The Rafael Power Processing Unit (PPU) for Electric Propulsion Systems

IEPC-2019-729

Presented at the 36th International Electric Propulsion Conference
University of Vienna, Austria
September 15-20, 2019

Boaz Shoor[1], Amoz Davidson[2], Dan Lev[3], Leonid Appel[4], Oren Epstein[5] and Jacob Herscovitz[6]
Rafael- Advanced Defense Systems Ltd, Haifa, 3102102, Israel
Email: orenp@rafael.co.il

Rafael's first generation Power Processing Unit (R-400PPU) is operating successfully, for over two years, in a LEO mission on-board the VENµS Micro-satellite. Presently, Rafael develops the 2nd generation PPU (R-400PPU MK2) aimed at serving as a common and generic solution for Rafael's Hall Thruster based Electric Propulsion Systems (EPS) in the system power range of 150 to 1000W. The R-400PPU MK2 consists of two major sub-units, the Power Supply Unit (PSU) and the Sequencing and Control Unit (SCU), and provides all power, telemetry and communication requirements for the EPS. It also contains a Thruster Selection Unit (TSU) that selects one of two thrusters for operation. PPU design consists of four development phases, one for each model: Bread Board (BB), Engineering Model (EM), Engineering Qualification Model (EQM) and Proto-Flight Model (PFM). In this paper we describe the main characteristics of the R-400PPU MK2, its stages of development and the initial integration test conducted with the Rafael thruster units and other subsystems and EPS.

[1] Head of the Electronic Systems Group, Manor Division, Electronics Department.
[2] Head of the Electronics Dept., Manor Division, Electronics Department.
[3] Ph.D., Electric Propulsion R&D Responsible, Manor Division, Space Department.
[4] Head of the Electric Propulsion Group, Manor Division, Space Department.
[5] Project Manager, Manor Division, Space Directorate.
[6] Chief R&D, Manor Division, Space Department.

I. Introduction

LEO satellite platforms are designed to perform a variety of missions such as Earth observation, atmosphere monitoring, rapid communication to earth, or purely scientific missions. To do so, different maneuver capabilities are required from the propulsion system – short periodic orbit maintenance activations, long high impulse orbit raising operation, low thrust attitude control impulse bits, continuous operation for drag compensation, and end-of-life disposal. Each mission requires a specific propulsion system tailored to meet mission maneuverability needs. The traditional propulsion systems used to perform these tasks were mainly based on chemical propulsion. Their main drawbacks were the mass inefficiency, that means a large mass of the system is dedicated to the propellant.

Recently, the Electric Propulsion Systems (EPS) are gaining more and more popularity among these missions, thanks to their improved mass efficiency, as compared to chemical systems. The newest communication constellations are all meant to carry EPS, for accomplishing these functions and also keep their cost at a minimum[1].

A typical EPS is comprised of at least one Thruster Unit (TU), a propellant supply sub-system (regularly a pressurized tank), a Propellant Management Assembly (PMA) and a Power Processing Unit (PPU) that supplies the electrical operating power and signals, as shown in Figure 1.

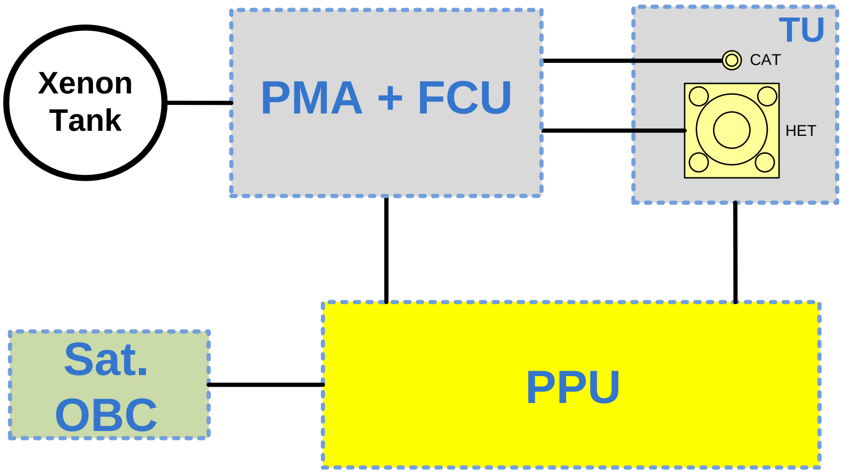

Figure 1. Typical Electric Propulsion System (EPS) architecture.

The PPU is the "brain" of the EPS, its main functions are to supply power to the TU and control the PMA and the Flow Control Unit (FCU) according to the desire operating power and thrust.

The PPU receive and act upon commands from the satellite On-Board Computer (OBC) and powered by the satellite power bus. It provides telemetry of EPS operation, like power levels, voltages, currents, temperatures, etc.

