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Informing FEEP thruster design utilizing the flight heritage from 194 thrusters in LEO and GEO

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Since 2018, 185 ENPULSION NANO propulsion systems, as well as 2 ENPULSION MICRO R^3 and 7 NANO AR^3 system have been deployed in orbit on 79 different spacecraft. These missions included a variety of different satellite bus sizes ranging from 3U Cubesats to >100kg buses, and different orbits in LEO and GEO, providing an abundance of on-orbit data for statistical analysis. Hundreds of heritage NANO systems have been acceptance tested and delivered to customers. This large-scale industrialization and flight heritage allows for a holistic way of gathering data from testing, integration and operational phases, deriving lessons learnt over a variety of different mission types, operator approaches, use cases and environments. Based on these lessons learnt, a new generation of propulsion systems is developed, addressing key findings from the large NANO heritage, and adding new capabilities, including increased resilience, thrust vector steering and increased power and thrust level. This work presents flight telemetry data of ENPULSION NANO systems and onorbit statistical data of the ENPULSION NANO as well as lessons learnt during onorbit operations, customer AIT support and ground test campaigns conducted at different facilities. We discuss how transfer of lessons learnt and operational improvement across independent missions across customers has been accomplished. Building on these learnings and exhaustive heritage, we present design updates of the new generation of propulsion systems informed by the lessons learnt.

I. Nomenclature

AIT = Assembly, Integration and Test
FEEP = Field Emission Electric Propulsion
GEO = Geostationary orbit
LEO = Low earth orbit
SMA = Semi-major axis

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II. Introduction

The first NANO thruster launched in 2018 marked the first propulsion system based on FEEP technology ever to be tested in space [1] conducted together with FOTEC [2]. Since then, a total of 185 ENPULSION NANO propulsion systems, 7 ENPULSION NANO R^3/AR^3 [3] and 2 increased power ENPULSION MICRO R^3 have been launched. These propulsion systems with flight heritage are shown in Fig. 1. The ENPULSION NANO propulsion systems that have reported telemetry to ENPULSION have accumulated a collective onorbit time of > 192 years. Note that only propulsion systems that have been commissioned successfully are counting towards these accumulated lifetime numbers. A more detailed description and evolution of statistical data availability and evolution is given in Refs. 4 and 5.

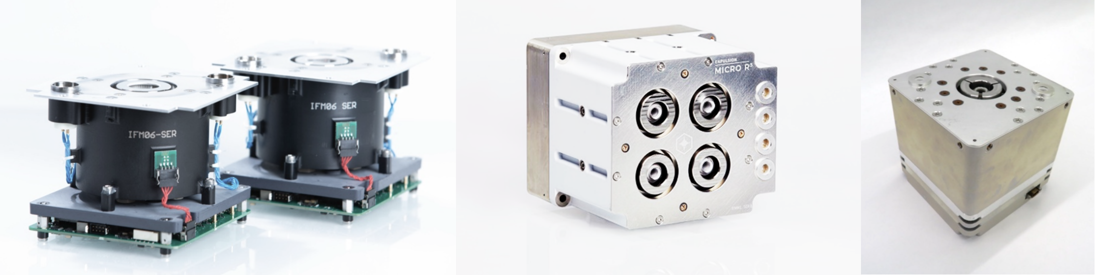

Fig. 1 FEEP propulsion systems with flight heritage: NANO propulsion system (left), MICRO R^3 (mid) and NANO AR^3 (right)

The launched propulsion systems have been used in a wide range of spacecraft platforms, orbits and applications as detailed in Refs. 4 and 5.

III. Working principle

The working principle of FEEP propulsion systems is based on generating thrust by electrostatic acceleration of metal ions, that have been extracted from a liquid bulk using high electrostatic fields applied between the metal propellant itself and a counter electrode commonly denoted extractor. In the ENPULSION FEEP systems, Indium, which is solid at room temperature during integration, AIT and launch, is liquified once in space and used as metal propellant. In order to achieve the local field strength necessary for ionization, the Indium propellant is suspended in sharp, needle like, emitter structures to leverage the field enhancing effect at the sharpened tips. When applying the high voltage potential difference, a so-called Taylor cone is established at the tip of the emitter needle, balancing the electrostatic pull and the surface tension of the liquid, further enhancing the local field strength which results in ion emission at the apex of the Taylor cone. The emitter needles are accomplished as porous structures to allow for passive propellant flow from the attached reservoir, replenishing propellant that has been emitted. To increase the total ion current, and therefore thrust, that can be drawn from the emitter structure through the established Taylor cone, multiple emitter needles are arranged in parallel, forming the so called "Emitter crown".

