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REGULUS Electric Propulsion System integration in Unisat-7 Microsatellite and in a 6 Unit CubeSat for IoD and tests

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Abstract

Today it is clear that nano/micro and small satellites will need to move in space for different reasons. As piggyback satellites, they may have the need to (I) reach the right orbit (when the satellite carrier does not have propulsion capabilities), (II) maintain the right orbit, (III) achieve the right relative position and (IV) change their orbit. As it's now clear that space is going to be crowded, these satellites will need (V) the capability to leave their orbit and re-enter in atmosphere. Moreover, when operating in VLEO, micro satellites need (VI) to have propulsion for drag compensation. REGULUS Electric propulsion (EP) system has been designed and manufactured to get the best compromise among the following parameters: technical performance, costs, simplicity (that is directly related to costs and reliability), robustness (small changes in technical requirements do not have to translate in consistent re-design, manufacturing and testing efforts), flexibility (customizations should be made with low non-recurrent activities). REGULUS thruster technology does not require electrodes, grids or a neutralizer, thus it doesn't have elements subjected to erosion. The use of iodine propellant also results in a compact and no pressurized tank. REGULUS FM performed acceptance tests and is going to be integrated in GAUSS' nanosatellites deployer systems, UniSat-7, before end 2020. During the IoD mission, scheduled for March 2021, REGULUS will be tested in orbit to prove UniSat-7 capabilities of orbital maneuvers and drag compensation. Another REGULUS FM has been integrated in a 6 Unit CubeSat realized by the Polytechnic of Turin for performance tests in the vacuum chambers at the University of Padua and will undergo the same test at ESA EPL facilities in ESTEC. The mechanical and electrical integration with the satellite platform has been completed and verification measurements have been performed at the University of Padua: thrust, plasma performance, EMI/EMC/RF interaction, high power and peak power required from the platform, thermal environment, external contamination due to the propellant and plume shape. This has been the first time that REGULUS has been tested in a real 6U platform. The present paper describes such integration activities and test campaigns. Overall, the exploitation of such activities aims to increase the micro satellites community confidence in EP systems integration in satellite platforms and to reduce the risks of operations in space.
Keywords: CubeSat, electric plasma propulsion, microsatellite, nanosatellite, REGULUS, UniSat-7.

Acronyms/Abbreviations

EMC	Electro-Magnetic Compatibility
FEEP	Field Emission Electric Propulsion
FM	Flight Model
IoD	In-Orbit Demonstration
LEO	Low Earth Orbit
MEPT	Magnetically Enhanced Plasma Thruster
RF	Radio-Frequency
SSO	Sun-Synchronous Orbit
TVAC	Thermal-VACuum

1. Introduction

During last decades, CubeSats have become increasingly common [1] mainly because of their extremely reduced cost and versatility with respect to traditional satellites for accessing space. These features are influencing considerably the space market that is changing towards a "New Space Economy" characterised by new players such as small companies, small countries and research centres, all associated by the opportunity of reducing manufacturing costs and obtain more reliable, flexible and high-performance systems.

In the near future, SmallSat constellations in Low Earth Orbit (LEO) will enter the market with a disruptive impact, changing many sectors from earth observation, natural disaster monitoring, communication, imaging to the development of the "internet of the things" [2,3].

However, to realize this new scenario and make it real, exploiting all its potential, SmallSats will need an on-board propulsion system, which can enable increasingly complex missions where orbit positioning and maintenance are required [4,5], as well as mobility.

In this context, many companies (e.g. Busek, Enpulsion, ThrustMe, Exotrail and T4i) and research centres are developing new propulsion technologies for small satellites, even though there are only few examples of past missions involving SmallSats with mobility capabilities [5]. This is mainly due to the fact that the integration of the propulsion system into a SmallSat represents an extremely challenging task, not only for the intrinsic complexity of a space thruster, but also for all the restrictions in terms of mass, volume, power and cost budgets that have to be taken into considerations.
An example of mission carrying a propulsion system onboard can be identified in the 1.5 U BRICSat-P launched in 2015, where four μCAT thrusters [6] were employed to detumble the satellite. In 2013, STRaND-1 [7,8] mission launched a 3U CubeSat with a Pulse Plasma Thruster (PPT) for orbital corrections and a water-alcohol resistojet for attitude control while in 2015 the SERPENS [9] mission launched a 3U CubeSat with a PPT to counteract orbital decay caused by atmospheric drag. Moreover in 2018 the IoD of a Field Emission Electric Propulsion, in particular the IFM Nano Thruster developed by the Austrian company Enpulsion, was accomplished [10].
In this context, REGULUS system [12] has been developed. In this work the design of the REGULUS electric propulsion system will be briefly presented. In Section 3 the current activities on the module will be introduced, with particular attention to the integration in the PoliTO CubeSat and the preparation for the integration in Unisat-7, along with acceptance tests. Finally, conclusions are drawn in Section 4.

