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Thermal testing campaign of the UPMSat-2

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Abstract

The UPMSat-2 is the second satellite designed and developed by the IDR/UPM as part of the UPM-Sats program. It is a scientific micro satellite of 45 kg whose aim is providing the required know-how to design, develop, manufacture, integrate, test and finally operate a complete space system. Furthermore, it serves as on orbit demonstration platform for space technologies. The UPMSat-2 launch is scheduled for summer 2019. The work here exposed includes the whole testing in thermal vacuum chamber, including the different challenges found with the aim of sharing the know-how gained.

1. Introduction

In the ‘90s decade the Instituto Universitario de Microgravedad “Ignacio Da Riva” IDR/UPM started the UPM-Sats program. It was a natural extension of the work carried out by the IDR/UPM in collaboration with the ESA (European Space Agency) since 1975. The program was originally conceived as an educative project, and it was meant to involve not only technical workers, but also professors and students of the E.T.S.I.A (Escuela Técnica Superior de Ingenieros Aeronáuticos). Furthermore, it also had strong scientific and technological goals since the aim was designing, developing, assembling, integrating, testing and operating a complete space system inside framework of the Universidad Politécnica de Madrid (UPM).

The first vehicle of the program was the UPM-Sat 1 (see Figure 1), which was successfully launched in 7 July 1995 from French Guayana. The satellite operated for 213 days in a polar sun-synchronous orbit, with an altitude of 670 km. Apart from the educational goals, the satellite was developed as an orbital scientific and technological testing platform. Thus, there were additional mission objectives. In particular, the satellite served as orbital platform to test the usage of liquid bridges as space accelerometers, in collaboration with the European Space Research and Technology Centre (ESA/ESTEC) in Noordwijk, Holland.

Figure 1: UPM-Sat 1 assembled in the adapter platform ASAP of the Ariane IV-40 launcher.

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The UPMSat-2 constitutes the next milestone in the program. It is expected to have an operating life of 2 years, operating in a sun-synchronous orbit of about 500 km of altitude. The aim is repeating the whole process developed in the UPM-Sat 1, but adapting the already qualified platform of its predecessor to the requirements of current launchers and incorporating new technologies to qualify. In addition, the UPMSat-2 now serves as a pillar of the Master Universitario de Sistemas Espaciales (MUSE) offered by the IDR/UPM. MUSE is a space oriented M.Sc. of UPM during which students experience a project-based methodology. Therefore, students from the first five promotions work or have worked in the design, manufacture and testing of the satellite.

At present, the UPMSat-2 is about to end phase D (qualification and production). The expected launch window is early September 2019. The flight model have already passed the acceptance testing. The European Cooperation for Space Standards (ECSS) defines what tests the vehicle and its payloads and subsystems must pass before launch [1]. Some of the main tests to carry out are mechanical, structural integrity, thermal and electrical I/F tests. Nevertheless, this article focuses only in the thermal testing campaign of the integrated satellite [2, 3].

Along the following sections of this document, a global view of the satellite's thermal control subsystem is provided. Main characteristics and design solutions are described. The sequence of thermal tests performed during the previous phases is briefly described. The standards and considerations taken into account in the design of the integrated satellite thermal test are explained and the results are described and discussed. The objective of this paper is sharing the experience gained through this project.

2. The UPMSat-2

The UPMSat-2 is a square-based 45 kg microsatellite with a geometrical envelope of 0.5 m x 0.5 m x 0.6 m. In Figure 2 the satellite's configuration is displayed. Four trays (A, B, C and D) form the structure, joined in their corners by four L-section beams. The adapter to the launcher is mounted on the lower side of the tray A, and four shear panels are mounted between trays A and B and between trays B and C. Lateral faces are covered by closing panels, bolted to the trays and to the L-section beams. Over each closing panel there is another panel, supported by brackets in the middle and hexagonal standoffs along the sides, which is meant to support the solar panels.

The internal configuration is shown in figure 2. The battery and the x-axis and y-axis magnetorquers are mounted on tray A, the electronics box (E-box) and z-axis magnetorquer are located on tray B, the magnetometers, reaction wheel and its electronics, and the experimental magnetorquer payload are mounted on tray C, and the experimental thermal switch payload is mounted over tray D.

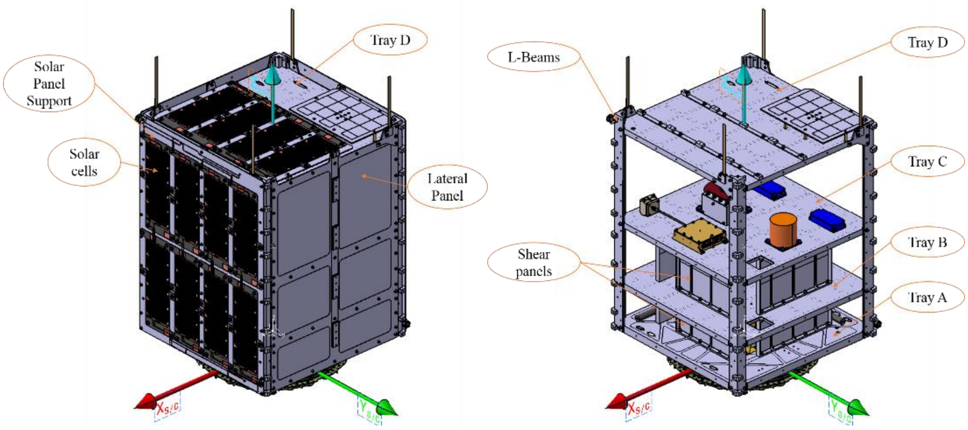

Figure 2: UPMSat-2 flight Model (FM) description. The picture on the left shows the external components (Solar panel removed for clarity) and the picture in the right shows the internal configuration.

