SSC21-P2-41

Small satellite design at the UPM Master in Space Systems (MUSE)

Santiago Pindado, Javier Cubas, Elena Roibás-Millán, Javier Pérez-Álvarez, Ángel Sanz-Andrés, Sebastián Franchini, Isabel Perez-Grande, Gustavo Alonso, Andrés García-Pérez, Marcos Chimeno-Manguan, Ignacio Torralbo, Juan Zamorano, Alejandro Alonso
Universidad Politécnica de Madrid
Plaza del Cardenal Cisneros 1, 28040, Madrid, Spain; 0034 910675955
santiago.pindado@upm.es

ABSTRACT

The Master in Space Systems (*Máster Universitario en Sistemas Espaciales* – MUSE) at UPM (*Universidad Politécnica de Madrid*) is an academic program organized at *Instituto Universitario de Microgravedad "Ignacio Da Riva"* (IDR/UPM) research institute. This is a 2-year Project Based Learning (PBL) master program which started in 2014. Since the first year of the MUSE, the students have participated actively in the development and construction of the UPMSat-2, an educational, scientific and in-orbit technological demonstration 50 kg-class microsatellite launched on September 2^{nd}, 2020. Students from MUSE have participated in all phases of the mission, from the design of subsystems to in-orbit operation, and including integration, calibration, and testing. In the present work, the most relevant characteristics of this master program are described, the importance of the satellite's design and development within the academic tasks being emphasized. Graduated MUSE students have a high employment rate in the most prestigious space engineering companies and institutions in Spain and other countries in Europe (ESA, AIRBUS-CRISA, INTA, GMV, DHV,…). Besides, a quite large percentage of the graduated students from MUSE continue their education with a Ph.D. These reasons have made MUSE the most successful academic program in Spain regarding space systems engineering.

INTRODUCTION

In July 2021, the 6^{th} cadre of students from the Master in Space Systems (MUSE – *Máster Universitario en Sistemas Espaciales*) from *Universidad Politécnica de Madrid* (UPM) successfully graduated. This relatively new master program was one of the results from a quite large heritage in space systems engineering at the IDR/UPM Institute, that started in the late 70s of the 20^{th} century with research on liquid bridges under microgravity conditions[1–8] (see Figure 1).

Other relevant achievements of this research group in the last decades are:

- The ESA Handbook on Spacecraft Thermal Control of the European Space Agency[9].
- The UPM-Sat 1 satellite. Launched in 1995, this was the first 100% Spanish satellite ever developed, and the 10^{th} university space mission in History[10–12].
- CPLM payload for the MINISAT mission[13].
- The thermal control of the instrument OSIRIS for the ROSETTA mission[14].
- The thermal control of the balloon-borne telescope SUNRISE[15,16].
- And other more recent works such as the thermal analysis of the NOMAD payload in ExoMars mission[17,18], the SO/PHI and EPDS payloads in Solar Orbiter mission[19–21], or the MEDA sensors in Mars 2020 mission[22,23].

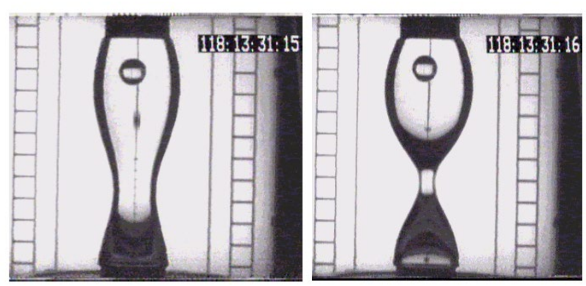

Figure 1 1993 Spacelab-D2 mission (experiment STACO), breaking of a cylindrical volume liquid[24,25].

The expertise in space systems from the IDR/UPM Institute was organized as a master program within the period 2010 and 2014, and in September 2014 the first lessons of MUSE were given to a selected group of students at the Aerospace Engineering Faculty from UPM.

The Master in Space Systems (MUSE) from UPM

The Master in Space Systems (MUSE) from UPM[26–29] is a 2-year and 120-ECTS (European Credit Transfer and Accumulation System) academic program. In Table 1, the subjects included in MUSE are shown.

