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Lessons learnt from operating the first Cubesat mission equipped with a Hall thruster

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ABSTRACT

Only a few electric propulsion solutions on-board small satellites have been operated in space, even if propulsion is nowadays seen as one of the most important subsystems for the future of small satellites. Exotrail demonstrated its Hall Effect Thruster propulsion solution in space at the end of 2020. It was the first Hall thruster ever flown onboard a satellite weighing below 100kg of mass, while also being the only known permanent magnet Hall Thruster demonstrated in space. Operations of small satellites with propulsion is a novel field and the behavior of such thrusters in space still brings new challenges.

Exotrail developed its ExoMG™ propulsion system demonstrator between November 2018 and September 2019, when the flight model was delivered to the small satellite manufacturer NanoAvionics. The satellite was eventually launched in November 2020 and following the commissioning of the platform, the thruster was conditioned and subsequently fired. These two last steps will be detailed.

The propulsion system consists of the propellant storage and regulation system, the control and power electronics, the actual thruster consisting of an anode and a cathode and a mechanical and thermal interface. It is operated through Exotrail's ExoOPS™ - *Operations* software. The different subsystems will be described as well as their interaction. Each of them has many observables that will be detailed and discussed – typically temperatures, voltages.

The operations software enables the monitoring of the orbital parameters, the maneuver generation, the housekeeping of the propulsion unit and the preparation of the maneuvers. It will be briefly described as it is the main software tool to understand the behavior of the thruster.

The commissioning operations of the propulsion unit are firstly focused on health check and controllability of the environmental parameters. Then a health check of the active parts of the propulsion is performed. Finally, the firing sequence is initiated. The different steps, the expected and actual results will be presented and discussed.

Finally, we will present the performance estimation of our propulsion unit. Thanks to our on-board GPS data, we perform maneuver restitution and we compare the in-flight performance with ground tests.

DESCRIPTION OF THE PROPULSION UNIT

Electric propulsion for small satellites

The propulsion subsystem for a satellite is critical to deliver high quality services. Propulsion have historically been falling in three categories: solid, liquid and electrical. The first type of propulsion, solid motors, are mainly used to provide short and powerful boosts [1]. This technology is used for rockets, but also for high-ΔV impulsive maneuvers. Liquid propulsion is the most used in the satellite industry [2]. Liquid thrusters rely on a one or more liquid propellants to generate gas in a nozzle and provide a thrust. Complex bi-propellant thrusters are used to perform orbit raising and simpler monopropellant thrusters are used for station-keeping and other low-ΔV maneuvers [3]. Finally, electrical propulsion, though used for a long time on Russian satellites, emerged in the last two decades as the breakthrough in propulsion both for orbit raising and station-keeping, but also for interplanetary missions [4] [5].

The main advantage of electric propulsion is its high fuel efficiency with its specific impulse in the range of 500 to 5000 seconds. However, the achievable thrust with those systems is typically orders of magnitude lower than their solid or liquid counterparts. It produces thrust by ionizing a gas and accelerating the newly created ions to very high velocities. The energy required for ionization comes from the electrical power system of the satellite – solar panels and batteries.

For small satellites, propulsion is still a major technical challenge. When for satellites weighing more than 100 kg some solutions exist, there are only very few commercial solutions for satellites of less than 100 kg.

Exotrail is developing and commercializing propulsion units based on the Hall Effect technology. This technology is used for its high thrust-to-power ratio, within the realm of electric propulsion. It enables to perform maneuvers to position the satellite in its revenue-generating orbital position, and this quicker than other electric technologies. It has been used since the 70's in Russia for satellites with an available electrical power of around 1.5 kW. Since then the development of Hall Effect Thrusters (HET) have been targeting bigger and bigger satellites with major developments targeting 5 kW and 20 kW thrusters. But lately, a major focus driven by the increasing adoption of small satellites was to create thrusters for satellites with an electrical power of typically 500 W [6].

