An off-axis iodine propulsion system for the Robusta-3A mission

Javier Martínez Martínez, Dmytro Rafalskyi, Ane Aanesland
ThrustMe
4bis rue des Petits Ruisseaux, Verrières-le-Buisson; 0181804931
javier.martinez@thrustme.fr

Xavier Laurand, Sara Vega Martínez, Gary Quinsac
CSUM - Université de Montpellier
950 rue de St Priest, Montpellier;
xavier.laurand@umontpellier.fr

ABSTRACT

The decrease of the force of the magnetic field in altitudes above Low Earth Orbits (LEO) drives the need for miniaturized propulsion systems that can provide attitude control. In addition, these systems are already needed for orbit maintenance, phasing and lifetime extension of small satellite missions, and could also help with end-of-life decommissioning and debris mitigation. The I2T5 cold gas thruster, an iodine-based propulsion system, will be integrated on the Robusta-3A mission, developed by the CSUM, along with several educational and scientific payloads, related to meteorology and technology demonstration.

The insights given on the development process of this mission are intended to provide enriching knowledge to the space community, mainly in three areas: small satellite missions design, when both scientific payloads and propulsion systems are used; off-axis primary propulsion systems, focusing on how to eventually overcome the problems related to attitude control and mission analysis of small satellite missions; the use of iodine as a propellant for scientific space missions, focusing on how to overcome the issues related to the use of this propellant, such as propellant bouncing, deposition on external surfaces and following corrosion risks.

INTRODUCTION

The last decades have seen an exponential growth in the number of small satellite missions, becoming more diversified, and enabling the access to space to sectors that couldn't access it before. As for the 31st of May 2018, 855 CubeSat missions had been launched [1], and the number is constantly increasing.

Historically the vast majority of CubeSat has been launched to LEO, where the attitude control could be performed using the magnetic field of the earth and reaction wheels. But the development of missions to GEO or even interplanetary orbits, such as the NASA's MarCO satellite launched in 2018, and the proposed ESA mission (AIM) CubeSat Opportunity Payload [2], require propulsion in order to insure the correct satellite attitudes and the desaturation of the reaction wheels.

The deployment of cconstellations and the commercial usage of satellite will require as well precise orbit positioning [3] and longer life times, which can only be achieved via the use miniaturized propulsion systems on board of these missions.

In addition, the growth of small satellite missions [4] in the last decades has reinforced the need for orbital debris mitigation. Several space agencies and organizations have already developed orbital debris mitigation guidelines. In France, this regulation is enforced under the name "Loi sur les Opérations Spatiales" (LOS) or French Space Operation Act (FSOA) [5] .

Finally more recent developments in the field of the VLEO satellite will require further advance and demonstration in low thrust long duration propulsion manoeuvres [6].

These missions are extremely diverse, so as it is the compromise on specific impulse, thrust and power that needs to be provided for them. This, in turn, enables a wide range of available technologies and propellants that can be addressed [7].

The last decade has seen an increasing interest in the use of iodine as a propellant for electric propulsion systems, mainly because of its density at storage, low ionization potential and relatively low vapor pressure, removing the requisites for high pressurization on the tanks [8,9]. However, this is not so obvious when it comes to cold gas thrusters. Most of the systems used until now use light gases, such as helium or nitrogen, for its high specific impulse and flight heritage [10]. The use of iodine as a propellant for cold gas missions is relatively recent [11] , since there is a tradeoff between the propulsion characteristics of the molecule for these kinds of systems, and the advantages inherent to the use of iodine.

From 2013, the CSUM and the van Allen foundation recognized the need to have a three-axis stabilized platform as one of the requirements for covering more aspects of satellite design and providing higher education returns and science value. There was also an interest to better understand and predict south French violent rain events or “épisodes cévenoles”.

The I2T5 propulsion system, a cold gas thruster operating with iodine, will provide support in the orbital maneuvers performed on board of the Robusta- 3A mission, developed by the CSUM.

The propulsion system was not been initially planned to be integrated in the spacecraft, however the CSUM and ThrustMe decided to collaborate about propulsion in order to provide educational opportunities, demonstrate further the off-axis propulsive technologies as well as improve the usage and operation of propulsion on small satellites. This propulsion system is a cold gas thruster, the I2T5, which operates with iodine as a propellant. The system can provide 0.2 mN of thrust with a total impulse of 75 N·s. To respect the payload constraints, the mission required the accommodation of the primary propulsion unit in the volume of 94x94x50 mm displaced from the center of mass of the spacecraft. This resulted in a space propulsion system whose thrusting axis is not aligned with the symmetry axis of the satellite and in which the nozzle is therefore highly tilted (by 60 degrees) in order to cross the satellite center of mass and be compatible with the existing attitude control design.

The challenge of restricted volume was then tackled by using iodine as a propellant, adapting the tank configuration to the area available. As the thruster is off-centered with respect to the center of gravity, the bouncing or equivalent sloshing of the propellant was studied, and the problem was mitigated by using an embedded matrix to bound the solid sublimating propellant. The deposition of iodine is simulated for the representative conditions at the exit in order to avoid deposition in cold surfaces or transient problems due to flow instabilities, which could cause various failures in the thruster operation. Mission analysis is started in order to design the required pointing rules with respect to power management, ADCS stability and communication management during the thrust period.

Robusta-3A

Since the creation of the center in 2012, hundreds of students have been working on all aspect of CubeSats design, AIT (assembly, Integration and Test) and Operation. While most of the work is performed by students, each aspect of the mission has well defined technological and scientific rationales.

The CSUM has launched 3 1U CubeSats, most notably Robusta-1B, in 2017, which is still operational after almost 3 years in Space [12,13].

Following 6 years of preliminary studies the Robusta 3A mission entered Phase B in 2017 and the launch is currently forecasted for 2021, placing the spacecraft into a Sun synchronous polar orbit. The satellite, a 3U CubeSat developed by the Montpellier Space Center (CSUM), will support three main objectives; to serve as an educational platform, to generate scientific data which will allow to better predict and improve meteorology related phenomena, and to serve as a technological bench for several payloads and platforms.

Educational Objectives

One key aspect of the project is to give students direct hands-on training on all the aspect of a satellite mission, from design to integration and operation. Students are involved via projects, internship or more recently challenges.

At the end of 2019, 128 students had been involved into the project, with at least 100 more to be involved before the end of life, 16% of which are on the PhD level, 61% MSc and 23% BSc. Figure 1 displays the distribution of these students per year.

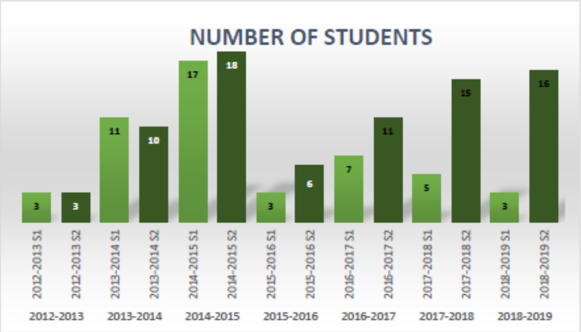

Figure 1: Robusta-3A number of students involved per semester

In the frame of the project, the CSUM will also organize challenges, supported by the Nanostar project.

One of the challenges relating to propulsion is to offer students from participating universities the opportunity to suggest a control algorithm for the propulsion phase of the mission.

In more details, the students are provided with: a simplified satellite CAD Model, matrix of inertia, center of mass coordinate, ADCS component as well as the I2T5 technical information. With this information they must suggest an AOCS control algorithm which is able to maintain the I2T5 thrust axis in a cone of 5° with respect to the orbit velocity vector for as long as possible.

Several constraints are further given such as considering the saturation of the reaction wheels saturation, changes of the center of gravity as the propellant depletes, etc.