With some exceptions such as Advanced Mathematics 1 and 2, Project Based Learning (PBL) is the teaching methodology used in almost all subjects from MUSE. Besides, three subjects are specifically oriented to PBL: Case Study 1, 2 and 3, in which students are encouraged to work in a space engineering project, sometimes carried out in a company such as DHV Technology or GMV.

Table 1: Curriculum of the Master in Space Systems of the Technical University of Madrid (MUSE)

Semester	A4
Semester 1	Advanced mathematics 1
	Space environment and mission analysis
	Vibrations and aeroacoustics
	Graphic design for aerospace engineering
	Systems engineering and project management
	Space industry and institutions seminars
Semester 2	Advanced mathematics 2
	High speed aerodynamics and atmospheric reentry phenomena
	Space structures
	Power subsystems
	Heat transfer and thermal control
	Communications
	Data housekeeping
	Case Study 1
Semester 3	Space materials
	Quality assurance
	Production technologies
	Space integration and testing
	Orbital dynamics and attitude control
	Case Study 2
Semester 4	Case Study 3
	Final Project (Master Thesis Dissertation)

The UPMSat-2

The UPMSat-2 is a 50-kg microsatellite fully developed by the IDR/UPM Institute that was launched in September 2020 (see Figure 2 and Table 1). Leaving aside its purpose as a technological demonstrator platform, it has proven to be an extremely useful tool for improving the educational aspects of MUSE.

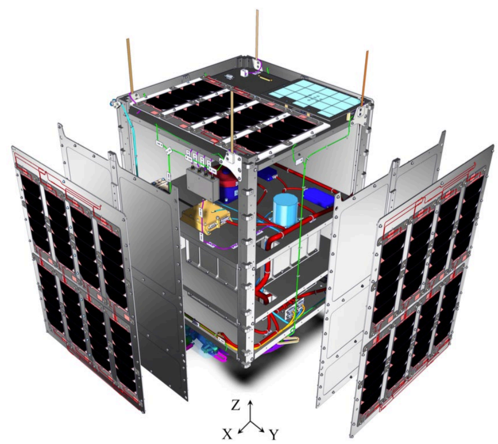

Figure 2 CAD drawing of the UPMSat-2.

Table 2: Style Specifications

Mission Life	2 years
Mass	50 kg
Dimensions	0.5 x 0.5 x 0.6 m^3
Orbit	Sun-Synchronous: • 97º inclination • 10:30 Local Time of the Ascending Node (LTAN)
Attitude Control system	Purely magnetic: • SSBV magnetometers (1 nominal, 1 spare) • ZARM Technik AG magnetorquers (3 axis actuation) • Magnetic control law designed by IDR/UPM
Thermal Control	Passive for the microsatellite, active for battery thermal stability
Power	Power subsystem based on solar photovoltaic panels and a battery: • 5 body-mounted solar panels of Azur Space 3G28C triple junction solar cells. • Li-Ion battery of 18 Ah designed by SAFT • Direct Energy Transfer (DET)
On-board Electronic Box (EBOX)	Based on FPGA (designed by IDR/UPM and TECNOBIT (Oesia group) and programmed by STRAST/UPM). The E-BOX includes the on-board computer; data handling; power supply control; and power supply distribution.
Communications	• Uplink and downlink at 437 MHz (additional downlink at 400 MHz). • 4 monopoles antennae system for omnidirectional radiation pattern. • Ground station located in UPM Montegancedo campus

Aim of the present paper

The aim of the present paper is to present some insights on the way the development of the UPMSat-2 and other small satellite missions have improved the program of MUSE. On the one hand, this project represents a unique framework in which students can work directly and use the skills learned in the master program. On the other hand, the program of many subjects has been modified by the coordinators due to their work on the UPMSat-2[30].

In the following sections, the way that the coordinators of some MUSE subjects have included different aspects of the UPMSat-2 development is described. The specific small projects/testing campaigns/simulations carried out by MUSE students as Case Studies 1, 2, and 3, and the Final Project delivered as Master Thesis Dissertation, have been left aside from the present paper.

