VENµS – A Novel Technological Mission Using Electric Propulsion

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Venµs is a recently launched satellite, for super-spectral earth imaging and Electric Propulsion System (EPS) demonstration. The EPS includes a novel design, developed, qualified, manufactured and integrated by Rafael. The EPS will demonstrate mission enhancement capabilities and its space performance will be characterized. The system and satellite were carefully designed to comply with the mission goals and constraints. In addition to the EPS, a Technological Mission Center (TMC) was built for the command and analysis of the technological mission. The satellite is now beginning its in-orbit tests for the EPS and the rest of its components. Venµs mission duration is approximately four years, during which the satellite will operate in two major orbits.

I. Introduction

In the last two decades Rafael designed, produced and integrated chemical propulsion technologies that were utilized in all of the Israeli satellites and launchers. In parallel, Rafael began developing Electric Propulsion (EP) components while focusing on Hall Effect Thruster (HET) technology[1]. The main goal was to develop and supply EP components and complete Electric Propulsion Systems (EPS) for small and micro satellites, where power generation is limited and traditionally not many solutions existed. As part of the development efforts one major activity is VENµS - the first project in which Rafael supplied a complete EPS featuring the Israeli Hall Effect Thruster - IHET. The VENµS satellite was successfully launched on August 1st this year (2017) and will begin its mission following In-Orbit Testing (IOT).

II. The VENµS Program

Vegetation and Environment monitoring on a New Micro Satellite, or VENµS, is a joint program initiated in 2005 by both the Israeli and French space agencies (ISA: Israel Space Agency and CNES: Centre National d'Etudes Spatiales) [1,7]. Within the frame of the program, two novel missions will be executed: (1) Scientific mission and (2) Technological mission. In Israel, ISA's two subcontractors are Israel Aerospace Industry (IAI) and Rafael. The program goal is to design, build launch and operate a novel satellite, which will demonstrate multispectral imaging and orbit control using electric propulsion. Mission duration is slated for 4.5 years.

VENµS satellite was placed in orbit on August 1st, 2017. It was launched by Vega's tenth operational launch, from Kourou in French Guyana.

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Responsibility among the two space agencies are shown in **Error! Reference source not found.**. ISA is responsible for providing the satellite platform, the EPS, satellite control center, technological mission center and the operation of the satellite. CNES is responsible for the provision of the camera and the image ground segment. Launcher provision is a cost shared task between the parties. It is the first cooperation of this nature between Israel and France.

III. VENµS Missions

VENµS in space operation is divided into three phases: VM1, VM2 and VM3, as shown in Table 1. VM1 and VM3 are both characterized by a sun-synchronous and earth repeating orbits. This is mainly due to the requirements of the scientific mission, for imaging in constant angles. VM1 is the initial high altitude orbit at 720 km, while VM3 is a lower orbit at 410 km altitude. Both are earth repeating. For VM1, there are exactly 29 satellite revolutions in 48 hours, while for VM3 there are 31 revolutions. VM3 orbit was carefully selected [6] to provide the benefits of both scientific and technological missions.

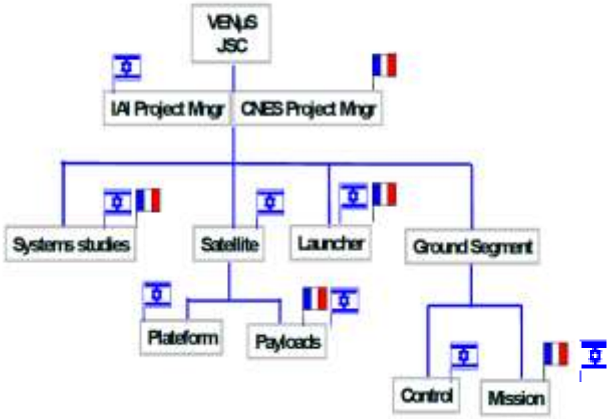

Figure 1. Responsibilities in VENµS program

VM2 is the phase in which the satellite changes the orbits.

Table 1. VENµS missions phases

Phase	Orbit	Duration	Technological Mission	Scientific Mission
VM1	720 km SSO, earth repeating	30 months	EPS experiments for characterization and orbit control	Super-spectral imaging
VM2	Orbit transfer	6 - 8 months	Orbit transfer	-
VM3	410 km SSO earth repeating	12 months	Orbit control in a high drag environment	Super-spectral imaging

A. Scientific Mission

The scientific mission is earth imaging in a superspectral mode. It is carried out by a superspectral camera acting as the scientific payload. It will provide a two day revisit rate, which will enable the scientists to carry out research on a temporal basis of images taken at a constant viewing angle and a constant sun angle.

