VENμS – Updates on Technological Mission using the Israeli Hall Effect Thruster (IHET)

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Abstract

Venμs is a satellite launched in 2017, for super-spectral Earth imaging and Electric Propulsion System (EPS) demonstration. The EPS includes a novel design, developed, qualified, manufactured, integrated and fueled by Rafael. The EPS demonstrates mission enhancement capabilities and its in-space performance is 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 in orbit and performs EPS operation and characterization. After successfully conclusion of In Orbit Test (IOT), Venus started the first mission phase. Every month a dedicated EPS experiment is performed; and thus far the EPS operated well and demonstrated excellent results. The Technological Mission Center already posted technical results and characteristics from the EPS operation in space. Mission is continuing with additional planned four years of in space activity.

Keywords

Hall Effect Thruster, Electric Propulsion System, Technological Mission, In Orbit Test

I. Introduction

In the last two decades Rafael is 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 systems for small and micro satellites, where the power generation is limited. One major activity is the VENμS EPS (R-400EPS) - the first project in which Rafael supplied a complete Electric Propulsion System (EPS).

II. The VENμS Program

Vegetation and Environment monitoring on a New Micro Satellite, or VENμS, is a joint program of both the Israeli and French space agencies [2]. Within the frame of the program, two missions shall be executed: (1) Scientific mission and (2) Technological mission. The VENμS satellite was launched in August 2017 on-board the Vega launcher.

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The space exploitation started at the end of 2017, after completing the In Orbit Test (IOT) phase. The space mission is planned for a 4½ years. During this period, the satellite is planned to conduct a combination of imaging and orbit control activities, using its two payloads: Scientific and Technological payloads.
During the 'scientific mission' phases, the satellite shall perform Earth imaging in super-spectral mode for vegetation and environment monitoring. For these phases, the EPS will strictly correct the orbit, which must remain sun synchronous and Earth repeating - a "must" for super-spectral imaging.
The technological payload is an Electric Propulsion System (EPS) which is now space qualified, and will perform the required strict orbit control, to satisfy the imaging requirements. It will also perform orbit transfer. The French space agency, CNES, is in charge of the Scientific Mission, with a dedicated mission center (SMIGS) in Toulouse, France.
The Technological Mission operations is funded and executed by the Israeli Space Agency (ISA). The satellite was built, integrated and now operating by IAI, Israel. Rafael has developed the components and the R-400EPS – the VENµS Electric Propulsion System. ISA is responsible for the execution of the Technological Mission using a dedicated Technological Mission Center (TMC) located in Rafael - Haifa, Israel.

III. Technological Mission

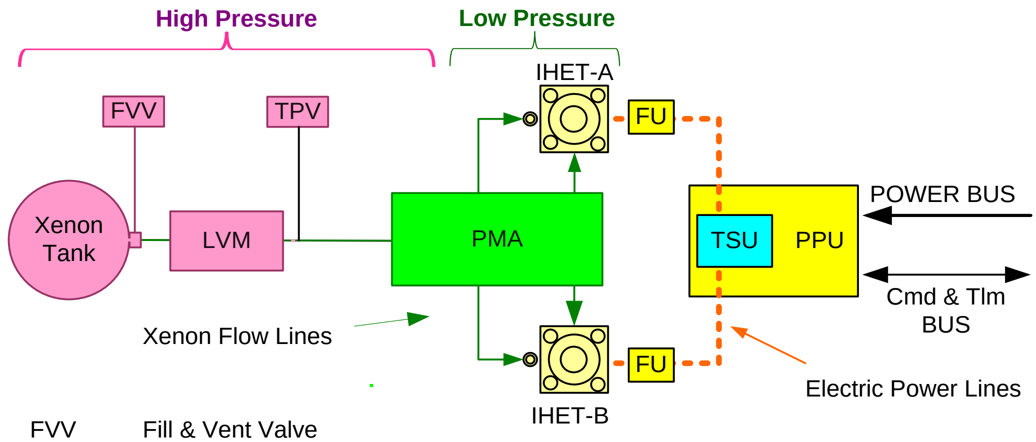
The 'Technological Mission' (TM) phases consist of the operation and qualification of the electric propulsion system in space, orbit control and orbit transfer. As its technological payload, VENµS incorporates the Israeli Hall Effect Thruster (IHET), which was developed for this mission. It is designed to suit well the Venµs small satellite, which can produce modest power. IHET's anode power range is between 300 W and 550 W and will use a total of 16 kg of Xenon propellant to complete its mission. The IHET is part of Rafael's 1st generation of the family of Electric Propulsion Systems, denoted as the R-400EPS.
The two main objectives of the technological mission, space verification and mission validation, are to be achieved by a series of experiments that will test the EPS performance and then by three mission phases in which the EPS will correct the orbit and also transfer it, as described in ref. [7].
The first mission phase, VM1 is mainly concerned with super-spectral imaging at 720 Km altitude. This orbit must be precisely controlled since it is both sun synchronous and Earth repeating, to fulfill the strict imaging requirements. During the 2½ years of VM1, the Technological Mission shall perform once a month a characterization experiment followed by an orbit reinsertion maneuver. This phase already begun and some initial results are described in the following section.
Following VM1, the next phase is VM2 which will demonstrate an orbit transfer maneuver, entirely performed by the EPS.
The orbit transfer maneuver will be from a 720 Km orbit to a lower orbit at 410Km. This major orbit change, of about 300 km altitude, 1.2° inclination angle, while controlling the RAAN and equatorial crossing local time is expected to consume about 7.5 kg of Xenon.

