MEPS Project – Engineering Model Development and Testing Status

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Micro-Satellite Electric Propulsion System (MEPS) is a development and qualification programme jointly supported by the European Space Agency (ESA) and the Israeli Space Agency (ISA) aiming at the full space qualification of a low power electric propulsion system specifically designed to be used onboard for small satellites (mini- and micro- class). The system is conceived to have maximum flexibility to be appealing for a wide variety of missions, ranging from drag-compensation to spacecraft de-orbiting. To date the system components were developed to bread-board and engineering models level and take part in system integration tests. Currently Rafael and Sitael, the two prime companies that are in charge for the system development, are approaching the thruster units endurance test campaign, in parallel to power processing unit and propellant management assembly development.

I. Introduction

IN the past decades electric propulsion has become an increasingly accepted and utilized means of propulsion for a variety of space missions and applications; from orbit keeping or orbit raising on-board GEO communications platforms, through attitude control or de-orbiting maneuvers aboard small satellites and to long term interplanetary missions to distant celestial bodies[1]. In particular, there is an increasing interest in low power electric propulsion systems suitable for orbit raising and de-orbiting maneuvers for Low Earth Orbit (LEO) satellite constellations[2]. For such satellite platforms and required maneuvers Hall thruster technology is most suitable thanks to the thrust levels and specific impulse delivered by these propulsion devices.

For such reason Hall effect technology has been adopted for the Micro-satellite Electric Propulsion System (MEPS) project. The electric propulsion system is a joint Israeli-European endeavor with the aim of introducing to

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the market a qualified low power electric propulsion system that can effectively respond to the rising market needs of SmallSat missions[3,4]. The MEPS project is composed of two main parties – Rafael, who is in charge of the Hall thruster, hollow cathode and Propellant Management Assembly (PMA) development, and Sitael, who is in charge of the Hall thruster and Power Processing Unit (PPU) development.

MEPS is an affordable system, conceived with a two design-to-cost approach, intended to significantly extend the capabilities of mini satellites operating in LEO and to enable new classes of EP-based missions.

Typical applications for small satellites are: (1) Orbit transfer, (2) Drag-compensation for VLEO missions, and (3) De-orbiting. Of the possible applications listed orbit transfer has a strong appeal for small satellites that often are embarked on a launcher as piggyback payloads to be released on orbits that are quite different from the target one; in such cases an orbit transfer completed by means of an electric propulsion system can save a significant amount of propellant mass. The MEPS key specifications are listed in Table 1.

Table 1. Key specifications of the MEPS

Specification	Value
System Power	150-300 W
# of Thruster Units (TU)	2
Thrust Level	5-15 mN
Total Impulse	60 kN-s
Ignition Cycles	>2,000
Mass	< 16 kg

The present paper describes the MEPS project architecture, followed by the current status of the project, and system components in detail.

II. System Architecture

MEPS architecture is based on a fully redundant configuration, with two thruster units, operating once at a time due to power budget constraints, and an internally redundant Power Processing Unit (PPU). A Thruster Switching Unit (TSU) is used to switch the power lines to one of the two thrusters. While this configuration (illustrated in Figure 1) privileges reliability, thanks to its high level of modularity, it can be easily converted to a less sophisticated single-branch architecture. Single-branch option has no redundancy, but is lightweight and considerably cheaper. System specifications and system architecture have been defined considering a range of candidate missions that could greatly benefit from the use of low-power EP systems.