Only a few subjects of MUSE have been selected as example in this paper. They represent well what is carried out in almost every subject of the master program.

SPACE ENVIRONMENT AND MISSION ANALYSIS (1st SEMESTER)

The objective of the course taught in this subject is that the student knows what, in a broad sense, is called the environment of the spacecraft, where everything that the vehicle is exposed to must be included. Furthermore, in this subject some general aspects of cosmonautical missions are considered, including a description of the most general types of missions as well as the operations involved in them.

Small satellite missions in which the IDR/UPM Institute participates, such as the UPMSat-2 or the UNION/LIAN-HÈ satellite proposal (in conjunction with Beihan University), are often used as examples to explain the particularities and environment of LEO and Sun-synchronous orbits. However, the most interesting use of these real scenarios is as a case study in mission analysis exercises like: orbit propagation, calculation of access times or mission lifetime[31]. See Figure 3.

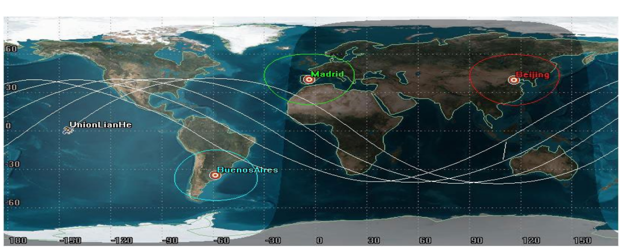

Figure 3: Example of Access analysis in STK for the UNION/LianHe mission[31].

The exercises are presented as open problems that students must solve in groups using mission analysis programs such as STK and GMAT.

SPACE STRUCTURES (2nd SEMESTER)

The UPMSat-2 structural model[32,33] is presented as a case study in the practical lessons of the subject Space Structures, carried out by FEM analysis with Nastran-Patran©. The students have to design a 50-kg FEM model composed of horizontal trays, L-size pillars and lateral panels. Then, the models are analyzed under the same load levels used in the calculations carried out in the UPMSat-2 development, to verify that they will be able to endure the vibrations and noise produced during the launch. See Figure 4.

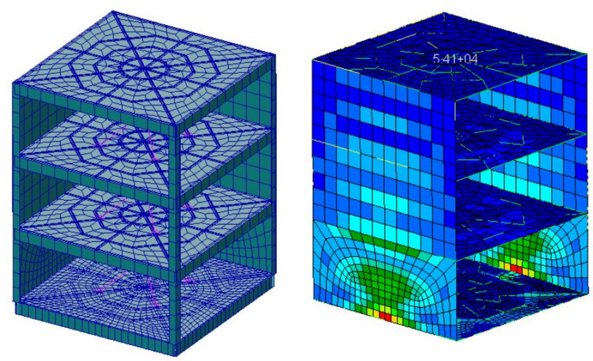

Figure 4: FEM model of the UPMSat-2 by MUSE students (left), and its Nastran-Patran© calculation (right).

HEAT TRANSFER AND THERMAL CONTROL (2nd SEMESTER)

As in the previous case, practical work within the subject Heat Transfer and Thermal Control is carried out taking the UPMSat-2 thermal analysis[34] as a case study. In fact, it can be said that the thermal control of this mission has been analyzed with the contribution of MUSE students.

After an analysis of the thermal environment of the mission, the thermal analysis begins by dividing the satellite into subsystems, parts and instruments. Each modeled part (ESATAN©) is integrated into a model representing the whole satellite. At this point, some prediction of the satellite temperatures within the mission can be made. Finally, the model is correlated with data extracted from experiments carried out in thermal vacuum chamber, to adjust the calculated values during the mission. See Figure 5.