Finally, in VM3 phase, VENµS will keep its imaging activity at a circular sun-synchronous orbit while maintaining a 2-day revisit ground track. Since the satellite size is relatively large, hence it has a considerably large cross-section; the orbit will be densely corrected, up to four times a day.

IV. VENµS EPS

A. System

The Venµs EPS (see Refs. [2,7]) is designed to support and operate two IHET-300 thrusters. Besides the thrusters, the EPS main components are the Propellant Management Assembly (PMA), Digital Xenon Flow Controller (DXFC), Power Processing Unit (PPU), and 2 electrical Filter Units (FU). The propellant tank is storing highly pressurized Xenon. System architecture is presented in
Figure 1.



FVV	Fill & Vent Valve
LVM	Latch Valve Module
PRA	Pressure Regulating Assembly
FC&TVM	Flow Control & Thruster Valve Module
PPU	Power Processing Unit
TSU	Thruster Selecting Unit
TPV	Test Port Valve

Figure 1. Venµs EPS schematic block diagram

One notable feature of the EPS is the ability to throttle the anodic power of its thrusters, according to the available power supplied by the bus platform in orbit. This proves to be an essential feature in a LEO satellite, since the power levels produced by the solar arrays are variable and change according to satellite's true anomaly angle in each revolution.

The Digital Xenon Flow Controller (DXFC) (shown in Figure 3) uses flow restrictors to control the total Xenon flow through the anodes; therefore controlling the discharge power and thrust levels.

It is automatically commanded by the PPU to regulate propellant flow and operate the thrusters at the commanded power level (see Ref. [7]).

A Thruster Selection Unit (TSU) is responsible for selecting the active thruster, as commanded by the PPU and the Technological Mission Module (TMM).

B. HET-300 Thruster

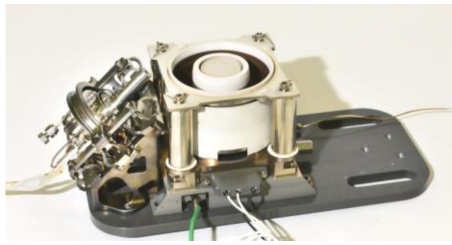


Figure 2. HET-300 flight model

The heart of the EPS, is the Hall Effect Thruster (HET), codenamed IHET-300, shown in Figure 2. It operates on Xenon, which is ionized by electrons emitted from the cathode and accelerated in the form of plasma via a high electric field.

Table 1. IHET-300 Main Characteristics @ 300W

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

The main characteristics of IHET-300 are listed in Table 1. This thruster, which employs low power, is specifically designed to be used onboard small and micro satellites. Its useful range of operation is between 250 to 600W. Thus, it can utilize the instantaneous available power from the satellite as explained above.
The IHET-300 mass is about 1.5 kg and its dimensions are 170x120x90 mm

C. Propellant Management Assembly (PMA)

The PMA role is feeding Xenon gas, at the controlled pressure and flow, to the selected thruster.
It mainly consists of adapted and qualified COTS. Ref. [5] describes the development and qualification process of most EPS components.

