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VENμS Program: Broad and New Horizons for Super-Spectral Imaging and Electric Propulsion Missions for a Small Satellite

Jacob Herscovitz
Space Systems Directorate Rafael Advanced Defense Systems Ltd.
P.O.B. 2250 (M5), Haifa 31021, Israel
jacobh@rafael.co.il

Arnon Karnieli
The Remote Sensing Laboratory Ben Gurion University
Sede Boker Campus 84990, Israel
karnieli@bgu.ac.il

ABSTRACT

Vegetation and Environment New Micro Satellite (Venμs) is a joint venture of the Israeli and French space agencies for development, production, launching, and operating a new space system. Venμs is a Low Earth Orbit (LEO) small satellite for scientific and technological purposes.

The scientific mission includes vegetation monitoring and water quality assessment over coastal zones and inland water bodies. It will be specifically suitable for precision agriculture tasks such as site-specific management and/or decision support systems. For this purpose the satellite has apparatus for high spatial resolution (5.3 m) and for high spectral resolution (12 spectral bands in the visible and near infrared wavelengths), as well as orbit for high temporal resolution (2 days revisit time). The satellite's orbit is a near polar sun-synchronous orbit at 720 km height. The satellite will acquire images of sites of interest all around the world. The satellite will be able to be tilted up to 30 degree along and across track; however, each site will be observed under a constant view angle.

The technological mission consists of space verification and validation by mission enhancement capability demonstration of a newly developed Israeli Hall Effect Thruster (IHET) system, used as a payload. IHET is developed and manufactured by Rafael and this will be its maiden flight. The heart of the IHET is the HET-300 thruster, which produces about 15 mN thrust, operating at 300W anodic power. This thruster and the based-on Electrical Propulsion System (EPS), is specifically developed for usage onboard micro or small satellites, which can supply as little as 300 to 600 watts for operation. The technological mission will be targeted to qualify the IHET in space as well as validate it by demonstrating orbit transfer and strict orbit keeping in a high drag environment.

The Venμs satellite is currently in manufacturing phase, its launch weight is 260 kg, and it is planned to be launched in 2010.

This paper will present Venμs system with emphasis on the two main missions (scientific and technological) of Venμs and the respective payloads along with main design considerations of the electrical propulsion system.

I – INTRODUCTION

Recent initiative of the Israeli Space Agency (ISA) and the French space agency (CNES) is aimed at developing, manufacturing, and operating a new Earth observing satellite called 'Vegetation and Environment monitoring on a New Micro Satellite' – VENμS[5].

The satellite is shown in Figure 1 and is planned to be launched in mid 2010. Venμs will perform two missions in space: a Scientific Mission and a Technological Mission.

The scientific mission is earth imaging in a superspectral mode and its objectives are the provision of 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. The scientific mission will be carried out by a superspectral camera acting as the scientific payload.

The technological mission is about electrical propulsion for space. As its technological payload, Venμs will incorporate the Israeli Hall Effect Thruster (IHET), shown in Figure 6. The IHET is a recently developed electrical thruster by Rafael. It's designed specifications suit well the use onboard micro and small satellites. This mission will check IHET performance in space, as well as demonstrate mission enhancement capabilities.

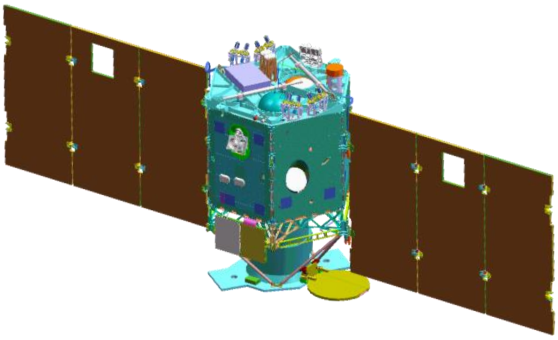

Figure 1 – Venµs satellite model

Since these two missions will supply vast amount of space data, two support ground facilities are built, to process and analyze the data.

The Scientific Mission Image Ground Segment (SMIGS) is the center of the Venµs imaging processing facility. It will define and command the imaging targets for the satellite and will process and distribute the products, to the scientific community.

