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Large number system integration aspects: on orbit data and lessons learnt from launching 144 FEED propulsion systems

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Abstract

This manuscript discusses the on orbit data availability and system integration aspects of the ENPULSION NANO liquid metal FEED propulsion systems. We present flight data from thrusters on LEO spacecraft, and present and discuss data availability from 142 NANO propulsion systems that were launched in the previous 4 years on 64 different spacecraft, ranging from 3 U Cubesats to > 100 kg platforms. In parallel, new propulsion systems based on FEED technology have been developed, expanding the thrust and power range and introducing new features, as well as lessons learnt from the large space heritage of the NANO. Two of these new propulsion systems have been launched to space so far. In this work we present telemetry of NANO operation over several hundred hours as well as aggregated on orbit statistical data of the NANO including the thrusting time over all units in space which accumulated to > 3000 h of thrusting. We then discuss challenges encountered and present lessons learnt during on orbit operations, customer AIT support and ground test campaigns conducted at different facilities.

Keywords: System integration, Flight heritage, Orbital statistics, FEED, Electric propulsion, Lessons learnt

Introduction

This work focusses on aspects of integrating, launching and operating a large number of small propulsion systems on a variety of different spacecraft platforms. Miniaturized electric propulsion has been considered as enabling technology for small spacecraft missions [1, 2] with many different technologies in development [3–7], primarily categorized in chemical and electrical systems based on the source of power for propellant acceleration. Electric propulsion systems are commonly distinguished by the nature of charged particle acceleration. Propulsion systems can be evaluated along the leading performance parameters such as thrust, specific impulse and thrust or power densities. The liquid metal Field Emission Electric Propulsion (FEED) technology discussed in this work is typically categorized at the high specific impulse and lower thrust segment of the spectrum [7]. FEED systems are based on electrostatic ionization of a liquid metal propellant in combination with electrostatic acceleration of the ions. Besides the propulsion

systems discussed in this work, this technology is also studied at the Jet Propulsion Laboratory [8, 9]. Colloidal thrusters, a technology similar to FEEP but based on liquid, colloidal, propellants, was verified in space as part of the ST7 mission [10–12]. Using ionic liquids as propellants, electrospray thrusters have shown capability for significant miniaturization in terms of size and power consumption [13], and a large variety of systems are currently in development [13–20]. These systems typically feature reduced thrust and specific impulse compared FEEP but can be operated at lower voltage levels and increased thrust to power ratio [7] and allow for bipolar operation by expelling both positively and negatively charged ions.

In this work we focus on the ENPULSION NANO thruster, a FEEP electric propulsion system with a total system input power of less than 40 W, that was originally designed for Nanosatellite applications. However, the modular nature of the integrated propulsion system has allowed integration into much larger platforms, typically featuring 4 or more thrusters, and as presented in this work, to date the majority of propulsion systems has been deployed on Microsatellites, with platform masses ranging above 100 kg.

After launching in Dec 2018, the first successful demonstration of the NANO thruster (formerly IFM Nano Thruster) in orbit in 2019 in an IOD conducted together with FOTEC [21, 22] also marked the first demonstration of a propulsion system based on liquid metal FEEP. Since then, 141 additional NANO systems were launched. In addition, a higher power and total impulse thruster, the MICRO R³ has been developed, which was successfully demonstrated in orbit in 2021. To date, hundreds of flight models of NANO and MICRO propulsion systems have been manufactured, acceptance tested and delivered to 36 customers. Based on lessons learnt during manufacturing, AIT and in-space operation of the NANO, a new generation of propulsion systems with increased resilience has been developed, denoted the NANO R³ product family. The first propulsion model in AR³ configuration, with thrust vectoring capability, was recently launched and verified on orbit.

This paper provides an overview of the launch statistics of the ENPULSION systems, as well as selected accumulated operational metrics, including total accumulated on orbit time. We discuss the limitations of the data imposed by visibility of customer data in some instances. Based on this, we derive lessons learnt, best practices and limitation based on AIT, on orbit operations and ground tests over a large number of propulsion systems and different implementations for a standardized electric propulsion system.

Propulsion system description and integration aspects

To date, three propulsion systems based on the proprietary FEEP technology have achieved flight heritage: the NANO, shown in Fig. 1, the higher power ENPULSION MICRO R³ (Fig. 2, left hand side) [21, 23–25] and the NANO AR³ (Fig. 2, right hand side) [26], a successor of the heritage NANO with added thrust vectoring capability. The underlying FEEP technology generates thrust by electrostatic acceleration of Indium ions. These ions are extracted from the liquified Indium propellant on the apex of Taylor cones, which are established by the same electrostatic field on sharp emitter structures. To increase thrust, these emitter structures, and therefore the ion emission sites, are multiplexed. The propellant transport is based on capillary forces from a non-pressurized reservoir to the porous emitter structures. The



Fig. 1 Heritage system with significant flight heritage: NANO propulsion system



Fig. 2 Next generation R³ propulsion systems in space to date: MICRO R³ (left) and NANO AR³ (right)