Scientific Objectives

GEMMOC stands for **G**NSS **E**mbarqué en pleine **M**er pour la **M**été**O**rologie et la **C**limatologie, or Sea ship boarded GNSS for meteorology and climate studies. GNSS (Global Navigation Satellite System) are currently the most widely used localization techniques, with accuracy down to few meters for real time positioning and few millimetres with post processing. For a precise coordinate estimation, especially the vertical value, the GNSS calculation requires an estimation of the propagation delays induced by the signal's travel through the atmosphere, specifically to the water vapour content of the troposphere. From this "tropospheric delay"**,** *the Integrated Vapor Content (IWV*) can be then calculated. Since the late 90's ground GNSS measurements and IWV have been used in order to study the atmosphere and support weather forecast. There are numerous advantages: the antenna is passive; ground deployment is relatively low cost in energy and maintenance; etc. Hence, usage of fixed GNSS antennas for climate studies or experimental meteorology field campaign has become common. Permanent GNSS ground network contribute to weather forecast with quasi real time IWV estimation.

However, until now, only the data from fixed ground based GNSS receiver stations have been used and integrated into operational weather forecast tools. Seas and oceans are, nevertheless, the location of severe weather phenomena that threaten costal populations and infrastructure as well as maritime traffic. Figure 2 shows an example of such violent events, while most of the IWV is concentrated along the cost of Spain, all available measurements were done from ground-based observation points. This could have been different with maritime mobile stations.

Routine observation of seas, oceans and the atmosphere above them is mostly done nowadays with satellite observation completed by in situ fixed measurement buoys and ships. They are mostly equipped with pressure sensors, temperature sensors and salinity sensors. All these ships have the potential of becoming new measurement platform as long as they are adequately equipped for GNSS measurements. Hence, they could provide information about the entire water vapor content and not only local surface information. However, the main difficulty lies in the fact that the ships are moving and that current technics are mostly developed for still measurement station.

Consequently, the GEMMOC project has for objective to study and improve GNSS measurement data processing from on board equipment, both weather forecast (real time) and climate study (post treatment). Preliminary results confirm the quality of shipborne IWV retrievals and opens up prospects for its use in climatology and meteorology [14,15].

The cooperation had also been established between the ROBUSTA-3A project and the GEMMOC project to study a first mission concept and what could be the requirement of a nanosatellite (or small constellation) to support weather forecast (quantity of data, quality, time delay in processing, etc). A first internship has already been completed at ENSTA Bretagne on this topic.

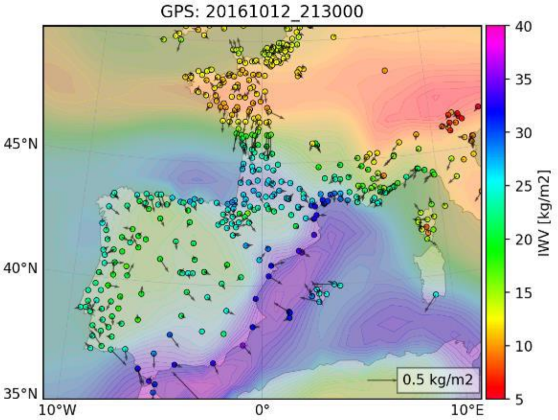

Figure 2: Example of calculated IWV during CO Sanchez associated with heavy precipitations and strong winds over France, Spain and Italy. The points represent fixed ground measurement stations.

Technological Objectives

Finally, the Robusta-3A satellite is the support for five technology demonstration:

- The I2T5 side-thrust propulsion system, a 0.5 U cold gas thruster which operates with iodine as a propellant.

- A credit card size UHF software designed radio able to be able to emit up to 3W. This board is coupled with a radiation tolerant controller (delatchers, FRAM, ECC in the RAM, dual core processor with lockstep) develop by UM and is reconfigurable in flight.

- Improved solar panel deployment hinges developed by CLIX Industries in France.

- Solar Panel HDRMs development by NIMESIS in France.

- Harness co-developed with Latécoère Interconnection System of Montpellier which will apply proven airplanes harness manufacturing technologies applied to satellites.

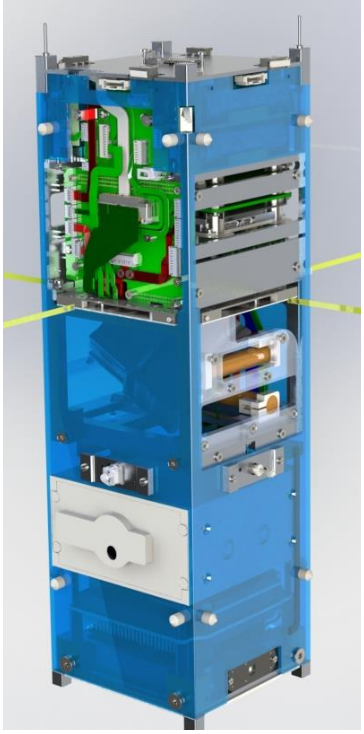

Figure 3: View of the ROBUSTA-3A satellite, with the I2T5 installed and displayed in white, left lower side

THE I2T5 TECHNOLOGICAL DEMONSTRATION

The I2T5 demonstration has the following objectives:

- Educational insight on the integration and operation of propulsion systems in a 3U CubeSat.

- Demonstrate I2T5 capabilities and "off-axis" thrust capabilities.

- Learn how to operate into the legal environment of the FSOA (French Space Operation Act).

- Have an insight into the thermal and deposition behavior of cold gas iodine thrusters integrated in small satellites.

THE I2T5 PROPULSION SYSTEM

The I2T5 is a 0.5U cold gas thruster which operates with iodine as propellant.

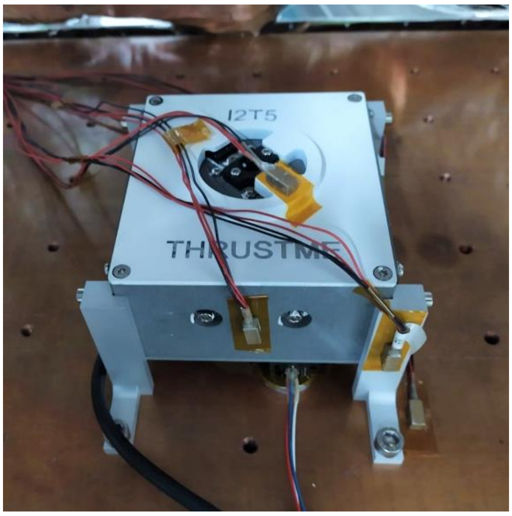

Figure 4: I2T5 thruster, axial thrust version, during the thermal vacuum qualification campaign

The system has been previously reported in literature [11], and we will therefore limit ourselves to a brief technical description. The core element of the system is the iodine reservoir, which contains the substance in solid state. The system is self-pressurized, and the pressure of the system can be precisely controlled by regulating the vapor pressure of the gas in the reservoir. This is done through the thermal management system, which also maintains the necessary temperatures along the path of the gas to prevent deposition on any component, in order to prevent blockages or clogging. The gas is throttled and accelerated through the nozzle, which then discharges to vacuum, generating the thrust in the process.

The use of a substance which has a high atomic weight, although very beneficial for the case of electric propulsion [16], doesn't seem so advantageous when cold gas systems are considered. The velocity of the gas assuming no heat losses in the flow path can be described as [17]:

$$v_e = \sqrt{\frac{2\gamma}{\gamma-1}\frac{RT_0}{M}\left[1-\left(\frac{p_e}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right]} \qquad (1)$$

where R = universal gas constant, M = molecular mass, T_0 = stagnation temperature; γ = ratio of specific heats and p_e / p_o = ratio of pressures at the exit and the tank respectively. This ratio is usually very small when the gas expands in a well expanded nozzle and can be neglected in first approximation. As it is clear from equation 1, lighter gases produce higher exit speeds of the system, and therefore, higher values of thrust.