The Technological Mission Center (TMC) will command the technological mission operations in space. It will also process the data and analyze the performance of the IHET.

Ground control facility for the satellite will be located in Israel and the images receiving station will be in Kiruna, Sweden.

Figure 2 shows the Venµs system and its components (in space deployed mode).

Venµs is a demonstration mission developed in cooperation between ISRAEL (ISA - Israel Space Agency) and FRANCE (CNES – Centre National d'Etudes Spatiales).

CNES is responsible for the provision of the camera and the image ground segment. ISA is in charge of the platform (provided by IAI - Israel Aerospace Industry and RAFAEL – Advanced Defense Systems), the IHET system, the satellite control center and the operation of the satellite.

During its mission, Venµs will demonstrate the combined mission of science and technology, when it will image from the low orbit of 410 km altitude, in a high drag environment, using the electrical propulsion system to keep its orbit accuracy.

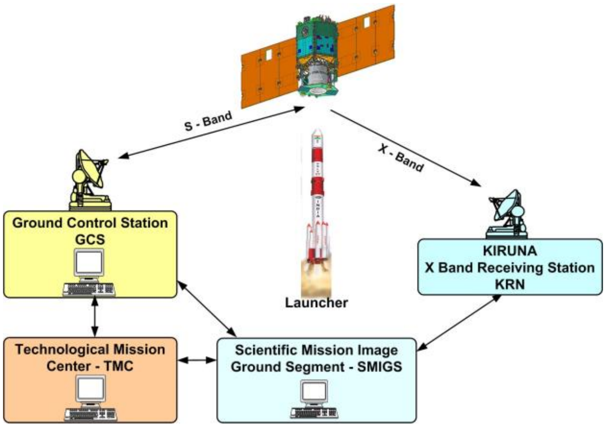

Figure 2 - Venµs system (space operation phase)

II – VENµS MISSIONS

Venµs mission lifetime in space will be more than 4 years. During its lifetime, the satellite will perform the scientific and technological missions alternately, in three main phases: Venµs Mission 1 (VM1), VM2 and VM3.

The first mission phase, VM1, which will start after IOT (In Orbit Test), will be mainly devoted to the scientific mission. It will last up to 2½ years. During VM1, Venµs will acquire images at its nominal 720 km orbit. Once a month, the IHET will be operated for a couple of days, performing various experiments, and orbit control to return the satellite to the nominal VM1 orbit. Once a year, between mid October to mid November – when no crops or agriculture growths have to be imaged - a whole month will be dedicated to the technological mission. In this month, intensive technological experiments will be performed.

Following VM1, the second mission phase, VM2 will start descending Venµs satellite to a new lower orbit. It will last up to six months, during which no imaging will take place. The technological mission will be performed and the IHET will be operated each revolution until the satellite reaches the new VM3 orbit of 410 km.

Then, VM3 phase will follow. This is the combined mission, when both the scientific and the technological missions will be operated in an interleaving mode. This is the most ambitious phase, when the satellite will constantly alternate between imaging and IHET firings. Because of the high drag, the IHET will need to correct the orbit after every three imaging revolutions. VM3 phase is planned for one year, and after that the satellite will be disposed.

Venµs Orbits

Venµs orbits are summarized in Table 1.

Table 1 - VENµS Orbits

	VM1 – High Orbit	VM3 – Low Orbit
Orbit Type	circular, earth repeating sun-synchronous	circular, earth repeating sun-synchronous
Altitude	720 km	410 km
Revisit Time	2 days (29 orbits)	2 days (31 orbits)
Swath Width	27.5 km	13 km
Imaging resolution	5.3 m	2.9 m
Local Time of Descending Node	10h30 a.m	10h30 a.m

Initial orbit Insertion

After launch, the satellite needs to enter the VM1 orbit, and to correct launcher insertion errors. The nominal plan is to correct these errors with the chemical propulsion system. Since the designated launcher (PSLV) may leave satellite at quite large orbit errors, the IHET will be considered to be used to correct injection errors. Using IHET for this task will be at the expense of the resources allocated for the rest of the technological mission duration.

III – THE SCIENTIFIC MISSION

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 capabilities in the framework of the European Global Monitoring for Environment and Security Program (the "GMES Program").