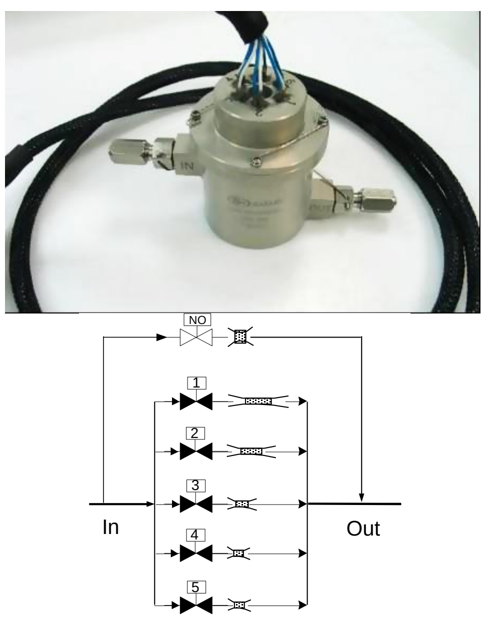


Figure 3. DXFC: flight model (top) and schematic block diagram (bottom)

D. PPU

The PPU contains the diverse power supplies and control circuits for operation and management of primarily the thrusters and the whole EPS components. The SCU is the control module of the PPU. Besides controlling the power supply and the ignition sequence, the PPU also implements the communication with the satellite OBC, monitors all signals and prepares the EPS telemetry.

The PPU block diagram is shown in Figure 4 herein with its main connections to the EPS sub-assemblies. The PPU is thermally insulated from the satellite and its radiator on the bottom side is exposed to space for cooling by heat radiation.

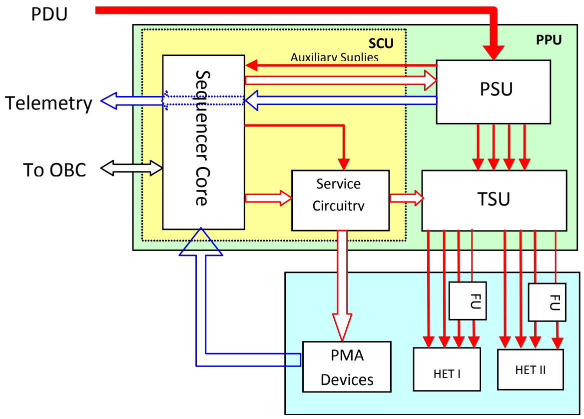


Figure 4. PPU block diagram

Figure 5 shows the PPU flight model, while Table 2 shows its main characteristics.

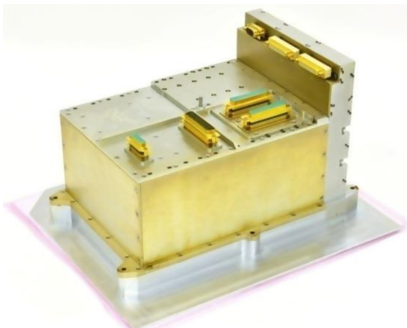


Figure 5. PPU flight model

Table 2. 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, 34 to 42 V

	Communications: Dual redundant CAN-Bus

V. 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 EPS, and to the technological mission.

TMC receives telemetry from the satellite and processes it. In addition, it performs other functions, such as preparation of updated operation commands for the technological mission, and analysis and diagnostics of the performance of the electrical thrusters. The TMC evaluates EPS performance, in the verification and validation phases. It computes the thrusters' performance (thrust, specific impulse, efficiency – vs. power) and it models the EPS behavior in space, during varying conditions as well as aging information.

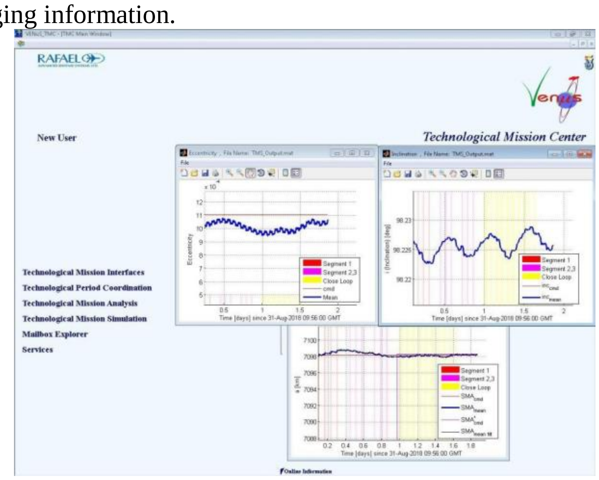


Figure 6. TMC operational GUI

Figure 6 shows how the TMC is operated through a dedicated Graphical User Interface (GUI).

