

In-Space Demonstration of High Performance Green Propulsion and its Impact on Small Satellites

Kjell Anflo, Ben Crowe
ECAPS AB Sweden P.O. Box 4207 SE-171 04 Solna; +46 8 6276305
kjell.anflo@sscspace.com

ABSTRACT

This paper summarizes the pre-launch activities and the results from the in-space demonstration of a novel propulsion system on the PRISMA main satellite, using a “Green” monopropellant. This propellant is a storable ADN-based monopropellant blend (i.e. LMP-103S). The basic mission for the High Performance Green Propulsion System (HPGP) has been successfully completed and all primary objectives of TRL 7 have been met. The HPGP technology is now flight proven and ready for implementation on future missions.

The HPGP thruster specific impulse measured in-space is coherent with the measurements performed on ground in the near vacuum test stand. The in-space back-to-back performance measurements between the HPGP and hydrazine propulsion systems shows the Specific Impulse (Isp) improvement for the LMP-103S propellant is higher than expected compared to hydrazine. The specific impulse measurements were performed by means of onboard accelerometers, GPS and precision propellant gauging. The methodology and results from the HPGP performance measurements are discussed in the paper as well as the comparison between the HPGP and hydrazine systems’ performance.

The demonstrations performed on PRISMA take this technology a significant step forward towards its use in future space applications. It is concluded that after more than 10 years of R&D, the HPGP technology has emerged as an enabling technology for improved performance, enhanced volumetric efficiency, reduction of propellant handling hazards and significantly shorter launch preparation operations. The progress of the development has been presented in several papers since 2000.

The HPGP technology has already been selected as the propulsion baseline for several new small European and U.S. missions where improved density impulse is of major importance.

After one year in orbit the PRISMA basic mission has been successfully completed. The extended mission is ongoing and the in-space demonstration of the HPGP propulsion system will continue to provide ΔV to new experiments.

INTRODUCTION

This paper describes the launch campaign of the “Green” HPGP propulsion system on PRISMA and describes the methodology and performance results of its first in-space demonstration. Comparisons to a typical hydrazine system are provided as well as applications of HPGP technology in future small satellite missions.

The HPGP propulsion system is the first in-space demonstrator of the HPGP technology and is also used for providing ΔV to the PRISMA main satellite. The PRISMA spacecraft, mission objectives and overview have been described in numerous papers ref [1 - 7].

II. PRISMA’s Propulsion Systems

The Main PRISMA satellite has three propulsion systems, including the experimental cold gas micro propulsion system. The hydrazine and HPGP systems provide the satellite with the required ΔV to be used for the various experiments. The monopropellant hydrazine propulsion system is equipped with six 1 N thrusters and has a tank capacity to provide ΔV up to 120 m/s. The HPGP propulsion system has two 1 N thrusters and has a tank capacity to provide a ΔV of up to 60 m/s. The two liquid propulsion systems are capable of being operated simultaneously or separately which adds redundancy. Separate experiments have been planned and executed uniquely for the HPGP system with the objective to demonstrate at TRL 7 and further obtain a flight proven technology.

The HPGP system thrust vectors are directed towards the centre of gravity of the spacecraft and achieve “near” torque-free motion in all directions. As the center of gravity changes with propellant consumption, misalignment of the thrusters w.r.t. to centre of gravity can be compensated for with the reaction wheel torque. None of the thrusters are pointing directly in the rendezvous direction, (i.e. towards PRISMAs other satellite, TARGET). ΔV is nominally generated autonomously using hydrazine or in a combination of the HPGP and hydrazine propulsion systems, while the performance measurements are conducted with one propulsion system at the time.

III. 1 N HPGP Propulsion System

The PRISMA HPGP system consists of one diaphragm-type propellant tank with a capacity of 5.5kg (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 propellant and the pressurant gas are stored in the same tank and the propellant is separated from the Helium pressurant by means of a diaphragm. The pressurant acts on the flexible diaphragm and pushes the propellant via the system filter to the thruster propellant Flow Control Valve (FCV). The hydraulic schematic is shown in Figure 1.