The PPU contains a Thruster Selection Unit (TSU) that selects one of two thrusters for operation (if more than one is available in the EPS) and mitigates its plasma noise.

II. VENµS R-400PPU Heritage

Space systems activities at Rafael were initiated three decades ago to support Israel's entrance to space era. Rafael designed, built and integrated all Israeli satellites and launchers propulsion systems, using chemical propulsion technologies. Two decades ago, Rafael started development of Electric Propulsion for space, focusing on Hall Effect Thruster (HET) technology, for small and micro satellites, where power generation is limited. VENµS[2] is the first project in which Rafael supplied a complete EPS. VENµS satellite was launched in 2017 and is successfully operating in space, including its EPS.

The VENµS satellite includes a complete on-board electric propulsion system: denoted R-400EPS (see Figure 2) based on two low power Hall effect thrusters. The Hall thrusters, denoted IHET-300, operate in the 300-600W power range according to mission requirements. The electric propulsion system, and components, were designed, manufactured, qualified, integrated and tested by Rafael. These include the Hall thrusters, PPU, flow controller, propellant tank and other propellant management components.

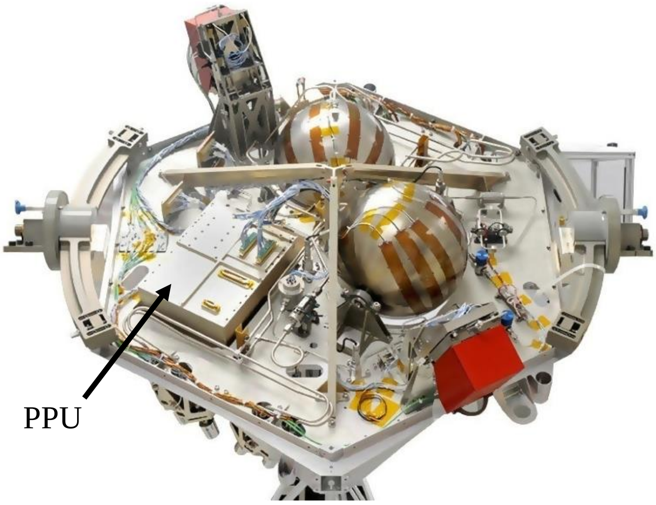

Figure 2. VENµS satellite EPS

The Venus R-400PPU[3] is the Rafael first generation of PPUs that has been developed. A needs review was conducted and requirements for the unit were defined according to mission, satellite and EPS sub units. Due to the fact that this is the first EPS and PPU to be developed in Rafael, wide diagnostic and configurability options have been integrated in the PPU. The PPU has the ability to be updated with parameters, which allows for maximum flexibility and the ability to select an operating configuration for optimization. The PPU also has the option of operating in manual mode, which enables the execution of a required operating scenario with complete control over the operation of each power supply in the required timing. In addition, the PPU sends telemetry of various voltages and currents of its components, which are used in analysis and system optimization.

The PPU has been functioning well for two years in orbit, according to telemetry data analysis.

The R-400PPU block diagram is presented in Figure 3 herein with its main interfaces to the EPS sub-assemblies.

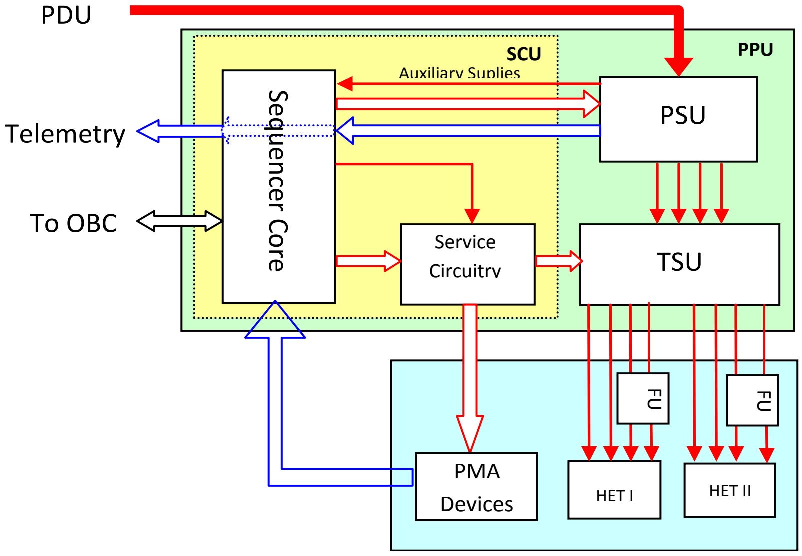

Figure 3. R-400PPU block diagram in EPS environment

The PPU is powered from an unregulated DC source – the satellite power through its Power Distributing Unit (PDU). The PSU section comprises of eight types of power supplies. Four power supplies are required to operate the thrusters, while the remaining four (marked as AUXPS) are used to power other devices associated with the EPS. Figure 4 shows the flight model of the PPU. The upper part, where the electrical connectors are located, is located in the satellite hull. The bottom part is mounted outside the satellite and the flat radiator radiates the excessive heat to space.