The major objective of the VENµS scientific mission is to provide digital spaceborne data for scientific studies dealing with the monitoring, analysis, and modeling of land surface functioning under the influences of environmental factors as well as human activities. It is also aimed at demonstrating the relevance of superspectral, high spatial resolution observations combined with frequent revisit.

In order to implement these goals, the mission will acquire frequent, high resolution, superspectral images of sites of interest all around the world. During VM1 the satellite will orbit in a near polar sun-synchronous orbit at 720 km height. The whole satellite and camera will be able to be tilted up to 30 degree along and across track. This configuration will result in a 2-days revisit time, 27 km swath, a camera resolution of 5.3 m, and the capability to observe any site under a constant view angle. The system will cross the equator at around 10:30 AM local time.

The satellite will carry the VENµS Super-Spectral Camera (VSSC) as its scientific payload. It is characterized by 12 narrow spectral bands ranging from 415 nm to 910 nm. The band setting was designed to characterize vegetation status, including through red-edge bands, and to estimate the aerosol optical depth and the water vapor content of the atmosphere for accurate atmospheric corrections. One of the bands, at 620 nm, is duplicated and both bands are positioned at the extremes of the angular field in the scan direction. The 1.5° difference in look angle between these two will allow three-dimensional imaging that will enable to construct a Digital Elevation Model (DEM) of the earth surface and assessing clouds heights. The spectral band setting could also prove useful for coastal areas and inland waters studies. The data will be acquired over existing or planned experimental scientific sites with size ranging from a few kilometers to 27 x 100 km or more. The tilting capability will provide more flexibility in selecting the sites, enabling to detect targets at up to 360 km off-nadir. All data for a given site will be acquired with the same observation angle in order to minimize directional effects. The baseline product for these selected sites is time composite images of geometrically registered surface reflectance at 10 m resolution.

B. Technological Mission

1. Mission Objectives

There are two main objectives to the technological mission: space verification and validation**Error! Reference source not found.**.

Verification will be achieved by IHET operation in space environment. Its performance will be tested and qualified. Validation will be demonstrated for some mission enhancements operations.

2. IHET Verification

The verification of the IHET will start immediately after launch, in the IOT period. A series of experiments are planned to test the IHET. The verification goals are to test the proper operation of the thrusters and the whole electrical propulsion system in space, and to check the performance (thrust, specific impulse, efficiency).

Each year, there will be a dedicated technological mission month to perform multiple experiments and accumulate activation time. At the end of each experiment, IHET thrusters will be used to bring the satellite back to its nominal orbit.

All IHET experiments and operations will be analyzed and processed by the Technological Mission Center (TMC). Each IHET activation will result in an orbit change. These changes will be monitored and recorded continuously, by the GPS equipment of the satellite. The TMC will fit the best estimations of the instantaneous thrust that match the orbit change. Other vital data, such as operating power, temperatures, propellant mass flow rate, etc., will be downloaded by the satellite telemetry, and analyzed in TMC along with the orbit data.

3. IHET Validation

IHET validation will be demonstrated during the three mission phases – VM1, 2, 3.

Since the most noticeable advantage of an electrical propulsion system is its high specific impulse (Isp), compared to conventional monopropellant propulsion systems usually used in small satellites, the IHET challenge will be the demonstration of its capabilities in enhancing and augmenting the mission.

As said in the scientific mission description, one of the unique features of this mission is perpetual imaging in a constant viewing angle, at a constant sun angle lighting on the target. This requirement is a very stringent task to accomplish, and it calls for a very delicate and accurate orbit control system, along with orbit control actuators, the HET thrusters.

In addition to the planned evaluation experiments in VM1, the IHET will be used once a month to control the orbit and return the satellite to nominal orbit.

In VM2, the effectiveness of the IHET will be demonstrated by orbit transfer from one LEO (720km) to the lower LEO (410km) VM3 orbit. This major orbit change, of about 300 km in altitude , 1.2° in inclination angle, and controlling the RAAN and equatorial crossing local time (performing a maneuver of about 350 m/s) will need about 7.5 kg of Xenon.

Finally, in VM3, VENµS will keep imaging at a circular sun-synchronous orbit while maintaining the 2-day revisit ground track. VENµS platform has a considerable cross-section area and will exhibit quite a large atmospheric drag, which at this altitude plays a significant role. In VM3, the thrusters will have to be used intensively, to keep the imaging requirements accuracy (see **Error! Reference source not found.**). This task is hardly achievable by a comparable traditional chemical propulsion system, with the same mass of allocated propellant.

