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Test campaign of a Cubesat equipped with a helicon plasma thruster

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Abstract

The increasing interest in CubeSat platforms ant their capability of enlarging the frontier of possible missions impose technology improvements. Miniaturised electrical propulsion systems (ePS) enable new mission for multi-unit CubeSats (6U+). While ePS have achieved important level of knowledge at equipment level, the investigate the mutual impact of ePS and CubeSat technologies at system level risking to limit the application of this technology. The interaction between CubeSat and ePS should be assessed in terms of electromagnetic emissions (both radiated and conducted), thermal gradients, high electrical power management, surface chemical deposition, and quick and reliable data exchanges. This paper shows how a versatile CubeSat Test Platform (CTP), together with standardised procedures and specialised facilities enable the acquisition fundamental and unprecedented information. Measurements can be taken both by specific ground support equipment placed inside the vacuum facility and by dedicated sensors and subsystems installed on the CTP, providing a completely new set of data never obtained before. CTP is constituted of a 6U primary structure hosting the ePS, avionic subsystems, batteries and mechanisms. For the first test campaign, CTP hosts the helicon plasma propulsion system, called Regulus and developed by T4I. After the integration and the functional test in laboratory environment, CTP + Regulus performed a Test campaign in relevant environment in the vacuum chamber at CISAS, University of Padua. The test campaign foresees the activation of Regulus for a different time duration and at different power levels. The present paper deals with the description of the entire campaign (lasts from July to September 2020), from the integration up to the performance and functional test in vacuum conditions.

Keywords: Miniaturized electric propulsion system, Cubesat test platform, Cubesat Environmental Tests

Acronyms/Abbreviations

1. Introduction

CubeSats are obtaining a tremendous interest in the last years thanks to their low cost and fast delivery compared with bigger spacecraft missions.

Although the small form factor, the new generation of CubeSat can operate both as support of bigger spacecraft and as stand-alone platforms organized in large constellations. They can pursue advanced objectives in scientific experiments and Earth observation, technological demonstrations, communication networks, and interplanetary exploration (references from [1] to [7])

These new CubeSat require the development of adequate technologies that enhance performance and increase mission success, maintaining a reduced cost and a fast time-to-orbit. Advanced communication systems with higher data rate [8] thermal control systems [9], precise attitude control systems, navigation [10] and effective propulsion systems are the most promising technologies that would provide the quality jump to CubeSats.

In the framework of miniaturized propulsion systems, the developers of electric propulsion systems are growing. Despite of the large number of developers [11], [12] very few CubeSats have flown up today and these systems, especially in Europe, are not still ready mainly because of the lack of a robust integration and verification process with other subsystems of CubeSat. Beyond the stand-alone performance, the propulsion systems interactions, compatibility, and mutual impact on the CubeSat shall be investigated and assessed. That highlights the importance of a complete verification campaign, in order to avoid infant mortality deriving from design weakness and/or ineffective assembly, integration and verification (AIV) planning and execution due to non-standardized processes and lack and/or unavailability of facilities [13]. On the contrary, effective verification process may help to improve the reliability of small satellites [14].

The verification and validation (V&V) process is critical both for small satellites and for Electric

Propulsion (EP) System. Only in the last years some effort was made in this direction mainly providing general guidelines and advices. However, now, small satellites are extensively tested only against launch environment requirements due to the request of launch authorities. On the contrary, minor efforts were made to the verification of functional and operational requirements, that are fully demanded to CubeSats developers. To reduce time and cost, in the small satellite framework, developers and integrators tend to abuse of the analysis in place of test but only part of the answers on software and hardware functionalities can be obtained [15]. This condition is deeply true in the verification of miniaturized (electric) propulsion system point of view because severe rules (i.e. safety requirements and constraints) imposes great efforts to guarantee a complete and reliable verification process. Moreover, specific (and changing with the type of EP system) conditions are required (i.e. a vacuum environment). That result in a very expensive and time-consuming AIV. Moreover, the facilities for bigger propulsion systems are not tailored for the verification of small systems. New facilities able to perform in situ tests and diagnostics are the “Automated Integrated Robotic System for Diagnostics and Test of Electric and ・-Propulsion Thruster”, at Singapore [16], the Propulsion “In the Loop” test bench at University of Stuttgart [17] and the “ESA-Prop Test Platform for CubeSat Propulsion Systems” [18]. However, all these facilities are still under preparation or certification.