Exotrail's thrusters are in the range of 50 – 200W per unit. With a clustering capability, the adressable range of electrical power ranges from 50 to 800 W. This is the commercially available HET with the lower power. The commercial product is called ExoMG™. It relies on a highly modular architecture and thus can be integrated easily. The propulsion system has all the subsystems to be used in a platform with regular interfaces.

Other technologies use other physical means to ionize gases and have different specific impulse and different thrust-to-power ratio. These other technologies typically tend to produce higher specific impulse but lower thrust-to-power ratio than the Hall Effect technology.

Propulsion unit based on a Hall-Effect Thruster

The Hall-Effect technology relies on the ionization of a gas in a chamber with significant magnetic and electrical fields thus accelerating the ions in one direction and creating thrust. Figure 1 shows the principle of an HET: an external cathode provides electrons to start a discharge in the discharge channel formed by ceramic walls – typically Boron Nitride. An anode feeds xenon gas and, at the same time, attracts the electrons. The xenon is ionized by the flux of electrons from the cathode to the anode. The interaction of the electric field created between the anode and the cathode and the magnetic field generated around the ionization chamber accelerates the ions. These ions are neutralized by electrons emitted by the cathode in the downstream region.

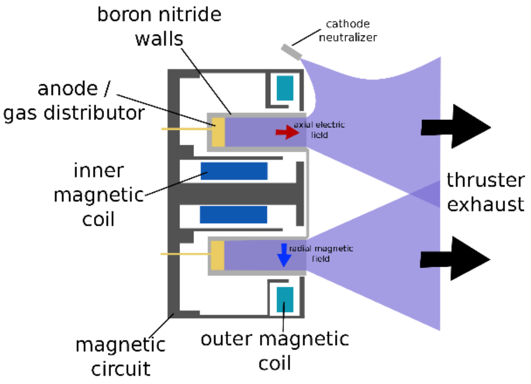

Figure 1: Hall-Effect Thruster Schematics

The typical performances of such thrusters are:

- Thrust-to-power ratio: 40 to 60 mN/kW
- Specific impulse: 500 to 2000 seconds

For electric propulsion technologies, Hall-Effect thrusters have a relatively low specific impulse, but given their high efficiency, their thrust-to-power ratio is the best-in-class. It enables them to perform rapid maneuvers to deliver the satellite where it generates revenues. Thus, HETs are used for most of all-electric satellites: from massive telecommunications satellites in the geostationary orbit to the smaller satellites build for mega constellations [7].

Overview of the propulsion unit

This ion generator and accelerator is one of the key parts of Exotrail's product. It is called the thruster head. To properly control this thruster head, subsystems must be added and are shown on Figure 2:

- **A tank to store the xenon propellant**: the black tank can be customized to store the required amount of gas the mission,
- **A propellant management system**: pressure regulation and mass flow control systems within the blue-capped module,
- **A power processing unit and a control unit**: both boards are in the electric box below the gas management system.

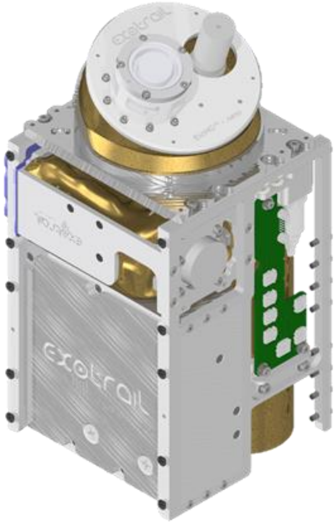

Figure 2: Typical layout of a propulsion unit

The bundle of the thruster, the propellant management system, the power processing unit, and the control unit is a propulsion system. This propulsion system can be easily integrated on any satellite with typical interfaces. These interfaces are:

- Power supply in between 6 and 34 V and a current of 3 – 12 A,
- Data link with the satellite in CAN, RS485, etc.
- Structural and thermal link.