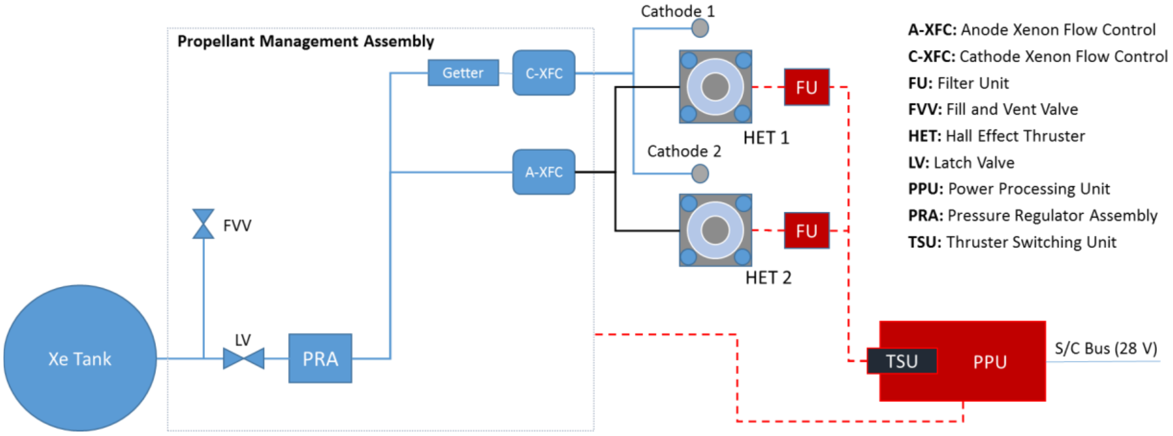


Figure 1. Micro-satellite Electric Propulsion System (MEPS) architecture.

III. Components and Development Status

A. CAM200 Hall Thruster (Rafael)

Rafael's CAM200 Engineering Model (EM) (Shown in Figure 2) was designed, manufactured, integrated and initiated its testing campaign during 2014 and 2015. Lessons learned and further improvements from CAM200 Development Model (DM) were implemented in the CAM200-EM with the purpose of producing a lighter-weight, electrically and mechanically robust thruster capable of operating in the expected environment of space[5]. In addition, an effort was made to simplify some of the manufacture procedures of the thruster; therefore making it quicker to produce and cost effective. Key features of the CAM200 Hall thruster are presented in Table 2.

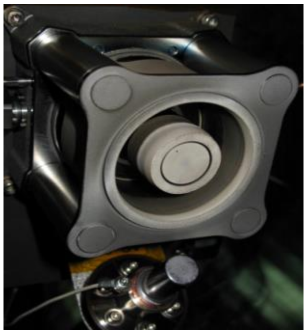


Figure 2. Picture of CAM200 Engineering Model (EM).

During last year the thruster has undertaken two main activities[6]:

(1) Steady state characterization in a new facility – The CAM200-EM thruster was successfully operated at Sitael and its performance validated. The thruster was operated at its six operational points between 100 W and 250 W, according to the MEPS project specifications. Measured thruster performance is in line, and within error bars, with the performance measured at the Asher Space Research Institute (ASRI) at the Technion, Israel. These results validate the performance recorded in past publications on the CAM200 thruster.

(2) Ion flux measurements in the thruster plume – The angular distribution of the CAM200 ion current density was measured using a rotating array of Faraday probes. It was found that the divergence angle of the thruster is less than 40° at discharge power levels of 160 W and above. This finding, which coincides with divergence angles of high power Hall thrusters, explains the high efficiency produced by the CAM200 thruster and significantly lowers the impact that this thruster may have on spacecraft it will be installed aboard.

Table 2. Key features of the CAM200 low power Hall Thruster.

Property	Value
Discharge Power	100-300 W
Discharge Voltage	150-400 V
Xenon Mass Flow Rate	0.5-1.4 mg/s
Thrust	6 mN @ 100 W 14 mN @ 250 W
Isp	900sec @100W 1,500sec @250W
Lifetime	>60 kNsec

The CAM200 thruster is currently undergoing ignition test activities. Additionally, a Qualification Model (QM) of the thruster is under production and planned to be integrated and tested in 2018.

B. HT-100 Hall Thruster (Sitael)

HT100 is the lowest power EP thruster ever developed in Europe, with a nominal operating power of 175 W. It can be operated in a power range between 140 and 300 W, with a peak efficiency exceeding 35% and a maximum specific impulse of about 1,300 s. With a design based on permanent magnets and a total mass lower than 450 g, HT100 is also the most lightweight Hall thruster of this class.

Table 3. HT100EM Detailed Performance.

Parameter	Value
Power Range	140 – 300 W
Thrust Level	5 -15 mN
Specific Impulse	900-1300 s
Thrust Efficiency	Up to 40%
Total Impulse	>60 kNs
On-off cycles	>2000
Thruster lifetime	>2000h
Thruster mass	≤450g

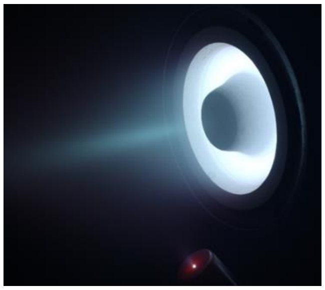


Figure 3. HT100 firing in SITAEL vacuum facility.