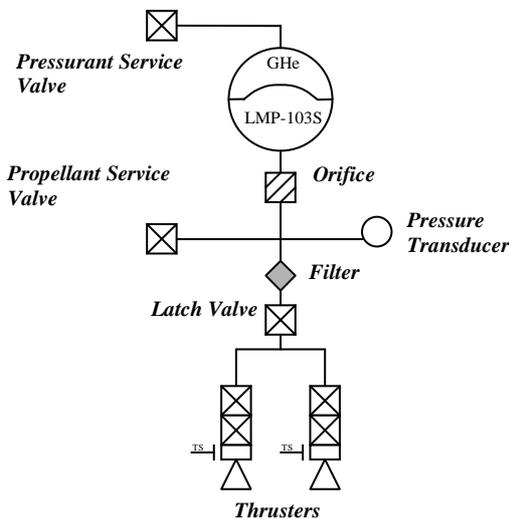


Figure 1. Hydraulic schematic for the HPGP system

The system operates in blow-down mode, meaning that the feed pressure decreases proportional to the amount of consumed propellant. The nominal Beginning of Life (BOL) feed pressure is 18.5 Bars at 20°C and Maximum Expected Operational Pressure (MEOP) is 22 bars at 50°C. The nominal blow-down ratio is 3.8:1 allowing the feed pressure to decrease to approximately

5 bars when all the propellant is consumed. The thrust, due to the change in feed pressure, will decrease from its Beginning of Life (BOL) force of nominally 0.9 N, down to 0.25 N at End of Life (EOL). The HPGP system dry mass is 3.9kg (including brackets and thermal hardware) and the wet mass is 9.4kg. All fluid components, including the thruster flow control valve are conventional “Commercial Off-The-Shelf” (COTS) components with extensive flight heritage. The Spacecraft System Design w.r.t. incorporation of the HPGP propulsion system is described in [2].

IV. Launch Campaign

The PRISMA spacecraft, Ground Support Equipment (GSE) 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. Due to its hazardous nature, the hydrazine propellant had to be transported from Germany by ship to St.Petersburg and then transported to Yasny, months in advance of the launch campaign. The launch campaign started on May 20th and lasted for 18 days in total. Seven effective working days, including contingency, were planned specifically for the HPGP launch campaign. The campaign included the following main activities:

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

The propellant loading for all propulsion systems required five days in the fueling hall and began with loading the Micropropulsion cold gas system, thereafter the HPGP system and finally the hydrazine system. During the PRISMA launch campaign the benefits of loading a “Green” propellant compared to hydrazine were apparent. As the propellant is non-carcinogenic and has low toxicity, loading the spacecraft with LMP-103S was performed without SCAPE suits. 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 vapor. The fueling and pressurization of the HPGP system was declared as a “Non Hazardous Operation” by the Yasny Launch Base Range Safety. Therefore other activities such as launch preparation of the other co-manifested satellite, PICARD, could continue without restrictions during the HPGP fueling. In contrast all activities were stopped and both the CNES and SSC teams vacated the Yasny Launch Base for two days during the fueling of hydrazine.

All activities related to the HPGP propulsion system loading i.e. unpacking, GSE preparation pre-loading checkouts, safety meetings, fueling, pressurization, decontamination and packing was performed by a crew of only three, of which two specialists carried out the fueling over an effective period of six working days. In comparison the hydrazine activities required a crew of five fueling over a fourteen day period. In addition the Launch Base hydrazine fueling support team consisted of more than twenty specialists.

