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ABSTRACT

In recent years, the development of small-size satellites by companies, research institutions and universities have become common practice. This terend is based on the need for providing an easy and low-cost access to space for those institutions and companies that cannot afford the use of the usual big industrial platforms. In this context, the IDR/UPM Institute (*Instituto Universitario de Microgravedad 'Ignacio Da Riva'*) of *Universidad Politécnica de Madrid*, has been developing the UPMSat-2 microsatellite along the past years. This is one of the most relevant projects in the current space engineering activities at IDR/UPM, which integrates university professors, research staff of IDR/UPM, and students of the Master in Space Systems (MUSE). Going back to the UPMSat-2 mission, it should be underlined that this type of small-size satellite requires reliable communication systems able to ensure the quality of the communication link between the satellite and ground control, but they must also be optimized in terms of costs. Therefore, the use of Commercial-Off-The-Shelf (COTS) components, which are normally developed for terrestrial applications, has become a usual practice in such kind of small-size satellite missions. Thus, these communication subsystems require deep tests campaigns to ensure their proper operation and to increase the reliability. From this point of view, a suitable balance between the limited resources available in this kind of university-satellite missions and the complexity of the testing techniques is needed. IDR/UPM professors and MUSE students have performed the full design, manufacture and testing of the UPMSat-2 communications systems (flight and ground). This paper summarizes the development of the whole UPMSat-2 communication system, describing the tasks required for its implementation, and focusing on how they were harmonized and integrated within the academic plan of the Master in Space Systems (MUSE).

Keywords: Communications subsystem; Design, integration and testing; University-class Satellite; Project-based learning; Master's degree

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Introduction

The IDR/UPM[1] Institute (University Research Institute of Microgravity "Ignacio Da Riva") of the *Universidad Politécnica de Madrid* (UPM) is a research, development and training center oriented to space science and technology. It was founded in 1974, under the direction of the professor Ignacio Da Riva (1930-1991) with the initial name of LAMF/ETSIA; but it was not until 1998 when it was consolidated as an official research institution associated with the UPM.

Over the years, the IDR/UPM Institute has worked on many space projects (Sanz Andres et al., 2006), such as the Solar Orbiter (Pérez-Grande et al., 2009; Pérez-Grande, I., 2011) or the Sunrise (Barthol et al., 2011); and it has collaborated with large space institutions such as the National Aeronautics and Space Administration (NASA) or the European Space Agency (ESA). However, among all the space projects developed by the IDR/UPM Institute, one of the main milestones was the development, launch and operations of the UPMSat-1, a university and scientific satellite whose main mission was the demonstration of the capacity of the UPM to design, develop, build, test, integrate and operate a satellite with modest features, while keeping in the execution of the mission all the complexity of a complete space system (Ayuso et al., 1996; Meseguer and Sanz-Andrés, 1998; Sanz-Andrés et al., 2003; Sanz-Andrés and Meseguer, 1996).

After the success of the program and as a logical continuation, a space project called UPMSat-2 has been developed in the last years. It has been carried out by work teams which gathers professors and contracted IDR/UPM staff, Bachelor's and Master's degree student and Ph.D. students (Pindado Carrión et al., 2017); with the collaboration of other research teams from UPM. The aim of the project is the development of a small satellite using the experience acquired with the UPMSat-1 and incorporating current space industry new technologies and improvements. It has been possible thanks to the growing trend led by the industry, research centers and universities, focused on the generation of smalls satellites that allow these institutions to access space activities without having large budgets or industrial platforms that used to be associated with these projects.

The UPMSat-2 project, like its predecessor, has several objectives that cover both scientific- technological applications as well as educational purposes. It is in this last area where this project has been used for the training of students of the Master's Degree in Space Systems[2], a study program of the UPM completely taught and directed by the IDR Institute. Through the activities generated by the UPMSat-2 program, the students have carried out internships, supervised assignments, Case Studies (CE) and Master's Thesis (*Trabajo Fin de Master* - TFM). In addition, students had the opportunity to learn through a real space project, integrating the different subsystem designs in the Master's Degree subjects.

[1]http://www.idr.upm.es/.
[2]Máster Universitario en Sistemas Espaciales - MUSE, http://muse.idr.upm.es/.

Overview of the Master in Space Science (MUSE)

The Master's Degree in Space Systems (MUSE) is a quite recent official program organized and directed by the IDR/UPM Institute, which allows students to approach the space industry through project-based learning (PBL) (Pindado et al., 2016). This methodology is based on the research institute's own experience in different space projects, which have either been developed or are in actual development. This is a two-year master's degree with 120 ECTS (European Credit Transfer and Accumulation System) aimed to provide both theoretical knowledge and practical expertise in the space field. It is based on PBL (Brodeur et al., 2002), which means that students face real problems with a non-unique solution and encourages students to find agreement solutions to trade-off between different solutions to find a suitable design result.