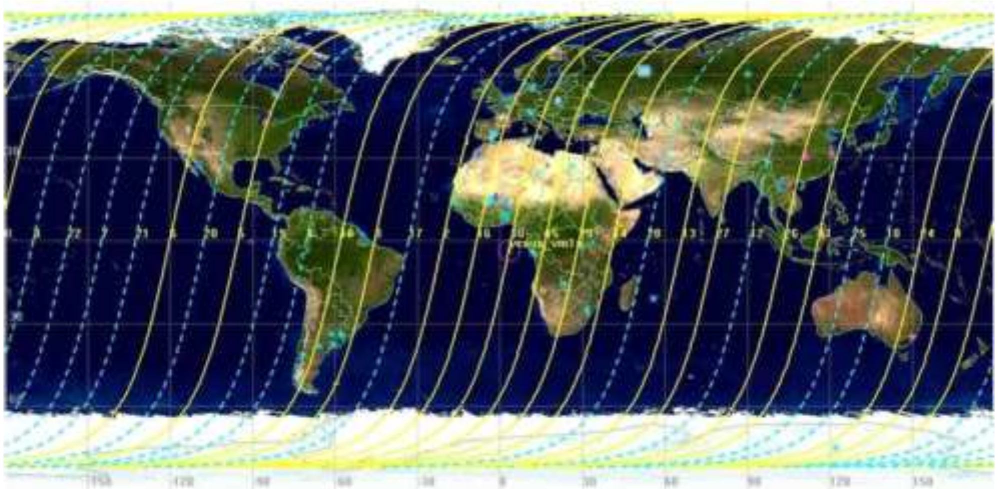

Figure 2. VM3 orbit allocation: Imaging revs in yellow, IHET revs in dashed blue

In this phase, the images resolution increases and its swath decreases with respect to VM1 mission phase. The challenge of VM3 is to comply with as many scientific mission requirements, as in VM1 and to accomplish the combined mission, of achieving the scientific goals with the proper technology use.

During the whole VENµS mission, both the IHET and the dedicated orbit control algorithms, will be validated and certified for this type of mission– imaging in low orbits with significant drag.

IV. VENµS Satellite

VENµS satellite platform is based on a heritage IAI platform: Improved Multi-Purpose Satellite (IMPS) which was adapted to this mission, as shown in Figure 3.

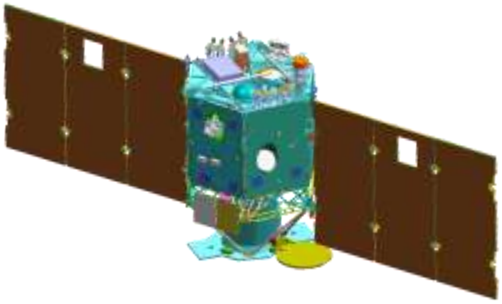

Figure 3. Venµs satellite model

The IMPS modifications concern mainly the base plate - to accommodate the 2 IHET thrusters and the propellant tanks. In addition to the IHET which serves as a payload, the satellite contains also a backup chemical propulsion system, operated by hydrazine and eight 1N thrusters. A 7 Kg Hydrazine tank is used to feed it. The satellite power production and management system is capable to drive the high energy demand of the IHET system (at operating range up to 550W) and the housekeeping equipment onboard. Two RF links (X-band and S-band) are implemented to carry the housekeeping information exchange (commands and telemetry) and the image data. Image data is stored on an on-board memory recorder (a total size of 240 Gbits) to be later downloaded to Kiruna earth station, where access is available. The Attitude and Orbit Control System (AOCS) contains two Star Trackers, GPS and Reaction Wheels, giving very high pointing accuracy performance while imaging. It also allows the high agility required by the attitude control for the large number of imaging sites in every single pass. Internal structure of Venus satellite is shown in Figure 4.

Since the IMPS bus has fixed solar panels, a dedicated analysis and design was carried for the thrusters and solar panels architecture, placement and pointing direction on the satellite. This was necessary because the thrusters need large amounts of power during their operation, for the whole illuminated part of any revolution. It is impossible to

Figure 4. Venµs satellite internal view

satisfy this requirement optimally in all points of the orbit, so a compromised solution was engineered. To solve this problem, some design trades were performed on five basic architectural configurations, of HET and solar panels placement on satellite (see **Error! Reference source not found.**). Configuration B3 proved to be the best, taking into account selected criteria (power, complexity, heritage, drag…).