The decontamination of the hydrazine loading cart and waste handling of hydrazine was a major operation compared to LMP-103S. The decontamination of the hydrazine Fueling Cart required a team of three people during three days. The toxic waste from the hydrazine operations was 29 liters of hydrazine (the space batch), 400 liters of contaminated de-ionized water and 70 liters of IPA. The destruction of the hydrazine was characterized as a “significant operation” by the Launch Base. In contrast the decontamination of the HPGP Fueling Cart was performed within one hour by one technician. The waste was 1 liter propellant and 3 liters of contaminated, non-toxic IPA/de-ionized water which were disposed of the launch base team at no charge.

The current cost 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 follow the same principal steps for the two liquid propellant systems, the total man hours during the campaign for preparation, fueling and decontamination of hydrazine were four times higher than for LMP-103S. Also the pre-campaign activities required much more effort to handle the hydrazine-related issues than for LMP-103S. The cost of Phase E1 was three times greater for hydrazine than for the HPGP system.

V. In-Space Demonstration

The In-Space Flight Demonstration of the HPGP propulsion system was comprised of commissioning, four blocks of specific HPGP firings and a combined operation with the HPGP and hydrazine systems firing during different formation flying experiments.

On June 23 2010, eight days after launch, the commissioning of the PRISMA HPGP propulsion system was performed as planned.

The first in-space firings were performed on June 24 2010. The first firing sequence 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 2.1cm/s ΔV increase. The propellant consumption for the maneuver was nominal. The HPGP propulsion system was thus declared ready for operations.

VI. Fired Sequences

More than 200 firing sequences have now been performed in orbit, consisting in total of more than 34,000 pulses with an accumulated firing time of 2.3 hours. Each firing sequence has contained between 1 and 500 pulses. The HPGP propulsion system has been operated in the following operational firing modes:

- Quasi Steady-State (Continuous firing)
- Pulse Mode (Duty factors between 0.15 to 50%)
- Off-Modulation (Duty factors between 50 to 99%)
- Single Pulse (Single pulses or very low duty factors).

The in space fired sequences, which map the characteristics of the 1 N thruster, are demonstrated in Figure 2.

The operational box is limited to a minimum T_{ON} of 50ms at low duty by the command time of the thruster’s driver electronics. At low T_{ON} but high duty, restrictions of the 1Hz command time of the onboard system unit are encountered. Due to satellite momentum management, firing sequences exceeding a total impulse of 30Ns are generally not permitted. This implies that single pulses are restricted to approximately 30 seconds at BOL or approximately 120 seconds at EOL. Below the blue solid line the duty cycle is so low that the thruster is essentially operating in single pulse mode.

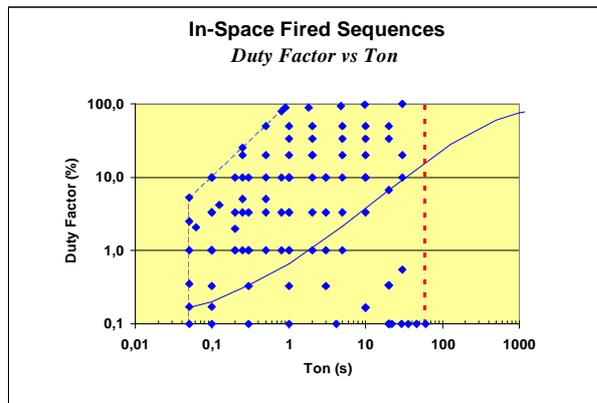


Figure 2. In-Space HPGP Fired Sequences

VII. In-Space Performance Measurements

The thruster performances that can be characterized in space are thrust, I-bit, specific impulse and density impulse. Other performances such as thrust roughness and pulse centroid delay have been previously characterized by firing on ground in a near vacuum environment.

A Thrust

The thrust is derived from the calculated spacecraft mass and the acceleration of the spacecraft in the axis of the thruster. The thrust is also determined from the generated ΔV calculated by the onboard GPS, in conjunction with the commanded thrust time and the average spacecraft mass.