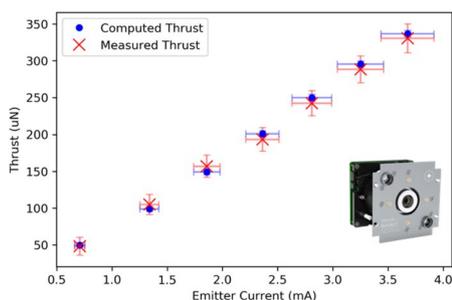
system uses Indium, an inert and non-toxic metal [27] as propellant, which is in solid state when not actively liquified and the propellant thereby remains in solidified state during assembly, integration and launch, which allows the propulsion systems to be shipped fully loaded. The propulsion system design is fully integrated, and propellant tank sizes are not customized to individual missions, resulting in an off-the-shelf product. Typical missions scale total impulse therefore by accommodating multiple propulsion systems or accept increased propellant loading. Besides mechanical interfaces, the propulsion systems only require a thermal and electrical interface. Since the propulsion modules are not customized, the interfaces can be controlled via a standard set of documents that are applicable over a large range of mission integrations. The off-the-shelf nature of the propulsion system allowed to scale the production by implementing processes from aircraft and automotive industries such as lean manufacturing [28]. Hundreds of flight units have been delivered to date, each undergoing at a minimum a standard acceptance test process, including ion emission verification, thermal survival temperature cycle testing, vibration testing and final functional acceptance testing.

In addition to the standardized acceptance testing performed on each propulsion unit shipped, qualification testing is currently ongoing for the R³ propulsion system

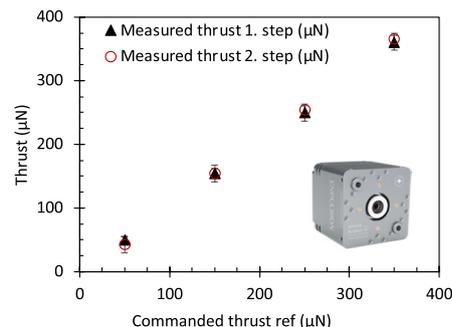
family including shock, radiation, EMC, direct thrust measurement, ion beam divergence and extended duration testing. Several independent thrust measurement campaigns have been conducted on the NANO, at facilities of two space agencies, two customers and at FOTEC. The NANO R³ and MICRO R³ have both been tested on FOTEC’s direct thrust measurement facility [29]. Figure 3 shows sample results of such test campaigns, comparing the directly measured thrust to thrust commanded or computed by telemetry for each of the systems. The thrust model used for internal computation of the thrust is based on measured emitter potential and emitted ion current as well as a factor accounting for inefficiencies due to beam spreading [29]. Results displayed have been acquired at the ESA test facility (NANO) and at FOTEC (NANO R³ and MICRO R³).

On-orbit demonstration of the NANO

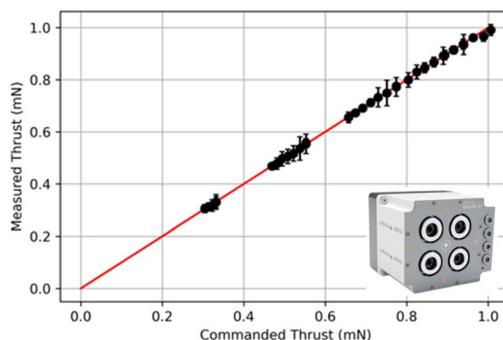
The first IOD of the NANO, which also represents the first propulsive operation of a FEEP thruster in space, has been reported in [21, 22]. This IOD was conducted on a 3U Cubesat launched in 2018, and included an independent thrust verification by comparing the s/c altitude change expected from propulsion system telemetry, to the altitude change determined by GPS measurements before and after at 15 min and a 30 min thrusting maneuver. A comparison of expected (from propulsion system telemetry) to observed (GPS) altitude change is given in Table 1, and confirms the good agreement of FEEP thrust models seen in ground test campaigns (Fig. 3).



NANO (thrust measurement at ESA facility) [29]



NANO R³ (thrust measurement at FOTEC facility) [30]



MICRO R³ (thrust measurement at FOTEC facility)

Fig. 3 NANO, NANO R³ and MICRO R³ direct thrust measurements, facilities and original publication indicated if applicable. NANO (thrust measurement at ESA facility) [29]. NANO R³ (thrust measurement at FOTEC facility) [30]. MICRO R³ (thrust measurement at FOTEC facility)

Table 1 Change in average spacecraft semi-major axis due to thrust maneuver, measured from GPS data and calculated from propulsion telemetry, from [21]

Maneuver parameters	Average change in semi-major axis, m	
	Calculated from thruster telemetry	GPS measurements
Test 1: $I_{em} = 2$ mA, 15 min	72	70 ± 5
Test 2: $I_{em} = 2$ mA, 30 min	115	116 ± 5

As part of the IOD, the controllability of the propulsion system to perform precise thrust steps, as well as thrust repeatability after several idle days, were verified as discussed in Refs. [21, 22]. Minimum impulse bit capability using different control modes was shown in Ref. [27].

