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The UPMSat-2 Satellite: An Academic Project within Aerospace Engineering Education

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Abstract

In the present work, the UPMSat-2 satellite project is analyzed as an academic tool to involve different groups of students into a challenging and quite complete space engineering project, encouraging them not only to develop specific skills in relation to a single subsystem of the satellite, but also to harmonize their work with the results from other groups of students working on other different subsystems. The UPMSat-2 satellite has revealed itself as a formidable way to gather students and professors around a common engineering task. Due to its 50-kg size, this spacecraft allows a more complex engineering design, testing, qualifying, and management tasks when compared to nano-satellites such as cubesats. Furthermore, the UPMSat-2 is used as a platform to qualify space technologies for engineering enterprises (Iberespacio, Bartington, SSVB, Tecnobit, Arquimea…). Therefore, students involved in this project are in contact with commercial enterprises from the space sector, this fact being crucial in order to increase their motivation. The different groups of students are mentored by the professors of *Instituto Universitario de Microgravedad "Ignacio Da Riva"* (IDR/UPM Institute). These students mainly coming from two different engineering degrees at *Universidad Politécnica de Madrid* (UPM):

1) Bachelor's Degree in Aerospace Engineering, and
2) Master's Degree in Space Systems (*Máster Universitario en Sistemas Espaciales* - MUSE).

The educational benefits of the UPMSat-2 program in relation to the Master's Degree in Space Systems (MUSE) are thoroughly described in this work, some examples of the projects carried out by the students being also summarized in order to show a full spectrum of its possibilities.

Keywords: Active learning, Project-based learning, Satellite design, Space technology, University-class satellite.

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Introduction

Among the different reasons that drove professors and other academic staff from IDR/UPM Institute to integrate the UPMSat-2 project within the academic activities at *Universidad Politécnica de Madrid* (UPM), one of them should be clearly highlighted: it is the most proper way to teach and train students on space engineering practices. This statement is based on the work carried out at IDR/UPM on space systems engineering, that has produced a quite large number of researchers that were trained in the different branches of this discipline (structural analysis, thermal control, attitude control, measuring systems, testing in low gravity, etc.). Besides, it should be highlighted the solid foundations on space engineering at IDR/UPM, acquired through different and relevant projects carried out in the last decades.

In the following subsections the expertise on space systems at IDR/ UPM is summarized, together with an overview of the Master's Degree in Space Systems (in which the development of the UPMSat-2 satellite is integrated).

Space Engineering Background at IDR/UPM Institute

It is well-know that engineering programs at the university allow a close collaboration between professors and students in a scientific and professional project. For the professors that integrate the IDR/UPM Institute, this has been one of the most important goals during the last decades. Some examples of these projects in space technology and systems are listed below (Pindado et al., 2016):

- The CPLM payload (the acronym stands for Liquid Bridge Behavior under Microgravity experiment, in Spanish), designed and manufactured in the late 90s for the Spanish satellite mission MINISAT-01 (Sanz-Andrés et al., 2001).
- The thermal control of the instrument OSIRIS (Optical, Spectroscopic and Infrared Remote Imaging System) in the Rosetta mission of the European Space Agency (ESA) (Thomas et al., 1998).
- The thermal control of the balloon-borne telescope SUNRISE (Barthol et al., 2011; Pérez-Grande et al., 2009).
- The thermal control subsystem and the structure analysis of the NOMAD payload for the ExoMars mission (Neefs et al., 2015; Patel et al., 2017).
- The thermal control subsystem and the structure analysis of the SO/PHI and EPD payloads for the Solar Orbiter mission (Fernández Rico and Perez-Grande, 2011).

Within the last decade, small-satellite[1] programs at universities are gaining an increasing importance in educational engineering programs related to space technology. Furthermore, it can be said that since the

[1] According to J.R. Wertz small-satellites have a mass of less than 500 kg, with the following sub-classifications pic-sat (0.1-1 kg), nano-sat (1-10 kg), micro-sat (10-100 kg) and mini-sat (100-500 kg) (Straub, 2015).

development of the cube-sat concept, the number of university-class satellites has boosted (Swartwout, 2013). These spacecraft development programs bring together most of the aforementioned educational actions (*i.e.*, PBL, collaboration with industry, and engineering research programs) at the university.

Among the advantages of the satellite programs in space engineering degrees it could be mentioned the following ones:

- They improve the students' background, facilitating job placement after graduating (Kroeker et al., 2014; Voss et al., 2012).
- The students have an immediate feedback on the benefits of their work (Straub et al., 2013).

However, these programs present some drawbacks:

- The development process of the spacecraft is not fully carried out by experienced professionals.
- Testing procedures need to be speed up some times, as these projects (*i.e.*, university-class satellite missions) can't delay the launch.
- It is complicated to harmonize an educational degree with a satellite development program (a master's degree is generally a 2-year degree program whereas a satellite program is run during longer periods).

In any case, the most important issue to keep in mind when developing a university-class satellite mission is that the educational purposes have the priority and must remain above the mission itself (Swartwout and Jayne, 2016).

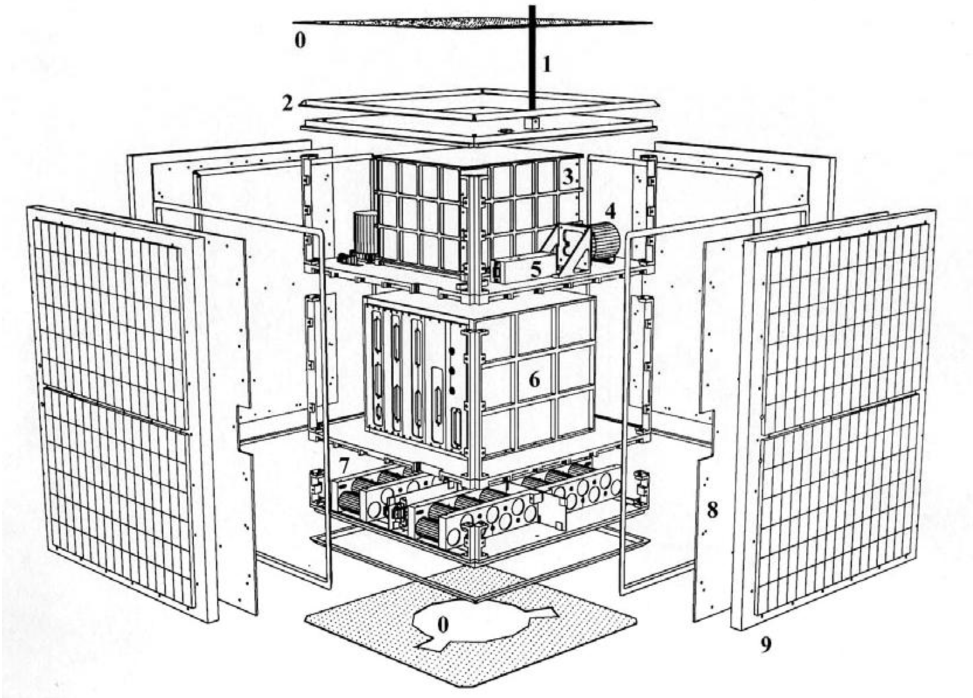
A Relevant Past Achievement: The First University-Class Satellite Developed in Spain. The UPMSat-1 Mission

The UPMSat-1[2] was a 50-kg microsatellite developed under the guidance of Prof. Sanz-Andrés, who is at present the head of the IDR/UPM Institute (Meseguer and Sanz-Andrés, 1998; Sanz-Andrés et al., 2003; Sanz-Andrés and Meseguer, 1996). This satellite was successfully launched in 1995, and represented a joint effort from professors, students and other staff of the Aeronautical Engineering school of UPM (see Figure 1).