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 fly in a near polar sun-synchronous orbit at 720 km height. The whole system 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 (see Table 2). 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 (Figure 3). 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. Strong efforts are devoted to provide high quality data, both in term of radiometry (e.g. SNR around 100), geometry (e.g. multitemporal registration better than 3 m), and atmospheric corrections. Other products such as vegetation indices, LAI, fPAR, chlorophyll index, and others, are being considered for development and distribution along with the raw data.

Table 2: Band setting, their location, width, and main application.

Band #	Center (nm)	Width (nm)	Main applications
B1	420	25	Atmospheric correction, water
B2	443	40	Aerosols, clouds
B3	490	20	Atmospheric correction, water
B4	555	20	Land
B5	638	24	Vegetation indices
B6	638	24	DEM, image quality
B7	672	16	Red edge
B8	702	24	Red edge
B9	742	16	Red edge
B10	782	16	Red edge
B11	865	20	Vegetation indices
B12	910	20	Water vapor

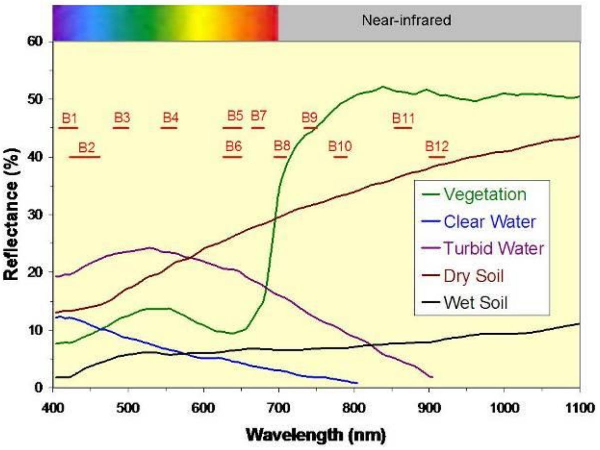

Figure 3 - Band setting with respect to several spectra of common ground features

The VSSC comprises a catadioptric objective, a focal plane with 4 detector units each with 3 separate CCD-TDI arrays, operating electronics, operational control and thermal control[2]. The output of the camera is fed to an on-board storage unit, from which it is transmitted to the ground stations when these are within communications range. The 12 spectral bands are scanned sequentially in push-broom mode by the 12 parallel detector arrays in the focal plane. General view of the VSSC is illustrated in Figure 4. The VSSC is developed and manufactured by ELOP.

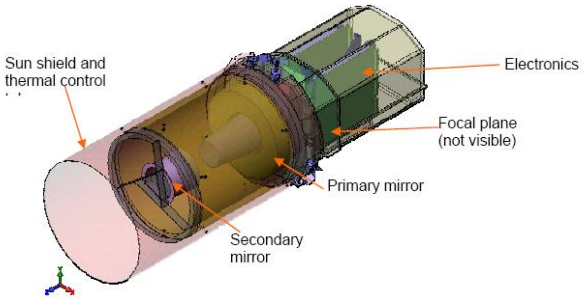

Figure 4 - General view of the VENµS VSSC camera

IV - THE TECHNOLOGICAL MISSION

Mission Objectives

There are two main objectives to the technological mission: space verification and validation[1].

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.

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 at various operating conditions (constant and variable power levels). 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). In addition, the lifetime of the IHET will be checked and the performance behavior of these parameters as they reach the EOL.

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 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, gas temperature, propellant mass flow rate, etc., will be downloaded by the satellite telemetry, and analyzed in TMC along with the orbit data.

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 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. Since VENμS platform was reused from a former program, it doesn't fit ideally for a very low altitude mission. Its cross-section area is quite large and the atmospheric drag at this altitude plays a significant role. In VM3, the thrusters will have to be used intensively, to keep the imaging requirements accuracy (see Figure 5). This task is hardly achievable by a comparable traditional chemical propulsion system, with the same mass of allocated propellant.