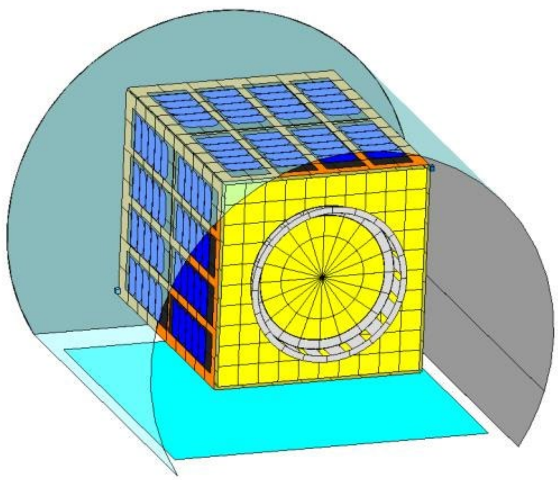

Figure 5: Geometrical Mathematical Model of the UPMSat-2, developed for carrying out thermal analysis and correlate the results with the ones from testing in vacuum chamber.

DATA HOUSEKEEPING (2nd SEMESTER)

The core topics of this subject are computer structure, operating systems or programming. As most MUSE students have a degree in aerospace engineering and little experience with these topics, they are taught at an introductory level.

Nevertheless, to motivate students, examples of the UPMSat-2 On Board Computer (OBC) structure are used to illustrate the concepts of computer structure such as processor, memories and input/output devices. See Figure 6.

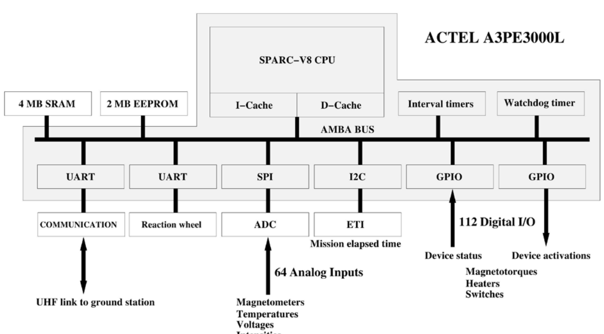

Figure 6: Computer structure of UPMSat-2

In addition, the course includes a guided practice on the development of a simplified version of the UPMSat-2 on-board software that can be seen in Figure 7. The objective is to introduce students to the problems of software development for this type of systems, while strengthening the concepts expressed in the topics of operating systems, programming, and real-time systems. In this practice they have to program an embedded computer similar to that found in flight computers using the usual software development tools.

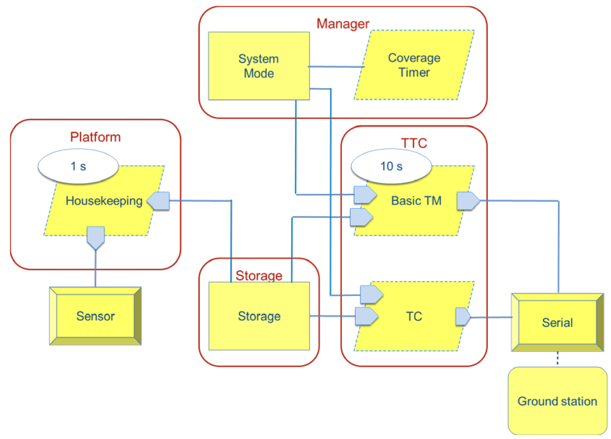

Figure 7: Simplified scheme of the UPMSat-2 on-board software.

ORBITAL DYNAMICS AND ATTITUDE CONTROL (3rd SEMESTER)

The subject Orbital Dynamics and Attitude Control introduces the most relevant aspects of the orbital dynamics necessary for the understanding of the functionality of the orbit and attitude control subsystems in a space vehicle. The GNC (Guidance Navigation and Control) measures and controls the position in space. It also includes the ADCS (Attitude Determination and Control Subsystem) that determines and controls the orientation of the spacecraft in space.

Thanks to the UPMSat-2 mission, the institute has a complete simulator of the ADCS of a real satellite (see Figure 8).