Regarding the thermal control subsystem, its objective is maintaining the satellite and its instrumentation within the specified temperature ranges during its operative lifetime. The satellite is spin-stabilized in a Sun-synchronous low Earth orbit (LEO). Thus, the effect of main thermal radiation sources such as Sun irradiation and planet infrared radiation can be considered periodic out of the eclipse areas. Albedo, dissipation of instruments or energy saving mode are the main sources of irregularities out of the periodic behaviour of the spacecraft. As a result, the thermal design relies mainly in passive elements (see Figure 3). The bottom and top trays, A and D respectively, are insulated from the space using black multi-layer insulation blankets (MLI). In addition, the surface finishing of the rest of the structure

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is alodine aluminium, which provides the structure with isolating thermo-optical properties. On the other hand, the solar panel support panels are covered in kapton. This allows the satellite to be heated by the Sun.

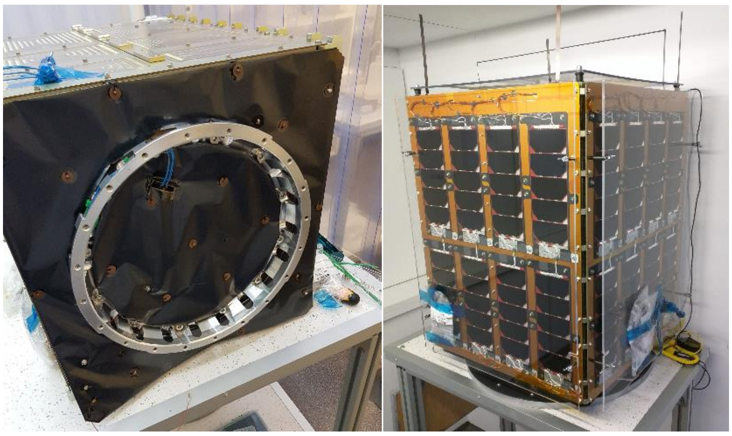

Figure 3: Lower MLI and solar panels covered in kapton as main elements of the passive thermal control subsystem of the UPMSat-2.

However, the temperature of the battery cannot drop below 8 ºC while charging. Consequently, passive thermal control is not enough to maintain the battery within their operative range, which is far narrower than the rest. Thus, a particular design solution was defined for the battery:

First, heat exchange between the battery and the rest of the spacecraft is minimized. Therefore, the battery is wrapped in single-layer insulation blankets (SLI) to isolate the battery in radiative terms. Figure 4 shows the final configuration of the battery cover in SLI and mounted on tray A. In addition, a delrin base is mounted between the battery and the tray A to act as an insulating spacer in the mechanical interface (see Figure 5). By doing so, an independent thermal environment is obtained for the battery. This makes battery's temperature change rates considerably slower, but not null. Then, an active thermal control loop is required to maintain the temperature above 8 ºC.

Such active thermal control circuit consists of four heaters and four thermostats. These circuits are directly connected to the battery and therefore they are independent from the spacecraft's computer. There are two different kind of heaters: two of them are part of the battery, they dissipate 0.9 W each and they are located between the cells and the base, the other two are external. They dissipate 2.2 W each and they are located on the lower side of the battery's base. Figure 5 shows the battery base with the external heaters and the four thermostats. Thermostats fail in close circuit mode, which means heaters would dissipate continuously in case of thermostat failure. To avoid this, each line delivering power to the heaters has two thermostats connected in series. Furthermore, there are two independent lines providing each kind of heater with power, one goes to the internal heaters and the other to the external ones.

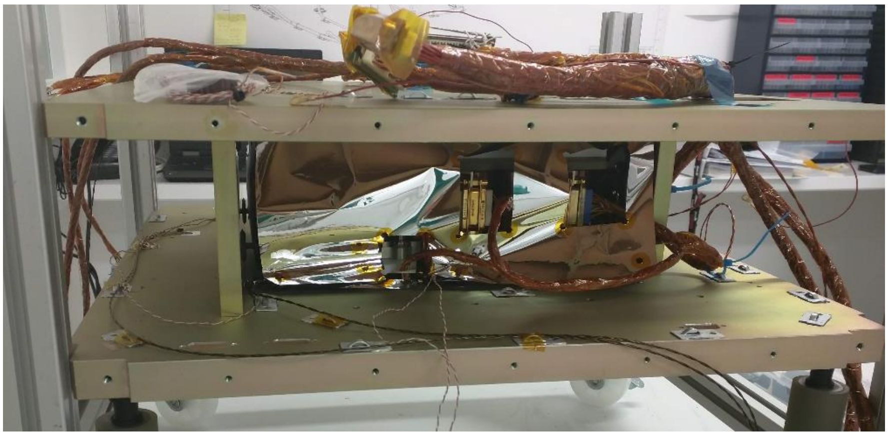

Figure 4: Battery mounted on the spacecraft and wrapped in SLI.

