³Cat-1: A MULTI-PAYLOAD CUBESAT-BASED SCIENTIFIC AND TECHNOLOGY DEMONSTRATOR

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ABSTRACT

This paper introduces ³Cat-1, the first project of the Universitat Politècnica de Catalunya to build and launch a pico-satellite. Its main scope is to develop, construct, assembly, test and launch into a Low Earth Orbit a CubeSat with seven different payloads (mono-atomic oxygen detector, Graphene transistor, self-powered beacon, Geiger radiation counter, wireless power transfer, new topology solar cells and wireless power transfer experiment) are all fitted in a single unit CubeSat. On one hand, this is mainly an educational project in which the development of some of the subsystems is carried out by Master Thesis students. On the other hand, the satellite demonstrates its capabilities as optimum platform to perform small scientific experiments, and to demonstrate some of the new technologies that it incorporates. ³Cat-1 launch is scheduled by summer 2014.

1 INTRODUCTION

The CubeSat initiative started in 1999 as a collaborative effort between Prof. Jordi Puig-Suari at California Polytechnic State University, and Prof. Bob Twiggs at Standford University Space Systems Development Lab [1]. The purpose of the project was to provide a standard for pico-satellites to reduce the cost and the development time, increasing the accessibility to space to universities, research institutes, and small enterprises, giving them the possibility to sustain frequent launches.

³Cat-1 is the first satellite of the Universitat Politecnica de Catalunya (UPC). Conceived initially as a simple educational project with an optical camera in the visible part of the spectrum, it has evolved with the addition of new scientific payloads such as a mono-atomic oxygen detector, a couple of deployable Tesla coils to study the effect of plasma in the coupling, a Geiger counter, and a MEMs-based IMU to sense the Earth's magnetic field. In addition, a few technology demonstrators will be tested: a graphene transistor, a new topology of solar cells, and an energy harvesting experiment based on Peltier cells using the temperature gradient between the solar cells and the inside of the satellite. A huge effort in terms of system and software integration has been performed in order to fit and make the systems compatible between each other. However, ³Cat-1 has also meant a large effort in real-time processing, including a task scheduler based on the predicted

available power, communications etc. ^{3}Cat-1 is nowadays finalizing its integration and test phase (see figure 1), and its launch is expected by June 2014.

However, ^{3}Cat-1 is intended to be the first of a series of pico- and nano-satellite projects. ^{3}Cat-2, under development now, is a 6U CubeSat carrying aboard a GNSS-R payload for Earth Observation [2]. Its performance has been validated in a stratospheric balloon under the Balloon EXperiments for University Students (BEXUS 16/17 campaign) coordinated by ESA's Educational Office.

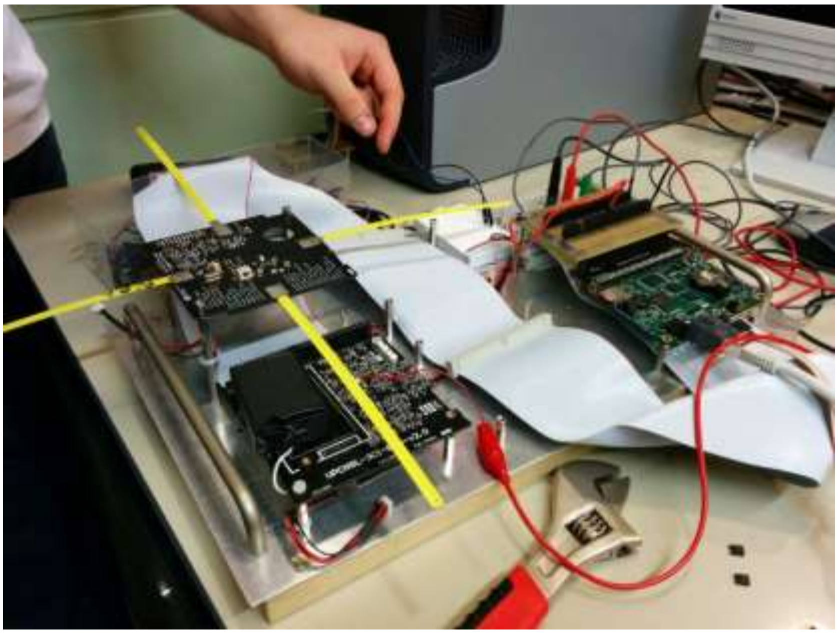

Fig. 1: Testing the flat satellite on April 2014.

2 MISSION OBJECTIVES

CubeCat-1 is an educational project from Universitat Politecnica de Catalunya. CubeSat initiatives at UPC started in 2007, and now are supported by a regular course in the new CDIO-oriented (Conceive Design Implement and Operate) curricula at Telecom Barcelona entitled "Payloads and Subsystems for Small Satellites" [2]. This subject is supported by an amateur ground station, and a laboratory with the following testing facilities: TVAC, shake table, and 3 axes Helmoltz coils for CubeSats up to 6U. Up to now, more than 79 undergraduate student have already been involved in the design, implementation, and testing of our first Cubesat: ^{3}Cat-1, a 1U CubeSat.

