Overview, Qualification and Delivery Status of the HEMP-Thruster based Ion Propulsion System for SmallGEO

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Abstract: The Business Unit Electron Devices of Thales Deutschland has developed and is currently qualifying a novel type of ion propulsion system based on High Efficiency Multistage Plasma Thrusters HEMP-T’s. The HEMP-T Assembly is being developed in the frame of the HEMP-TIS project (HEMP Thruster In orbit verification on SmallGEO), that was initiated and ordered by German Space Administration DLR. The Assembly was to fly on the Small Geostationary Satellite (SGEO) in the frame of ESA’s ARTES 11 program. The platform was developed by OHB System for the Hispasat AG1 mission. Currently the change of the integration of the HEMP-T assembly to the new Heinrich Hertz Mission is in preparation, which also uses the SGEO as platform.

The HEMP-T Assembly consists of four HEMP-T Modules and one Power Supply and Control Unit PSCU which supplies the HEMP-T Modules with electric power and controls their operation. The HEMP-TIS project includes all associated component development, system engineering, testing and qualification activities, and the delivery of the respective flight units.

The manufacturing and formal environmental qualification of all of the qualification units has been completed successfully. The units are currently subjected to lifetime testing including the EQM power supply. The qualification life testing is in progress now since mid of 2015 and the end of life testing will be reached by end of March 2018.

The Manufacturing of the flight units is completed and acceptance testing has been commenced. The respective PFM-PSCU has been delivered to Thales after successful acceptance testing, as well as the harness. All of these units have been subjected to End to End testing and confirmed the adequacy of the system design.

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I. Nomenclature

FCU = Xenon propellant Flow Control Unit  
HEMPT = High Efficiency Multistage Plasma Thruster  
HEMPTIS = HEMP Thruster In-orbit-verification on SmallGEO  
MMS = Mechanical Mounting Structure  
OHB = OHB System AG  
PSCU = Power Supply and Control Unit  
THR = Thruster  
NTR = Neutralizer

II. Introduction

THALES Electronic Systems is developing and qualifying a novel type of ion propulsion system based on the High Efficiency Multistage Plasma Thrusters HEMPTs in course of DLR’s HEMP-TIS program. This so-called HEMPT Assembly (HTA) is intended for being integrated on OHB’s SmallGEO geo-stationary satellite platform to perform attitude and orbit control manoeuvres [1]. The benefits of the HEMPT Assembly ion propulsion system are due to its high propellant exhaust velocity which allows for a significant reduction in propellant consumption. As a result the satellite starting mass can be reduced by several 100 kilograms compared to a conventional chemical propulsion system. As a consequence the satellite payload mass is increased and launching costs are reduced at the same time.

The HTA consists of four HEMPT Modules (HTM) and one PSCU which supplies the HEMPT Modules with electric power and controls their operation. Each of the HEMPT Modules integrates a HEMPT 3050 ion thruster, an HCN 5000 Hollow Cathode Neutralizer and a Flow Control Unit (FCU) which doses the Xenon propellant into the thruster. The particular positioning of the four HEMPT Modules on SmallGEO allows for all necessary position correction manoeuvres in the geo-stationary orbit and for momentum wheel off-loading, respectively.

The core technology of the ion propulsion system is represented by the HEMPT ion thruster, which has been developed by Thales Electron Devices for about 15 years (from concept feasibility [2]) exclusively based on own technologies and patents.

The HEMPT is based on a particular magnetic confinement of the Xenon propellant discharge which at the same time allows for efficient propellant ionisation and ion acceleration. Besides its performance the HEMPT exhibits the unique feature of negligible thruster erosion and therefore shows excellent long-life capabilities [7], [9]. In addition, the HEMPT design concept and operational characteristics enable ion propulsion system architecture with minimum complexity and thus high reliability and cost efficiency [11].

Figure 1 HTA system architecture  
Figure 2 3D-View of Hemp Thruster Module

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Key Parameters and a general description of the HTA are provided in [10] and in [11].
Further Development activities and Performance Prediction for future applications are elaborated in [16].

III. Change to the H2Sat Mission

Figure 3: H2Sat Propulsion System with HEMP Thrusters for North South Station Keeping

The HEMP Thruster Assembly will be used by OHB System on the Heinrich Hertz mission (H2Sat) based on the SmallGEO platform launched in 2017. The H2Sat mission is a German satellite project aiming to demonstrate new telecommunication technologies in the geo-stationary orbit and to deliver telecommunication capacities to the German Federal Armed Forces. The planned high satellite lifetime of 15 years in combination with a high payload capacity above 400 kg requires a mass-efficient propulsion system to be compliant to common launcher performance. The H2Sat propulsion system is composed of a chemical propulsion system and an electrical system for North/South station keeping with high total impulse demands. Compared to the heritage SmallGEO mission the cold gas system and additional EP thrusters for East/West station keeping have been substituted by additional chemical thrusters similar to the EDRS-C mission to reduce the satellite dry mass and complexity.