Since 2017, ESA is carrying out a program with the cooperation of the Politecnico di Torino that aims at offering a one-stop test facility for the verification and validation of CubeSats with propulsion system. The program has been divided in three phases and, at this time, the second phase is the final step. In the first phase the objective is to host the miniaturized electric propulsion systems, called Regulus and provided by T4I, in the CubeSat Test Platform, CTP, a 6U Cubesat platform based on CubeSat technology, compliant with CubeSat standard and to verify the entire platform in laboratory and in relevant conditions, in particular in the vacuum chambers at CISAS/UniPd and at ESA Propulsion Laboratory.

2. Platform description

The Cubesat Test Platform features an Al-alloy 6U structure, which a Propulsion Box hosts the propulsion system (up to 4U), and a Service Module contains the on-board avionics (1U), and battery packs(1U) [18].

The miniaturized electric propulsion system integrated in the platform is Regulus the helicon plasma thrusted provided by T4I. The main specifications of the QM of Regulus are reported in Table 1 [19], [20], [21], [22], [23], [24], [25].

Table 1: Regulus main features

Thrust	0.5 mN @30W (0.2-0.7) mN
Specific Impulse	600 s @ 30 W (220-900) s
Total Impulse	3000-11000 (up to unlimited) Ns
Required power	50 W (range 20-80 W)
Mass flow	0.1 mg/s
Propellant	Iodine (I2)
Volume **)**	1,5 U @ 3000 Ns 2 U @ 11000 Ns
Weight	2.4 kg @ 3000 Ns

The CTP’s structure is fully compliant with the CDS in terms of external geometrical interface and material (apart from surface coatings and treatments). The structure is constituted by two truss-like parts joined through four brackets and closed by panels. The internal layout can be adapted depending on the specific test. For the first application, a bulkhead is fixed to separate the propulsion box from the rest of the platform.

The avionics (Fig 1) is constituted by the on-board computer for command and data handling functions, the electrical power system (PCDU and battery, no solar panels), and the communication module (UHF for housekeeping and experiment data) and two boards that constitutes the Electric Propulsion Interface System (EPIS).

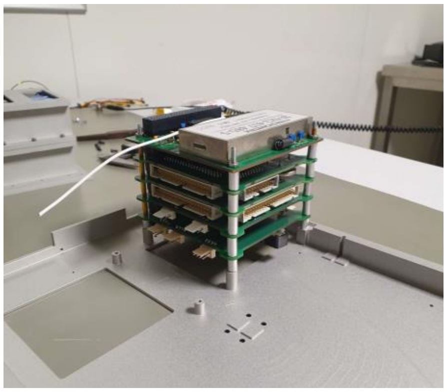

Fig. 1: Avionics stack

EPIS provides the interfaces of CTP towards the EP system and the instruments and devices to measure the parameters for assessing the mutual interactions between CTP and EP system. Two main parts constitute EPIS: the Data Logger (DL) and the High-Power Management System (HPMS). The avionics boards are in-house developed electronic boards resulting representative of the basic Cubesat technology. Data Logger gathers all the information about the radiation and thermal environment and the power consumption of the EP system. The HPMS supplies electrical power at a regulated voltage to the EP system using the energy of two dedicated battery packs; battery packs are recharged thanks to an external source and recharging control circuits. Beside up to twenty temperatures sensors mounted in the critical points inside CTP, a set of small board are mounted on the bulkhead for the assessment of the radiated and conducted emissions. Four pairs of RF sensing circuits are mounted on opposite sides of the bulkhead: a set of four circuits stay towards the avionics box while other four circuits stay towards the propulsion system box. The RF sensing circuits are highly tuned pass-band filters, tuned respectively on the following range of frequency: 1-10 MHz, 20-50 MHz, 50-100 MHz, 400-500 Mhz. Moreover, a nineth circuit called LISN (Line Impedance Stabilization Network) is mounted between the HPMS output and the Regulus power input: this circuit allows to evaluate the radiation environment generated by the propulsion system when it absorbs current (Fig.2).