Table 1: Comparison of different propellants. Except for iodine (solid at ambient temperature conditions), data of density and theoretical specific impulse taken from [17], at 20ºC and 5000 psi of stagnation pressure

Propellant	Density (kg/m^3)	Theoretical Specific Impulse (s)	Impulse density (kg·s/m^3)
Hydrogen	28.35	284	8051
Helium	56.7	179	10149
Nitrogen	395.65	76	30069
Argon	565.45	57	32231
Iodine	4930	29.5	145290

However, we believe that iodine can overcome this major drawback with many other advantages over typical cold gas systems commonly found in spacecraft. Its high storage density makes the impulse density actually much higher than many common propellants, as shown in Table 1, which can be a strong advantage in small satellite missions, where the space available and the constraints on the payload configuration limit the use of other propellants. The vapor pressure characteristics of the halogen makes it in addition a self-pressurized system, reducing the mechanical complexity of the elements in the flow path, and increasing its reliability. Even more important, it removes the need for storing the gas at high pressures, therefore reducing the qualification requirements and the risk of leaks during manipulation or launch.

As previously described, iodine is toxic and a strong oxidizer. To therefore prevent the presence of iodine in the facilities or at the spacecraft surfaces prior to performing the firings, the thruster has a sealing mechanism to prevent the exit of the propellant. This sealing is made through a polymeric gas-tight membrane system.

THRUST AND MASS MEASUREMENTS

The stability of flows is crucial for the system. Self-pressurizing propellants are able to maintain and sustain an operating pressure by precisely controlling the temperature of the propellant, which drives the saturation pressure of the substance and the operational pressure of the system itself.

In contrast with other typical cold gas thrusters, this removes the need for using complex regulation valves. A failure of these systems in typical propulsion systems can lead to a decreasing operating pressure in the tank, which decreases the level of thrust over time. In addition, the pressure of the system is low enough to remove any special qualification and installing procedures for high pressure systems. In the case of iodine, this pressure is on the order of 6000 Pa for 100 ºC.

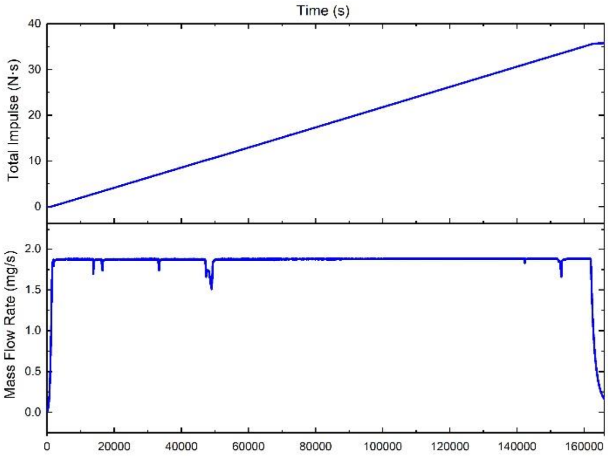

Figure 5: Mass flow rates as a function of time during the lifetime testing of the I2T5 [11]

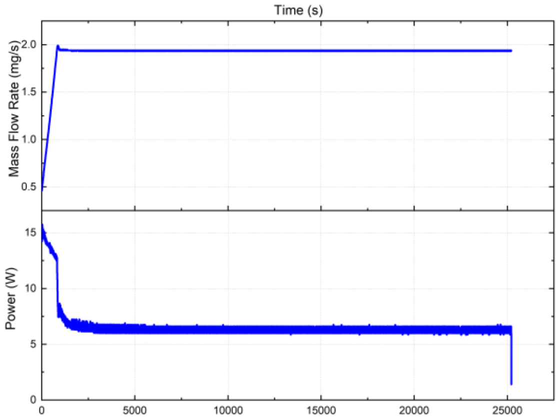

Figure 6: Mass flow rates as a function of time for a 7 hours firing

The mass flow rates of the system have been monitored under several tens of cycles to observe the effect of short, long and on/off cycling on them. This stability is shown in Figure 5, which corresponds to the lifetime testing of the thruster, as well as in Figure 6, which displays the results on a 7 hours firing of the system prior to the residual thrust period, where the propellant cools down.

In addition to the stabilities of the flows, the measure of the thrust of the system was fundamental for the validation of the theoretical design. The thrust measurements have been performed with a single pendulum thrust balance developed on site [8]. Since the balance needed to be calibrated before operation, this was done using a set of weights which created a displacement on the axis that would be measured. These calibration results served afterwards as a means for repeatable correlation between the absolute value that was measured and the force in reality. The thrust is measured after calibration through the displacement of the beam in the axis of thrust.

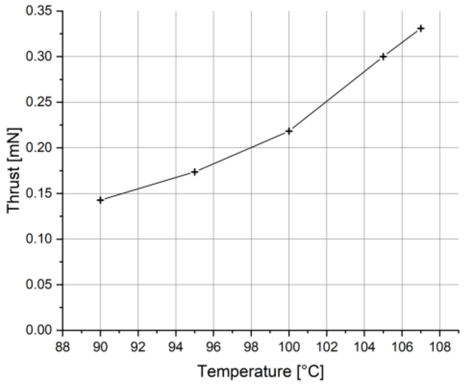

Figure 7: Thrust measured for the I2T5 thruster at several operational temperatures

Figure 7 shows the thrust levels measured at several operational temperatures of iodine in the main reservoir, and therefore at the corresponding levels of pressure of the gas, increasing as well with temperature. Due to the miniaturization of the thruster and the performance levels required, the nozzles used have a throat diameter which falls under the sub-millimeter range. In addition, and due to the low pressures of the system, the fluid has an increasing rarefaction level that grows with the flow path before exiting into space, where free molecular conditions occur.

The theory of small nozzles under these conditions has been of particular interest over the last years to predict the behavior of such miniaturized systems. When the rarefaction levels increase, there is a point at which the use of convergent-divergent traditional nozzles may no longer be interesting, because the thrust levels produced by these systems are almost equivalent to those of a thin orifice [18], much easier to manufacture. In addition, the roughness of the nozzle walls is also a fundamental design consideration. The boundary layers developed in these rarefied systems are highly developed, occupying a large part of the internal area, so a careful design and manufacturing will improve viscous losses over the fluid path. Both an orifice configuration and a nozzle with equivalent throat size were tested. In addition, two convergent-divergent nozzles with the same geometry were compared to analyze the influence of the roughness feature size. Before electropolishing, both nozzles showed internal roughness features of several tens of micrometers in average (20-30 µm feature size). After performing electropolishing on one of the nozzles these were reduced one order of magnitude. The thrust increases in the three cases with the operational temperature as expected, since this influences the pressure at the chamber, but the higher levels of thrust corresponded to the electropolished nozzle [11]. This configuration was therefore the one used in the thruster, where the design was adapted to provide a side version of the thruster, maintaining its propulsive efficiency.

The losses in the flow path can be reduced by adapting the geometry as well to these moderate Knudsen number flows. Typical divergent half angles for traditional nozzles are on the order of 15 degrees, whereas in these cases they are closer to double this value to improve the efficiencies for the gas expansion, optimizing the trade-off between minimizing the viscous losses and the inherent geometric losses of the nozzle [19].

In addition, the simulation of the flow in micronozzles is challenging because it remains a problem relatively unstudied with respect to typical simulation of nozzles in space propulsion systems, performed typically through the numerical resolution of the Navier-Stokes equations. The simulation of rarefied flows with continuum methods can lead to the underestimation of heat transfer, drag and other effects [20]. One of the possibilities is to perform direct Monte Carlo simulations, which allow to simulate the flow with stochastic particle-based methods. This is important when the flows break the hypothesis for treating them as a continuum and should be studied in the molecular level. One way to predict the behavior of the flow is through the Knudsen number:

$$Kn = \frac{\lambda}{D} \qquad (2)$$

which relates the mean free path λ to a typical length of the system, D. When the flows have values of this parameter very small, which approach to zero, the inter-molecular collisions are dominant and the non-equilibrium effects, negligible. However, as this number increases, the molecular collisions are scarcer since the mean free path increases, and the non-equilibrium effects must be studied and treated [21].