In addition, CubeCat-1 pretends to acquire the know-how to manufacture CubeSats and prepare more complex missions in the future. To achieve this objective, this first satellite has been designed as a mixture of space qualified, COTS (Commercial Of The Shelf), and UPC-designed subsystems, in order to achieve a compromise between the risk of failure and the cost. After several problems with space qualified components and the availability of them to provide to the students, the major economical effort has been applied to acquiring the capabilities to self-qualify our self-designed subsystems and commercial components. The next sections in this paper, will briefly describe ^{3}Cat-1 mission, but first of all, the list of payloads and experiments is presented:

- MEMS mono-atomic oxygen detector, to detect the presence of this chemical component in the ionosphere [4].
- Graphene transistor, to be tested in true space conditions [5],

- Self-powered beacon, from Peltier based energy harvesting techniques
- Wireless power transfer, using Tesla coils to study the effect of ionized particles on them [6]
- New topology solar cells using IBC Si technology [7]
- Geiger radiation counter, to calculate the radiation during the orbit
- CMOS Camera to get optical Earth pictures from the orbit.

Finally, it is important to remark some other subsystems to validate which are:

- Electric Power Subsystem, fully designed at UPC.
- Communication Subsystem, partially designed at UPC using a COTS transceiver without amplifier.
- Attitude determination subsystem based on a COTS and validated in our testing facilities.
- Attitude control, designed at UPC.
- Photodiodes, placed in the faces of the satellite and used for attitude determination experiments.

3 ^{3}CAT-1 CONFIGURATION

^{3}Cat-1 is a single unit CubeSat so it must comply with the CubeSat Design Specifications standard [8]. Fitting all these technologies and payloads in a single unit CubeSat requires a large dedication of systems engineering. The systems of ^{3}Cat-1 are distributed five floors of PCBs as it can be seen in figure 1.

The first floor contains the deployable payload (wireless power transfer coils), the graphene transistor, the Geiger counter to characterize the radiation, and the electric part of the Peltier harvesting system. This last one is placed there to ensure having temperature gradient when the satellite flies over the ground station because it is the side that will be getting the Sun heat.

The second floor has the On-Board Computer on it while the third one has the Electric Power Subsystem. It is placed right in the middle of the structure for better thermal stability and getting higher temperatures, especially important for the batteries. The weight of the batteries close to the geometric center makes easier balancing the center of masses. Finally, EPS is radiation sensible and contains a hard reset that will force a reboot of the entire satellite every 48h and should never fail.

The fourth floor has the ADCS board, the MEMS mono-atomic oxygen detector and the camera. The MEMS is placed close to the camera field of view hole for better chances to have mono-atomic oxygen entering to the detector.

The coms subsystem is placed on the fifth floor in order to have the less satellite structure interfering the communication. It has the transceiver, the beacon, the RF part of the Peltier beacon and the antennas.

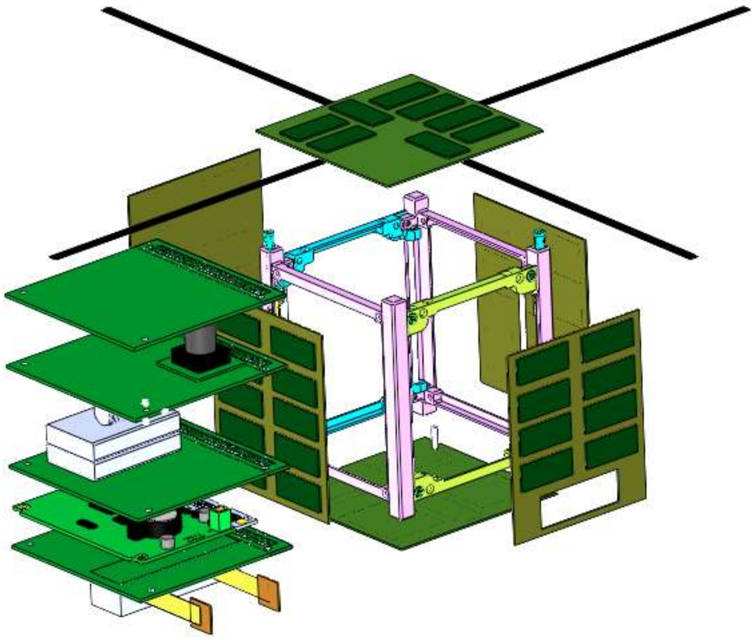

Fig. 2: [3]Cat-1 CAD scheme

4 POWER BUDGET

The power budget of such a complex system is a balance between the power that is consumed and the one that can be generated by the satellite. The first step to calculate it is establishing what the minimum power requirements to satisfy the mission are. This is shown in table 1.