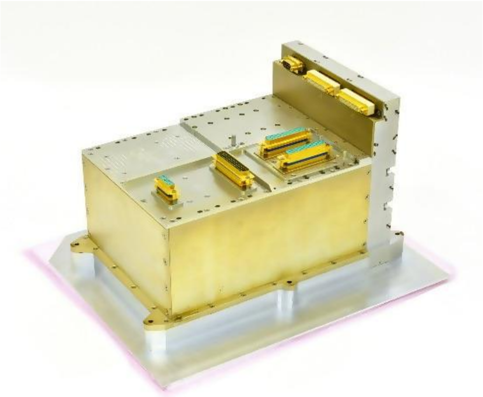

Figure 4: VENμS R400-PPU (FM)

III. Rafael 2nd Generation PPU – R-400PPU MK2

Rafael is continuing the development of its next generation of EPS: R-200 EPS[4][5] is a system for 100-300W anodic power range, while R-800EPS is intended for 600-900W anodic power range. Both systems are based on Rafael heaterless cathodes[6] and advanced FCU with Thermal Throttle (TT) flow control unit.

To support each EPS, a 2nd generation PPU (R-400PPU MK2) is being developed. This new PPU will support thruster operation in the range of 100W up to 900W anodic power for LEO missions. This new PPU is based and draws heritage from Venus R-400PPU. R-400PPU MK2 main characteristics are shown in Table 1.

Table 1. R-400PPU MK2 main characteristics.

Characteristic	Value
Mass	Less than 11kg
Efficiency at max. power	92%
Anodic power	up to 900W @ 310 Vdc
Anode voltage PS	Controllable - 200,250,275, 300Vdc
Magnetic Field PS	up to 2.6A, variable control
Cathode PS	500 VDC for breakdown; 5 keeper current source levels
Auxiliary PS	5Vdc and 28Vdc
Thermal control	Conduction through base plate
Redundancy	Full cold redundancy, reconfigurable in space Branches cross option
Input power	Unregulated bus, 94 to 106 Vdc
OBC Interface	Dual redundant CAN-Bus & RS422

The PPU design plan includes four development phases, one for each model: Bread-Board (BB), Engineering Model (EM), Engineering Qualification Model (EQM) and Proto-Flight Model (PFM).

The PPU is fully compatible with the Rafael R-200EPS and R-800EPS. It has a total efficiency of above 91% and the ability to support a wide range of operating power levels (100-900W).

The modular design of the unit enables high flexibility in determining its configuration and redundancy, to match the desired mission need. The unit is fully redundant up to 600W anodic power and uses graceful degradation for power levels from 600W up to 900W (anodic). The ability to cross branches and using combination of PS and SCU from different branch makes the PPU highly reliable.

The R-400PPU MK2 is radiation-tolerant, based on electronics components that are proved to withstand LEO conditions.

The new R-400PPU MK2 includes 3 major sub-units (see Figure 5):

- The Power Supply Unit (PSU) that generates the required voltages and currents needed for the TU, PMA, FCU and SCU operation.
- The Sequencing and Control Unit (SCU) which is responsible to control the PPU and the whole EPS. It provides the sequencing of the power supplies when needed to ignite and operate the TUs, it controls and operates the PMA and FCU modules, it controls the TU operating power and it is in charge of interfacing with the OBC through TM/TC communication ports.
- The Thruster Selection Unit (TSU) which enables to select the desired operating TU (1 of 2).

