THE FIRST IN-SPACE DEMONSTRATION OF A GREEN PROPULSION SYSTEM

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ABSTRACT
This paper describes the first in-space demonstration of a “Green” propulsion system on the PRISMA main satellite. The PRISMA mission is a unique opportunity to demonstrate the High Performance Green Propulsion (HPGP) system in space, and thus take a significant step towards its use in future space applications. The PRISMA mission objective is to perform autonomous rendezvous and formation flying (Main and Target Satellite) including homing and proximity operations. The PRISMA satellites were launched on Dnepr from Yazny in June 2010, Figure 1. The HPGP system is used both for providing the required delta-v for the PRISMA main satellite manoeuvres and as an experiment with the objective to demonstrate performance in space. Delta-v is nominally generated in an autonomous and combined operation of the HPGP and Hydrazine propulsion systems while the performance measurements are performed with one propulsion system at the time. PRISMA is an international technology demonstration program with Swedish Space Corporation as the Prime Contractor and major contributions from DLR, CNES and the Technical University of Copenhagen.

INTRODUCTION
This paper describes the launch campaign, LEOP, commissioning and initial phase of the first in-space demonstration of a “Green” propulsion system on the PRISMA mission, Swedish Space Corporation (SSC).

The mission objective is to perform autonomous rendezvous and formation flying with the Main and the Target Satellites, including homing and proximity operations. The satellites are shown in Figure 2. A significant part of the mission is the demonstration of ECAPS High Performance Green Propulsion (HPGP) system.

The HPGP system is used both for providing the required AV for the PRISMA main satellite manoeuvres and as an experiment with the objective to demonstrate performance in space. The PRISMA satellites, mission objectives and overview have been described in numerous papers ref [1 - 12].
The PRISMA and PICARD (CNES) satellites were successfully launched with Dnepr from the Yasny Launch Base (Russia) at 14:42 UTC on June 15th, 2010, see Figure 1. The satellites were injected into a sun synchronous orbit with an inclination of 98.28°. Initial perigee was 730 km and the apogee was 790 km. The ground track is shown in Figure 3 and a view over Russia seen from PRISMA is shown in Figure 4. The Dnepr launch service was provided by ISC Kosmotras (Russia) and the Dnepr rocket has been manufactured by Yuzhnoye (Ukraine).

The ground station at ESRANGE (Sweden) established contact with PRISMA during its first passage at 16:14 UTC on June 15th and the Mission Control Center (MCC) in Solna (Sweden) could start executing the LEOP tasks. After two days of LEOP the PRISMA satellites (still clamped together) were declared ready for commissioning. Monitoring of the thermal conditions and tank pressure of the HPGP and Hydrazine propulsion systems began on the second day of the flight and they were found to be nominal.

**Figure 2. The PRISMA Satellites**

**Figure 3. PRISMA’s Ground Track**

**Figure 4. View over Russia from PRISMA’s DVS camera (Lat 62.07, Long 55.40)**

**PRISMA PROPULSION SYSTEMS**

The Main PRISMA satellite has three propulsion systems where the HPGP and the Hydrazine systems provide the satellite with the required ΔV to be used for the various experiments. The Hydrazine propulsion system is equipped with six 1 N thrusters and has capacity to provide ΔV up to 120 m/s. The HPGP system has two 1 N thruster and has the capacity to provide a ΔV of up to 60 m/s. The two liquid propulsion systems are therefore planned to be operated simultaneously but can also be operated separately which adds redundancy. Separate experiments are also planned for the HPGP system with the objective to demonstrate in-space performance.

The thrust vectors are directed towards the centre of gravity of the spacecraft so that torque-free motion can be created in all directions. Any misalignment of the thrusters w.r.t. centre of gravity can be compensated with reaction wheel torque. None of the thrusters are pointing directly in the rendezvous direction.

A Nitrogen cold gas micro propulsion system is also flying as an experiment on PRISMA ref [8]. Figure 5 shows the three PRISMA propulsion systems.
ΔV is nominally generated in an autonomous and combined operation of the HPGP and Hydrazine propulsion systems while the performance measurements are performed with one propulsion system at the time.