Subsystem	Power (mW)	Duration - Frequency
Electric Power Subsystem	100	Allways on
On-Board Computer	120 / 30	On / stand-by
Comms RX	60	Dutty clycled: 10s on, 60 off
Comms TX	2400	10min - twice a day
Comms Beacon	100	10s – every 3min
Attitude determination*	10	1s – every 10s
Control system*	100	10 min, before camera picture
PL – MEMS*	200	5min, once per orbit
PL – Graphene*	500	20s, once per orbit
PL – Harvesting Beacon	0	50ms, every 10 to 30seconds
PL – WPT*	800	1s, once per orbit
PL – Geiger*	120	1min, after MEMS, WPT and GFET
PL – Camera*	400	15s, once per orbit

Tab.1: Power consumption

The power demand of the satellite depends on the power of the devices and how long they are active. To increase the chances of a successful mission, the frequency and the duration of the tasks marked with an asterisk can be changed on flight using the appropriate telecommand. On the other hand, the power generated depends on the orbit type where the satellite is flying, the solar panels available, their orientation, and the devices to transform and save the collected energy. The power budget must be conservative, and suitable for different types of orbits. Table 2 specifies the power obtained for different 600 km Sun-synchronous orbits.

Orbit	**Sunlight (%)**	**Max power (mW)**	**Avg power (mW)**
6 am-6 pm	100	2763	2763
9 am-9 pm	73	2998	2149
12 am-12 pm	64	2880	1833

Tab.2: Solar energy per different orbits

A pessimistic case in analyzed using a 12am – 12pm orbit, in which all the payloads are used in one orbit and a transmission is made. From the results, shown in figure 2, it can be seen the energy input and output as well as, the state of charge (SOC) of the battery. As it can be seen the power budget required can be satisfied. However, from the results, it is taken the decision to avoid establishing communication if there is no Sun-shine on it. Otherwise, the batteries may suffer discharge stress and compromise the long term mission.

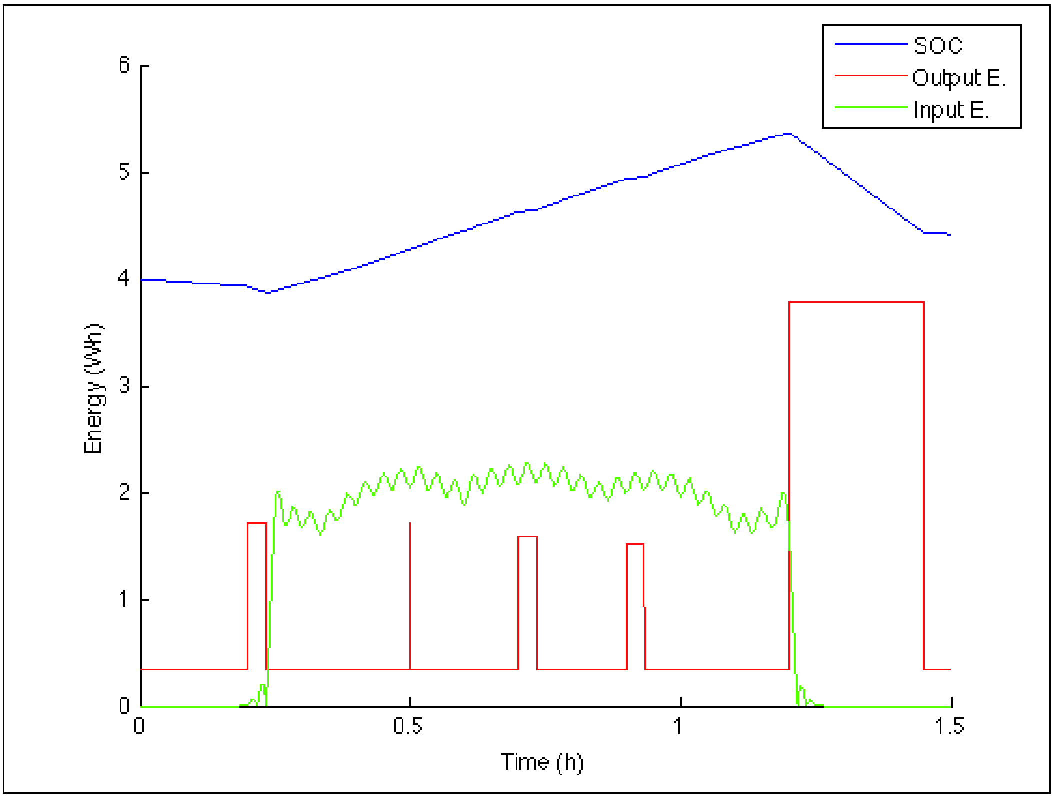

Fig.3: Evolution of the state of charge of the batteries

5 ELECTRIC POWER SUBSYSTEM

The electrical power system (EPS) is one of the critical systems of the satellite because without power supply none of the other systems can operate. The EPS is involved in the generation of electrical energy, its storage in the batteries, the regulation and control of the power and the distribution in power buses. The main aims of the EPS are:

- Supply a continuous source of electrical power to satellite subsystems during mission lifetime, supporting power requirements for average and peak electrical load.
- Provide regulated power buses, suppress transient bus voltages, and protect against bus faults.
- Provide command and telemetry capability for EPS health and status and control to the On-Board Computer.
- Provide command telemetry for the different experiments: solar panels, photodiodes, Peltier thermocouple, and MEM capacitor.
- Maintain the batteries above 0°C to avoid freezing.