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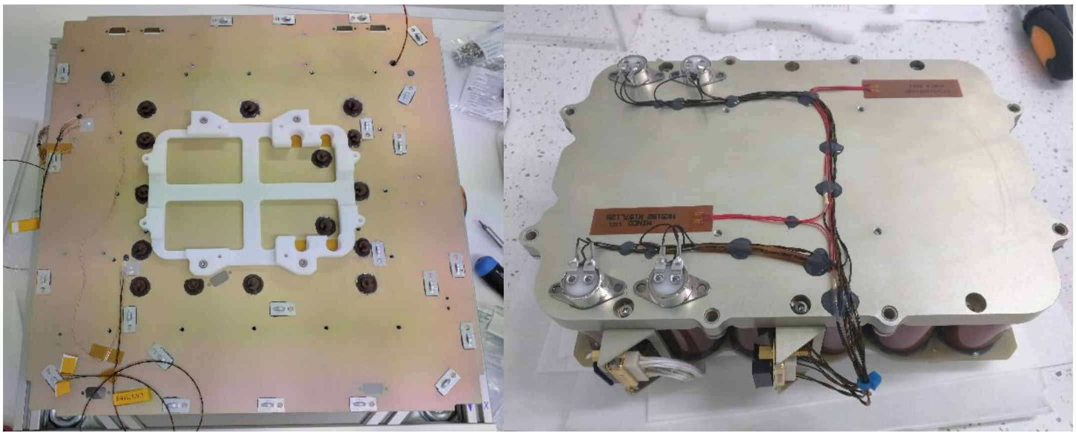

Figure 5: Left: battery delrin insulating spacer. Right: battery base with the thermostats and the external heaters.

3. Thermal testing campaign

Testing of the system to be launched is a key milestone in every space mission [4]. Even though simulation capabilities have increased drastically in the recent past, verification of the numerical predictions through testing is required, and the thermal control subsystem is not an exception. Every spacecraft related to the ESA and following the ECSS overcomes a thermal testing campaign prior to the launch.

Such testing campaign is performed in specific infrastructures called thermal vacuum chambers. These chambers are closed vessels with a series of pumps connected in order to reduce air pressure to vacuum levels and with the capability to be heated or cooled. Such facilities are designed to simulate as closely as possible the thermal environmental conditions the spacecraft is expected to experience in space [5].

Thermal tests are classified in Thermal Cycling Test (TCT), Thermal Vacuum Test (TVT), Thermal Balance Test (TBT) and bake-out according to their objectives [4, 5]. In addition, there are different standards that define the guidelines and basic requirements every thermal test shall accomplish in space missions [1-4]. In the European scenario, the applicable standards are the ECSS [1-3]. They provide the requirements to perform the verification by testing of space segment elements and equipment on ground, as well as the basic characteristics every thermal test shall present.

Indeed, [1] defines the minimum requirements to follow during the thermal tests of space systems. It is stated that the temperature rate of change shall be lower than 20 K per minute. It is also specified that functional tests shall start after a dwell time equal or greater than 2 hours and that there shall be functional tests at the beginning and the end of the test, but also during a hot and cold cycle. It is also specified that there shall be at least five thermal cycles, including one non-operating cycle.

In addition, regarding the temperature margins to apply, the basic margins scheme of space missions is displayed in Figure 6.

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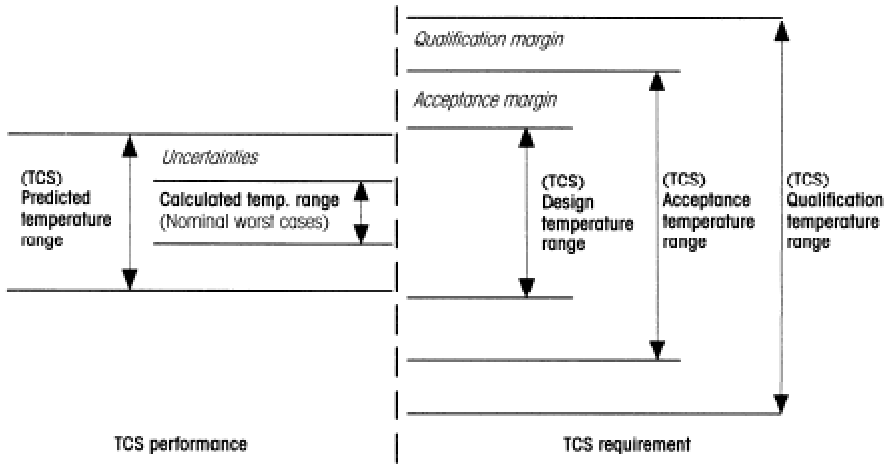

Figure 6: Temperature margin definitions, according to ECSS, for thermal control system (TCS). Image extracted from [3].