B Acceleration

The acceleration is measured with two different methods during the firings a) via onboard accelerometers and b) onboard GPS. The first method uses the onboard accelerometers to obtain an acceleration component in the axis of the firing thruster. The second method uses the onboard GPS to calculate a total ΔV for the maneuver. The total commanded thrust time obtained from the onboard system unit is then used for calculating the total acceleration.

The accuracy of the two acceleration methods is often affected by the nature of the firings such as the commanded pulse length, duty factor and whether the maneuver was in along or cross track. Therefore the acceleration from the accelerometers is cross-referenced with the GPS acceleration to obtain the most accurate assessment of the acceleration.

C Specific Impulse

Neither the HPGP nor hydrazine propulsion systems are equipped with mass flow rate meters, however the

satellite mass is determined in static conditions before and after each firing sequence. Since the commanded thrust time is known, the mass flow rate of the thruster can be calculated for any sequence. Specific Impulse is established from the thrust and the mass flow rate. The onboard system unit records the satellite's conditions with a sampling rate of 1Hz, and hence the satellite mass, the thruster force and specific impulse is calculated and updated every second during an experiment.

D. Measurement Process and Accuracy

The I-bit is determined from the thruster firing time and the calculated thrust. The spacecraft mass is calculated as the sum of the spacecraft dry mass plus the propellant masses in the HPGP and hydrazine tanks. The propellant masses are calculated via the Ideal Gas Law and density changes, using the propellant temperatures and pressures within the tank volumes.

The calculation of the propellant mass is subject to errors which arise from inaccuracies in the sensor performance as well as errors in the processing chain that converts the raw sensor data into a calibrated output signal.

For example the pressure transducer accuracy is dependent on its current operational pressure and its current temperature. The output signal, which is amplified and sampled using a digital to analogue converter, is also subject to inaccuracies. Further errors are also introduced when the digital output is equated to a measured output pressure using a calibration curve. Since errors are propagated through each stage of the measurement chain, a final Root Mean Square (RMS) error is associated to the performance of each onboard sensor.

Analysis has been carried out that indicates that the pressure transducers have a relative error of 1.3%, the temperature sensors has a relative error of 3.9% and for accelerations greater than 1 second the accelerometers provide an error of approximately 2.5%.

Since the propellant mass is determined from the measured temperature and pressure, it was estimated that at 16 bar of propellant feed pressure a propellant mass throughput of approximately 3.5g was required to achieve an accurate propellant flow and therefore accurate Isp. This throughput was achieved by firing a single pulse, for example, for a total on time of at least 10 seconds.

Similarly at 8 bar a propellant throughput of 6.5g was needed to ensure that the Isp was calculated accurately.

This was approximately equivalent to a 20 second steady state pulse.

IX Demonstrated Performance

The HPGP thruster performance measured in-space is coherent with the measurements performed on ground in the near vacuum test stand. The detailed results from the in-space demonstration are given in [1] and summarized below.

A Steady-State Isp

The steady state Isp is plotted as a function of pressure. The Isp decreases with pressure due to the blow down operation of the system. Ground test data, (red) provide performance values at minimum and maximum operational pressures. Flight data (blue), demonstrates coherency to ground test data at similar pressures.

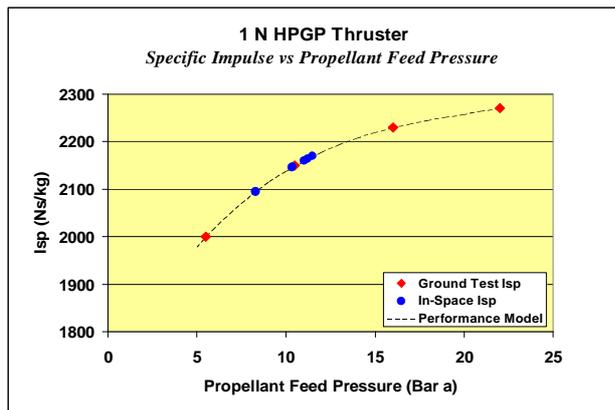


Figure 3. Steady-State Isp

B Single Pulse Isp

The variation in specific impulse in single pulse operation as a function of T_{ON} is shown below.

