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Environmental test campaign of a 6U CubeSat Test Platform equipped with an ambipolar plasma thruster

Fabrizio Stesina*[1], Sabrina Corpino[1a], Eduard Bosch Borras[2], Josè Gonzalez Del Amo[2], Daniele Pavarin[3,4], Nicolas Bellomo[3] and Fabio Trezzolani[3]

[1]*Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino, Italy*
[2]*European Space Agency (ESA), ESTEC, Kepleerlan 1, Noordwijk, The Netherlands*
[3]*Technology for Innovation (T4I), Via Altinate 125, 35121 Padova (PD), Italy*
[4]*Università di Padova (CISAS), Via Venezia 59/4. 35129 Padova (PD), Italy*

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Abstract. The increasing interest in CubeSat platforms ant their capability of enlarging the frontier of possible missions impose technology improvements. Miniaturized electrical propulsion (EP) systems enable new mission for multi-unit CubeSats (6U+). While electric propulsion systems have achieved important level of knowledge at equipment level, the investigation of the mutual impact between EP system and CubeSat technology at system level can provide a decisive improvement for both the technologies. The interaction between CubeSat and EP system 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 standardized procedures and specialized 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 EP system, representative CubeSat avionics and batteries. For the first test campaign, CTP hosts the ambipolar 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. This paper is focused on the test campaign description and the main results achieved at different power levels for different duration of the firings.

Keywords: CubeSat Test Platform; environmental tests campaign; miniaturized ambipolar plasma thruster; small satellites

1. Introduction

With the strong market demand for affordable space assets, the number of CubeSats will continue to grow. CubeSats can pursue advanced objectives in scientific experiments and Earth observation, technological demonstrations, communication networks, and interplanetary exploration.

*Corresponding author, Ph.D., E-mail: fabrizio.stesina@polito.it
[a]Professor, E-mail: sabrina.corpino@polito.it

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However, to achieve these objectives, the modern CubeSats technology still needs improvements, and the process of manufacturing, assembly, integration, and verification should be got more efficient. Propulsion is one of the enabling technologies because a large variety of operational capabilities can be achieved by performing attitude and orbit maneuvers. Valuable examples of operational capabilities that enables new mission concepts are: performing a variety of operational capabilities, including drag compensation in Very Low Earth Orbit (Bertolucci *et al.* 2020), orbit maintenance and station-keeping in LEO, formation flying (Edlerman and Kronhaus 2017, Cresto Aleina *et al.* 2016, Lafleur and Apffel 2021) in mega-constellation missions (Curzi *et al.* 2021), deorbiting maneuver (Hakima and Emami 2020), proximity operation in servicing missions (such as observation and inspection of ISS (Nichele *et al.* 2018), a debris (Richard-Noca *et al*. 2016) or an operative vehicle (Corpino *et al.* 2020), interplanetary transfer and planetary orbiting control (Walker *et al.* 2017, Schoolcraft *et al.* 2017, Krejci *et al.* 2019, Corpino *et al.* 2020).

In the framework of miniaturized propulsion systems, the amount of products (based incremental and disruptive technologies) is growing, and many developers is working in the CubeSat world. In (Lemmer 2018), author provides a deep review of the state of art up to 2017, while Tummala and Dutta (2019) report the miniaturized propulsion systems state of art up to 2018. Levchenko *et al*. (2018) highlight the perspectives of small satellites equipped with propulsion systems and propose detailed description of the technologies. Similarly, Krejci and Lozano (2020) compare the different technologies, defining specific figures of merit and showing the gaps that should be filled to improve all the technologies. Stand-alone performance and capabilities of incremental and disruptive propulsion system technologies are deeply investigated by the propulsion system developers. In 2021, O'Reilly *et al.* (2021) trace a complete review of electrostatic, electrothermal and electromagnetic propulsion technologies based on state-of-the-art research and the current knowledge base, providing the most actual snapshot of miniaturized electric propulsion systems. Miller (2018) compares the advertised performance of existing chemical, cold gas, and electric propulsion systems across two representative small satellite missions with the goal of providing mission-enabling information to the small satellite research community.

Developers sink great efforts to define the main performance parameters of the propulsions systems components (King *et al.* 2021, James *et al.* 2015) to optimize the configurations (Lim *et al*. 2016), to characterize components (Habl *et al.* 2020) from chemical and electrical point of view, often confining the attention at propulsion system level. Experimental characterization of plasma properties along the magnetic nozzle of an electron cyclotron resonance thruster is presented in Correyero *et al*. 2019, Mazouffre *et al*. (2019) show the characterization of the plume made in laboratory conditions for EXOTRAIL hall thruster. University of Stuttgart proposes a Pulse Plasma Thruster, called Petrus, verified through hardware in the loop simulations that allows to evaluate the performance of the propulsion system Montag *et al.* (2018). In (Zaberchik *et al.* 2019), verification at component level has been conducted for propellant tank, thruster assembly, pressure regulators, and fill and vent valve for Adelis-SAMSON nano-satellite cold-gas propulsion system. The qualification test campaign of a Pulsed Plasma Thruster is proposed in (Tsay *et al.* 2017) with focus on mechanical, thermal cycling and EMC tests. An iodine-fueled RF ion propulsion system (compatible with the 6U CubeSat form-factor) is developed by Busek that performed integration, functional test at component level ((i.e., the flight PPU subsystem, including a demonstration of thruster-cathode hot fire with the full suite of PPU breadboards) and the random vibration test of other mechanical parts (e.g., the gimbal elements) (Glenn Lightseym *et al.* 2018). Reissner *et al*. (2016) show the setup and the results of the performance tests (made at Georgia Tech facilities) of a cold gas (with the majority parts manufactured with 3D-printing technology) for attitude control thruster produced for the BioSentinel spacecraft. Endurance test of 10000 hours on FEEP Enpulsion propulsion system are presented in (Pallichadath *et al.* 2018).

Notwithstanding these extensive test campaign at component and propulsion system levels, rarely the propulsion systems are integrated in a CubeSat platform and very few CubeSats with propulsion system have flown up today (Potrivitu *et al*. 2020).

The complex integration with the actual small satellites technology and the difficulty to effectively complete a test campaign at system level are getting slower the development of projects with CubeSats equipped with propulsion system. The reduced integrability derives from a lack of knowledge about the mutual impact between the propulsion systems technologies and the actual CubeSat technologies in terms of interfaces, electrical power consumption, electromagnetic compatibility, generated thermal environment, and chemical contamination.