Propulsion system operation and application

Previous publications [21, 22] presented the early subsystem commissioning efforts conducted during the IOD of the NANO in 2018, and telemetry from commissioning and early-stage operation of multiple propulsion systems on a small satellite [23]. Refs. [30, 31] presented data from additional NANO systems onboard of another ESPA class spacecraft spanning approximately 3.5 days, during which the propulsion systems were operated at different thrust set points and firing durations to optimize system power and thruster duty cycle, allowing to optimize the full system from a power standpoint and to understand the thermal situation during extended orbit change operation. Figure 4 shows a sample orbit change maneuver of two parallel firing NANO systems, using a constant thrust approach for a different ESPA class spacecraft. A segment of just over 420 hour total maneuver duration is shown, with a 12 hour detail highlighted for one of the systems, showing the constant thrust operation at mission specific duty cycle.

The miniaturized high voltage electronics of the propulsion systems introduce a certain control noise to the applied voltages, which translates into a thrust noise. This noise is larger than the noise contributions that would stem from the Taylor cone emission physics. Figure 4 plots the non-averaged telemetry transmission, which is conducted at a low frequency of 1 Hz, showing the resulting noise from the high voltage control.

The NANO propulsion systems have been used in different configurations on a range of spacecraft ranging from 3U to > 100 kg systems, and are used in a variety of different applications. Typical applications that use or plan to use the NANO have been:

- bring into target orbit, in conjunction with ride share
- formation and cluster initiation
- maintenance of precise orbits to improve ground track
- constellation rollout
- deorbiting

Figure 5 shows an example combining multiple of the above applications by plotting the semi-major axis evolution of two spacecraft carrying multiple NANO systems each. The data shows the initial natural decay of both spacecraft before commissioning of the propulsion systems, followed by a propulsive transfer to the target orbit. Once reaching

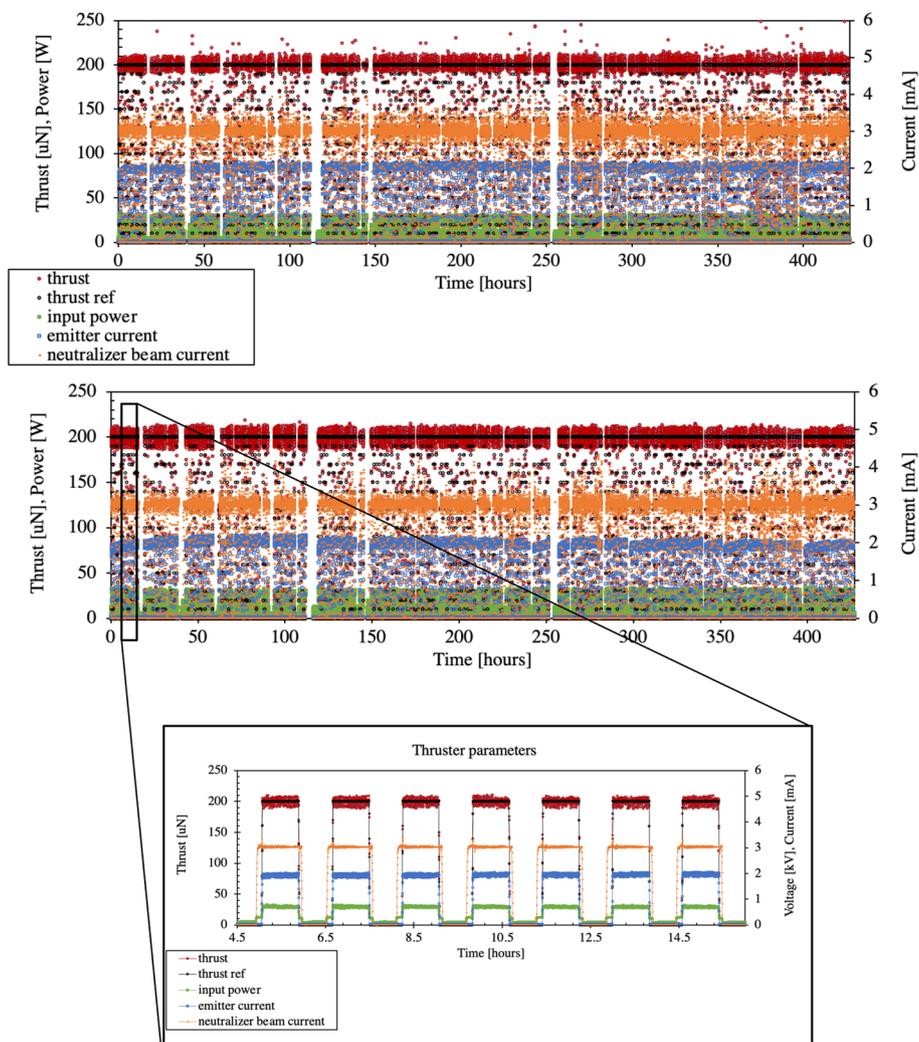


Fig. 4 Constant thrust maneuver using two NANO propulsion systems with firing duty cycle in accordance to orbital cycle [31, 32]

the target orbit, in this case a repeat ground track orbit, the propulsion units were frequently used to maintain precise target orbits, in this example to improve the ground track for an earth observation instrument. The data shows two spacecraft that were launched from a shared launch vehicle, including in-plane separation achieved by staggered orbit acquisition maneuvers.