To simplify the use of propulsion, the product takes care of:

- Storing the propellant and delivering it with the good mass flow,
- Converting the unregulated power to the higher voltage power required to operate the thruster,
- Control both the power supply and the propellant management system from simple, highly configurable commands,
- Thermal management of the thruster head which rejects minimal thermal flux to the inside of the satellite.

IN-ORBIT COMMISSIONING OF THE THRUSTER

Launch and early operations

Exotrail contracted with NanoAvionics to provide a platform, to launch it and to operate the satellite for a technical demonstration of its thruster. The Lithuanian satellite manufacturer provided its M6P platform.

The mission is named R2 and the satellite has been integrated in Fall 2019 with an ExoMG™ prototype provided by Exotrail and another payload for technology demonstration too.

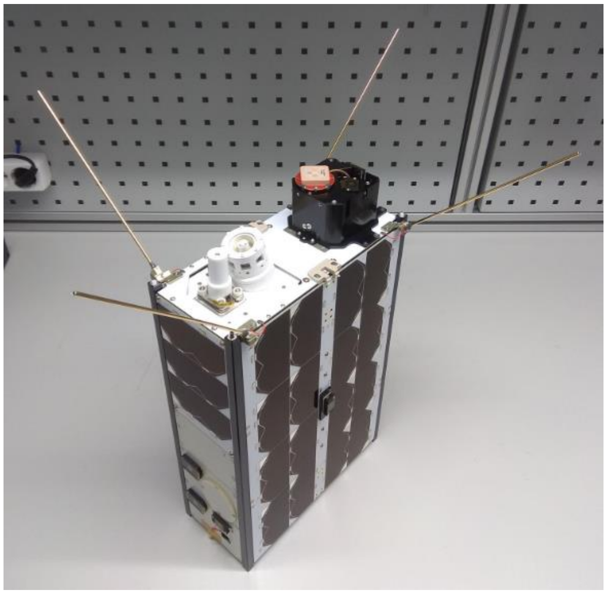

Figure 3: Propulsion unit as integrated inside the R2 satellite

The launch was delayed due to the COVID outbreak and subsequent closure of the launch base, leading to a shelf storage of one year for the satellite and the propulsion unit.

The launch happened on Nov. 7, 2020 from Sriharikota, India. The PSLV launcher injected R2 in an orbit with the following characteristics:

- Altitude of 571 km,
- Inclination of 36.9°,
- Eccentricity of 0.001.

The satellite is tracked since Nov. 13, 2020 by the 18th Space Control Squadron which provides tracking data on the www.space-track.org website. This data was used to establish the first contact with the satellite and start the operations on the satellite.

From Nov. 13 to early December, the satellite was commissioned by NanoAvionics. All platform subsystems have been checked and configured in their nominal status. By Dec. 4, 2020, Exotrail was able to routinely use the satellite to test the propulsion unit.

The following sequence is followed prior to the first ignition attempt:

- Status checks of the passive components: thermal behavior, tank pressure…
- Active checks of the critical subsystems: mass flow control and power converters.

All plots shown after are taken from ExoOPS™ - *Operations*, the software developed for operations of complete satellite systems by Exotrail which is presented in the last section.

Status checks

The propulsion unit is powered from the satellite power conversion and distribution unit (PCDU), controlled by the on-board computer of the satellite. This PCDU provides the 3.3V, 5V and 12V lines, necessary for this version of the ExoMG™, to the control unit which distributes the power to the other subsystems.

Once the control unit is powered from the 3.3V line, it starts to generate data. This data is collected by a payload controller through a CAN bus.

The values which are gathered by the control unit are:

- Status: uptime, software mode, data generation frequency…
- Thermal housekeeping: temperature of the electronics, the fluidic subsystem, the thruster head…
- Electrical housekeeping: voltages and currents at the input and the output of the electronics, from the satellite PCDU to the thruster head and sensors,
- Fluidic housekeeping: pressure inside the tank, after the pressure regulator…
- Last command sent and thruster head observables: thrust, voltage and current to the thruster, mass flows…

More specifically, temperatures are taken from, with redundancy:

- The two electronic boards,
- The two tanks,
- The mass flow controllers,
- The thruster head holding plate,
- And the plasma generator.