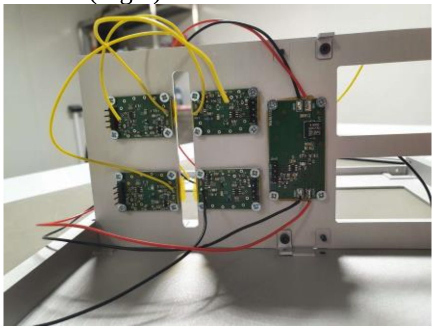

Fig. 2: RF sensing circuits and LISN circuit on the bulkhead

Two lines guarantee communications between the platform and operators: a RF link in UHF band and a wired serial line that directly connect the on-board computer with the Ground Support System. Command & Data Handling is based on ARM-9 microcontroller that manages data and commands time, operations and on-board failures. Sensors and acquisition circuits provide the information (e.g. voltages, currents, temperatures, magnetic fields, and electrical fields). Electrical Power System is constituted by a board that controls and distributes power to the other subsystems and manages the avionics battery packs recharging. Batteries (both the Avionic Battery packs and the Propulsion Battery packs) are installed in the second unit of the Service module and can be recharged during the test thanks to an external line connected to GSE through vacuum chambers umbilicals. Fig 3 provides a total view of the Service Module.

Fig. 3: A view of the Service module

Regulus is then integrated in PS box, along the main axis of the platform, mechanically fixed using 12 M3 screws and connected to the CDH board via I2C. The communication is managed using a CSP protocol. Similarly, the power input of Regulus is connected to the HPMS step-up circuit output power via the LISN circuit (Fig 4).

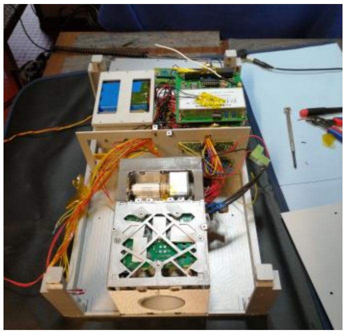

Fig. 4: a global view of the internal layout of the CTP +Regulus

The platform is fully representative of a 6U CubeSat flight unit, which can be used for qualification of propulsion systems as well as verification of onboard avionics. The total weight of the CTP + Regulus is less than 6 kilos (Fig. 5).

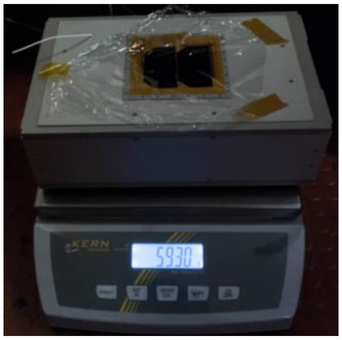

Fig. 5: CTP fully integrated

3. Verification campaign

Inside an exhaustive verification plan, this paper is focused on the test sessions in laboratory conditions conducted both in the clean room of the Politecnico di Torino and at the CISAS laboratory in Padua and, even, the most relevant test campaign, made in vacuum conditions at CISAS. All these tests mainly consist of interface tests, full functional tests and performance tests.