Moreover, the verification process is critical especially for small satellites and for Electric Propulsion (EP) System. The verification of EP system is constrained by severe rules (i.e., safety requirements and constraints) for any type of propulsion system (chemical or electric, miniaturized or very large). Small satellites verification and qualification processes is not standardized, and few efforts have been led in this sense (ECSS 2016). Moreover, any propulsion system requires specific (and changing with the type) conditions to be tested. That implies high cost for rent and long duration activities, stretching the schedule and the cost of a project conversely the paradigm “low cost and fast delivery”, typical of CubeSats projects. In addition, from the side of the small satellites, the verification process, a limited standardization can be observed. Although an effective and exhaustive verification process would help to increase the reliability of small-scale satellites, only in the last years some effort was made in this direction mainly providing general guidelines and advice. Up-to-now, small satellites are extensively tested against launch environment requirements upon request of launch authorities, but minor efforts have been committed to the verification of functional and operational requirements, that are fully demanded to CubeSats developers. Often, to reduce time and cost, developers and integrators tend to abuse of the analysis in place of test. However, pure analysis and simulation alone give only part of the answers to verify software and hardware functionalities. In fact, the real system may exhibit behaviors that cannot be modelled perfectly, thus affecting the outputs to a great extent. Moreover, it is difficult to model the interdependencies between elements, especially when new and disruptive components/subsystems are considered. There are a high number of facilities equipped for stand-alone tests of miniaturized propulsion system, very few facilities can perform in situ tests and diagnostics of entire small-satellite systems especially for platform equipped with propulsion systems, and actually they are still under preparation or certification, e.g., “Automated Integrated Robotic System for Diagnostics and Test of Electric and mu-Propulsion Thruster”, at Singapore (Lim *et al*. 2018).

Since 2017, ESA and Politecnico di Torino are carrying out a research program with the objectives of 1) building specific instruments for the verification and validation of miniaturized propulsion systems and 2) identifying an effective and standardized Assembly Integration and Verification (AIV) process for CubeSats equipped with propulsion systems. The final goal is the construction of a facility focused on the qualification for launch of the integrated space system and the assessment of the impact of new technologies at system/subsystem level. The program has been divided in three phases. The research program roadmap passes through various steps that allows to prepare ground support equipment and the facility before their validation. The crucial element characterizing the program is a Test Platform that is representative of a CubeSat. The CubeSat Test Platform (CTP) has the capabilities to mechanically host and provide power to a wide range of the Propulsion Systems available on the market. CTP gathers unprecedented data from sensors mounted inside the platform or on its surfaces that can be merged and analysed together with the information obtained from diagnostics elements mounted inside the test facility but not belonging to CTP (Stesina *et al.* 2020).

In the actual phase of the research program, the first selected miniaturized propulsion system, an Ambipolar Plasma Thruster, called Regulus, provided from T4I (Manente *et al.* 2018) has been integrated in the CTP and a test campaign in vacuum chamber has been conducted to demonstrate the capability of the platform and the EP and, even, to investigate the mutual impact between CubeSat technology of the CTP and propulsion system.

The paper describes the CTP and Regulus (Section 2), their integration and the verification campaign process (Section 3) and reports and discusses the results of the verification campaign (Section 4), highlighting the assessment of the mutual impact between CTP and evaluating the performance of the entire platform.

2. CubeSat Test Platform (CTP)

The CubeSat Test Platform (Stesina *et al.* 2019) has the capability 1) to interface the majority of the European miniaturized electric propulsion systems in terms of power supplying, communication protocols, command and data exchange, mechanical and fluidics interfaces, and 2) to gather unprecedented information on the thermal environment, the radio-frequency emissions and the electromagnetic interference, the electrical power consumptions, and the chemical contamination of the platform surfaces and external elements (such as solar panels). The CubeSat Test Platform is divided in two modules (Fig. 1) divided by a bulkhead: the Service Module contains the avionics boards (1U, called Avionics box) and battery packs (1U, called Battery box) and the Propulsion Module hosts the propulsion system occupies up to 4U.

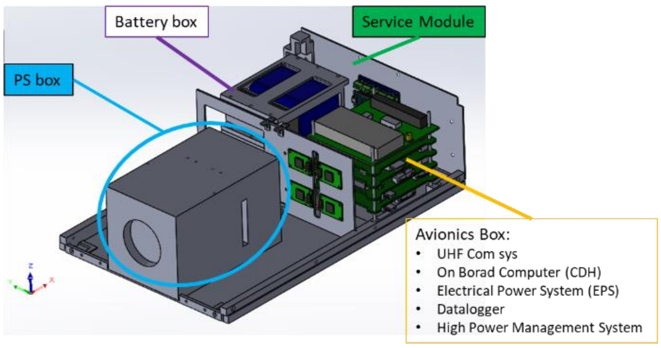


Fig. 1 Internal layout of CTP

The external interfaces (Fig 2) are available on the $+Y$ face, including the battery packs recharging ports, the hardline connectors, and switches.

The battery box accommodates the Avionics Battery (AB) packs (1.8 Ah @ 7.4 V) that provide power to the avionics systems and the Propulsion Battery (PB) packs (5.2 Ah @11.1 V) dedicated to supply the Propulsion System. Battery packs can be recharged from an external source, also when a test is ongoing.

Fig. 2 External view of the CTP, with detail of the external interfaces

The avionics systems are the Electric Propulsion Interface System (EPIS), the Command &Data Handling (CDH), the Electrical Power System (EPS), and the Communication System (COM SYS).

Electric Propulsion Interface System (EPIS) provides the interfaces of CTP towards the propulsion system and the instruments and devices to measure the parameters for assessing the interactions between the CTP and the propulsion system. EPIS manages the power towards the propulsion system thanks to a board (called High Power Management System (HPMS) board). The HPM board hosts the booster circuit that supplies in output 12 V regulated with a maximum output current of 5A, and the battery recharger for PB packs. The expected recharging time is less than 6 hours for a complete recharge. PB packs provide up to 5.2 Ah at 12 V and their output is controlled by dedicated 'Remove Before Test' switches. Protection circuits prevent overcurrent, over voltage, or short circuits on the power bus; refresh fuses are added to each line, especially for the connection towards the propulsion system. Acquisition circuits gather the measurements of the voltage and current and temperature for PB packs, step-up circuits, and the consumption on the 3.3 V and 5 V power bus lines. The output of the ADC is connected to the 104-pins bus to provide the sampled values to the SPI bus. These measurements allow for the estimation of the power consumption in any phase of the test, for different modes of operations of the propulsion system.

EPIS acquires many measurements through an electronics board (Data Logging board) that hosts the conditioning RC filters and amplifiers and two 16-channel Analog-to-Digital Converter (ADC). The outputs of the ADC are passed to the CDH board via an SPI bus. Sixteen temperature sensors (twelve NTCs and four PT1000s) provide temperatures of the Propulsion Module in the range [-20; 120] degC and [-40; +350] degC, respectively. The PT1000 sensors are located near to propulsion system while the NTC are fixed on the faces (+Y, −Y, +Z, −Z), inside Propulsion Module close to the propulsion system and on the external surfaces. Other NTCs are installed in the avionics box and the battery packs: all sensors characterize the thermal environment. Eight micro-RF circuits measure the radiated emissions. The circuits are pass-band filters, tuned on different ranges by changing few cheap, passive components, conferring high flexibility to these elements. The RF sensing circuits are mounted on 20mm x 30mm sized boards: two boards for each range of frequencies are available and all the boards are installed on the bulkhead (four on the side towards the Service module and four towards the Propulsion Module, as in Fig. 3). The conducted emissions are measured using a dedicated circuit called Line Impedance Stability Network: it enables to evaluate the radiative environment generated by the propulsion system along the power supply line. LISN circuit is based on the LTC55x RF receiver and measures the current ripple generated along the line with high accuracy (1 mA) and with a sample rate of 1Hz.