In the case of the I2T5, the flow in the conditions encountered at the reservoir is typically in the continuum regime, whereas the flow few diameters away from the nozzle falls already in the free molecular regime.

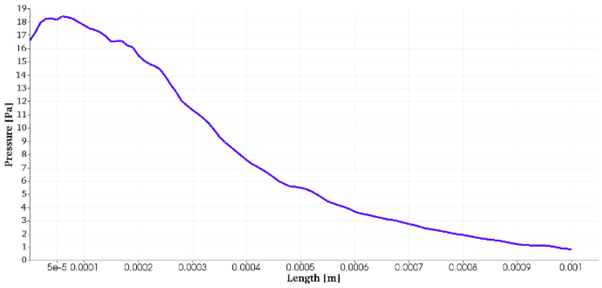

Figure 8: Pressure of the flow along the nozzle axis with residual pressure conditions at the inlet (P=20 Pa, T = 293K)

Figure 8 shows the decrease in pressure along the nozzle when the thruster is operating with a lowered entry pressure close to 20 Pa, corresponding to the temperature ambient conditions.

The particularities of the side version made important an additional thrust measurement, in which this eccentricity in the thrust vector was taken into account as well. For this, an additional thrust campaign will be performed, with the thrust measured using the exact configuration that will be retrieved in the system.

Table 2: Tests performed during the qualification campaign of the thruster in 2019

Test performed	Main objective
Ambient thermal cycling	25 cycles, T_{min} = -25ºC, T_{max} =60ºC Electronics turned on in every cycle
Thermal vacuum cycling	4 cycles, T_{min} = -25ºC, T_{max} =60ºC Electronics turned on during 1 hour in each of the cold/hot cycles
Vibration testing	Sinusoidal and random vibration testing Sinusoidal vibration levels from 5 to 100 Hz Random vibration levels from 10 to 2000 Hz
Shock testing	9dB/oct in frequencies 100-1000 Hz 1000 g in frequencies 1000-5000 Hz
Leak testing (internal)	T = 100ºC, 24 hours. Leak inferior to 0.1% of the tank weight

Table 2 resumes the qualification tests performed on the propulsion system in 2019, prior to the first flight, in addition to the internal lifetime and cycles testing previously mentioned already. Of especial importance to avoid problems with iodine was to guarantee a minimal leak rate of the system.

Figure 9 shows the results of the thermal vacuum testing of the I2T5, where the electronics were turned on during one hour in each of the 4 cycles, both in the hot and cold steady cases, to verify that the thruster was still operative.

DEPOSITION STUDIES

The main advantage of iodine is that it can be stored as a solid, with low vapor pressure, removing the problem inherent to pressurized systems, as it was previously stated. This, however, can also cause that the substance deposits on the outer surfaces, creating layers of iodine that may re sublimate again during the hot periods of the orbit and redeposit again in other surfaces.

The process of deposition of these iodine molecules when they first interact with the surfaces is driven by chemical adsorption, and the molecules arriving can be held in the surface due to the intermolecular bonds generated by their van der Waal forces [22,23]. Iodine, as part of the halogens is a strong oxidizer, and tends to interact with an elevated number of substances. To mitigate this problem, a careful design of the outer surfaces of the thruster can be made so that the molecules in the outer plume are directed towards the outer space. However, due to interaction in the free molecular flows, and backfiring effects in small geometries there will be an amount of molecules that bounce back and return to the spacecraft. This iodine might create a monolayer by chemical adsorption in surfaces which are prompted to react with the oxidizer, so mitigation via a careful selection of the materials in direct contact with the plume needs to be done. On top of this monolayer, iodine can deposit as previously described. If the pressure of the vapor is greater than the vapor pressure at the temperature of the surface concerned, iodine will deposit on it. The typical temperatures at which iodine will condensate for the mass flow rates used in the thrusters follow under the cryogenic conditions, where the deposition temperatures are typically lower than -50ºC [8].

The CSUM has simulated the Worst Hot Case and Worst Cold case to obtain the temperature of the ROBUSTA-3A satellite with the help of the Thermica Satellite software.

At the time of writing, the model of 2277 nodes is defined to represent the capacity, thermal conductivity, interface contact and optical surface properties. The temperatures are then calculated using a stabilized cycling transient solver, a Crank-Nicolson algorithm. The temperature convergence criterion is set to 2° Celsius on all nodes.

For the worst cold case, the simulation considers an altitude of 800km, orbitals fluxes such as the albedo flux, solar flux, and eclipses indirect shadow, as well as the dissipations have all been set to 0W.

Figure 10 presents the temperature maps at the coldest point of the cold case orbit. While the internal temperature remains in the working range of electronics (>-20°C) the outside surfaces are colder. As it can be inferred from the image, the temperatures on the lateral panels of the spacecraft fall into hotter values than the values expected for causing the deposition of iodine, so no significant surface deposition is expected to occur.

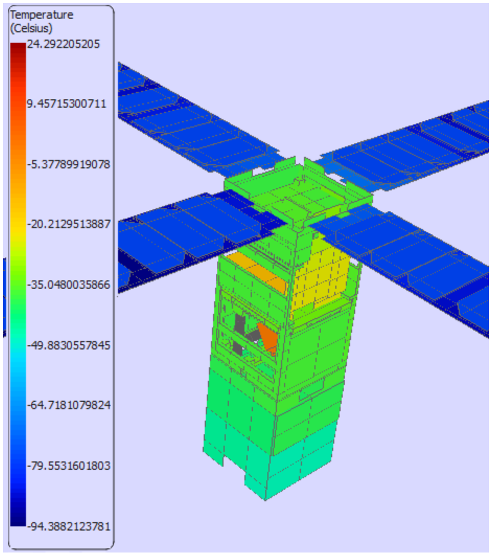

Figure 10 : Worst Cold Case Temperatures of the ROBUSTA-3A Satellite, out of eclipse

The solar panels, which are the coldest elements of the spacecraft, are far from the field of view of the thruster. One has to take into account that, as presented in the Preliminary Mission Analysis section, the orbit altitude will be lower, the unit consumption and dissipation will be higher than presented in the Worst Cold Case, and hence higher temperatures are to be expected and deposition is expected to be negligible.

Finally, the Sun sensors have been placed onto the "X-sides" of the satellite and the propulsion system faces the "+Y side" (Figure 10) in order to further minimize the deposition risk during the mission.

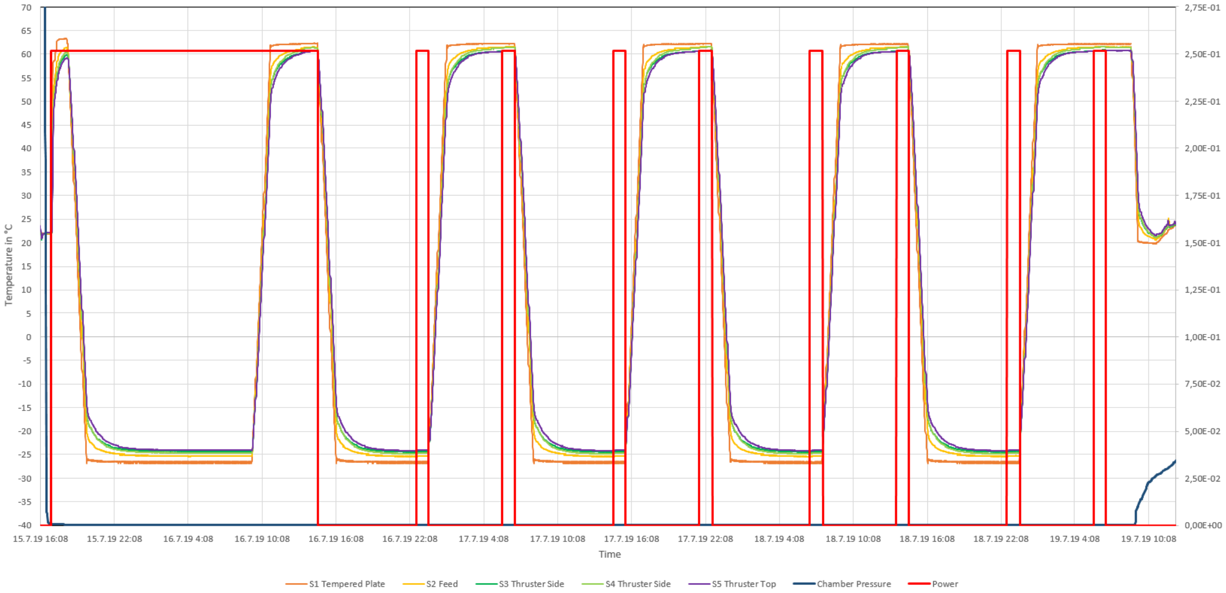

Figure 9: Thermal vacuum testing results for the I2T5 axial propulsion system[24]

PRELIMINARY MISSION ANALYSIS

The aim of this paragraph is to present, the preliminary analysis done in order to demonstrate that the mission is feasible and that it was indeed possible to operate the I2T5 and change the orbit in such way that results could be measured.