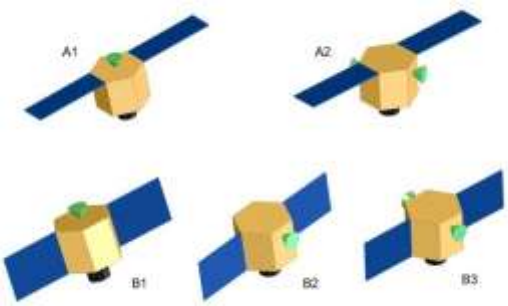

Figure 5. Possible architectural configurations of thrusters and solar panels

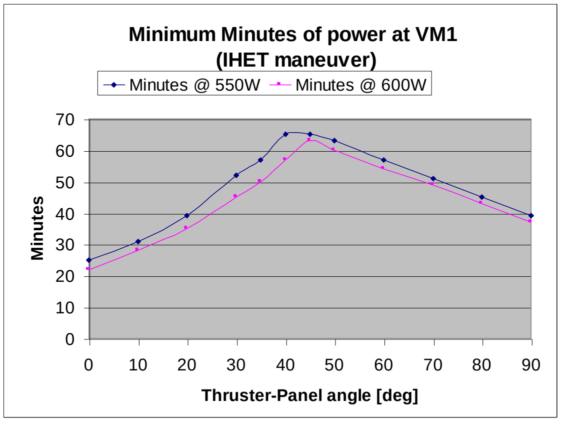

Figure 6. Power production capability vs. thrusters-panel angle

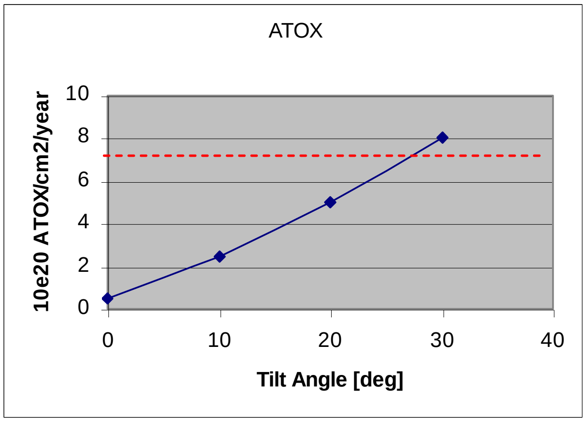

Figure 7. VSSC ATOX flux at tilts angles, and allowed tolerance Camera Tolerance of 7.3•1020 ATOX/m2/Year

For this configuration, **Error! Reference source not found.** shows the power produced by the panels, in terms of minute of minimum IHET power, in VM1, when the thrusters fire in plane. The optimum angles are about 35 to 45 degrees, between the thrusters and panels plane. Another consideration that restricted this angle was the ATOX flux, allowed into the VSSC due to satellite tilt. This limits the angle below the optimum, as shown in Figure 6. **Power production capability vs.** **Figure 7. VSSC ATOX flux at tilts angles, and allowed**

thrusters-panel angle **tolerance Camera Tolerance of 7.3•1020 ATOX/m2/Year**

. Finally, the angle of 25º was chosen and is implemented on the satellite architecture.

Wet mass of the satellite at launch was 264 kg, and it consists of a hexagonal shape body with two deployable solar panels.

V. VENμS EPS

C. Propulsion System

The IHET system (see **Error! Reference source not found.**) is designed to support and operate two HET-300 thrusters. Its main components are the Propellant Management Assembly (PMA), Digital Xenon Flow Controller (DXFC), Power Processing Unit (PPU), and 2 Filter Units (FU). The propellant tank is storing 16 kg of high pressurized Xenon. The PPU contains the power supplies and the sequencer command logic to operate the thrusters. The FU's function is to filter and mitigate the thrusters' oscillations.