A surface mounted MEMS triaxial magnetometer belongs to the Data Logging board allows to monitor the Magnetic Field variations inside the CTP.

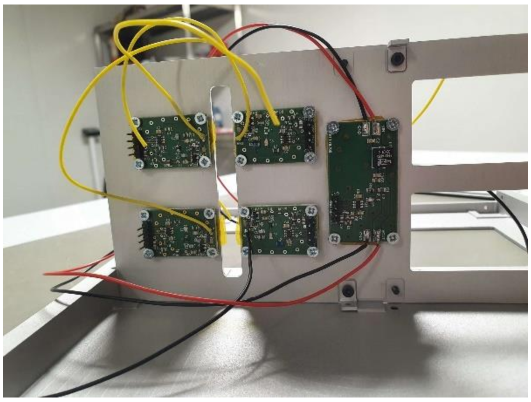


Fig. 3 RF sensing circuits mounted on the bulkhead

The Command and Data Handling, the Electric Propulsion System and the Communication System are representative of a traditional CubeSat bus. Command and Data Handling (CDH) is based on an ARM-9 microcontroller that manages data and commands, time and synchronization, operations, and on-board misbehaviors. SPI, I2C, and CAN buses and serial lines guarantee the data exchange between the subsystems and a set of non-volatile memories (i.e., Flash and an external SD card) stores the data. The CDH software manages onboard operations and communications, and even controls the propulsion system activity. The software can manage different communications protocols and physical layouts, also through specific protocols such as CSP, facilitating the interface with a wide range of miniaturized propulsion systems. Through the Interface Control Documents provided by the propulsion system developer, an independent, customized software module is implemented and then integrated with the entire onboard software. Moreover, the setups of the propulsion systems (i.e., the required power, the communication protocol, the list of commands, etc.) can be pre-loaded on the memory card or commanded through the Ground support system before and during the test sessions, conferring a high versatility to the CTP. The Electrical Power System (EPS) board that regulates voltages, controls, and distributes the power to all the avionics systems and manages the avionics battery packs recharging. The Avionic Battery packs can provide up to 1.8 Ah @ 7.4V and are installed in the second unit of the Service module, near to the PB packs. They can be recharged in less than 2h and guarantee a long test duration (over 8 h without recharging) because of the low power consumption of the Avionics systems. Two lines guarantee communications between the platform and operators: a wired serial line that directly connect the on-board computer with the Ground Support System and a RF link in UHF band. The latter is representative of a CubeSat communication system (COM SYS) and is the qualification model of the e-st@r CubeSat (Busso *et al.* 2016). The CTP's structure is fully compliant with the CubeSat Design Specification 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.

All the main boards are mechanically mounted on a stack trough four bars that fix the board to the primary structure and they exchange power and data through a 104-pins connector (Fig. 4).

Fig. 5 shows the internal layout of the CTP equipped with Regulus. Regulus is fixed through twelve screws to the primary structure, the thruster is located along +X face. The bulkhead separates the propulsion box from the Service box.

Fig. 4 Avionics box

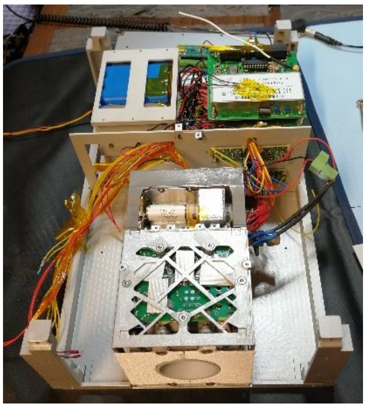


Fig. 5 Internal layout of CTP equipped with Regulus

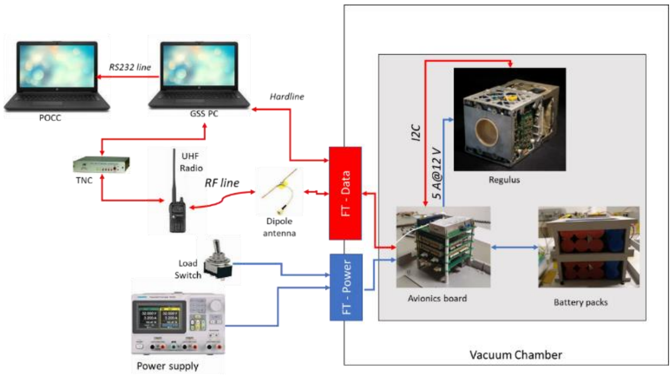


Fig. 6 Environmental test setup

3. Test campaign

The AIV plan follows a bottom-up approach from the single element and subassembly of the CTP up to the entire system, both in laboratory conditions and in relevant environment (Stesina 2019). This paper is focused on the last part of the verification campaign that consists in the environmental tests performed on the CTP equipped with Regulus in vacuum chamber at Centro di Ateneo di Studi e Attività Spaziali "Giuseppe Colombo" - CISAS laboratory of the University of Padua.

3.1 Test setup

The block scheme of the setup for the environmental tests is reported in Fig. 6. CTP equipped with Regulus is fully integrated and all sensors and sensing circuits are connected to the respective boards: the temperatures sensors are fixed using Kapton tape as reported in Fig. 7 (in the Service Module) and Fig. 8 (in the Propulsion Box) while the RF sensing circuits are mounted on the bulkhead (as shown in Fig. 3). In order to prevent RF reflections inside the chamber that could distort the EM measurements, the dipole antenna is not mounted on the CTP surface but the output of the COM SYS radiomodule is carried outside the vacuum chamber through the "Data

Fig. 7 Position of the Temp sensor in the Service box

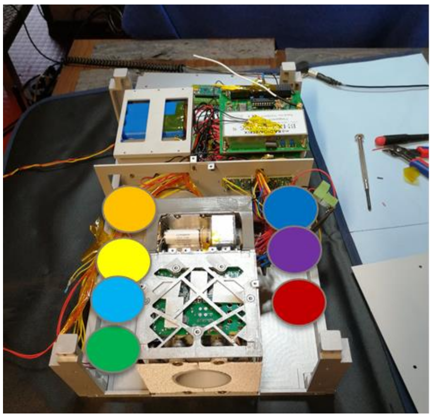


Fig. 8 Position of the Temp. sensors in the Propulsion System box

Feedthrough" using a coaxial cable.