As it can be seen in figure 3, the EPS subsystem has a modular design based on Points of Load (POL). These POLs adapt the unregulated voltage from the ^{3}Cat-1 Power Bus to what is required by the fed subsystem, and are able to avoid over currents and detect latch-ups to increase the mission survival possibilities even if parts of the satellite fail. Finally, POLs are normally off unless are enabled by the EPS PIC which responds to the appropriate command from the On-Board Computer (OBC). This is done to safe energy whenever is possible.

The unregulated power bus is fed from the battery charger. Apart from charging the batteries, this battery charger is able to provide energy to the unregulated power bus from the solar panels, from the batteries and form both of them. This last situation is expected every time the transceiver downloads the data requested by the Ground Station. Between the solar panels and the battery charger a battery of switches is placed. These switches are the Remove Before Flight, the kill switches of the CubeSat structure and a Hard Reset system. The hard reset is used to reboot the entire satellite every 48h. This system gives robustness to ^{3}Cat-1 as it is a prevention against bugs in the OBC and EPS PIC.

The solar panels are the only satellite energy source and will be placed in all the faces of the CubeSat. However, not all the faces will have the same type of solar panels. To minimize the risk of full mission failure, five faces of the satellite will have space qualified SpectroLab solar panels with an average efficiency over 27%, while the sixth one will have the CellSat solar panels designed by the Electronics Department of the UPC, and manufactured at UPC clean room. The EPS will send the status information of all solar panels to the on-board computer. The CellSat solar panels are based on crystalline Si back-contact solar cells. In these devices we use a Al_2O_3 layer to passivate the front side of solar cells providing an average photovoltaic efficiency up to 13%. Such panels have been chosen in order to study the degradation of the material in true space conditions.

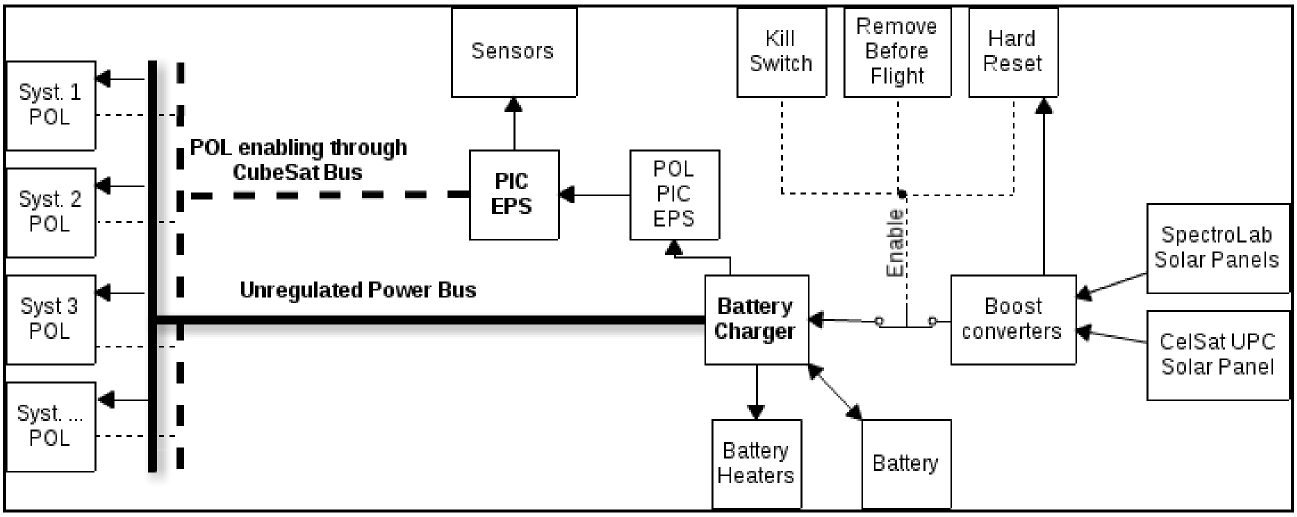

Fig. 4: Electric Power Subsystem architecture

6 ATTITUDE DETEMINATION AND CONTROL SYSTEM

To determine the attitude of the satellite none space qualified system is used. Consequently, a triple redundant system is developed:

- COTS gyroscope: the commercial of the shelf gyroscope is a micro-electromechanic (MEM) device that will be used as main attitude determination system in the ^{3}Cat-1.
- Photodiodes: placed on each face of the CubeSat, the photodiodes act as a coarse solar sensor, providing a redundant estimation of the satellite's attitude. These results will be compared to the results of the gyroscope determine a possible failure of the gyro.
- Solar panels: in case the gyro or the photodiodes fail, the solar panels output power will also be used to determine the satellite's attitude.