Following the guidelines defined by ECSS, the engineering model philosophy was applied. Thus, different models of the critical components were previously tested with qualification margins. In particular, the structural thermal model (STM) of the complete satellite, the battery and the E-box where tested in the thermal vacuum chamber.

The thermal vacuum test here presented corresponds to the acceptance test of the UPMSat-2 FM. Therefore, the objectives were:

- Providing data for the verification of the thermal mathematical model (TMM).
- Verifying the functionality of the UPMSat-2 in vacuum and the defined hot operational and cold operational cases.

3.1 Test setup

The thermal vacuum test of the integrated and operative UPMSat-2 represented a challenging project since the very beginning. As a result, the power, software, AIV (Assembly, Integration and Verification) and thermal engineers worked very closely to find compromise solutions to the different faced issues.

For instance, the satellite's geometrical envelope is a box of 0.5. m x 0.5 m x 0.6 m, but without considering the antennas nor the adapter cone of the separation system. Real envelope of the device under study is 0.5 m x 0.5 m x 0.784 m. Thus, the satellite could not be accommodated in the vacuum chamber vertically over the adapter cone as expected. Consequently, an ancillary bar structure was required in order to accommodate the spacecraft horizontally, without damaging the solar cells on the lateral faces. However, even in the new orientation, there was not a wide margin between the satellite and the chamber's shroud. Furthermore, the satellite is kept in vertical position over its adapter cone, and so the assembly of the ancillary structure had to support the satellite in vertical position while ensuring a safe rotation of the system to orientate it in the thermal test configuration. Final configuration is shown in Figure 7. It can be observed that the satellite lies on four delrin pieces, which are designed to ensure solar cells do not support any weight.

However, the narrow margins were not just a geometrical issue. The distance from the shroud to the antennas was so small they could not transmit. In fact, the energy would not have left the antenna, it would have gone back through the circuitry. Therefore, there was a risk of burning the transmitter or the amplifier. Taking into account that the problem of margins could not be solved, it was decided to omit the transmission functional test inside the chamber. Transmissions were checked in the cleanroom after the thermal test.

Another critical point was the battery. One of the success criteria of the test was checking that the active thermal control of the battery works. Then, during the cold phases of the test, the heaters demand power from the battery. Also all the functional tests carried out used battery's power in order to test the spacecraft's flight configuration. Nevertheless, there is no Sun simulator inside the chamber, and the battery cannot be charged through the solar arrays. Consequently, an electrical interface between the satellite and the outside EGSE(Electrical Ground Support Equipment) was required.

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An external interface was assembled outside of the vacuum chamber. It connected the battery's charging line for ground segment operations with a multimeter to monitor battery's voltage and current intensity, and a power supply unit to charge the battery when required. In addition, a charging procedure was also written, explaining when and how charge the battery during the test.

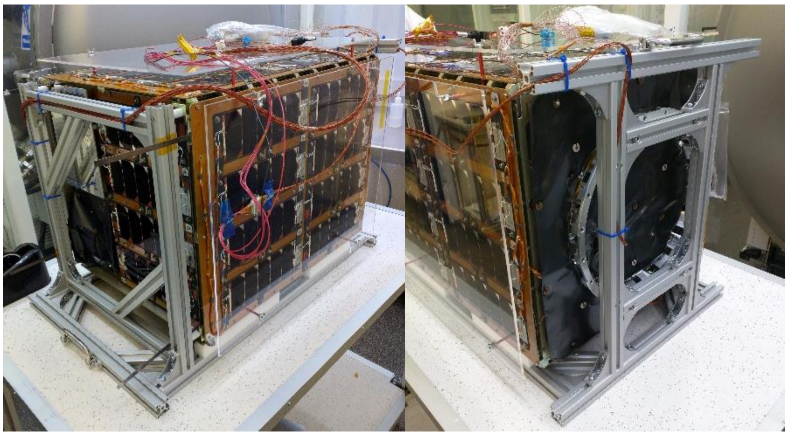

Figure 7: UPMSat-2 ready to be introduced in the thermal vacuum chamber.

From a thermal point of view, since the UPMSat-2 conductive path with the chamber passed through insulating delrin pieces and an auxiliary structure, heat exchange during the test would be mainly radiative. Taking into account the spacecraft is a massive element with a considerable heat capacity and the vacuum chamber availability, the duration of the test became an issue. Therefore, radiative exchange between the chamber and the spacecraft had to be maximized. The chamber's shroud is black painted, but the baseplate is not. Therefore, it was decided to cover the baseplate with kapton in order to rise its infrared emissivity.

Regarding the data acquisition, two interfaces were available:

- The thermal vacuum chamber software. The chamber allows 30 additional thermocouples apart from the internal ones. This means only a maximum of 30 temperatures would be used to monitor the test through the thermal chamber's control software.
- The interface between the satellite and the EGSE allowed the reception of telemetry data, which includes temperatures of the integrated sensors, current intensity and voltage of the on board computer lines (OBC). A software was set up to display such data in a table and in engineering units. Nevertheless, such data were only available when the E-box was operating. Moreover, although the engineer running the test could use these data, it was not available in the chamber's control software. Thus, live control was required.