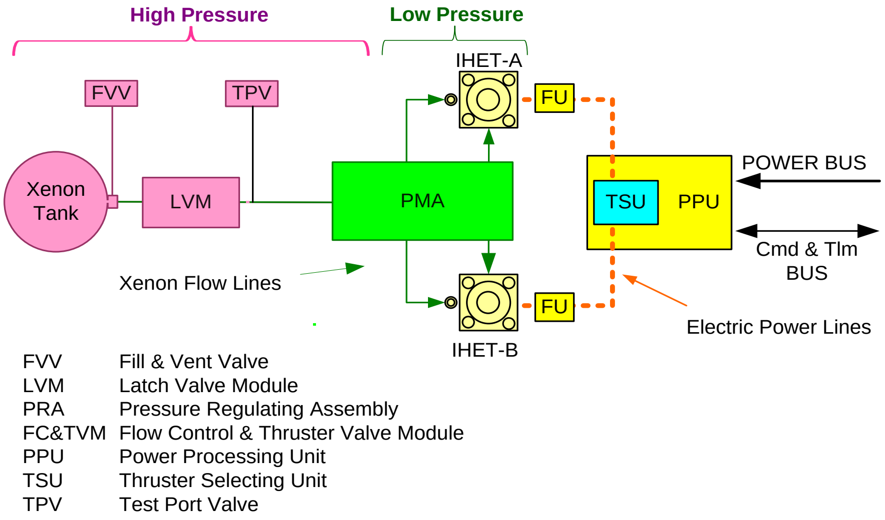

Figure 8. VENμS electric propulsion system block diagram

For a mission requiring flexibility in operating the satellite's thrust, a variable thrust mechanism is needed. Unlike regular solutions applied to ION thrusters, the IHET system incorporates a single DXFC that serves as the "throttling" device to both thrusters, thanks to internal redundancy. This device allows digital control of the Xenon flow rate through the HET-300 anode. The DXFC (see **Error! Reference source not found.**) uses four flow restrictors to control the total Xenon flow. Gas flow through each restrictor is controlled by a latch valves. In addition, it has two backup restrictors to act as redundant flow paths, in case of failure. The variable flow causes more or less Xenon atoms to ionize, resulting in variable thrust and power consumption. The DXFC and the embedded PPU control algorithms enables Venμs to utilize whatever power is available from its solar panels.

Although the IHET system has two thrusters, it can operate only one at a time. For this purpose, the Thruster Selection Unit (TSU) inside the PPU selects and switches the operating power supply to the active thruster.

D. HET-300 Thruster

Figure 9. HET-300 flight model

The heart of the technological payload, the IHET, is the Hall Effect Thruster (HET), codenamed HET-300. It operates on Xenon, which is ionized by electrons emitted from the cathode and accelerated as plasma using a high electrical field.

This thruster is ideal for use onboard small and micro satellites, operating nominally at only 300 W anode power. However, its useful range of operation is between 250 to 600W. Thus, it can utilize the instantaneous available power from the satellite. HET-300 performance at 300W is listed in Table 2. HET-300 mass is about 1.5 kg and its dimensions are 170x120x90 mm

Table 2. HET-300 Main Characteristics

Thrust @ 300W (EOL)	> 14.3 mN
Specific Impulse @ 300W (EOL)	> 1210 sec
Power Operation Range	250W to 600W
Operating Life	> 1100 hours
Number of Operation Cycles	> 2000
Total Impulse	> 135 kNs

Recent laboratory tests results of thrust and Isp of the qualification model at EOL are plotted in Figure 10.

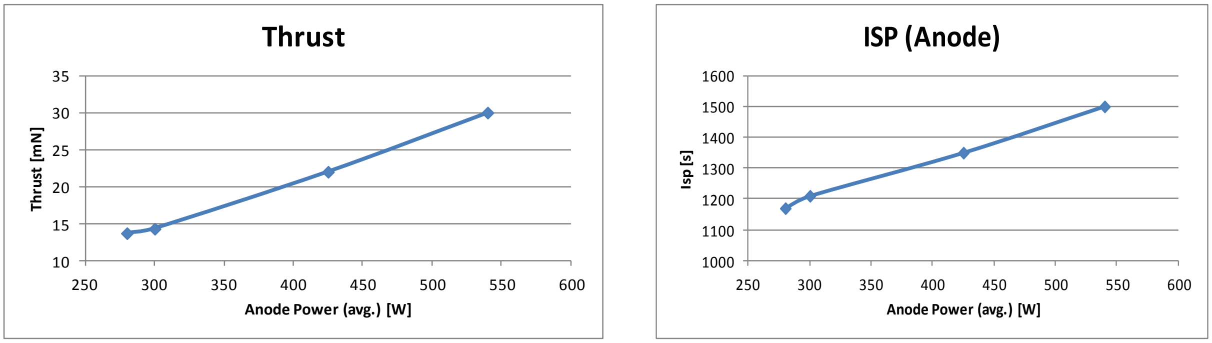

Figure 10. HET-300 thrust (left) and Isp (right)