3.1. Full Functional Test sessions

Full Functional Tests (FFT) has the objectives to meet the main functional, operative, interface and physical requirements @system and subsystem levels. These tests allow demonstrating that CTP can perform all the intended functions:

- Data collection, packet preparation and transmission from CTP

- Commands reception, validation, decoding, interpretation, execution and transponder transmission by the CTP
- Correct batteries charge/discharge rates
- Correct transitions between operative modes
- Correct power supply and management of the PS

The first session was performed at Politecnico di Torino, the CTP did not still include Regulus that has been substituted by dummies models and electro-functional models (EFM) to confirm the mechanical, electrical and data interfaces (Fig 6). The second FFT session was conducted at CISAS in Padua after the integration of Regulus in the Propulsion box of the CTP (Fig 7). In this phase, other functionalities are verified:

- CTP electrically supplies Regulus the required power.
- CTP exchanges data packets and commands with Regulus. That enables the Regulus activation and deactivation, propulsion system internal modes transitions (excluded the firing activation) were verified.
- The thermal behaviour of the EPS board, HPMS board, battery packs and Regulus do not compromise the operations of the CTP.
- Mechanical connection is confirmed, and PS is safely fixed to the CTP structure.

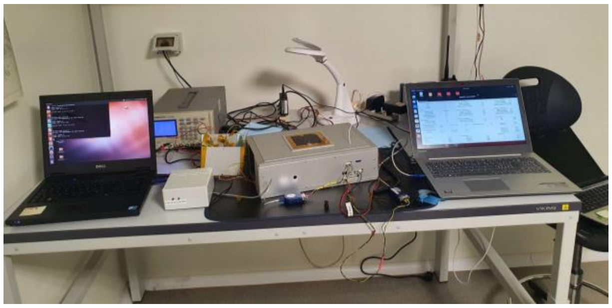

Fig. 6:FFT setup @Politecnico di Torino

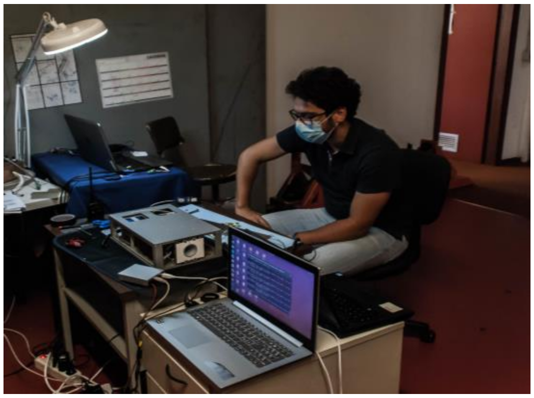

Fig. 7: FFT @ CISAS UniPD

3.2 Test campaign in vacuum chamber

For the vacuum chamber tests, the platform is mounted on the thrust balance, and the thrust balance mounted inside the chamber. The thrust measurements are supported by a laser interferometer for balance displacement measurement, and a faraday probe is installed outside the thrusting direction for radial scanning. Moreover, a dedicated feedthrough allows the connection of the Ground Support System (GSS), Workstation, Load switch, RF antenna, and power supplier from outside the chamber. GSS constitutes the main interface between CTP and the operators. The GSS has two communication lines, corresponding to the two lines of the CTP. Workstation permits a direct connection with the CDH controller monitoring its right execution and providing a further point of test control. The external Xenon reservoir is connected to the CTP and re-filling the Regulus tank when needed. At the end, the calibration of the balance is performed, and the chamber prepared up to achievement of the vacuum conditions. Fig. 8 reports the installation of the thrust balance with CTP inside the vacuum chamber.

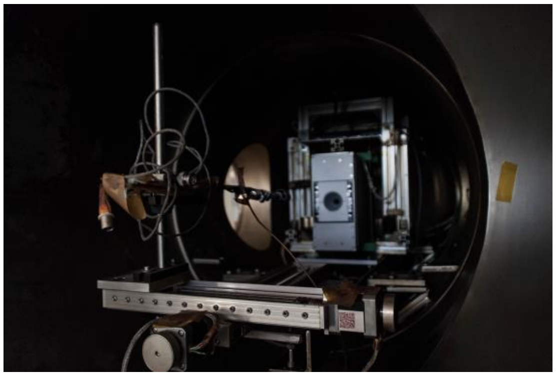

Fig. 8: CTP mounted on the thrust balance inside the vacuum chamber

Three major sessions were performed: a pre-test session confirm the correct activation and de-activation sequence, though quick heating and firing of a couple of minutes to inspect the plasma output. Then, two sessions were dedicated to the thrust measurements and thermalization that allows to understand the thermal environment inside the CTP during the different mode of operations. The thrust test sequence is reported in Fig 9: three different level of thrust are measured at regular intervals for at least 3 times. The thermalization test profile is shown in Fig.10: the propulsion system has a reduced warm-up time and a firing duration of at least 30 minutes.

