the data contained inside the FFU. Its primary functions are to deploy the parachute at an appropriate altitude, and to transmit the location of the FFU once it lands, via a redundant heterogenous communications system.
- **Payload Command & Data Handling**: responsible for running all payload algorithms (ADCS and SDR modulation), as well as saving the experiment data to redundant storage. The PCDH subsystem contains the SDR and a connector for the UHF antenna.
- **Payload (HISPs & pFDAs)**: consists of the actuators and sensors for the attitude determination and control system (ADCS) experiment.

DOI: 10.13009/EUCASS2019-779

In addition to the subsystems of a standard CubeSat bus, the FFU contains a recovery system, which implements a redundant heterogeneous communication system. This is done to maximize the chance of the FFU being retrieved after the flight. A GlobalStar STINGR module is used to receive GPS coordinates and transmit them via its built-in satellite modem to the GlobalStar network. As a backup, a VHF beacon is used to provide the position of the FFU to the recovery crew.

The FFU has a total size of 1.3U (130x100x100 mm), with the bus and experiments taking 1U and the remaining 0.3U being used for the recovery compartment (shown in pink in Figure 5.b.)



(a) TUPEX-6[17] (b) TUPEX-7

Figure 5: Comparison of TUPEX-6 and TUPEX-7 FFUs

While the TUPEX-7 FFU design inherits some of the design from its predecessor, there are a number of crucial differences:

1. The side panels are much more than merely structural members in TUPEX-7. Instead, they also contain the actuators (pFDAs and magnetic coils) and attitude determination sensors (sun sensors, gyroscopes and magnetometers), also known as HISPs.

2. The pFDAs are planar instead of L-shaped. Therefore, they produce an angular momentum vector normal to the face of each side panel instead of a tetrahedral momentum vector. Additionally, the inner channel is surrounded by another hull to increase the mechanical reliability of the actuators.

3. The recovery compartment uses springs and a wire melting mechanism instead of permanent reversible electromagnets. This reduces the moment of inertia of the FFU, enabling more possibilities for ADCS experiments.

4. The recovery compartment is independent from the rest of the FFU bus, including its own batteries and sensors to determine when to deploy the parachute and begin transmitting its location. This change was done to reduce the risk of being unable to recover the FFU due to a single failure in the EPS or the controller area network (CAN) bus.

5. An SDR is included in the payload, command, and data handling (PCDH) subsystem, as an experiment in flexible and low-cost communications system.

4.2.3 Pogo-Pin Interface

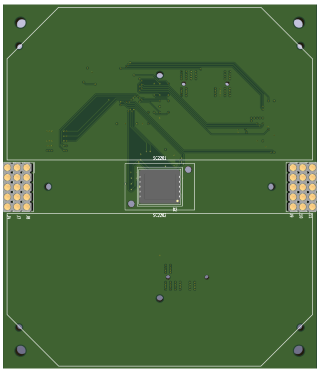
In order for the TUPEX-7 team to assess the status of the FFU during the launch campaign, some form of data connection with the GS is necessary. While the FFU contains a communications system, it should not be used for this purpose for several reasons. First, transmitting radio signals while inside the rocket is difficult due to the high attenuation caused by its aluminium body. Also, the communications system on the TUPEX-7 FFU is not capable of receiving commands from the GS. And finally, there could be a problem with the experimental communications system itself, rendering the team unable to troubleshoot the FFU. For these reasons, it was decided to use a temporary electrical connection between the RBE and FFU. This has the added benefit of also being able to recharge the FFU's batteries while inside the rocket.

DOI: 10.13009/EUCASS2019-779

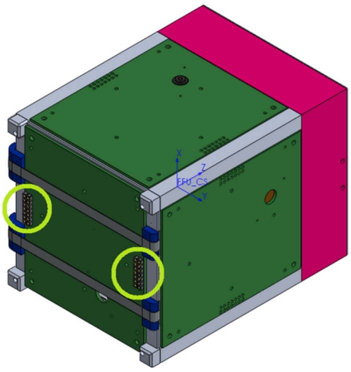
Table 2: Excerpt of TUPEX-7 requirements relevant to the PPI

Req. ID	Text
O17/02-005	During arming of the rocket motor, the TUPEX-7 system shall not transmit or do power switching of any kind (enforcing radio silence).
F20/02-009	The RBE shall charge the FFU's batteries *[...]* using the power provided by the RXSM dedicated charging line.
D20/01-017	The RBE shall provide a communication link to the ground station until ejection *[...]*.