Table 1. *Subjects Included in the MUSE 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 re-entry phenomena	3.0
		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	3.0
		Heat transfer and thermal control	6.0
		Power subsystems	3.0
		Space structures	4.5
		Space materials	4.5
		Systems engineering and project management	6.0
PBL	31.5	Case Study 1	1.5
		Case Study 2	7.5
		Case Study 3	9.0
		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

The MUSE academic plan consist of 19 different subjects, 3 Case Studies and Master's Thesis (see Table 1). MUSE subjects are classified according to whether they are monodisciplinary, PBL or can be considered as a blend of both concepts. The list with the number of ECTS associated to each subject is also shown in Table 1. It is important to highlight the subjects defined as "Case Study", in which the students, tutored by a MUSE professor, must develop a research activity regarding a project that is being carried out in the IDR/UPM Institute. Thus, students perform research and development task in a real space project.

Regarding the distribution of the subjects along the academic years, some modifications have been introduced in year 2018-2019 with regard to previous years, so all the theoretical subjects of the fourth semester are moved to previous ones. This has been done to allow the students working stages at companies during the Master's Thesis, exchanges with other universities, etc. A distribution of all the MUSE subjects depending on the semester is included in Table 2.

Table 2. *Time Schedule (in terms of Semesters) of the Master in Space Systems of the Technical University of Madrid (MUSE)*

Semester	Subject
1st	Advanced mathematics 1
	Space environment and mission analysis
	Vibrations and aeroacoustics
	Systems engineering and project management
	Graphic design for aerospace engineering
	Spacecraft propulsion and launchers
2nd	Advanced mathematics 2
	Communications
	Data housekeeping
	Heat transfer and thermal control
	High speed aerodynamics and atmospheric reentry phenomena
	Space structures
	Power subsystems
	Case Study I
3rd	Space materials
	Quality assurance
	Production technologies
	Space integration and testing
	Orbital dynamics and attitude control
	Case Study II
4th	Space industry and institutions seminars
	Case Study III
	Final Project

Finally, it is important to emphasize that, in order to implement this PBL methodology, the MUSE students have the possibility to take part in IDR/UPM projects. This has been proved as a way to get a closer collaboration between the students and the teachers and the IDR/UPM staff. Also, through this collaboration, MUSE student can acquire knowledge and experience in real space projects.

Approach to the Communications Subsystem within MUSE

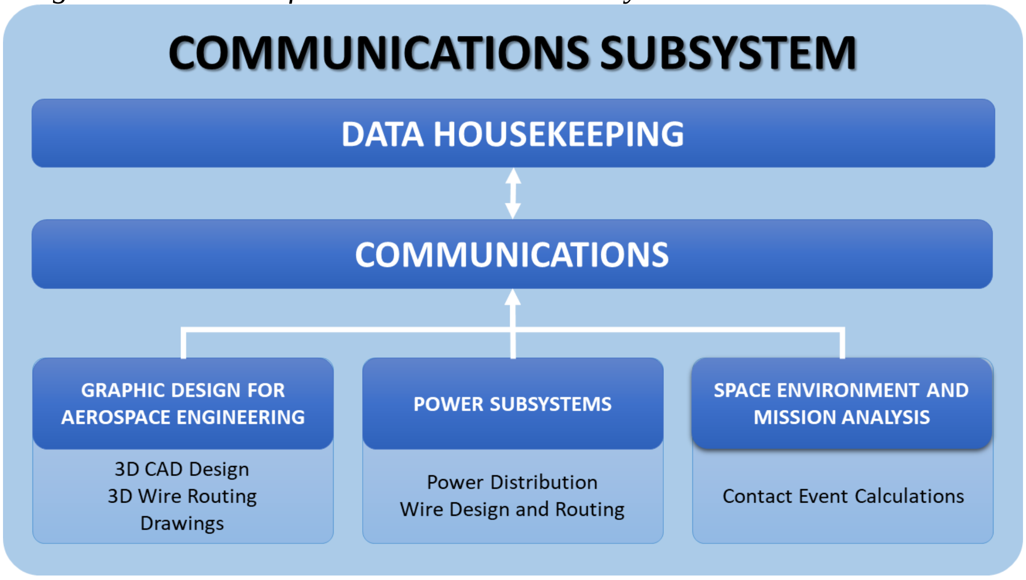
In a space project that involves the design of a satellite, there are many subsystems that play a fundamental role for the proper satellite operation. The communications subsystem is responsible for ensuring telecommunication between the satellite and another system, which may be either another satellite or a ground station. In order to understand how a project related to space communications is included in an academic program such as MUSE, it could be reasonable to define first what is understood by communications and what is the purpose of this process in a satellite.