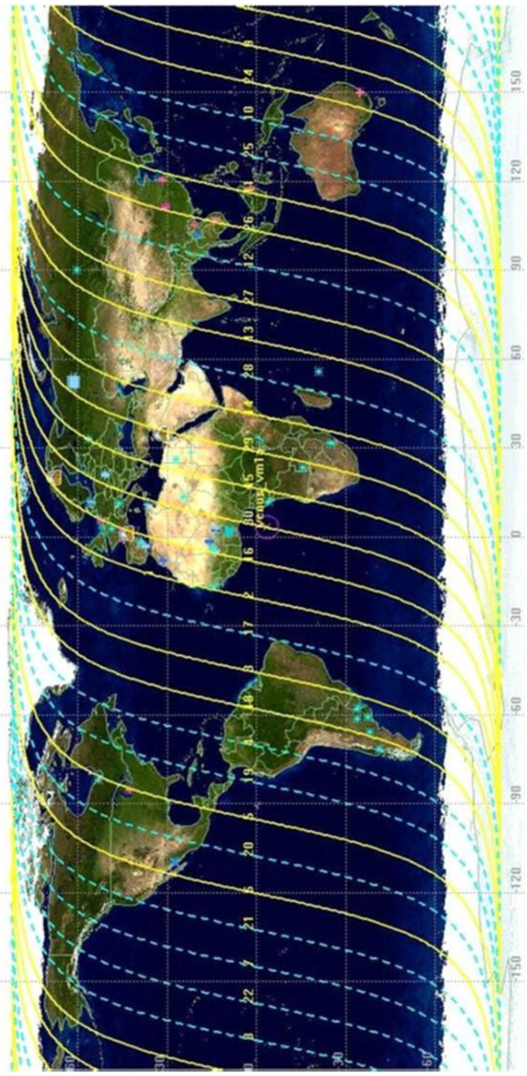

Figure 5 – VM3 orbit allocation: Imaging revs in yellow, IHET revs in dashed blue

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.

HET-300 Thruster

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 3.

Thrust (@300W)	> 15 mN
Specific Impulse (Isp @ 300W)	> 1300 sec
Nominal Anodic Power	300 Watts
Power Operation Range	250W to 600W
Operating Life	> 1000 hours
Number of Operations	> 2000
Total Impulse	> 90 kNs

Table 3 – HET-300 Main Characteristics

HET-300 mass is about 1.5 kg and its dimensions are 170x120x90 mm.

Figure 6 - HET-300 model

Recent laboratory tests results of thrust and Isp are plotted in Figure 7 and Figure 8.

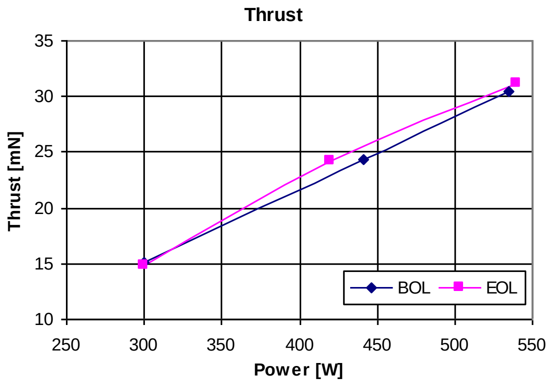

Figure 7 – HET-300 thrust [mN] produced vs. anode power [W] as measured in IHET-EM

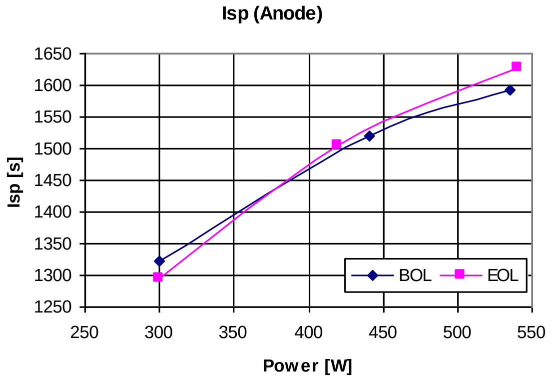

Figure 8 – HET-300 Specific Impulse [s] vs. anode power [W] as measured in IHET-EM