Once installed in the vacuum chamber, CTP is activated and deactivated through an external Load Switch (LS) that provides to the operators a direct control on CTP power supplying.

The Ground Support System (GSS) enables the Politecnico di Torino (PoliTO) operators to monitor and control the test execution. GSS is designed to provide full control over the CTP, while providing telemetry readings at least every 5 seconds. GSS has the same communication lines of the CTP: a Hardline serial connection and a RF line made of a Terminal Node Control (TNC) and a UHF bi-band radiomodule. The GSS operator can interact with the software through a Graphical User Interface (GUI) designed to provide all the significant readings in the same window, sorted per type, and that provides a dedicated window to control the CTP.

The Propulsion system Operation Control Centre (POCC) is operated by a dedicated operator from T4I and responsible for the Propulsion System (PS) under test. POCC receives the PS telemetry every 5 second and can send request of command for the PS through the GSS that validates the request and then proceed with the sending.

Power supplier recharges the battery packs both during the operation and at the end of each test. Two separated channels allow recharging independently Avionics battery packs and Propulsion battery packs.

CTP platform is mounted on the thrust balance (Fig. 9), specifically designed for RF thrusters of small-to-medium size (Trezzolani *et al*. 2018) and capable of measuring the thrust and specific impulse generated by Magnetically Enhanced Thruster (MET) with an uncertainty of 10-20%. The displacement of the balance is read with an HP5529A laser interferometer, placed outside the vacuum chamber and capable of sub-μm resolution. Calibration is carried out by means of known masses and the uncertainty is calculated with a Monte-Carlo algorithm, which accounts for the geometric and mass uncertainties involved in the measurement. Moreover, the algorithm considers also the zero-position drift induced by the thermal gradients.

Fig. 9 Photo of the CTP installation on the Thrust Balance

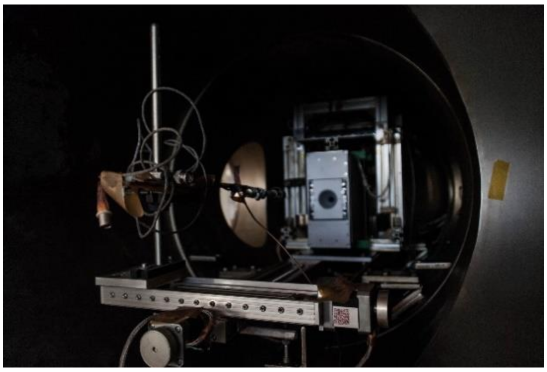


Fig. 10 CTP mounted on the thrust balance inside the vacuum chamber

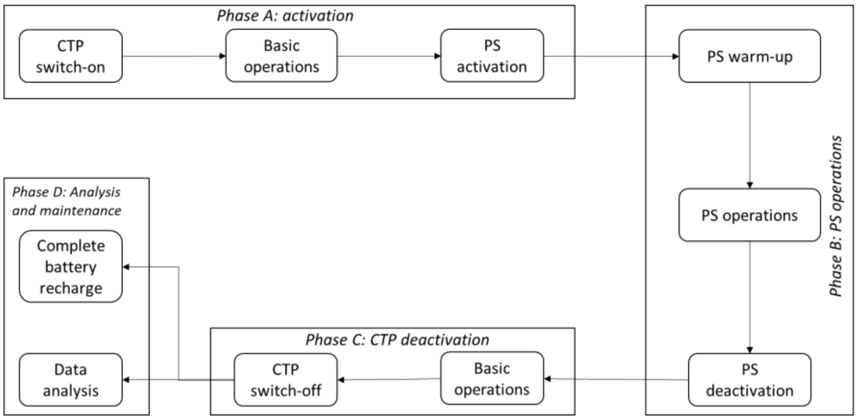


Fig. 11 Test sequence

The thrust balance is mounted inside the vacuum chamber (Fig. 10) at the propulsion laboratory of CISAS. This high vacuum facility consists in a 2-meters long, 0.6m wide cylindrical vacuum chamber, connected to a pumping system composed of a turbo-molecular pump and a diffusive pump, with the relative back-pumping system. The overall pumping capacity is 12600 l/s. Pirani vacuum meters and Penning gauges are employed to measure the pressure in several points along the pumping circuit and in the chamber itself, up to a pressure of 10-8 mbar.

Xenon gas is supplied from an external bottle by means of a MKS1179B mass flow controller.

Moreover, a dedicated feedthrough allows the connection of the Ground Support System (GSS), Load switch, RF antenna, and power supplier from outside the chamber. GSS constitutes the main interface between CTP and the operators

3.2 Test execution

Two test sessions are performed: 1) Thrust test and 2) Thermalization test. Both the tests follow the same sequence, reported in Fig. 11.

Each test is divided in four phases: Activation (part A), Propulsion System Operations (part B), CTP deactivation (part C), Data analysis and maintenance (Part D). The main differences between

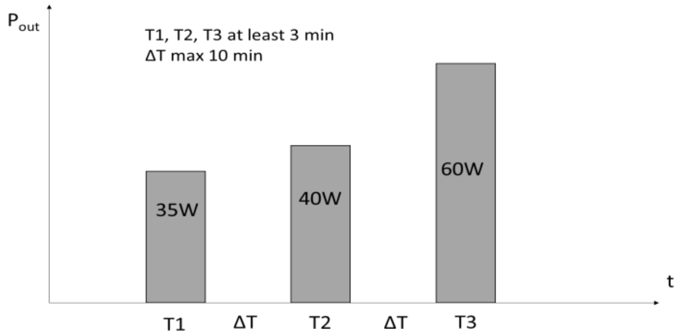


Fig. 12 Thrust test sequence for Regulus operations phase

the tests are in the Part B where warm-up, propulsion system operations and deactivation vary in terms of number and type of operations and duration.

In Phase A, CTP is switched on, the EPS starts to power the avionics systems, CDH software bootstraps, the communication lines initialized, and all critical parameters checked up to confirm that the CTP is ready to enter in basic mode. If some problem arises, the CTP enters in dormant mode and send a warning message to the GSS. On the contrary, if the activation is successfully completed, CTP gathers data and transmits it via COM SYS. In case, reception of a command from the GSS, CDH validates and executes it. If the telemetry data remain nominal for at least 5 minutes, the GSS operators send the command to activate the Propulsion System. Now, the HPMS step-up line is activate and the output towards the propulsion system enabled, the exchange of data and commands occur, and the setup of PS parameters is completed. The phase A ends when the telemetry shows a nominal behaviour for at least 5 minutes.

Phase B begins with the warm-up of Regulus to heat up and achieve the temperature required for the thrust. When this condition is gained, operator can send a command via hardline to activate the thrust. As said before, different sequences of operations are planned according to the test.