The HEMP thruster will be used as the nominal thruster for station keeping over the entire lifetime, which will demonstrate the innovative thruster system to be suitable for commercial application. For the H2Sat satellite with a mass of 3400 kg the HEMPT thruster assembly can save a total of 300 kg propellant compared to similar full chemical propulsion systems and up to 50 kg compared to a Hall Effect system.

The H2Sat mission has recently started into the phase C with the satellite launch scheduled for the year 2021.

Although the H2Sat mission will be a small GEO spacecraft, as HispaSat AG1 was, the accommodation is different. In particular the number of thruster modules per branch is reduced from 4 to 2 thruster modules. As a consequence, operational time per thruster is increased. This has been considered for the life test qualification, the qualification test scope is usually an envelope above both requirement sets.

The challenge is that the hardware is readily built, and could be subjected to acceptance testing immediately. However the platform design may be still subject to change and accordingly the test scope and time has to be agreed wisely.

As OHB has been rewarded the contract for phase C and D just recently, the activities for the implementation of the HTA on H2Sat are now progressing with the cooperation of in particular OHB, Thales and DLR.
IV. Verification Status

A Overview
As far as possible, performance requirements were verified on component level; after successful verification component integration into the HEMPT Module was performed followed by verification on Module level. For the first qualification test this was done on an Engineering Qualification Model (EQM) of the HEMPT Module which has successfully undergone performance, mechanical and thermal vacuum testing.

As a first test to demonstrate the lifetime, a HEMPT Module Engineering Model EM has been subjected to a 4900h endurance test (1300h with PSCU-EM) and 3100h extension [7] which covers the required mission lifetime of 4800h of the Hispasat AG1 Mission.
Several more verifications covering cathode humidity exposure, PSCU to s/c interoperability, s/c sputtering compatibility, transmission interference, correlation with adjacent thrusters, magnetic stray field on adjacent thruster have been successfully completed and confirmed the adequacy of the Module and the full system. [11,19]

Meanwhile HTM QM1 and HTM QM2 were manufactured and subjected to full environmental qualification comprising performance, mechanical and thermal vacuum testing. As the program is being altered to suit a different mission, the respective (more stringent) requirements relevant for environmental qualification have been analysed and the test levels for environmental testing were chosen to envelop the both missions right before conducting environmental qualification testing.

B Results on QM level
The formal qualification tests of the HTM-QMs consist of three major test blocks: Performance test, Mechanical test, Thermal Vacuum test.

Figure 4 HTM-QM1 during MIP

Figure 5 HTM-QM2 during MIP
As a precursor of the flight model acceptance test sequence and as first dominant element of the HTM qualification test sequence, HTM-QM1 was subjected to a functional reference test, that comprises a full performance test and a performance mapping at the thermal vacuum interface temperatures. This kind of test was introduced to have the performance data produced during thermal vacuum testing already available prior to mechanical and full TV testing with relatively low time impact and for comparison with the thermal vacuum test. Prior to, during and after these tests, as part of the nominal qualification and acceptance tests, the units were subjected to bonding isolation test, leak test and purifier health test (only prior) without anomalies. Details of the purifier health test are given in [13].

The first test block “Performance Test” determines the key performance parameters like thrust, power demand, ISP, beam properties of the individual HTMs at ambient temperature. As such it provides the first dataset embracing the mechanical tests.

During mechanical test, the qualification units are subjected first to resonance search, followed by sine vibration and random vibration. Prior and after shock testing additional resonance search is performed to proof the absence of mechanical change during the individual test steps. It should be noted, that the mechanical loads have been increased, as the new mission is more demanding. For instance, shock profile was altered resulting in necessary loads up to 3000g and sine tests up to 30g were required.

Thermal vacuum testing then commences with a performance test in order to compare the performance before and after mechanical testing. As next step the HTMs are operated for 4 hours at maximum thermal conditions and worst case power throughput demonstrating sufficient margin for the in orbit operation. Then thermal vacuum cycling is conducted, where the HTMs are started and operated at cold and hot interface/ radiation environments alternatingly. A final performance test confirms the stability of performance over mechanical and thermal environments.