The extractor counter electrode is arranged in a circular fashion surrounding the ion emitter crown to allow for high transparency of the ejected ions while supporting the electrostatic field used for ion extraction and acceleration. This ion emitter geometry has a long development heritage used in different propulsion concepts for scientific missions [6] and cumulated in the design of the NANO thruster [7]. In a recent development, leveraging the spatial distribution of the emission sites around the emitter crown, the ENPULSION NANO AR^3 propulsion system was developed, the uses three different counter extractor elements surrounding the emitter crown. The electric potential of these segments can be individually controlled by the onboard electronics, allowing to throttle the ion emission from the emitter crown spatially, changing the overall thrust vector which is a sum of all individual ion emission beamlets.

IV. ENPULSION THRUSTERS IN LOW EARTH ORBIT

Analogous to the distribution of the majority of spacecraft, the majority of ENPULSION propulsion systems has been employed in low earth orbit. Telemetry of propulsion systems, as well as sample usage applications, have been discussed in Refs. 4 and 5, and are reproduced in this section. In addition, additional propulsion system telemetry parameters on the ion emitter subsections are presented.

Fig. 2 shows the time evolution of the semi-major axis of two spacecraft in LEO, each equipped with multiple heritage NANO propulsion systems. After initial natural orbit decay following deployment from the shared launch vehicle, the propulsion systems were used to increase the spacecraft orbits to their target orbit in a staggered manner to spread the spacecraft along the orbital path. After acquiring the target orbits, the NANO propulsion systems on both spacecraft were used to precisely maintain the orbits of both spacecraft to optimize their ground coverage.

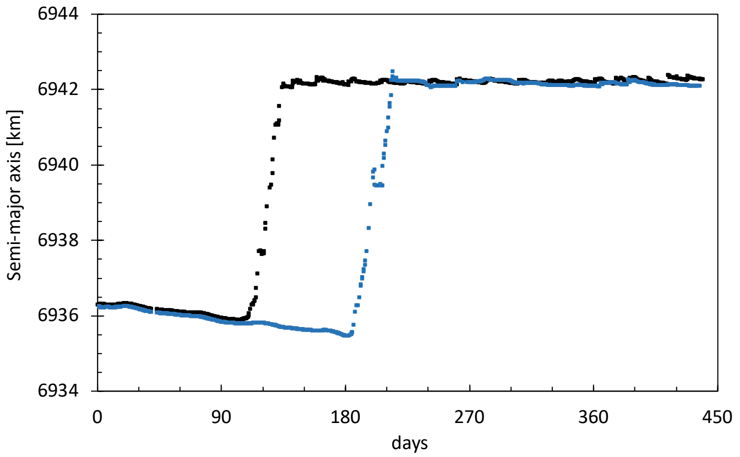

Fig. 2 Evolution of orbital parameters through propulsive maneuvers of two different pairs of spacecraft to gain and maintain the target orbits [4,5]. Data taken from Ref. 8.

Ref. 4 provided telemetry examples of NANO propulsion systems in LEO orbits performing a multitude of propulsive operations over at timeframe of over 80 hours on two propulsion systems operated in parallel at different thrust and power levels. Fig. 4 reproduces the telemetry parameters thrust and emitter and extractor voltage, while Fig. 4 expands on this by showing the corresponding emitter subsection telemetry. During the maneuver shown, the thrusters were operated at different extractor voltage settings. The ion emission current, and therefore thrust, are dependent on the total discharge voltage, that is the difference of emitter to extractor voltage. When operating in thrust or current control as in the example shown, different extractor voltage settings translate to different emitter voltage settings for constant ion current, and therefore different final ion exhaust velocities and emitter power required.