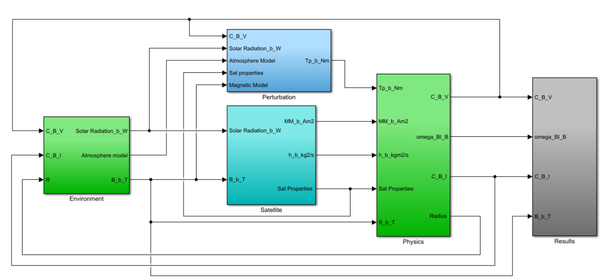

Figure 8: ADCS model of UPMSat-2 in Matlab/Simulink.

The simulator is developed in Matlab/Simulink and includes:

- Models of the environment and ephemerides (Sun and Earth position, magnetic field, and irradiation).
- Orbit propagation.

- Orbit and attitude perturbations (aerodynamic forces and torques, solar radiation forces and torques, gravitational torque and magnetic residual torque).

- Sensor and actuators models.

- OBC model, including control laws and attitude determination.

This model is used as a basis for teaching students the different parts of an attitude simulator, and for them to test different attitude controls. The characterization tests of the UPMSat-2 sensors (magnetometers and solar sensor) and actuators (reaction wheel and magnetorquers) are also used in this subject. The students do practical exercises in which they have to adjust an instrument model (see Figure 9) to real results obtained during the functional tests (see Figure 10).

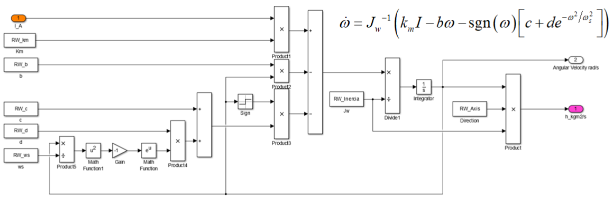

Figure 9: ADCS model of UPMSat-2 in Matlab/Simulink.

In summary, the UPMSat-2 mission has provided very valuable tools, models and real results that allow MUSE students to learn about the ADCS of a satellite in a practical way. Furthermore, most of the acceptance and calibration tests of sensors and actuators of the ADCS were performed as case studies of MUSE students.

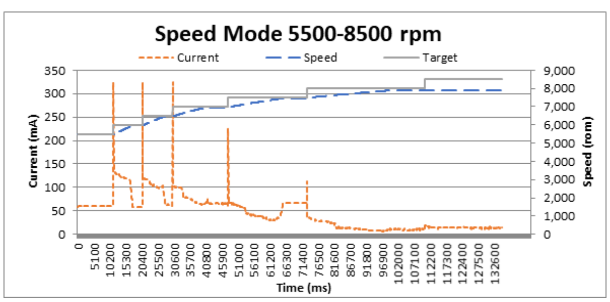

Figure 10: Functional **test of the UPMSat-2 reaction wheel. Current and speed is monitored while different angular velocities are commanded.**

CONCLUSIONS

Small satellite missions have been part of master MUSE since its inception. Thanks to the UPMSat-2 among others, students have had the opportunity to participate in the design, testing and operation of a real satellite, motivating them and providing challenging problems for their case studies.

Also noteworthy is the fact that the participation of teachers in this project has provided them with a practical vision that they would not otherwise have. Furthermore, the development of the projects itself has provided tools, models, simulators, software, and hardware that have become educational tools within the master.

In conclusion, the UPMSat-2 has been a fundamental and highly appreciated tool both by the students and the teachers of the Master. This being only a small part of the benefits that the project has had, in which it can be included more than a dozen of Ph.D. theses presented and in preparation and in preparation, and numerous scientific publications.

All this makes that the institute is already planning new small satellite missions for being used as and educational tool for new cadres of students.

Acknowledgments

Authors are grateful to the IDR/UPM staff for their constant help regarding the UPMSat-2 development. Besides, Authors will be always indebted to the MUSE students who were involved in this project.

UPMSat-2 launch was funded by the European Union in the frame of the Horizon 2020 IOD/IOV Programme.

References

1. Da-Riva I, Pereira EA. A regular perturbation approach to surface tension driven flows. *Acta Astronaut*. 1982;9(4):217-224.