Results of performance and functional reference tests of the HEMPT Module QM and qualification tests of NTR QMs are given in the following Tables below. The provided parameters thrust, power and specific Impulse where tested at the qualification temperature extremes and at ambient temperature. Deviations over temperature remained within measurement uncertainties.
Table 2. Qualification results on QM level.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Req.</th>
<th>Test value</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust (over Temperature)</td>
<td>44mN</td>
<td>Typ. 44.8mN</td>
<td>Y</td>
</tr>
<tr>
<td>Thruster power (over Temperature)</td>
<td>1380W</td>
<td>1383 – 1390W</td>
<td>Y</td>
</tr>
<tr>
<td>Worst Case thruster power</td>
<td>1450W</td>
<td>≥1450W</td>
<td>Y</td>
</tr>
<tr>
<td>HTM specific Impulse (=v/g) (over Temperature)</td>
<td>2300s</td>
<td>Typ. &gt;2400s</td>
<td>Y</td>
</tr>
<tr>
<td>Mechanical load sine vibration</td>
<td>30g</td>
<td>30g</td>
<td>Y</td>
</tr>
<tr>
<td>Mechanical Load Random</td>
<td>11.6gRMS</td>
<td>11.6gRMS</td>
<td>Y</td>
</tr>
<tr>
<td>Mechanical Load shock</td>
<td>2000g</td>
<td>up to 4000g</td>
<td>Y</td>
</tr>
<tr>
<td>HTM Minimal Interface Temperature</td>
<td>-15°C</td>
<td>-15°C</td>
<td>Y</td>
</tr>
<tr>
<td>HTM maximum Interface Temperature at TRP</td>
<td>65°C</td>
<td>65°C (operating) 80°C (non-operating)</td>
<td>Y</td>
</tr>
<tr>
<td>launch fairing environment</td>
<td>40+20 days</td>
<td>60 days</td>
<td>Y</td>
</tr>
<tr>
<td>maintenance free time</td>
<td>3 month</td>
<td>3 month (analysis)</td>
<td>Y</td>
</tr>
</tbody>
</table>

All tests defined in the environmental qualification plan were successfully performed and all parameters are within the specification with the allowed tolerances for testing. Qualification testing of the second HTM (HTM-QM2) confirmed the results of HTM-QM1 [15,19].

In addition to the environmental qualification the PSCU interoperability was confirmed by a coupling test of PSCU-EQM with HTM-QM1, showing flawless operation.

In regard to these results, the HEMP-Thruster Module HTM3050 and the full system is considered fully qualified.

C Life Test Status

The HTA Lifetime Test plan was elaborated in order to fulfil the SGEO and H2Sat qualification requirements. The test plan includes simultaneous testing of two HTMs, HTM-QM1 and HTM-QM2, in the same vacuum facility. HTM-QM1 will demonstrate 8500h of operation what corresponds to a qualification factor of 1.3 for lifetime. It will accumulate around 10k of cycles to create the required cycle load on the PSCU for H2Sat and from the HAG1 mission for the HTM. The 10k cycle number is the envelope of both missions, as for HAG1 there is higher cycle number (there was NSSK and EWSK), for H2Sat there is higher lifetime (only 2 thrusters instead of 4). In order to reach this high number of cycles in a reasonable time the cool down time with respect to in-orbit operation is reduced.
HTM-QM2 is conducting cold cycles all the time. This requires cool down times of more than 5h. Due to this a qualification factor of 0.8 for lifetime can be reached within the intended test duration.

Thales has started the Lifetime Test with two qualification HEMP Thruster Modules, HTM-QM1 and HTM-QM2, and with one qualification power supply and control unit, PSCU-EQM end of May 2015. The HTM-QM1 and the HTM-QM2 were first switched on according to the Lifetime Test plan at the end of August 2015. Seen from today the life test will be completed end of Q1 2018 [21].

This Lifetime Test is unique in the field of electrical propulsion: It includes simultaneous and fully independent operation of two thrusters in the same vacuum chamber. This has never been dared in a life test before and shows the high level of confidence gained in this technology.

Simultaneous operation has been decided to allow the testing of the both objectives cycles and cold start loads in minimum test duration and test cost. If the simultaneous operation would be prohibitive, there would be a test duration penalty and complex handshake issues.

Both HTMs and the PSCU-EQM were successfully switched on according to the test sequence and have accumulated a number of operating cycles and operating hours by now: the HTM-QM1+PSCU-EQM have accumulated >6600 operating hours and >7880 operating cycles, the HTM-QM2 has accumulated >3580 operating hours and >2025 operating cycles. Performance parameters are stable and within the specifications. The HTMs demonstrate a stable (simultaneous) operation in the same vacuum chamber throughout the test. Today no sign of erosion or life limiting effects outside the expectations have been identified.

Accordingly the Lifetime Test continues and to have completed its planned scope by end of march 2018.
V. Flight Hardware Status

Manufacturing of HTM FM1..4 has been accomplished. This involved the following steps: First the HTMs are readily assembled from the components Thruster, Neutralizer and Mechanical mounting structure. Then they are mated with their FCU and the joints welded. Subsequently each module will see acceptance / qualification test sequence as demonstrated on the HTM-QMs namely leak test, performance or functional reference test, mechanical environment testing and thermal vacuum testing.