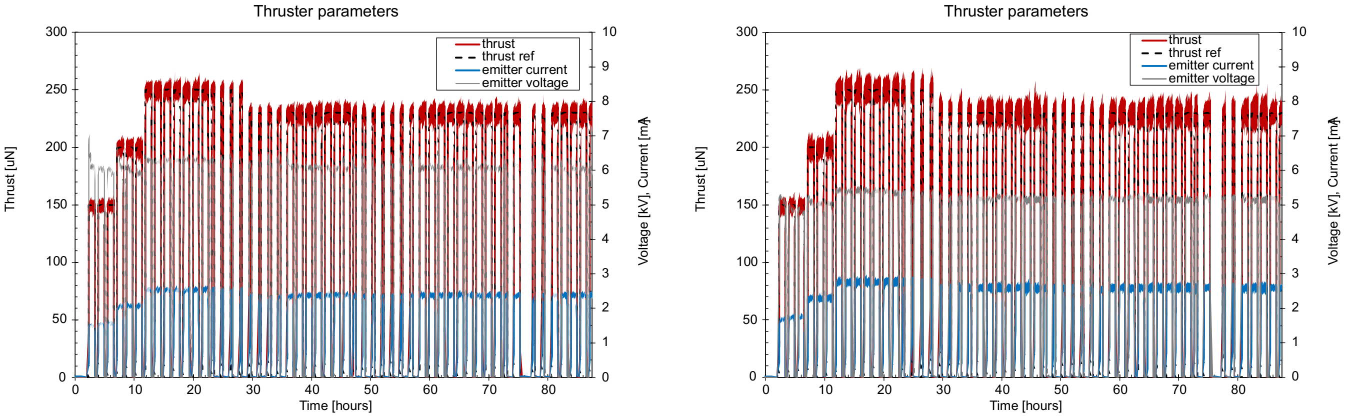

Fig. 3 Two ENPULSION NANOs used in parallel during orbit acquisition maneuver on one LEO spacecraft, operated at different thrust and power levels and duty cycles to optimize overall system [Ref. 4].

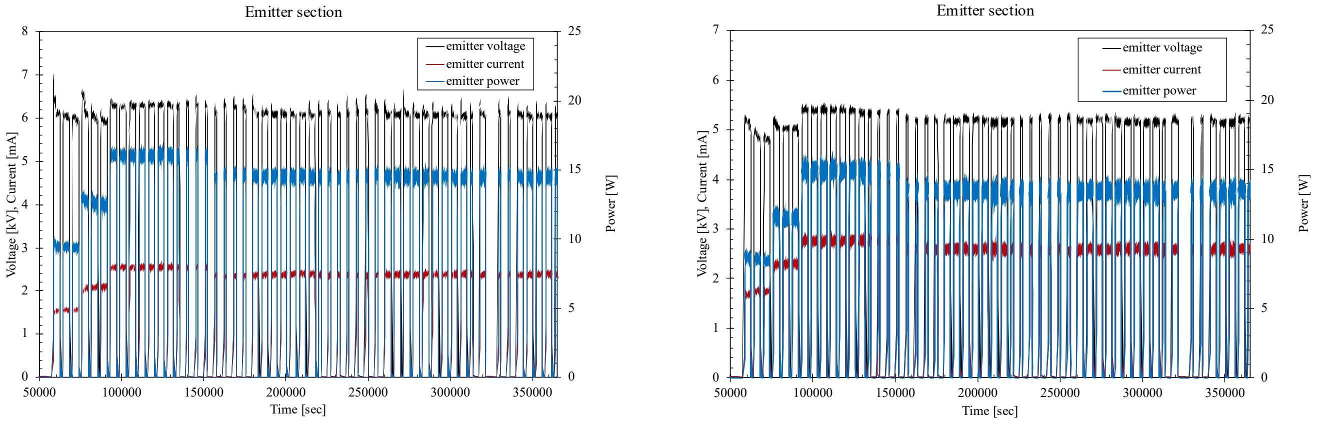

Fig. 4 Emitter and extractor voltages and corresponding emitter current.

V. ENPULSION THRUSTERS IN GEOSTATIONARY ORBIT

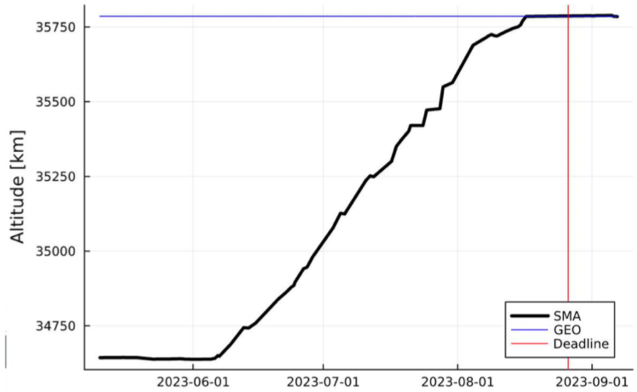

Fig. 5 Semi-major axis of a Cubesat acquiring geostationary orbit after launch using multiple AR^3 [taken from Ref. 9]

Multiple NANO propulsion systems as well as novel NANO AR^3 propulsion systems have been launched to orbits outside of low earth orbit. One spacecraft has been using multiple NANO AR^3 systems to reach the GEO slot, and for phasing between different slots and to perform momentum dumping [9]. The semi major axis change of the spacecraft during GEO acquisition is shown in Fig. 5 [9].