While the ROBUSTA-3A has a relatively large battery to cope with the main data collection and relay mission, it cannot operate the I2T5 for very long periods of time. One must also consider the fact that ROBUSTA-3A has no on-board GNSS and must rely on TLE to estimate altitude changes. These two facts prove to be a challenge for I2T5 operation and quantification of the results.

The aim is to operate the I2T5 by 3-hour cycles, up to 10 separate cycles in total, within a few weeks, in order to clearly distinguish a change in orbit, which is linked to the I2T5 Operation.

In order to simplify the operation the team opted not to perform communication with the ground segment while the propulsion was in operation. However, the Robusta-3A satellite broadcasts key health status information via UHF at all time.

Since the Sun synchronous orbit would provide communication opportunities twice a day with the CSUM ground segment in Montpellier, the operation concept calls for alternating paths with commanding of the satellite and dumping of detail telemetries and paths where propulsion is performed and the ground segment is allowed to receive status via the emitted beacon. A further option to be studied is to receive help from other stations, such as SatNogs, in order to receive updated information. In order to avoid conflict with the FSOA (French Space Operation Act) it was decided to lower the altitude of the satellite during the firing periods.

One more thing to account for is the time required both to establish the maximum thrust and then to allow the cool down of the I2T5 and mitigate the residual thrust. Based on Figure 6 it was estimated that the time required to establish full thrust is 15 min and the cool down time is estimated to be 1h.

Based on the above constrain the team settled on the following operation concept for the operation:

1- Command the satellite to align the I2T5 Thrust vector to the velocity vector.

2- Wait (10min) for target to be reach and ADCS to stabilize.

3- Switch the propulsion ON for 3h15min. This is equivalent to 15min of 12W consumption for the warm up, and 3h of 6W consumption in steady state.

4- Switch the propulsion to “IDLE” mode for 1h to allow for cool down. The residual thrust will further lower the satellite altitude.

5- Switch the propulsion OFF and command the satellite back to a Sun pointing attitude (10min).

Orbit Change

Assuming this mission profile, which lasts about 4.5 hours, and a spacecraft mass of 4.3 kg, the thruster is capable of increasing the semi-major axis in 930 meters. This maneuver can be repeated several times and uses around 5% of the total available iodine in the propellant tank. This in turn would allow to increase the duration of the mission considerably, and in the case of this demonstration to de-orbit quicker and hence reduce risk associated with end of life and space debris.

Case to Consider for Power Budget and ADCS Calculation

As the launch date and launcher are not yet known for the ROBUST3A-3A mission, it is difficult to estimate what cases shall be considered both to verify the power budget constrain and the ADCS capabilities.

The team had settled on the orbit for the mission analysis of the main mission. It was decided to use the same for the I2T5 mission, until a launch was booked.

Table 3 Preliminary Mission Analysis Orbital parameters

Semi-major Axis (km)	**Eccentricity**	**Inclination (°)**
6977.6	0.0012103	97.9
Argument of perigee (°)	**Right ascension of ascending node (°)**	**True Anomaly (°)**
178.9	As needed for local hour	Time dependent

Further working the team identified a set of 8 cases that would be analyzed to demonstrate the mission is feasible and model the satellite behavior during the mission.

As the mission analysis is only in preliminary phase and the ADCS laws are not yet optimized, only the results of case N°2 and N°7 are presented. As explained in the results chapter latter, this is already sufficient to demonstrate the mission feasibility.

Table 4 Summary of the mission analyses cases selected for analysis

N°	Local Time	Time of year	Comments
1	6am	December	Solar panel pointing optimized
2	6am	December	Solar panel pointing not optimized
3	6am	June	Similar to case N°1 but different equinox
4	12h	December	Solar panel pointing optimized
5	12h	December	Solar panel pointing optimized. Similar to case n°4 with a start time in full Sun
6	12h	June	Solar panel pointing optimized
7	12h	June	Solar panel orientation not optimized
8	12h	December	Same as case N°4, addition a yaw flip during maneuver to assess further optimization of energy inputs.

While many parameters may be discussed and cited, the the propulsion power consumption, crucial for the mission analysis, is given and derived from the testing results of the I2T5, and equal to:

Thruster Consumption during warm up = 12W+20% margin

Thruster Consumption in steady state = 6W+20% margin

PRELIMINARY MISSION ANALYSIS

Methodology

The CSUM is establishing a process for performing complex mission analysis and obtain meaningful power, attitude and thermal results based on mission requirement. The tools are based on Scilab/CELESLAB Toolbox, Simu-CIC and VTS courtesy of CNES, MATLAB/Simulink and Thermica, courtesy of Airbus. All file are exchanges using the CIC format, derived from the CCSDS protocol [25]. The process is described in Figure 11.

In a first step, a Mission Analysis code, running under Scilab allows to define the best targeting coordinate for the science mission, these can later be transferred to the ADCS simulation in order to compute attitude and Sun exposition (arrow 1). This block is not used for the propulsion mission, it is submitted as a student paper to the 4S symposium 2020 [26].

In a second step, the feasibility of the attitude control is investigated by the ADCS simulation. Such a simulation is currently being developed using MATLAB/Simulink. At the moment, the target attitude is computed for each ADCS mode and then transferred to the ADCS simulation. When it comes to the propulsion phase of the mission, the use of the remaining degree of freedom to optimize the power collection of solar panels is still lacking. Later on, we will discuss its main impact on the current results. Given the target attitude, expressed with quaternions, this tool simulates the CubeSat with its expected configuration of sensors and actuators:

- Three reaction wheels in a pyramidal configuration for precise attitude control, especially during orbital maneuvers. The CubeWheel Small reaction wheels from CubeSpace were chosen;

- Three CubeRod S magnetorquers from CubeSpace for rough attitude control and reaction wheel off-loading;

- A set of sensors for attitude determination, namely Sun sensors, magnetometers and gyroscope.

Here, we briefly introduce the ADCS simulation logic. The attitude determination is currently not taken into account in the simulation, which is equivalent to considering that the attitude is perfectly known at any given time. Following the classic ADCS control loop, a PD controller evaluates a torque command from the difference between the target and current attitude. The command is then transformed to account for the actuators configuration. The equations of motion, namely kinematic and dynamic equations, are responsible for computing the change in spacecraft attitude due to the applied torques.

During propulsive maneuvers, a major aspect is the inherent disturbance torque resulting from the misalignment of the thrust axis with the center of mass of the spacecraft. Such a disturbance often overcomes classic external disturbances such as gravity gradient or solar radiation pressure, and may result in mission loss [27]. In the case of ROBUSTA-3A, the propulsion system has to be positioned far away from the CubeSat's center of mass to respect the payload constraints. Hence, reaction wheels shall actively compensate the resulting disturbing torque while providing the required pointing, although the thrust axis is tilted by ~ 60 degrees in order to minimize the perturbation.