The assessment of the mutual impact between Regulus and CTP has been made in terms of conducted and radiated RF emissions, power consumption medium and peak for different level of thrust, thermal environment inside the platform both on the avionics box and in the propulsion system proximity, chemical contamination in terms of performance degradation of a solar panel mounted on the +Z face of CTP.

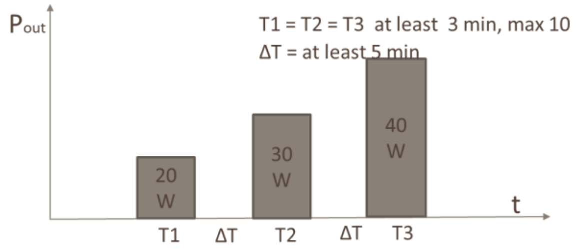

Fig. 9: test sequence for thrust measurements

Fig. 10: test sequence for thermalization test

4. Results

This paragraph is dedicated to the test results specifically for the assessment of mutual impact, from the platform point of view. In particular the focus is on the thermalization test because the results of thrust test sessions are reported in IAC-20,C4,5,17,x60498. In detail, the thermalization test consists of a first phase in which the platform is in basic mode and the Propulsion System OFF. After the reception of the command for the activation, the propulsion system enters in its initialization phase (consumption of less than 0.3 A) that includes also the opening of a valve (consumption of about 0.5 A). When the PS starts the firing (in this case no pre-heating/warm-up phase has been done) at 30 W a consumption of 4.2 A is observed and this value progressively decreases during the firing time due to the completion of the heating for the main components. After 45 minutes, a command from GSS stops the firing and enables a cooling phase (consumption about 2 A) for 15 minutes. Then the PS return in stand by status up to the complete switch-off and the return of the CTP in basic mode.

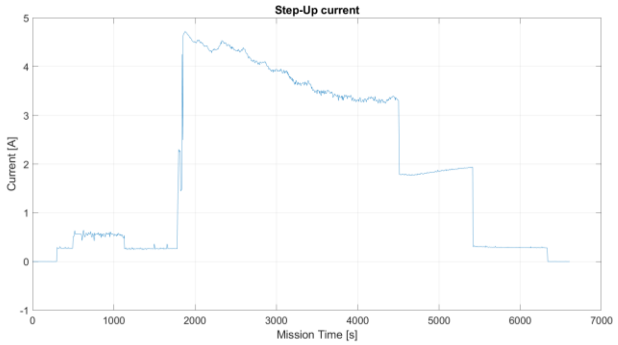

Fig. 11: current absorbed by Regulus

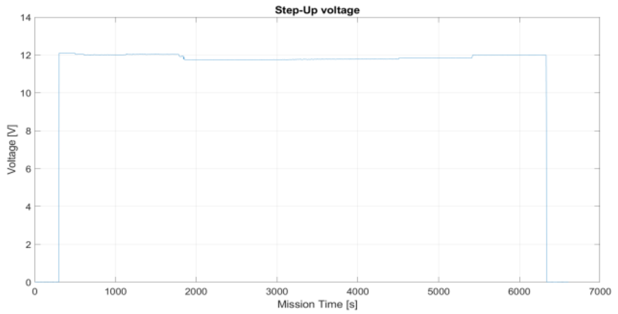

Fig. 12:Voltage in output of HPMS towards PS

During the thermalization test the batteries provide the required current with discharge voltage of 1.1 V after 45 minutes of firing, battery temperature increases of ten degrees during the firing a slightly go back after the end of the firing. The step-up circuit provides the voltage in the range 11.7 and 12.06 V according to the loads current request.

