Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels
UNIVERSITAT POLITÈCNICA DE CATALUNYA

TREBALL FINAL DE GRAU

Títol: Electronic system in a suborbital payload

Autor: Guillem Quintana Buil

Director: Dr. Ricard González Cinca

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Director: Dr. Ricard González Cinca

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Resum

Aquest document mostra la feina realitzada dins del projecte BOILUS del Departament de Física de la Universitat Politècnica de Catalunya. El projecte ha estat realitzat per alumnes de l'Escola d'Enginyeria de Telecomunicacions i Aeroespacial de Castelldefels, que pretenien continuar amb la línea d'investigació del laboratori envers d'interacció entre ones acústiques i el processos d'ebullició en condicions de microgravetat.

Tot i que el projecte engloba molts àmbits diversos, el document se centra en presentar el projecte i l'aportació que he fet en aquest. Aquesta aportació bàsicament ha estat el disseny i construcció de l'electrònica embarcada i disseny i implementació d'un protocol de telemetria entre l'experiment i una estació terrena que en recollia els resultats.

També s'exposen els problemes que es van observar relacionats amb compatibilitat electromagnètica i com es van abordar i solucionar sempre que es va poder.

Title: Maqueta de TFG

Author: Guillem Quintana Buil

Director: Dr. Ricard González Cinca

Data: 15/07/2016

Overview

This document shows the work realized inside the BOILUS project from the Department of Physics of the Universitat Politècnica de Catalunya. The project has been done by students from the Escola d'Enginyeria de Telecomunicacions i Aeroespacial de Castelldefels, who were trying to continue with the investigation performed in the microgravity laboratory about the interaction between the acoustic fields and the boiling processes in microgravity conditions.

Although the project includes diverse fields, the document is centered in presenting the project and explaining my own contribution into it. This contribution has been basically the design and construction of the electronics embarked and the design and implementation of a telemetry protocol between the experiment itself and a ground station who control it and display data.

Also the electromagnetic compatibility problems found are presented, and how they were fixed if possible.

Agraïments

A totes les persones que han ajudat a fer possible aquesta feina, especialment als integrants del equip BOILUS amb els que he compartit alguns dels millors moments de la meva vida.

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Chapter 1. Context

1.1 REXUS Program

1.1.1 Introduction

The REXUS (Rocket Experiment for University Students) program allows German and Swedish university students to carry out scientific and technological experiments on sounding rockets. Each year, two rockets are launched from Kiruna, Sweden, carrying up to 8 experiments fully designed and manufactured by student teams. European students can apply in this program occupying the Swedish slots, also.

The basic idea behind REXUS is to provide an experimental space platform for students in the field of space technology. Besides additional study motivation, the students also gain experience in scientific experimental probe design, project teamwork and management which are important knowledge for their future careers.

The REXUS program is realized under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). Finally, 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 prove technical support to the student teams throughout the project.

1.1.2 The Rocket

The REXUS consist of a one-stage solid rocket (the Improved Orion engine is used as the propulsion unit), and the payload. The rocket offers two minutes of microgravity or three of spaceflight (with strongly variations with the payload mass). A typical configuration is shown in Fig. 1.1; however, it can varies on each flight with the aim of optimizing the vehicle and experiment characteristics.

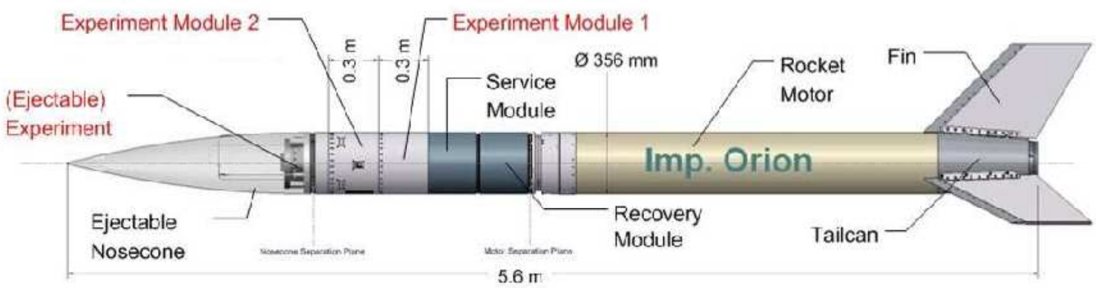

Fig. 1.1 Typical REXUS configuration from REXUS user manual

The main performance of the rocket is described on the REXUS user manual, and the performance data can be check on the Microgravity Laboratory on the UPC, but in general terms the rocket performs as follows on Table 1.1:

EVENT	Time (s)
Lift-off	0.00
Burn-out	26.00
Nose cone ejection	61.00
Yo-Yo release	65.00
Motor separation	66.00
Apogee (approx.)	140.00
Parachute opening (approx.)	380.00
Payload impact (approx.)	800.00

Table 1.1 Main events on REXUS rockets

1.1.3 Calendar

In this section, the REXUS timeline and the main events of the program are presented. The duration is about 18 months. Along this period, experts are performing detailed reviews of the experiments that implies, from the team's point of view, preparation of lectures about the status of the experiment and continuous updates of the documentation belonging to the experiment. This last part is going to be detailed in next sections.

The program is divided in six phases well differentiated. The first one is called phase 0 and takes place the previous months before the selection workshop. The key point is the proposal document and the presentation in front of the experts. If the team passes this point, then, they are officially part of REXUS program. After that, phase 1 starts.

From this point, the team has to work deeply in the experiment design by taking into account all the requirements from the REXUS User manual. Along this phase, the Student Training Week takes place, where experts from DLR, SSC, ZARM and ESA perform lectures about interesting fields such as software, electronics, mechanics, project management and outreach, in order to guide the teams. Besides, there is the first review called PDR (Preliminary Design Review). The students must prepare a presentation about the status of the experiment, critical points and the incoming tasks. If the team passes this review, the experiment starts the phase 2.

Along the second phase, the team keeps working on the design taking into account the recommendations and considerations received during the PDR. The main event in this phase is the second review of the project; it is called CDR (Critical Design Review) where the status of the experiment should be already in an advanced point. Likewise, another presentation must be performed by the team which is assessed by the experts and argued with the team.

Once the CDR is passed, the phase 3 begins. Along this phase, the design of the experiment must be frozen. The review, which is called IPR (Integration Progress Review), takes place at team's facilities. After checking everything is progressing properly and reviewing the incoming weeks, phase 4 starts.

From this moment, the team will be focused on the assembly of the experiment. Along this phase, the experiment will be almost fully assembled and ready for shipment. The review is called EAR (Experiment Acceptance Review). The experts come back to the team's facilities. At the end of this phase, the Integration Week takes place. At least, two members of the team will assist to the Integration Facilities to perform the remaining tests, such as the vibration test which are really important to pass.

Finally, along the phase 5, the launch takes place. The remaining preparations and tests will be performed. After the flight, which is phase 6, it is time for documentation and data analysis.

To sum up, the REXUS calendar has a well-structured organization that allows the evolution of the experiment and the team. The constant review of the status of the experiment has a key role in the correct development of the experiment.

1.1.4 Documentation

The Student Experiment Document (SED) contains all the information belonging to the experiment and the team. This document is divided in different sections which are shown in Table 1.2. Along the project, each member of the team has been in charge of updating their own section but always taking into account their partners work.

As said, SED is a detailed guide about the BOILUS experiment. It has been modified several times along the project, always reviewed by the experts from DLR, SNSB and ESA. The inappropriate evolution of this document or the experiment itself should have meant the removal from REXUS program.

CHAPTERS	CONTENT
1. INTRODUCTION	Background, objectives, team details and contact
2. REQUIREMENTS	Functional, performance, operation, design and limitations
3. PLANNING	Tasks, calendar, outreach and risk analysis
4. DESCRIPTION	Interfaces, components, mechanics, electronics and software
5. TESTS	Tests and verifications of requirements
6. CAMPAIGN	Operations during launch, activities pre- and post-flight
7. DATA ANALYSIS	Results and data analysis plan
8. APPENDIXES	Reviews, datasheets, outreach, Gantt, simulations…

Table 1.2 SED chapters

1.2 BOILUS team

1.2.1 The experiment

The BOILUS experiment was the last step on the investigations performed in the Microgravity Laboratory on the UPC. The goal of the experiment was to study the interaction of the UltraSounds during BOILing processes in microgravity environments.