According to Swartwout and Jane's work on university-class satellites, UPMSat-1 mission should be classified as Educational and Technological, because it combines both the purpose of training students and the purpose of being a technological demonstration (*i.e.*, space qualification) (Swartwout and Jayne, 2016).

[2] Also known as UPM-Sat 1.

Figure 1. *Sketch of the UPMSat-1: 0- Multilayer Insulation, 1- Antenna, 2- Magnetic Coils, 3- Liquid Bridge Cell, 4- Gyroscopes, 5- Magnetometers, 6- Electronics Box, 7- Batteries, 8- Side Panels, 9- Solar Panels*



A significant number of academic works were carried out in relation to the UPMSat-1 mission:

- 5 Master's Degree thesis concerning:
    - The satellite payloads (liquid bridges, optical sensors…).
    - Orbital analysis.
    - Thermal control.
    - Structural analysis.
- 3 Ph.D. dissertations in relation to:
    - Accelerometers calibration on microgravity[3].
    - Thermal behavior of batteries for space missions[4].
    - Thermal contact conductance[5].

Besides, this project produced a successful collaboration between the Aerospace Engineering school[6] and the Telecommunications Engineering school[7] of *Universidad Politécnica de Madrid* (UPM), in order to develop the on-board computer of the satellite.

[3] This Ph.D. dissertation, carried out by Julian Santiago Prowald, has more than 17000 downloads (1300 downloads within the last year) from the open-access repository of *Universidad Politécnica de Madrid* (UPM). Available at: http://oa.upm.es/368/.
[4] Ph.D. dissertation by Elvira González Folgar.
[5] Ph.D. dissertation by Isabel Pérez Grande. This Ph.D. dissertation has more than 7950 downloads (350 downloads within the last year) from the open-access repository of *Universidad Politécnica de Madrid* (UPM). Available at: http://oa.upm.es/370/.
[6] *Escuela Técnica Superior de Ingenieros Aeronáuticos* (ETSIA).
[7] *Escuela Técnica Superior de Ingenieros de Telecomunicación* (ETSIT).

Julián Santiago Prowald, head of the Structures Section of the European Space Agency (ESA), who was one of the students involved in the early 90s in this project, has said in relation to this satellite program:

> "The UPMSat-1 was the first 100% Spanish satellite, that is, fully designed, developed and built in Spain. This was an amazing engineering challenge carried out by professors and students of *Universidad Politécnica de Madrid* (UPM), under the supervision of Prof. Meseguer and Prof. Sanz. Thanks to this project, an academic, technical, and scientific line was developed among the other projects related to space technology carried out by the group of professors that later founded the IDR/UPM Institute"

Unfortunately, the UPMSat program had to be slowed down for almost 15 years as all resources from the group of professors that lead that project were focused on the IDR/UPM Institute foundation[8], and on space engineering projects in collaboration with the European Space Agency (ESA).

The Master's Degree in Space Systems of the Polytechnic University of Madrid (MUSE)

The Master's degree in Space Systems of *Universidad Politécnica de Madrid* (MUSE[9]) is a recent program that inherits the almost 50-year tradition in space projects carried out by the staff of IDR/UPM Institute (Pindado et al., 2016).

This is a 2-year degree with a huge academic load based on multidisciplinary education and Project Based Learning (PBL). This way to understand education on engineering has revealed as a key factor in the academic institutions along the past decades, as students who took multidisciplinary studies "produced an engineering solution that was better than that of their monodisciplinary contemporaries as measured by external industry professionals" (Hotaling et al., 2012).

[8] The IDR/UPM Institute (*Instituto Universitario de Microgravedad "Ignacio Da Riva"*) was established as a research institution inside *Universidad Politécnica de Madrid* in 1998.
[9] *Máster Universitario en Sistemas Espaciales*. http://muse.idr.upm.es/.

Table 1. *Subjects Included in the Master in Space Systems (MUSE) of Polytechnic University of Madrid, Classified by Type of Learning*

Type of learning	ECTS (total)	Subject	ECTS
M	54	Advanced mathematics 1	6.0
		Advanced mathematics 2	6.0
		High speed aerodynamics and atmospheric reentry phenomena	4.5
		Vibrations and aeroacoustics	4.5
		Quality assurance	4.5
		Space industry and institutions seminars	1.5
		Production technologies	4.5
		Space integration and testing	4.5
		Spacecraft propulsion and launchers	4.5
		Orbital dynamics and attitude control	4.5
		Communications	4.5
		Data housekeeping	4.5
M+PBL	34.5	Graphic design for aerospace engineering	4.5
		Space environment and mission analysis	4.5
		Heat transfer and thermal control	6.0
		Power subsystems	4.5
		Space structures	4.5
		Space materials	4.5
		Systems engineering and project management	6.0
PBL	31.5	Case Study 1	3.0
		Case Study 2	7.5
		Case Study 3	6.0
		Final Project	15.0

M – mono-disciplinary learning subject; M+PBL – mono-disciplinary learning subject with some load carried out by Project Based Learning; PBL – Project Based Learning subject

Besides, the importance of training on space systems and procedures with regard to space engineering degrees has been also highlighted (Jazebizadeh et al., 2010). In an engineering degree, this training can only be achieved by PBL, collaboration with industries, or by engineering/scientific programs carried out inside the academic institution. On the one hand, PBL emerges in engineering degrees as the best way to harmonize the academic requirements and the needs from industry (Brodeur et al., 2002). On the other hand, collaboration with the industry and mentorship is required to meet the last standards in relation to hardware and technical procedures, interact with professionals, and create links for the future professional careers (Voss et al., 2012).

In Table 1 the subjects of this Master's degree are classified in three categories: mono-disciplinary learning (M); mono-disciplinary learning with some academic load carried out by PBL (M+PBL); and pure PBL subjects (PBL). The academic load in terms of ECTS[10] is also indicated. As it can be observed in the aforementioned Table 1, Project Based Learning is present in more than 50% of the Master's degree academic load.

[10] European Credit Transfer and Accumulation System.