In the thrust test, the objective is to measure the thrust and verify the behaviour of the CTP for different levels of thrust. This test should confirm the performance of the prolusion system when hosted inside the platform. For the presented propulsion system, the selected power levels were 35 W, 40W and 60W. The maximum voltage level was not achieved because the required total power would exceed the performance of the CTP. It must be pointed out that these power levels were just indicative, their purpose was to provide intuitive labels to the low-, mid- and high-power operation commands. The actual power absorption had to be verified through testing.

The sequence of the operations is reported in Fig. 12. The thrust measurement is gathered following these steps:

a. starting an acquisition of the thrust balance once steady-state operation is reached,
b. letting the system operate at steady state for at least 2 minutes,
c. suddenly turning off REGULUS's RF system,
d. stopping the acquisition after 2-3 additional minutes.

In the thermal test, the objective is to assess the propulsion system performance variations for long thrusts, the endurance of the CTP and the heat distribution. In this test, the PS operations consist of a long firing (at least 30 minutes) with a reduced warm-up, in order to let thermalize the system (Fig. 13).

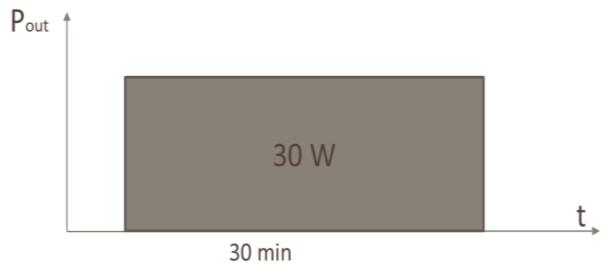
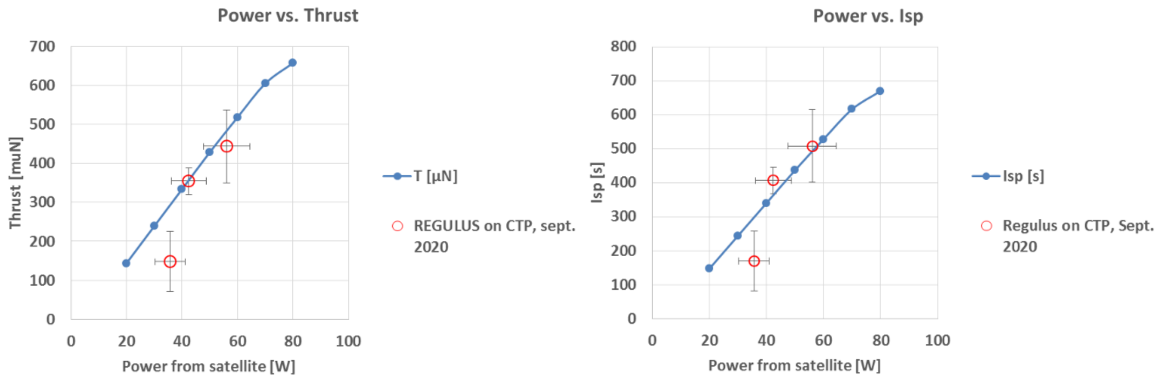


Fig. 13 Thermalization test sequence for Regulus operations phase



(a) Thrust to power values (b) Specific impulse to power values

Fig. 14 Regulus performance

4. Test results

4.1 Thrust verification

Fig. 14(a) and Fig. 14(b) shows, respectively, the Thrust and the Specific Impulse values for different values of power. The blue lines report the expected theoretical results for different level of provided electrical power and the red circles the values measured with the balance during the test. While a little difference exists for the lower values a good compliance is observed for higher levels of power

Fig. 15 shows the trends of the current (blue lines) and the voltage (red lines) during the entire environmental test. After the reception of the command for the activation (after 600 s), the propulsion system enters the initialization phase (consumption of less than 0.3 A) that also includes the opening of a valve (consumption of about 0.5 A). Then, the propulsion system enters in the pre-heating phase for 4000 s with a current consumption in the range 1.5 to 2.75 A. When the pre-heating ends, the system enters in the start automatic sequence that brings to first firing that requires a power of about 35 W. Then, the sequence continues with requests at 40 W and 60W. The system works properly for entire duration of the test without loss of power also at the maximum power of 60 W.

Fig. 16 shows the trend of the temperatures in the Avionics Box. All components remain in the operative range. It is interesting to observe the behavior of the thermal strap mounted on the critical HPMS items: a temperature sensor is mounted on the thermal strap (blue line) and on the upper side

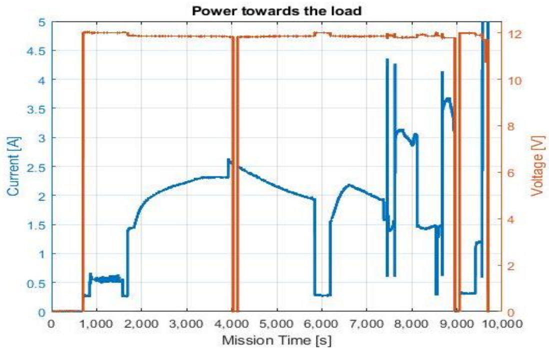


Fig. 15 Power consumption during the Thrust test

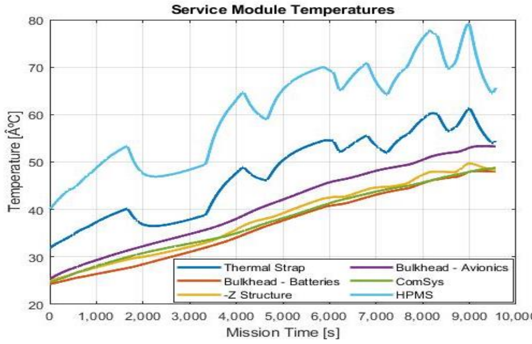


Fig. 16 Service module temperatures

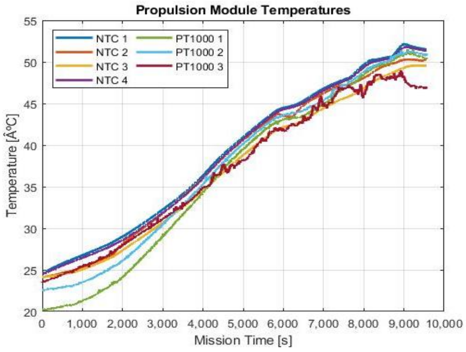


Fig. 17 Propulsion module temperatures

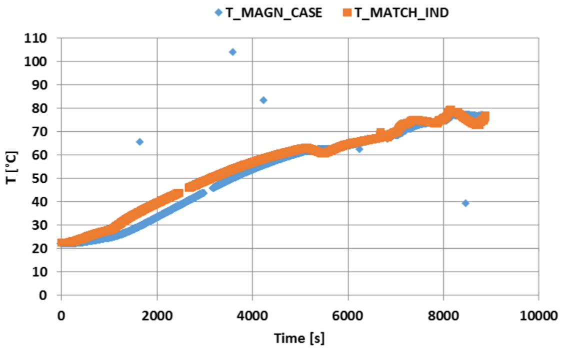


Fig. 18 Temperatures inside the case of regulus

of the HPMS (cyan line).