The idea behind this investigation was to model this processes and find how they affect the heat transfer and the mass transfer (Bubble dynamics, coalescence, and detachment from the hot spot). With all this data is pretended to develop a technology which could improve the fuel consumption of cryogenic rocket engines used in long term space missions.

For that reason, the Team applied for the REXUS program on October 2014, obtaining a microgravity platform where perform the experiment.

1.2.2 The team

The BOILUS team was formed by 5 people, with different roles (Fig. 1.1).

Anna Garcia Sabate was the team leader and also in charge of mechanics and thermal simulations. She was on the final year of her PhD.

Sergi Batlle Soler was in charge of software, and also helped in electronics and assembly. He used this experience as his bachelor thesis.

Victor Sierra Urueña was in charge of physics and protocol of the experiment.

Gabriel Lopez Martinez was in charge of physics, protocol of the experiment and the test-cell design.

Finally, I was in charge of electronics, telemetry, assembly, and also helped in software.

Fig. 1.1 From left to right: Sergi Batlle, Guillem Quintana, Anna Garcia, Gabriel Lopez, Victor Sierra

1.2.3 Experimental setup

The experimental set up consisted of a test cell and the following systems:

1. Bubble generation
2. Acoustic wave generation
3. Data acquisition

The external dimensions of the test cell were 61 x 45.25 x 58 mm (HxWxL). The test cell had two windows through which the cavity was illuminated by a LED matrix, homogenized by a diffuser sheet and the phenomena was recorded by a camera. A piezoelectric transducer (PZT) with a nominal frequency of 160kHz was attached to the wall of the test cell. On the opposite side of the PZT there was a heater that generated the boiling phenomena to be recorded.

Bubbles were generated by means of a 1 cm^2 heating element mounted at the bottom of the test cell. It consists of an electrical resistance heated by Joule effect in contact with a flux meter and a copper plate with thickness of 40 µm. The flux meter was equipped with one thermocouple, which will allow to measure the heat flux transmitted to the liquid and the wall temperature.

Temperature and heat flux measurements were recorded by an Arduino hardware platform used as an acquisition data module.

Since Arduino only has 10 bits of resolution, a 16 bit ADC (ADS1115 from Adafruit) was placed between the heater thermocouples and the flux meter, and the Arduino board in order to obtain an adequate conditioning using I2C interface.

The test cell had another orifice where an overpressure valve was connected. A tube came out from the overpressure valve into a waste tank where the excess was collected.

The standing acoustic field was generated by the PZT, driven by an arbitrary waveform generator (Tabor Electronics 5325) and amplified by an x10 power amplifier (Tabor Electronics 3322). These two devices are PCI cards that were inside a mini computer (MXC – 4000/2G, AdLink Technology Inc.), which has no moving parts (i.e. no fans and HDD changed to SSD).

Finally, a camera (GoPro Hero 3+ Black Edition) recorded the detachment mechanism of the bubbles. The obtained videos were directly saved in the SD card inside the camera.

The experiment was inside a 220mm module, and it was divided in two levels. On the lower level there was the PC (with function generator and amplifier inside), which take the most volume inside the module. The upper level was used to position the rest of the equipment, test cell, camera, LEDs, DC-DC converter and Arduino. A block diagram of the experimental setup can be observed in Fig. 1.2.

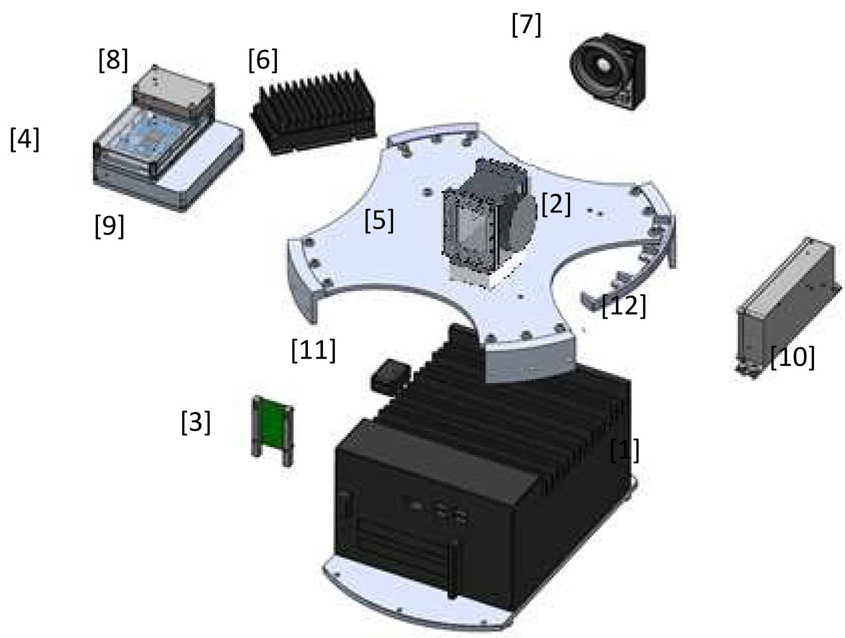

Fig. 1.2 Exploded view of the equipment with labels. [1] PC, [2] intermediate bulkhead and wall mounts, [3] LED matrix, [4] Arduino, [5] test cell, [6] DC-DC

converter, [7] GoPro Hero3+ and [8] heater control PCB, [9] thermocouple's control PCB, [10] interface PCB, [11] waste tank and [12] D-SUB bracket.

1.2.3 Experimental Protocol and timeline

The experiment was autonomous in order to be executed without a person executing the different orders. This is the reason for using three signals for start different events. The first signal to be received was the Start Of Data Acquisition (SODS), which was used for switch on the GoPro camera and start recording. Four minutes later the Lift Off (LO) signal arrived, this signal was used to start the piezoelectric functionalities and for synchronize the video data with the accelerometer and the stored data of the computer. The last signal to be received was the Start Of Experiment (SOE), it was received when the experiment enter in microgravity and was used for power on the heater. Finally, after nine minutes from LO the GoPro was switched off and after ten minutes from LO the PC was switched off in order to avoid malfunctions during the landing.

EVENT	Time (s)
Power on	-600
SODS	-240
GoPro on	-237
Lift-off	0.00
PZT on	26.00
SOE	74
Heater on	76
Heater, PZT and GoPro off	540
PC off	600
Payload impact (approx.)	800.00

Table 1.3 Experiment timeline

Chapter 2. Electronics

2.1 Electronic Requirements

There were several requirements on the electronics of the BOILUS experiment. Some of them were due to the physics of the experiment, others correspond to the rocket where the experiment was flying, and other ones refers to the reliability. Consequently, we could differentiate four types of requirements: functional, design, operational, and performance requirements. On Table 2.1 the different requirements are presented with its indicator:

INDEX	REQUIREMENTS
F.01	The experiment shall heat the liquid in the test-cell
F.03	The experiment shall measure the heat flux of the heater
F.04	The experiment shall measure the temperature inside the test-cell
F.05	The experiment shall record a video of the phenomena inside the test-cell
F.06	The experiment shall measure accelerations suffered in different axis during the flight
P.01	The heater shall be able to use a power of 6 W to generate boiling
P.06	The heat flux measurement shall be made at a rate of 120 measurements every second
P.07	The heat flux measurements shall be possible between 0 and 60kW/m2
P.08	The heat flux measurements shall be made with an accuracy of +/- 0.3 kW/m^2
P.09	The temperature measurement shall be made at a rate of 20 measurements every second
P.10	The temperature range shall be possible between 0 and 90 ºC
P.11	The temperature measurements shall be made with a resolution of +/- 0.1 ºC
P.12	The acceleration measurements shall be made at a rate of 120 measurements every second
P.13	The acceleration measurements shall be made with a resolution of +/- 0.005 G
P.14	The acceleration measurements shall be possible between 0 and 6g
P.15	The camera should record in 720p120 video mode (slow motion)

P.17	The total power consumption shall be lower than 30Wh
P.18	The system peak power consumption shall be lower than 130W
D.03	The module's internal thermal dissipation must not heat up the outer structure more than 10ºC above the ambient temperature
D.04	The module's internal thermal dissipation must not heat up the parts close to or in contact with the feed-through cable to more than +70ºC
D.05	A module's internal thermal dissipation must not heat up parts facing other modules to more than +50ºC
D.06	The heat transport by convection must be limited in such a way that the air temperature at the module interfaces does not exceed the ambient temperature by more than 10ºC
D.08	The experiment systems shall be able of withstand centrifugal forces due the spin of the rocket
D.09	The experiment systems shall be able of withstand longitudinal forces of 20g
D.10	The module shall be able of withstand an impact at 8 m/sec
D.15	The module shall not disturb electrically other modules
D.18	The LED matrix shall face the camera form the opposite side of the test-cell
D.28	The heater shall be able to maintain a boiling process during the microgravity phase
O.07	The space segment shall execute commands based on specific signals received from the REXUS SM (SODS, SOE,LO)

Table 2.1 Electrical and electronics requirements from SED. INDEX means F: functional, P: performance, D:design, O: operational

However, there were also several statements that were not requirements, however, we need to follow. These ones were some design, soldering, and assembly procedures.