2. REGULUS EP system

REGULUS (see Figure 1) is a complete electric propulsion system fed with iodine propellant that is being developed at Technology for Propulsion and Innovation (T4i). REGULUS technology relies on the RF Magnetically Enhanced Plasma Thruster (MEPT), which is integrated with electronics, fluidic line, and thermo-structural subsystems into a complete propulsion unit that fits in a 1.5 Unit Cubesat. The total system wet mass is below 2.5 kg.
REGULUS has been built with i2C and CAN BUS electrical interfaces to avoid difficult integration procedures and integrates COTS components to reduce its recurring costs. REGULUS will provide 0.6 mN thrust and 600 s specific impulse at 50 W of input power from the satellite bus, and a maximum total impulse of 3000 Ns. An expanded version with total volume of 2U is also available, with a total impulse of about 11000 Ns.

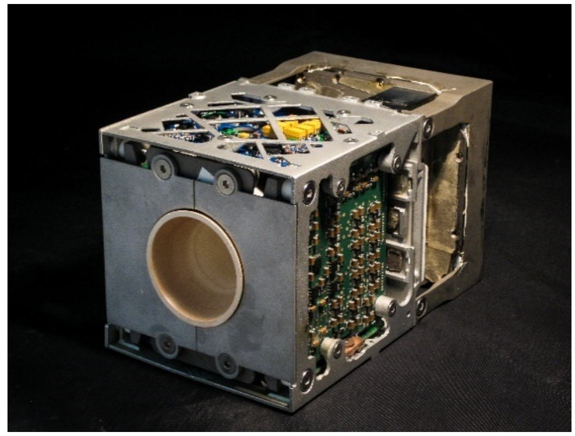

Figure 1 Picture of the REGULUS propulsion unit.

3. REGULUS current activities

Currently, REGULUS has been qualified and reached TRL 8. Its IoD is scheduled in Q1 2021 onboard UniSat-7, a cubesat carrier acting also as satellite operated by the Company GAUSS. The mission objectives for UniSat-7 are to inject 4 3U Cubesats into a 600 km height Sun Synchronous Orbit (SSO) and to act as a technology demonstrator to test specific payloads for future GAUSS CubeSat missions.
During the mission, REGULUS will perform different operations, as the simulation of orbital operations to spread CubeSats injection into different orbits, the variation of altitude, drag compensation at VLEO orbit, and finally UniSat-7 decommissioning.

3.1. REGULUS FM preparation for integration in Unisat-7

REGULUS is going to be integrated inside Unisat-7 (see Figure 2), a small satellite and at the same time a micro-platform able to host several CubeSats onboard and then deploy them in orbit.

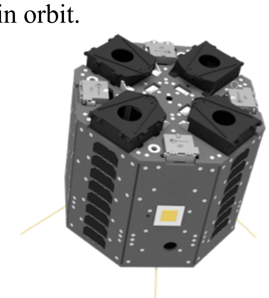

Figure 2 Rendering of UniSat-7, dispenser of the Italian company GAUSS onboard which REGULUS will perform the IoD.

Acceptance tests requirements and description

As for every space program, before integration, REGULUS FM undergone mechanical vibrations along with Thermal-VACuum (TVAC) tests for the acceptance of the propulsion unit.

Sinusoidal and random vibration tests have been performed considering the spectra of the Soyuz launcher (see Figure 3).