A reduction up to 20 degrees is observed thanks to the thermal strap confirming that the solution is effective. Temperatures increase up to 55 degrees in the Propulsion Box (Fig. 17): the rate of heating remains almost constant, and it seems that the equilibrium condition is not achieved at the end of the test.

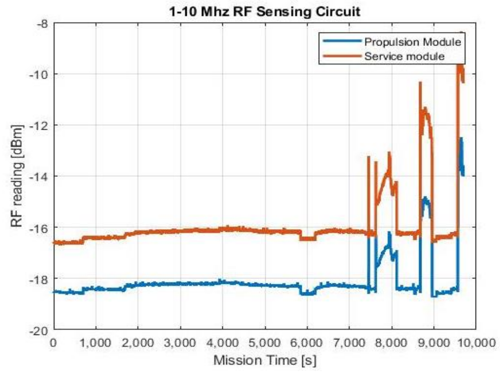
Moreover, the heat is uniformly distributed inside the box.

Fig. 18 reports the temperature on the magnet and on the internal face of the case of Regulus. Temperatures achieve the maximum value of 80 degC during the thrust at maximum power. This value is high but remains compatible with the operative range of Regulus.

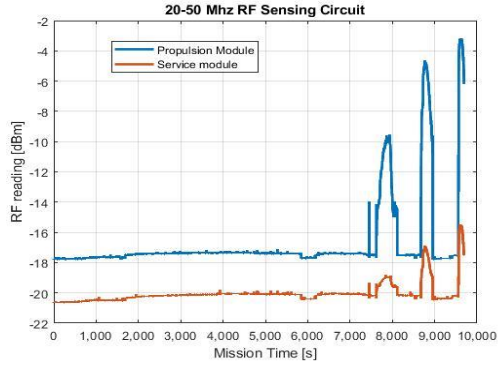
From the electro-magnetic emissions point of view, the operations of the propulsion system generate an increment of the noise levels especially in the range of 1 to 10 MHz (Fig. 19(a)) and 20-50 MHz (Fig. 19(b)) mainly due to the plasma. This increment is observed both inside the propulsion box and inside the avionics box: the most relevant increment of 15 dBm is observed in the range 20-50 MHz. These emissions do not compromise the operations both of Regulus and the CTP during the entire test: no losses of communication and no failures of the HPMS step-up are observed.

The variations observed at the 100-200 MHz (Fig. 19(c)) and 400-500 MHz (Fig. 19(d)) boards are negligible: for the latter, the RF transmission does not generate a significant emission inside the platform and does not affect the onboard operations because the RF power passes through the main lobe of the antenna and spurious emissions and side lobes are very low

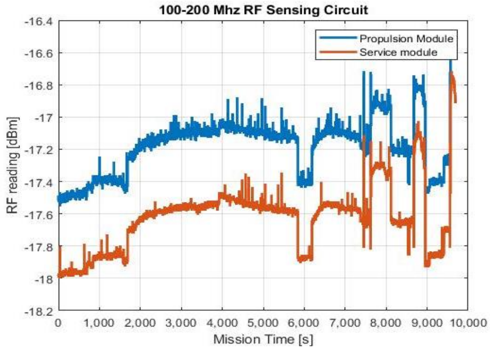
Fig. 20 shows the output of the LISN circuit: conducted emissions are negligible (under the -21



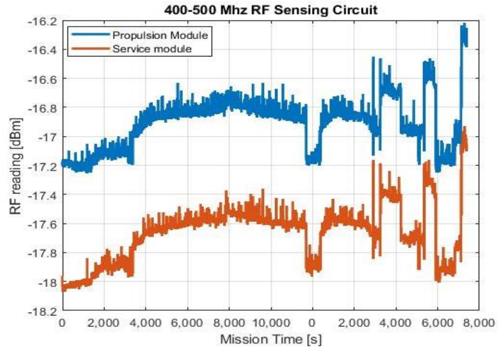
(a) Radiated emissions at 1-10 MHz during the Thrust test



(b) Radiated emissions at 20-50 MHz during the Thrust test



(c) Radiated emissions at 100-200 MHz during the Thrust test



(d) Radiated emissions at 400-500 MHz during the Thrust test

Fig. 19 Radiated emissions in Thrust test

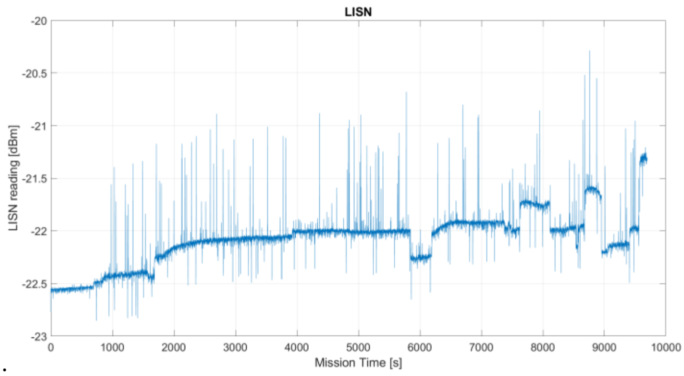


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Fig. 20 LISN sensing circuit output

dBm) and, even, the variations due to the different levels of power loads are less than 2 dBm

The Magnetic Field remains quite constant along the three main axes of CTP (see Fig. 21) and the values are compatible with Earth Magnetic Field, demonstrating that the generated magnetic field emission inside the CTP is negligible.