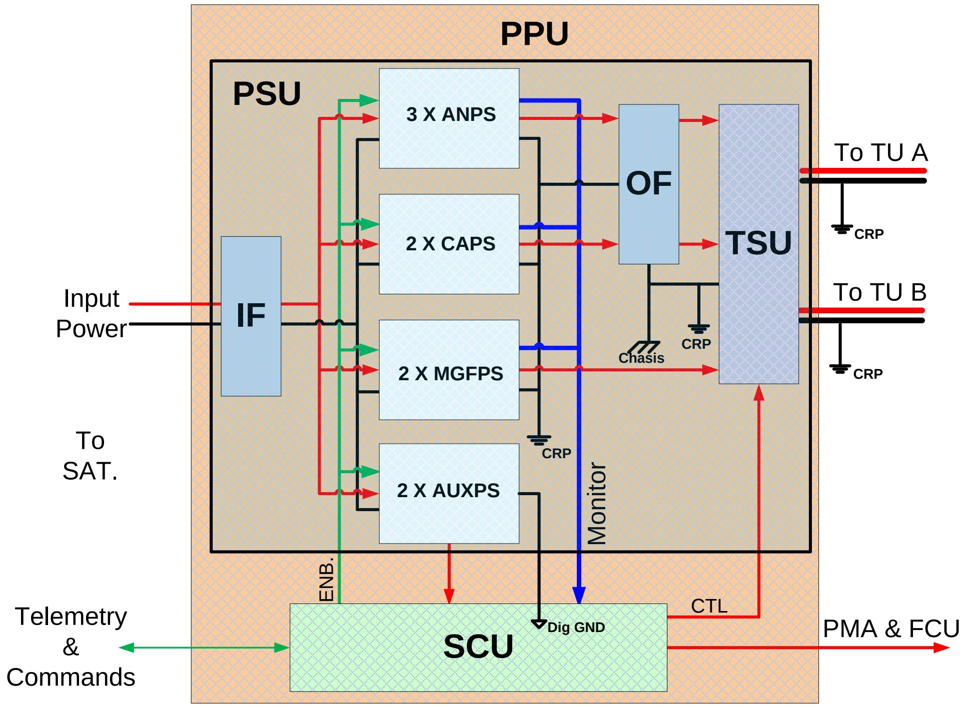

Figure 5. R-400PPU MK2 internal structure

A. R-400PPU MK2 SUBUNITS

i. Power Supply Unit (PSU)

The PSU includes the following modules:

Anode power module, consisting of 3 power supplies of 300W each that adds up to 900W in parallel. The design features a unique topology which enables high performance and efficiency.

The anode module can be configured to have one, two or three anode power supply units. This configuration will define the highest output power level and module redundancy. Thus, no excessive mass will be flown. In order to achieve an optimal TU operation in the range of 100÷900W, the anodic power module can supply four distinct voltage levels of 200V,250V,275V,310V.

The anode power supply has under-voltage and over-current protection that allow it to be immune to various situations in which the TU operates.

The Cathode power module supports both 1A and 2A of Rafael heaterless cathodes. It includes voltage/current power supply of 100W output. The module enables the cathode ignition by supplying high voltage. After ignition, the module functions as a current source with 5 current levels. All is controlled by the SCU which enables gradual heating of the cathode.

The Magnetic coils power module: provides up to 20W current source which enable to set the desired thruster magnetic field.

The module has continuous output current levels, also fully controlled by the SCU.

The Auxiliary power module includes housekeeping power supplies for PSU internal operation, SCU power and PMA modules supply.

The Filter Unit (IF & FU) – Input and Output filters. The input filter is used to filter the satellite bus power while the output filter is used to mitigate the thruster plasma noise in the range of 10-65 KHz in order to avoid PPU and Satellite damage.

The Thruster selection unit, is based on high voltage relays. It enables the selection of one of the two TUs for operation by switching TU electrodes to the power supplies output. The relays have an output loopback in order to achieve indication for switching success.

ii. Sequencing Control Unit (SCU)

The SCU is responsible for the logic and control management of the PPU. It controls each of the PSU power supplies and each one of the PMA components. It also samples critical voltages and currents across the PPU. These samples enable the SCU to adequately control the operation of the thrusters and the whole EPS.

The SCU logic is implemented by using a FPGA device and a microcontroller. The SCU electronics circuits on board are designed to deal and implement of the required protection and algorithms in order to deal with single events effects. The SCU interfaces the OBC through TM/TC communication ports.

The SCU has the following internal structure and interfaces as shown in Figure 6:

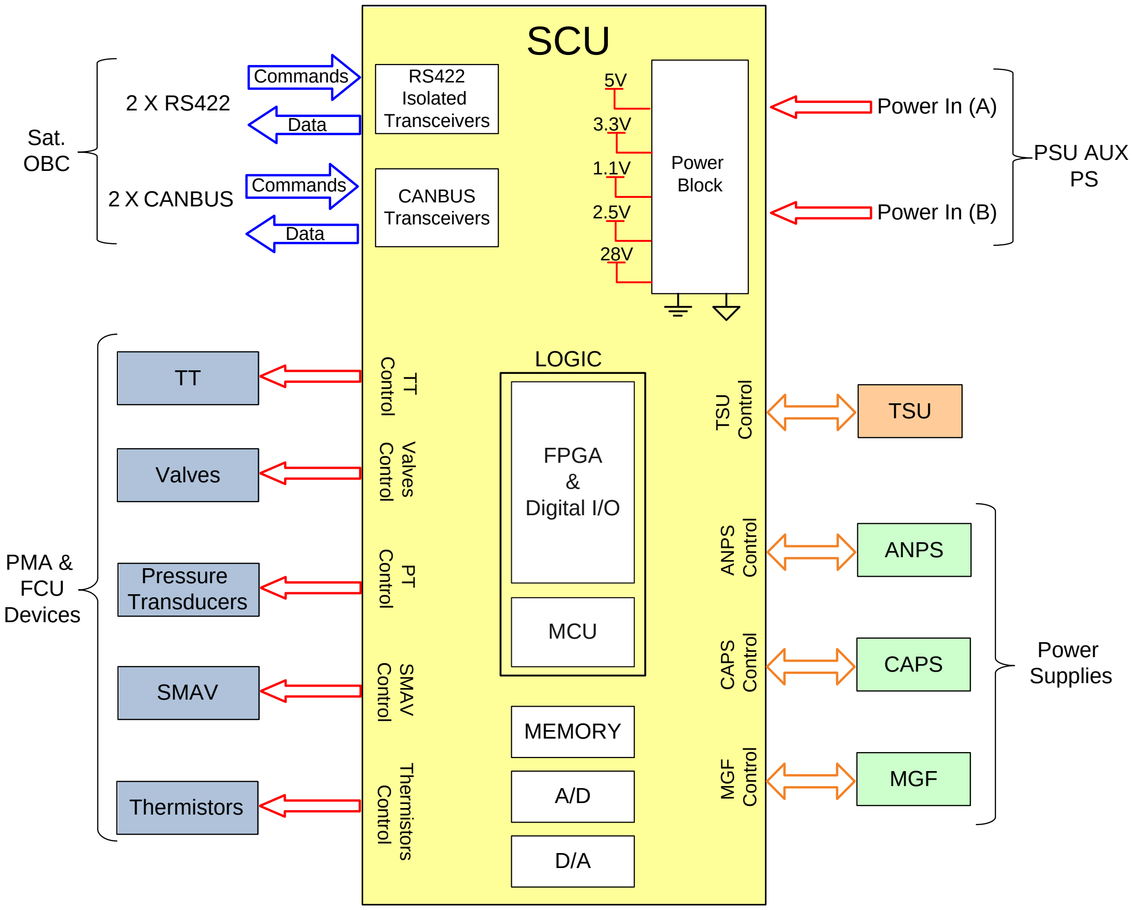

Figure 6. SCU Internal structure and interfaces.

B. R-400PPU MK2 Interfaces

i. Electrical

The R-400PPU MK2 input voltage is 100Vdc ±6Vdc nominal, to suit most modern platforms. However, it will be possible to adapt its input voltage to any other platform requirement, using a modular input stage. When using 900W anodic power, a 1000W input bus power is needed. The SCU implements a TM/TC communication port with the satellite OBC via dual redundant CAN-Bus & RS422.

The PPU interfaces the PMA and FCU sub units like solenoid and latch valves, pressure transducers, temperature sensors and TT for power, operation commands and operating diagnostics.

ii. Mechanical

The R-400PPU MK2 has a rectangular structure consisting of two assemblies – PSU assembly and SCU assembly. The assemblies connect to each other in a snap without the need of internal binding. The R-400PPU MK2 can physically interface the satellite using 6 mounting lugs.

The R-400PPU MK2 has a main connector for the satellite power and communication interface, 2 TUs Output connectors and 2 PMA&FCU output connectors (for redundancy). All connectors are type D.

The R-400PPU MK2 dimensions are less then 290x240x160 mm (LxWxH) and weight approximately 10Kg.

Figure 7 shows the CAD model of the R-400PPU MK2 engineering model.

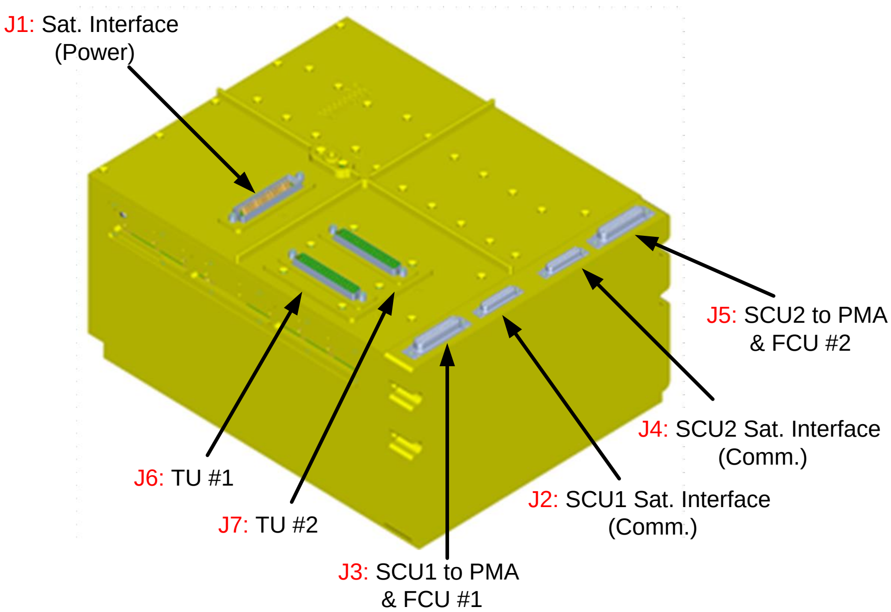

Figure 7. R-400PPU MK2 EM CAD model

iii. Thermal:

The R-400PPU MK2conducts its heat through a base plat to the satellite.