In concrete, the standards followed where the ECSS-Q-ST-70-08C (Manual soldering of high-reliability electrical connections) and the ECSS-Q-ST-70-38C (High-reliability soldering for surface-mount and mixed technology). The ESA through the 'Institut für elektronik im DLR oberpfaffenhofen' provide a one week course on these standards with practical lessons for allowing us to design and solder the PCBs with maximum guarantees.

2.1.1 Electrical interface

In order to fulfill the presented requirements, the first step was to identify the electrical interfaces which were providing the experiment with power, the different signals, and the communication lines. Here appears the REXUS service module, which is carried in all REXUS flights.

The REXUS service module (Fig. 2.1) acts as an interface for all carried experiments, and its objectives are to establish the communication between the ground and the different experiments, and the control of all the experiments. Furthermore, the Service Module monitors the quality of the ambient conditions, the flight parameters (acceleration, angular rates) and the housekeeping data. It also delivers power to the experiments.

The Service Module consists of two sections. The first one contains the electronic part of the Service Module (E-Box), while the other devices such as RF-parts, GPS, sensors and batteries are mounted on the bulkhead of this module. [1]

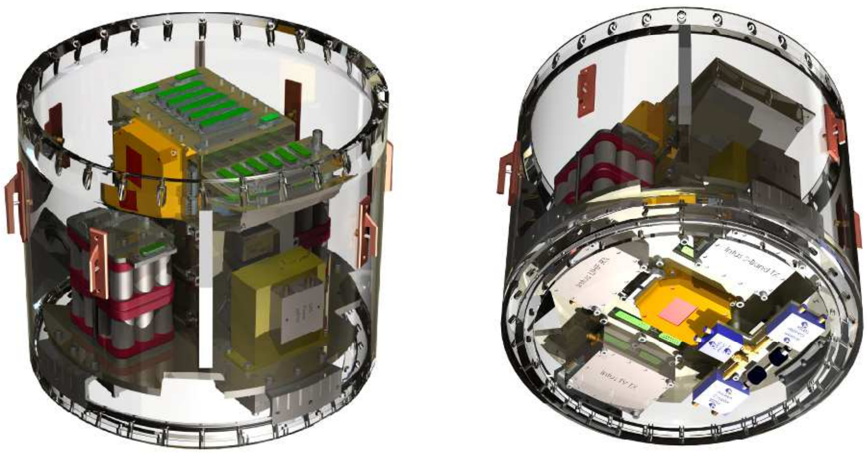

Fig. 2.1 REXUS service module CAD from REXUS user manual

The interface between the REXUS service module and the experiment was through a D-SUB 15 connector were all communication, control, and power lines were implemented, but not all of them were used as it can be seen in Table 2.2.

Pin No	Name	Remarks
1	+28V	PC Power supply
2	Charging (28V/1A)	**Not used**
3	SODS	Camera Power Control
4	SOE	Heater Power Control
5	LO	Function Generator Control
6	EXP out+	Telemetry Control
7	EXP out-	Telemetry Control

8	28V GND	PC Power supply GND
9	+28V	To DC/DC Converter
10	n.c	**Not used**
11	n.c	**Not used**
12	Charging Return	**Not used**
13	EXP in+	Telemetry Control
14	EXP in-	Telemetry Control
15	28V GND	DC/DC Converter GND

Table 2.2. D-SUB 15 pin allocation

The reason for not using the charging lines is due to the lack of batteries in our experiment that could be charged in that way (as far as the GoPro battery was plugged).

2.2 PCBs

Several PCBs were needed to implement the different functionalities requested. Each of the PCBs has a single function in order to reduce damage loses in a malfunction case, facilitate the validation and verification processes, and facilitate the interchangeability with the spare units minimizing the costs.

All the PCBs were packaged on aluminum boxes for several reasons, the most remarkable is its mechanical properties (they needed to survive loads higher than 20g), but also because they prevent metallic floating dust to touch the electronics and produce malfunctions, and because could minimize capacitive interferences if they are grounded.

2.2.1 Interface PCB

The interface PCB is used to receive the power required for the experiment, the Lift-Off (LO), Start Of Data Storage (SODS) and Start Of Experiment (SOE) signals, and the RS-422 communication with the ground segment.

The three signals have been conditioned due to the fact that they are interconnected to other experiments, where are also connected to +28 V (via a pull-up resistor), direct connection to a 5 V device (as our Arduino Mega) can cause damage or malfunction (Fig. 2.2).

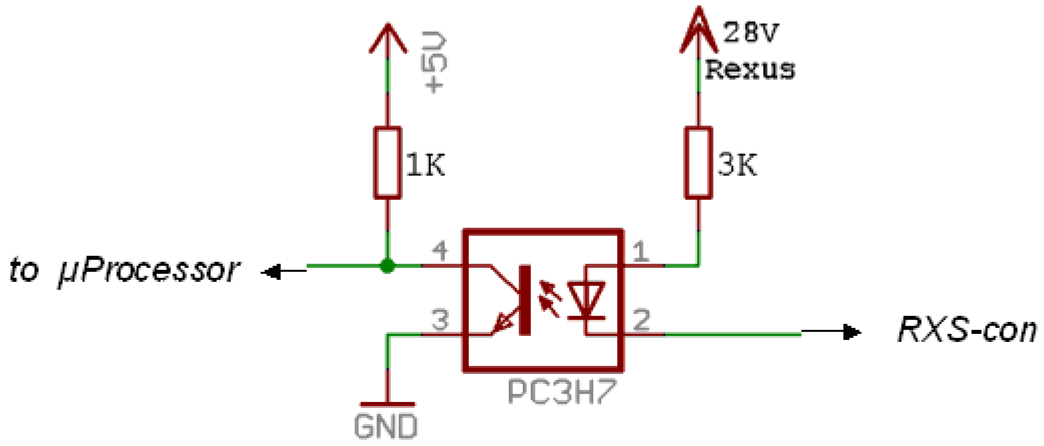

Fig. 2.2 Schematics using an optocoupler for signal isolation from REXUS user manual

Also, and due to the limitation on the maximum ripple that the experiment was able to introduce on the power lines, we used the two power channels for supply different devices and minimize the ripple that we were introducing.

The power line that supply the PC was more challenging due its high ripple, so a network filter was introduced on the PCB. Also this line was thicker than the rest with the aim of avoiding self heating in vacuum and microgravity conditions.

This PCB has several inputs and outputs apart from the D-SUB 15 explained bellow on the Table 2.3:

Pins	D-SUB 9 telemetry	D-SUB 9 Power&triggers
1	**EXP out-**	**28V PC**
2	**EXP out+**	**SODS**
3	**EXP in+**	**SOE**
4	**EXP in-**	**GND Arduino**
5	**-**	**28V DC/DC**
6	**-**	**GND PC**
7	**-**	**LO**
8	**-**	**5V Arduino**
9	**-**	**GND DC/DC**

Table 2.3 Interface PCB Inputs and Outputs

The PCB board is shown on Fig. 2.3 with all these design parameters implemented:

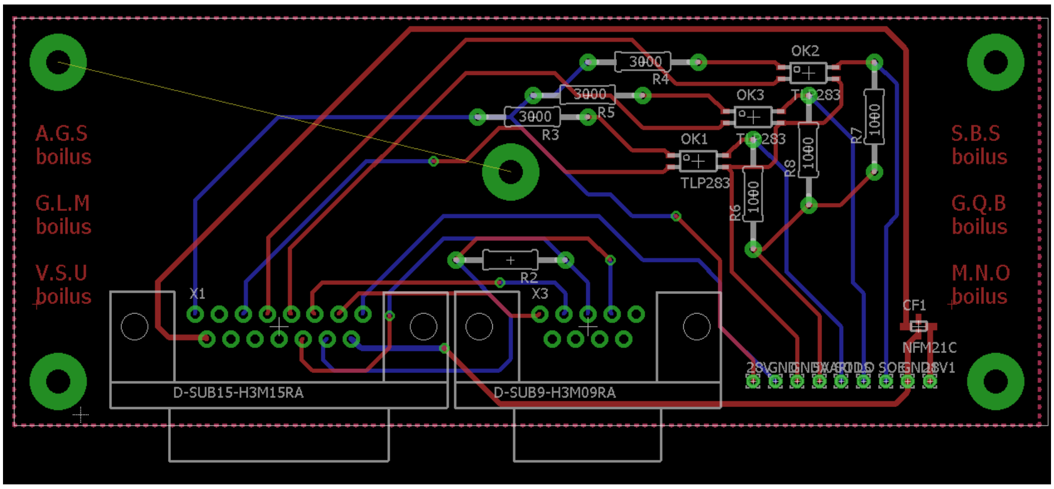

Fig. 2.3 Interface PCB board

For mechanical and design reasons, the D-SUB 9 for the power and triggers was not implemented on the board, but connected through cables. As it can be observed there are 5 holes that were used for the PCB assembly with the experiment (Fig. 2.4).


Fig. 2.4 Interface PCB on its aluminum box

2.2.2 Heater power control

The Heater power control PCB was designed to control the power that was being supplied to the Heater. As only three different powers were demanded for the experiment (and 0 W is one of this options) two NPN transistors were used as a switch (working between cut and saturation).

A special configuration was used for avoid overheating on the transistors and on the resistors that were used on this PCB (Fig. 2.5).

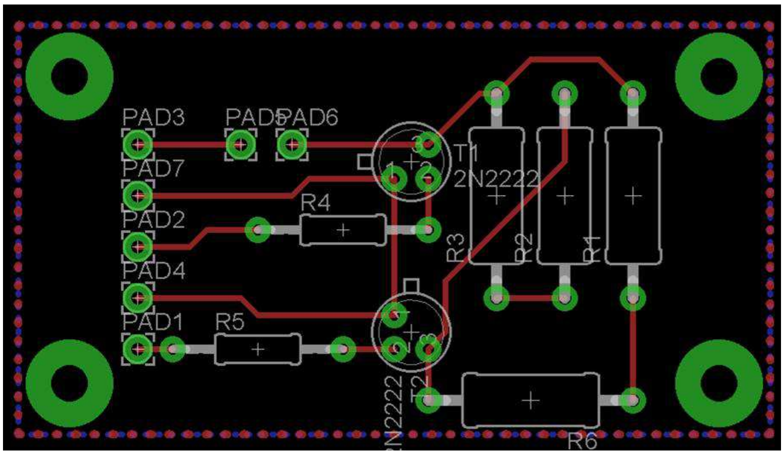

Fig. 2.5 Heater Power PCB board

The interface of this PCB was a D-SUB 9 with the connections shown on Table 2.4:

Pins	Heater Power Control PCB
1	**-**
2	**GND Heater**
3	**-**
4	**GND DC/DC**
5	**12V DC/DC**
6	**12V Heater**
7	**GND Arduino**
8	**DO7 Arduino**
9	**DO2 Arduino**

Table 2.4 D-SUB 9 Heater power PCB connections

Finally, the PCB has four holes for enabling a reliable assembly in its aluminum box (Fig. 2.6).

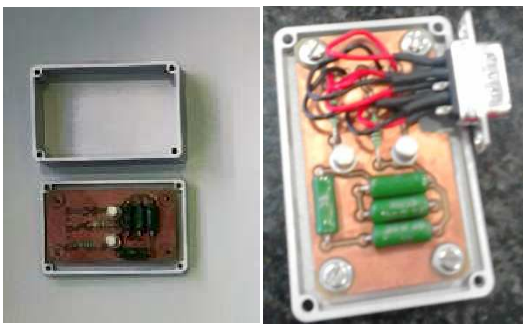

Fig. 2.6 Heater power PCB mounted on its aluminum box, and with de D-SUB connector

2.2.3 Heater data acquisition

The Heater data acquisition PCB was designed in order to read the output data from the heater sensors. One T type thermocouple, an unknown thermocouple, and a heat flux meter were implemented (Fig. 2.7).

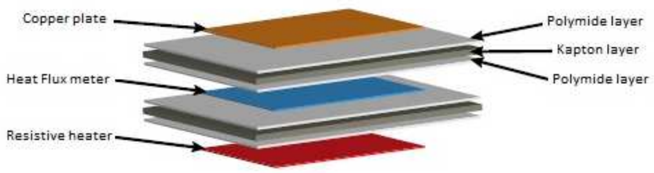

Fig. 2.7 Heater schematics (left), and heater connections (right) where the power lines are red, the T thermocouple is brown, and the yellow and blue lines are the unknown thermocouple and the heat flux meter

The T thermocouple was used as the cold junction temperature compensator for the unknown thermocouple, and its conditioning consist on the AD595 device for having a linear output with temperature in the desired range of measure. Then the signal was amplified by a gain and after all passes through a low pass filter (Sallen-Key type).

Due the low sensibility of the unknown thermocouple and the heat flux meter, and the desired resolution the signal of both, the signals were send into an Anagogic to Digital converter of 16 bits of resolution which sends the data to the Arduino through I2C digital communication port (see Table 2.5 for its connections).

Pin Name	Remarks
VDD	This pin is fed from Arduino 5V
GND	Arduino GND
SDA	Connected to Arduino pin 20
SCL	Connected to Arduino pin 21
ADDR	Connected to GND
ALRT	(Not used)
A0	Unknown thermocouple (+)
A1	Unknown thermocouple (-)

A2	Heat flux meter (+)
A3	Heat flux meter (-)

Table 2.5 Analogical to Digital converter pin allocation

Finally, the interface was a D-SUB 9 with the connections shown on the Table 2.6, but the thermocouples were soldered directly into the PCB in order to reach a higher accuracy.

Pins	**Remarks**
1	**This pin is fed from Arduino 5V**
2	**Arduino GND**
3	**T thermocouple output signal**
4	**-**
5	**-**
6	**-**
7	**-**
8	**SDA from I2C**
9	**SCL from I2C**

Table 2.6 with the D-SUB 9 connections

The PCB was fixed into its box by the four holes in the corners as it can be seen on the Fig. 2.8.

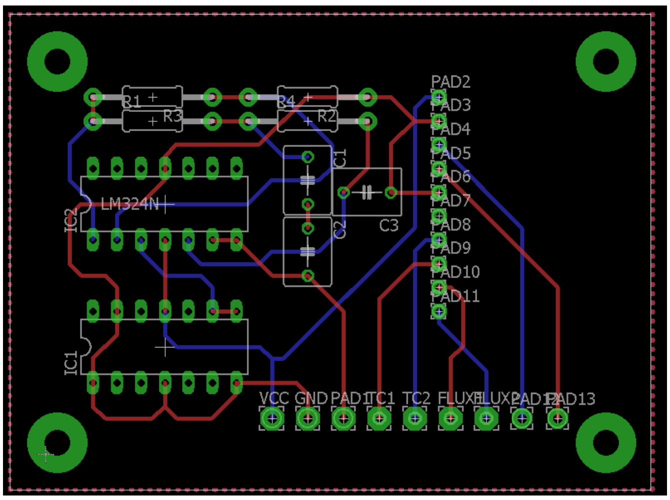

Fig 2.8 Heater Data Acquisition board

2.2.4 Thermocouples data acquisition

Initially, five T thermocouples were mounted with the objective of measure the temperature field inside the Test-Cell; but, after some test, it was decided not to measure that data due lack of interest. Then, it was decided to use them for obtain House Keeping data, that means, measuring the temperature of different devices in the experiment. Table 2.7 shows what was measured by each of this thermocouples.

Thermocouple	**Remarks**
1	**PC temperature**
2	**DC/DC temperature**
3	**Module temperature**
4	**Test-cell temperature**
5	**Heater power PCB temperature**

Table 2.7 Temperature measured devices

These thermocouples were conditioned as the T thermocouple attached on the Heater, meaning by the use of the AD595 for having a linear response with temperature, then amplifying the signal and filtering.