Once the attitude has been determined, the actions to control the satellite can be applied. The control of the ^{3}Cat-1 is a mix of active and passive systems. As passive system, a permanent magnet will align the satellite's axis with the Earth's magnetic field. The induced oscillations, as a pendulum, will be dumped using strips of materials with high magnetic permeability to dissipate the energy of the movement. Finally, a magneto-torque is used to increase the pointing precision of the camera.

7 COMMUNICATIONS

The communications system is also considered one of the critical systems of the mission because if the satellite works properly, success relies on the contact with the satellite and the transmission of data. The initial communication system was designed to use AX.25 compatible with GENSO. However, some technical issues between the OBC and the transceiver on one side, and the uncertainties around GENSO project forced a deal break decision.

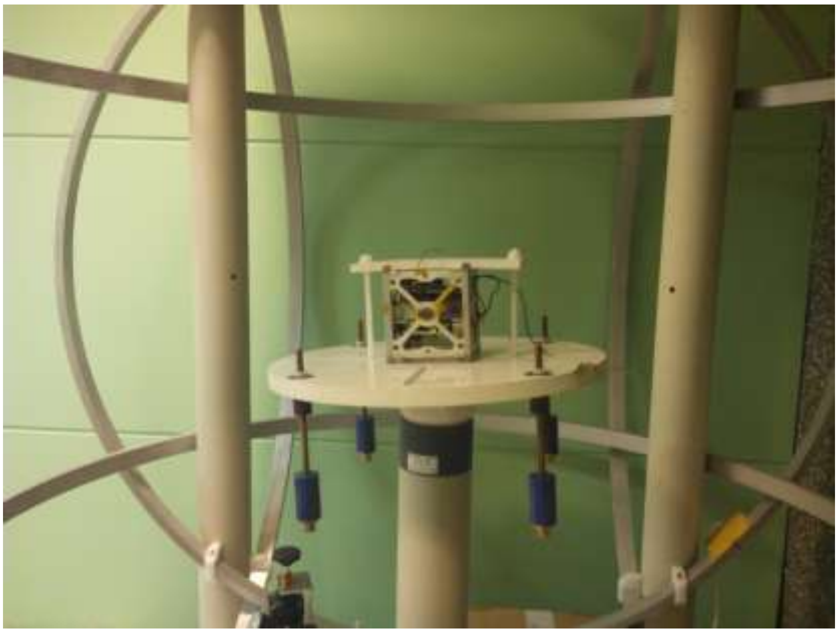

Fig. 5: Testing attitude determination and control in the Helmhotlz coils

Nowadays, ^{3}Cat-1 uses a transceiver with a proprietary protocol and operates at 437MHz FSK. The signals emitted by the transceiver are mixed in a RF combiner with both the *normal* beacon and the *self –powered Peltier* beacon. The antenna of the ^{3}Cat-1-1 is a pair of crossed dipoles with circular polarization made of metric tape which is covered by Teflon. This material was successfully used in the Delfi−C3 satellite [9]. Due to the passive attitude control of the satellite, the antenna has been designed not to be too directive so it can cope with pointing errors larger than 20°. Finally, the antenna deployment will be performed by melting the Nylon wire that holds the dipoles in their storage configuration.

Fig. 6: Long distance communication test

As part of the infrastructure, a GENSO compatible ground station has been installed in the UPC

Campus Nord. This ground station can receive and transmit signals using the AX.25 protocol, an open source protocol already in use in many CubeSat missions, but it can also switch to any other transceiver. This second configuration will be used for ^{3}Cat-1 operation, where the original Ground Station computer is still used to control the antenna rotors and decode the beacons, while a Raspberry Pi Single Board Computer is used to transfer and process the data of the transceiver.

Fig. 7: Ground station at Barcelona UPC TelecomBCN

8 PELTIER BEACON

An energy harvesting experiment is used to feed a self-powered beacon system. This system uses a Peltier cell thermoelectric generator to get its energy. Thermoelectric generators (TEG) have a slow dynamic response. Therefore, they cannot be used on fast rotating systems that act as low-pass filters. Therefore, the TEGs can only be placed in the faces directed towards the Sun.

This configuration and the temperature distribution has been analyzed using Thermal Desktop® (see Fig.4). As result of this study, it was decided that the appropriate placement of the TEG is the opposite side respect to the communication subsystem.