The internal heat conduction is based on conducting the heat of the power supply boards to the side of the unit and from there, down to the base plat. All power components are mounted on the base plat to allow optimum heat dissipation. The R-400PPU MK2 heat dissipation on steady state operation at 1000W bus power (at 900W anodic power) is less than 60W.

IV. R-400PPU MK2 And EPS Sub-System Integration Tests

In order to prove the concept of the PPU, a breadboard model was developed (see Figure 8). This breadboard consisting of a standalone PSU assembly and an SCU board. The breadboard includes all the required functions and interfaces that reflect the final product, but with no thermal and no final mechanical design. To cool the breadboard , an internal baseplate is used.

The breadboard configuration allows the PPU to be tested against the various scenarios and loads and reduce several risks as early as possible in the PPU development.

The breadboard phase has been successfully completed; integration tests with R-200 and R-800 TUs and respective PMA have been successfully completed.

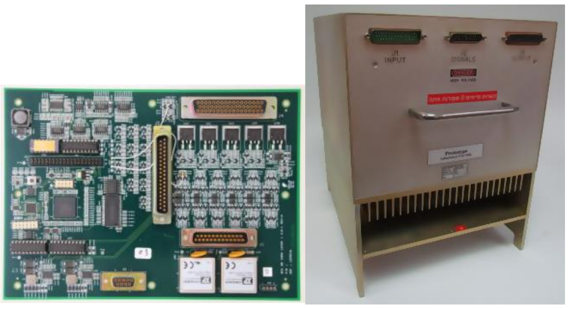

Figure 8. Right: Power Supply Unit (PSU) and Left: Sequencing and Control Unit (SCU) breadboard

A. PPU breadboard with Thruster Unit integration test

As part of the development process of the breadboard, integration tests with the R-200 and R-800 thruster units have been performed. The purpose of these tests was to validate the PPU ability to operate the main thruster power unit (Anode PS); thruster unit ignition sequence and transition to steady state operation (Keeper PS); and to provide the required current to the thruster magnetic coils.

The breadboard was located next to the vacuum chamber and connected to the thruster unit via dedicated electrical feedthroughs (see Figure 9). To validate PPU operation spanning over the entire power output regime two thruster units were used in two separate tests. During each test the PPU ignited the cathode, following by a full ignition of the thruster until steady state operation was reached. The PPU operated each thruster unit at a variety of discharge power levels for the duration of several minutes to over an hour at each point (see Table 2). Overall, the PPU successfully ignited and operated the Hall thrusters at power range of 100-900 W. It should be noted that during each ignition sequence the required cathode ignition voltage was lower than 500 V, usually in the range of 350 V.

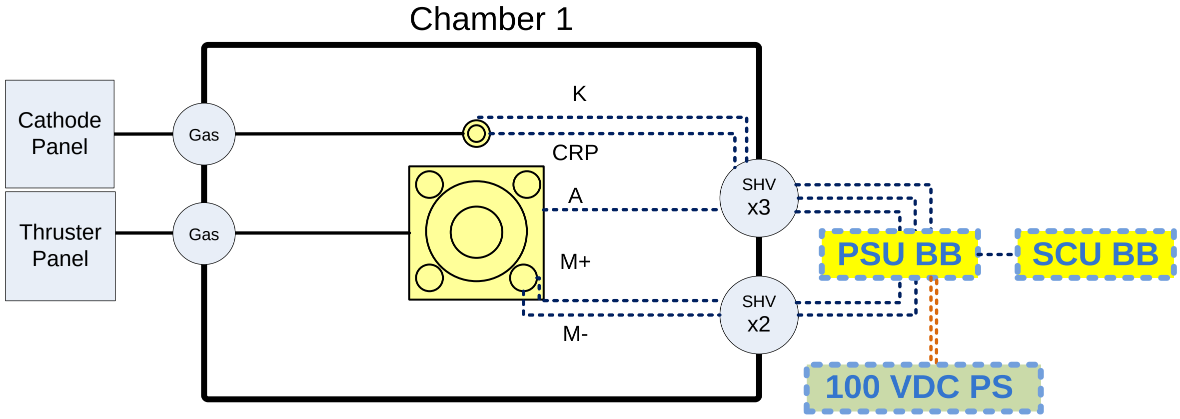

Figure 9 - Experiment schematic of the PPU breadboard and thruster units integration test.

Thruster	Power [W]	V_d [V]	Cathode Voltage [V]	Magnet Current [A]
R-200	100	275	< 500	2.5
	250	275	< 500	2.5
R-800	600	310	< 500	2
	700	310	< 500	2
	800	310	< 500	2
	900	310	< 500	2

Table 2. PPU breadboard and thruster units operation tests.