It is already a contrasted fact that this Master in Space Systems is earning good reputation among the Spanish space fairing and engineering companies. At present, the first two classes from MUSE have graduated (Class of 2016 and Class of 2017), with successful performance in terms of recruitment by the space engineering sector:

- Class of 2016. All graduated students working in engineering companies/research institutions such as the European Organization for Nuclear Research (CERN[11]), INTA[12], CRISA[13] or IDR/UPM. Two of these students are currently carrying out their Ph.D. under the supervision of professors from IDR/UPM.
- Class of 2017. All graduated students are working in companies such as CRISA, GMV[14], Karten Space[15], Bercella Composite Materials[16], INDRA[17], GAMESA[18], and INABENSA-ABENGOA[19], or carrying out their Ph.D.

Since the first academic year (2014-2015) the students of MUSE have been involved in projects related to the UPMSat-2 mission, this project being a success in terms of student motivation. Besides, as the professors of the IDR/UPM Institute are also integrated in degree programs different from the Master in Space Systems (the Bachelor's and Master's Degrees in Aerospace Engineering, for example), students from these other programs had (and have, currently) the opportunity to carry out some academic work related to the UPMSat-2.

Aim and Structure of the Present Work

The aim of the present work is to demonstrate, using the UPMSat-2 mission as case study, the academic benefits of a satellite program when it is coordinated with academic programs in space engineering.

In Section "The UPMSat-2 Satellite" of the present work, the UPMSat-2 mission is summarized together with the goals achieved in the aerospace engineering programs at *Universidad Politécnica de Madrid* (UPM), before its integration as an educational platform within the Master in Space Systems (MUSE). This integration of the UPMSat-2 mission in the MUSE program is thoroughly described in Section "The UPMSat-2 Satellite as an Educational Platform in a Master's Degree". Additionally, some of the projects carried out by MUSE students in the past two years are shown in

[11] *Conseil Européen pour la Recherche Nucléaire*. https://home.cern/.
[12] National Institute of Aerospace Technology "Esteban Terradas" (INTA). Spanish National Aerospace Research Agency. www.inta.es/.
[13] *Computadoras, Redes e Ingeniería, S.A.U*, Spanish company fully integrated into Airbus Defense and Space. http://www.crisa.es.
[14] https://www.gmv.com/en.
[15] http://kartenspace.com.
[16] https://bercella.it/.
[17] https://www.indracompany.com.
[18] http://www.gamesacorp.com/es.
[19] http://www.inabensa.com.

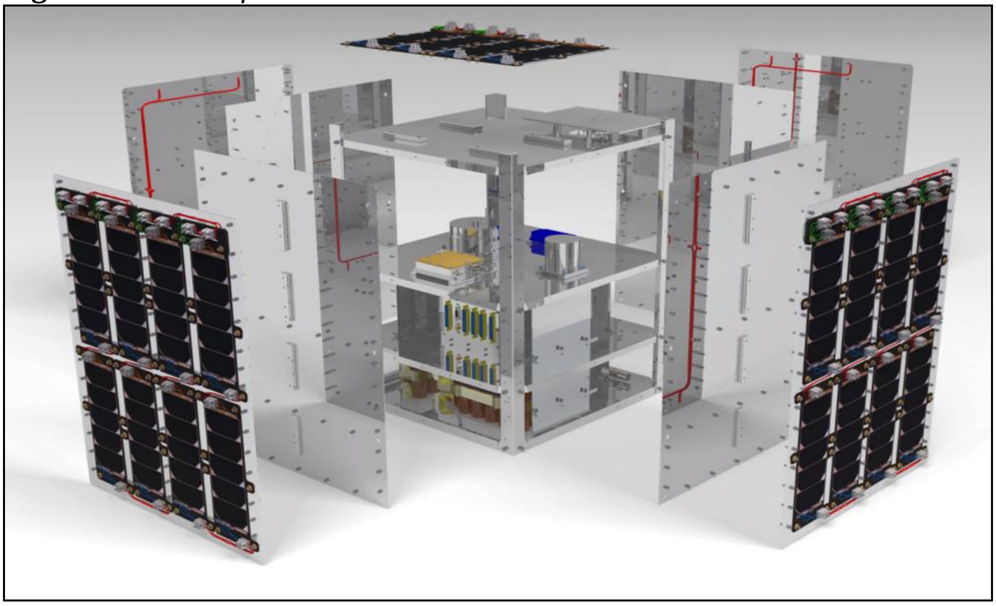
this section as an example of the possibilities of the aforementioned integration. Finally, conclusions are summarized in the “Conclusions” Section.

The UPMSat-2 Satellite

The UPMSat-2 is a 50-kg university-class satellite (see Figure 2). This is a long-term project that started in 2009. In Table 2 some characteristics of this mission are summarized. UPMSat-2 mission was initially planned as a challenge for the IDR/UPM staff in order to continue with the satellite program initiated with UPMSat-1.

During the first part of this project, from 2009 to 2013, a first engineering and flight model was produced. After the delay of the initially planned launch[20], a new model has been produced, involving students from the Master in Space Systems (MUSE) in the project. The mission has suffered a second delay in relation to the launch, the most probable date being by the end of 2018 or beginning of 2019.

Figure 2. *Sketch of the UPMSat-2*



It should be also mentioned that the UPMSat-2 mission represents the framework for a successful collaboration between many partners. Among them, it should be mentioned:

- The IDR/UPM Institute, as the leader of the project.
- The STRAST research group of *the Polytechnic University of Madrid*. Responsible of developing the UPMSat-2 on-board and ground control station software.
- TECNOBIT, as the E-BOX developer (see Table 2), together with IDR/UPM and STRAST.

[20] The UPMSat-2 is planned to be launched as secondary payload in an Earth observation satellite launch.

- EADS CASA Espacio. Company that has greatly supported the design and construction of the electrical and communication wire harness of the satellite.
- INTA[21], that has provided a capital support in relation to the ground control station development and testing.
- SAFT batteries. Company that supplied the battery of the satellite and gives support in relation to ground and pre-launch maintenance.
- CT Ingenieros[22], that has given the IDR/UPM students access to their software Phenicia, in order to ease the harness development.

DHV Technology[23]. Company that has followed the UPMSat-2 program with great interest, being a solar cells/panels supplier in future IDR/UPM satellite programs.