Table 2 lists some requirements that flow down from the REXUS User Manual and TUPEX-7's own operational requirements. These requirements are fulfilled by a set of pogo pins between the RBE and FFU, forming the so-called pogo-pin interface (PPI). The concept for the PPI was first introduced in the TUPEX-6 mission.[16]



(a) Top view of the pogo pin interface on the HISP, with possible location of solar cells shown in the silkscreen.



(b) Isometric view of the pogo pin target pads on the FFU

In addition to the power and data signals conveyed via the PPI, it is also used to sense the ejection status on the RBEE and FFU. This is implemented as a voltage divider, where a pull-up resistor is present on the HISP and a pull-down resistor is present on the pogo pin carrier board on the RBE. Thus, depending on whether the FFU is inside the RBE or not, a different voltage will be present at the output of the split voltage divider.

In comparison to the TUPEX-6 PPI, TUPEX-7's has two sets of 3x5 pins instead of 2x15. The pins for a daisy chained JTAG interface were removed and replaced with the control pins for a radio silence latch inside the FFU, and the ejection probe voltage line was added.

The rearrangement of the pins on the PPI was done to facilitate future solar panel integration on the HISPs. While the development of the PPI on TUPEX-6 and -7 was a natural consequence of the requirements of the missions, the possible future uses of a temporary electrical connection on CubeSats are explored in Section 6.2.3.

4.3 Development Process

To accommodate the relative complexity and compressed mission lifecycle of TUPEX-7, the team has instituted an agile development process towards achieving functional flight hardware as early as possible following a recommendation from the project advisors. Each subsystem has been divided into different levels of testable functional units; those units are then designed and tested before moving onto the next. Each unit is then to be combined into more complex functions which are consequently designed, assembled, and tested e.g. on a breakout board. This process is iterated until the realisation of all subsystems, and ultimately, the complete systems. Interwoven into this process are the documentation and use of standards and conventions for designing, testing, and reviewing throughout the hardware development. The purpose of this agile methodology, when compared to the more traditional linear approach to development, is to avoid bottlenecks caused by the failure of individual components or functions and enable higher development speed and quicker turnaround of prototypes.

DOI: 10.13009/EUCASS2019-779

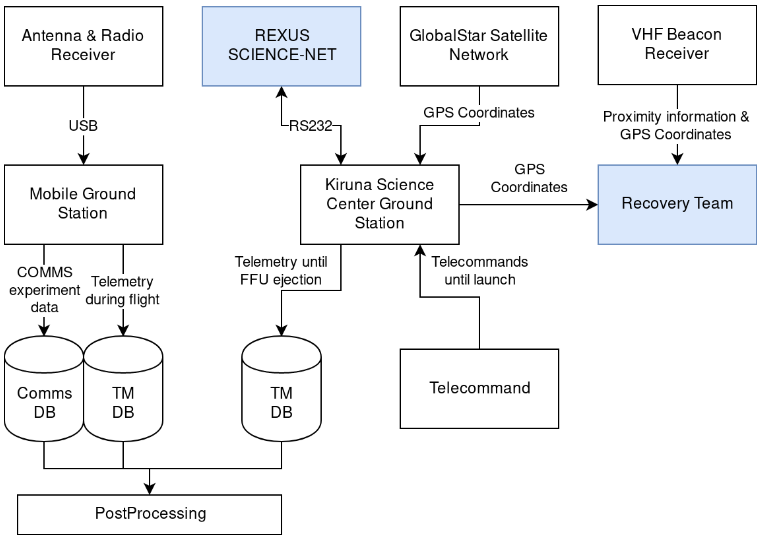


Figure 6: Overview of the components of the Ground Segment. Items in blue are provided by REXUS.