Telecommunications, specifically the possibility of achieving good connection over long distances, have been closely linked to the space sector since its inception. An example is the launch of the world first satellite, the Sputnik I, which issued a single beep on a radio signal. Space industry has evolved from this simple signal to the current large communications and television broadcasting satellites, which handle a large amount of information. In general, the communications subsystem is responsible for both sending and receiving information between the spacecraft and the ground control. Although there are satellites whose main mission is telecommunications (TV, military information, etc.), a satellite with any other main objective needs this subsystem, which is of vital importance for the development of the mission.

The signals used to interchange data are nothing but electromagnetic pulses molded or manipulated by the transmitter in such a way that contains information that the receiver can understand. As for the communication subsystem itself, it is formed by a set of antennae and transceivers to be able to communicate with the monitoring stations, sending collected data and receiving instructions from them. These instructions are processed by the control system, which could be the satellite’s main computer, or certain components from the OBDH (On-board Data Handling) Subsystem. That is the reason why a proper communication between the satellite and the ground must be ensured, both by making a robust design and by conducting the appropriated test. It should also be mentioned that this communications link can also be stablished between two satellites, e.g. the design of a constellation or several satellite flying in training.

Due to the importance of the communications subsystems as part of any satellite project, the necessary knowledge to carry out a good design of this subsystem was included in the MUSE program, being taught either by theoretical lessons or by PBL methodology. In the following sections, several examples of the activities carried out by the MUSE academic program in the field of communications are summarized.

Figure 1. *Interface Scheme of the Different Knowledge Required for the Design, Integration and Test of the Communication Subsystem*



As shown in Table 1 and Table 2, the communications subsystems are an intrinsic part of the MUSE learning program, covered under the subject obviously denoted as “Communications”. However, the different subsystems of a satellite are not isolated models that can be understood independently, as each single one is supported by the others to achieve a correct fulfillment of the mission requirements. Therefore, MUSE academic plan has preserved links and enough coordination between the different subjects. The most relevant subjects within MUSE program related to the correct design, integration and testing of a spacecraft communications subsystem are shown in

Figure **1**. These subjects are the following:

- “Communications”: All the theoretical concepts of the communications subsystem are considered in this subject, specifically those that do not belong to any other subsystem. The students learn the elements that define a communication link and their design factors, that is how to calculate a link budget. In the subject, real satellite models are used in the exercises, to bring students the opportunity to handle real data. Among these satellites, the UPMSat-2 is used as an example for these calculations.
- “Data Housekeeping”: This subject refers to the on-board data handling subsystem, OBDH. Students learn the different parts that make up an On-Board Computer (OBC) and its operation, including the algorithms and the different operative modes. Regarding its effect on communication processes, the OBC is responsible for storing the information to send, as well as interpreting the signals received by the antennae. In addition, the OBC storages and manages all the operational routines and functions of the satellite, including those which affect the communication subsystem (Herrero Sánchez, 2018).
- “Graphic design for aerospace engineering”: 3D modelling is an important tool in order to make a correct design of the communications subsystem. This knowledge is acquired by MUSE student in this subject, where they have an approach to the 3D software Dassault Systemes CATIA®. In addition, 3D wiring and harnessing is included among the different modules taught in this subject, which is used to include electrical components of the communications subsystem, and their connections in the satellite 3D model.
- “Power subsystems”: The management and distribution of electrical power is necessary to choose between different parts and components (i.e., their power consumption), in order to fulfill the mission requirements. The design criteria of minimizing mass and power (being also aware that the more power consumption means a more sophisticated heat control), is very common in the space industry, so the knowledge obtained in this subject are used both in the design of the communications or any other subsystem.
- “Space environment and mission analysis”: An important part when dimensioning the components that will define the link budget is to know the access times of the spacecraft from ground control, as well as the number of these accesses. This information is used to calculate the necessary data rate, and after that, to define the transceiver configuration to meet the requirements. One of the practical activities of this subject is training on both GMAT® and STK®. Using these tools many orbital characteristics can be calculated, including the contacts with the ground stations.

One of the most important aspects of the MUSE program is the amount of academic load devoted to practical skills. In addition to some practical subjects, this training is performed within the Case Studies and the Master's Thesis (TFM).