On-orbit statistics

Table 2 summarizes the number of propulsion systems currently on orbit and the number of spacecraft the propulsion systems are distributed, ranging from 1 propulsion system on a 3U Cubesat, to a cluster of 7 systems on a > 100 kg class spacecraft. In total, 144 propulsion systems have been launched, on a total of 66 different spacecraft.

Figure 6 shows the launch evolution of the NANO over 4 years since the IOD. Popular rideshare launches can be identified by corresponding stepwise increase in number of

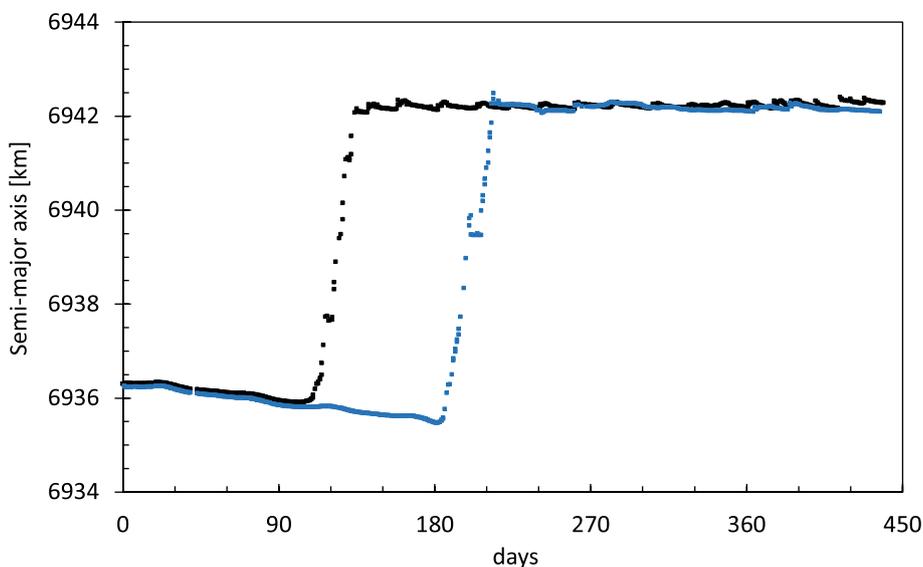


Fig. 5 Average semi-major axis evolution of two spacecraft using multiple NANO systems for orbit transfer each, arbitrary relative time in days: natural decay before propulsion system usage, followed by orbit acquisition, followed by precise orbit keeping during operational mission. Both spacecraft were launched on the same rideshare, data shows drifting separation [31, 32]. Data taken from [33]

Table 2 Summary of ENPULSION propulsion systems in space

Propulsion System	Number of s/c	Number of Thrusters	Thrusters on Cubesats	Thrusters on ESPA class s/c	Different launches
NANO	64	142	22	120	20
NANO AR ³	1	1	1	0	1
MICRO R ³	1	1	0	1	1

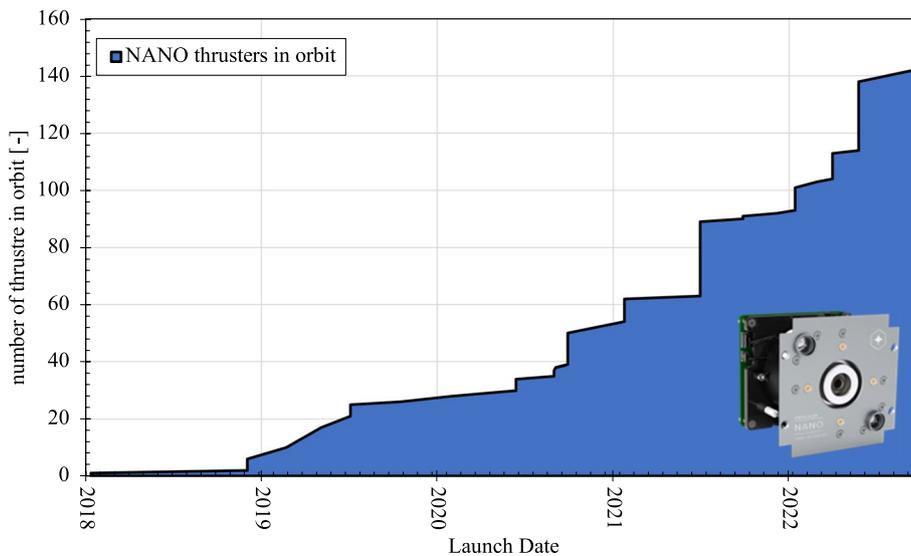


Fig. 6 Launch history of the NANO

propulsion systems on-orbit, typically consisting of several spacecraft with one or more propulsion system onboard participating in the same launch.

On-orbit telemetry data availability

Given the commercial nature of most of the missions employing ENPULSION propulsion systems today, data availability becomes the premier challenge for statistical analysis since thruster operation is often conducted without direct involvement of ENPULSION. Nevertheless, we are able to continuously receive significant amounts of telemetry, creating a valuable basis for statistical analysis of on orbit propulsion performance and behavior.