The TMC was developed by Asher Space Research Center (ASRI) of the Technion, in conjunction with Rafael specifications.

VI. In-Orbit operation

After the launch of Venµs satellite, a series of In Orbit Tests (IOT) were performed. These tests checked and assured that the platform and its payloads were capable to start the mission period.

The technological mission experiments started on early 2018 and are continuing till now.

E. Technological Experiments

Venus mission is structured as three consecutive phases. The first phase, named VM1. During this phase the satellite is performing each month a technological mission experiment. The satellite is imaging for 28 days and the last couple of days in the month are dedicated to a Technological Mission experiment.

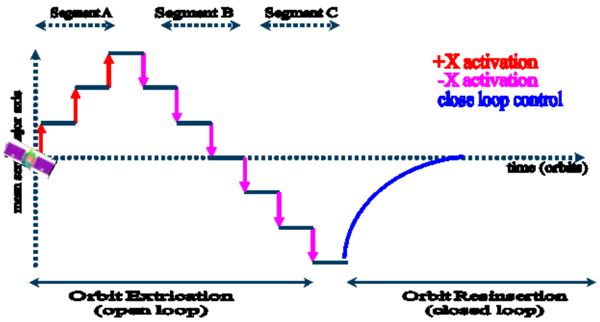


Figure 7. Design of VM1a experiment

Each experiment consists of orbit extrication in three Open Loop (OL) segments, and is finished with orbit reinsertion in a Closed Loop (CL) segment, as shown in Figure 7. Each OL segment consists of three satellite revolutions, with an one long EPS activation at a constant power for each rev. In the first segment, EPS activations are raising the orbit, by proper satellite attitude alignment of the thruster with the velocity vector. %%%The second and third segments also contained EPS activation for consecutive three revolutions each, but the satellite attitude was commanded by the TMM so that the orbit SMA will decreases. At the end of each segment, the EPS was idle for one revolution, dedicated to orbit measurements and estimation. The overall design goal is to finish the three segments with the orbit below the nominal. And then, the CL segment starts to operate. The TMM in CL is commanding the EPS to fire and operate on each consecutive revolution for a duration and altitude instantaneously calculated, until the orbit reaches the target value. Table 3 presents the cumulated operation duration of the entire experiment, as previously described, with the EPS firing durations for each satellite revolution.

F. Experiments data

Since its launch, Venus performed several technological experiments. Each experiment was analyzed and the performance of the thrusters, system and mission was compiled. Each experiment contributed to the performance database which is accumulating the data. Each experiment is characterized by the typical power applied in the Close Loop segments. Till now, the experiments applied 300W, 400W and 500W anodic power.
Table 1 shows the various experiments to date.

Table 3. Technological Mission experiments to date

Date	Anode Power [W]	OL Act.	CL Act.	HET1 act/hours	HET2 act/hours	Total ΔV [m/s]
21/2/2018	400 W	3 x H1 6 x H2	1 x H1 1 x H2	4 / 1.03	7 / 1.31	0.64
28/3/2018	500 W	3 x H1 6 x H2	4 x H1 3 x H2	7 / 2.6	9 / 5	1.59
9/5/2018	300 W	3 x H1 6 x H2	3 x H1 8 x H2	6 / 1.1	14 / 1.4	0.52
17/11/2018	300 W	3 x H1 1 x H2	N/A	3 / 0.82	1 / 0.23	0.20
28/1/2019	300 W	3 x H1 6 x H2	1 x H1 1 x H2	4 / 1.13	7 / 1.21	0.46
25/2/2019	400 W	3 x H1 6 x H2	1 x H1 1 x H2	4 / 1.45	7 / 1.55	0.84
21/3/2019	300 W	3 x H1 6 x H2	2 x H1 1 x H2	5 / 1.55	7 / 1.47	0.66
16/4/2019	500 W	3 x H1	1 x H1	4 / 1.19	7 / 1.53	1.03

		6 x H2	1 x H2			

G. Propellant consumption

Calculations were made to determine the propellant used. Periodic telemetry provides the pressure and temperature data of the Xenon tank. Using this data, the Xenon propellant quantity is tracked, by using the propellant gas characteristics. On loading campaign in 2017, the tank was pressurized with 16.1 kg high purity Xenon. As for now, the propellant tank is estimated to contain 15.9 Kg of Xenon.