The first operation performed on the propulsion unit was to power it for 3 days to gather thermal data. This data enabled us to confirm the thermal model and validate the concept of operations regarding the thermal behavior of the thruster head. Figure 4 and Figure 5 show the temperature of the electronics and of the thruster holding plate during the status checks. The values between -5°C and +15°C are well within the operational range, confirm the thermal model and validate the concept of operations with regards to low or high base temperature firings.

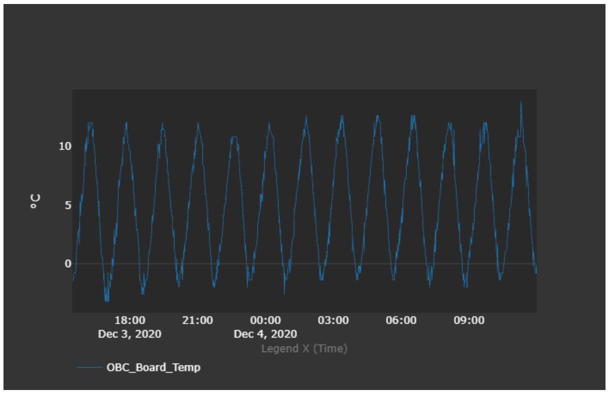

Figure 4: Temperature of the electronics during the status checks

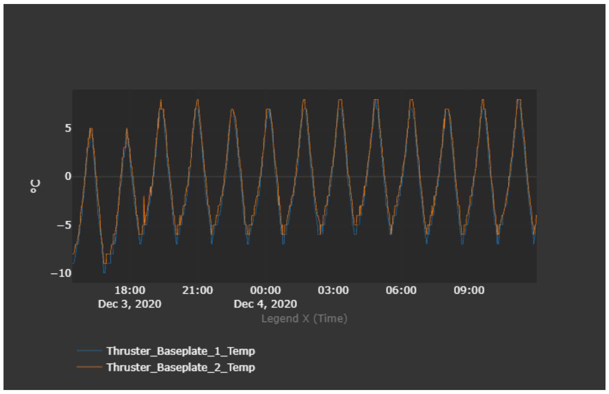

Figure 5: Temperature of the thruster head during the status checks

In addition to the thermal validation, we also monitored the pressure inside the tanks to assess possible leaks during launch. Figure 6 shows the evolution of pressure within the tanks during the status checks. The amplitude of the oscillation is less than 10% of the mean value.

The propellant quantity stored in the tanks is computed thanks to the knowledge of the volume, the pressure, and the temperature of the tanks. The mass of propellant is then computed with information from the National Institute of Standards and Technology.

The mass of propellant before and after the launch were as expected and did not show any leak due to the launch.

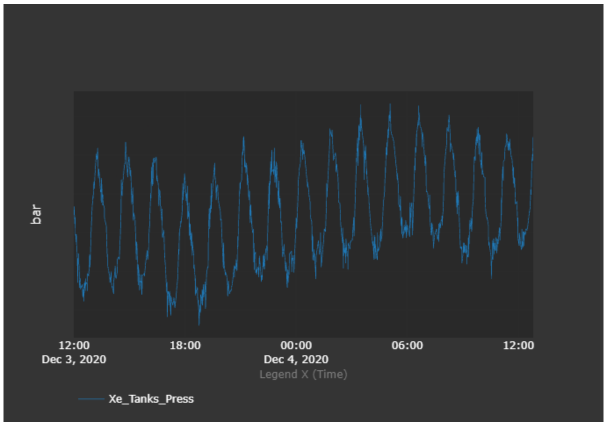

Figure 6: Pressure inside the tanks during status checks

First firing

To fire the thruster, fluidic control and electronics must be controlled. The first subsystem to be controlled is the mass flow regulation. Figure 7 shows the schematics of the fluidic system. Both lines, respectively for the anode and for the cathode, were tested.