Figure 7 shows the data availability of accumulated on orbit telemetry times for the heritage NANO systems currently in space that ENPULSION has received full telemetry on. From Fig. 7 it would appear as if hot standby times scale with accumulated thrusting time. However, from operations support we often see that during mission operations, propulsion systems are frequently kept in hot standby for weeks or even months between thrusting maneuvers, which would make us expect hot standby times accumulating even in times of little thrusting operation. The fact that this is not reproduced in Fig. 7 shows that the data shown does not correspond to the true accumulated on orbit times, but only to the portion that is made available to ENPULSION in the course of review and support, which is often skewed around specific customers and operational constraints (eg. when support is provided during a change of thruster operation). In addition, repetitive thrusting maneuvers and hot standby durations are less frequently reported to ENPULSION to minimize customer effort. Only data where the full telemetry was provided to ENPULSION is included in the data shown,

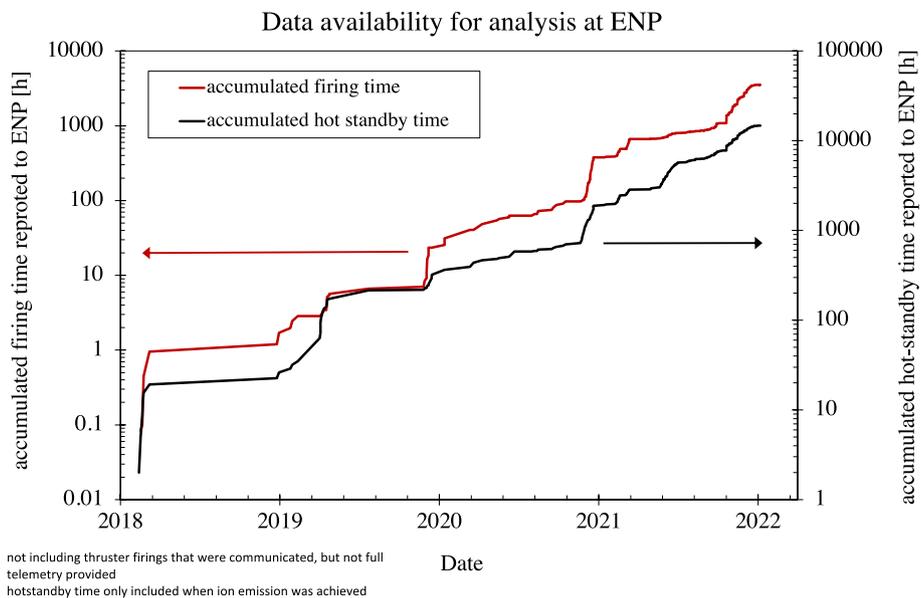


Fig. 7 NANO propulsion system data availability for analysis at ENPULSION: Accumulated firing time and hot standby time for which full telemetry was made available to ENPULSION. The scaling of hot standby time with firing time indicates that the data shown is limited by data visibility, and accordingly represents minimum accumulated times, with true on-orbit times likely higher, based on customer communication [31, 32]

while firing and hot standby durations reported by the customer qualitatively, without delivering telemetry, is not included. This means that the actual accumulated firing time and hot standby times on orbit are likely to be higher, and the data shown in Fig. 7 corresponds to the lower bound of accumulated durations.

With only one MICRO R³ and NANO AR³ system each on orbit at time of writing it is not possible to present data without allowing to infer on customer and mission profile.

The data underlying the high-level parameters shown in Fig. 7 represents an exhaustive source for analyzing propulsion on orbit performance over a large number of different missions, usages and customers.

Table 3 provides high-level statistical data availability, as well as the longest accumulated firing of a single propulsion system of over 650 hours of thrusting [31, 32]. Note that propulsion systems that are awaiting commissioning, e.g. only used in deorbiting, are not included in this summary.

System integration aspects: lessons learnt

Based on the significant heritage and data available on the NANO, several lessons learnt, and issues observed can be derived [31, 32]. These learnings can then be used to inform operators, while maintaining mission confidentiality, through the standardized documentation including user manual. In addition, lessons learnt are a valuable source for product improvement and ongoing product development. This section gives a brief discussion of aspects encountered.

1) Value of flexibility to change on-orbit command software

A significant benefit of the large number of parallel on orbit commissionings and operations is the opportunity to improve operation across different missions. The large amount of data, operation time accumulated and learnings from multiple propulsion systems operated in different architectures and operation modes, allows for continuing learning of system behavior on orbit and improvement of propulsion system operation, including optimized commissioning strategies or identification of new FDIR conditions. This can create significant benefit as learnings can be shared across missions and customers by infusing findings into new revisions of the user manual, without violating mission confidentiality. However, to fully leverage this potential, operators are required to have the flexibility to change their on orbit com-

Table 3 Accumulated On-orbit operation time of all NANO systems, as of Feb 2022

	Accumulated time ^b
Accumulated orbit life for all operational propulsion systems where ENPULSION has visibility on thrust generation ^a	58.3 years
Accumulated orbit life for all operational propulsion systems between launch and last telemetry of thrust maneuver made available to ENPULSION	22.0 years
Longest accumulated firing time on a single propulsion system (launched in June 2021)	> 650 hours