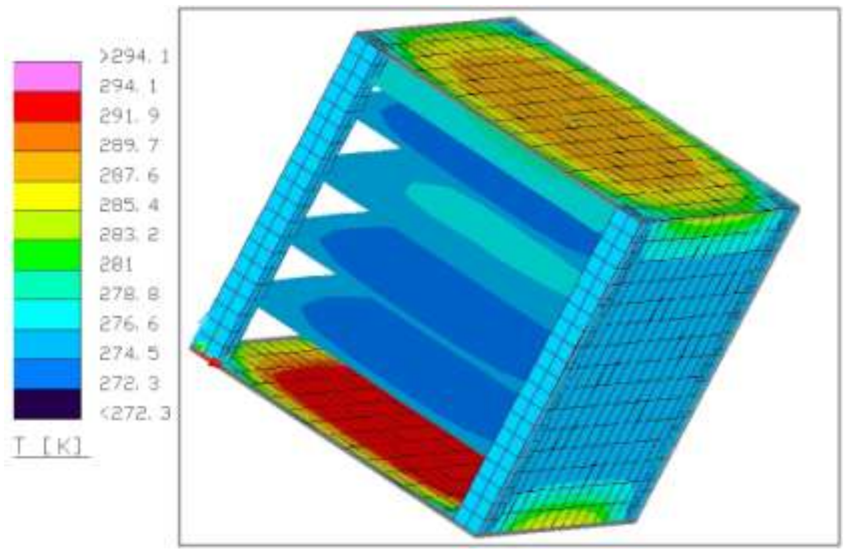

Figure 8: temperature distribution

The configuration was analyzed with two different Peltier cells which measured properties are shown in table 3.

Model	**R_{elec}**	**$R_{thermal}$**	**Seebeck voltage**	**Footprint**
A	4.5 Ω	4.6 K/W	24mV/K	20 x 20 mm
B	330 Ω	18 K/W	110mV/K	Φ 9.5 mm

Tab. 3: Thermoelectric generators performances

The results obtained (Fig. 5) for both TEG show that enough voltage will be generated to run an small circuit or application. However, a circuit to adapt the output voltage and/or store energy is needed. Most of these circuits need a minimum input voltage, so the type of thermoelectric module chosen will be a compromise between the power obtained and the minimum voltage needed to boost up the circuit to run the system.

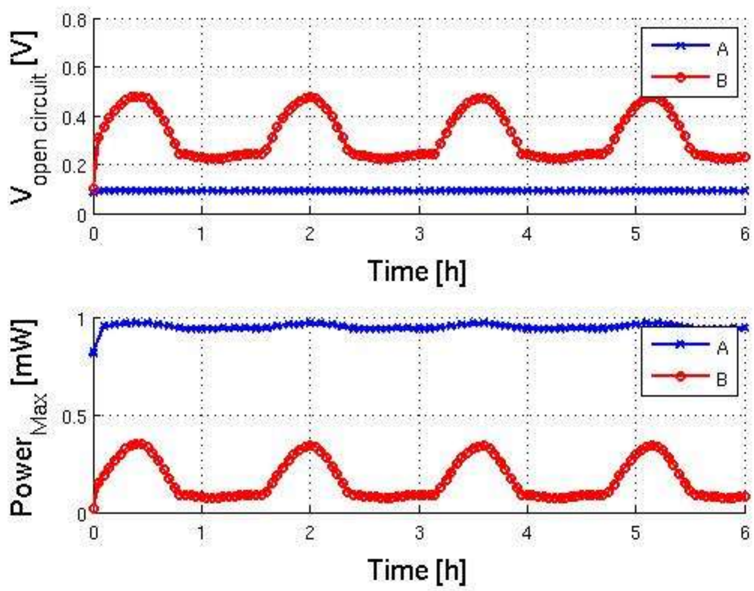

Fig. 9: Open circuit voltage and power expected in orbit.

9 OPTICAL SENSOR

The optical sensor of the satellite is based on a simple CMOS VGA digital camera (640 x 480 pixels) including JPEG compression. This camera has been chosen to reduce the transmission time of the satellite, and maximize the number of images that can be transmitted. The main objectives are to obtain images from the Earth's surface from space while solving the complex problem of a whole satellite mission. To avoid damages in the camera, the Sun light must not enter in its field of view.
Figure 3 shows the part of the Earth's in the Northern hemisphere that will be covered by the camera thanks to the pointing achieved by the passive control system of the satellite.