PSCU Manufacturing has also been completed. The PSCU was manufactured and acceptance tested involving full performance, mechanical environment as PFM and thermal vacuum testing as PFM by Airbus Friedrichshafen. A Conducted Emission EMC testing was done in addition. Subsequently this unit was delivered to Thales and has been subjected to End to End testing. The flight harness sets have also been delivered by OHB and Airbus. The necessary manufacturing activities on the high voltage terminals are done.
VI. End to End test results

As the PSCU acceptance testing was completed and it is the unit of the flight set, that is needed for integration first, it was decided to perform the end to end (E2E) test of the HTA prior to the full completion of the acceptance testing of the HTM-FMs. For E2E testing all of the four HTMs, the PFM PSCU and the flight harness are located inside the vacuum chamber as indicated in the figure 11 and 12.

The HTMs are protected from the test environment by dedicated shrouds covering all thermo-functional surfaces. The PSCU and Harness were also covered and shielded to maintain cleanliness and to protect against the plasma environment resulting from the thrusters operation.

The E2E test successfully demonstrated the following elements:
- In orbit commissioning procedures e.g. good health tests
- Venting of all 4 FCUs simultaneously
- Neutralizer activation on all 4 Neutralizers simultaneously
- Start up and Operation of any of the 4 thrusters
- Overlapping operation of 2 HTMs
- Recovery procedures

The E2E test was the most complex test performed so far at ULAN facility. Despite the wide experience gathered during the SGEO project, as a matter of fact, a few non-conformances were observed during testing. Therefore, in order to verify the requirements affected, some variations to the original test procedures were necessary. These were accepted as it could be shown that the non-conformances were originated from facility effects and are not to be expected in orbit and could be resolved solely by refinement of the operational procedures, confirming the adequacy and flexibility of the system design. [17]

Next steps on the HTM-FMs will be the completion of acceptance testing and delivery of the flight set.

Figure 10 Overview of the test set-up for HTA E2E test

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Figure 11 Accommodation of the four HTMs in the Vacuum test facility.
VII. Status Thrust Vector Scanner

One important verification step of the acceptance test sequence is the absolute measurement of the thrust vector of each HTM flight model. As the H2Sat satellite will not be equipped with a thruster orientation mechanism, the knowledge of the absolute thrust vector with high accuracy is key to keep the propellant margins for momentum wheel offloading low. To satisfy this demand, Thales has set up a thrust vector scanner measuring the full hemisphere of the thruster plume with 37 retarding potential analysers.

![Thales thrust vector scanner building blocks](image)

Readily this device is installed in the ULAN facility. The installation was requiring repositioning of several vacuum system elements due to geometric overlap. The core functionality like movement and basic communication with electronics has been reached. The geometric calibration, electronic calibration, Sequencing software and evaluation software have been completed as well.

In particular the geometric calibration is challenging, as the desired measurement accuracy is 0.3° absolute [20], requiring absolute angular position accuracies of 0.1° and less and position accuracies of around 1mm.

![The Thales thrust vector scanner installed within the ULAN vacuum chamber](image)

Also important is the fact, that one full hemisphere sweep shall be sufficiently fast to allow characterization of the thrusters at different operational temperatures. Accordingly a single energy sweep has been reduced to 20sec. This requires the electronic to simultaneously acquire 40 pico-ampere-meter channels isochronous with a data-acquisition frequency of 100Hz. For a full hemisphere scan a time of 15 minutes is considered today.

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In parallel the thrust balance has been upgraded to the most recent version also present in the life test facility. This Version has shown the most stable performance of all thrust balance versions.

Today, the ULAN facility is featuring the most complete and comprehensive set of thruster diagnosis equipment usable for development, qualification and development.

The commissioning tests confirmed the capabilities of the thrust vector scanner. Predicted performance has been achieved.

VIII. Conclusion

TES has further developed its HEMPT technology to set up a reliable and cost effective ion propulsion system. Supported by German Space Administration DLR through the HEMP-TIS project, a HEMPT Assembly has been set up for OHB’s SmallGEO platform.

HTM-QM1 and QM2 have been successfully subjected to the formal environmental qualification sequence and are readily subject to life test together with PSCU-EQM.

The HTMs and the PSCU demonstrate a stable (simultaneous) operation in the same vacuum chamber throughout the life test.

The life test program has progressed so far, that the elements for reaching qualification factor 1 have been accomplished. All designated flight units FM1..4 have been tested for full performance. The E2E test successfully demonstrated the full interoperability of the flight set and confirmed the adequacy of the system design. With the successful environmental qualification of the HTM-QMs, and the completed E2E test, the HTA now has reached TRL 7. Life test is in its last phase.

Next steps are the completion of the HEMPT Module and System lifetime qualification, the delivery of the flight HEMPT Assembly to OHB and the operation in orbit, in order to reach TRL 8 and TRL9 respectively.

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References