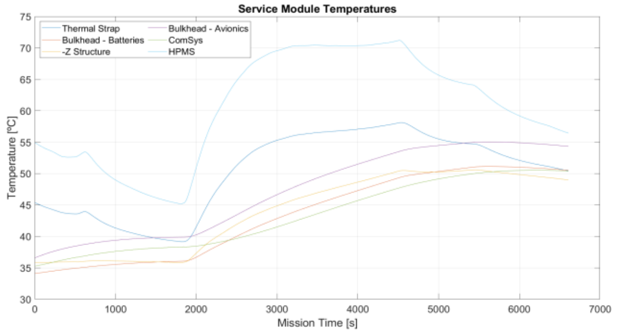

Fig. 13: Temperatures in the Service Module

From the thermal point of view, the temperatures of all the components remain in the operative range. Interesting is to observe the behaviour of the thermal strap mounted on the critical HPMS items: a temperature sensor is mounted on the thermal strap (blue line in Fig 13) and on the upper side of the HPMS (cyan line in Fig 13). A reduction up to 20 degrees is observed thank to the thermal strap confirming that the solution is effective.

Temperatures increase up to fifty-five near the propulsion system temperature increase up to fifty-five (Fig.14) where 7 temperature sensors were mounted.

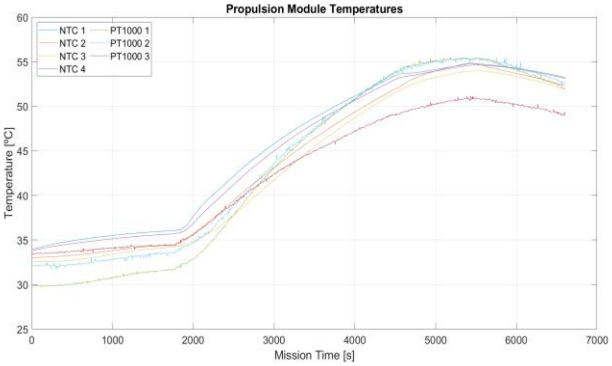

Fig. 14: Temperatures in Propulsion Box

The radiofrequency emissions are evaluated in four frequency ranges (Fig. 15, Fig.16, Fig.17, Fig.18): the operations of Regulus generate an increment of the noise levels in particular in the range of 1 to 10 MHz and 20-50 Mhz. This increment is observed both from in the propulsion box and in the avionics box. In particular, the most relevant increment of 20 dB of is observed in the range 20-50 MHz. However, all these emissions do not compromise the operations both of Regulus and the CTP during the entire test: no losses of communications, no failures of switching of the step-up HPMS are observed.