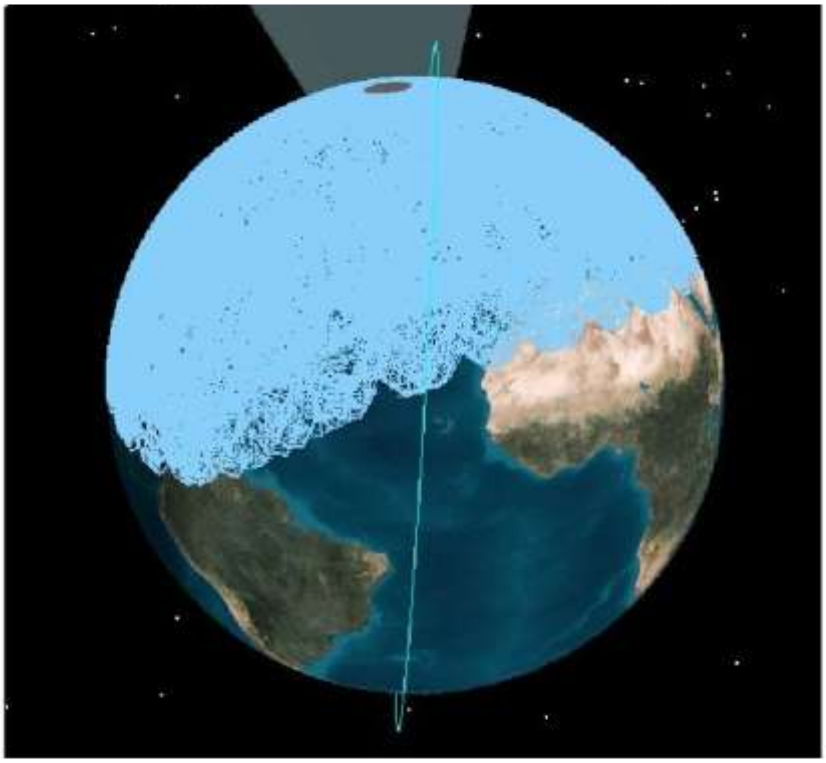

Fig.10: surface covered by the optical sensor

10 TESTING FACILITIES

Different facilities have been acquired to qualify satellites and components at NanoSat Lab [10].

The Thermal Vacuum Chamber (TVAC) is the first space environment equipment bought in NanoSat Lab (see Fig. XXX). Its purposes are to test equipment in high vacuum conditions with a wall as similar as possible to the real space environment, and have the ability to qualify nano-satellites, specially to have the opportunity to do the out-gassing and thermal cycling tests required by launchers. It was dimensioned to be able to fit in a 6U CubeSat for qualifying purposes. The TVAC can be heated by 1kW infrared lamps and cooled down by liquid nitrogen fed from a 50L reservoir. Furthermore, inside the TVAC there is a rotating platform over which a 2U CubeSat can be spun.

Fig. 11: Qualifying COMMS PCB on the NanoSat Lab shaker

Since January 2013, NanoSat Lab is equipped with a SignalForce air-cooled shaker from Data Physics (model V400 - DSA 5-10K). With this facility, NanoSat Lab is able to do random noise, pure sinusoidal and shock tests to qualify components and nano-satellites.

Finally, a 3 axis Helmholtz coils are used at NanoSat. The main applications of this equipment are testing and calibration of magnetometers and, attitude determination and control tests (with the air bearing). Controlled by a programmable power source they can emulate the evolution of the magnetic field during an orbit. They were provided by Serviciencia, an Spanish company located in Toledo.

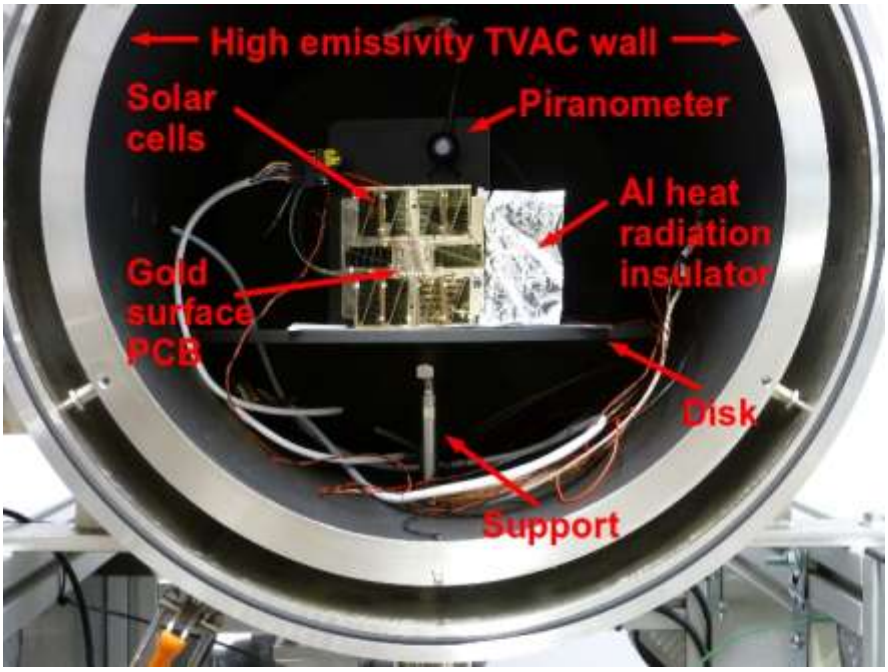

Fig. 12: TVAC chamber testing thermoelectric generator harvester and self-powered beacon

11 CONCLUSIONS

Designing a pico-satellite, even based on the CubeSat standard, is a very complex multi-disciplinary project. ^{3}Cat-1-1 is a pioneer multitasks and multi-payload CubeSat that demonstrates the capabilities of this technology. The work performed so far is paving the path for future more sophisticated missions. Many subsystems such as the EPS, the transceiver, the ADCS, and even parts of the software will be re-used again in future missions. At the time of writing this document the last boards of ^{3}Cat-1-1 are being tested and integrated. As mentioned before, ^{3}Cat-1 launch is scheduled by this summer 2014. Further details will be published soon within the PhD Thesis of Mr. Roger Jove.

