THE SPANISH CONTRIBUTION TO THE 1ST ESA ACADEMY'S CONCURRENT ENGINEERING CHALLENGE: DESIGN OF THE MOON EXPLORER AND OBSERVER OF WATER-ICE (MEOW) MISSION

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ABSTRACT

The IDR/UPM Institute[1] (*Instituto Universitario de Microgravedad 'Ignacio da Riva'*) joined the 1st European Space Agency (ESA) Academy's Concurrent Engineering Challenge in September 2017. The aim of this Challenge was to gather around students of different ESA members or associated States to design a mission in the ESA Educational Concurrent Design Facility (CDF). Three more groups from *Universidad Politécnica de Madrid* (Spain), *Politecnico di Torino* (Italy), and University of Strathclyde (United Kingdom) were invited to join the Challenge. The purpose of this exercise was the design of a mission proposed by ESA. *Universidad Politécnica de Madrid* (UPM) was represented by students and professors from the Master in Space Systems (*Máster Universitario en Sistemas Espaciales* - MUSE[2]), who successfully developed a full mission (Moon Explorer and Observer of Water-ice - MEOW-), which is described in the present work. This mission fulfilled all ESA requirements. In this paper the educational point of view is described (students preparation, challenges encountered, lessons learned, etc.).

1. INTRODUCTION

1.1. The Concurrent Engineering (CE) approach to space mission early design

The design of space missions is a complex task even at preliminary and conceptual design phases. All engineering disciplines and sub-disciplines are interconnected up to a certain degree, and no one can be neglected when optimizing the whole mission. The classic mission design approach required a large number of design iterations, representing each one a small step in the design evolution, and involving changes to a limited group of the mission subsystems. This drawback led the introduction of the Concurrent Engineering (CE) within the space mission/systems design by the end of the 20th century [1]. CE is defined as a method of design/develop a product with all the stages of the process conducted simultaneously, so that it is based on:

- task parallelisation, and
- taking into account all the elements of the system's life-cycle from the beginning of the design phase.

As a result of the CE approach, a collaborative, co-operative, collective and simultaneous engineering working environment can be created, the efficiency and effectiveness of the whole design team being greatly increased. Besides, product quality is also improved, as CE facilitates early error detection.

The European Space Agency (ESA) started to apply CE in the 90s. Euromoon and Venus Sample Return missions partially applied the method in their mission studies. Nevertheless, the real standardization of the procedures was not started until the Concurrent Design Facility (CDF) was established at ESTEC in November 1998. The Italian Space Agency's CESAR (Central European Satellite for Advance Research) was the first case study in 1999 [2].

The new methodology developed during these projects is known as Integrated Concurrent Engineering (ICE). It consists in multi-disciplinary system development emphasising the response to customer expectations [3]. The final objective of ICE is to concentrate the effort in the interdisciplinary aspects of spatial design, minimizing the boundaries and the loss of time in interactions and communication between disciplines. A Concurrent Design Facility (CDF) is a facility specifically formulated for that, it can host a team of experts (usually one per discipline) in the same room and facilitates its calculations but also the data exchange between them [4], [5].

ICE involves a big amount of data, originated from different sources and disciplines. This information has to be conveniently stored, shared and transmitted. So, it deals with big data typical problems. As a consequence, in 2010 ESA presented the Technical Memorandum for Engineering Design Model Data Exchange [6], in an effort to facilitate CE and promote this methodology. This document represents an open data exchange standard, which includes common data definition in order to facilitate the information exchange among ESA, partner Agencies, European space industry and institutes during early phases of space systems design.

1.2. The Concurrent Design Facility (CDF) as an educational tool within the Master in Space Systems (MUSE) at UPM

The Master's degree in Space Systems (MUSE) is a 2-year program with 120 ECTS. Subjects are both

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[1] http://www.idr.upm.es
[2] http://muse.idr.upm.es/index.php/es/

theoretical and practical; all related with space sciences research and technology and they are classified into five different groups of subjects:

- Advanced Mathematics
- Space Projects Definition
- System Engineering
- Spacecraft Subsystems
- Case Studies I, II and III, and Final Project

Within MUSE's academic program two learning methodologies have importance: Multidisciplinary Teaching and Project Based Learning (PBL). IDR/UPM professors firmly believe that both methodologies are of special relevance for teaching about space systems.