As it can be observed on Fig. 2.9, this PCB was the biggest one, and due to the environmental effects of the rocket (at a certain point there are really high loads on all the payload), there were used 5 holes for mounting the PCB.

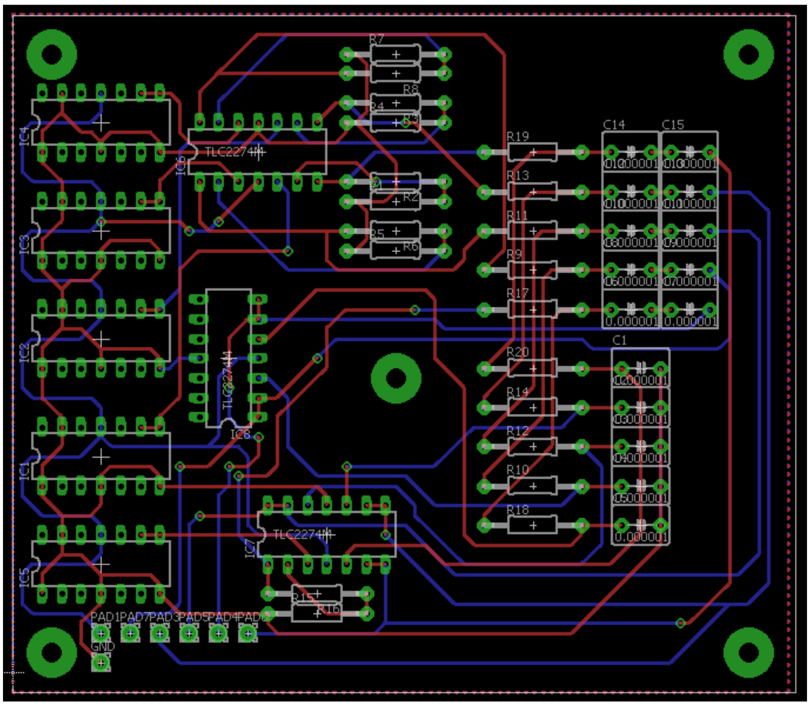

Fig. 2.9 T Thermocouples conditioning PCB

Another appreciation is that the T thermocouples were soldered directly in the same pads as the AD595 in order to achieve a higher accuracy.

The interface of this PCB was again a D-SUB 9 (Fig. 2.10) connector mounted on the aluminum box, and its connections can be observed on Table 2.8.

Pins	TCs PCB
1	**TC1 signal**
2	**TC2 signal**
3	**TC3 signal**
4	**TC4 signal**
5	**TC5 signal**
6	**5V Arduino**
7	**GND Arduino**
8	**-**
9	**-**

Table 2.8 D-SUB 9 Thermocouples acquisition pin allocation

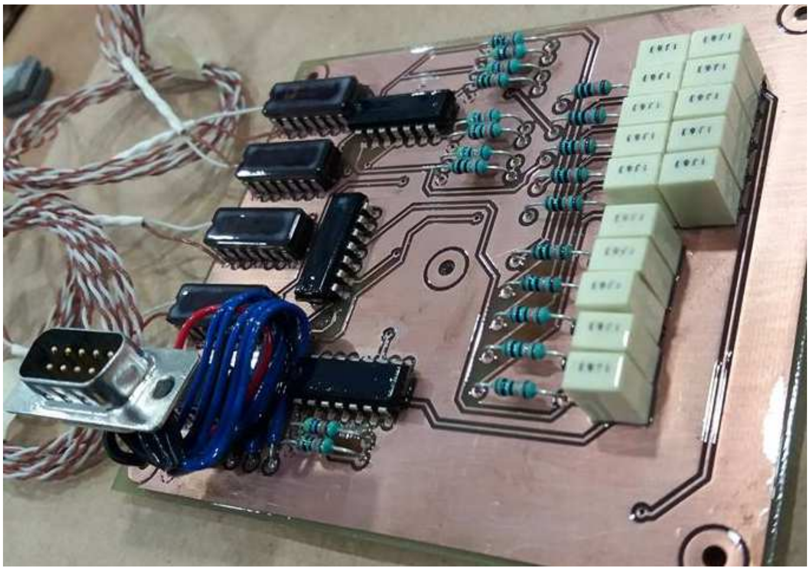

Fig. 2.10 Final Thermocouples acquisition PCB

2.2.5 Accelerometer data acquisition

The accelerometer selected to acquire data through the flight was the ADXL335 (Fig. 2.11). It is an analogical 3-axis ±3g device, which allowed to know the microgravity quality; and also, to synchronize the different data with the events in the flight. This accelerometer was placed in a breakout board ready to be read analogically. Besides, a calibration was done before the acquisition of data.

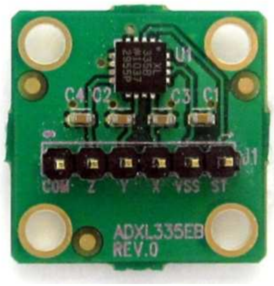

Fig. 2.11 Accelerometer ADXL335 board

This accelerometer was placed under the test-cell for scientific reasons (this data was important for the results analysis process).

2.2.6 GoPro switch

The GoPro has an interesting way for switch on and off. The main button produces a short circuit between power and ground lines (Fig. 2.12), and depending on the duration of the short it can be switch on/off or change the recording options. If the duration is longer than 1 second it switches on/off, but if it is lower changes its configuration.

Initially, the GoPro was switched on and off by a mechanical relay, but was declined due to the fact that the high loads of the rocket could damage it and cause a malfunction. So we started using the solid state relay HFW1201L01. However, after some testing the GoPro seemed not to be working as expected (only worked if the battery was plugged just before sending the switch signal).

Consequently, the relays were removed and a transistor was used. As the objective was short the battery, the signal that was being sent into the transistor was directly connected from the Arduino, leaving the cable as the only resistance in between. This solution worked perfectly during all the test, and was robust against the loads of the rocket.

Fig. 2.12 GoPro with the button removed showing the short mechanism

2.2.7 GoPro status

This PCB was designed to have a feedback from the GoPro in the ground station. In the case this signal did not arrive before the lift-off we had the option to abort the launch and check what was going on.

So, taking into account that there is a LED blinking when the GoPro is recording, we mounted a photo resistor just in front of it (we avoid connecting directly this signal into our Arduino, because it could cause malfunction in the GoPro).There was also a fix resistor and the signal was measured in between both resistors, so a high and a low measure could be identified (Fig. 2.13).

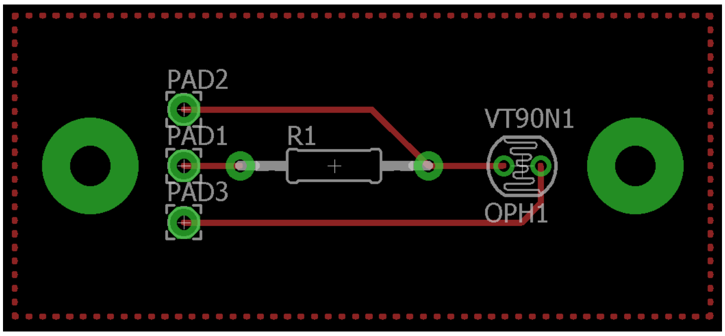

Fig.2.13 GoPro Status PCB board

2.2.7 LED Matrix

Due to the lack of natural light inside the module, the GoPro needed an artificial source of light to record the experiment inside the test-cell. That was the reason for mounting a platform which carried the LEDs that were doing this job. This was made by the use of the LED matrix PCB (Fig. 2.14).

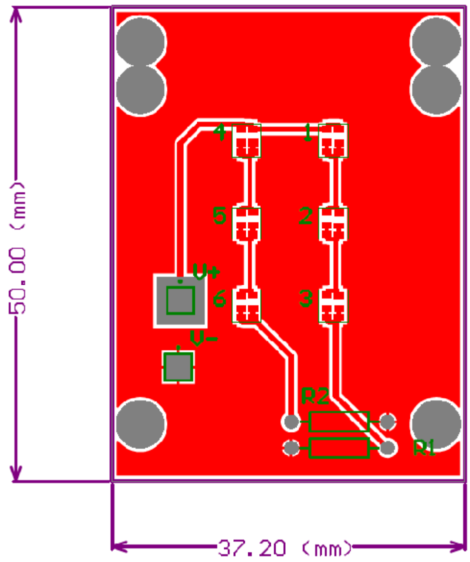

Fig. 2.14 LED matrix PCB board

On this PCB, the LEDs where SMD (surface mounted device) and there were also present some resistors which were fixing the current that was going through each line (the current is fixing the luminosity of the LEDs).