4.4 Ground Segment

The Ground Segment has several purposes related to the operation of the experiment and the storage of data to fulfil the scientific/engineering objectives. It is used for sending telecommands to the RBE and FFU while the rocket is still on the launchpad, to perform self-checks and toggle the radio silence state. Before and during the flight, it is responsible for recording the RBE and FFU telemetry until the deployment of the experiment. Additionally, the mobile ground station records FFU telemetry and payload data from the communications experiment after the FFU antennas deploy. And finally, the GS is responsible for receiving coordinates from the FFU once the parachute has deployed, to enable recovery of the FFU.
In order to achieve these functions, the Ground Segment is composed of the following parts, as seen in Figure 6:

4.4.1 Kiruna Science Center Ground Station

The main ground station is located in the Kiruna Science Center near the launchpad. This ground station consists of a laptop running software inherited from previous satellite missions at TU Berlin, which provides functions for creating and sending telecommands, as well as receiving telemetry and storing it in a database.

The operator at the KSC GS is responsible for coordinating countdown events with the REXUS team. This includes responding to “go-no go” polls, monitoring the state of charge of the FFU’s batteries and managing the radio silence requirements.

Towards the end of the flight, the FFU will begin sending its GPS coordinates to the GlobalStar satellite network. The operator on the KSC GS receives these messages and relays the information to the recovery crew.

4.4.2 Mobile Ground Station

The Mobile Ground Station is located on Radar Hill, about 5 kilmeters away from the launch pad. It consists of a Yagi antenna, a radio receiver and a laptop. The main purpose of the Mobile GS is to receive data from the FFU during its descent, in the communications experiment phase.

It is running the same ground station software as the KSC GS, but it does not transmit telecommands to the FFU.

4.4.3 Recovery Team

As part of the REXUS campagin, a recovery team is available, whose responsibility is to recover the payload of the rocket as well as other ejectable experiments, such as the TUPEX-7 FFU. The recovery team, with access to a helicopter, can navigate to coordinates provided by the team and retrieve and return the main payload.

DOI: 10.13009/EUCASS2019-779

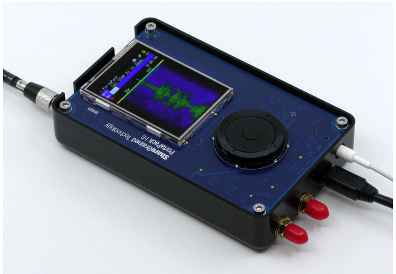


Figure 7: Image of the PortaPack H1.

As a backup to the GlobalStar system, the FFU includes a VHF beacon transmitter which broadcasts its GPS coordinates to nearby receivers. To enable the recovery crew to locate the FFU if the GlobalStar system fails, TUPEX-7 will provide a handheld receiver based on the Portapack H1 (Figure 7).

5. Expected Results

TUPEX-7 aims to demonstrate a number of technologies in the near-space environment (see Table 1). In order to prove that the objectives have been accomplished, several sets of data will be collected during the experiment, as described in the sub-sections below. Throughout the flight of the TUPEX-7 FFU, housekeeping telemetry and payload data will be stored on redundant non-volatile storage.

5.1 Housekeeping

The housekeeping telemetry will be used to compare the power usage and temperatures with the values predicted by the analyses presented in Chapter 4, as well as to analyze the root cause of a failure should one occur. The recorded housekeeping parameters include:

- electric power system (EPS)
  - Measured voltage and current at each voltage line. [V, A]
  - Switch status. [boolean]
  - Temperature sensor readings. [ºC]
- on-board computer (OBC)
  - Mission elapsed time. [s]
  - Current mission phase. [number]
  - Number of source packets stored in non-volatile storage. [number]