The PBL approach is essential in engineering. It allows improving the problem resolution skills of the students. Students lean to make preliminary research, analyse possible solutions and develop proposals. When the project is related with space technology, the solution typically cannot be obtained without collaboration between disciplines. Space mission design has a multidisciplinary character, it usually requires a team of system engineers and domain specialists that work together to find a solution that accomplish the overall mission main requirements. During the first stages of the design multiple possible solutions are available. They have to be evaluated, discarded or modified by subsystem specialists, in such a way that the process cannot be sequential, because that will result in excessive cost and time consumption. CE is the result of trying to optimize the process, reduce and simplify the mission scenarios and solutions, and minimize the effort. Working in multidisciplinary projects provides the students the opportunity to work collaboratively and increase their teamwork and communication skills, learn about the expertise areas of other teammates and solve the complex challenges of today's engineering practice.

In Table 1, the MUSE academic load (measured in ECTS[3]) based on Multidisciplinary and PBL Learning Methodologies is summarized for each group of subjects. Except for Advanced Mathematics subjects, which are a tool for the rest of disciplines, all the categories have important contribution of these methodologies. Furthermore, over 50% of the total academic load is multidisciplinary and based on PBL.

CDF has been used as an education tool for teaching CE to the students. By introducing CE in the MUSE a triple objective is achieved. First, it allows the students to be up to date with the latest design trends, which drives the graduates to a fast insertion into the labour market. Second, the students are taught to be competitive, as the product realization needs to be a smart concurrent process. Finally, the working sessions get students to discard the obsolete concept that products and systems realization consist of sequential steps of design, almost independent with each other

MUSE students approach to CE in different ways. During the Case Study I, II and III and/or the Final Project (see Table 1), they learn about the development of a CDF by participating in the design and implementation of the modules. Besides, they train on CE practice by joining full mission design sessions, and being part of challenges such as the one described in the present work (see Figure 1).

Group	Total ECTS	Learning methodology
Advanced Mathematics	12.0	100% Mono-disciplinary
Spacecraft Subsystems	28.5	53% Multidisciplinary + PBL
Space Projects Definition	22.5	60% Multidisciplinary + PBL
System Engineering	25.5	30% Multidisciplinary + PBL
Case Studies and Final Project	31.5	100% Multidisciplinary + PBL
TOTAL	120	55% Multidisciplinary + PBL

Table 1. The five groups of subjects included in the Master of Space Systems (UPM), classified by type of learning (mono-disciplinary or multidisciplinary + PBL)

CDF is a key tool to support the learning methodologies used in the MUSE. The multidisciplinary teaching process can be intensified with CE sessions, where the relations between different disciplines are shown. Besides, students participation on real working sessions contribute to reinforce the PBL academic load.

Figure 1. Second-year MUSE students in the IDR/UPM CDF during the 1st ESA Academy's Concurrent Engineering Challenge

1.3. The Concurrent Design Facility (CDF) at IDR/UPM

The space systems engineering facilities of IDR/UPM Institute are located in the Montegancedo campus of UPM. These facilities include manufacturing plants, an ISO-8 clean room, a vacuum thermal chamber, a vibration room, etc. In July of 2011, the IDR/UPM and ESA signed an agreement to develop a CDF for educational purposes. The resulting facility involves a

[3] European Credit Transfer and accumulation System

system engineer (or session conductor) workstation together with twelve more workstations for space mission subsystems specialists, an audio-visual distribution system with four shared screens, a server, and a videoconference system. Since its first operative version, the CDF is continually under development following the indications of the ESA's Technical Memorandum for Engineering Design Model Data Exchange (CDF) [6].

In addition to the hardware, the CDF needs appropriate software to perform CE. IDR/UPM's CDF software is based on the ESA's software OCDT (Open Concurrent Design Tool), a central data model design to be the future standard tool for CE activities in the European space community [7]. The OCDT consists of several elements. On the server side, it needs a persistent data store, web service processor, firewalls and protocols [8]. To interact with the database, the subsystems workstations use an add-in on top of Microsoft Excel©, the ConCORDE (Concurrent Concepts, Options, Requirements and Design Editor).