**Figure 5. PRISMA’s Propulsion Systems (Hydrazine=Red, HPGP=Green and Micro propulsion = Purple)**

**HPGP SYSTEM**

The HPGP system uses the first “Green” storable monopropellant qualified for space flight, which is the ADN-based LMP-103S. The hydraulic schematic is shown in Figure 6.

The PRISMA HPGP system consists of one diaphragm-type propellant tank with a capacity of 5.5 kg (i.e. 4.5 L) of LMP-103S propellant, two service valves, one pressure transducer, one system filter, one isolation latch valve and two 1 N thrusters. The HPGP thruster delivers up to 6 % higher specific impulse (Isp), and up to 30 % higher density impulse than a comparable Hydrazine thruster. The propellant is also simpler to handle and is significantly less hazardous than Hydrazine. The propellant and the pressurant gas are stored in the tank and are separated by means of a diaphragm. The pressurant (helium) acts on the flexible diaphragm and pushes the propellant via the system filter to the thruster propellant flow control valve.

The system operates in blow-down mode, meaning that the feed pressure decreases proportional to the amount of propellant consumed. The nominal Beginning of Life (BOL) feed pressure is 1.85 MPa at 20°C and MEOP is 2.2 MPa at 50°C.

The nominal blow-down ratio is 3.8:1 and the feed pressure will decrease to 0.5 MPa when all propellant is consumed. The thrust will due to the change of feed pressure decrease from 0.9 N at BOL to 0.29 N, nominally.

The HPGP system dry mass is 3.9 kg (including brackets and thermal hardware) and the wet mass is 9.4 kg.

All fluid components, including the Thruster Flow Control Valve are conventional “Commercial Off-The-Shelf” (COTS) components with extensive flight heritage.

**Figure 6. The HPGP Hydraulic Schematic**

**Figure 7. 1 N HPGP thruster**
The 1N HPGP thruster has been subject of a hot firing life test accumulating propellant throughput, pulses and firing time which are four times higher than the PRISMA mission requirements. The 1N HPGP thruster is shown in Figure 7.

LAUNCH CAMPAIGN

The PRISMA satellites, Ground Support Equipment and the HPGP propellant (LMP-103S) were shipped by air from Sweden on May 17th, 2010. Transport of the LMP-103S propellant by air was possible since it has been approved for transport according to UN Class 1.4S. The only item that could not be included in the main transport was the Hydrazine that due to its hazardous nature had to be transported from Germany by ship to St Petersburg and then by land transport to Yasny months in advance before the launch campaign. The launch campaign started on May 20th and lasted for only 18 days in total. The campaign included the following main activities:

1. MAIN and TARGET satellites Checkout
2. Propulsion Systems Checkout
3. TARGET mating to MAIN
4. Pressurization of the Micro propulsion system
5. Fuelling of HPGP system
6. Fuelling of the Hydrazine propulsion system
7. Final preparation, arming and red tags removal
8. Mounting on the Dnepr Space Head Module

During the PRISMA launch campaign the benefits of loading a “Green” propellant compared to Hydrazine was obvious. As the propellant is non-carcinogenic and has low toxicity, loading the spacecraft with LMP-103S is performed without SCAPE’s. Only clean room clothes with splash protection were used, as shown in Figure 9. In spite of its high energetic content, LMP-103S is classified as an insensitive substance (NOL 1.3). Furthermore, it is not flammable and is also environmentally benign. Unlike Hydrazine the LMP-103S propellant is not sensitive to air or water vapour. The fuelling and pressurization of the HPGP system has been declared as a “Non Dangerous Operation” by the Yasny Launch Base Range Safety. Therefore other activities such as launch preparation of the other satellite PICARD could continue without any restrictions during the HPGP fuelling. In contrast all activities were stopped and the PICARD and SSC teams left the Yasny Launch Base for two days during the fuelling of Hydrazine.