On that PCB there were also 4 holes for allowing the PCB to be mounted on the correct position.

Chapter 3. Telemetry

3.1 Telemetry Requirements

The use of telemetry in the experiment corresponds to the availability of downlink and uplink for the experiment (the uplink was only available before lift-off through an umbilical). This telemetry was used to check the status of the experiment on a ground station, to download housekeeping data, and to send some command if needed.

Just like the electronics, the Telemetry had some requirements to guarantee a correct function (see Table 3.1).

INDEX	REQUIREMENTS
F.08	The experiment shall send the current status of the systems on board
F.09	The experiment should send the data obtained from the sensors on the experiment
P.16	The downlink data rate should not be greater than 20 kbps
D.14	The downlink data rate shall not be greater than 500 kbps
D.24	The space segment shall retrieve data from all experiment sensors and status
D.25	The ground station shall store the received data from the sensors
D.26	The ground station shall decode the received data into readable data sets
D.27	The ground station shall display the flight and experiment status
O.01	The experiment shall be capable of being turned on and off repeatedly while on the launch pad
O.04	The experiment shall accept request for radio silence while on the launch pad
O.07	The space segment shall execute commands based on specific signals received from the REXUS SM (SODS, SOE,LO)

Table 3.1 Telemetry Requirements from SED

On the other hand, the experiment had some demands which had not the requirement status, but they were mandatory. Thus were to leave at least a three milliseconds delay between each frame that the experiment was sending on the downlink, and at least a ten milliseconds delay for the uplink. The only baud rate available was 38400, the maximum load of the downlink was 500kbps for all the experiments, and the uplink works in the same way, but the maximum load was around 100kbps.

3.2.1 Telemetry interface

The telemetry was sent by the PC from the COM1 which was configured for sending data via the protocol RS-422. This port was communicated with the interface PCB (this PCB has a 1k resistor between the lines as demanded) and then the D-SUB 15 takes over. Then, the service module process and send it to the ground station, where the data received is given back through an RS-232.

3.2 Telemetry Protocol

With all the data, we designed a protocol for the downlink and the uplink. Taking into account that the transmission could be interrupted during the flight, and some frames or bytes could be lost, we design this protocol to be enough reliable.

3.2.1 Uplink

As the amount of data to send was only six different commands, the uplink frames had the shape presented on the Table 3.2.

Data type	Number of bits
Sync words	8
Uplink orders	8

Table 3.2 Uplink frame

The Sync word had the mission of synchronizing the message on the space segment in order to be read correctly. Then, the Byte with the orders had six signals. This signals or orders are shown on Table 3.3.

Bit number	Order
1	**Uplink been send**
2	**Test mode**
3	**Stop test mode**
4	**Nominal mode**
5	**Switch GoPro**

6	**Blackout**
7	**-**
8	**-**

Table 3.3 Uplink orders to be send

The test mode was switched on during the performed test on the lab and the ones performed during the Bench test (Integration Week, and Launch campaign).

The nominal mode was tested in the lab and also during the same milestones than the test; but, it required special preparation before performing nominally.

Stop the test mode allows the ground segment to stop the test mode and reset the values, and perform another test or start being nominal.

Switch GoPro allows the ground station to switch on/off the GoPro, needed before the Blackout, or most commonly used for save battery during the test performed with the rocket on the launch pad. Also allows the ground segment to switch on the GoPro if it does not start automatically when expected.

The Blackout was sent only during the test to force the experiment to switch off before it was powered off. Also used for interrupting a test or aborting the experiment.

Finally, the total load of data being sent on the uplink was 65 bytes/sec.

3.2.2 Downlink

The downlink frame structure was slightly different. The frames were also fixed (no variable length frames) with a control word before each data as shown in Table 3.4. The control words were unique for each data type.

Data type	Number of bits (include Correction Code bits)
Sync words	24
ID counter	16
Experiment status (Control word)	8
Experiment status	8
Signals(Control word)	8
Signals	8
Piezo values(Control word)	8
Piezo values	8
Heat flow(Control word)	8
Heat flow	16
TCs Heater(Control word)	8
TCs Heater	16

Accelerometer X(Control word)	8
Accelerometer X	16
Accelerometer Y(Control word)	8
Accelerometer Y	16
Accelerometer Z(Control word)	8
Accelerometer Z	16
TCs 1(Control word)	8
TCs 1	16
TCs 2(Control word)	8
TCs 2	16
TCs 3(Control word)	8
TCs 3	16
TCs 4(Control word)	8
TCs 4	16
TCs 5(Control word)	8
TCs 5	16
End of Data Transmission(Control word)	8

Table 3.4 Downlink frame

Three bytes were used for synchronization due to the fact that inside the frame some data could have the same values than a Sync word of two bytes; so, three bytes were guaranteeing that the synchronization was always possible.

Initially, the ID counter was sending a counter of the frames already sent, but as this data was not relevant (the real data was stored at the PC).Finally, it changed to the timer of the experiment, which was giving to the ground segment information of the synchronization of the experiment with the service module.

The experiment status was a byte with data referring to certain devices of the experiment and showing if they were on or off. These devices were the ones shown in table 3.5.

Bit number	Meaning
1	**PC status**
2	**Arduino status**
3	**Heater status**
4	**Piezo status**
5	**GoPro status**
6	**Thermocouples status**
7	**LEDs status**
8	**Accelerometer status**

Table 3.5 Experiment status Byte data

The signals byte has two different kind of data, first of all there is a feedback of the uplink with the operational mode at the moment (test or nominal), and then it sends the status of the SOE, LO, and SODS signals as observed on table 3.6. The last two bits are reserved for the heater status, showing if it is being powered at 6 or 12V.

Bit number	Meaning
1	**Uplink status**
2	**Test mode**
3	**Nominal mode**
4	**SOE**
5	**LO**
6	**SODS**
7	**6V Heater**
8	**12V Heater**

Table 3.6 Signals byte data

Then the Byte with the piezo values is sent, and this byte sends also two types of data. The first bit corresponds to the output of the function generator, this means whether is working or not. The second type of data shows the output frequency of the function generator (Table 3.7).

Bit number	Meaning
1	**Output**
2	**41 KHz**
3	**82 KHz**
4	**164 KHz**
5	**-**
6	**-**
7	**-**
8	**-**

Table 3.7 Piezo byte data

After that byte, the rest of the data bytes are just a numerical value recorded on the sensor. This data occupies 2 bytes each. Due to the fact that the A/D has a resolution of 10bits, and for avoid the resolution degradation the data was sent using more bits than needed.

Finally, the total load of the downlink line was of 10kbps.

3.3 Telemetry Software

The experiment protocol described on chapter 1 needed a software that support it on the space segment and the ground station. This software was programmed using Labview because the experiment was ruled by a Labview code, and also due to the fact that programming serial communications with Labview is not too complicated.

3.3.1 On board

The code on the experiment side was always sending the downlink frames, and when it received an uplink acted in consonance. So basically, there were two different loops running simultaneously. Note that the way they are integrated on the main code is explained in the bachelor thesis of Sergi Batlle Soler.

3.3.2 Ground Segment

On the ground segment the code was used as a master of the experiment and the flow chart diagram can be observed in Fig.3.1.