Finally, each discipline needs a module to perform the calculations. The specialist will use it to design its subsystem. During the process, some variables will be calculated with the requirements of other modules, while the specialist will be free to fix the value of others, inherent to his module. For example, in the thermal subsystem module the total power dissipation may depend on the power subsystem estimations about power consumption, while the thermal insulation of the spacecraft and thermo-optical properties of the spacecraft can be selected by the thermal specialist. The results of the module shall meet the thermal requirements of the mission.

Depending on the mission and its critical requirements, these subsystems shall be more or less complex. It is convenient that the modules are as versatile as possible, but when the mission goes beyond the conventional, new capabilities could be added. Eventually, it may be necessary to increase the number of modules or even reduce it.

2. THE 1ST ESA ACADEMY'S CONCURRENT ENGINEERING CHALLENGE

Developing the education strategy of ESA, its Education Office called in March 2017 for the 1st ESA Academy's Concurrent Engineering Challenge to spread the concurrent engineering philosophy to European aerospace students. The challenged was focused on student groups (between 15 and 25) that should work in a CE scheme designing a satellite in a short time period with the support of two system engineers.

The challenge was held on September 12th – 15th simultaneously in several CDF facilities: both ESA Member and Associate State universities as well as in the ESA Academy's Training and Learning Centre. In this first edition, four student groups took part in the challenge: students selected by ESA Academy's Training and Learning Centre at the European space Security and Education Centre (ESEC) in Belgium, a group of students from *Politecnico di Torino* (Italy) and from University of Strathclyde (United Kingdom), and a group of students (Figure 1) from MUSE MSc of *Universidad Politécnica de Madrid* (Spain).

During the four days of the challenge, the students at each location were divided in smaller groups that were devoted to each of the main disciplines involved (i.e., structures and configuration, power, orbit analysis, thermal, attitude and orbit control, communication and data handling.).

The work of each smaller team was interconnected through the CDF to assess the system design and the fulfilment of the mission requirements along the four-day challenge. Each day, a progress meeting involving all the participating CDFs was held to ponder the situation and share the design choices and difficulties found. A final meeting at the end of the challenge allowed to compare the designs achieved by each team and to learn from the different engineering decisions made along the way

2.1. The Challenge proposed mission

The aim of the mission proposed for the challenge is to look for Moon Surface areas that could be used as locations for a future human base. The feasibility of the surface to this end is determined by the presence of water. Therefore, the mission shall make pictures of the surface with enough resolution to evaluate this presence of water, 10m/pixel. The search area is the Moon South Pole where high water/ice content is expected to be found.

In addition to the presence of water, to consider an area feasible for human permanent occupation two secondary elements are to be considered: First the lunar radiation (both in surface and in lunar orbit) and second the micro-meteorite environment in order to ensure the safety of a long term orbiter (e.g. relay satellite, escape shuttle, etc.).

These objectives are to be fulfilled by a small low-cost mission that is considered to be possible taking into account the current development of Cube-sat missions. From the point of view of mission operation, an ESA management is assumed and beginning of project Phase-A is not expected to start before 1st January 2019 with a probable launch time around 2023 (assuming its development in four years).

The specific mission requirements stated by ESA for the mission are:

- The mission shall make pictures of Moon South Pole areas with high-expected water/ice content, with a resolution of 10 m/pixel.

- The mission shall observe the lunar radiation and micro-meteorite environment.
- The mission shall consist of a single satellite or a single plane constellation.
- The mission shall stay in Lunar orbit for 2 years.
- The mission shall be launched using an Ariane shared GTO (Geostationary Transfer Orbit).
- The mission shall be compatible with any launch date between years 2023 and 2025.
- The total combined mass of the whole system shall be 300 kg.
- The mission should use COTS (Commercial-Off-The-Shell) components.
- The mission shall have and end of life disposal manoeuvre.
- The mission shall use direct to earth communication.