E. Propellant Management Assembly (PMA)

The PMA feeds the pressure and flow conditioned propellant to thrusters. All these components were developed, manufactured and qualified. Most of them incorporate COTS components, which were modified and adapted to the system. One particular component, the DXFC was specifically developed and manufactured to support Venμs mission that requires flexibility in operating the satellite's thrust in a flexible manner, which depends on the instantaneous power produced by the solar panels. Unlike other HET systems with constant operating power - the IHET system incorporates a single DXFC that serves as the "throttling" device to both thrusters. This device allows digital control of the Xenon flow rate through the HET-300 anode. The DXFC (see Figure 11) uses four flow restrictors to control the total Xenon flow. Gas flow through each restrictor is controlled by a latch valves. In addition, it has two backup restrictors to act as redundant flow paths, in case of failure. The variable flow causes controllable variable thrust and power consumption. The DXFC and the embedded PPU control algorithms enables Venμs to utilize whatever power is available from its solar panels, thus exhibiting maximum efficiency.

Figure 11. Controller (DXFC): flight model (left) and block diagram (right)

F. PPU

The PSU contains the diverse power supplies and control and management signals. These power supplies are feeding the HETs' power requirements and provide power for auxiliary units, such as valves and sensors. A Thruster Selection Unit (TSU) selects the active thruster to operate. The thruster selection causes connecting the selected thruster to the PSU supplies, upon selection command received from the On Board Computer (OBC) prior to each operation. The SCU is the control section of the PPU. Its main function is controlling the ignition and operation of the HETs. It also implements the communication with the satellite OBC, monitors all signals being traced during mission, handling and acquisition of data, manages the sequence of the thruster's operation, redundancy management and powers and controls EPS components. The PPU block diagram is shown in Figure 12 herein with its main connections to the EPS sub-assemblies. The upper part, where the electrical connectors are located, is placed in the satellite hull. The bottom part is exposed outside the satellite and the flat radiator cools the PPU. **Error! Reference source not found.** shows its main characteristics.

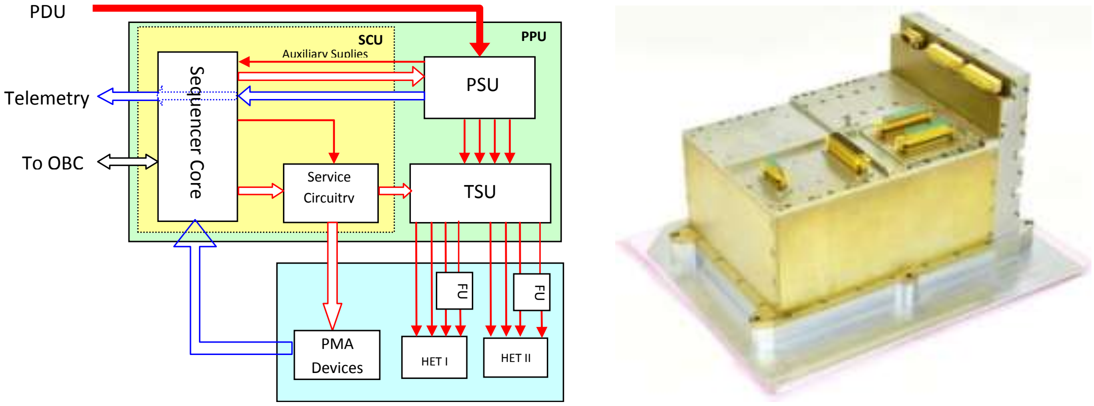

Figure 12. PPU block diagram in EPS environment (left) and flight model (right)

EPS development posed a big challenge on the design team because it must perform all Venus missions within the allocated performance and reliability requirements. A systematic reliability approach was adopted (see Ref. 8) in order to deliver the required mission reliability. All subsystems are redundant, except the Xenon tank. The design has no single point of failure. PPU has dual power supplies and two redundant SCUs. All solenoid and latching valves are redundant. The two thrusters are also functionally redundant, although the mission budgets are based on consecutive operation of both.

Table 3. PPU main characteristics

Characteristic	Value
Mass	Less than 12kg
Efficiency at max. power	91%
Anodic power	up to 600W @ 300 VDC
Thermal control	Autonomous, through bottom radiator
Anode voltage PS	300 VDC
Magnetic Field PS	0.6 - 2.6A, variable control for optimal performance
Cathode Heater Current	Selectable up to 11 ADC
Cathode keeper Voltage	60 VDC
Auxiliary PS	5 VDC, 16 VDC and 28 VDC
Redundancy	Full cold redundancy, reconfigurable in space
Interface	Power: Unregulated bus 24 to 42 V Communications: Dual redundant CAN-Bus

Fault Tree Analysis (FTA) and Failure Modes and Effects Analysis (FMEA) tools were selected to analyze the reliability of the whole system, as can be seen in **Error! Reference source not found.**. The PPU has full redundancy as shown in Figure 13 **– Example of Failure Fault Trees and Results** **Figure *14***.