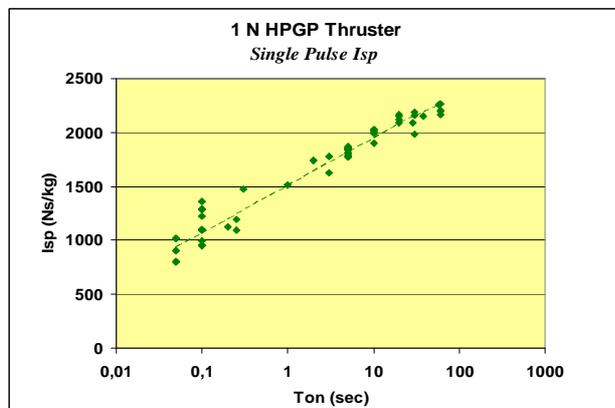


Figure 4. Single Pulse Isp. First half of the mission.

The flight data is obtained from all operational pressure ranges. Most PRISMA formation flying maneuvers are executed using small to large single pulses.

C Pulse Mode Isp

The variation in Specific Impulse in pulsed operation as a function of propellant feed pressure and duty cycle is shown below. The performance of each pulse is taken at thermal equilibrium. The relationship between Isp and duty is provided at 3 different pressure ranges: a) high pressure of 17.5-15 bar (red), b) 12-10 bar (green) and c) 9.3-7.7 bar (blue). At high duty, the thruster operates at near steady state performance, where as at low duty the pulse chain performance tends towards single pulse performance.

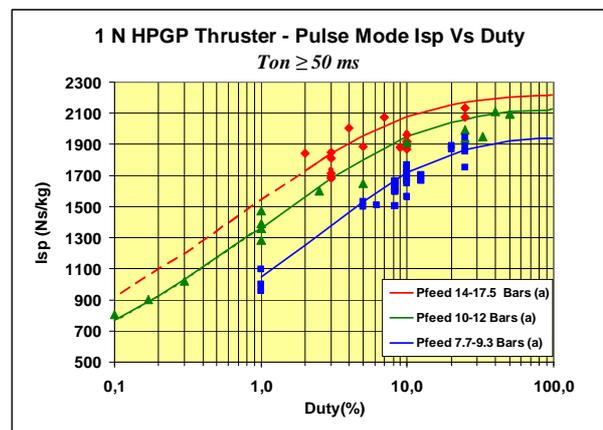


Figure 5. HPGP Pulse Mode Isp

VII. Comparison with Hydrazine

Back-to-back in-space comparison between the HPGP and hydrazine propulsion systems shows significant Isp and density impulse improvements for the HPGP. The comparison is performed at comparable thrust levels and results summarized in Table 1.

Table 1 HPGP Performance vs Hydrazine	
Steady-State Firing: I _{sp} for last 10 s of 60 s firings	6-12 % Higher Isp than Hydrazine 30-39 % Higher Density Impulse than Hydrazine
Single Pulse Firing: T _{on} : 50 ms – 60 s (First half of the mission)	10-20 % Higher Isp than Hydrazine 36-49 % Higher Density Impulse than Hydrazine
Pulse Mode Firing: T _{on} : 50 ms – 30 s Duty Factor: 0.1 – 97%	0-12 % Higher Isp than Hydrazine 24-39 % Higher Density Impulse than Hydrazine

For Steady-State the improvement in HPGP Isp over hydrazine is 6% at BOL and 12% towards EOL. Due to the spacecraft system limitations, pulses or pulse sequences are restricted to 30 Ns and hence the obtained performance can be considered quasi steady state.