Presently, it has been developed at EQM level, performing a number of major tests aimed at its on-ground validation:

- Performance characterization / repeatability
- Endurance test
- Vibration test, structural analysis
- Thermal vacuum test

- Full characterization with Kr propellant
- Coupling test with the PPU BB

This was an extensive pre-qualification test campaign, carried out with the specific purpose of highlighting potential criticalities before starting the official MEPS test campaign.

The design of HT100 thruster has been updated several times in the past few years until a consolidated configuration has been frozen and two thrusters have been assembled in the latest configuration and were both operated and fully characterized in SITAEL vacuum facilities, showing equivalent performance. The following table shows the main features of HT100.

C. Heaterless Hollow Cathode (Rafael)

In recent years Rafael has been developing a low current heaterless hollow cathode, denoted the Rafael Heaterless Hollow Cathode (RHHC) (Figure 4). Heaterless technology was adopted for the faster ignition durations, cathode heater reliability issues and cathode heater power supply mass savings[7]. During cathode development particular attention and efforts were invested in (a) Thermally-efficient design (b) development of manufacturing processes and (c) ability to operate the cathode with various commercially available emitters. The development involved the study of heaterless ignition and operation, the development of reliable manufacturing processes, study of failure modes and cathode operation characterization in steady state. The cathode is designed to operate in the low current regime, between 0.5 A and 1.1 A, and couple with both the CAM200 and the HT-100 Hall thrusters, according to the MEPS project specifications. The RHHC specifications are listed in Table 4.

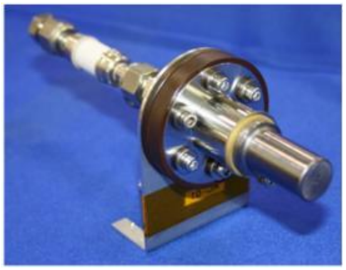


Figure 4. Picture of Rafael Heaterless Hollow Cathode (RHHC).

Table 4. Key features of the Rafael Heaterless Hollow Cathode (RHHC).

#	Requirement	Value
1	Discharge Current	0.3-1.2 A
2	Xenon Mass Flow Rate	0.1-0.25 mg/s
3	Lifetime	4,000 A×hr
4	No. of Startups	3,500
5	Ignition Voltage	< 400 V
6	Mass	170 gr

Additionally, during storage, air-borne transportation and installation in the test facility, some sensitivity to high temperature and humidity was discovered. This issue was thoroughly investigated and means of prevention developed accordingly. Consequently, proper transportation and storage appliances were produced.

In the past year, and within the frame of the MEPS project, the RHHC completed several key tests tailored to demonstrate the cathode's ability to meet project requirements and withstand future projected operation as part of a Hall thruster based propulsion system[8]. These tests included:

(1) 5,000 hour endurance test – The purpose of the test was to examine steady state cathode operation under a diode mode setup, against an anode plate. The cathode operated at its nominal operation point of 0.8 A with mass flow rate of 0.25 mg/s. During the test the cathode operated continuously and with no spontaneous shut-downs. At the end of the test the cathode showed no signs of degradation and could easily keep operating if needed.

(2) 3,500 ignition cycles test – The purpose of the test was to examine the ability to fully start the cathode from a cold state. The test included a fast, under 10 sec, cathode stratup until steady state discharge was sustained. Following the startup the cathode was let to operate continuously for 5 min to assure it reaches thermal steady state condition. After operation the cathode was turned off and let to cool-down for 15 min to assure cold state condition prior to the subsequent ignition. The cathode successfully passed the test and will continue to accumulate more ignition cycles in the future.

(3) Coupling with Hall thrusters – The cathode was coupled with both the CAM200 and the HT-100 Hall thrusters. The coupling test included both a steady state operation phase and an ignition test in which a suitable startup scheme was explored for each thruster. Steady state operation for both Hall thrusters was proved successfully. Ignition with the CAM200 Hall thruster was successful by lowering magnetic coil current and allowing immediate plasma formation in the thruster-cathode gap. Thruster initiation with the HT-100 Hall thruster is still under work as the thruster consists of permanent magnets; therefore unable to reduce its magnetic field intensity. However, special ignition schemes are currently developed by Rafael to confront the ignition issue and allow reliable thruster stratup.

Currently, a Qualification Model (QM) of the cathode is under production and is planned to be assembled and tested by early 2018.