Table 2. *Outline of the UPMSat-2 Mission*

Mission Life	2-year
Orbit	Sun-synchronous: • Noon • Altitude: 600 km • Period: 5828 s
Mass	50 kg
Dimensions	0.5 m × 0.5 m × 0.6 m
Attitude Control	Magnetic: • SSBV[24] magnetometers • ZARM Technik AG[25] magnetorquers • Control law designed by IDR/UPM (Cubas et al., 2015)
Thermal Control	Passive
Power	Based on solar photovoltaic panels and batteries: • 5 body-mounted solar panels (Selex Galileo SPVS-5 modules with Azur Space 3G28C triple junction solar cells) • Li-ion battery designed by SAFT[26] • Direct Energy Transfer (DET)
On board electronic box (E-BOX)	Based on FPGA (designed by Tecnobit S.L.[27] and programmed by STRAST/UPM[28]). Includes: • On-board computer • Data handling • Power supply control • Power supply distribution
Communications	• Link at 436 Mhz frequency

[21] National Institute of Aerospace Technology "Esteban Terradas" (INTA). Spanish National Aerospace Research Agency.
[22] http://www.ctingenieros.es.
[23] https://dhvtechnology.com/.
[24] http://www.ssbv.com/.
[25] http://www.zarm-technik.de/.
[26] https://www.saftbatteries.com/.
[27] http://grupooesia.com/avionica/.
[28] http://www.dit.upm.es/~str/.

	• 4 monopole antennae system • EMXYS[29] communication card installed in the E-BOX • Ground station software programmed by STRAST, hardware configuration supervised by INTA
Payloads	• Bartington magnetometer • SSBV rotation wheel • Iberespacio thermal microswitch • Solar sensors • Tecnobit on-board computer (E-BOX)

In relation to the educational aspects of this project, two different paths have being explored:

- On the one hand, the professors involved in the project have offered (mainly from 2009 to 2014) some lines of work as a part of their duties as university professors, these work load being mostly carried out through final year degree projects in the Aerospace Engineering Bachelor's degrees and doctoral studies.
- On the other hand, since 2014 and once the Master in Space Systems (MUSE) was organized, the UPMSat-2 became the perfect platform to train the students of this master in space technical requirements at professional level, taking into account that the main objective of their work is a real mission.

Projects Related to the UPMSat-2 Satellite in Aerospace Engineering Bachelor's Degree

As previously mentioned, several final year degree projects related to the UPMSat-2 development have been carried out[30]. Besides, it should also be pointed out that the academic programs at the Aerospace Engineering school of *Universidad Politécnica de Madrid* (UPM) allow the students to do some training in engineering companies as part of the academic load. Even more, the work carried out by the students during these training periods can be linked to their final year degree project, increasing its academic benefits.

Until now, approximately 30 final year project works have been developed in aspects related to the UPMSat-2 mission, these works being mainly focused on:

- Mission analysis[31].
- Integration, verification and quality assessment. These works included documentation development, and tests planning and verification procedures.
- Requirements definition, structural analysis (MSC Nastran) and optimization of the different parts (pillars, trays, panels…).

[29] http://www.emxys.com/.
[30] Some of these works are included in: http://bit.ly/2mYSmdR.
[31] See: http://oa.upm.es/32350/; http://oa.upm.es/37269/; & http://oa.upm.es/37267/.

- Attitude control definition, requirements, and analysis of different solutions.
- Power sub-system requirements, sizing, and predesign (including space-qualified parts selection)[32].
- On-board computer software definition, testing and documentation following ECSS E40/E80/Q80 standards. This particular line of research is carried out by STRAST group (De La Puente et al., 2015).

Doctoral Studies Related to UPMSat-2 Mission

Doctoral studies and programs towards the more qualified Ph.D. graduates are a key factor in academic satellite programs. These high profile students can share their research with other students from bachelor's and master's degrees. Furthermore, they are also and important asset for the program in relation to companies from the space sector, taking into account that these companies are normally interested in hiring the most trained personnel.

At present[33], three Ph.D. dissertations have been successfully carried out at the IDR/UPM Institute, directly related the UPMSat-2 project:

- Multidisciplinary Design Optimization Application to Conceptual Design of University-class Microsatellite Projects[34], by Dr. Ravanbakhsh, who works at present at the Department of Extraterrestrial Physics of the *Christian-Albrechts-Universität zu Kiel* (Germany).
- Magnetic Attitude Control System for a Small Satellite. Impact on the Thermal Performance[35], by Dr. Farrahi, who currently works at the Centre for Automation and Robotics (CAR) CSIC-UPM[36].
- Analytical models for the power subsystem and the attitude control subsystem of a microsatellite[37], by Prof. Cubas, from *Universidad Politécnica de Madrid* (UPM).

Besides, seven more Ph.D. students are currently working in several research lines associated to the UPMSat-2 mission at the IDR/UPM Institute. These research lines are associated to space instruments testing procedures and thermal analysis.

Finally, it should be also mentioned STRAST research group, as some of their Ph.D. students are developing lines to complete their dissertations on real-time systems (De La Puente et al., 2011).

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[32] See: http://oa.upm.es/32348/; http://oa.upm.es/32599/; http://oa.upm.es/32598/; & http://oa.upm.es/32568/.
[33] April, 2017.
[34] http://oa.upm.es/32215/.
[35] http://oa.upm.es/37207/.
[36] https://www.car.upm-csic.es/.
[37] http://oa.upm.es/39063/.

The UPMSat-2 Satellite as an Educational Platform in a Master's Degree

Since 2014, the UPMSat-2 project has proven to be a very good educational tool for the Master in Space Technology (MUSE) of *Universidad Politécnica de Madrid*. As mentioned, there are several subjects in which such a project represents the perfect framework for Project Based Learning (PBL) in relation to a specific aspect of the subject, as this specific aspect might be better understood by the practical training involved in a project. In the first part of this section, several examples regarding this kind of subjects are shown.

After that, some of the projects carried out in the subjects devoted to PBL (Case Study I, II and III, and Final Degree Project) are described as an example of the educational possibilities of the UPMSat-2 mission.

Examples of PBL as Educational Tool within MUSE Subjects

<u>Power Subsystems</u>

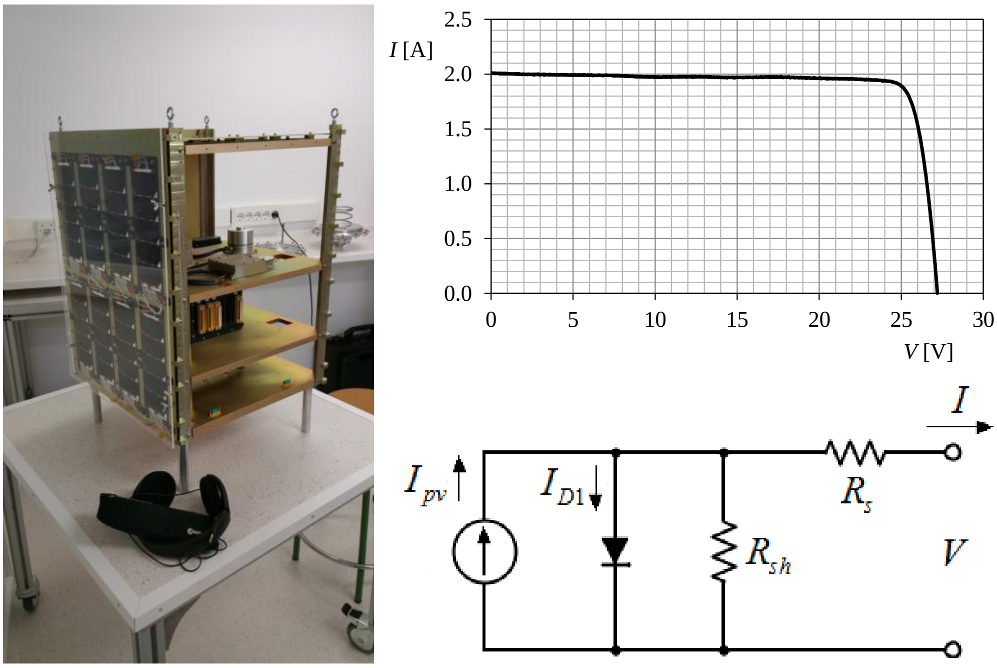
This is a 4.5 ECTS subject taught during the second semester of the Master's first year. Apart from lessons on elements of spacecraft power subsystems, predesign of a simple power subsystem, primary and secondary energy sources, power distribution (DC-DC converters, harness...) and power subsystem integration, students have to analyze the UPMSat-2 mission from the power subsystem point of view. This study is organized in 4 simulations carried out using Matlab-Simulink:

- 1st simulation: Analysis of the UPMSat-2 solar panel behavior. One of the solar panels is analyzed through its equivalent circuit model taking into account different temperatures and solar radiation angle with respect to the panel's surface (in Figure 3 a picture of the UPMSat-2 in which one of the solar panels is shown, together with its measured voltage-current performance curve, and the circuit model that –once fitted to the testing results– can simulate its behavior).
- 2nd simulation: Modeling the behavior of a 18 A·h Li-ion battery based on data from charging and discharging cycles performed to a real battery.
- 3rd simulation: Analysis of the power distribution (power and currents) through the UPMSat-2 taking into account its power consumption along one day and the efficiency of the DC-DC converters.
- 4th simulation (simulation of the UPMSat-2 mission): Analysis of the UPMSat-2 power subsystem behavior using the Simulink algorithms developed in the previous simulations. Specific questions to be answered from the simulation:

    - Is it possible to complete the mission (that is, to carry out one cycle of experiments, testing all payloads)?

- How many cycles of experiments can be performed during the mission?
- What is the largest battery depth of discharge level? Does the UPMSat-2 reach low battery or critical battery levels[38]?
- Failure analysis. The mission under the following failure cases is also studied:
    - Failure on one solar panel.
    - Failure on two solar panels.
    - Failure on half of the battery cells series (battery capacity is at 50%).
    - Failure on both one solar panel and half of the battery cells series.

Figure 3. (Left) *UPMSat-2 at Integration Process* (Top-Right) *UPMSat-2 Solar Panels Power Performance (i.e., I-V curve), at AM 0 Irradiance* (Bottom-Right) *1-Diode/2-Resistor Equivalent Circuit Model for Solar Cell/Panel Simulation*



In addition, another multidisciplinary project is carried out by the students of the Power Subsystems subject: Electrical harness design and manufacturing. When a new space product is being manufactured, the key points to be taken into account are related to functionality, mission specifications & requirements, and cost. To ensure the proper operation of any kind of space instrumentation (or even the entire spacecraft), the harness design and manufacture requires special attention. Furthermore, it

[38] Three different situations are considered for the power subsystem: 1) Normal battery level: mission is run as expected; 2) Low battery level: experiments are immediately stop and payloads are turned off; 3) Critical battery level: all systems including on-board computer are switched off during 5 hours, waiting the battery to be charged (the UPMSat-2 power subsystem is Direct Energy Transfer design).

can be said that an incorrect harness design might have negative effects in terms of spacecraft performance and, therefore, in terms of the project cost.

This project combines the present subject with Graphic Design for Aerospace Engineering (GDAE), which is taught in the semester before. In GDAE students learn to define the required connectors and connection points and the geometrical bundles, which will behave as a space reservation for the wiring they will contain, whereas in Power Subsystems students are focused on the wiring definition to provide electrical behavior for the geometrical bundles.

The harnessing project is scheduled as follows. Firstly, a harness-problem is proposed in a platform similar to the UPMSat-2. From these conditions the students create their harness design using Computer-Aided Design (CAD) (see Figures 4 and 5). Then, they plot the isometric and flattening drawings in order to manufacture the harness, all this manufacturing process (cutting and stripping cables, pin crimping…) being carried out in accordance with the established standards of aerospace industry.

Figure 4. *Computer-Aided Design (CAD) Drawing of the Harnessing Project at the Power Subsystems Subject of the Master in Space Systems (MUSE)*

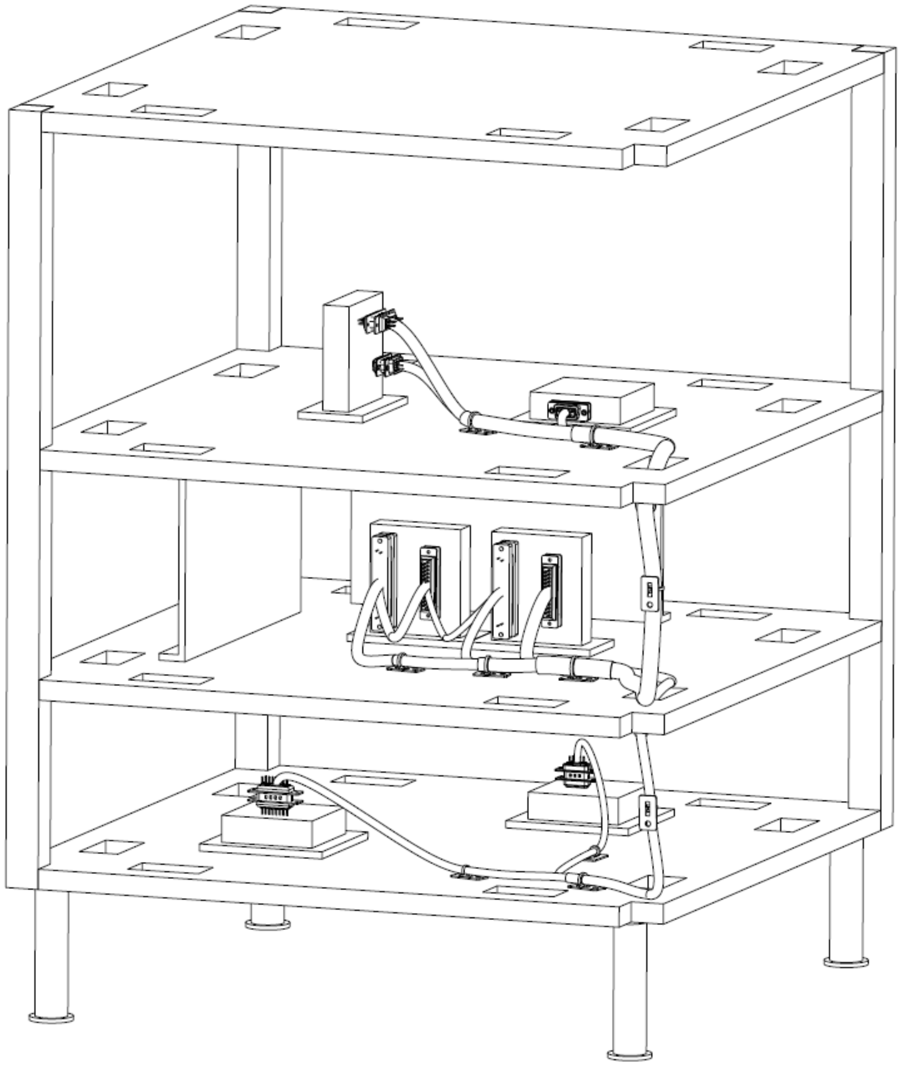
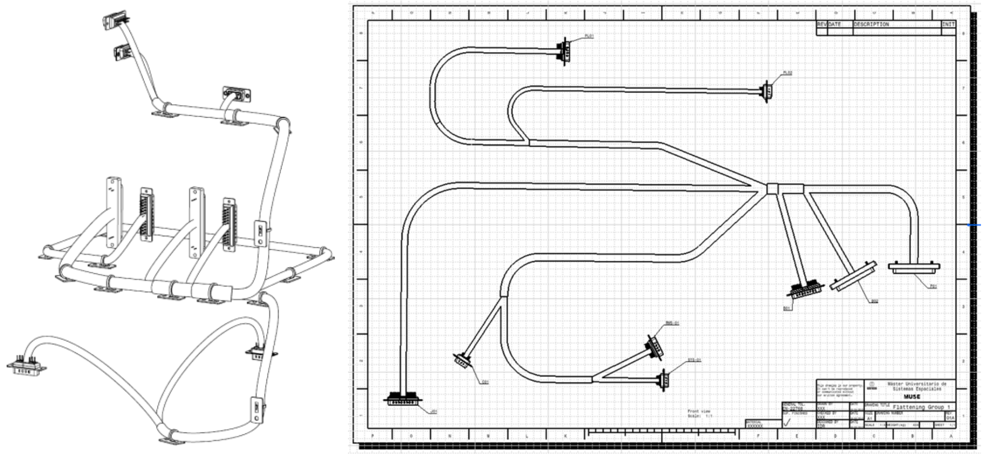