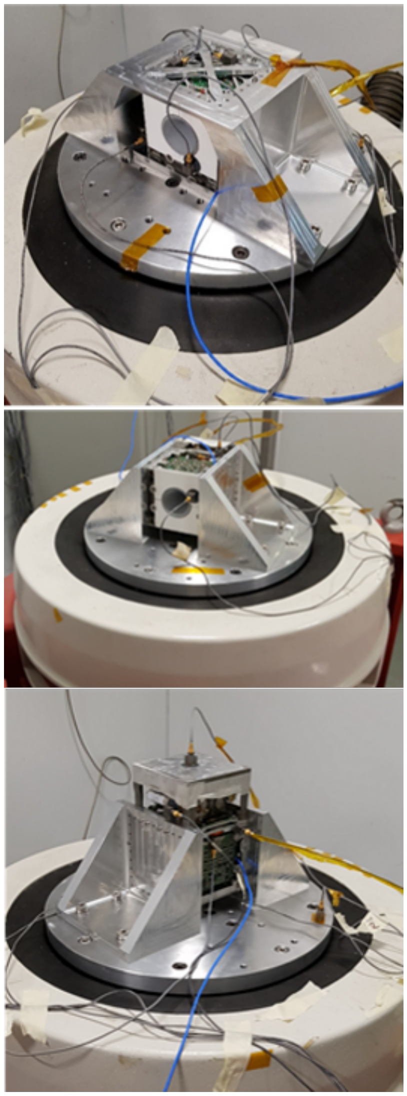

Figure 3 REGULUS acceptance test: X axis (top), Y axis (centre) and Z axis (bottom).

After the vibration tests, the module was inspected and subsequent functional tests were performed; since no structural and or functional failures were detected, acceptance tests were considered complete.
TVAC acceptance tests were performed using a custom system internally developed at T4i to assess REGULUS operativity, following the parameters recapped in the following Table 1.
Full functional tests were performed before and after the TVAC tests to verify the nominal operation of the system: 1) single boards tests to confirm their integrity after the severe environmental conditions and 2) entire nominal operative tests on REGULUS loaded with Iodine in vacuum, including heaters & valves activation and temperature and pressure sensors control tests.

Table 1 Acceptance TVAC parameters.

Parameter	Value Reached
Minimum pressure	8·10-3 mbar
Temperature range	-20 ÷ +50 °C
Dwell time	60 min
Temperature rate	1°C/min
# of cycles	4

Tests confirmed that REGULUS is fully operational and ready for launch, and now is in integration phase with the main carrier.
Software integration and electronics compatibility tests (EMC, peak and mean power during all functional states) have been performed in Q2-2020 using mock-up versions of the flight electronics.

3.2. REGULUS integration in PoliTO CubeSat

In parallel to the acceptance tests of REGULUS, a second FM was used for the integration inside a 6U CubeSat realized by the Polytechnic of Turin [13,14,15] (Figure 4).

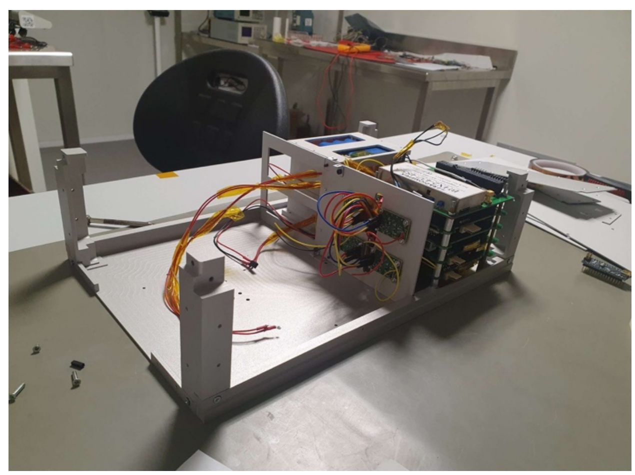

Figure 4 PoliTO 6U CubeSat.

The test aims at verifying the electrical, thermal and data interfaces between CTP and REGULUS. The complete 6U undergone performance tests in the vacuum chamber at the University of Padua and will then be further tested at ESA facilities in ESTEC.

Integration and functional tests

The schedule for the tests is shown in *Figure 5*. The first day was used for the integration of REGULUS in the 6U CubeSat. This was quite straight and only minimal issues were encountered in this phase (see Figure 6).