^a note that this includes time accumulated between the last telemetry was made available to ENPULSION and Feb 2022, assuming that during normal operations, any anomaly would be reported to ENPULSION

^b as several customers provide telemetry after commissioning only intermittently to ENPULSION, the two values are considered a lower and upper bound for accumulated times. Also note that propulsion systems not yet commissioned are not appearing in this table

mand sequences and command structures to implement new findings. As this can cause additional implementation and validation efforts, it is observed that operators may tend to neglect or significantly delay implementation of such newer findings. The outcome of such lack of timely implementation of new findings has been observed to range from continuing to perform unnecessary extra tests, to omitting the implementation of a new FDIR condition that was found in another customer mission, which in the worst case, could lead to failure.

2) **Propellant solidification cycling and propulsion system resets**

When high voltage is applied to the ion emitter after launch for the first time, a thin oxidation layer has to be overcome and therefore voltages to initiate the emission are higher, increasing the likelihood of sparks between the emitter and the extractor. The high voltage sections of the PPU are designed to be resilient against such sparking events, which occur primarily during the early startup of ion emission from the emitter needles, but internal interferences in the HV and LV sections of the heritage PPU of the NANO have been found to be capable of triggering electronics resets that can cause the propulsion system electronics to reboot into idle state. Since the PPU is also used to control the propellant temperature to maintain the propellant in liquified state during ion emission, such resets can lead to propellant solidification, if not acted upon within several minutes of the reset by the OBC by commanding temperature control mode. It has been found that especially during early thruster life, solidification cycles can bear the risk of thruster degradation, if repeated solidification cycles are performed without properly conditioning the ion emitter by achieving sustained ion emission first. Most customers have been able to implement the recommended FDIR measures to identify such resets and command the propulsion system back to liquefaction mode within several minutes. However, relying on an external FDIR implementation is considered a certain risk, especially given the combination of increased occurrence of sparking events at early commissioning, in combination with the higher risk of degradation by repeated solidification cycles which is also amplified during early commissioning stages. Both aspects of the early commissioning stage, during which the thruster-system interaction is typically less well understood, can lead to failure in systems that are unable to successfully detect such events. To refrain from relying on the external FDIR implementation on OBC side, resilience of the PPU against sparking to maintain propellant liquification throughout commissioning, was a design driver on the upgraded propulsion system development of the NANO R³ series and MICRO R³.

3) **Volatile contamination during storage, AIT and launch**

Exposure of the ion emitter to a contaminating material that features more favorable wetting properties on Tungsten than Indium, was found as a root cause for decreased propellant availability at the emission sites, which can ultimately result in a loss of ion emission. Examples of such materials include silicone oils, hydrocarbon lubricants or volatiles of certain epoxies. This effect can be augmented by the fact that the NANO design (contrary to the new R³ generation design) features large internal venting paths that form, in many cases, the largest venting path of the spacecraft. This leads to a situation in testing and deployment in space, in which a significant proportion of the internal volume of the spacecraft and therefore volatiles from non-

space compliant materials, could be vented through the NANO ion emitter. Exhaustive compatibility studies of commonly used materials, including exposing samples during curing, have been conducted based on material lists provided by a range of customers.

4) **OBC commanding forbidden states**

Instances have been encountered during which forbidden command states, e.g. forbidden high voltage settings during propulsion system operation in manual mode, or violation of the startup sequence of auxiliaries, such as the neutralizer prior to ion emission when operated in manual mode, were commanded. In the NANO, commanding such forbidden states can lead to damage, or loss, of the propulsion system. Three main causes leading to these events are highlighted:

- a. In an instance observed, an anomaly was caused by sending overlapping command sequences, e.g. following a trigger of an FDIR while executing a command script, which was remedied by a manual reset of the propulsion system, but without aborting the continuing command script. After manual thruster initialization, the propulsion system therefore received command segments from the OBC from the inadvertently continuing earlier script.
- b. Starting from an undefined state due to a previous, not fully executed, or incorrectly finished script: While the NANO performs a full initialization when power cycled, no initialization of the command registers is performed between thrust maneuvers. This bears the risk of an undefined propulsion system state after a thrust maneuver was commanded, if not properly commanded to initial state. It has been observed that in subsequent activation of subsections of the PPU, the thruster was in such cases effectively commanded to the previous set-point, which can lead to issues in case of time sensitive startup sequences, such as the required start of the neutralizer before ion emitter activation to guarantee neutralization through all stages of the operation.
- c. Due to insufficient ground verification of commanding scripts: Errors in commanding sequence scripts sent by the OBC have been encountered, which may have been avoided with increased effort and time spent in ground verification. However, this is amplified by the strong time pressure in a majority of the missions, and the typically stringent facility requirements necessary to perform an EP propulsion end-to-end verification after integration. The latter capability is in many cases beyond the capability of most Smallsat customers and necessitates assistance by the propulsion provider to assist such joint testing in the propulsion manufacturer facilities.