Finally, the thermocouples were distributed looking for a global vision of the spacecraft's thermal behaviour. This way, additional telemetry data would only be required in the functional tests, during which hot spots and wider thermal gradients were expected. Additionally, four temperature reference points (TRP) were defined, one on each tray. These TRPs would be the control temperatures, and would be the reference to look at when reaching the temperature ranges and stabilization criteria on each cycle. The UPMSat-2 inside the thermal vacuum chamber is shown in Figure 8, in the test configuration and with the thermocouples connected to the chamber's data acquisition ports.

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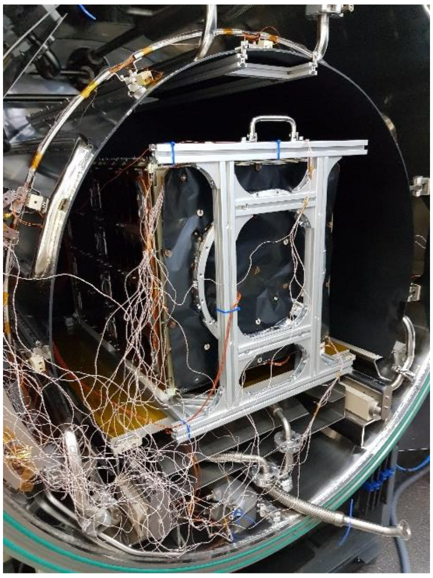

Figure 8: UPMSat-2 inside the thermal vacuum chamber and ready to start the test.

3.2 Test description

Test requirements and tolerances can be found in the procedure. Nevertheless, for the sake of clarity, the main test drivers are specified below:

- The equipment will be tested in a thermal vacuum environment having a pressure of 10^{-5} mbar or less.
- Telemetry data (including power consumption if possible) shall be recorded during the functional tests.
- Power provided to the battery during the whole test shall be recorded.
- Stabilization criteria:
  - In TBT cycles, TRPs must be in range and temperature change rate must be equal or smaller than 1 ºC/h during a dwell time of 2 hours [1].
  - In TCT cycles, TRPs must be in range and temperature change rate must be equal or smaller than 3 ºC/h during a dwell time of 30 min [4].
- The tolerances to be met are:
  - T_{max}: 0 ºC to +3 ºC
  - T_{min}: -3 ºC to 0 ºC
  - Within the temperature range: -17 ºC to +30 ºC.
  - For pressure below $1.3 \cdot 10^{-3}$ mbar 80%

The nominal temperature profile followed by the TRPs during the test is displayed in Figure 9. The different phases and functional tests to perform are also represented:

- ◇ Represents the thermal balance. Power mode 2 (nominal on orbit operating mode) is maintained until stabilization criteria is reached.
- ⊗ Represents start functional test.
- ✩ Represents functional test at maximum power dissipation (TBT_HOT_test on Table 1).

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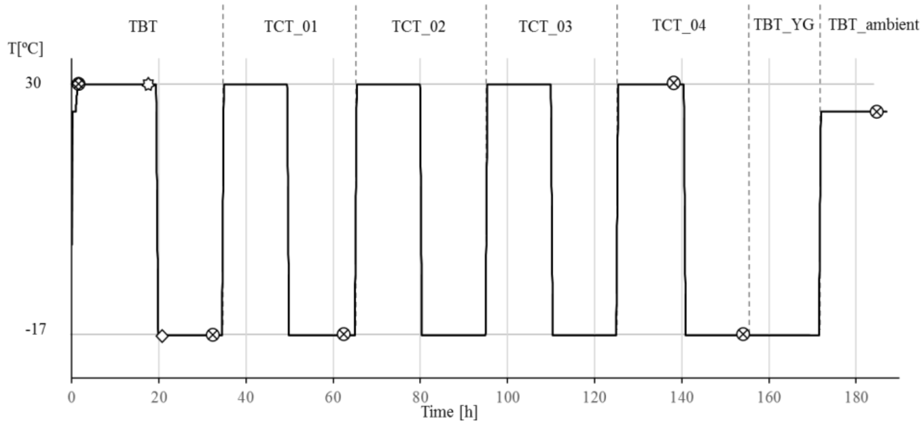

Figure 9: Test profile with the different phases and functional tests identified. Symbols are defined in the text.

The test profile consists of two consecutive thermal balance tests, one hot and one cold, with a maximum power functional test between them. Then 4 thermal cycles are performed. After finishing the regular test, a specific phase named TBT_YG is carried out, in which the spacecraft is turned off and spatial thermal gradients are forced by heating the baseplate to hot thermal balance temperature while maintaining the shroud at cold thermal balance temperature. The aim of this phase is to collect data for the correlation of the thermal properties of the support panels of the solar arrays and their mechanical assembly with the satellite. The temperature ranges TPRs must accomplish during the different phases of the test are displayed in Table 1.

Table 1: Temperature ranges of TRPs during stabilization phase.