B. Closed-Loop Control integration tests

The PPU has the ability to regulate propellant flow in order to maintain a constant thruster unit power consumption. The power control is performed by a closed-loop regulation of the propellant flow using a thermo-throttle. The PPU delivers heating current, in the range of a few amperes, that heats the thermos-throttle, thus regulating the mass flow rate to the thruster unit. The SCU samples the discharge current and compares it to the target current, corresponding to the target power. The SCU, according to the chosen control technique, regulates the propellant flow until the desired discharge current is obtained.

To validate the SCU capability to perform closed-loop control of the discharge power two separate tests were conducted.

In the first experiment, conducted at Rafael's space department clean room, the SCU was connected to the propellant management assembly via direct connections to the thruster and cathode solenoid valve and the thruster thermos-throttle flow controller (see Figure 10). Since at this experiment no thruster operation was involved, the SCU controlled the mass flow rate by receiving a mass flow rate reading from a mass flow meter located upstream from the solenoid valves. During the experiment the SCU received a target mass flow rate value. The SCU then controlled the thermo-throttle flow controller while constantly receiving mass flow rate readings from the mass flow meter.

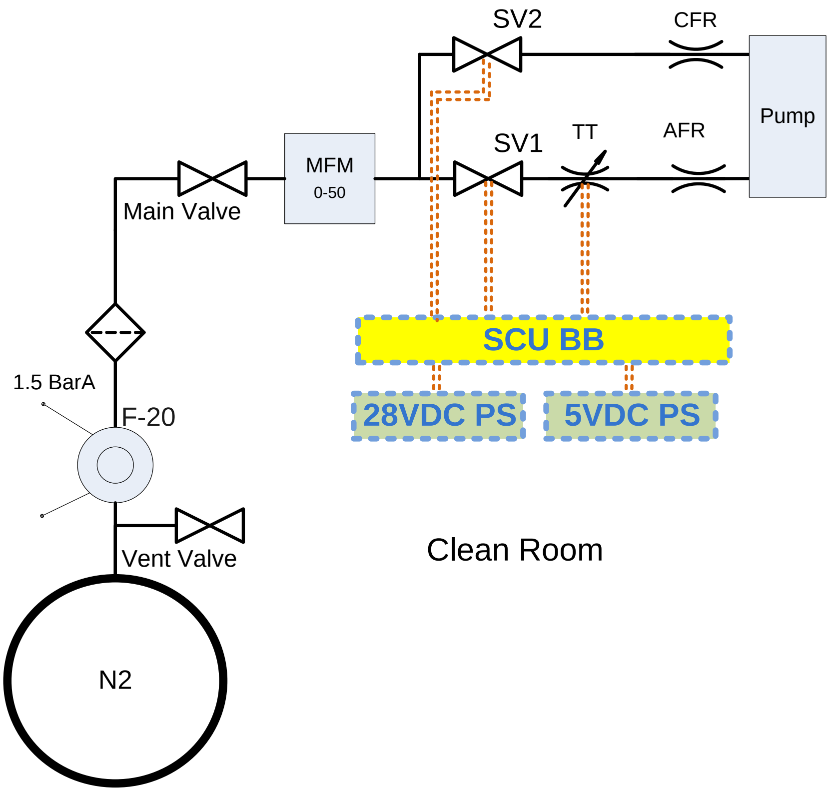

Figure 10. SCU closed-loop operation experiment without TU

In the second experiment, conducted at Rafael's electric propulsion facility, the SCU was positioned next to the vacuum chamber and connected to a thermo-throttle flow controller via dedicated electrical feedthroughs (see Figure 11). The R-800 Hall thruster unit was operated using laboratory power supplies while the thermos-throttle was operated directly by the SCU that also monitored the thruster's discharge current. Once a target discharge current was input to the SCU it regulated the thruster's mass flow rate until the desired current was obtained. Using this technique the thruster unit operation power was throttled between four points (see Table 3).