5) **Beam interaction with metallic structures (Baffle/Facility)**

Due to the neutral droplets ejected from the FEEP emission site during ion emission that can condense on surfaces that have a direct view path to the emission site, baffles to shield sensitive equipment have been sometimes employed, when placing sensitive equipment within the view of the emission site could not be avoided. Such a baffle is however not only blocking the unwanted droplet trajectories but is also exposed to the high angle portions of the high energy ion plume, which in turn leads

to backspattering of the baffle surface material to the emitter. This leads to a situation in which the ion emitter is exposed to a – usually metal – surface which experiences ion impingement of different energies, depending on distance and angle at which the baffle is introduced into the field of view of the thruster. Similarly, when operating a FEPP in a vacuum chamber, such as in a verification campaign, the chamber walls are hit by high energy ions and can lead to secondary species emission and significant backflow during ground test campaign [34].

Depending on geometry, material choice and operation modes, it has been observed that metal backflow from features implemented by the customer to shield sensitive equipment that would violate the defined plume stayout zones can lead to degradation effects of the ion emitter over extended duration operation. The same degradation mechanism has been reported during ground test campaigns. The degree of such degradation is dependent on the specific materials employed, geometries such as view angle and distance of the obstruction, and operation mode, eg emission current level, of the propulsion system. For example, the presence of metal backflow condensing on the emitter, if soluble in the propellant, can lead to locally changed physical properties of the propellant, if the ratio of backflow to reemitted flow is large, as can be the case when introducing a significantly large metal surface into the stayout zone, which then comes in contact with the ion plume.

The interaction when introducing an obstruction into the ion beam of any EP system is a complex topic and is highly depending on the specific geometry and materials, as well as the system operating parameters, typically requiring dedicated experimental characterization of each specific configuration. During customer integration support, we have performed a significant number of in-depth investigations of specific customer integrations and operation points, as well as material compatibility studies, complemented by establishing significant understanding of the ion beam properties at ENPULSION and FOTEC [35–37].

Due to this interaction of the ion emitter with material backflow either from baffle obstructions or facility walls, testing FEPPs in new environments on ground remains a difficult endeavor that typically requires several iterations to minimize facility impact on the ion emitter, a prerequisite to allow testing emitters for extended durations of time.

6) **Space environment interaction effects:**

Certain aspects of the orbital environment are complex to simulate during ground testing but remain relevant to the on orbit performance of the propulsion system.

a. **ATOX in combination with lower orbits and hot standby facing in RAM direction**

We have noticed a potential correlation showing degradation of performance for specific lower orbits in combination with extended hot standby operation, with the spacecraft pointing the propulsion system with liquified propellant in RAM direction, in combination with not performing any thrusting operation (ion emission). During hot standby, the metal propellant is held in liquified state at increased temperature, facilitating oxidation buildup in combination with

ATOX in lower earth orbits when facing RAM direction for extended durations. While oxides can be removed to some extent by ion emission when thrusting, oxide buildup during extended idle times when kept in hot standby and facing RAM direction could lead to potential emitter degradation. While this is currently in investigation including on orbit verification, this effect can be mitigated by means of implementing a stayout orientation for lower orbits when propellant is liquified and no thrust maneuvers are performed.

b. **Operator negligence of local environment during operation, eg. high geomagnetic activity**

While the PPU of the heritage NANO system has been matured through testing, it remains a COTS component based high voltage electronics. Given the lack of EEE part lot control, and therefore limited applicability of radiation testing results across different production lots, usage in orbit commends certain safety precautions, which may include safety precautions like suspension of high voltage operation during significant geomagnetic activity. Two measures have been implemented to remedy such failure case:

- Increase awareness at customers, especially customers with strong focus on Newspace business cases, of potential risk and limitations.
- New generation NANO R³ and MICRO R³ propulsion systems that are developed with a focus on PPU resilience, including part lot control.

7) **Propellant accumulation on extractor**

The accumulation of propellant droplets accumulating at the inward facing circumference of the extractor ring during long duration operation has been previously reported [38, 39]. If not counteracted, this can lead to changes in the electrical field geometry and ultimately establish a physical, and therefore electrical bridge between the emitter and the extractor. So far, this effect has not been encountered in space. As this is a deposition mechanism and not an erosion effect, it is reversible by melting the deposited Indium. This so-called cleaning has recently been verified successfully during an endurance test campaign. Recent tests however have indicated a stronger dependency of the rate of clogging with respect to the emitter mass flow, which can lead to higher clogging rates than previously reported [40, 41]. A model of the clogging process which provides good agreement with experimental data is described in Ref. [41], and a method of removing such propellant accumulation by changing the operational parameters of the thruster before a short can occur has been experimentally verified on ground. This method can be executed after accumulating a certain period of operation to remove and redistribute the propellant at the extractor without additional means required and can be implemented on orbit if telemetry would indicate the need for such a “cleaning” procedure.

Implementing lessons learnt and expanding capabilities

Incorporating lessons learnt as described in section VIII, the development of new propulsion systems and product updates has focused on:

- Improved operations by increasing propulsion system autonomy and resilience in terms of software and resets.
- Increased electronics resilience, including EEE part lot control.
- Increased agnostic against system integration issues, eg by minimizing satellite internal outgassing impacting sensitive propulsion components.
- Improved firmware including fully automatic thruster operation to minimize opportunities for command errors.