For Single Pulses the improvement in HPGP Isp over hydrazine is 10% at BOL increasing to 20% towards EOL.

For Pulse Mode at very low duty and low propellant feed pressure, the HPGP performance is comparable to the hydrazine performance. However at BOL propellant feed pressures and for duty factor above a few percent, the HPGP performance can be up to 12% better than for hydrazine.

A theoretical improvement of 6% was expected between HPGP and hydrazine performance, however the back to back in space comparison demonstrates higher performance in most cases. When validating the results, all HPGP and hydrazine calculations were evaluated by the same process.

I X Future Small Satellite Missions

Future small satellite missions will benefit from HPGP due to its improved density impulse over hydrazine and significantly simplified pre-launch activities. From a performance perspective the HPGP system is able to offer approximately 36% more propellant than hydrazine for any mission ΔV . This allows more margin to be added to the mission lifetime, a larger ΔV to be executed or a reduced tank size of the propulsion system, all of which are important criteria for any small sat mission.

The environmentally benign nature of LMP-103S enables significantly simplified transportation, handling and storage of the propellant as compared to hydrazine. As the first and only flight-proven, storable “green” propellant available, HPGP systems will allow future satellite missions to meet more stringent environmental restrictions. Additionally, with significantly reduced man-hours and minimal protective equipment for a HPGP fueling team, operations with LMP-103S can reduce preparation time and cost for all pre-launch activities. Simplified ground operations are particularly attractive to help reduce the costs for small satellite missions. Furthermore, in light of the shorter timelines which are able to be achieved (due to simplified transportation and launch campaign ground operations), HPGP systems also provide important benefits to satellite missions which require increased “responsiveness”.

Several PRISMA like 1N HPGP systems are already base lined or considered for near term small satellite missions [5]. These spacecraft will be equipped with either three to four 1N thrusters and 5.5 kg of propellant, or eight 1N thrusters and 11kg of propellant.

1N HPGP systems have also been baselined for medium size (up to 1,000kg) satellite missions. These propulsion systems are typically equipped with eight 1 N thrusters and will carry ten times the propellant mass compared to PRISMA. The HPGP systems will be used for orbit raising, orbit correction and plane changes.

The 1N HPGP system is ideal for propulsion modules which can be attached to small satellites and cubesats for either orbit raising or de-orbit operations.

Finally, the low-hazard nature of HPGP systems makes them ideal candidates for spacecraft that will launch as “secondary” payloads (such as ESPA-class satellites) which cannot interfere with or increase the risk to the primary spacecraft.

X. Conclusions

After one year in space the demonstration of the first High Performance Green Propulsion system has been successfully completed and all planned objectives and goals have been met. As a result, HPGP has now achieved flight proven status – and is planned for implementation in a variety of upcoming missions.

The HPGP technology has been demonstrated as an enabling technology for improved performance and enhanced volumetric efficiency. Results show that the HPGP system has 6% to 12% higher steady state specific impulse and 31% higher density impulse than the hydrazine system. For single pulses a performance improvement of 20% Isp can be achieved with HPGP and in pulsed mode operation performance improvements up to 12% are achievable compared to hydrazine.

For small satellites the HPGP propulsion system has about a 32% higher ΔV capability over hydrazine. In addition the propellant loading is simpler, less time consuming and significantly less hazardous.

The 1N HPGP system has already been baselined in a medium sized satellite mission, operating in steady state and single pulse mode for orbit raising and orbit maintenance. Other possible roles for the 1N HPGP system include orbit transfer, plane changes, and as an attractive solution for de-orbiting due to the environmentally benign nature of the LMP-103S.

Acknowledgments

This work has been performed under contract from the Swedish National Space Board (SNSB). The authors wish to acknowledge the sustained support from SNSB and SSC. The authors also acknowledge the strong support from SSC management and the effort of all co-workers in this project from ECAPS, SSC, Royal Institute of Technology, and EURENCO-Bofors. The authors also wish to acknowledge the DLR crew at the German Space Operations Center (GSOC) in Oberpfaffenhofen during the HPGP 4 operations in May 2011 and personnel at the three Ground Stations at Esrange, Weilheim and Inuvik.