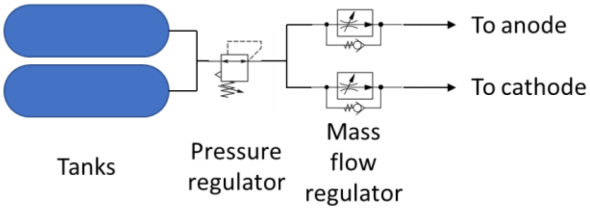

Figure 7: Fluidic system schematics

The mass flows are regulated independently one from the other. Figure 8 shows the mass flow going to the cathode first, then to the anode. Both flows are within the acceptable margins.

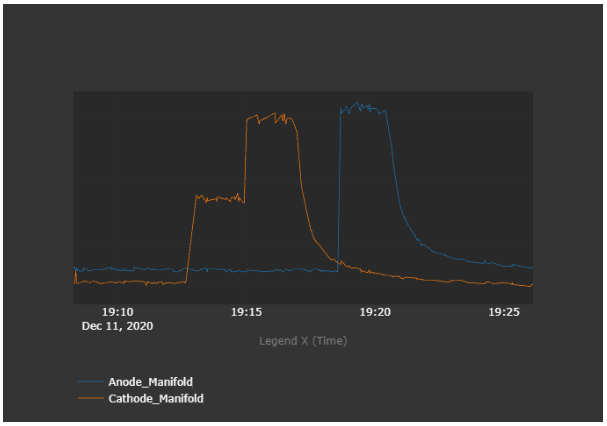

Figure 8: Cathode and anode mass flows tests

After this fluidic test, the power converter is tested. The cathode heater converter is tested first. The cathode is heated thanks to a moderate current between 4 and 5 A for a short duration. During this period, the voltage is also monitored to check that the heater characteristics have not drifted during launch. Figure 9 shows the voltage and current fed to the cathode. The ratio between the two (the nonlinear resistance of the heater) is nominal.

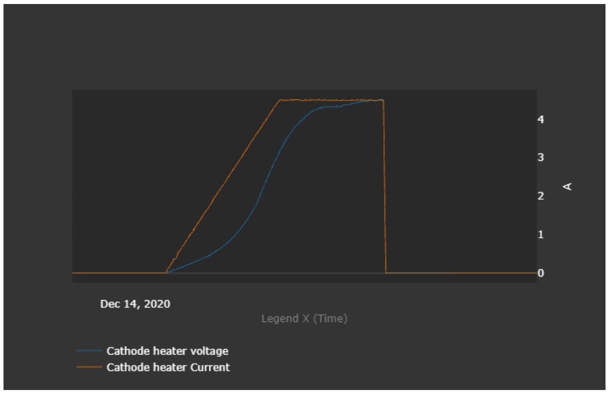

Figure 9: Cathode heating during checks

Finally, before attempting the first ignition, the anode converter is tested. It supplies high voltage to the thruster head to start and sustain the plasma. For the test, it was set to 400V as shown on Figure 10. The sensing at the output of the converter shows a nominal value.

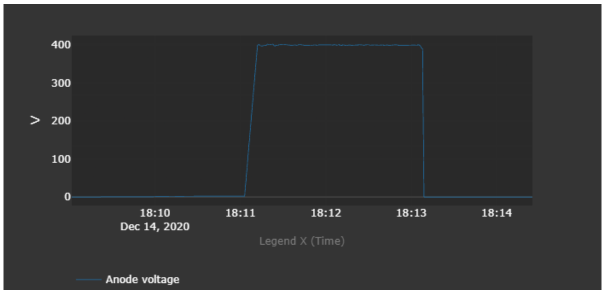

Figure 10: Discharge voltage during checks

After these final status checks, the propulsion unit was deemed ready to perform the first firing attempt.

This first firing attempt was nominal and resulted in thruster ignition for the commanded duration of 10 minutes.