This estimation is using the basic calculation method. Since it is based on raw and crude measured data from the satellite – the achieved accuracy is mediocre. In the future, we consider to improve the computation of the propellant using the flow rate and the firing time. This method should produce better accuracy.

This method of integration will be possible once we finalize the calibration of the system.

H. System fine optimization

During the analysis of the telemetry data, it was observed that the system operation can be further optimized in space. This optimization is the tuning of the actual power levels according to the desired.

Recalling that the flow controller is a DXFC, which utilize flow restrictors – these tiny devices dictate the propellant flow amount during firing operation. The initial flow setup at ignition is set by the PPU and then it is controlled in close-loop, to achieve the commanded thrust (power). It was observed that at ignition, the actual flow rate was lower than needed, and the thrusters ignite at a lower power. After ignition, the PPU compensated the flow, and achieved a steady operation at the desired level of thrust.

Thus, an optimization campaign was initialized, to recalibrate the flow controller and achieve best thrust and power conformance to the commands. In the process of this fine tuning, the actual figures of power and their corresponding DXFC values were accumulated and processed.

This optimization process is possible due to the careful design of the system, which accommodate tuning parameters for many features in the system. These parameters resides in non-volatile memory in the PPU, which are not erased nor forgotten even when PPU power is down. This important feature enables Rafael to cope with non-optimal conditions in the ground and GSE calibrations and to control most of the EPS functionality in space, with a minimum overhead of data transmission from the Ground Station.

I. Orbit control

An important feature of the Technological Mission is orbit reinsertion, after each experiment. The reinsertion segment is a closed-loop orbit control, that controls the SMA, eccentricity and inclination.

During the operation period so far, the reinsertion algorithm proved to be very accurate, when it achieved accuracies of less than 100 meters in SMA. The algorithm is working autonomously. The final reinsertion orbit is commanded by the TMC. It takes in account the estimated ground track drift during the next month imaging period. It can thus compensate the heavy sun activities, which are characterized by recent satellite decay, as derived from the orbital telemetry. This scheme proved to be very useful in the operation of the satellite and it significantly eases the orbit control for such a delicate mission.

Typical orbit reinsertion occurs during two satellite revolutions, and each thruster fires once or twice.

Table 4 shows a typical experiment data. Each row is a distinct satellite revolution (“rev”). The blue highlighted rows are orbit estimation revs. Other rows are either Open Loop (OL) or Close Loop (CL).

On each rev, the firing power and estimated thrust is shown.

Table 4. Typical experiment performance data

			IHET1			IHET2		
Rel. Rev.	Abs. Rev.	Rev. type / Segment	Duration [min]	Max. Pwr. [W]	Thrust [mN]	Duration [min]	Max. Pwr [W]	Thrust [mN]
17	8618	Est.						
18	8619	Est.						

19	8620	OL-1	16.7	298	14.7			
20	8621	OL-1	16.7	292	13.4			
21	8622	OL-1	16.7	290	13.3			
22	8623	Est.						
23	8624	OL-2				11.2	301	15.2
24	8625	OL-2				10	301	16
25	8626	OL-2				13.2	301	15.6
26	8627	Est.						
27	8628	OL-3				13.2	301	15.7
28	8629	OL-3				13.2	301	15.6
29	8630	OL-3				13.2	301	15.4
1	8631	Est.						
2	8632	CL	18.7	440	24.3	14.2	457	N/A
3	8633	CL	24	460	N/A			

This experiment exhibits a good orbit correction in only 2 revs, of only 70 m above the commanded nominal.

Figure 8. Normal ignition sequence of thruster 1

Other data that the TMC analyzed is the statistics of thrusters activations, as shown in Table 5 and also the thrust deviation vector as shown in Table 6.