Figure 5. *Manufacturing Drawings of the Harness Design Project of Power Subsystems (MUSE)*



Space Environment and Mission Analysis

The aim of this subject is to introduce the students to the environment in which spacecraft operates, and the general aspects of space missions. Additionally, some specific missions are more thoroughly described.

In this subject, the students are trained in the use of different simulation tools such as:

- General Mission Analysis Tool (GMAT) and
- Systems Tool Kit (STK),

to study the problems related to orbits and orbital maneuver that are involved in a space mission. In addition, it should be mentioned that students that pass this subject obtain the STK-certification Level 1.

Leaving aside the lessons programmed, a practical exercise is proposed to the students. The UPMSat-2 mission has been analyzed by the students as part of the academic content of the subject. Within this project, the students are required to solve different problems related to launching trajectories, orbit's decay, access time windows, etc.

Space Materials

This subject is focused on the most characteristic materials for space applications:

- metallic alloys (based on aluminum, magnesium, beryllium and titanium), and
- composite materials.

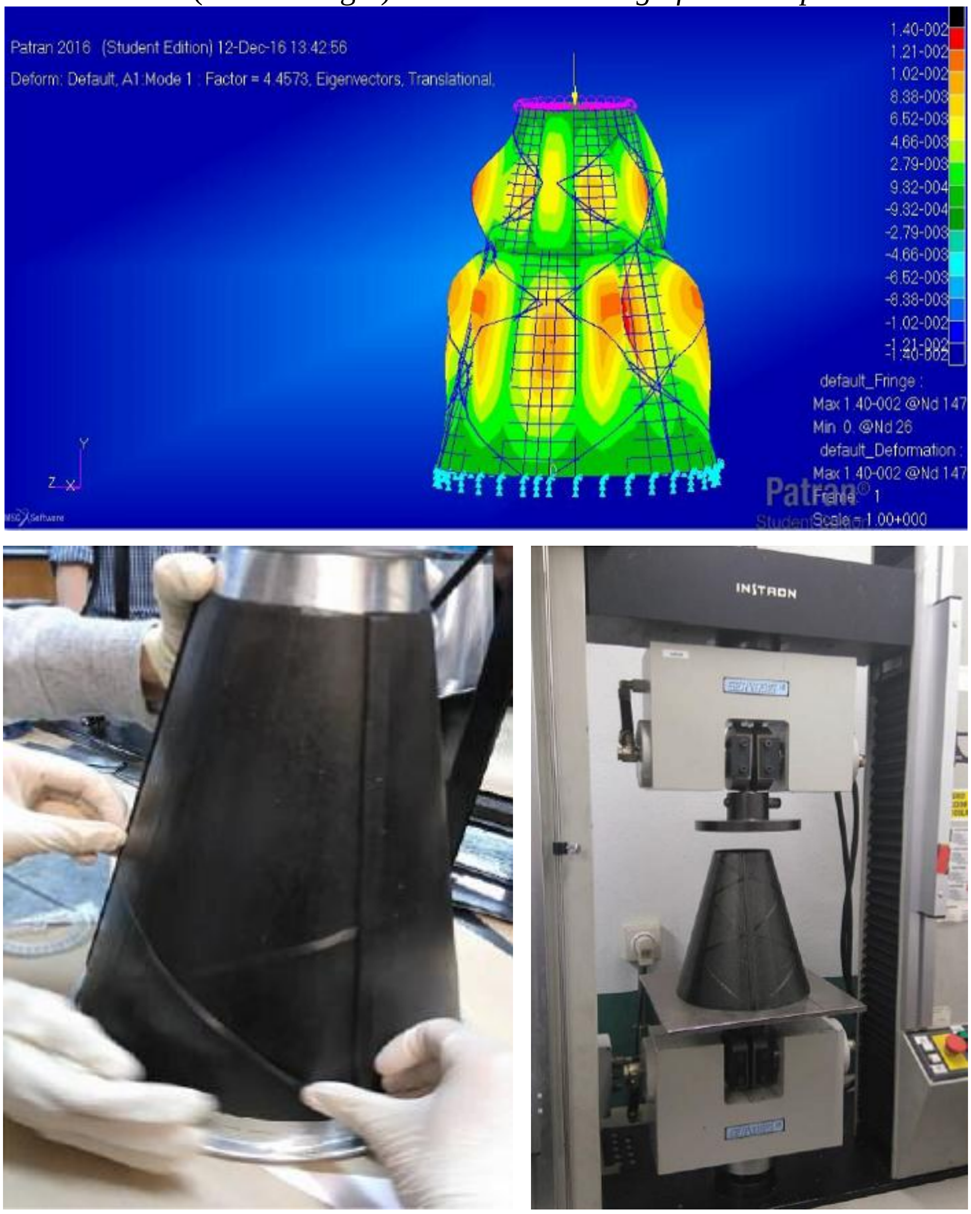
In addition, it should be pointed out that the educational approach of this subject is mostly practical, as it is focused on a high technology sector such as the space industry.