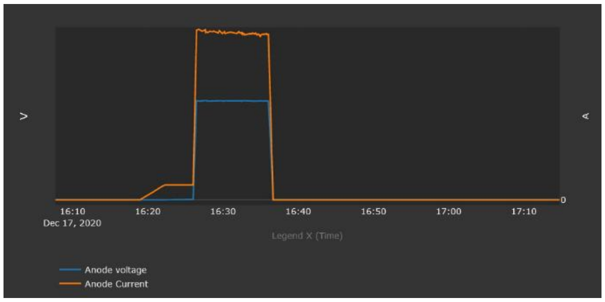

Figure 11: Current and voltage to the anode during the first ignition

OPERATIONS SOFTWARE AND PERFORMANCE ESTIMATION

Overview of ExoOPS™ - Operations

Exotrail is developping a software suite for mission analysis and operations of satellites. Historically, developments were focused on the propulsion side of the operations. Today, Exotrail is integrating all the necessary building blocks to build an operations center.

First the concept of ExoOPS™ - *Operations* will be described, then the focus will be put on on the space dynamics side of the software which enables the estimation of the performance of the thruster.

The operations of the R2 satellite are shared by three partners: Exotrail, NanoAvionics and Leaf Space. Exotrail takes care of the operations of its payload and of flight dynamics computations. NanoAvionics takes care of the operations of the platform and manages the flow of information between the three partners. Leaf Space provides their Leaf Line ground-station-as-a-service product and handle data transmission to and from the satellite.

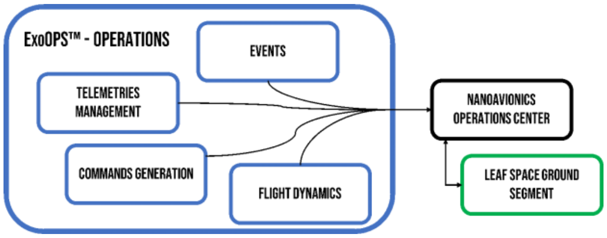

Figure 12: Schematics of the operations for the demonstration mission

ExoOPS™ is used for this mission as a payload control center and incorporates many modules used in operations and shown in Figure 12:

- **Events management**: time tagged events are computed and are displayed to the operator. They mix events linked to the platform, flight dynamics and payloads. Events are ground station passes, eclipses, firings, nodes…
- **Telemetries management**: telemetries are gathered, stored and made accessible to the operator. All available telemetries are easily accessible and sorted in customizable dashboards. Alerts and alarms can be parametrized based on their values,
- **Commands generation**: commands for the thruster, PCDU, GPS receiver and attitude control subsystems are generated directly in the software and configured for given maneuvers. Generation of commands for other thrusters, payloads or satellite subsystems can be easily integrated,
- **Flight dynamics**: the main area of expertise of Exotrail, this module covers all the required features for operations, from precise orbit restitution and propagation to maneuver design and execution.

The flight dynamics module includes an orbit determination algorithm which is used to reconstruct the orbit of a satellite from various data feeds. For this mission, GPS data is used. It also allows to monitor the performance of the thruster thanks to a maneuver estimation technique.

Satellite tracking

Historically, small satellite tracking relied on publicly available data from ground-based systems such as NORAD TLE available through various web interfaces.

This technique is very simple, and straightforward. It yields very good results in predicting ground station contacts for non-maneuvering satellites.

Yet, when a satellite is maneuvering, the NORAD TLE information may not be enough operations planning. Precise orbit propagation is implemented in the operations software and allows for the simulation of the planned maneuvers. These models are more accurate and based on the real hardware.

This precise orbit propagation enables the use of TLE even for maneuvering satellite if no other positioning data is available.

To improve the quality of the orbit determination, the use of on-board positioning data is recommended. For the R2 mission, GPS data was available and is used to perform accurate satellite tracking, even when the satellite is maneuvering.