Phase	**TBT_HOT**	**TBT_HOT_test**	**TBT_COLD**	**TCT_HOT**	**TCT_COLD**
TRPs Temp [ºC]	27 to 30	25 to 28	-17 to -20	30 to 33	-17 to -20

These temperature ranges were defined considering the orbital temperature predictions of the satellite thermal model. However, there was no solar simulator inside the chamber. Thus, the temperature of the lateral panels, which are the closing panels of the main structure, was taken as the reference. The reason is the lateral panels constitute the main radiative environment for most of the instruments on board of the UPMSat-2. Then, the extreme temperatures reached by the TRPs during the tests are the maximum and minimum temperatures reached by the lateral panels on orbit, plus the simulation and acceptance margins [1].

Test predictions were calculated using the UPMSat-2 TMM built in ESATAN-TMS. A new TMM was built, with the UPMSat-2 inside the thermal vacuum chamber TMM. The conductive interface between the satellite and the baseplate was not geometrically represented, the conductive couplings were hand calculated and introduced in the conductance matrix. The geometrical mathematical model (GMM) used to calculate the test predictions is shown in Figure 10.

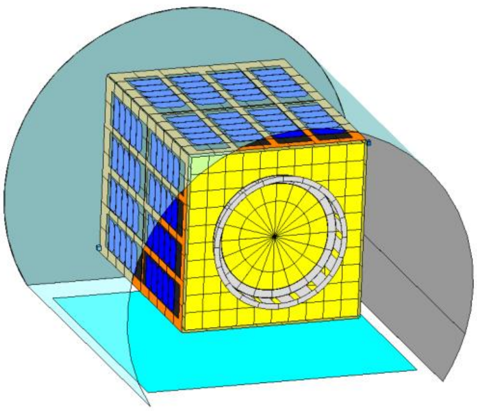

Figure 10: GMM of the UPMSat-2 inside the thermal vacuum chamber.

The expected temperature evolution during the thermal test is displayed in Figure 11. It can be observed that the temperature of the battery does not drop below 8 ºC thanks to the active thermal control circuit.

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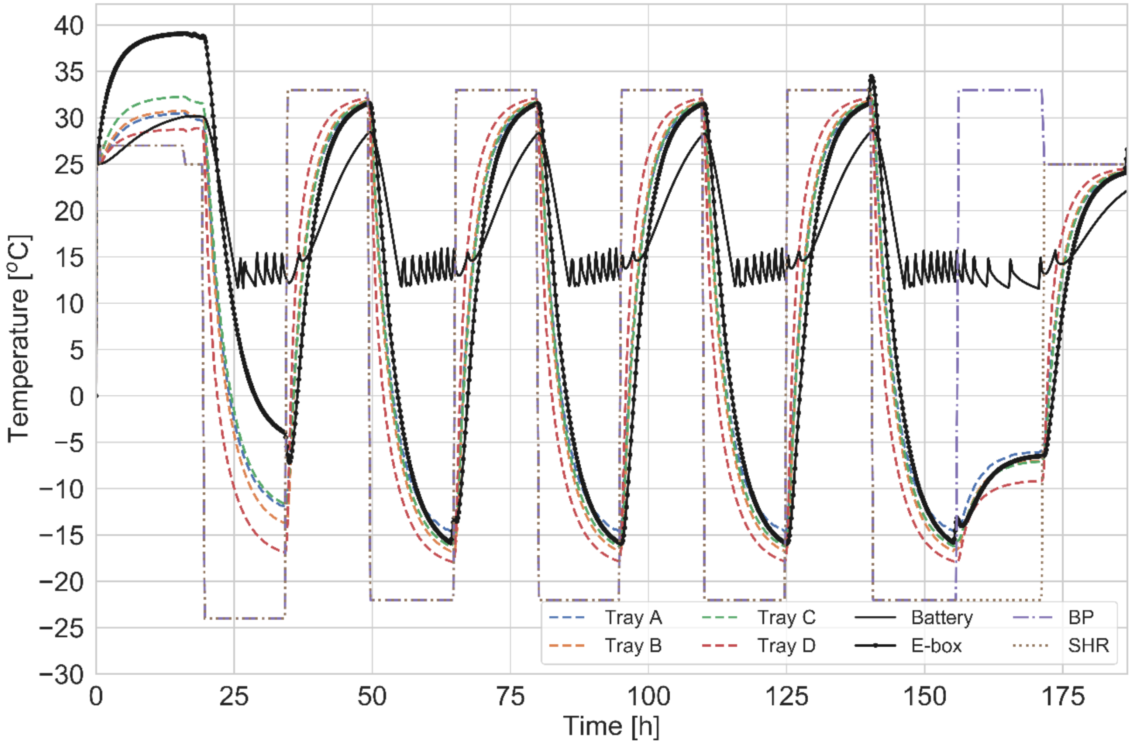

Figure 11: Test temperature prediction. Only temperature of the trays (TRPs), the battery and the E-box are displayed. SHR and BP are the boundary temperatures of the chamber.

3.2 Test results

The most relevant phases of the tests are displayed in Figures 12 to 14. For the sake of clarity, only the temperatures of the TRPs and the thermocouples located on the battery and the E-box have been plotted.