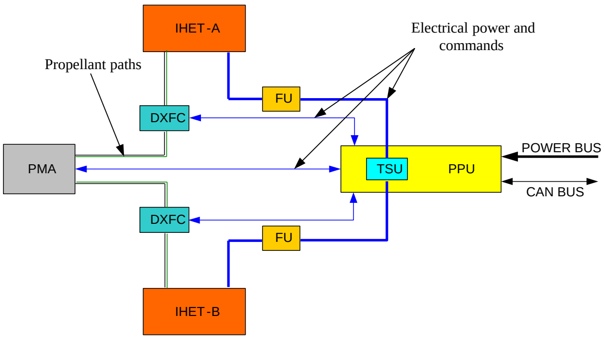

Figure 9 – IHET system block diagram

IHET Propulsion System

The IHET system (see Figure 9) 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 PMA is composed of a tank storing 16 kg of high pressurized Xenon and a set of valves, pressure reducers and manifolds to transport the gas. 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.

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 Figure 10) 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.

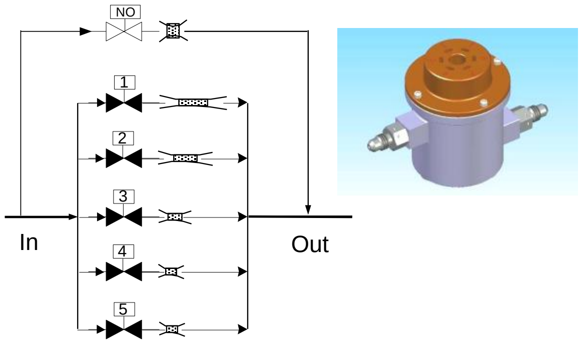

Figure 10 - Digital Xenon Flow Controller (DXFC)

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.

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).

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 will reside and operate within its premises.

V – DESIGN CONSIDERATIONS

Reliability Considerations

In order to achieve all mission goals, the Venµs IHET system had to be carefully designed, taking in account engineering considerations such as architecture, reliability and other factors.

Several life limiting factors characterizes Hall Effect Thrusters in general[4]. Among them are cathode number of ignitions and thruster's discharge chamber walls erosion. Those and other concerns like plume interaction with the satellite or propulsion system reliability were encountered and solved at the process of the electric propulsion system detailed design. The Venµs satellite mission plan was revised and tailored to meet the capabilities and restrictions of the electric propulsion system with "HET 300" thrusters.

To predict thruster performance degradation and life expectancy due to channel wall erosion, an erosion model was prepared. The model includes a hydrodynamic flow of the plasma inside the discharge channel enabling to analyze erosion of the channel walls over time. The model predicts that the maximum erosion rate is about 1 nm/h. Based on the wall erosion, HET-300 life time and its performance were predicted (see Figure 11).

The design of the IHET system incorporates a degree of redundancy that will allow the desired reliability in space operation.

First of all, there are two thrusters. Although they are pointed to opposite directions, each one can back the other, functionally.

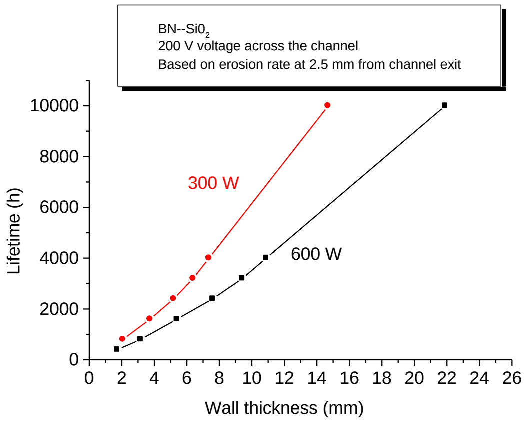

Figure 11 - HET-300 erosion based lifetime prediction

In addition to the thrusters, the valves on the PMA are redundant and the PPU has redundant power supplies, for every source needed (see Figure 12). Lastly, the PPU has 2 redundant Sequencing and Control Units (SCU), that each can operate the IHET independently.

IHET Tests

A life test is planned to start in mid 2008, which will validate thruster life, reliability and will also enable to calibrate the simulation models. Currently an Engineering Model (EM) thruster already exceeds mission requirements of 1000 hours. It achieved more than 1370 hours and still running. Figure 13 shows preliminary life test results of the EM. In this graph the thrust results are plotted for three power level tests, during the test period. These tests are being run by Soreq NRC in Israel.