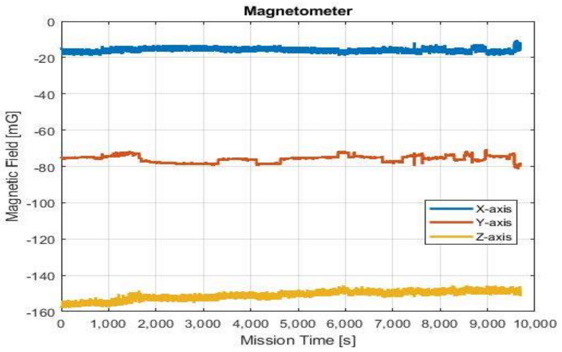


Fig. 21 Magnetic field measured during the environmental test

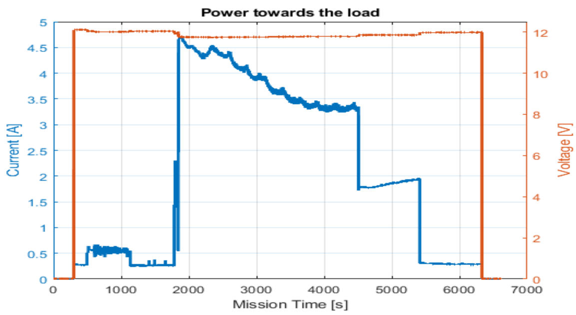


Fig. 22 Power consumption during the Thermalization test

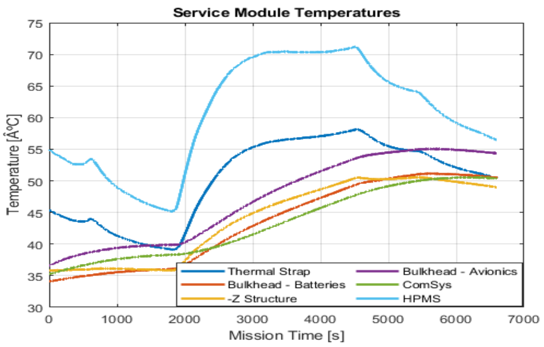


Fig. 23 Service module temperatures

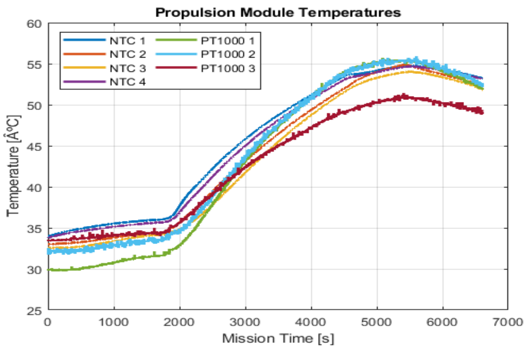


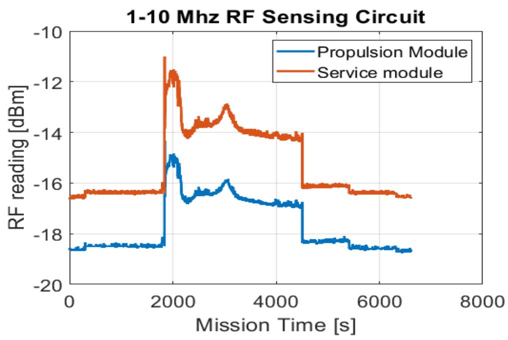
Fig. 24 Propulsion module temperatures

4.2 Thermalization test

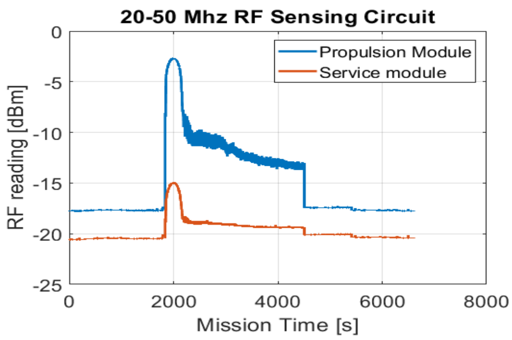
This section is dedicated to the results of the Thermalization Test (Stesina *et al.* 2020). Fig. 22 reports the power trends for the entire test. After the reception of the command, the propulsion system enters in activation phase (consumption of less than 0.3 A) that also includes the opening of a valve (consumption of about 0.5 A, between 500 and 1200 seconds). In this test, the warm-up phase is skipped to represent a worst case for the heat generation but also to demonstrate the capability of Regulus to have a quick time-to-thrust. When the propulsion system starts the firing at intermediate power, a consumption of 4.2 A is observed and this value progressively decreases due to the completion of the heating for the main components, progressively improving the thrust to power ratio. After 45 minutes (from 1800 to 4400 seconds), a command from GSS stops the thrust and enables the cooling phase (with consumption of about 2 A, from 4400 to 5300 seconds) for 15 minutes. Then, the propulsion system returns in stand-by up to the complete switch-off and the return of the CTP in basic mode for about 5 minutes.

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 and slightly go back after the end of the thrust. The step-up circuit provides the voltage in the range 11.7 V and 12.06 V according to the loads current request.

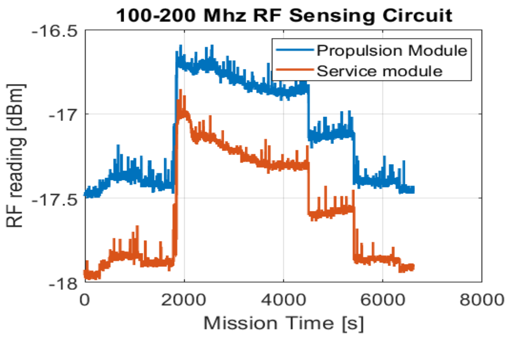
The temperatures of the components remain in the operative range. Again, the thermal strap



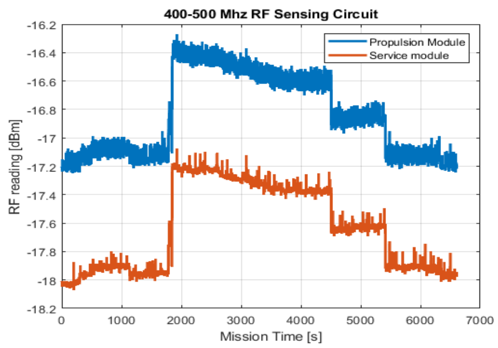
(a) Radiated emissions at 1-10 MHz during the Thermalization test



(b) Radiated emissions at 20-50 MHz during the Thermalization test



(c) Radiated emissions at 100-200 MHz during the Thermalization test



(d) Radiated emissions at 400-500 MHz during the Thermalization test

Fig. 25 Radiated emissions in Thrust test

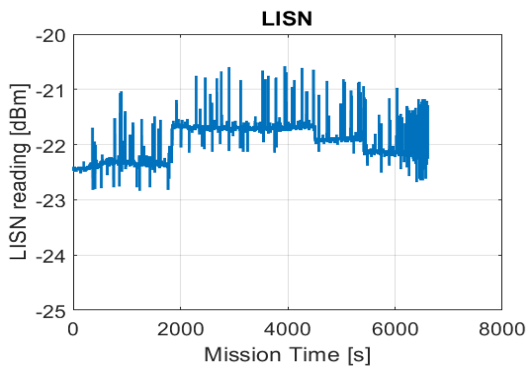


Fig. 26 LISN circuits measurements trend during the Thermalization test

mounted on the critical HPMS items guarantees a reduction up to 20 degrees (see the difference between blue line and cyan line in Fig. 23) that keep safely these elements inside the operative ranges.

The radiofrequency emissions are evaluated in the four frequency ranges (Fig. 25 (a), (b), (c), (d)): 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.