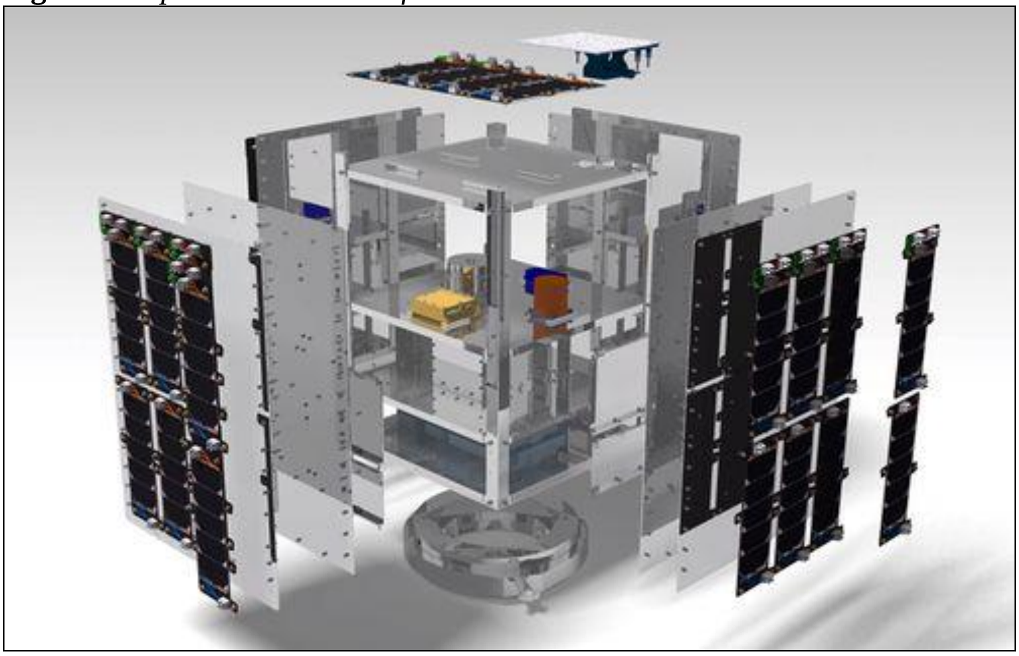
During Case Studies and the TFM, MUSE students have the possibility to choose between different projects in which the IDR/UPM Institute is working. Some of these projects have been related to communications, specifically with the UPMSat-2 communications subsystem.

As shown in Table 2, the three Case Studies are carried out in a different semester, each one with a higher workload than the previous one. Thus, the first semester is reserved for theoretical and basic subjects, while in the second one, the Case Study I is included, with 1.5 ECTS. The second year, however, has a Case Study II (7.5 ECTS) in the third semester, and a Study Case III (9.0 ECTS), for the last semester. It is worth mentioning that said Case Study III may be extended to the TFM.

UPMSat-2 Communication Subsystem

The UPMSat-2 is a 50 kg university satellite (Figure 2) made by the IDR/UPM Institute as a continuation of the UPMSat-1 (launched in 1995). The project began in 2009 as a challenge for the institute staff and as a technological demonstrator.

Figure 2. *Exploited 3D Model of the UPMSat-2*



Source: IDR/UPM Website.

Over the years and mainly due to different delays (initially the UPMSat-2 launch was planned for 2013), several models have been generated in collaboration with the MUSE students. Currently, the UPMSat-2 is at the stage of integration of the flight model, with a planned launch date in August 2019.

It should be highlighted that several collaborations with different industrial/research groups have been carried out within the UPMSat-2 mission program. Two examples should be mentioned. On the one hand, the STRAST (*Sistemas de Tiempo Real y Arquitectura de Servicios Telemáticos*) research group from UPM, has developed the OBC together with TECNOBIT[3] and the ground station software (De La Puente et al., 2015). On the other hand, the National Institute of Aerospace Technology (*Instituto Nacional de Técnica Aeroespacial* - INTA) provided a fundamental contribution by supporting the IDR/UPM Institute during the development and testing of the ground station.

As previously mentioned, the UPMSat-2 communication subsystem has been developed in collaboration between the IDR/UPM Institute staff and the MUSE students through the Case Studies and TFM. In the following sub-sections, the final state of the UPMSat-2 communication subsystems is summarized, the activities associated with the flight segment or the ground segment being reviewed separately. Finally, the calculations belonging to the link budget are included.

[3]http://grupooesia.com/ingenieria-tecnobit/.