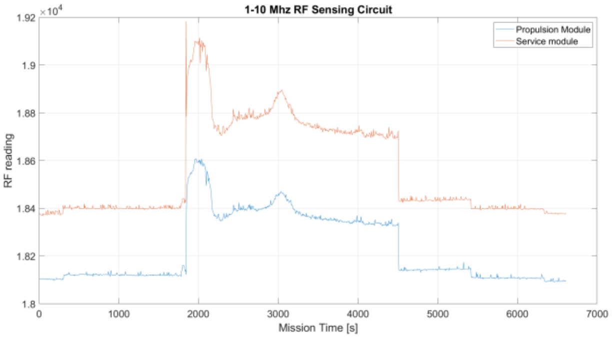

Fig.15: Trend of the RF emissions in the range 1-10 MHz

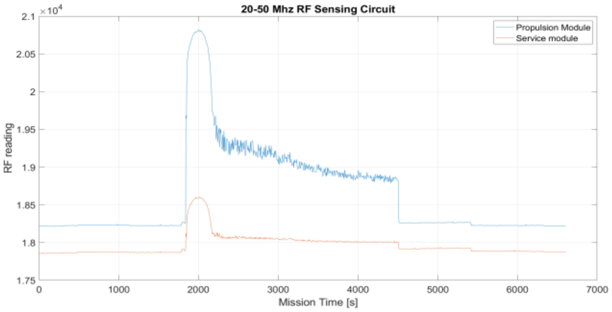

Fig. 16: Trend of the RF emissions in the range 20-50 MHz

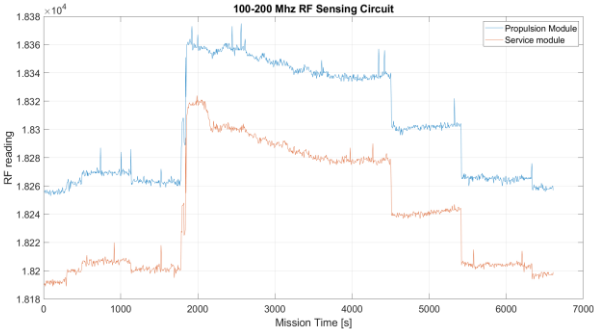

Fig. 17: Trend of the RF emissions in the range 100-200 MHz

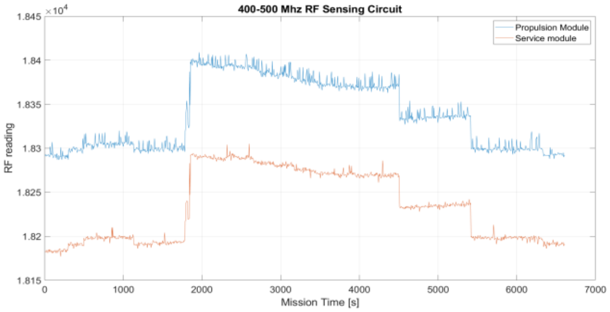

Fig. 18: Trend of the RF emissions in the range 400-500 MHz

As said above, the LISN circuit allows to assess the conducted emissions due to a load (i.e. Regulus) on the power supplier (i.e. HPMS output). Fig.19 shows that this kind of emissions is definitely negligible: variations can be observed for the different levels of power load but the different values in figure correspond to an emission of few dBm

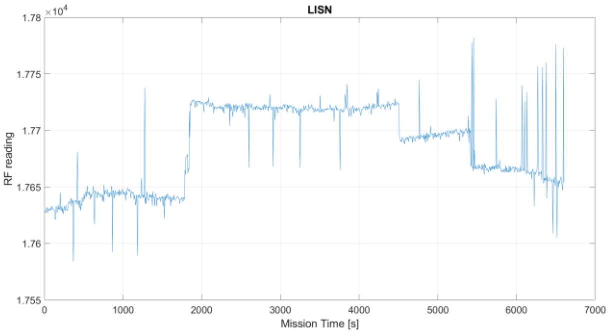

Fig. 19: LISN circuits measurements trend

5. Conclusion

This phase of the test campaign allows the assessment of the mutual impact of an electric propulsion system and the Cubesat technology at system and subsystem levels. From the platform point of view, CTP demonstrates the capability to manage the on board operations with traditional protocols, the capability to provide high power (up to 60 W, a very relevant value for a 6U Cubesat) from CTP to Regulus has been guaranteed in any operative mode and for long time.

Variations of the RF noise emission has been observed during the test according to the operative mode of Regulus, but no major impact is observed on the CTP operativity. The generated thermal environment by the propulsion system during long firings and by the battery recharging at high rate should be considered in detail and TPS/TCS system (at least passive) would ensure safer operation conditions. From the propulsion system point of view, it is demonstrated the possibility for a Regulus to be integrated in a Cubesat platform without major impact on the basic avionics systems.

Future works are driven by the improvement of the data exchange between Regulus and the platform in terms of communication reliability (e.g. implementing information redundancy techniques), the improvement of the thermal protection of the avionics, and the improvement of the sensors and sensing circuits calibration. Moreover, mission tests, including different mission profiles for a 6U Cubesat with propulsion system, would allow to assess the impact of the propulsion system at mission level. At the same time, test session in thermo-vacuum chamber would improve the assessment of the thermal environment inside the CTP.

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