D. Power Processing Unit (Sitael)

General Description

The PPU enables the single operation of any one of the thrusters in their complete thrust range, ensures full performance for an unregulated power bus voltage from 22V to 34V and is composed of the following functional blocks:

- PPU Power Module A and B (PPM-A and PPM-B, for redundancy) which implement the power electronic circuits necessary to supply any of the two Thruster Units (TU-A and TU-B)
- Thruster Switching Unit (TSU) which contains the electromechanical circuits enabling the selection of any one of the Tus
- Filter Unit (FU) which has the purpose to filter the high frequency current noise typically associated with the Tus
- PPU Control Module A and B (PCM-A and PCM-B, for redundancy), which provide the communication with the satellite and the control of the PPU and EPS valves.

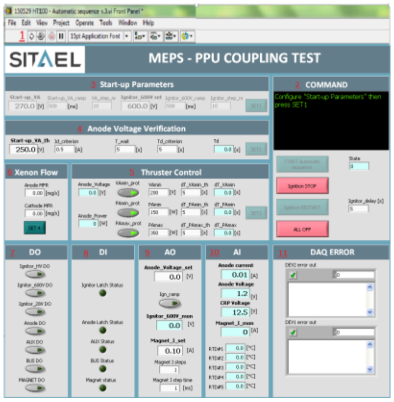
Figure 5. Picture of the PPU Breadboard.

In order to test the PPU functionalities and to permit the coupling with the TUs, a PPU BB (see Figure 5) has been assembled and tested. The breadboard does not implement the redundancy of the final unit; consequently, the TSU is not implemented on the breadboard as well.

In particular the breadboard implements the modules necessary to drive each type of TU:

- Anode Power Supply suitable for both the CAM-200 and HT100
- Cathode Power Supply for the RHHC
- Magnetic Field Power Supply only for the CAM-200 (HT100 has permanent magnets).

The functions of the PCM necessary to drive the two TUs are implemented using the Labview GUI which is displayed in Figure 6. The GUI performs the start-up sequence necessary to ignite the cathode and to establish the anode discharge current in automatic mode and is flexible enough to permit the use of each converter independently from the others in manual mode.



Configure "Start-up Parameters" then press SET1

Start-up_VA 270.0 [V]
Ignitor_600V set 600.0 [V]
Start-up_VA_th 250.0 [V]
Id_criterion 0.5 [A]
Anode MFR 0.00 [mg/s]
Cathode MFR 0.00 [mg/s]
Anode_Voltage_set 0.0 [V]
Ignitor_600V_mon 0.0 [V]
Magnet_I_set 0.10 [A]
Anode current 0.01 [A]
Anode Voltage 1.2 [V]
CRP Voltage 12.5 [V]
Magnet_I_mon 0 [A]

Figure 6. Screenshot of the PPU GUI.

Coupling Tests

Coupling tests have been performed in order to verify the capability of the PPU BB to ignite the two TUs (Rafael's CAM-200 with RHHC and SITAEL's HT100 with RHHC) and keep the discharge stably on in steady state condition for different power levels.

The test was carried out at Sitael premises in Pisa over several weeks, in order to verify the capability of the PPU architecture to drive both thruster units over different operating points. Special attention was devoted to the cathode ignition procedure, which has been attempted in two different ways:

1) Classical ignition as per TU Specifications, applying a high voltage to start-up the cathode

2) Alternative procedure, to gently ignite the cathode after a pre-heating with a carefully tuned current discharge flowing between cathode and keeper

The latter procedure is meant to ignite the cathode avoiding the application of a high voltage. This has a very beneficial impact on the cathode lifetime.

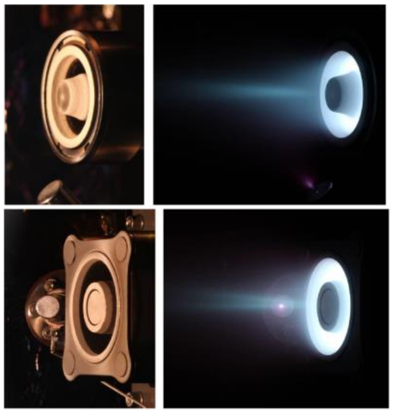


Figure 7. HT100 (top) and CAM200 (bottom) firing at SITAEL premises during the coupling tests.

E. Propellant Management Assembly (Rafael)

MEPS PMA (Figure 8) is designed as a highly versatile component of the electric propulsion system. Its design meets stringent performance requirements on the one hand while providing a high level of tailoring flexibility on the other hand, with a goal of minimizing Non-Recurring Engineering (NRE) activities for future projects. The PMA design achieves these highly ambitious goals by a combination of generic building blocks which are responsible for its main functions: propellant isolation, pressure regulation, flow control, and propellant gauging and health monitoring. Each of these building blocks has several implementation variants depending primarily on the type of mission defined by the customer. A rough distinction between the missions is drawn by examining the two extremes, an “agency”-type mission, where performance and reliability are of prime importance versus “constellation”-type missions where cost and production rate are the main design drivers. Each building block can be implemented by using space grade components manufactured by Rafael or available from other qualified suppliers or by using COTS components, screened and adjusted for space use by Rafael.