Flight Segment

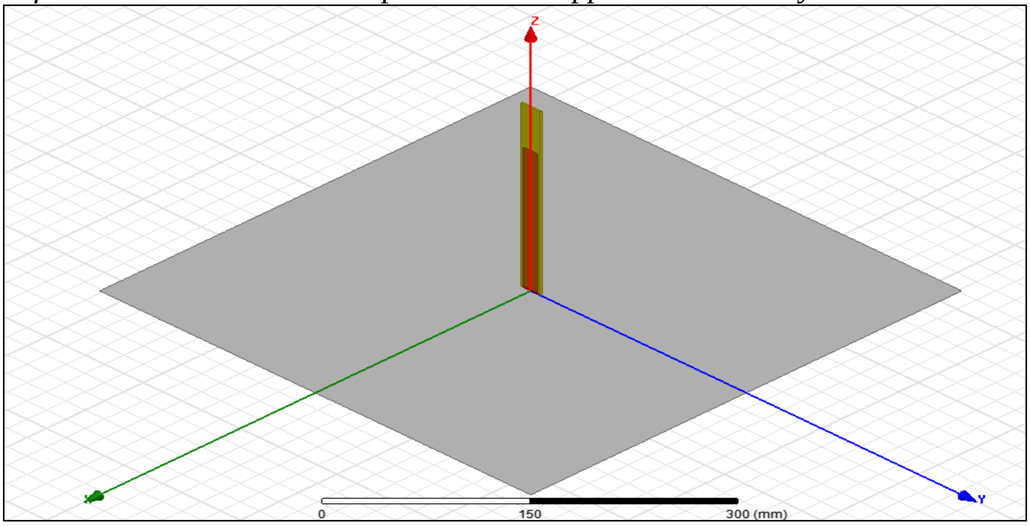
Monopole and Satellite Configuration

Unlike its predecessor, the UPMSat-2 was defined to work at two different frequencies: at 400 MHz and at 437.4 MHz. Based on the UPMSat-1 design, a monopole antenna configuration was selected.

The first step to define this subsystem was to calculate the behavior and losses that may occur in the antenna. These losses vary depending on the frequency at which the monopole is tuned. To define this value, simulations were performed with ANSYS HFSS® software, representing the operative conditions of the antenna and its properties. This work was developed by MUSE students as Case Study from 2016 to 2017, under the supervision of IDR Professors.

To analyze the monopoles behavior, a main frequency was defined (437.4 MHz) for setting its optimal tune length, so losses that would occur at this principal frequency and at 400 MHz were calculated. In the simulation, the monopole has an initial length of 172 mm. In terms of thickness, two design options were studied, 4 mm and 15 mm. The monopole was mounted on a tray of 445 mm x 445 mm x 5 mm modeled in aluminum, simulating the top satellite tray. An image of the ANSYS HFSS® simulation using these initial values is shown in Figure 3.

Figure 3. *Simulation Model of the UPMSat-2 Monopole Using ANSYS HFSS® Software. It Includes the Monopole and the Support Satellite Tray*

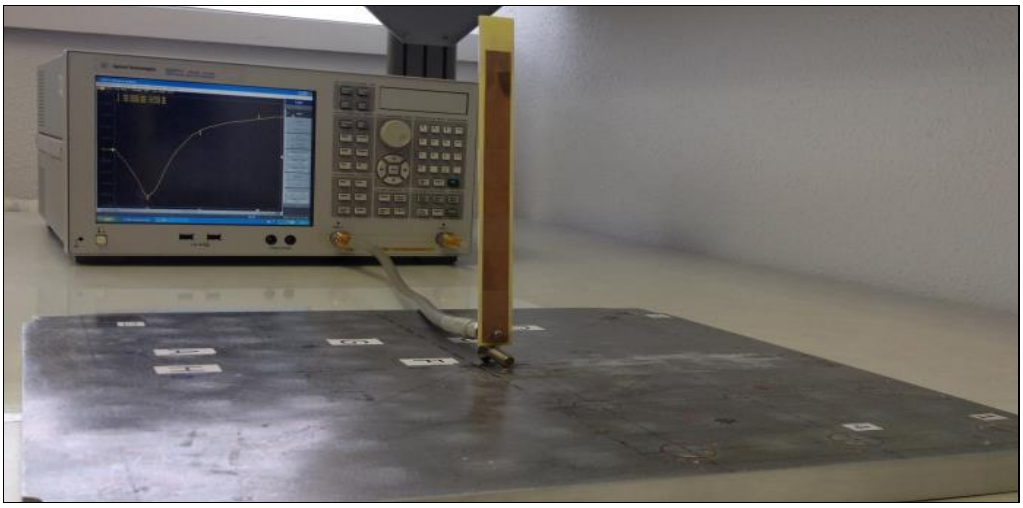


Source: UPMSat-2: Monopole Configuration and Mounting Design (Case Study III, 2017).

Once the optimal dimensions were defined, the fabrication of a test model with the same properties was carried out. That model was tested at INTA facilities to validate the results obtained with the simulation (see

Figure 4).

Figure 4. *Test Model of the UPMSat-2 Monopole used to validate the Results Obtained with the Simulation Model*



Source: UPMSat-2: Monopole Configuration and Mounting Design (Case Study III, 2017).