Exotrail implemented an Unscented Kalman Filter [8] to estimate both the satellite state – position, velocity – and the model parameters. This filter is fed with data from a commercial-grade GPS receiver. This data is fused with the maneuvering plan of the satellite to better match observations and expected behavior of the spacecraft.

Figure 13 shows the evolution of the semi-major axis during a maneuvering phase. The orbit determined by the filter allows for the detection of each firing. The frequency of updates of the position and its precision are dramatically improved compared to the use of the TLE data only.

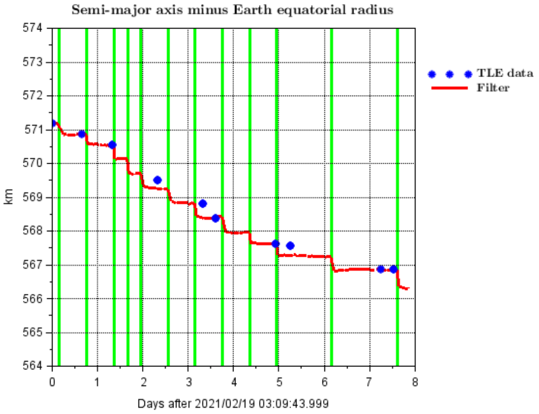

Figure 13: Semi-major axis evolution during a maneuvering phase with data from TLE (blue) or from the orbit determination algorithm(red), with the dates of the firings (green)

In Figure 14, the along-track error is plotted. This is the distance along the track of the satellite between the position estimated by the orbit restitution made from GPS data and the orbit restitution made from TLE.

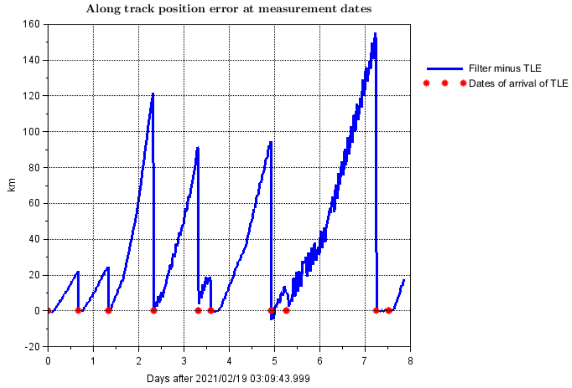

Figure 14: Along-track error between the orbit restituted by the filter and from the TLE

For a satellite orbiting at an altitude of approximately 550 km, a typical S-Band ground station need a position estimate with an along track error lower than 40 km to contact the satellite. Therefore, **the use of orbit restitution, and propagation with the right models are a necessity for the operations of small satellites equipped with propulsion.**

Performance estimation

Figure 15 shows the workflow for flight-dynamics-related events for the R2 mission. This figure incorporates all the different algorithms and building blocks (in green) and the data required (in blue) which are mastered by Exotrail.

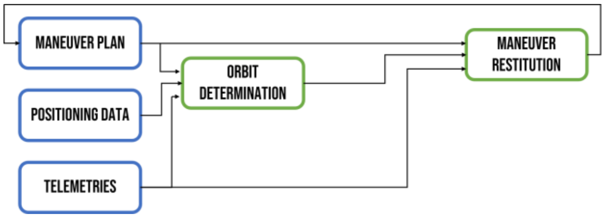

Figure 15: Workflow for orbit determination and maneuver restitution

The orbit determination must be fed with the timeline of firings to improve the model of propagation. The more accurate the maneuver parameters are, the more accurate the orbit determination will be. Therefore, it is important to estimate the actual in-flight thrust of the propulsion unit.

From the telemetries of the propulsion unit, the firing duration can be precisely assessed. Also, the attitude of the satellite during the maneuver is retrieved and processed. Along with the expected thrust, the knowledge of the actual maneuver guarantees a good *a priori* for maneuver estimation.

Then, an inverse algorithm based on the observed change in orbital elements is used. The maneuvering model used during the inversion process has been developed in-house and relies on an analytical model for low-thrust maneuvers described in [9].