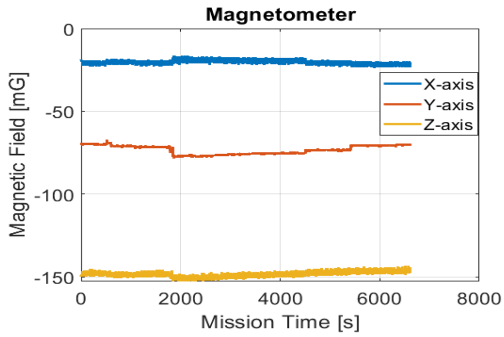


Fig. 27 Magnetic field measured during the Thermalization test

Table 1 Some results of the test campaign

	Thrust test	Thermalization test
Duration of the test [s]	9888	6870
Delivered energy [Wh]	29,8	37,2
Number of received packets [#]	9573	6661
Amount of gathered data [Kbyte]	2393,25	1665,25

This increment is observed both in the propulsion module and in the avionics box. In particular, the most relevant increment of 20 dB of is observed in the range 20-50 MHz. However, these emissions do not compromise the operations of the entire platform because neither losses of communications nor failures of switching circuits of the step-up on HPMS are observed.

Fig. 26 shows that the conducted emissions are negligible because the low variations (less than 1 dBm) can be observed accordingly with variations of required power by the propulsion system

The Magnetic Field remained quite constant along the three main axes of CTP (Fig 27). The values are compatible with Earth Magnetic Field. The differences between the magnetic field revealed during the different test sessions derives from the different day and hours of the day in which the test was performed and the different boundary conditions in the laboratory.

Table 1 summarizes the results of the test campaign in terms of duration, total energy, number of packets and amount of data.

5. Discussion

The Cubesat Test Platform delivers the desired electrical power to propulsion system. The HPMS supplies the expected power to the propulsion system in any phase of test campaign up to the maximum value of 5.2 A, very close to upper limits of the system. In fact, a transient anomaly appears only when the borderline conditions of power request has been reached at the end of the Thrust test. The power was delivered, and the propulsion system continued to fire but a ripple appeared on the output voltage and the minimum values went out from required boundaries. To overcome this problem, some components could be optimized to enlarge the operative range up to 80-120 W (i.e., 7A-10 @ 12A). This improvement guarantees to overcome this problem with major part of the miniaturized electric propulsion systems for small-sats available on the market.

Table 2 Main achievements

Achievement	Description
Assessment of the Radiated Emissions	Eight sensing circuits measure the emissions in four tunable ranges of frequency
Assessment of the Conducted Emissions along the power supply line towards the propulsion system	A dedicated LISN circuit reveal ripples on the current absorption
Characterization of Thermal Environment	Up to 32 temperature sensors mounted inside the platform
High power supplied towards the PS Voltage towards the PS	Up to 60W for 6U [12; 28] V
Versatility to different protocols adopted in the CubeSat field and available for comms with the PS	I2C, SPI, RS232, RS485, CAN bus. CubeSat Protocol (CSP), AX-25 protocol
Rapid prototyping of the code dedicated to propulsion system and ease to manage the setup parameters and the operations before any test	Modular software Setup parameters of the propulsion system are loaded from dedicated files where the power level, the protocols, the data format, and the list of commands are saved
High communication and data reliability and high quantity of gathered information	Up to 12 packets/min through two lines of communication with the GSS (wired RS232 line, RF line in UHF band) Information redundancy (CRC algorithms and Hamming codes are implemented) Data saved every second in two non-volatile memories for data storage (EEPROM and SD card)
Large volume to host propulsion system and tank and other instruments, in case Compliance with the CDS	Up to 4U and 9 Kg of PS for Structure sizes lower than the CDS specifications and CTP mass lower than 3Kg (without propulsion system) for 6U
Long duration of the battery packs and quick recharging	PS battery packs capacity >2h of test @60W without power recharging (quick recharge <2h, low recharge <4h) AV battery packs capacity >8h of test without recharging (quick recharge in <2h)

The electromagnetic emissions do not affect the onboard avionics system for any operative mode of the propulsion system. CTP works properly saving/storing, transmitting data e receiving command. The radiated emissions are not negligible, especially at lower frequencies (1-10 MHz and 20-50 MHz), when the propulsion system works and a high electrical power amount is required. These frequencies correspond to the operative frequency of the Regulus (1.8 MHz) and the switching circuits of the HPMS (5 MHz). COM SYS emissions due to the RF transmission power do not affect the propulsion system. No impact due to conducted emissions (LISN measurements) is observed demonstrating that Regulus does not generate noise along the power supply line. Similarly, the magnetic field emission is negligible/comparable with respect to the Earth Magnetic Field, meaning that the generated magnetic dipole can be compensated by the actuators of the small satellites.

However, some communication anomalies occur on the external hardline between CTP and GSS. The anomaly appears intermittently during maximum power operation. Although a grounding anomaly was revealed between the CTP and the GSE cables, it should be a point of attention the consequence of emissions generation on the CTP surface. As improvements, cables with a better quality (higher quantity of shielding) will be selected for the connections CTP/GSE.

The heating is remarkable both in the Service Module and in the Propulsion Module: 20-25 degC in an hour of thrust during the thermalization test and, similarly, with a longer warm-up phase in the thrust test impose to take care the problem. The major causes of these increments are the electrical power supplying to the propulsion system (as expected), the not-optimized distribution of the heat through the primary structure in vacuum conditions, and the propulsion battery (PB) packs recharging in vacuum. Moreover, a quicker recharging leads to a relevant increment of temperature on the HPMS board components and the PB packs. During the test campaign, no anomaly due to the thermal environment appeared because temperature on all the critical components remain within the operative range, but for longer firing the heat could grow up to values that compromise the operations of CTP and/or Regulus. To reduce the problem, possible solutions are the application of Multi-Layer Insulators (MLI) and other thermal straps on specific components or subassemblies while a more effective but more expensive solution is the development of a dedicated control system based for example on small heat-pipes.

We must also point out that the vacuum chamber itself heats up to 30-35°C during prolonged operation, providing a rather warm environment with respect to the one found in orbit, which may have impacted the thermal behavior of the system.

6. Conclusions

Miniaturized propulsion systems are achieving important results at the component and subsystem levels and now are required to increase their level of readiness to support a new era of CubeSat missions. Now, they should prove their integrability at system level with the existing small satellites technology through ad hoc verification campaigns. A complete verification imposes devices, ground support equipment and facilities able to provide the measurements of the generated environments and phenomena inside and in proximity of a CubeSat equipped with a propulsion system, confirming the right integration and/or anticipating undesired behavior and support the definition of corrective actions.

The paper presents the test campaign plan, execution and results conducted by Politecnico di Torino, T4I and University of Padua under the supervision of the ESA Propulsion laboratory on an innovative helicon plasma thruster installed on a 6U CubeSat Test Platform, developed to host a wide range of propulsion systems and support the verification campaign of miniaturized propulsion system. In details, the test campaign allows the assessment of the mutual impact at system level. From the platform point of view, CubeSat Test Platform 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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