In a third step, the attitude quaternion may be transferred to the EPS simulation tool (arrow 3) and Thermica (arrow 4). Further down the line the reaction wheel power consumption curves will also be included into the set of transferred data.

The Thermica model allows to compute the expected temperature of the solar panels and the batteries as well as the required heater power. They can then be transferred to the EPS Simulation (arrow 5), at the moment only the temperature is inputted into the EPS simulation.

The behavior of the energy power system (EPS) in the mission can be calculated with the information obtained from the ADCS and thermal simulations. This energy simulation is essential to know the level of the Depth of Discharge (DoD) of the batteries when the propulsion is in operation. A requirement for a mission to be successfully executed is that the DoD of the batteries cannot exceed 80%. The Robusta-3A has four rechargeable Li-ion cells, with a total capacity of 73 W·h.

The Robusta-3A power input is composed of four solar panels with six triple Junction Solar Cell Assembly 3G30A, producing a maximum input power of 33.38 W. These panels were modeled to calculate the input energy. This model has three inputs: temperature of the solar panels, angle of the solar panels concerning the sun, and position of the satellite in orbit to know if the solar panels are in eclipse or not. The thermal model provides the temperature (arrow 5). Solar panels decrease or increase energy efficiency, depending on their temperature [29]. On the other hand, the ADCS simulation model provides the solar panels' angles and the satellite position (arrow 3). The radiation incident on the solar panels at each instant in orbit is known with these two variables. The more the irradiance, the more the power given by the solar panels increases.

Another important information to calculate the energy behavior in orbit is the satellite's power budget. All the maximum powers consumed by each system are modeled, and the operating modes of the satellite are defined. The ADCS simulation also provides these operating modes (arrow 3), which defines the working of the satellite in every moment. For example, when the satellite is in Sun pointing mode, the satellite consumption is close to 4.21W.

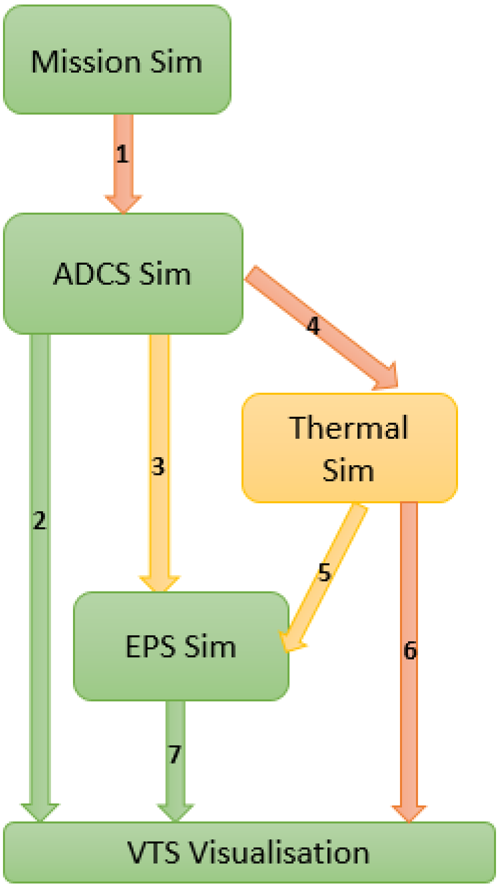

Figure 11 Mission Analysis Tools Flow at CSUM, including current status (Green: functional block/chain, Orange : under development and Red : to be developed)

Finally, to calculate the DoD of the batteries and the satellite's energy behavior, it is essential to study the worst case. For this, efficiencies and losses of the satellite are defined. For subsystems designed and not tested in flight (ECCS category D), a margin of 20% is defined. For subsystems of category ABC, a loss of 10% is defined. Moreover, the efficiency of the EPS is defined. EPS has an input efficiency of 85%, a distribution efficiency of 85%, and a charge and discharge efficiency of the batteries of 80%.

Results

Results for case N°2

Figure 11 shows the power behavior of the satellite when the off-axis iodine propulsion system is turned on. The energy input (input), the consumption of the satellite (output), and the response of the DoD can be observed. The figure determines that in the different thrust phases, which begins around the fifth hour of the simulation and ends around the ninth hour, the DoD curve does not reach 80%. As a matter of fact, it reaches 55%. In the conclusion of these simulations, the Robusta-3A Satellite power subsystem can supply sufficient energy to the propulsion system and ADCS.

For case N°2 the ADCS perform well within the limits of the mission specifications, as displayed in **Figure 13** and Figure 15

In **Figure 13**, the pointing error never exceeds 2°, which has to be compared with the specification of 5°. As expected, the target pointing is harder to follow when the thruster is firing. Yet, this margin will be reduced once the limitations due to attitude determination will also be simulated. Another crucial aspect is the saturation of reaction wheels. Indeed, reaction wheels tend to saturate when they must compensate a constant disturbance, which means that they reach their maximum velocity.

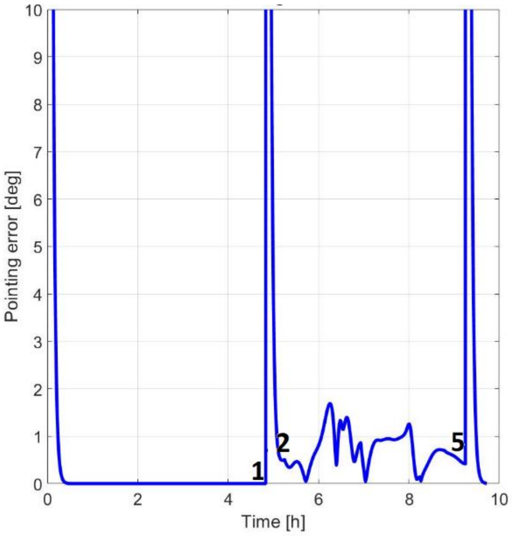

Figure 13 : Pointing error during one scenario. Numbers refers to the sequence of operation as defined in the Preliminary Mission Analysis paragraph.

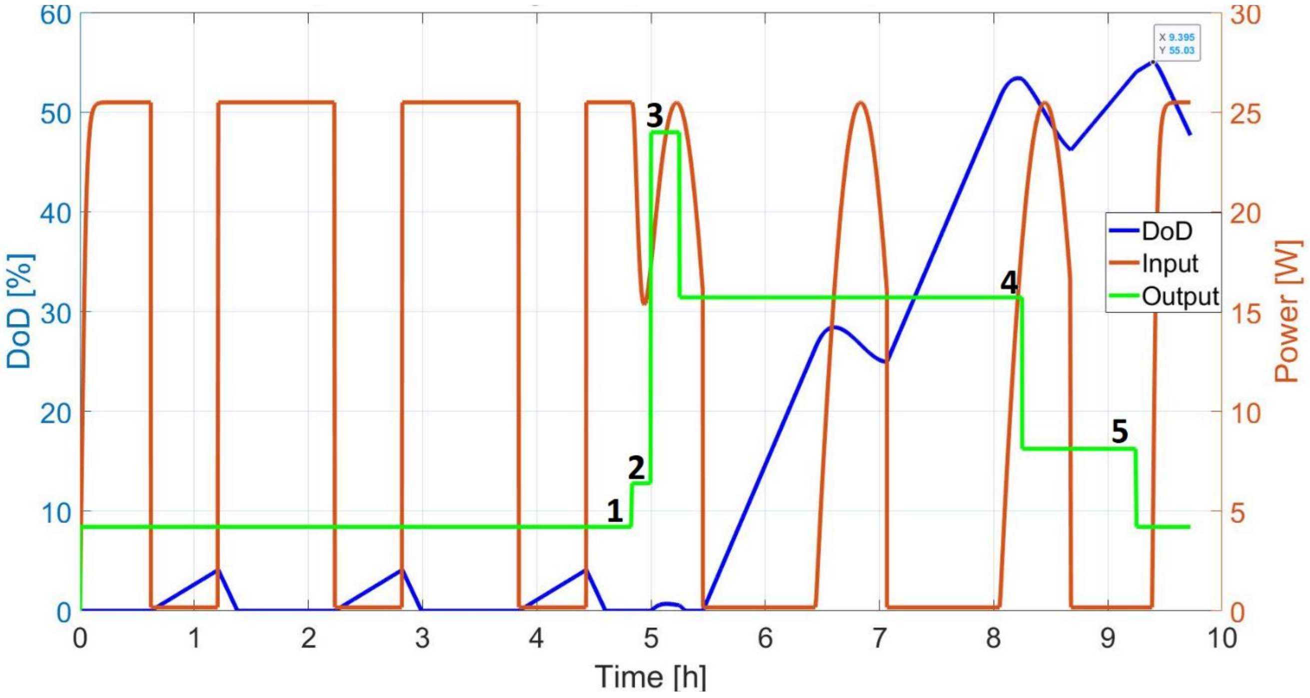

Figure 12: Case N°2 power results: Depth of discharge v input power v output Power. Numbers refers to the sequence of operation as defined in the Preliminary Mission Analysis paragraph.