5.2 Attitude Determination and Control Experiment

After ejection, the FFU should de-tumble using its pFDAs. The magnetic coils are then going to be used to de-saturate the remaining angular momentum within the pFDAs. When the FFU reaches rotational equilibrium, the pFDAs will be used to perform a slew manoeuver about an axis which involves the three of them. At the end of the manoeuver, the magnetic coils will be used again for de-saturation to achieve stillness. An additional manoeuver consists of reaching a certain angular rate. To assess the performance of the ADCS, the following payload data from the ADCS experiment will be recorded during the milli-gravity phase:

- Sensor readings
  - Light measurements from each sun sensor photodiode. [dimensionless vector]
  - Angular rates from each gyroscope. [deg/s]
  - Magnetic field vectors from each magnetometer. [uT]
- Actuator status

DOI: 10.13009/EUCASS2019-779

  - pFDA speed. [-1..1]
  - Magnetic coil current. [mA]
- Commanded attitude. [quaternion]
- Estimated attitude. [quaternion]

The angular rates measured by the gyroscopes and the attitude estimates generated by the ADCS system will be compared with simulations performed on the ground. By analyzing the differences between the commanded and estimated attitudes, as well as with the expected results obtained by simulation, the TUPEX-7 team will be able verify the technological readiness of the ADCS and improve its performance if necessary.

5.3 Communications Experiment

In the communication phase, a known payload will be transmitted from the FFU to the GS and also in the opposite direction. This will allow a measurement of bit error rate of the communications system. The bit error rate can be used to calculate the effective user data rate. The communications experiment will generate the following payload data:

- Measured received signal strength. [dBFS]
- Raw demodulated data (i.e. before processing). [binary]
- Bit error rates. [err/bit]
- Effective user data rates (after error correction). [bits per second]

The data analysis will consist of plotting the bit error rates and received signal strength over time, which will be compared with the tests performed in the laboratory. After obtaining these performance parameters, it will be possible to assess if the implementation of the communications system is suitable for future orbital missions or if significant changes are necessary.

6. Next Steps in the Development of an Educational CubeSat Bus

Being that TU Berlin has both a strong history of small satellite mission success and plans to continue, the TUPEX-7 bus has largely been designed for potential use in future educational CubeSat missions. A successful mission will expose the bus to rigorous environments and push the Technology Readiness Level to TRL 6, thus advancing the bus and its demonstrated technologies towards future spaceflight. The design's focus is to accomplish successful technology demonstration in the milli-gravity environment, but it does impart some flexibility for future space application. This includes a modular HISP design, the SDR's ability to communicate on multiple frequencies, and a vastly improved payload-to-volume ratio. However, it is important to note that a few minutes in milli-gravity does not equate to a much longer LEO mission–several adjustments would be necessary to evolve the TUPEX-7 bus into its spacefaring successor.

6.1 Electrical Power Subsystem

The EPS of TUPEX-7 is tailored to the requirements of the mission, although some aspects of it are developed with modularity and extensibility for future missions in mind. The following subsections focus on the changes that would be necessary to make the PCDU and battery compartment suitable for an orbital space mission.

6.1.1 Power Control and Distribution Unit

The PCDU controls and distributes electrical power on 6 channels (5 for the HISPs and pFDAs and 1 for the other FFU subsystems). Each channel consists of a set of latches that monitors the voltage and current on each line and provides a mechanism to open or close the circuit.

An additional channel would be required to supply power to a HISP that would be placed on the top-most face of the FFU, where the recovery compartment currently sits (see Figure 5.b). Furthermore, if the mission contained a payload with high power requirements, an additional channel may need to be added to the PCDU design. But due to the modular design of the PCDU, this change can be implemented provided that there is sufficient PCB area.

DOI: 10.13009/EUCASS2019-779

However, due to the low-cost philosophy and short duration of TUPEX-7, none of the components in the PCDU are redundant, meaning that a single failure can compromise the entire mission. Therefore, a future orbital CubeSat bus based on the TUPEX-7 design should incorporate hardware redundancy in the power channels and microcontroller.