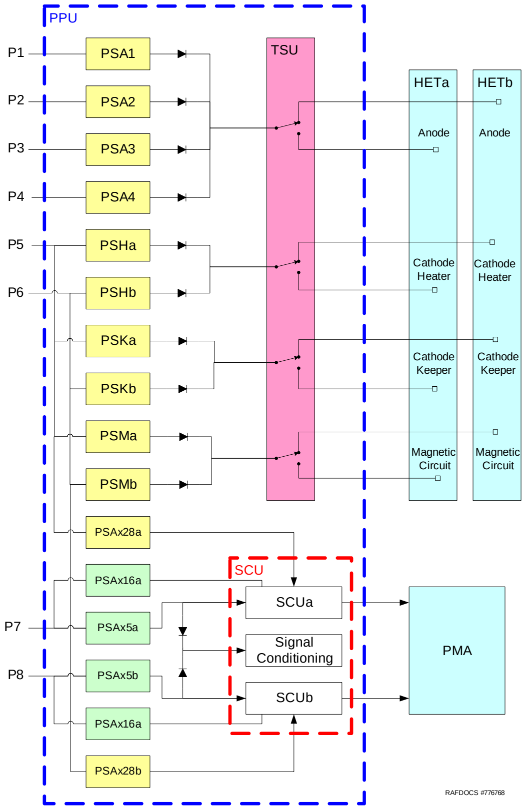

Figure 12 - PPU redundancy architecture

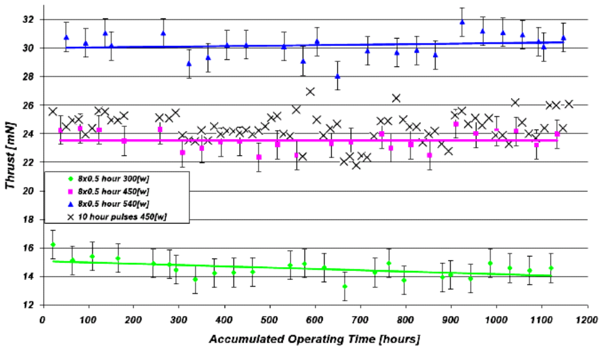

Figure 13 – Accumulated tests results of thrust

Since laboratory tests cannot actually simulate real space, because the gravity and the size of the vacuum chamber), the IHET tests will be continued in space, mainly in VM1, to fully examine its performance.

Satellite Architecture

Venµs is implemented on a modified Improved Multi Purpose Satellite (IMPS) bus platform, which is designed by IAI-MBT. The IMPS modifications concern mainly the base plate - to accommodate the 2 IHET engines and the propellant tanks. In addition to the IHET which serves as a payload, the satellite contains also a 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 600W) 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 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.

Since the IMPS bus has fixed solar panes, 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 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 Figure 14). Configuration *B3* proved to be the best, taking into account selected criteria (power, complexity, heritage, drag…).

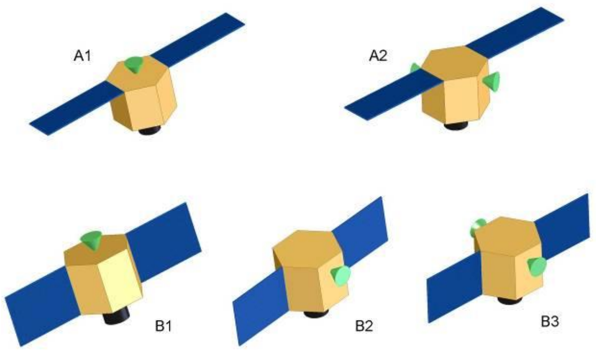

Figure 14 –Possible architectural configurations of thrusters and solar panels

For this configuration, Figure 15 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