All activities related to the HPGP system loading i.e. unpacking, GSE preparation pre-loading checkouts, safety meetings, fuelling, pressurization, decontamination and packing was performed by a crew of only three, i.e. two fuelling specialists and one technician, during seven days while the comparable Hydrazine activities required a crew of five fuelling specialists for fourteen days. In addition the Launch Base fuelling support team consisted of more than twenty specialists.
The decontamination of the Hydrazine loading cart and waste handling of Hydrazine is a major operation compared to LMP-103S. The decontamination of the Hydrazine Fuelling Cart required a team of three people during three days. The waste was 29 litres of Hydrazine (residues after fuelling), 400 litres of contaminated deionized water and 70 litres of contaminated Isopropyl alcohol (IPA). The destruction of the Hydrazine was charged extra by the Launch Base. In contrast the decontamination of the HPGP Fuelling Cart was performed within one hour by one technician. The waste was 1 litre propellant (residues after fuelling) and 3 litres of contaminated but non-toxic deionized water and IPA, which were destructed by the launch base team at no charge.

The current price for small quantities of LMP-103S is similar to the price of Hydrazine procured in Europe (but produced in China). Even though the pre-loading, checkout and loading procedures follows the same principal steps for the two liquid propellant systems, the total man hours during the campaign for preparation, fuelling and decontamination of Hydrazine, are more than three times higher than for LMP-103S. Also the pre-campaign activities required much more effort for handling the Hydrazine issues than for LMP-103S.

On June 3rd, 2010, the PRISMA satellites were delivered to Kosmotras for integration into the Dnepr Space Head Module.

Figure 10. Integration of PRISMA into the Space Head Module (Yasny)

The launch of PRISMA was shared with the PICARD satellite. Dnepr’s capacity is over 400 kg to 700 km orbit. The inclination and sun synchronous orbit that Dnepr could provide was ideal for launching the PRISMA/PICARD small satellites combination. The Dnepr launch vehicle was therefore selected at an early stage. Figure 10 shows the integration of PRISMA into the Space Head Module.

GROUND SEGMENT

The ground segment utilizes SSC’s Satellite Operations facilities in Kiruna (Sweden), as well as the newly developed Check-out and control ground support equipment RAMSES [7].

• Mission Control Centre (MCC) contains the Mission manager and the engineering and analysis power. MCC prepares the operations, generates and validates (via a simulator environment) the flight procedures and analyses generic platform performance flight data, see Figure 11.

• Operations Control Centre (OCC) provides the routine operations and surveillance and executes the TM/TC up/downloads according to MCC instructions. OCC utilises existing antennas and infrastructure, but has been completed with a RAMSES installation.

• Experiment Control Centres (ECC), one for each experimenter group works remotely via internet. The ECCs prepares experiment scenario procedures (for MCC to validate) and analyses experiment data.

The MCC, OCC and one ECC are located at SSC in Solna, (Sweden). The SSC mission control concept can be found in ref [11].

Figure 11. PRISMA Mission Control Center during HPGP Commissioning
IN-SPACE FLIGHT DEMONSTRATION

The In-Space Flight Demonstration of the HPGP system comprises commissioning, four blocks of HPGP specific firings and combined operation with the Hydrazine system during the different autonomous formation flying experiments.

On June 23, 2010, eight days after launch, the commissioning of the PRISMA HPGP system was performed as planned. The commissioning of the HPGP system became a “text book” exercise and all functions and data were nominal. The commissioning was performed according to Table 1 below.

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Activity</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>116</td>
<td>- Monitor propellant tank temperature and pressure&lt;br&gt;- Monitor thrusters valve temperature</td>
<td>Nominal</td>
</tr>
<tr>
<td>117</td>
<td>- Start pre-heating of thrusters catalyst beds</td>
<td>Nominal</td>
</tr>
<tr>
<td>118</td>
<td>- Monitor thrusters catalyst bed temperature&lt;br&gt;- Blanking pressure venting&lt;br&gt;- Open isolation valve to fill lines&lt;br&gt;- Monitor tank pressure drop</td>
<td>Nominal</td>
</tr>
<tr>
<td>119</td>
<td>- Priming firing sequence</td>
<td>Nominal</td>
</tr>
</tbody>
</table>

The first in-space firings were performed on June 24, 2010 where 100 ms single pulses where fired. The first firing demonstration was a pulse train of forty 100 ms pulses at a duty cycle of 1%. The firing was performed along-track and GPS data verified the predicted 2.1 cm/s ΔV increase. The propellant consumption for the manoeuvre was nominal. As HPGP system is now “Ready for Action”, the operations continues with commissioning of other spacecraft subsystems.