Metallic materials for space applications are studied from a theoretical point of view. During the theoretical lessons the fundamentals of the different metallic alloys used for the aforementioned space applications are introduced, as well as ESA methodologies for materials, their selection, and their standards. Afterwards, students are required to analyze different applied cases: high temperature for space launchers, manufacturing in space environment, high vacuum characterization, etc.

In contrast, the composite materials learning approach is mostly practical, and is carried out by the complete development of a representative aerospace structure made of composite materials. This project comprises the following tasks:

- In a first step, every student designs a Finite Element Method (FEM) model using NASTRAN/PATRAN® of the aerospace structure made with composite materials in order to fulfill some design specifications (maximum deformation, failure analysis, dynamic behavior…).
- Afterwards, the students are organized in groups in order to develop all the manufacturing specifications and sketches. Following this specifications, the composite structures are manufactured by the students themselves using materials and equipment similar to the ones used in the aerospace industry.
- The last step is a mechanical test in order to verify the FEM Model (all this process, from the NASTRAN/PATRAN® calculations, to the manufacturing process, and the final mechanical testing in shown in Figure 6).

Figure 6. (Top) *Finite Element Method (FEM) Analysis of a Spacecraft Component Designed by Students in the Subject Space Materials* (Bottom-Left) *Manufacturing of the Component with Composite Materials.* (Bottom-Right) *Mechanical Testing of the Component*



Case Study I, II and III, and Final Degree Project

As it is clear from Table 1, the core, in terms of academic load, of the Project Based Learning in the Master of Space Systems (MUSE) is carried out by the students in the subjects Case Study I, II and III, and Final Degree Project. However, it should be pointed out the differences between these subjects. Case Study I is a 90-hour[39] practical exercise that students can be carried out in groups from 2 to 4 people, whereas Case Study II and Case Study III are 225- and 180-hour[40] are projects carried out by groups of 2

[39] Academic load per individual student.
[40] Academic load per individual student.

people (although individual projects are also allowed). The Final Degree Project is a 450-hour engineering project that has to be carried out individually by the students (groups of 2 students are allowed in special cases).

Taking into account the work load related to any spacecraft subsystem development, the proposed projects sometimes cover both Case Study III and Final Degree Project (and sometimes Case Study II is added).

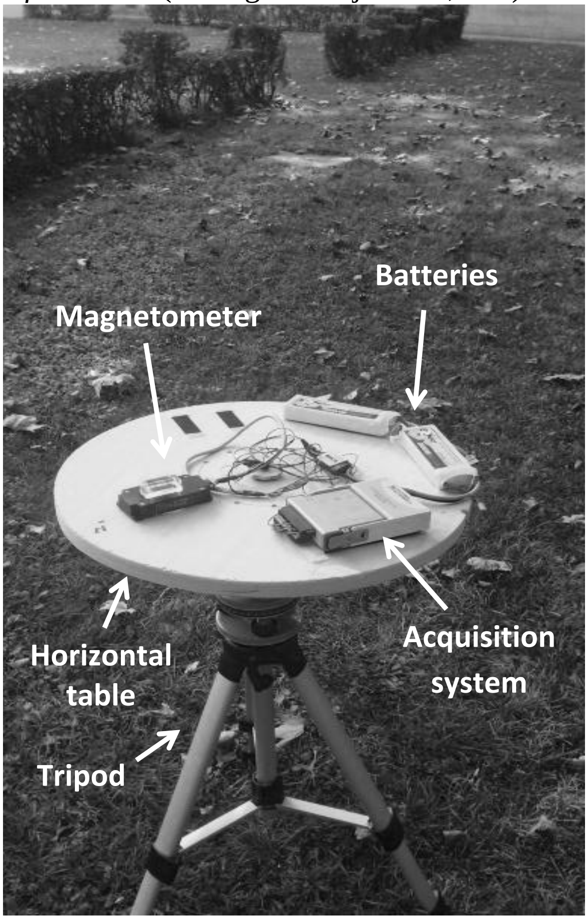
It should be pointed out that although Case Study I could be considered a too short project in terms of academic load, its importance is key from the educational point of view. It allows the students to identify their own skills and limitations, and also to face an industrial engineering challenge. Besides, this subject allows the academic staff of the Master in Space Systems (MUSE) to better understand the capabilities of each student, this knowledge being crucial in order to design the correct work load for each student within Case Study II, Case Study III and the Final Degree Project.

Since 2015 several projects covering different aspects of the UPMSat-2 mission (subsystems, payloads…) have been carried out by the students of the Master in Space Systems (MUSE) as Case Study I, II, or III, or Final Degree Project. Among them, the following ones could be mentioned:

- Development of the UPMSat-2 electrical ICD[41].
- UPMSat-2 solar sensors testing and characterization.
- SSBV reaction wheel testing and characterization.
- 3D design verification of the UPMSat-2 structure.
- E-BOX design and manufacturing report.
- UPMSat-2 battery maintenance, including Arduino-based hardware development for this task.
- UPMSat-2 flight model integration (mechanical assembly procedure).
- UPMSat-2 magnetometers (SSVB and Bartington) characterization (the testing setup –outside rotating table to avoid magnetic interferences, computer, acquisition system, batteries, trypod, etc.– of the corresponding testing campaigns is shown in Figure 7).
- UPMSat-2 magnetorquers characterization.
- UPMSat-2 harness design.
- Topological optimization of UPMSat-2 mission structural parts (both the spacecraft and testing auxiliary parts).
- Analysis of uncertainties related to small-diameter screws (present in UPMSat-2 structure).

[41] Interface Control Document.

Figure 7. *Testing Set-up to Check the UPMSat-2 Magnetometers Performances* (Rodriguez-Rojo et al., n.d.)



At present, the UPMSat-2 is in the final integration stage, with some vibration and thermal analyses still needed. All these tasks will be carried out by the students of the Master in Space Systems (MUSE). In the following sections two examples of the work carried out by MUSE students as Case Study II, Case Study III and Final Degree Project are described.

Example 1 "The UPMSat-2 Ground Station"

Two students of the Master in Space Systems (MUSE) have worked for more than one year on the UPMSat-2 Ground Station, their work being carried out within the framework that integrates the subjects Case Study II, Case Study III and Final Degree project. This work has been supervised by staff from both IDR/UPM Institute and INTA.

The UPMSat-2 communication subsystem is being defined with the main objective of assuring data transmission between the flight and ground segments, which are simultaneously being developed. The link between the two will be established in an amateur band at a frequency of 436 MHz.