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

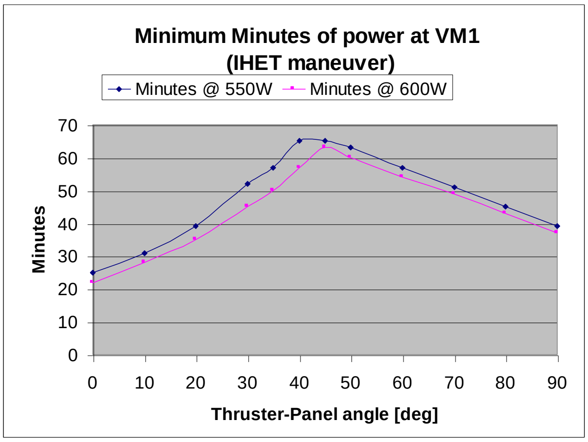

Figure 15 – Power production capability vs. thrusters-panel angle

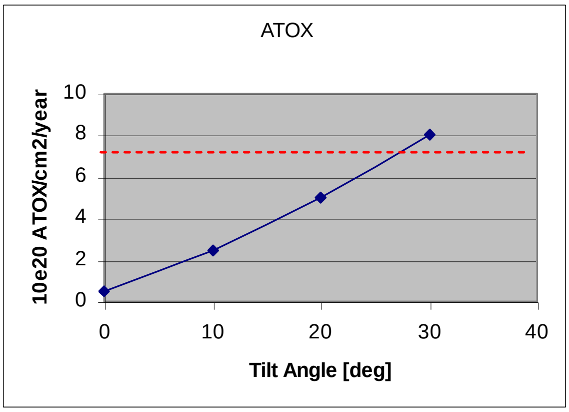

Figure 16 – VSSC ATOX flux at tilts angles, and allowed tolerance Camera Tolerance of $7.3 \bullet 10^{20}$ ATOX/m^2/Year

Orbits Architecture

In order to implement the technological mission in VM3, the orbit has to satisfy the scientific requirements for superspectral imaging along other criteria. A study[3] was made in order to select the best orbit for the VENµS VM3 phase.

The possible orbits are shown in Figure 17. They are characterized by earth-repeating. Candidates (see Table 4) were selected for a trade study.

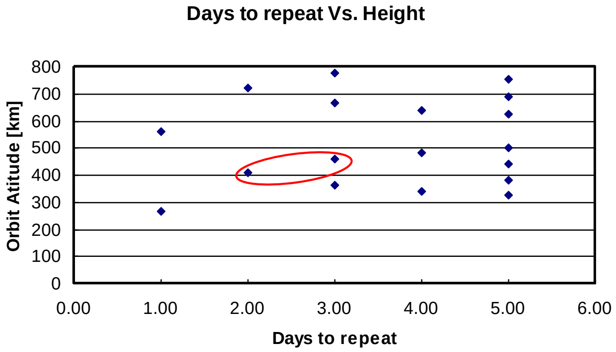

Figure 17 – Possible circular sun-synchronous earth-repeating orbit's altitude vs. repetition period. Circled points designate the candidate orbit alternatives considered for VM3

The different orbit candidate alternatives were compared according to pre-determined criteria: revisit time, imaging resolution, throughput and processing capability, demonstration of mission enhancement and others. Based on analysis of each orbit to these criteria, the final orbit was chosen to be alternative 1 – the 410 km orbit.

Table 4 - VENµS VM3 candidate orbits alternatives

	Alternative 1	Alternative 2	Alternative 3
Description	Sun-synchronous, two-day Earth repeating orbit	Sun-synchronous, three-day Earth repeating orbit	Sun-synchronous, two-day Earth repeating orbit
Semi major axis	6788.76 km (410 x 410)	6837.98 km (460 x 460)	7098.09 km (410 x 1030)
Eccentricity	< 0.001	<0.001	0.0435
Inclination	97.073°	97.255°	98.27°
Orbits to repeat	31	46	29

VI - SUMMARY AND CONCLUSIONS

In this paper, the Venµs scientific mission and the technological mission were described.

Both these missions make benefit of newly developed payloads, that when combined, will demonstrate unique mission-enhancement features, rarely seen on small satellites. Venµs will be able to provide superspectral earth images on a regular basis, for two grow periods, from two distinct orbits.

Venμs demonstrates a mission carried out at low orbit, where the drag force is significant.

The technological mission of VENμS will demonstrate the feasibility of using IHET for orbit control in a way that enables undisturbed imaging mission. This capability might be useful for small size microsatellites carrying high resolution missions.

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