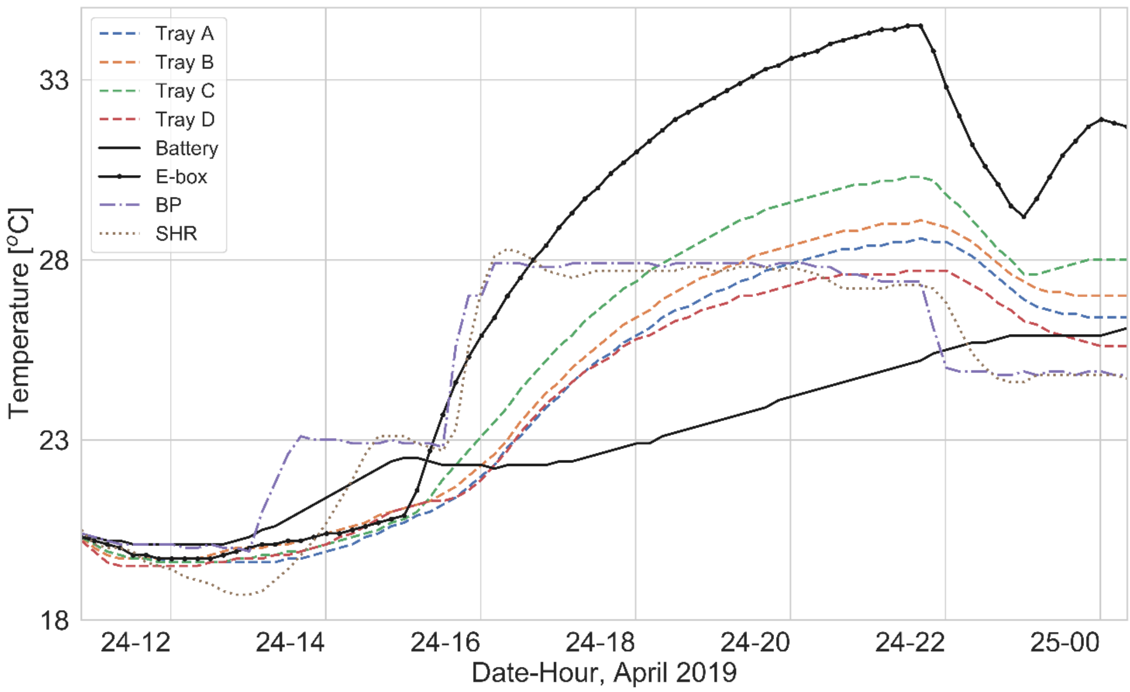

Figure 12: Temperatures measured during the hot thermal balance phase of the test.

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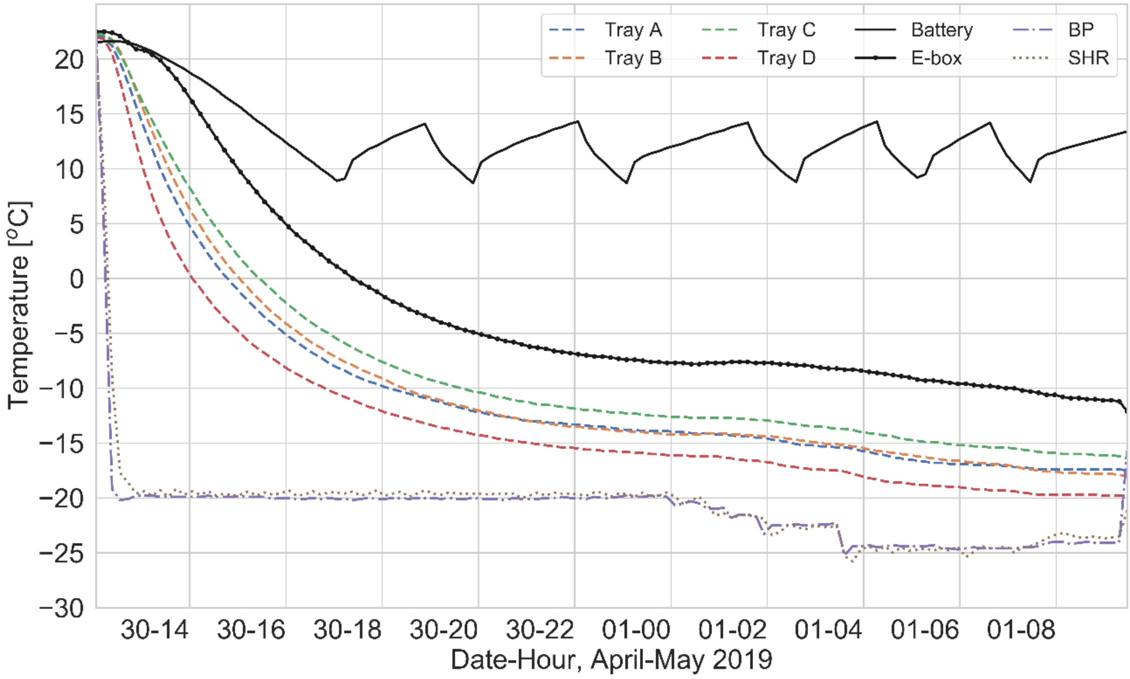

Figure 13: Temperatures measured during the cold thermal balance phase of the test.