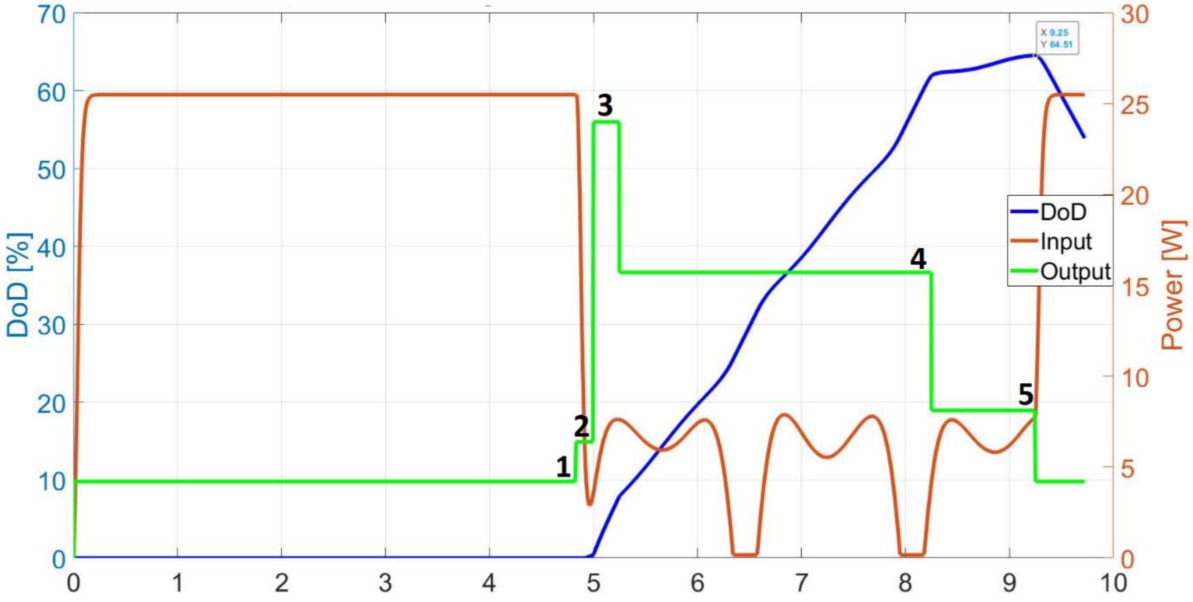

Figure 14: Case N°7 power results: Depth of discharge v input power v output Power. Numbers refers to the sequence of operation as defined at the very beginning of the Preliminary Mission Analysis paragraph.

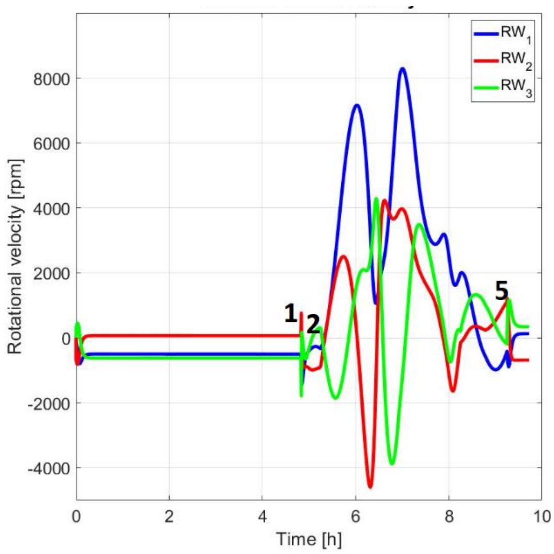

Figure 15 : Velocity of the three reaction wheels during a scenario. Numbers refers to the sequence of operation as defined in the Preliminary Mission Analysis paragraph.

When it happens, other actuators, in our case magnetorquers, are required to desaturate the wheels. One can see in Figure 15 that only one reaction wheel reaches its maximum velocity of 8000 rpm even if no desaturation logic was simulated. This is very promising before implementing the zero-crossing algorithm which will prevent problems such as attitude jitter and faster aging of the wheels.

Results for case n°7

Figure 12 shows the power behavior of the satellite when the off-axis iodine propulsion system is turned on. The figure determines a worst-case DoD of 64.51%. This exceeds the case with eclipse, which may be explained by the fact that while the solar panel remain longer in the Sun it is with a much lower angle with respect to the normal of the solar cells, hence, less power is harvested. This behavior shows room for improvement into the maneuver strategy and possible optimization of the ADCS pointing algorithm.

For case N°7 the ADCS behaves in a very similar way as for case N°2. Hence, we do not present here the results of the ADCS simulation for case N°2.

Validation and Visualisation

The correctness of the attitude validation is checked by transferring the results to a display tool called VTS.

There, the trajectory of the CubeSat, together with its attitude and other relevant information can be displayed in a 3D environment (see Figure 16 and arrow 2 of Figure 11).

Further down the line, the results of the EPS simulation and thermal simulation may be added to the VTS visualization. (arrow 7 and 6). This addition will allow us to verify the proper time synchronization of all the simulation as well as to offer a single view for training of the team and performing the operation.

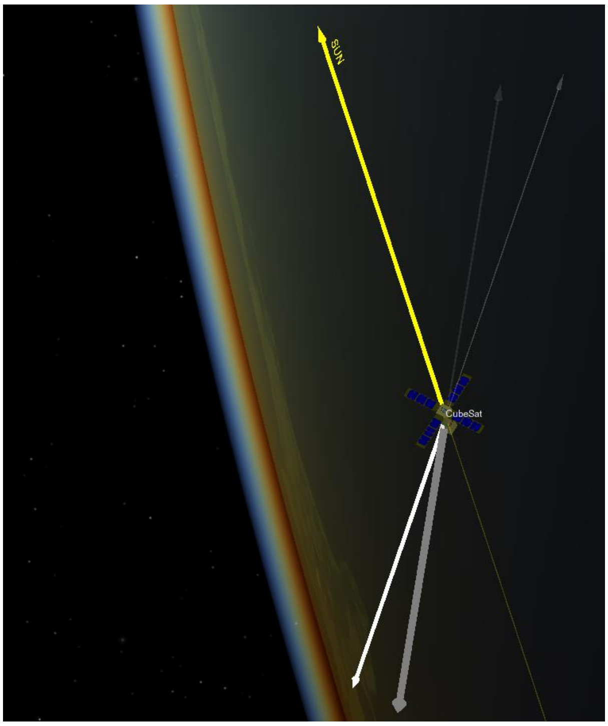

Figure 16 : Results visualization using VTS. The yellow, white and black arrow indicate the Sun direction, the satellite velocity in the inertial frame, and the thrust direction respectively.

CONCLUSION

The ROBUSTA-3A developed by the CSUM Spatial Centre with funding from the Van Alen Fundation (FVA), the French Aerospace Center (CNES) and Interreg Sudoe Program through the European Regional Development Fund (ERDF) will demonstrate a 3-axis stabilized platform of the CSUM and support the GEMMOC project by gathering water content data for improved weather prevision in south France.