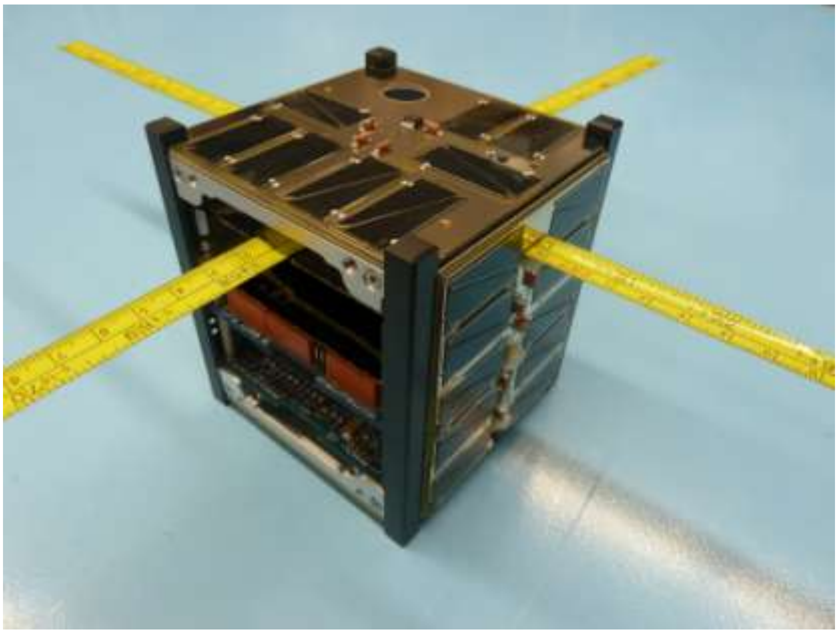

Fig. 13: Mechanical integration of ^{3}Cat-1.

12 AKNOWLEDGEMENTS

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13 REFERENCES

[1] H. Heidt, J. Puig-Suari, A.S. Moore, S. Nakasuka, R.J. Twiggs, "CubeSat: A new Generation of Picosatellite for Education and Industry Low Cost Space Experimentation", *Proceedings of the 14th Annual/USU Conference on Small Satellites*, 2001.

[2] H. Carreno-Luengo, A. Camps, I. Perez-Ramos, G. Forte, R. Onrubia, and R. Díez, "3Cat-2: A P(Y) and C/A experimental nanosatellite mission", *Proceedings of the 2013 IEEE International Geoscience and Remote Sensing Symposium*, Melbourne, Australia, July 2013.

[3] R. Bragós, A. Camps, and A. Oliveras, "Design of the Advanced Engineering Project course for the third year of electrical engineering at Telecom BCN," *Proceedings of the 8th International CDIO Conference,* Brisbane, Queensland, Australia, 2012.

[4] J. Ricart, J. Pons, E. Blokhina, S. Gorreta, J. Hernando, T. Manzaneque, J. L. Sanchez-Rojas, O. Feely, and M. Domıınguez. "Control of MEMS vibration modes with pulsed digital oscillators: Part II - simulation and experimental results". *Transactions on Circuits and Systems I*, 2009.

[5] M. Iannazzo, S. Rodriguez, A. Rusu, M. Lemme, and E. Alarcon, "Design-oriented Characterization of Graphene-FET based Ring-Oscillators: a Device-circuit Co-design Perspective", to be submitted to *IEEE Transaction on Circuits and Systems II*

[6] E. Bou, E. Alarcón., A. Saenz-Otero, C. Mandy. "Translayer optimized co-design of in-space microwave based wireless power transfer". *Proceedings of the International Symposium on Circuits And Systems.* IEEE 2010.

[7] P. Ortega, R. Jove-Casulleras, A. Pedret, R. Gonzalvez, G. Lopez, I. Martin, M. Dominguez, R.A lcubilla, and A. Camps, "An IBC solar cell for the UPC CubeSat-1 mission," in *2013 Spanish Conference on Electron Devices*, 2013.

[8] California Polythecnic State University, "CubeSat Design Specification.", 2009.

[9] J. Bouwmeester, G.T. Aalbers, W.J. Ubbels, "Preliminary Mission Results and Project Evaluation the Delfi-C 3 Nano-satellite", *Nano-Satellite Small Satellite Systems and Services*, Greece, 2008

[10] NanoSat Lab, http://www.tsc.upc.edu/nanosatlab .