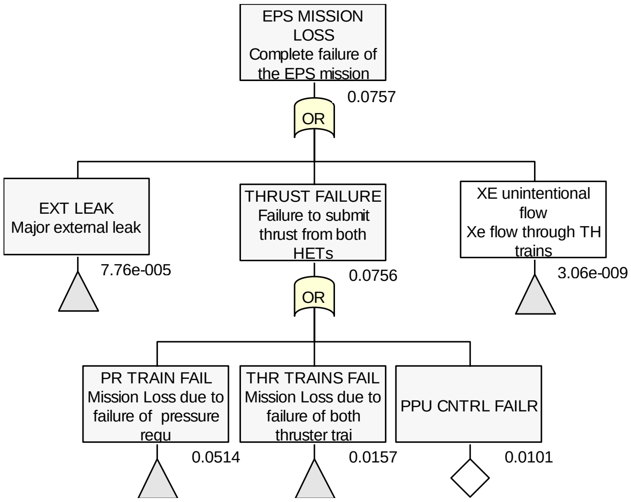

Figure 13 – Example of Failure Fault Trees and Results

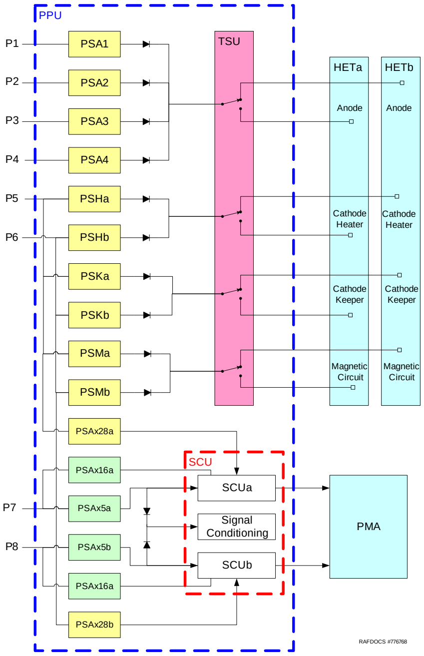

Figure 14. PPU redundancy architecture

G. Fueling Campaign

Since Venµs has two propulsion systems, the EPS and a monopropellant for backup – two fueling campaigns were performed. The first one was the Xenon loading. Rafael team loaded 16 kg of Xenon into the EPS tank, at a pressure of 84 bar. This pressurization took place on the integration site, right before shipping. Since Xe is an inert and nontoxic gas, it was possible to do it before shipping and thus save a few expensive days in the launch site. Pressurization was performed with a dedicated Xenon Transfer and Recovery System (XTRS), a ground GSE composed of gas boosters and flow control valves. Pressurization duration was mainly governed by the constraints of tank temperature and Maximum Expected Operation Pressure (MEOP). Overall, it took a couple of days to complete all steps of this fueling.

The second fueling took place at the launch site, in Kourou. Rafael team fueled 7 kg of Hydrazine into the Hydrazine Propulsion System (HPS) tank. This operation was essential to be done at the launch site, before launcher encapsulation, because of the hazards of Hydrazine.

H. Technological Mission Center

The Venµs Technological Mission Center (TMC) is a ground-based facility that performs the evaluation and analysis of the data related to the technological payload (the IHET) and to the technological mission.

TMC receives data from the satellite via other ground facilities and receiving stations (S band satellite telemetry through SCC and X band satellite telemetry through the SMIGS).

It performs several functions, such as preparation of updated operation commands for the technological mission, and analysis and diagnostics of the performance of the electrical thrusters. TMC will evaluate the HETs performance, in verification and validation phases. It will compute the thrusters' performance (thrust, specific impulse, efficiency – vs. power). The goal is to model the IHET behavior in space, during varying conditions as well as aging information.

Another task is Orbit Managing and Performance Analysis. It will be accomplished by performing system-level analysis of the orbit control function performance during all technological mission operation phases.

TMC will also track and record the interaction between IHET and the satellite subsystems, to complete and validate the ground-based assessments and analysis of IHET plume influence on satellite external subsystems (such as solar panels) and also the electrical and magnetic influence (such as the effect of the IHET on the magnetometers). The TMC is operated through a dedicated Graphical User Interface (GUI) as seen in Figure 15.