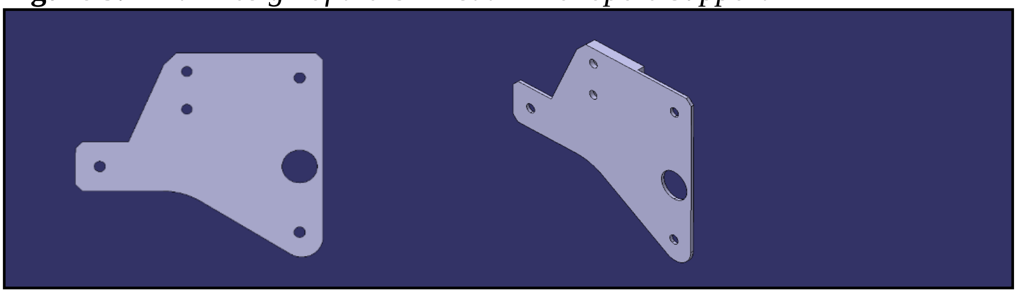
After the characterization of the monopoles, it was necessary to study their configuration in the satellite. This work started with two different initial designs: the one from UPMSat-1, with a configuration of a single monopole in the upper tray; and the one from Optos[4], with four monopoles on each lateral face and oriented at 45º with respect to these faces. In addition, other configurations were analyzed, converging in a trade off with four vertical monopoles located on the axes of the lateral faces with the upper tray.

Monopole Support Design and Fabrication

Once the antennae configuration was completely defined, the design of the monopoles support system, which allows the antennae to be fixed to the satellite's structure, was carried out by a MUSE student in 2017. This work was presented as Case Study III. This preliminary design was later modified, due to manufacturing restrictions. These modifications being also studied as a part a different Case Study III in 2018 (

Figure **5**).

Figure 5. *Final Design of the UPMsat-2 Monopole Support*

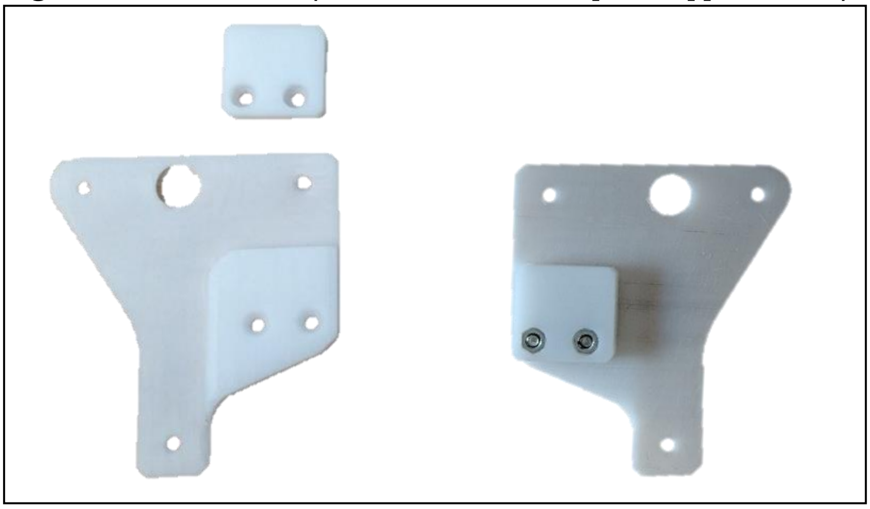


[4]OPTOS is a low-cost 3U Cubesat project of INTA, Madrid.

Source: Definición, montaje e integración del subsistema de comunicaciones del UPMSat-2 (Case Study III, 2018).

In addition to the monopole support 3D design, the manufacturing process was also included in the 2018 Case Study III. Two MUSE students were commissioned to manufacture several UPMSat-2 parts, including those from the communications subsystem. These supports were manufactured using a milling process. Figure 6 shows the final antenna supports.

Figure 6. *Final Result of the UPMsat-2 Monopole Support Manufacturing*



Source: Definición, montaje e integración del subsistema de comunicaciones del UPMSat-2 (Case Study III, 2018).

Electrical Equipment and 3D Wire Routing

As a result of the final configuration of the UPMSat-2 antennas, a splitter was included to divide the RF output power to each one of the four monopoles. In addition, a 90º of phase shift between monopoles was implemented to ensure a circular polarization.