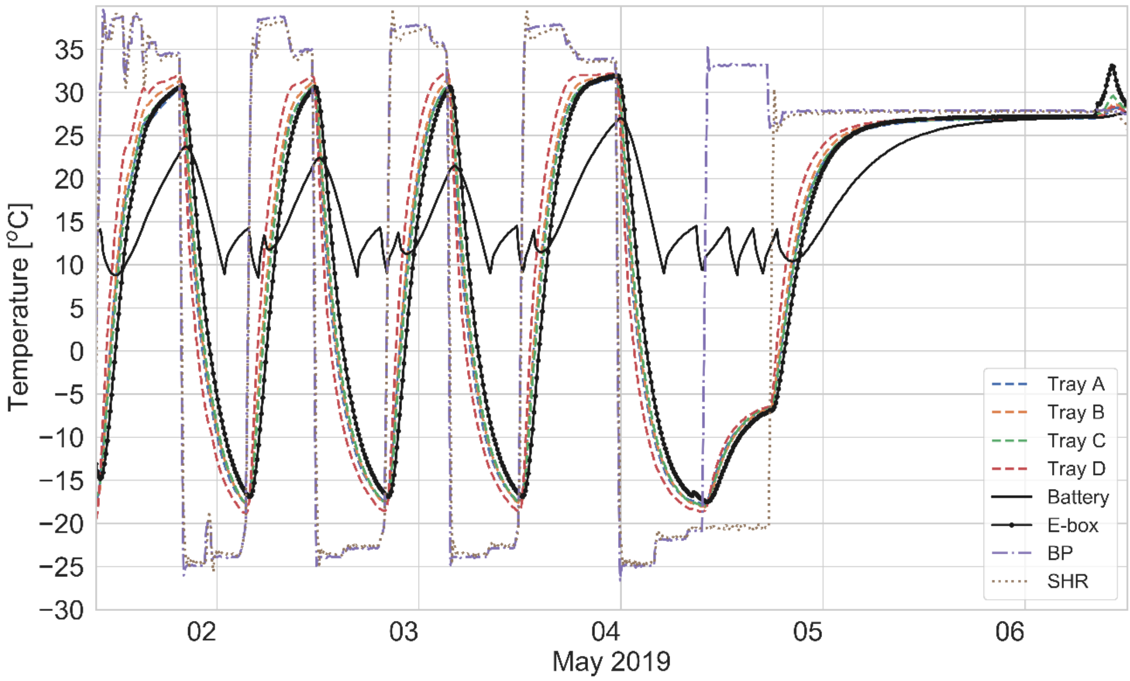

Figure 14: Temperatures measured during the thermal cycling and the YG thermal balance phases of the test.

The test verifies the correct functionality of the UPMSat-2 and all of its components and payloads in vacuum and under defined hot and cold conditions. Furthermore, the temperature of the battery is maintained within its operative range too. When the temperature drops down to 8.5 ºC, the thermostats activate the heaters and the battery is warmed up. Considering the fact that thermostats closing temperature is 10 ºC ± 3 ºC according to the manufacturer, several units were tested in order to choose the most appropriate ones. Therefore, taking into account the evidence, it can be stated the performance of the active thermal control circuit of the battery meets the requirements.

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4. Lessons learnt

The acceptance testing campaign of the UPMSat-2 has been a challenging project in every way. The complexity of testing a complete space system requires good communication and coordination between the different subsystems' engineers. Nevertheless, it has provided the IDR/UPM with priceless experience. Regarding the thermal testing campaign some lessons have been learnt:

First, communication and, in some cases, collaboration between the different experts has been crucial to the success of the testing campaign. The teamwork between thermal, AIV and software engineers made possible the realization of the tasks while meeting the requirements and following a tight calendar.

Software is a critical issue. It is mandatory to make sure every necessity is covered before the test begins. Easy and fast access to data makes a difference. Indeed, the interactive plots displaying thermocouples' temperature, pressure and temperature change rates offer an advantageous position when controlling the cycles. Furthermore, telemetry data tables in engineering units allowed a complete vision of what was happening inside the satellite during the different functional tests. This provides with both evidence of the correct functioning of the system under study and data to seek and correct the potential bugs and anomalous behaviours that may arise during the test.

Definition of clear accesses and protocols for key components. In this case, both electrical and electronic access to the battery were required. As a result, a continuous monitoring of the battery was possible, allowing a certain flexibility in the test execution as the system behaviour was understood, thanks to data of the first phases. In addition, the electronic interface with the OBC, together with the data acquisition software allowed the engineers to access telemetry data via an ordered table in engineering units.

Selection of the thermocouples is the main driver in the test. Even though in this case there was access to telemetry data, thermocouples are the main source. Moreover, in most cases they are the only accessible data during the test. In general terms, the more thermocouples in the system under study the better. Nevertheless, make sure thermocouples collect representative data.

Finally, the main lesson learnt is nothing replaces a motivated and committed team. Unexpected mounting difficulties, software bugs, test delays, etc will certainly arise during the testing campaign. Therefore, committed engineers ready to make things roll even at the expense of certain coffee breaks are a must when schedules tighten.

Acknowledgements

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