Also, the current PCDU design and FFU bus are designed to only receive electrical power to charge the batteries from the RBE. On a satellite, the solar panels also supply power to the batteries. Additional circuitry is necessary to track the Maximum Power Point of each individual solar cell; this can be incorporated on the PCDU or HISPs. Thus, further thought is necessary to manage the different sources of power available to the PCDU on a future CubeSat mission.

6.1.2 Battery Compartment

The TUPEX-7 battery compartment is manufactured using additive techniques, specifically 3D printing in PA12. While this design choice allows for greater design flexibility and lower cost, it results in significant drawbacks for spacecraft.

For example, polyamides such as PA12 are susceptible to damage from γ-radiation. Table 23.3 of the Handbook of Environmental Degradation of Materials[18] shows that a dose of $3 \cdot 10^5$ to $2 \cdot 10^6$ rad causes mild to moderate damage to the structure of Nylon materials. Further research is required to select a material for the battery compartment that is suitable for the space environment. Additionally, thermal considerations are largely excluded from thorough analysis of TUPEX-7 due to the short flight duration, but a thermal management system for the batteries should be added for maximum reliabilty and lifespan of the batteries.

To upgrade the current design to be space-ready, other manufacturing options, such as conventional machining or 3D metal printing, should be explored, as well as performing a detailed structural analysis considering the long term effects of the space environment.

6.2 Highly Integrated Side Panels

In the TUPEX-7 design, the magnetic air coils surround the body of the pFDAs. The doctoral research in [10, 6.2.4.1, 4.4.3] shows that an air coil embedded in PCB material can be made using only three internal layers. This design was not used on TUPEX-7 due to the cost of manufacturing PCBs with more than four copper layers. However, this option is attractive for orbital spacecraft, because the channel volume occupied by the pFDAs can then be increased, resulting in a higher available angular momentum and torque.

Additionally, the original design of HISPs presented in[10] includes solar cells with S-band (2-4 GHz) patch antennae. The design of these so-called solar antennae was first introduced by N. Henze et. al.[19–21] These were not included in TUPEX-7 for several reasons: first, designing a communications system (including power amplifier) that operates in the S-band range is significantly more complicated than UHF/VHF as implemented on TUPEX-7 due to the stricter PCB design requirements imposed by the shorter wavelength. Also, the beamwidth of patch antennae is much narrower compared to the monopole antennae used on TUPEX-7, which imposes stringent attitude control requirements. Lastly, TUPEX-7 does not need solar cells for its mission. However, utilizing the fully featured HISPs on future 1U CubeSat missions will further the state of the art in satellite integration and miniaturization.

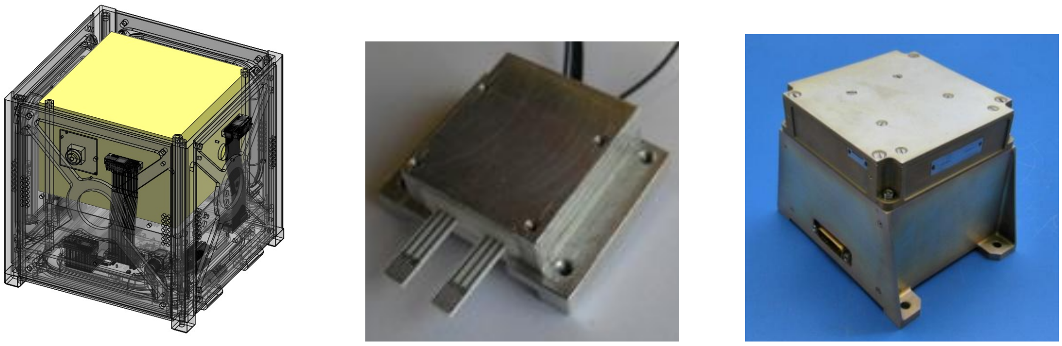
It may also be beneficial to add a miniaturized star tracker to a HISP that does not contain antennae, for increased attitude determination accuracy. However, this would require a high-bandwidth connection to the PCDH subsystem or additional computational resources on the HISPs.