3. MUSE STUDENTS PROPOSAL: THE MEOW (MOON EXPLORER AND OBSERVER OF WATER/ICE) MISSION

The mission designed by MUSE students during the 4-days session [9], is classified into five different phases ranging from the deployment of the satellite in the GTO orbit to the disposal manoeuvre. The different phases can be summarized as follows:

- Mission phase 1: Comprises the deployment of the spacecraft into GTO from the Arianne V upper stage, the attainment of a stabilized attitude, deployment of solar panels and the conduct of checkout activities (ground system checkout and functional tests during ground station visibility periods). The estimated duration is about 1 week.
- Mission phase 2: This phase, of 3-months duration, comprises the transfer phase from GTO to Moon orbit, to place the spacecraft in a stable lunar polar orbit with a perilune altitude of 100 km. To be compatible with any launch date and to achieve the selected orbit, a Weak Stability Boundary (WSB) Low-Energy transfer trajectory from GTO to the Moon via Sun-Earth was selected. The orbit plane is changed in the moon capture to make the transfer valid for all epochs. A substantial amount of mass could be saved in case the orbit change is performed when the Sun crossed the ecliptic plane, but as this happens just twice a year, it will not fulfil the mission requirements. A similar limitation is found to use phasing orbits to optimise and correct manoeuvre errors in the orbit transfer.
- Mission phase 3: Due to the orbit perturbations in the Moon and the consequent cost of orbit maintenance the lunar imaging phase is limited to 10 months. As advantage of this high eccentric orbit a continue image of the lunar surface can be downlinked in each orbit period.
- Mission phase 4: After the 10 month imaging phase, the main objective of the scientific mission is considered achieved and the rest of the time is dedicated to the study of radiation environment and micro-meteorites detection.
- Mission phase 5: The end-of-life manoeuvre is performed. A final Delta-V is applied to deorbit the satellite in the Moon surface outside of the survey region.

To fulfil the science mission requirements, the following payloads on-board the spacecraft were selected:

- Terrain mapping camera: It is a stereoscopic instrument in panchromatic band for topographic mapping with high spatial and altitude resolution. The South Pole covered area is a circular surface of 600 km of diameter and the observation time is around 340 s. Therefore, 47 orbits are needed to complete the total South Pole surface mapping. The ground resolution at the orbit perigee is 5 m/pixel, for a 100 km altitude. When the satellite enters/exits the survey region (with an altitude of 260 km) the resolution is 9.2 m per pixel (in accordance with the mission requirements). The power consumption of the camera is 2 W and its mass is 6.3 kg.
- Spectrometer: For observation and detection of water and ice in the Moon surface. With a mass of 0.4 kg and a power consumption of 5 W, has a wide selection of models for measurements in 200-1150 nm wavelength ranges.
- Micro-meteorites detector: This payload measures the electrical charges generated by the impact of small masses on a gold surface. The power consumption is 1.8 W and its mass is 0.6 kg. It can detect particles between 7-10 g (at speed up to 20 km/s).
- Radiation detector: Composed of three detectors, one for the first energy range (200 keV to 100 MeV, for low linear energy transfer), and two for the second energy range (2 MeV to 1 GeV, for high linear energy transfer). Its mass is 5.6 kg and the power consumption is 7 W.

The primary structure is a semi-monocoque octagonal prism of 0.9 m high and 0.64 m of apothem, constructed from carbon fibre, and reinforced with eight stringers providing the stiffness needed to withstand loads during launch, as well as positive buckling and static loads margins. The total wet mass of the spacecraft (including margin of 20%) is 262 kg, fulfilling the total mass requirement at launch. A picture of the MEOW spacecraft is shown in Figure 3.

Thermal control system is passively controlled and consists of: 10 layered MLI; structural surfaces used as radiators with a black paint to get the desired surface finish; carbon fibre flexible thermal straps to get a 40 W/K heat flow to the radiators and heaters to prevent components from freezing during eclipse, consuming 15 W of total power. Maximum and minimum temperatures for the spacecraft structures are estimated from ESATAN© analysis, being 17°C and 10°C for the transfer orbit phase (WBS) and 42°C and -25°C during phase 3 and 4.

The propulsion system consists of a commercial bi-propellant (MMH/NTO) rocket engine (of 490 N thrust and specific impulse of 311 sec, with a mass of 4.5 kg including 20% mass margin), responsible for the main propulsion of the satellite during mission phase 2 (the transfer phase) and mission phase 5 (end-of-life). The total fuel tanks mass including the pressurization tank is about 11 kg. The total propellant mass needed for the mission is 141 Kg (including 21 kg of propellant for orbit maintenance in the Moon).

To properly photograph the Moon South Pole, a 3-axis stabilized system was selected. To determine the satellite attitude 2 sun sensors, 2 star trackers and 2 inertial measurement units were used. The main objective was to reach a nadir stabilized pointing during each spacecraft pass over the South Pole so a zero-momentum system composed of 4 reaction wheels (one of them for redundancy) was selected. For orbit maintenance and reaction wheels desaturation, 9 thrusters were positioned in the external surface to achieve the 3-axis control. Each thruster demands 16.5 W to be operated. The total mass of the AOCS system is 9 kg.