Table 5. EPS cumulative operation statistics up to date

Name	**IHET-1**	**IHET-2**	**Total**
Activations	63	84	147
Operation [hours]	13.83	13.17	27.00

Table 6. Thrust deviation as of Feb. 2018

	Deviation [deg]	
	IHET-1	**IHET-2**
Axial	0.34	0.4
Radial	43.12	-92.77

Finally, Figure 9 shows the graphical cumulative performance of the thrusters, including all historical data.

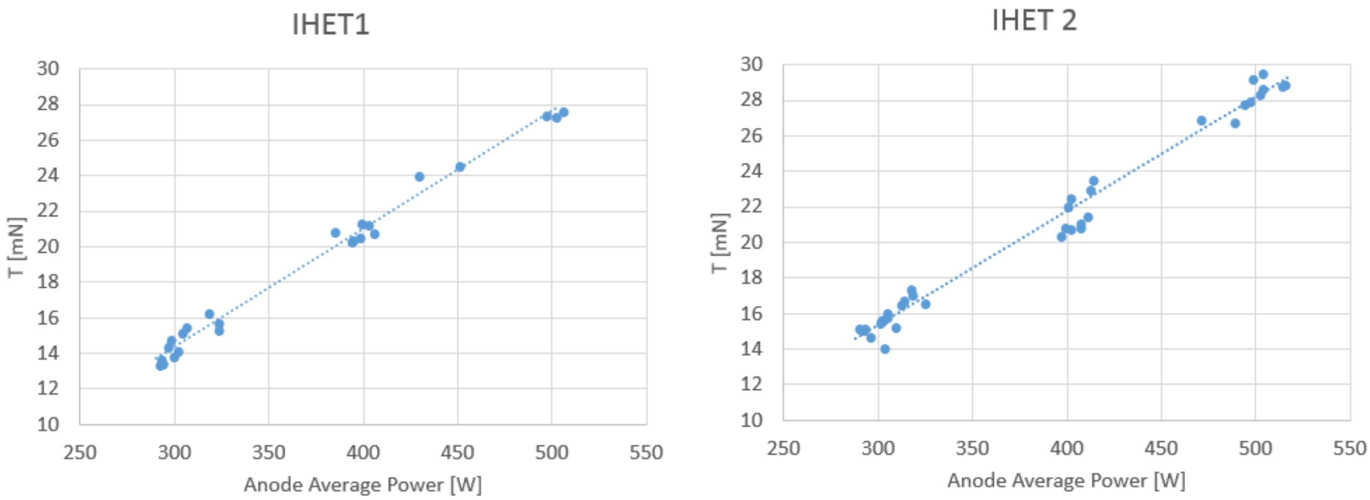


Figure 9. Cumulative thrust performance.

Future planned activity will be focused mainly on accumulating more EPS activations and operating hours in 720 km orbit. Afterwards, VM2 phase will commence where the satellite will perform a LEO-to-LEO orbit transfer, and then continue imaging at 410 Km, while the EPS maintains the orbit in a much denser operation scheme. At VM2 and VM3 phases, the EPS will face the greatest challenges and will operate at its complete capacity.

VII. Conclusions and Rafael's Electric Propulsion Beyond Venμs

Venμs is a highly sophisticated program, of a dual mission satellite. The technological mission successfully operates the EPS developed by Rafael to demonstrate LEO mission enhancement capability and characterize the EPS in space.
Venμs R-400EPS is a redundant design, variable power system, tailored for this mission.
The R-400EPS has successfully passed its IOT phase and is working properly according to specifications and expectations.
Rafael's Venμs R-400EPS successful demonstration is paving the way to many future missions, that could greatly benefit from its achieved technology in Electric Propulsion and Autonomous Orbit Control, at low altitudes and high drag environment.
The R-400EPS is the 1st generation of Rafael's EP system design for Small-Sats, and now is operating successfully in space. New Rafael's successors EP systems for Small-Sats are in the process of development - the R-200 and R-800 EPS. Rafael's EP Systems will cover the full power range between 100-900Watts, while leveraging the experience and know-how gained in Rafael, including design for manufacturing that enables low cost/high rate of production tailored solutions for the new space era.
The Authors wish to thank the Israeli Space Agency for its long term support of the program and to the Venus team that operates the mission. In addition, special thanks to ASRI team in the Technion, which developed the TMC, for their commitment and accompaniment of operations and mission analysis.

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