6.2.1 Payloads

Due to the highly integrated design of the TUPEX-7 FFU, owed largely to the favourable geometry of the actuators on the HISPs, there is a large payload volume available inside the FFU. The payload space shown in Figure 8 is 75x75x50mm (approximately 0.28U). This payload-to-volume ratio is comparable with commercial 1U CubeSat bus platforms such as the 1U Platform from Clyde Space[12] (0.2U payload volume) and the GOMspace 1U Platform[23] (0.3U volume). The key difference is that the TUPEX-7 1U bus includes precise three-axis attitude determination and control, while commercial alternatives with a similar payload-to-volume ratio are only capable of coarse pointing using magnetorquers.

As a direct consequence, various scientific or technology demonstration payloads that would otherwise require a 2U CubeSat bus could be integrated into a more compact satellite. For example, some of the sensors from the QB50 project[22] could be incorporated in the FFU. The dimensions of the FIPEX sensor in Figure 8.b are 36x30x12mm, with its electronics occupying 80x100x100mm. With some design changes to the electronics, the FIPEX sensor would fit in the 1U FFU bus. Similarly, the INMIS sensor assembly shown in Figure 8.c, whose dimensions are 100x100x40mm, could theoretically be modified to fit in a reduced footprint.

DOI: 10.13009/EUCASS2019-779



(a) 1U FFU bus (without recovery compartment) showing available payload volume in yellow.

(b) FIPEX Sensor.[22]

(c) INMS Sensor.[22]

Figure 8: Payload volume in the TUPEX-7 FFU and possible future sensor payloads

Additionally, the mechanical design of the FFU could be modified to accomodate larger payloads. For example, the location of the standoffs connecting the PCBs could be moved to a 90mm grid, yielding a few extra millimeters available for the payload. If a custom payload is being designed for the TUPEX-7 1U bus, then a few additional millimeters in X and Y can be utilized by extending the payload volume closer to the side walls, and providing cutouts in the payload for the cables connecting the HISPs.

6.2.2 Software-Defined Radio

SDRs have been used in many CubeSat missions to date, both as the communications system[23] and as the payload.[24,25] Using SDRs on satellites is attractive due to their flexibility. For example, one can imagine a future where instead of having fixed frequency allocations for each satellite, the population of satellites could detect sources of interference and adjust their RX/TX frequencies accordingly (Cognitive Radio[26]).

However, commercially available SDR modules are prohibitively expensive for most educational satellite projects. TUPEX-7 incorporates the bare board of a LimeSDR Mini SDR in its PCDH subsystem (shown in Figure 9) to perform a downlink communication experiment with a ground station as the first step in developing a low-cost SDR transceiver for use in future University missions.

Future developments should seek to integrate the components of the SDR module directly in the PCB instead of using the LimeSDR Mini as a discrete module. Furthermore, in order to attain duplex communication, a low noise amplifier should be added to the PCDH.

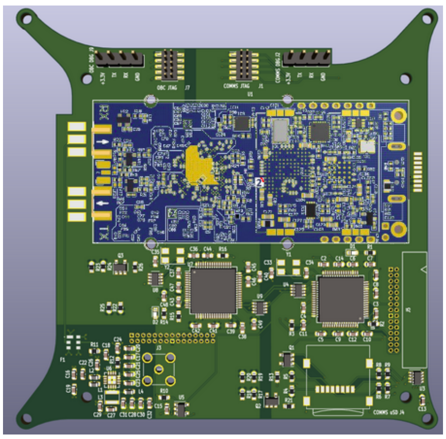


Figure 9: Front view of the PCDH PCB showing LimeSDR Mini[27] module.

6.2.3 In-Flight Umbilical Interface

To date, all CubeSats that have been launched are in an electrically dormant state, as required by the CubeSat Design Specification,[28] until they are ejected. This simplifies the design of the deployer, and reduces the risk of

DOI: 10.13009/EUCASS2019-779

unintentional activation of the satellite until the deployment detect that the CubeSat has been ejected.