The power plant subsystem consisted of two deployable and steerable solar panels and a lithium-ion battery of 400 Wh and 3 kg mass, able to provide the required electrical power during the Moon eclipse of maximum duration. The Power Control and Distribution Unit consumes 6 W and has 2.2 kg mass. During the second-year mission, on 5th May 2023, an Earth eclipse event of about the 78% of the orbital period will take place. During this event, the satellite is required to enter in latency mode (the OBC is switched off in order to allow the batteries to be charged) to ensure the survival of the mission.

The OBDH subsystem, based on COTS elements, is composed of an on-board computer or microprocessor (which consumes less than 1 W and has 24 g mass), the data handling system and the analog-to-digital converters (ADC).

Finally, for earth communication, a double system was selected: a S-band antennae system (with 5 S-band antennae distributed around the spacecraft structure) of 6 W of total power consumption for GTO orbit and WBS transfer; and a 2 X-band steerable antennae system for Moon orbit (17 W of total power consumption). With the 2 Mbps data downlink rate available, the data retrieved during each orbit can be downlinked along the 2-year mission except for some critical access dates. The main ground station and mission control will be located in Madrid, Spain (40.42ºN, 3.79ºW) although some other ground station options could be required to support the mission.

The mean duration access for the mission period is 3.1 hours of contact per day, so the 2 Mbps downlink data rate transponder is able to download the telemetry and payload data per day. The total mass of the communication system is 7.8 kg.

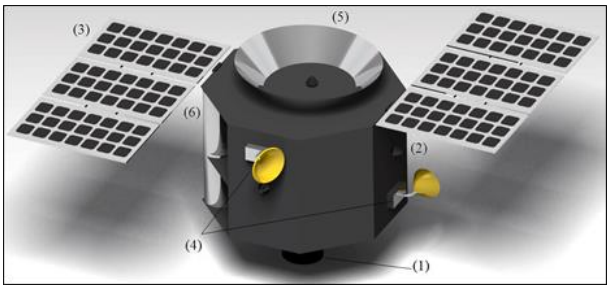

Figure 2. MEOW Spacecraft. (1) Main thruster, (2) attitude control thrusters, (3) deployable solar panels, (4) orientable X-band antennae system, (5) Launch adapter ring. S-band patch antennas and sensors are not shown in the image

4. FUTURE CHALLENGES AND CONCLUSIONS

Since its conception, the IDR/UPM MUSE MSc was project oriented as teaching methodology. This approach has been applied with different levels of integration along the years with the MUSE students as the main contributors to tools and utilities for space mission design, always under the direction of the MSc professors and the institute staff.

This approach involves the development of software and hardware solutions around UPMSat-2 mission [10] with first and second-year students working on subsystem models in a collaborative way. This framework of collaboration is essential as the first-year students are introduced into a CE scheme with little or none experience in such approach or some of the disciplines interconnected. To overcome this obstacle, support from second-year that have gathered a significant level of experience through the Case Studies and CDF design sessions is essential. This cooperation enables the comprehensive and resource-effective use of the CDF and ensures the success in the mission design studies.

To guarantee the success of the collaboration between first and second-year students, regular CDF sessions are held up. On February 2018, a CDF design session was conducted with the participation of three second-year students under the lead of an IDR/UPM system engineer and with the assistance of first-year students that had the opportunity to become familiar with the CDF available tools and to fully develop a Phase-0 space mission guided by their second-year classmates.

With the current implementation of CE and IDR/UPM CDF the academic potential has been proved clearly in terms of motivation and academic productivity in MUSE study cases as perceived and demonstrated by the MSc students. Beyond the academic profit of integrating the CE in the MSc curricula and design, the current IDR/UPM CDF has proven to be up to standard levels in Europe as highlighted by the successful participation in the 1st ESA Academy's Concurrent Engineering Challenge. The outcome of this experience was not only to show the students the needs and benefits of developing a mission design in a very short lapse considering simultaneously the design changes in each subsystem but also to plan and sketch improvements the CDF modules in order to tackle future IDR/UPM missions but also to support or sustain fully other space missions

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