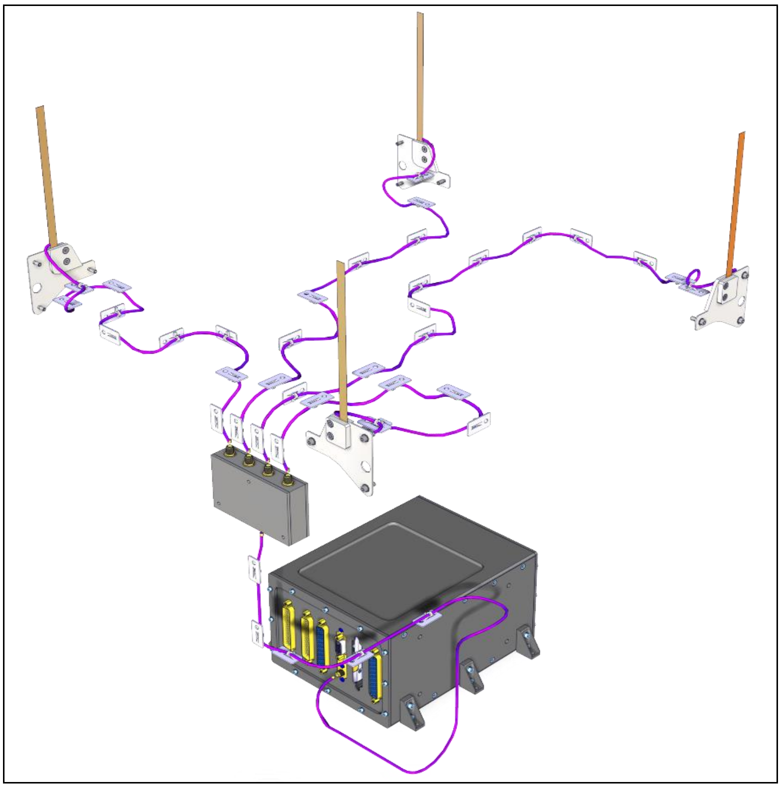
In order to involve new MUSE students, a Case Study II devoted to carry out the electrical and harness design of the communications subsystem was proposed. The first step of this Case Study was the definition of the splitter. At this point of the academic program (Case Study II and Case Study III), it should be underlined that students must not only perform theoretical work, but also face industry-specific tasks such as searching for existing equipment (Commercial-off-the-shelf - COTS), request information from distributors, compare components according to requirements and availability.

Subsequently, and once the splitter was defined and placed at the satellite structure, the wires from the antenna to this component and from there to the radio were routed (

Figure **7**).

Finally, full characterization of the equipment was carried out by testing the complete system performances. All data used and obtained from these results were employed to define the UPMSat-2 link budget.

Figure 7. *Isometric View of the Complete Communication Subsystem Equipment and Harness*



Source: Definición, montaje e integración del subsistema de comunicaciones del UPMSat-2 (Case Study III, 2018).

Flight Segment Integration and Test

Once the entire flight segment was designed, manufactured and integrated, several tests were needed to measure the actual radiation pattern of the antenna system. For these tests the Structural and Thermal Model (STM) of the UPMSat-2 was used (Figure 8).

Figure 8. *Radiation Diagram Measurement Test Using the STM*

Source: UPMSat-2 Communication Subsystem (TFM, 2017).

Ground Segment

Ground Station Detailed Design

Although the UPMSat-2 mission is very similar to the UPMSat-1, it was necessary to carry out a detailed re-design of the ground station facilities, mainly because of the communication link characteristics. This task was assigned to a MUSE student for their TFM. The first step of this work was to carry out a full study of the requirements that the ground station had to fulfill.

Once the requirements were established, the next step was to define the possible configuration for the ground segment, according to the equipment availability and the required performances. For this purpose, two different detailed designs of the communications subsystem ground segment were considered:

- Option 1: One ground station located at the *Universidad Politécnica de Madrid* (UPM), at the Montegancedo Campus.
- Option 2: Two ground stations, one located at the Montegancedo Campus (UPM) and the second one located at INTA in *Torrejón de Ardoz* (Madrid, Spain).

After designing and comparing these two options, it was decided not to divide the reception of information, and therefore a single ground station was stablished (Option 1). The communication with this option consists of two chains: one for a communication path (simplex) capable of receiving satellite telemetry data and the other for two communication paths (half-duplex) used for the transmission of the beacon, remote controls and the reception of telemetry.

The simplex communication chain is made with a UHF cross Yagi antenna operating at 400 MHz, connected in turn with the Airspy® receiver, while the half-duplex chain is made with an X-Quad antenna, Yagi UHF operating at 437 MHz and connected to the Kenwood TS-2000® radio, capable of receiving the audio signal (