2. Da-Riva I, Ruesga JM. Fluid-physics-module experiments. *ESA Spec Publ*. 1976;ESA SP-114:265-275.

3. Meseguer J. The breaking of axisymmetric slender liquid bridges. *J Fluid Mech*. 1983;130:123-151.

4. Meseguer J. Stability of slender, axisymmetric liquid bridges between unequal disks. *J Cristal Growth*. 1984;67(1):141-143.

5. Meseguer J, Sanz A. Numerical and experimental study of the dynamics of axisymmetric slender liquid bridges. *J Fluid Mech*. 1985;153:83-101.

6. Meseguer J, Sanz A, Lopez J. Liquid bridge

breakages aboard spacelab-D1. *J Cryst Growth*. 1986;78(2):325-334.

7. Da-Riva I. Stability of Liquid Bridges. In: Napolitano LG, ed. *Applications of Space Developments. Proceedings of the XXXI Int. Astronautical Congress, Tokio, Japan*. Pregamon Press Ltd.; 1981:69-80.

8. Slobozhanin LA, Shevtsova VM, Alexander JID, Meseguer J, Montanero JM. Stability of Liquid Bridges Between Coaxial Equidimensional Disks to Axisymmetric Finite Perturbations: A Review. *Microgravity Sci Technol*. 2012;24(2):65-77. doi:10.1007/s12217-011-9290-5

9. Da-Riva I, Meseguer J, Martínez I, Stroom C. Spacecraft thermal control design data. In: *ESA Spacecraft Thermal and Environ. Control Systems (SEE N 79-31266 22-18)*. ; 1978.

10. Sanz-Andrés A, Meseguer J. El satélite español UPM-Sat 1. *Mundo Científico*. 1996;169:560-567.

11. Meseguer J, Sanz-Andrés A. *El Satélite UPM-Sat 1*. Vol 1.; 1998.

12. Sanz-Andrés A, Meseguer J, Perales JM, Santiago-Prowald J. A small platform for astrophysical research based on the UPM-Sat 1 satellite of the Universidad Politécnica de Madrid. *Adv Sp Res*. 2003;31(2):375-380. doi:10.1016/S0273-1177(02)00629-4

13. Sanz-Andrés A, Rodríguez-De-Francisco P, Santiago-Prowald J. The Experiment CPLM (Comportamiento De Puentes Líquidos En Microgravedad) On Board MINISAT 01. In: *Science with Minisat 01*. Springer Netherlands; 2001:97-121.

14. Thomas N, Keller HU, Arijs E, et al. OSIRIS—the Optical, spectroscopic and Infrared Remote Imaging System for the Rosetta orbiter. *Adv Sp Res*. 1998;21(11):1505-1515.

15. Pérez-Grande I, Sanz-Andrés A, Bezdenejnykh N, Barthol P. Transient thermal analysis during the ascent phase of a balloon-borne payload. Comparison with SUNRISE test flight measurements. *Appl Therm Eng*. 2009;29(8):1507-1513.

16. Barthol P, Gandorfer A, Solanki SK, et al. The sunrise mission. *Sol Phys*. 2011;68(1):1-34.

17. Neefs E, Vandaele AC, Drummond R, et al. NOMAD spectrometer on the ExoMars trace gas orbiter mission: part 1—design, manufacturing and testing of the infrared channels. *Appl Opt*. 2015;54(28):8494-8520.

18. Patel MR, Antoine P, Mason J, et al. NOMAD spectrometer on the ExoMars trace gas orbiter mission: part 2—design, manufacturing, and testing of the ultraviolet and visible channel. *Appl Opt*. 2017;56(10):2771-2782.

19. Fernández Rico G, Perez-Grande I. Diseño térmico preliminar del Instrumento PHI de Solar Orbiter. In: *Actas Del VII Congreso Nacional de Ingeniería Termodinámica - CNIT7*. ; 2011.

20. Torralbo I, Perez-Grande I, Gasent-Bledsa JL, et al. Thermal Analysis of the Solar Orbiter PHI Electronics Unit. *IEEE Trans Aerosp Electron Syst*. 2020;56(1):186-195.