Thruster telemetry of three NANO AR^3 (denoted Thruster A, B and C here) are shown in Fig. 6.The data presented are low time resolution telemetry outputs with datapoints every 5-20 minutes. The plots on the left-hand side show the thrust, total system input power and ion emitter current telemetry readings during a time span of approximately 70 hours during the orbit acquisition maneuver. The right-hand side plots show the corresponding ion emitter subsection telemetry readings, including the emitter and extractor section voltage measurements. The NANO AR^3 is capable of actively controlling the resulting thrust vector by controlling the three independent extractor sections to different electric potentials. The right-hand side plots in Fig. 6 shows the voltage readings of the ion emitter, and the three corresponding extractor segments, as well as the achieved ion emitter current during multiple thrustings executed during the 70-hour time segment. Comparison of extractor voltages across different thrusters gives an indication of the different thrust vector angels commanded.

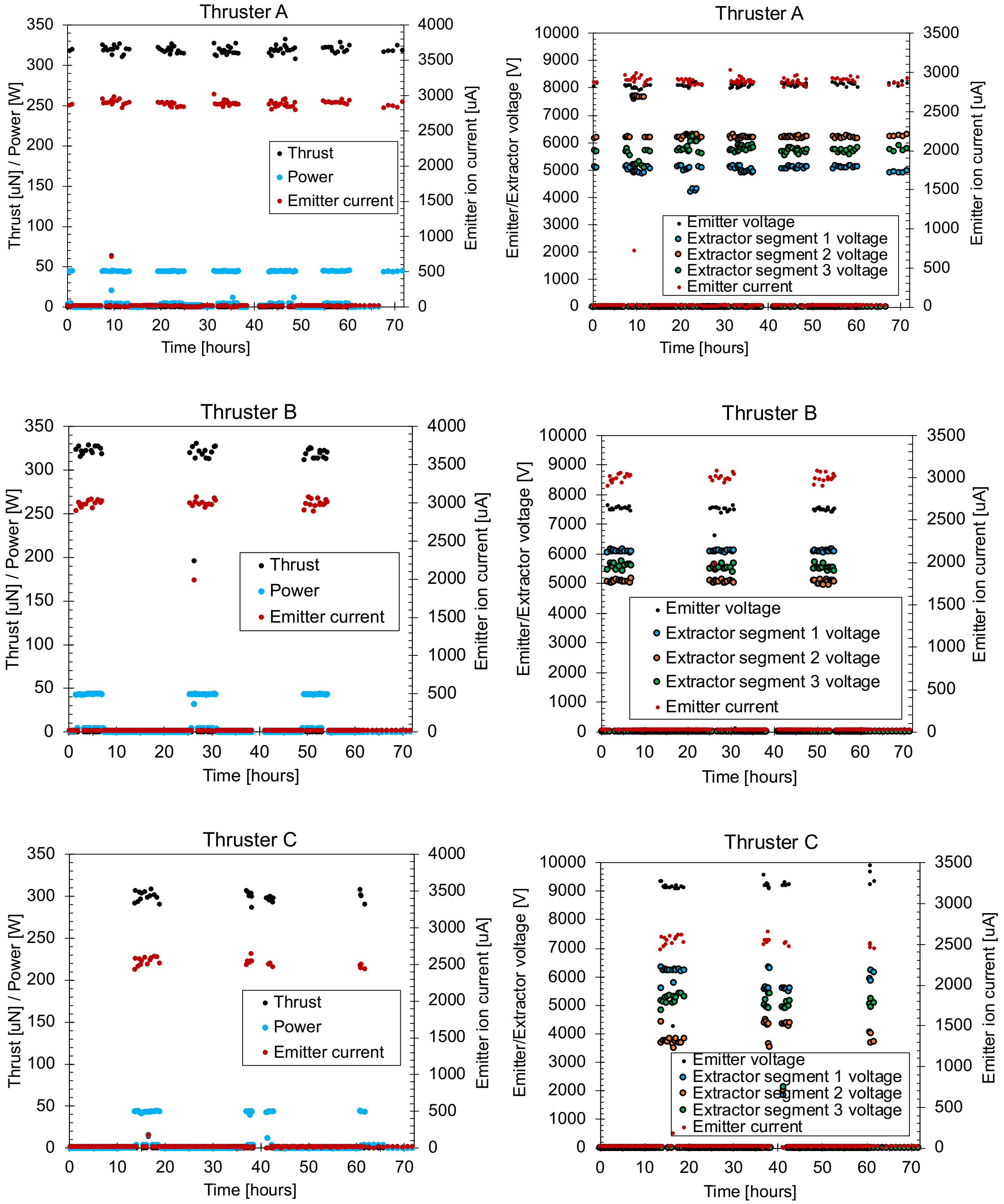

Fig. 6 Low resolution thruster telemetry of multiple firings during a 70-hour time span during the orbit acquisition. Right hand side plots show the different extractor segment voltage settings according to the different thrust vectors commanded.

The thrust vectoring capability of the NANO AR^3 propulsion systems was used to decrease momentum of the wheels during propulsive operations [9]. The decrease of momentum loading (top) during thrusting operations (bottom) is shown in Fig. 7.

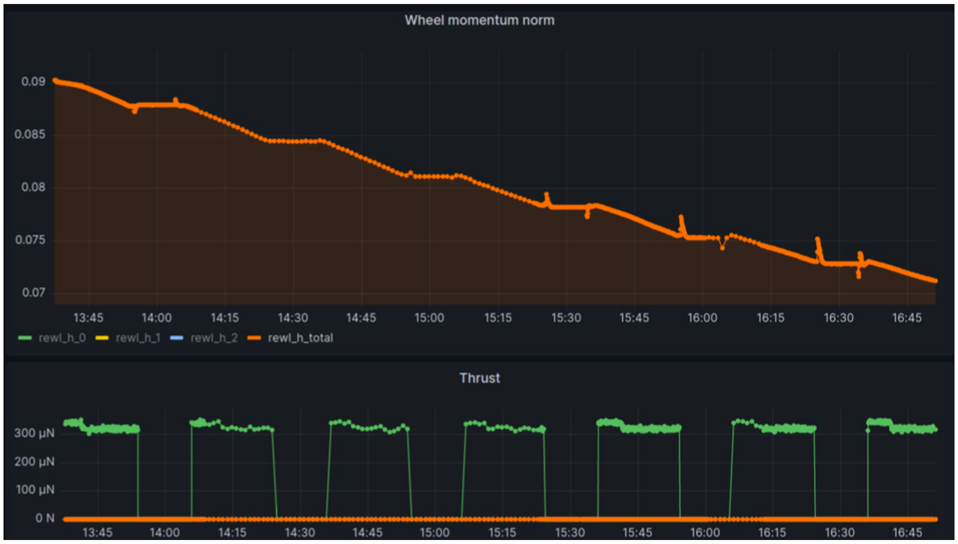

Fig. 7 Momentum dumping using the thrust vectoring propulsion system NANO AR^3 [taken from Ref. 9].

VI. FLIGHT STATISTICS

The updated launch history of the heritage NANO propulsion system is shown in Fig. 8, showing a steadily increase of on-orbit units governed by stepwise increases during popular rideshare launches in addition to dedicated launch opportunities. The data refers to the heritage NANO systems only, NANO R^3, NANO AR^3 and MICRO R^3 are not included in the data shown.