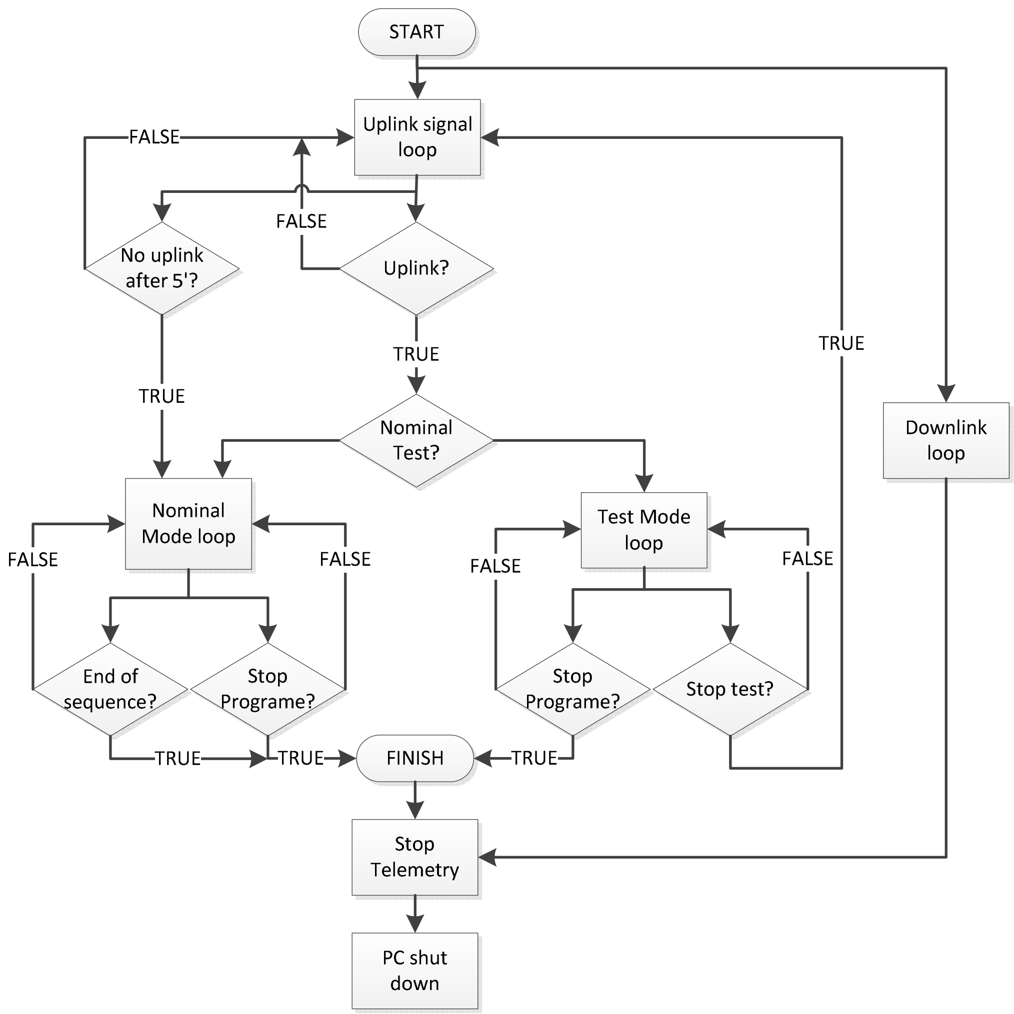

Fig 3.1 flow chart diagram for the ground segment from SED

This means that the user needs to send an uplink to activate the experiment; otherwise, the experiment will run automatically on the nominal mode after 5 minutes. The user has the capability of changing from test mode into nominal if needed. No matter what is doing the experiment, the user could send the blackout signal and shut down the PC.

Also, on the downlink loop, all the data received is stored in a .txt file for a later check with the real data stored on the experiment.

Finally, the Fig 3.2 shows the ground station user interface.

Fig 3.2 Ground station user interface

Chapter 4. Verification and testing

4.1 PCBs verification and test

Once each PCB was design and mounted, the first step for the validation process was to visually inspect each PCB with a microscope (Fig. 4.1). After the first inspection the PCBs were tested in several ways.

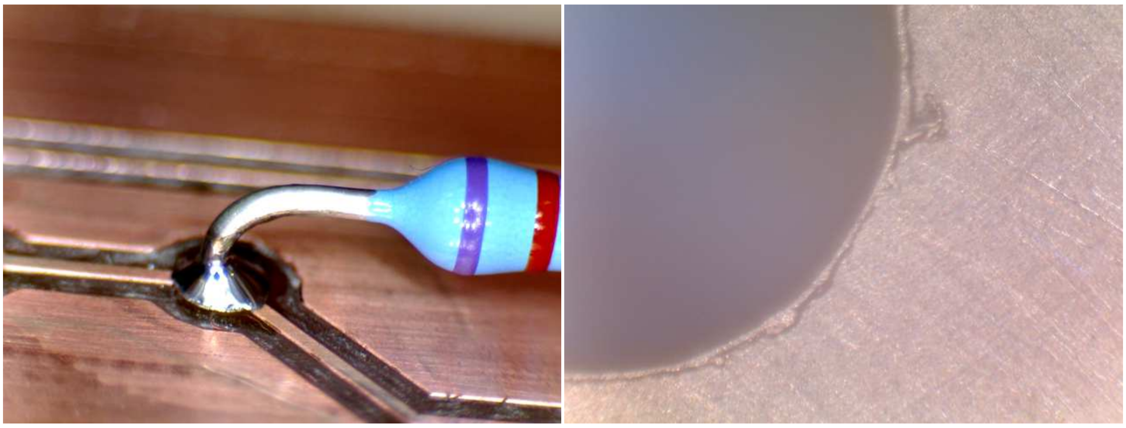

Fig. 4.1 Visual inspection image taken with the microscope

The first test was a simple test were the PCBs only needed to work as expected without any kind of malfunction. If the PCB passes this phase, was proved in vacuum (because that will be its natural environment). If no overheat was measured and worked correctly in vacuum conditions, it was considered a successful test. The last test was to operate with the rest of the electronics PCBs all together.

At that point, the PCB had the approval for flight, but still needed one more test before flight, and that was the full flight simulation test, were the PCB needed to work with the experiment assembled and following the experiment timeline.

Then, all PCBs worked as expected except two, the Heater acquisition PCB and the Thermocouples PCB. Both PCBs were working perfectly before the experiment assembly, but once it was mounted they showed an offset on the measures, and an interference between the lines.

After some investigation, we found that the DC/DC from the computer, and the external DC/DC that the experiment was carrying, were introducing a signal in all the structure (Fig. 4.2).

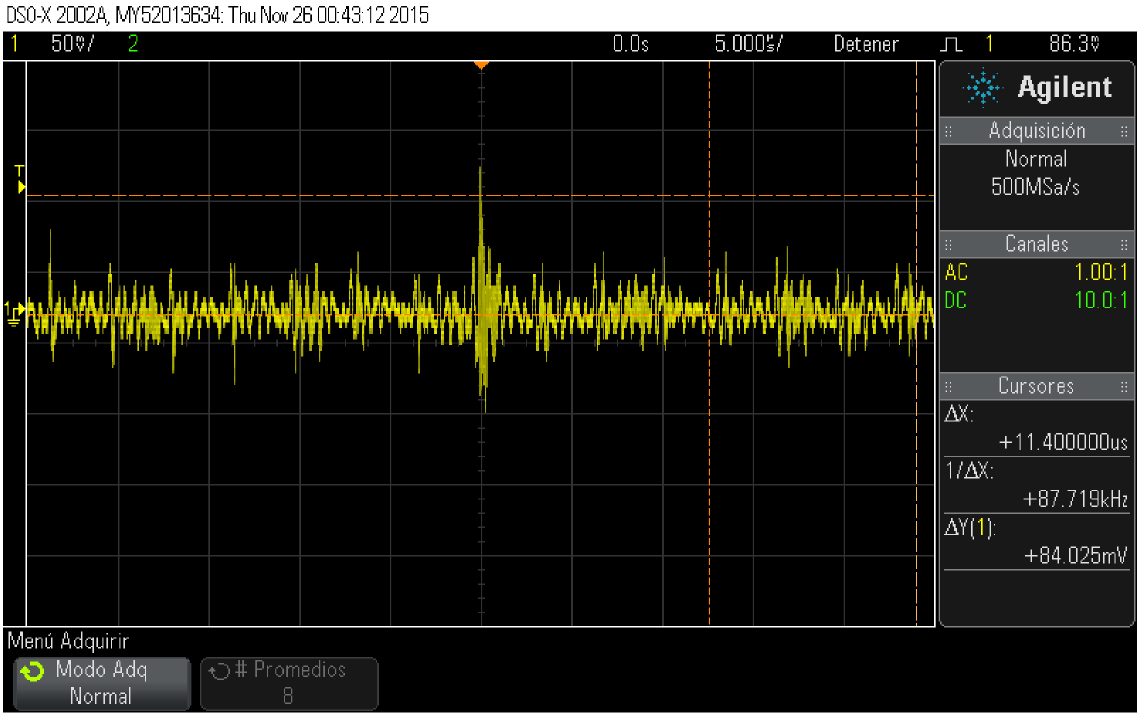

Fig. 4.2 Noise measured in the bulkhead

Finally, the Thermocouples PCB's interference was located, because it was found that the noise was being conductive, and the point where the interference was entering into the PCB were the thermocouples hot junction that was attached at several places of the experiment.