Performances of the thruster have been assessed. Table 1 compares the expected thrust – as expected from ground tests [10] – with the thrust given by in-flight data for some firings. A thrust 20% higher than expected is achieved.

Table 1: Firings performance expected vs realized

Firing #	Expected thrust [mN]	Realized thrust [mN]
1	**1.8**	**2.25**
2	**1.8**	**2.15**
3	**2.4**	**2.89**
4	**2.4**	**3.02**
5	**2.4**	**3.12**

Thanks to ExoOPS™ - *Operations* we have been able to monitor and control the propulsion unit, all spacecraft information required for operations of the thruster and to perform the advanced flight dynamics computation.

The capability to automatically process in-flight-generated data, generate accurate orbit prediction and assess the performance of the propulsion unit is paramount to the success of an operational mission with propulsion.

CONCLUSION

The R2 mission was a successful demonstration of the two main products of Exotrail: its propulsion unit ExoMG™ and its operations software ExoOPS™. This marks the first time a Hall thruster is flown on a <100kg satellite and the first time a permanent magnet Hall thruster is ignited in space.

The propulsion unit has been described thoroughly, and the thruster head principles have been explained. This thruster is mainly used to position satellites thanks to its high thrust-to-power ratio.

The hardware setup for the first ignition is described and the in-flight data is shown. After successful thermal, and gas management checks, electrical tests were performed. This full functionality checks enabled to fire the thruster at the first trial. The thermal model, fluidic management concepts and overall architecture have been validated. The checklist is also confirmed.

Finally, the operations center must be designed for satellites with propulsion. ExoOPS™ is natively designed for such satellites. The use of advanced flight dynamics and precise positioning data are required to schedule communications as well as estimate thruster performance. It is also required for precise positioning for payload use.

REFERENCES

[1] K. W. Naumann, A. Weigand and A. Ringeisen, "Solid Rocket Motors for the De-Orbiting of Satellites," *Proceedings of 8th EUCASS conference*, 2019.

[2] A. Okninski, J. Kindracki and P. Wolanski, "Multidisciplinary optimisation of bipropellant rocket engines using H2O2 as oxidiser," *Aerospace Science and Technology,* 2018.

[3] A. Pasini, L. Torre, L. Romeo, A. Cervone, L. d'Agostino, A. J. Musker and G. Saccoccia, " American Institute of Aeronautics and Astronautics 1 Experimental Characterization of a 5 N Hydrogen Peroxide Monopropellant Thruster Prototype," *Proceedings of the 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Vols. AIAA Paper 2007-5465, 2007.

[4] P. Rathsman, J. Kugelberg, P. Bodin, G. D. Racca, B. Foing and L. Stagnaro, "SMART-1: Development and lessons learnt," *Acta Astronautica,* no. 57, 2005.

[5] C. Steiger, E. Montagnon, F. Budnik, S. Manganelli, A. Altay, F. Striedter, H. L. Gray, J. Bolter, N. Wallace and O. Sutherland, "BepiColombo – Solar Electric Propulsion System Operations," *Proceedings of the 36th International Electric Propulsion Conference,* 2019.

[6] V. Kim, K. N. Kozubsky, V. M. Murashko and A. V. Semekin, "History of the Hall Thrusters Development in USSR," *Proceedings of the 30th International Electric Propulsion Conference,* 2007.

[7] J. Szabo, "Explosive growth in electric propulsion," *Aerospace America,* December 2019.

[8] E. A. Wan and R. van der Merwe, "The Unscented Kalman Filter for Nonlinear Estimation," 2000.

[9] P. Lascombes and D. Henri, "Electric Propulsion For Small Satellites Orbit Control And Deorbiting : The Example Of A Hall Effect Thruster," *AIAA 2018-2729*, 2018.

[10] A. Gurciullo, J. Jarrige, P. Lascombes and D. Packan, "Experimental performance and plume characterisation of a miniaturised 50W Hall thruster," in *36th International Electric Propulsion Conference*, Vienna, 2019.