The ground station will be located at IDR/UPM facilities and its primary function is to receive telemetry generated by the satellite and transmit telecommands to accomplish the mission objectives.

In order to fulfill the project, the students had to:

- Check hardware parts.
- Write all documents related to the Ground Segment using the standards from the space sector.
- Perform different tests and calculations. In particular, the onboard antennae system was characterized with ANSYS HFSS® simulations in order to determine the best configuration.

The work of these students has helped to define the best antennae configuration for the UPMSat-2, based on four vertical monopoles with circular polarization. In Figure 8, the testing configuration for the experiments carried out is shown, whereas one of the radiation diagrams obtained with these experiments is depicted in Figure 9.

Figure 8. *Testing of One Monopole Antenna for the UPMSat-2. Experimental Set-up*

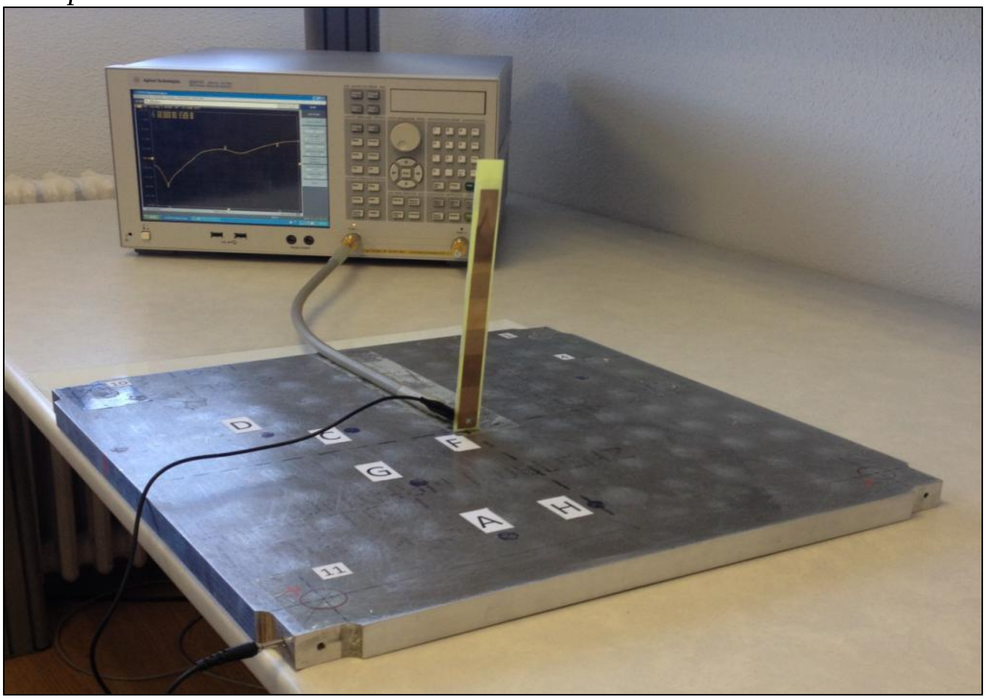
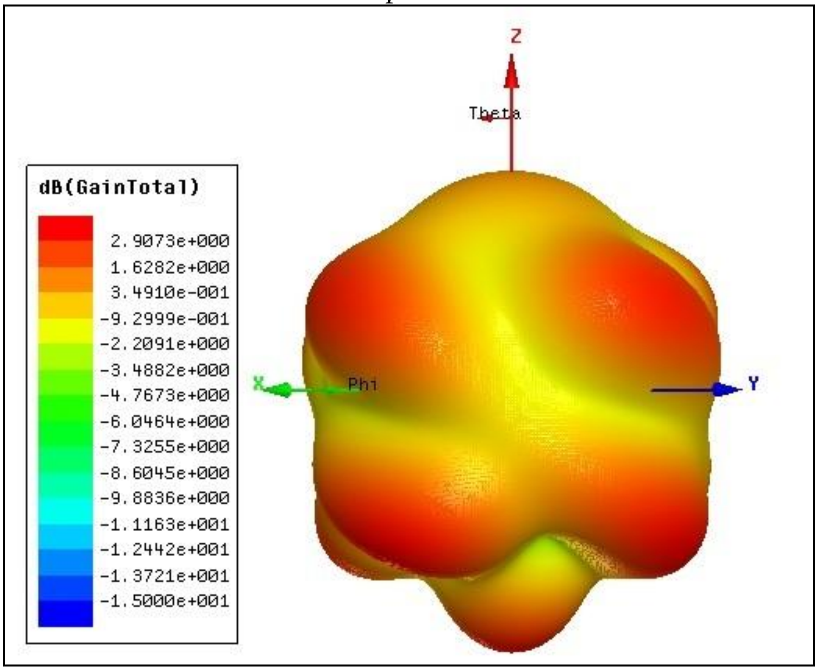


Figure 9. *Radiation Diagram of the UPMSat-2 Final Antennae Configuration, Based on Four Vertical Monopoles*



Example 2 "The UPMSat-2 Solar Panels Testing"

The solar panels of the UPMSat-2 were tested and characterized by two students of the Master in Space Systems (MUSE) within their Case Study II. The testing was based on the solar radiation. A set-up consisting of a box covered by a transparent plastic cover placed on an orientable table was built. The performance of the four lateral solar panels and the top panel were measured (that is, the current-voltage curves –*I-V* curves– were measured). The testing configuration developed for this measuring campaign is shown in Figure 10. The task carried out is indeed a quite complicated testing procedure that requires the following aspects to be taken into account:

- The spectral irradiance of the sun during the experiments, AM 1.5, in order to extrapolate the results to the spectral irradiance in space (AM 0).
- The temperature of the solar panels (which was rising from the initial value during each test, due to the solar radiation).
- The transmittance of the plastic cover of the box in which the solar panels were placed. This transmittance was kindly measured by CIEMAT[42].

[42] *Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas*. http://www.ciemat.es/.

Figure 10. *Testing Sep-up for the UPMSat-2 Solar Panels*

Thanks to the work of the students involved in this project the UPMSat-2 solar panels were characterized with a “low-cost” procedure. This work has been published in a prestigious journal (Roibás-Millán et al., 2017).

Conclusions

In the present paper the academic benefits of the UPMSat-2 mission development are discussed. This project has been successfully integrated in the Master in Space Systems (MUSE) at *Universidad Politécnica de Madrid*.

From the educational point of view, the UPMSat-2 mission has proven to be an extremely useful tool for the Master in Space Systems (MUSE). The different aspects of the mission (planning, developing, testing, systems integration, subsystems and payloads analysis…) cover almost all the academic load of the master. But, beyond this academic load:

- it represents a space engineering framework that allows the student to train their skills in one of the most demanding working environments,
- it boosts the students motivation, increasing their work capacity and improving their results, and

- the tasks carried out by the students are highly appreciated by the space engineering sector, this fact being based on the students employment rates once they are graduated.

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