To fix that interference, a layer of Capton was introduced between the thermocouple and the measured surface. This procedure is typical from space applications, and was learned from Koen de Beule (an electronics expert from ESA).The structure was also grounded to prevent similar problems in other experiments.

The Heater acquisition PCB could not be fixed, because the interference was capacitive, and due to the fact that this PCB was the only one in a plastic box (not aluminum because a lack of financial budget at the moment when it was mounted) it could not be cancelled. So the signals from the thermocouples of this PCB had an offset, and due to the fact that the module structure was returned to the ZARM after the flight, no more investigations could be done to fix the PCB or figure out the interference with more detail.

4.2Electrical budget test

The power consumption of the experiment had some requirements that established an electrical budget for the experiment. So, when all the experiment devices were mounted, a power consumption test was performed.

The test consists on use the cDAQ-9174, with the NI9201 module, measuring the voltage drop on a 0.24 ohms resistor. Two different tests were made, the first test did not activate the function generator (Fig. 4.3), and the second did (Fig. 4.4).

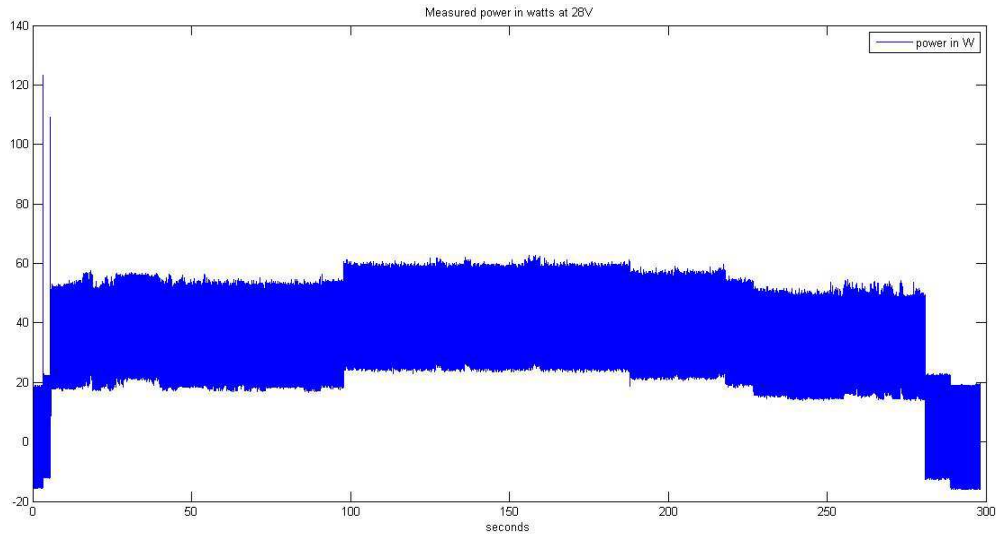

Fig. 4.3 Experiment power consumption without function generator

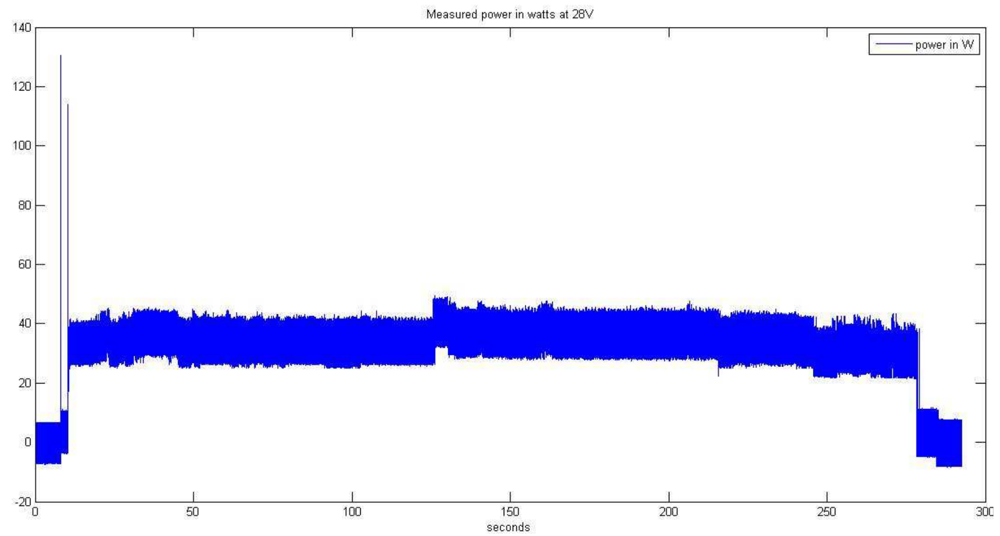

Fig. 4.4 Experiment power consumption with function generator

The experiment presented an average power consumption of 39 watts, that slightly varies depending on the power consumed by the heater and the function generator.

The two initial peaks above 100 watts were due to the power supply switch on, and due to the PC switch on. The first one does not represent any kind of problem, but the second one (despite it was on our requirement margin) was not possible to be performed by the experiment once in the rocket.

Due to the fact that without that peak the PC could not be switch on, during the meetings that we had with the MORABA and ZARM experts, we agreed that they would modify the rocket fuses in order to allow the inrush current demanded by the PC.

4.3Telemetry test

The telemetry was probed with the RX service system simulator (Fig. 4.5) were the experiment was connected through the D-SUB 15 and the simulator had a D-SUB 9 output with the RS-232 cable.

Fig. 4.5 RX service system simulator

This simulator has the capability of introducing noise in the communications lines, and loosing bytes if this capability is activated. This is used to simulate a flight where the byte loses are unavoidable. It was also used on preliminary test of interferences between different experiment during the integration week at ZARM facilities.

The telemetry worked as expected and no problems where found during this test.

4.4Others

Some other test where performed such like the Vibration test (Fig. 4.6), and several cold and hot countdowns in which the telemetry and the electronics were tested successfully.

Fig. 4.6 BOILUS experiment during vibration test at ZARM facilities

On the BOILUS SED, the report about the vibration test could be found, explaining the procedure and the results.

The Cold and Hot countdown consist on execute the experiment exactly as we would do it on the launch pad.

The cold countdown was performed in nominal mode and the test stopped at T-0 without sending the LO signal into the experiments; so, when that point was arrived the ground station sent the switch GoPro signal to power off the video camera, and after that sent the Blackout button before the service module power off the experiments.

On the other hand, the Hot countdown was done with the test mode in order to not activate the heater. This test was reproducing the hole countdown procedure and it arrives until T+600, that means that all signals were send to the experiment in the appropriate order.

All Countdown test were successful and all devices worked as expected.

Chapter 5. Conclusions

In this project we have designed and built the electronics and telemetry for an experimental setup that successfully flew in the framework of the REXUS program in March 2016.

The electronics worked as expected except as regards to the Thermocouples acquisition data PCB, the GoPro switch PCB, the GoPro status PCB, the Interface PCB, the Heater power control PCB, the accelerometer and the LED matrix, however the Heater acquisition PCB did not work well because one of the Thermocouples and the heat flux meter had an interference in the signal. The data could not be recovered due to the fact that after the flight the module and the bulkhead were returned to ZARM. Currently the board performs properly and it is not possible to figure out a solution for a problem that it is gone.

The ground station and the telemetry allowed us to know that the experiment performed well before the rocket was recovered. After the recovery, the video recorded with the GoPro was obtained and the data stored in the PC was collected and compared with the data stored in the ground station. The results were satisfactory because the data obtained were similar. More data was stored in the PC due to the fact that only part of the data was sent through the downlink.

For future similar works it is recommended to make a research on the ECSS standards before starting the design phase (some of our PCBs were redesigned several times before the ECSS lectures were taken).

Also in future works, electromagnetic compatibility interferences should be expected. Therefore, in the initial phases of the project some time should be reserved after the design phase in order to find and fix all the problems that this effects could generate.

Planning a good organization could take some time in the firsts steps of a project, but it is very recommendable, because it will allow the team not to waste time in critical phases fixing problems due to the lack of organization.

Chapter 6. Bibliography

[1]REXUS User Manual, RX_UserManual_v7-11_08Jan14.doc

[2]Student Experiment Documentation, RX20_BOILUS_SED_v4_13November15.doc