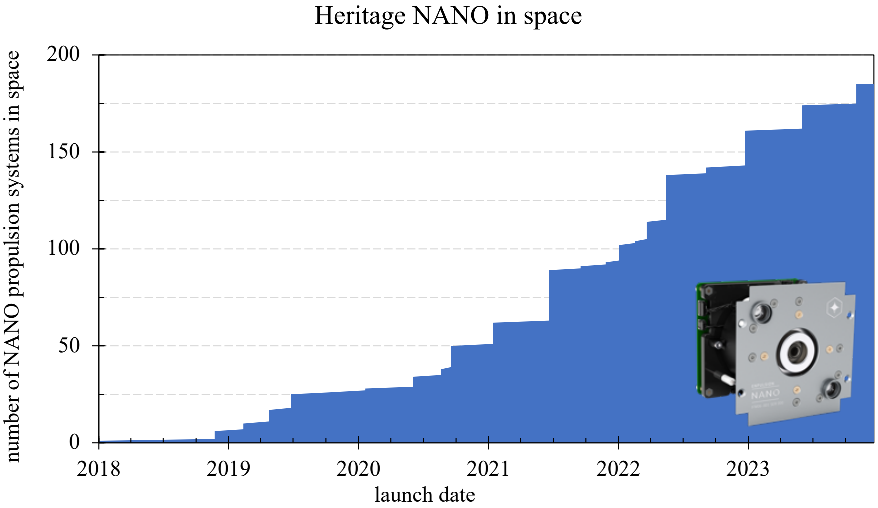

Fig. 8 Updated launch statistics of the heritage NANO propulsion system. This does not include the newer NANO R^3/AR^3 or the MICRO R^3.

Table 1 provides an update to the latest launch statistics. Spacecraft sizes range from 3U Cubesats to >100kg class ESPA satellites, and include missions in LEO and GEO. Data availability and visibility by ENPULSION is discussed in Refs. 4 and 5.

Table 1 Summary of ENPULSION propulsion systems in space as of Dec 2023.

Propulsion System	Number of s/c	Number of Thrusters	Different launches
NANO	74*	185*	22*
NANO R^3 / AR^3	4	7	4
MICRO R^3	2*	2*	2*

*Annotation: *Propulsion systems lost due to launch vehicle failures not included*

VII. LESSONS LEARNT AND PROPULSION DESIGN UPDATES

Refs. 4 and 5 discuss the lessons learnt based on the significant flight heritage, as well as customer AIT and test campaigns conducted at customer facilities.

A significant number of thrusters deployed on orbit have been subjected to use out of specification or out of the defined operational envelope as per user manual or operational recommendations, such as subjected to specific environments. These out of envelope use cases have been particularly valuable to generate lessons learnt und therefore expand the envelope of safe operations. These include operational aspects such as avoidance of repeated propellant solidification cycles without thrust maneuvers, potential contamination due to volatile outgassing from spacecraft or chamber structures, resilience against incorrect commanding, and adverse space environment aspects. Descriptions of these lessons learnt are given in Ref. 4.

A. Operational improvements across missions

Lessons learnt according to operational improvements have been successfully transferred across different missions while complying with customer confidentiality agreements, using a unified user manual. Regular updates and corresponding flexibility on user side to incorporate operational changes allowed to successfully improve operations on multiple different missions, incorporating learnings across largely different platforms and independent users. This allowed to timely address lessons learnt, including the avoidance of solidification cycles during out-of-envelope usage, commanding issues, effects of the local space environment and propellant accumulation on the extractor.

B. Informing design and design updates

Lessons learnt from flight experience have been strongly used to inform future thruster designs, as well as design updates of existing propulsion products. This includes lessons learnt regarding operation in actual space environment ranging from low earth orbits, high inclination orbits to geosynchronous orbits.

Based on the learnings from the heritage NANO thruster, the newer propulsion system generation including NANO R^3/AR^3 and MICRO R^3 have been designed to significantly reduce potential volatile contamination by preventing spacecraft venting paths, while simplifying integration. While the avoidance of solidification cycles without thrusting has been successfully addressed through operational improvements in many missions, a design update of the ion emitter propellant feed system has been successful in increasing the resilience against these out-of-envelope use cases, in addition to the operational recommendations. Similarly, the avoidance of adverse effects from local space environment and extractor cleaning is mitigated by design update. In addition to the fully updated electronics in the NANO R^3 family and MICOR R^3 systems to comply with increased radiation tolerance and reliability, a new firmware features higher level of automation to avoid command errors on subsystem level.

VIII. Conclusion

In this work we present the on-orbit statistics of the ENPULSION FEEP propulsion systems, including the launch evolution of the 185 NANO propulsion systems launched to date. We discuss use cases of heritage NANO systems in low earth orbit, and for the first time show telemetry of FEEP propulsion systems in GEO orbit, in the form of the new generation NANO AR^3 propulsion system that allows to actively control the thrust vector. We present the use case of these systems in a mission including semi-major axis increase to acquire the GEO slot after launch, as well as using the thrust vectoring feature to decrease wheel momentum. We then summarize lessons learnt through the exhaustive on-orbit heritage, and discuss resulting operational and design updates.

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