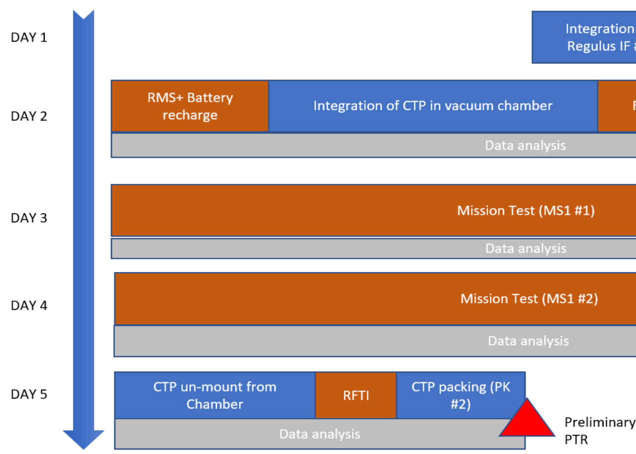

Figure 5 Test schedule.

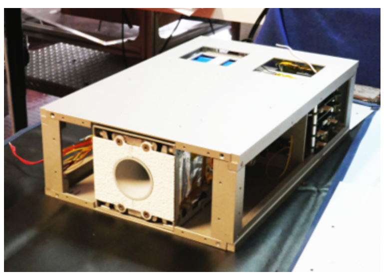

Figure 6 REGULUS integration inside the 6U CubeSat of PoliTO.

The second day was dedicated to the integration of the entire system inside the vacuum chamber and the chamber preparation (see Figure 7).

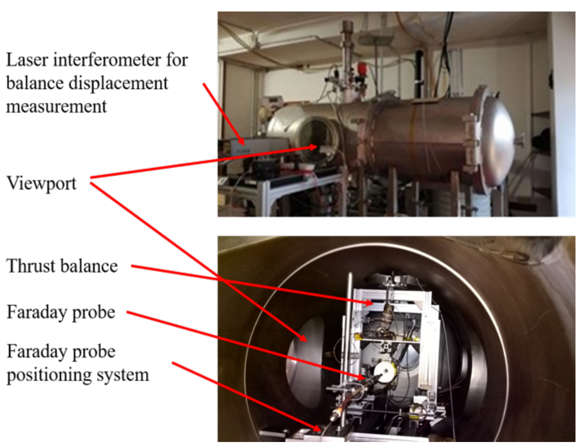

Figure 7 Integration of the system inside the vacuum chamber.

Mission tests were performed during third and fourth days while last day was used to un-mount the system from the chamber.

Functional tests (Figure 8) were performed during integration and the pass/fail criteria was based on functional interactions:

- CTP electrically supplies the propulsion system @ power levels.
- CTP exchanges data packets and commands with the propulsion system.
- The thermal behaviour of the EPS board, HPMS board, battery packs and propulsion system do not compromise the functioning of the CTP.
- Mechanical connection is confirmed and PS is securely fixed to the CTP structure.
- The “feedthrough” for the fluidic connection is guaranteed.

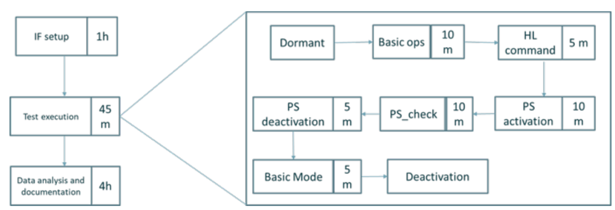

Figure 8 Functional tests perfomed after REGULUS integration.

RF/EMC/EMI test requirements and results

In order to perform a first check of RF disturbances, REGULUS's PPU-RF is turned on without gas flow. This is representative of the conditions met at start-up (when plasma is not yet ignited) or when, for any reason (i.e. discharge instability, external disturbances), the plasma suddenly turns off.

Telemetry data that were monitored during the tests were:

- Radiated EMi
- LISN measurement.
- Magnetic Field along x-axis (Bx).
- Magnetic Field along y-axis (By).
- Magnetic Field along z-axis (Bz).

- Continuous ion current monitoring with Faraday probe.

Variations of the RF noise has been observed during the test but no major impact was observed on the CTP operativity.
Other tests were performed to study the high power and the peak power of the thruster.
Telemetry data that were monitored during the tests were:

- PS battery #1 voltage, current and temperature.
- PS battery #2 voltage, current and temperature.
- Output voltage, current and temperature.
- Avionics temperature.

These assessments were performed both in RMS test and, even, in MS#1 and MS#2.