21. Solanki SK, Iniesta JCT, Woch J, et al. The Polarimetric and Helioseismic Imager on Solar Orbiter. *Astron Astrophys*. 2020;642:A11, 1-35.

22. Al. R-M et. The Mars Environmental Dynamics Analyzer, MEDA. A Suite of Environmental Sensors for the Mars 2020 Mission Enhanced Reader.pdf. *Sp Sci Rev*. 2021;217(48):1-86.

23. Sebastián E, Martínez G, Ramos M, Pérez-Grande I, Sobrado J, Rodríguez Manfredi JA. Thermal calibration of the MEDA-TIRS radiometer onboard NASA's Perseverance rover. *Acta Astronaut*. 2021;182(December 2020):144-159. doi:10.1016/j.actaastro.2021.02.006

24. Martínez I, Meseguer J, Perales JM. Wobbling of a liquid column between unequal discs. *Adv Sp Res*. 2005;36(1):26-35. doi:10.1016/j.asr.2005.03.155

25. Martínez I, Perales JM. Experimental analysis of the breakage of a liquid bridge under microgravity conditions. *Adv Sp Res*. 2011;48(3):465-471. doi:10.1016/j.asr.2011.03.012

26. Pindado S, Sanz A, Sebastian F, et al. Master in Space Systems, an Advanced Master ' s Degree in Space Engineering. In: *ATINER'S Conference Paper Series, No: ENGEDU2016-1953*. ; 2016:1-16.

27. Roibás-Millán E, Sorribes-Palmer F, Cubas J, et al. Implementation of Concurrent Engineering Approach in MUSE (Master in Space Systems) Master's Degree in Space Engineering. In: *ATINER'S Conference Paper Series, No: ENGEDU2018-2537*. ; 2018:1-19.

28. Alvarez Romero JM, Roibás-Millán E, Pindado S, Perez-Alvarez J, Sanz-Andrés Á. UPMSat-2 Communications System Design , Integration and Testing , within MUSE (Master in Space System) Academic Plan Athens Institute for Education and Research 8 Valaoritou Street , Kolonaki , 10683 Athens. In: *ATINER'S Conference Paper Proceedings Series ENGEDU2019-0177*. ; 2020:1-24.

29. Alvarez Romero JM, Roibás-Millán E, Pindado S, et al. Research-Based Learning : Projects of Educational Innovation within MUSE (Master on Space Systems) Academic Plan Athens Institute for Education and Research 8 Valaoritou Street , Kolonaki , 10683 Athens , Greece ATINER " s conference paper proceedings s. In: *ATINER'S Conference Paper Proceedings Series ENGEDU2020-0187*. ; 2020:1-20.

30. Pindado S, Cubas J, Roibás-Millán E, Sorribes-Palmer F. Project-based learning applied to spacecraft power systems: a long-term engineering and educational program at UPM University. *CEAS Sp J*. 2018;10(3):307-323. doi:10.1007/s12567-018-0200-1

31. Cubas J, Sorribes-Palmer F, Pindado S. The use of STK as educational tool in the MUSE (Master in Space Systems), an Advanced Master's Degree in Space. In: *AGI's 2nd International Users Conference: Ciao Roma!. 6-18 November. Rome, Italy*. ; 2016.

32. García-Pérez A, Chimeno Manguán M, Sanz-Andrés Á, Alonso G. Numerical results of modal coupling in the UPMSat-2 structure. In: *8th European Conference for Aeronautics and Space Sciences (EUCASS)*. ; 2019:1-12. doi:10.13009/EUCASS2019-338

33. García-Pérez A, Sanz-Andrés Á, Alonso G, Chimeno Manguán M. Dynamic coupling on the design of space structures. *Aerosp Sci Technol*. 2019;84:1035-1048. doi:10.1016/j.ast.2018.11.045

34. González-Llana A, Peinado-Pérez L, Roibás-Millán E, Pérez-Álvarez J, Torralbo I, Gómez-San-Juan A. Thermal testing campaign of the UPMSat-2. In: *8TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)*. ; 2019:1-11.