All TMC functions will be reported and distributed. Technological mission data gathered during Venµs mission (whether raw or processed) will be archived for future and extensive research. TMC is built by Rafael and operates within its premises.

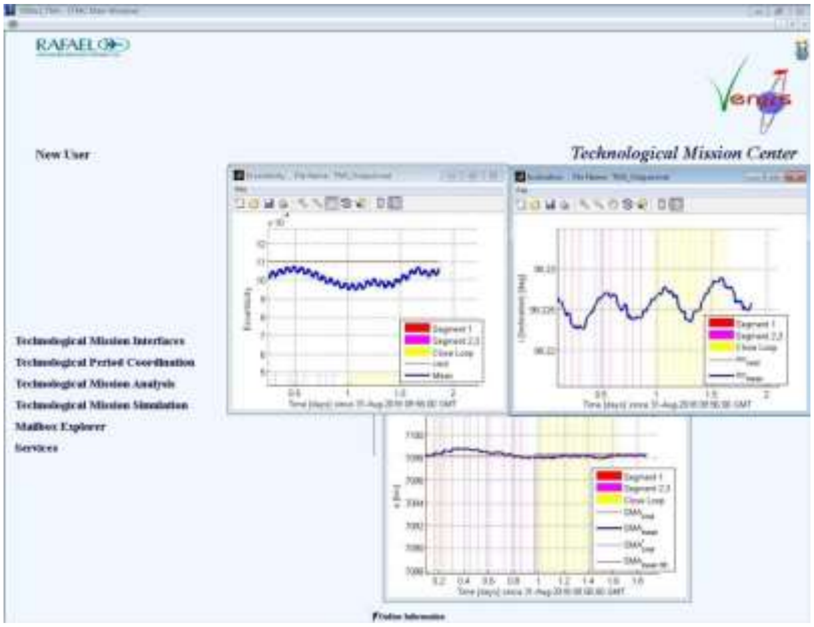

Figure 15. TMC operational GUI

VI. In-Orbit Tests

The next activity after launching the satellite is the In-Orbit Test (IOT). These are a group of tests that are performed on the satellite platform and on the payloads, to ensure that the hardware is working properly, once reaching space. The main concern is the launch process itself, where the satellite is exposed to harsh environment, like vibrations, accelerations, shocks, thermal conditions and outgassing in vacuum.

Table 4 . EPS-IOT tests

Cycle #	Test #	Test Name
1	1	SCU-1, PSU, PMA
2	6	SCU-2, PSU, PMA
3	2	TSU, Outgassing#1 (SCU1, TU-1)
4	7	TSU, Outgassing#2 (SCU2, TU-2)
5	3	First firing TU-1/2 (SCU1)
6	4	EXP01 Open Loop
7	5	EXP02 OPEN+CLOSED Loop

Main goals of EPS-IOT are to ensure the operability of the IHET system, to validate System Interfaces to satellite and to validate TM telemetry. EPS-IOT is an collection of tests to be run on satellite. These tests include all rage of tests, performed in a “bottom-up” sequence. This sequence will assure that each assembly is tested after successful test of its components.

The EPS planned tests, are detailed in **Error! Reference source not found.**. As shown in the table, first two tests are intended to check the basic electronics, the power supplies, the drivers and working parameters. In addition, these two initial tests will check the PMA: the interface to the EPS pneumatic hardware, the pressure and temperature sensors and the various valves. Each test will check its respective redundant branch. Upon successful completion, the next couple of tests will perform cathode outgassing. This is the initial outgassing in space, after the launch. It will prepare the cathodes for their first use. Next test is the initial firing attempt for both thrusters. The last two tests are “mission type” scenarios. The open loop is a VM1 type experiment that estimates IHET performance. Last test is the closed loop that will further correct the orbit and position the satellite in its nominal VM1 orbit, ready for imaging. EPS-IOT is planned to complete in about three months. Following IOT, the “real” VM1 mission will commence and the satellite will start its operational life.

VII. Conclusion

Venµs is a highly sophisticated program, of a dual mission satellite. The technological mission will use a recently Rafael developed EPS, to demonstrate missions enhancements and characterize the EPS in space. Venµs EPS is a redundant design, tailored for this mission.

Venµs demonstration will pave the way to many other missions, that could greatly benefit from its achieved technology and science.

The author wishes to thank all the hard working engineers, during the last decade, in Rafael, IAI and CNES which made this program possible.

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