Currently, Rafael is at the final stages of a thorough evaluation process of COTS components for the MEPS version of the Flow Control Unit (FCU) and EM testing of the unit. The evaluation process is tailored in accordance with ECSS standards in general and ECSS-Q-ST-60-13 in particular, on batches of COTS components, in this case, valves and flow restrictors. The evaluation covers Parts, Materials, and Processes (PMP) aspects of the COTS components’ design, their compliance with ESCC specifications, performance and lifetime characterization, and environmental effects, such as, dynamic loads, hard vacuum, and radiation. So far, the results of the evaluation are promising and Rafael is ready for the qualification stage of the development. A detailed failure modes’ and reliability analysis resulted in the formulation of a qualification test plan which, when performed on defined sizeable batch of components, enables to provide a test-proven reliability figure for the design. For example, lifetime characterization has shown that the COTS components can easily withstand a tenfold lifetime test versus the requirement, therefore, setting the qualification batch size to eight (8) components for a proven reliability of 99.9% at 90% confidence level.

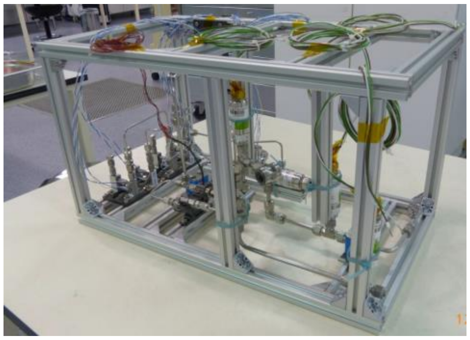


Figure 8. Picture of the experimental setup of the Propellant Management Assembly (PMA) at Rafael.

IV. Target Applications

MEPS started in late 2013 to fill a niche in the space market by providing a low-cost, low-power and integrated subsystem that can extend the intrinsic benefits of electric propulsion to small platforms operating in LEO. Among the many potential applications of low-power, HET-based propulsion systems, LEO communication satellite constellations, VLEO Earth observation missions and de-orbit applications seem to be the most promising near-term scenarios.

As a matter of fact, the recent interest of the private sector in LEO-HTS large constellations of small satellites has raised the need for cost-effective and efficient propulsion systems for constellation deployment and maintenance. Telecommunication and EO constellations would benefit from the high specific impulse of EP-based systems increasing the payload mass or reducing the launch mass. However, a minimum thrust level of several milli-Newton (usually around 10 mN) is needed to perform debris collision avoidance maneuver within a few hours. This requirement is of paramount importance in LEO altitude regions as the historical practice of abandoning spacecraft and upper stages at the end of mission life has allowed roughly two metric ton of space debris to accumulate in orbit. In this context, the uncontrolled growth of space debris population (~5% per year) has to be avoided to enable safe operations in space for the future. Active Debris Removal (ADR) missions would greatly benefit from the MEPS system given the high specific impulse provided (>1100 s) and, for contactless deorbiting strategies, the low divergence ion beam (<55° @ 95% of the total ion beam) for such low power Hall thruster based propulsion systems.

Another important application for MEPS-like systems is drag-compensation for VLEO satellites. Hall thruster have a higher thrust density with respect to other EP devices (i.e. ion engines) and can provide sufficient thrust to maintain a satellite at heights lower than 250 km, allowing for high-resolution imaging of the Earth’s surface.

Lastly, an electric propulsion system can also be a winning option for de-orbiting tasks as it is possible to complete the maneuver with substantial savings in propellant mass. In this case, at the end of mission life, the available power can be switched from the payload to the electric thruster, which then acts breaking the satellite and lowering its altitude until the denser layers of the atmosphere quickly complete the disposal process.

In particular, MEPS is a candidate solution for Rafael's LiteSat microsatellite. This is a new development microsatellite, achieving sub-meter resolution with an incredible low body volume (34x34 cm), thanks to an integrated design concept. With MEPS, the satellite can compensate a 300-350 km altitude orbit drag and is designed to be part of large constellations, providing dense coverage of target areas. Most of the MEPS design requirements were derived from this mission needs.

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