In order to lower the altitude of the satellite, perform the demonstration of an off-axis propulsion system for small satellite missions, and to gather more useful data on both the performances of cold gas thrusters operating with iodine in small satellite missions and of low-thrust maneuvers in the orbital environment consider, the I2T5, a 0.2 mN cold gas iodine thruster, has been integrated in the spacecraft. This paper presented the development process of the mission, focusing mainly on the aspects related of the propulsion system. The particularities of the use of iodine, such as its storage density considerations, propulsive efficiency and gas characteristics are considered and taken into account during the design. This is mainly interesting for solving the problems related to its use, such as corrosion related issues and deposition, which are addressed through material selection and simulation of the particular conditions encountered in the system.

The mission analysis has shown that the mission is feasible under the given circumstances and that one of the drivers is the optimization of the satellite attitude with respect to the Sun during the thrust phase.

Future work is required to finalize the operation design and to launch the mission: it will include the optimization of the satellite attitude control laws to account for a shift into the center of gravity of the spacecraft due to the propellant depletion, and to maximize the Sun constraints on the solar panels. The final configuration of the spacecraft will be studied to confirm its thermal behavior and to better estimate the needed cool down time. Once the final orbit is confirmed, and the subsystems integrated have their component performances frozen, including the I2T5 assembled in the satellite in order to perform whole level system tests, a final set of mission analysis will be performed in order to prepare the launch.

ACKNOWLEDGMENT

Both ThrustMe and the CSUM would like to acknowledge all people which make this mission possible:

- The French Government, through the prix - LAB 2017 - 19th Concours National d’Aide à la Création d’Entreprises de Technologies (Ministère de l’Enseignement Supérieur, de la Recherche et de l’Innovation) The van Allen Foundation and its founding members (Airbus, Expleo, Latécoère Interconnection System, University of Montpellier 3DPlus)

- CNES, French National Space Agency, via the INODIN and JANUS programs

- The European Union via the FEDER SUDOE Nanostart programs

- Région Occitanie, via funding of the development of a UHF Telecommunication Board.

References

1. Villela, T. and Costa, C. A. and Brandao, A. M. and Bueno, F. T. and Leonardi, R., “Towards the Thousandth CubeSat: A Statistical Overview,” International Journal of Aerospace Engineering, 2019.
2. Perez F. et Ale, “DustCube, a nanosatellite mission to binary asteroid 65803 Didymos as part of the ESA AIM mission”, Advances in Space Research, Vol.62(12), pp.3335-3356, 2018
3. N. H. Roth, B. Risi, C. C. Grant, and R. E. Zee, “Flight Results from the CanX-4 and CanX-5 Formation Flying Mission,”29th Annual AIAA/USU Conference on Small Satellites, 2015.
4. Spaceworks, Nano/microsatellite market forecast, 9th edition, 2019.
5. Legifrance, “LOI num. 2008-518 du 3 juin 2008 relative aux opérations spatiales,” 2008. [Online].
6. M. Leomanni, A. Garulli, A. Giannitrapani, and F. Scortecci, “Propulsion options for very low Earth orbit microsatellites,” Acta Astronautica, vol. 133,no. October, pp. 444–454, apr 2017.
7. Krejci, D. and Lozano, P., “Space Propulsion Technology for Small Spacecraft”, Proceedings of the IEEE, vol. 106, no. 3, pp 362-78, 2018
8. Martínez Martínez, J. and Rafalskyi, D. and Aanesland, A. “Development and Testing of the NPT30-I2 Iodine Ion Thruster,” 36th International Electric Propulsion Conference, Vienna, 2019.
9. Szabo, J. and Pote, B. and Paintal, and Robin, M., and Hillier, A. and Branam, R. D. and Huffman, E., “Performance Evaluation of an Iodine-Vapor Hall Thruster”, Journal of Propulsion and Power, vol. 28, 2012.
10. Rezaeiha, A., “Design and Development of a Flight-model Cold Gas Propulsion System”, 28th International Symposium on Space Technology and Science, 2011.
11. Martínez Martínez, J. and Rafalskyi, D and Zorzoli Rossi, E. and Aanesland, A. “Development, Qualification and First Flight Data of the Iodine Based Cold Gas Thruster for Cubesats,” IAA-AAS, Roma, 2020.
12. Bernard M., “Is ionizing dose a concern for CubeSats? Robusta-1B a go and find out for yourself mission” Proceedings of the 2018 4S Symposium, Sorento, Italy, May 2018.
13. Laurand X, “Lessons learnt during commissioning and one year of operation of the Robusta-1B 1U CubeSat” Proceedings of the 2018 4S Symposium, Sorento, Italy, May 2018.
14. Bosser, P., Olivier, B., and Nicolas, L.: IWV retrieval from ground and shipborne GPS receivers during NAWDEX, EGU General Assembly 2020, Online, 4–8 May 2020, https://doi.org/10.5194/egusphere-egu2020-6956, 2020
15. Bock, O., Bosser, P., Caumont, O., Legouge, R., and Laurain, N.: IWV retrieval from shipborne GPS receiver on hydrographic ship Borda, EGU General Assembly 2020, Online, 4–8 May 2020, https://doi.org/10.5194/egusphere-egu2020-7518, 2020
16. Goebel, D. M. and Katz, I., Fundamentals of Electric Propulsion: Ion and Hall Thrusters, NASA, 2008.
17. Sutton, G. P. and Biblarz, O., Rocket Propulsion Elements, Wiley, 2017.
18. Micci, M. M. and Ketsdever, A. D., Micropropulsion for Small Spacecraft, Progress in Astronautics and Aeronautics, vol. 187, 2000.
19. Louisos, W. and Alexeenko, A. A. and Hitt, D. L. and Ziliç, “Design considerations for supersonic micronozzles,” International Journal of Manufacturing Research, 2008.
20. Liu, M. and Zhang, X. and Zhang, G. and Chen, Y. “Study on micronozzle flow and propulsion performance using DSMC and continuum methods,” Acta Mechanica Sinica, vol. 22, pp. 409-416, 2006.
21. White, C. and Borg, M. K. and Scanlon, T. J. and Longshaw, S. M. and John, B. and Emerson, D. R. and Reese, J. M. and “dsmcFoam+: An OpenFOAM based direct simulation Monte Carlo solver,” Computer Physics Communications, vol. 224, pp. 22-43, 2018.
22. Boyd, I. and Stark, J. P. W., “Assessment of Impigement Effects in the Isentropic Core of a Small Satellite Control Thruster Plume,”

Proceedings of the Institution of Mechanical Engineers, vol. 203, pp. 97-103, 1989.

23. Scialdone, J. J. “Contamination Control and Plume Assessment of Low-Energy Thrusters,” NASA Technical Memorandum 104585, 1993.

24. Lengowski, M., Test Report of Thermal Vacuum Cycle Test for I2T5. Doc.-No. ThrustMe-RP-0001-IRS, 2019.

25. CCSDS, CCSDS 504.0-B-1 - Attitude Data messages (Issue May), 2008.

26. Jordanov V. et Ale, Mission analysis and target selection for the Robusta 3A mission, 4S Conference 2020 (pending)

27. Quinsac G., Segret B., Koppel C., Mosser B., Attitude control: A key factor during the design of low-thrust propulsion for CubeSats, Acta Astronautica, 2020, ISSN 0094-5765, https://doi.org/10.1016/j.actaastro.2020.03.053

28. Mueller, J. and Ziemer, J. and Hofer, R. and Wirz, R. and O’Donnell, T., “A Survey of Micro-Thrust Propulsion Options for Microspacecraft and Formation Flying Missions,” 5th Annual CubeSat Developers Workshop, San Luis Obispo, 2008.

29. Bellia, Youcef, and Fatima, “A Detailed Modeling of Photovoltaic Module Using MATLAB.” 2014.