Thrust performance, plume and thermal behaviour tests and results
Thrust performances were assessed during mission tests #1 and #2. For each power level (see Figure 9), thrust was measured following this procedure:

i) Reach a steady-state operation and start an acquisition of the thrust balance.
ii) Keep the steady-state for at least 2 minutes and let the system operate.
iii) Suddenly turn off REGULUS's RF system.
iv) Stop the acquisition after 2-3 additional minutes.

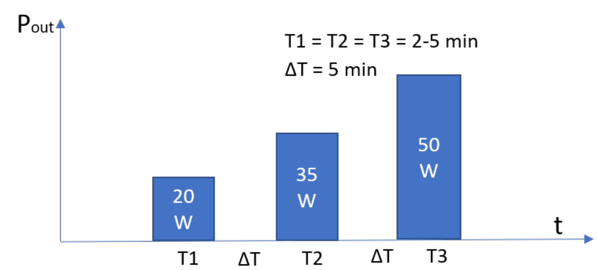

Figure 9 Power levels used during tests.

Thrusts outcomes were then obtained by the comparison between the different positions of the balance with the "plasma on" and "plasma off". The accuracy of the measurements depended on the mechanical sensitivity achieved by the balance once the CTP was in place.
After thrust measurements, it is appropriate to perform two radial scans with the Faraday probes in at least two axial locations along the plume. The scans must be performed 1-2 minutes after steady-state operation has been reached.
Telemetry data that were monitored during the tests were:

- Thrust measurements
- Mass flow rate measurements
- Output voltage, current and temperature
- PS battery #1 voltage, current and temperature
- PS battery #2 voltage, current and temperature
- Radiated EMI
- LISN measurement
- Magnetic Field Bx, By, Bz

In addition to thrust measurements, also plume analyses were performed to assess the possible contamination due to the operation of the spacecraft.
The test was organized with the following setup:

- CTP primary structure (faces –X, +Y, -Y, +Z, -Z) was covered by kapton tape strips.
- SiO2 non-operative cells were mounted on +Y, -Y, +Z, -Z faces of the primary structure.
- AsGa triple junction operative panel is mounted on +Y face.

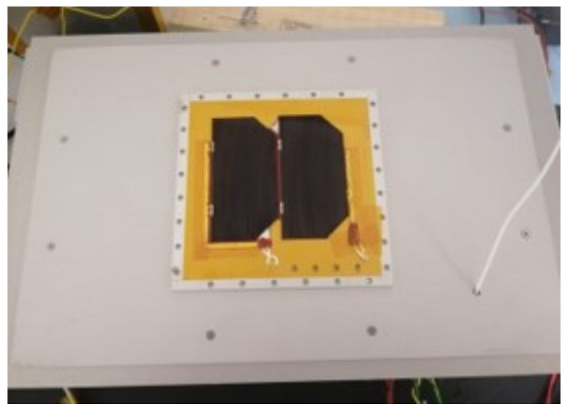

Figure 10 AsGa triple junction panel.

Before test campaign started, a flash test was conducted on the AsGa solar panel. This was done to record the initial power produced by the cells.
After the execution of MS#1 and MS#2 and the de-assembling of CTP from the vacuum chamber, the katpon tape strips and solar cells/panel were removed.
Chemical/microscopy analysis were conducted (ESEM equipment is available at Padua University) and in parallel AsGa solar panel was subject to a flash test in order to verify the loss (if any) of power due to residuals on the panel surface.
The pass/fail criteria was based on:

- Level of contamination due to propellant can be investigated (traces of implanted xenon atoms).
- Loss of power on AsGa solar power lower than 5% between the two flash test.

4. Conclusions

REGULUS is a propulsion subsystem suitable for Cubesats and Microsats missions, able to deliver up to 3000 Ns of total impulse at 0.6 mN of thrust with 600 s of specific impulse. A series of tests, regarding integration with mock-ups and acceptance of the FM, have been performed in order to be able to flight inside GAUSS Unisat-7 mission in Q1-2021. Moreover, to verify REGULUS with actual Cubesat units, integration and performance tests with University of Torino CTP

Cubesat platform has been performed at the University of Padova vacuum chamber, showing promising results. The same tests will also be performed in ESA EPL facility in ESTEC. Results and graphs of the test campaign will be available after the test campaign in ESTEC.

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