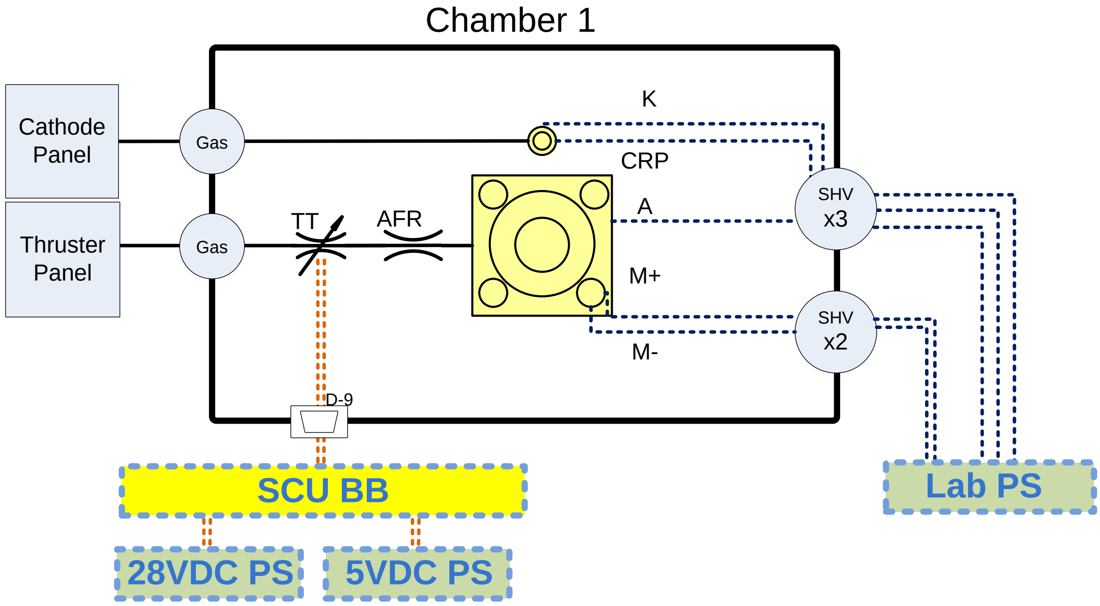

Figure 11. SCU closed-loop operation experiment with Thruster unit (R-800) operation.

Power [W]	I_{target} [A]	$I_{measured}$ [A]
577	1.92	1.924
750	2.5	2.5
450	1.5	1.504
750	2.5	2.5

Table 3. Thruster unit (R-800) operation points in the SCU closed-loop operation experiment.

Each one of the transitions converged into the required discharge current within seconds while minimizing the power required to operate the thermos-throttle flow controller.

V. R-400PPU MK2 Future Activities

Currently the development is in advanced stage of the EM. By the end of the year, the first EM will be completed and delivered for further testing.

The EM configuration will be identical to the PFM configuration in terms of electronic, mechanical and thermal design. The sole difference between the modules will be in the EEE parts, as the EM will not incorporate space grade components. Otherwise, all materials and assembly procedures will reflect the flight model.

After completing the EM manufacturing and integration tests with the R-200& R-800 EPS, the EQM will be manufactured. The EQM unit will undergo formal qualification tests in order to validate compliance to the environmental requirements.

The PFM will be developed after completing all the above phases.

VI. Summary And Conclusions

Rafael develops and manufactures the next generation of PPU for anodic power of up to 900W which is fully compatible with the Rafael R-200EPS and R-800EPS . This new PPU is based and draws heritage from Venus R-400PPU which has been functioning well for two years in orbit.

As part of the development process, the PPU breadboard phase has been accomplished. The PPU breadboard includes all the required functions and interfaces that reflect the final product. The breadboard successfully completed integration tests with R-200 and R-800 TUs. It also completed integration with PMA and FCU.

By the end of the year, the first EM will be completed and delivered for further testing. Following the EM phase, EQM and PFM will be available for qualification testing and for first mission in space.

VII. References

[1]. Dan Lev, Roger Myers, Kristina Lemmer, Jonathan Kolbeck, Hiroyuki Koizumi and Kurt Polzin. The Technological and Commercial Expansion of Electric Propulsion. *Acta Astronautica*, Vol. 159, 213-227, 2019.

[2]. Jacob Herscovitz, Dan Lev, Leonid Appel, Amoz Davidson, Sapir Berkman, Yonatan Amit-Shapira, Dror Bar-On, Michael Kedem, Ofer Salama, and Shimshon Adler, "Venus - First In-Flight Results of the Electric Propulsion System", In the *54th Joint Propulsion Conference (JPC)*, 9-11 July, 2018, Cincinnati, OH, USA. AIAA-2018-4464.

[3]. Jacob Herscovitz, Amoz Davidson, Pavel Gontmacher "Development, Qualification and Integration of the VENµS PPU". 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 28 - 30 July 2014, Cleveland, OH.

[4]. D. Lev, R. Eytan, G. Alon, A. Warshavsky, L. Appel, A. Kapulkin and M. Rubanovych. "The Development of CAM200 - Low Power Hall Thruster". *Trans. JSASS, Aerospace Tech. Japan*, 14(ists30), pp. Pb_217- Pb_223, 2016.

[5]. Franco DK, Lev DR, Appel L. Performance Validation and Plume Divergence of the CAM200 Low Power Hall Thruster. *Aeron Aero Open Access J.* 2018;2(2):75–78. DOI: 10.15406/aaoaj.2018.02.00033.

[6]. Dan Lev, Gal Alon and Leonid Appel. Low Current Heaterless Hollow Cathode Neutralizer for Plasma Propulsion - Development Overview. *Rev. Sci. Inst*. submitted. Under review.