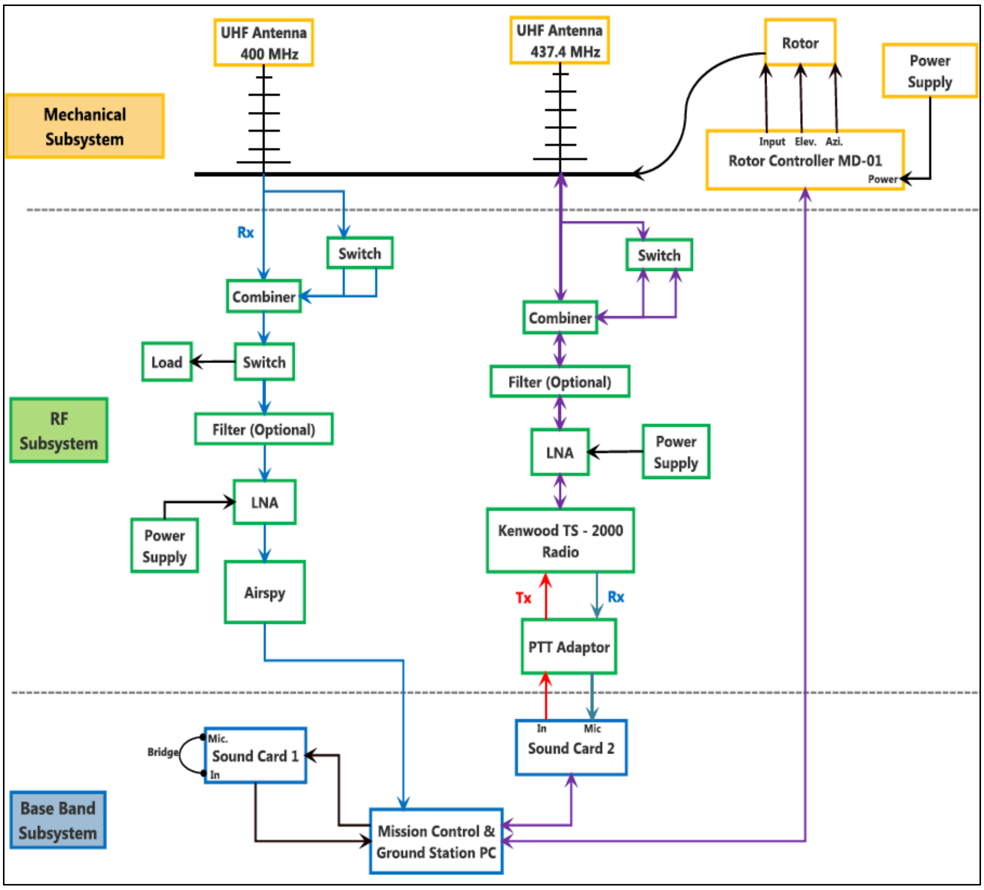
Figure **9**).

The mission control computer contains two sound cards, one for each chain, for the reception of the sound signals from the Airspy® receiver and the Kenwood radio. The same computer is also used to control the tracking equipment.

Both antennas are mounted on a crossbar and are controlled by a single Alpha Spid rotor to direct its orientation. The rotor allows controlling the orientation of the antennas by configuring the azimuth and elevation angles, with an accuracy of 0.1 degrees. The tracking system is responsible for tracking the satellite's orbit using Ham Radio Deluxe software, which is also used to control the antenna rotor.

The system, as shown in Figure 9, is divided into three subsystems: the mechanical subsystem, the RF subsystem, and the baseband subsystem.

Figure 9. *UPM Ground Station Architecture (Option 1)*



Source: UPMSat-2 Communication Subsystem (TFM, 2017)

Once the configuration was defined, the next step that took place between the responsible professors and the MUSE student was to characterize all the equipment, in order to be able to define its operation and to integrate them later. It is in this integration where students leave the most theoretical tasks and carry out PBL activities: tests to calculate the losses that occur in the components, studies to obtain an optimal configuration (whether it was convenient to place the filter before the LNA or vice versa) or perform the assembly of these components on the GS (

Figure **10**).

Figure 10. *RF Equipment Connection to the Communication Antenna*

Source: Definición, montaje e integración del subsistema de comunicaciones del UPMSat-2 (Case Study III, 2018).

Link Budget and Link Test

Link Budget

It was necessary to evaluate the quality of the communication signal between the satellite and the ground station to ensure that there is a correct transmission of data during the satellite operation. To do this, a link budget was calculated, collecting all the information that has been obtained from the characterization of all the components.

The calculations, both the uplink and the downlink, were calculated taking into account the WCS (Worst Case Scenario), including all the components data: the antennas gain, the maximum distance between the satellite and the ground station, or the RF available power. In all the cases studied, favorable link margins were obtained for the uplink and downlink.

Communication Link Test

Finally, these link budget results must be validated with a set of communication link tests. In order to realize this validation, the test and the values expected must be defined before they were carried out. This last section was implemented by the professor responsible for the development of the communication subsystem and a Ph.D. student (former MUSE student).

However, in order to ensure the continuity of the projects and encourage inclusion in the projects, test definition had been developed with the collaboration of a trainee student of the MUSE first year, so that it could serve as a continuation in his next Case Studies and TFM.

Conclusions

Throughout the document, the work related to the UPMSat-2 communications subsystem definition, design and testing have been presented. The required tasks are integrated within the MUSE academic plan through practical activities performed by students under supervision of IDR professors. In addition, all the learning know-how gained with the development of these activities had been difunded.

The incorporation of the different tasks based on the design, integration and testing of the UPMSat-2 in the MUSE academic program has contributed in several Study Cases, TFMs and Ph.D. Dissertations. Students have improved their knowledge of the subsystems considered as well as of the space industry in general. Finally, it has also served as motivation for them, getting involved in real space projects, an aspect which is highly appreciated by the space engineering sector.

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