The first HPGP experiment block; HPGP 1 (with duration of four days) is planned to be performed after target separation beginning of August. HPGP 1 contains a series of pulse trains and single pulses for performance mapping and demonstration of functionality within the operational box.

The current mission planning relevant to the HPGP system is shown in Table 2 below.

<table>
<thead>
<tr>
<th>OPERATIONS</th>
<th>Days</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEOP &amp; Commissioning Phase</td>
<td>7</td>
<td>Launch June 15, 2010</td>
</tr>
<tr>
<td>HPGP Commissioning</td>
<td>1-3</td>
<td>- Venting&lt;br&gt;- Priming&lt;br&gt;- Firings</td>
</tr>
<tr>
<td>Target Separation</td>
<td>7</td>
<td>Planned for 3rd of August</td>
</tr>
<tr>
<td>GPS Calibration</td>
<td>4</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Basic Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPGP 1</td>
</tr>
<tr>
<td>Autonomous formation flying</td>
</tr>
<tr>
<td>Proximity operations</td>
</tr>
<tr>
<td>HPGP 2</td>
</tr>
<tr>
<td>Autonomous Rendezvous</td>
</tr>
<tr>
<td>Collision avoidance</td>
</tr>
<tr>
<td>Autonomous formation flying</td>
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<tr>
<td>HPGP 3</td>
</tr>
<tr>
<td>Autonomous formation flying</td>
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</tbody>
</table>

<table>
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<tr>
<th>Extended Mission (Excluding Target)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPGP 4</td>
</tr>
<tr>
<td>Autonomous orbit keeping</td>
</tr>
</tbody>
</table>

Mission completion in June 2011 (1 year)
PERFORMANCE MEASUREMENT ACCURACY

The 1 N HPGP thruster has undergone extensive ground hot firing tests for characterization. This data will be used for comparison during the in-flight firings.

The In-Space performance measurements and demonstration of the HPGP system capabilities are limited by several factors such as platform limitations, mission and operations constraints.

The assessments for the thrust and Isp are based on the spacecraft mass, acceleration profile and orbit changes based on GPS data. The spacecraft mass is in turn determined from the propellant volume, derived from tank pressure and temperature. When combined with the time stamps from the onboard computer, the propellant mass flow rate can also be determined.

The accuracy of the planned in-space performance measurements has been assessed for the HPGP and Hydrazine propulsion systems. The in-space data (i.e. propellant mass, thrust and specific impulse (Isp)) are provided with a specific level of confidence based on the total propellant mass consumed. The in-space performance is then compared with the performance model which is based on extensive ground test data.

The analysis of accuracy and confidence includes the complete chain from the sensor accuracy through to the final performance readings, seen by the satellite operator. The assessment of the performance measurements accuracy is reported in ref [1].

Figure 12 shows the Main spacecraft relative orbit to the Target during upcoming experimental and handover manoeuvres between experiments.
CONCLUSIONS
The first in-space demonstration of a High Performance Green Propulsion system is ongoing. The commissioning of the PRISMA HPGP system was performed on the day eleven years after the very first experimental HPGP thruster was test fired.

After more than 10 years of R&D, the HPGP technology has emerged as an enabling technology for improved performance, enhanced volumetric efficiency. The first firings in space have been performed. Fuelling LMP-103S during the PRISMA launch campaign clearly demonstrated the benefits of using a “Green” propellant compared to Hydrazine w.r.t reduced risk, lead time and cost.

The PRISMA mission is a unique opportunity to demonstrate the HPGP technology in space, and thus take a significant step to towards its use in future space applications. The HPGP technology has also been selected as the propulsion baseline for several European and U.S. missions.

ACKNOWLEDGEMENTS
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