However, certain types of missions may benefit from the ability to communicate with the spacecraft before its deployment. For example, if one were to use a CubeSat-like spacecraft as a probe on a deep space mission (perhaps without solar panels), it would be desirable to be able to charge its batteries or modify its software after it has been launched into space. As an example, engineers on the Rosetta mission from the European Space Agency were able to communicate with its Philae lander[29] to perform payload checkouts, landing preparations, and even upload new software. This was accomplished using the Electrical Support System (ESS), described by S. McKenna-Lawler et. al,[30] which contains a temporary electrical connection used for data exchange, as well as a radio communications system.

In a similar way to the umbilical connection (MGSE/EGSE) that is disconnected upon liftoff on most rockets, an In-Flight Umbilical Interface can provide power and data connections to spacecraft while they are still in the carrier spacecraft. And as TUPEX-7 intends to demonstrate, such a temporary electrical connection can be used to detect the ejection status and begin the mission, without the need of a mechanical deployment switch.

7. Conclusion and Outlook

This paper presented the technological and scientific objectives of the student-lead TUPEX-7 mission, explaining the concept of the experiment and comparing the design of the experiment with the mission predecessor, TUPEX-6. The expected result from this experiment are outlined in Section 5. The design presented here shows that a student team can develop a 1U CubeSat bus with a high payload to volume ratio when compared to the state of the art (e.g. the 1U CubeSat bus of Clyde Space[12]). However, many of the FFU's subsystems need to be improved in a number of ways, which are discussed in Section 6, to achieve a bus capable of a space mission.

The next steps for the TUPEX-7 mission are to finalize the design of the subsystem PCBs and begin the AIV (Assembly, Integration and Verification) campaign. Finally, the experiment will be launched on the 28$^{\text{th}}$ REXUS rocket in March 2020. The publication of the flight results is expected for Q3-Q4 of 2020.

8. Acknowledgments

We are very grateful for our predecessors, the TUPEX-6 team, for their hard work and continued guidance; without them, our project would not be possible. We thank the entire REXUS/BEXUS programme, the DLR, ZARM, MORABA, SSC, and ESA for giving us the resources for a successful mission and an opportunity to learn. We also thank the Chair of Space Technology of the Department of Aeronautics and Astronautics at TU Berlin and their helpful scientific staff, especially our project advisors Sebastian Grau, Martin Buscher, and Jens Großhans for their time, dedication, and insight. We thank the Master of Space Engineering programme of TU Berlin for their generous support. Lastly, we thank every TUPEX-7 team member for their invaluable efforts towards the mission.

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Acronyms

ADCS Attitude Determination and Control Systems. 1

ADCS Attitude Determination and Control System. 2, 5, 6, 10

CAN Controller Area Network. 6

COMMS Communications System. 2

EGSE Electrical Ground Support Equipment. 3, 13

EPS Electric Power System. 2, 6, 9, 11

FDA fluid-dynamic actuator. 1, 2

FFU Free-Falling Unit. 1–13

GPS Global Positioning Service. 3, 6, 9

GS Ground Station. 2, 3, 7–10

HISP Highly-Integrated CubeSat Side Panel. 2, 5–7, 11, 12

HISPs Highly-Integrated CubeSat Side Panels. 2

MGSE Mechanical Ground Support Equipment. 3, 13

OBC On-board Computer. 10

PCB printed circuit board. 5, 11–13

PCDH Payload, Command, and Data Handling. 6, 12, 13

pFDA Pico-Fluid Dynamic Actuator. 2, 6, 11, 12

PPI Pogo-Pin Interface. 5, 7

RBE Rocket-Borne Equipment. 1, 3–5, 7, 8, 11

RBEE rocket-borne equipment electronics. 5, 7

REXUS Rocket Experiment for University Students. 3, 4, 7–9, 13

RXSM REXUS Service Module. 1, 3–5

SDR Software Defined Radio. 2, 3, 5, 6, 12, 13

SMS Structures and Mechanisms System. 2

TU Berlin Technische Universität Berlin. 1, 2, 8, 14

TUPEX-6 TU Berlin Picosatellite EXperiment 6. 5–7, 13

TUPEX-7 TU Berlin Picosatellite EXperiment 7. 1–14