References

1. Anflo, K. and Crowe, B., "In-Space Demonstration of an ADN-Based Propulsion System", 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, San Diego, 31 July – August 3, 2011
2. Prokrupa, N. and Anflo, K., "Spacecraft System Level Design with Regards to Incorporation of a New Green Propulsion System", 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, San Diego, 31 July – August 3, 2011
3. Anflo, K. and Crowe, B., "First Results from the In-Space Demonstration of a Green Propulsion System", IAA 50th Anniversary Celebration Symposium on Climate Change / Green Systems, Nagoya, 20-21 August, 2010
4. Anflo, K., Crowe, B., Persson, M., "The First In-space Demonstration of a Green Propulsion System", 24th Annual Conference on Small Satellites, Logan, 9-11 August, 2010
5. Lange, M., Holtzwarth M., Schulte G., Peukert M., Feindt O., "Feasibility Study and Performance Assessment of a Myriade Propulsion Module with an ADN based Green Monopropellant", 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Nashville, 25-28, 2010
6. Anflo, K., Crowe B., Persson S., "Launch and Early Operations of the First In-space Demonstration of a Green Propulsion System" Space Propulsion, 3 - 5 May, 2010, San Sebastian, Spain
7. Anflo, K., et al., "Flight Demonstration of New Thruster and Green Propellant Technology on the PRISMA Satellite", SSC07-X-2, Annual AIAA/USU Spacecraft Formation Flying Missions & Technologies, St-Hubert, Québec, 18-20 May 2011
8. Larsson, R., et al., "Autonomous Formation Flying in LEO", 4th International Conference on Spacecraft Formation Flying Missions & Technologies, St-Hubert, Québec, 18-20 May 2011
9. Larsson, R., D'Amico, S., Noteborn, R., Bodin, P., "GPS Navigation Based Proximity Operations by the PRISMA Satellites – Flight Results.", 4th International Conference on Spacecraft Formation Flying Missions & Technologies, St-Hubert, Québec, 18-20 May 2011
10. D'Amico, S., Ardaens, J.-S., Larsson, R., "In-Flight Demonstration of Formation Control based on Relative Orbital Elements", 4th International Conference on Spacecraft Formation Flying Missions & Technologies, St-Hubert, Québec, 18-20 May 2011
11. Nylund, M., et al., "SATSIM and Advanced Real-Time Multi Satellite Simulator Handling GPS in Closed Loop Tests", 4th International Conference on Spacecraft Formation Flying Missions & Technologies, St-Hubert, Québec, 18-20 May 2011
12. Noteborn, R., Bodin, P., Larsson, R., Chasset, C., "Flight Results from the PRISMA Optical Line of Sight Based Autonomous Rendezvous Experiment", 4th International Conference on Spacecraft Formation Flying Missions & Technologies, St-Hubert, Québec, 18-20 May 2011
13. Delpech, M., et al., "Formation Flying experiment based on Radio Frequency sensor: lessons learned and perspectives for future missions", 4th International Conference on Spacecraft Formation Flying Missions & Technologies, St-Hubert, Québec, 18-20 May 2011
14. Guidotti, P.Y., et al., "Flight results of the FFIORD Formation Flying experiment", 4th International Conference on Spacecraft Formation Flying Missions & Technologies, St-Hubert, Québec, 18-20 May 2011
15. Persson S., "Launch and Early Operations of the First In-space Demonstration of a Green Propulsion System" Space Propulsion, 3 - 5 May, 2010, San Sebastian, Spain
16. Hellman H., Persson S., Larsson B., "PRISMA – A Formation Flying Mission on the Launch Pad" IAC-09- B4.2.4