Incorporating these lessons, a new generation of propulsion systems based on core elements of the heritage product has been developed, which features several distinct improvements on the PPU that allow the overall system to meet commercially relevant lifetime requirements in a broad range of applications. This includes a redesign of the PPU targeting increased radiation resilience with the support from agencies, lot-controlled testing and a new firmware that allows full automatic propulsion system operation and recovery. The R³ design avoids several failure modes on user-side by protecting sensitive parts from handling-issues during AIT and features extended protection against errors during operations [40, 41]. In addition to these improvements, the AR³ propulsion system features added beam steering capabilities while maintaining an entirely passive system.

The new NANO R³ thruster family (Fig. 8) includes the addition of new capabilities to the FEEP propulsion systems, such as the thrust vector steering capability of the NANO AR³ system. This propulsion system, which shares the major propulsion system modules with the NANO R³, has the added capability to steer the net emitted ion beam by spatially distributed differential throttling of the ion emission sites. This is accomplished using multiple extractor electrodes, and does not require moving parts [42, 43].

Conclusion

This paper presents the on-orbit statistics of the NANO, NANO AR³ and MICRO R³ electric propulsion systems, with a total of 144 propulsion systems on 66 spacecraft launched to date. Through the significant number of propulsion systems launched, as well as the standardization of the NANO, we explore the opportunity to gather a statistical view of on orbit data of a large number of systems integrated in a large variety of

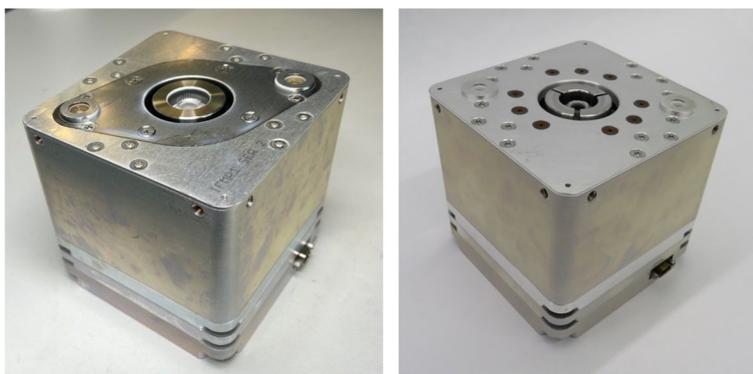


Fig. 8 NANO R³ (left) and NANO AR³ (right) propulsion systems

missions and integrator capabilities. We presented selected flight telemetry from propulsion systems, including a significant propulsive orbit maneuver, and discuss different applications, including an example of precise orbit keeping during the operational phase of two spacecrafts. We discuss data availability regarding a large number of NANO propulsion systems and based on this we present high level statistical data regarding total firing and hot standby durations. We report >3000h of total thrusting time summed over all NANO propulsion systems in space and report an accumulated firing duration for a single unit of >650 h on orbit. We discuss a variety of lessons learnt based on on-orbit operation, integration, and customer side ground test campaigns, which have been incorporated in the next generation ENPUSLION R³ propulsion products.

Nomenclature

AIT Assembly, Integration and Test.

COTS Commercial off-the-shelf.

EEE Electronic, Electrical and Electromechanical parts.

EP Electric Propulsion.

ESPA EELV Secondary Payload Adapter.

FDIR Fault Detection, Isolation, and Recovery.

FEED Field emission electric propulsion.

HV High Voltage.

IOD In Orbit Demonstration.

LV Low Voltage.

OBC On-Board Computer.

PPU Power Processing Unit.

SEE Single Event Effect.

Authors' contributions

Conceptualization, methodology, data collection, visualization and analysis, and interpretation as well as original draft preparation and review was performed by David Krejci. Alexander Reissner contributed in data interpretation, manuscript review and editing, and funding acquisition. The author(s) read and approved the final manuscript.

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Availability of data and materials

The data presented in this manuscript includes proprietary customer data. Data can be reviewed onsite at ENPUSLION at reasonable request.

Declarations

Competing interests

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References

1. Selva D, Krejci D (2012) A survey and assessment of the capabilities of Cubesats for earth observation. *Acta Astronautica* 74:50–68

2. Malphrus BK, Freeman A, Staehle R, Klesh AT, Walker R (2021) Interplanetary Cubesat missions, from: Cubesat Handbook, pp. 55–121
3. Martinez-Sanchez M, Pollard JE (1998) Spacecraft electric propulsion – an overview. *J Propuls Power* 14(5):688–699
4. Lemmer K (2017) Propulsion for Cubesats. *Acta Astronautica* 134:231–243
5. Rummala AR, Dutta A (2017) An overview of cube-satellite propulsion technologies and trends. *Aerospace* 4(4):58
6. Lev D, Myers RM, Lemmer KM, Kolbeck J, Koizumi H, Polzin K (2019) The technological and commercial expansion of electric propulsion. *Acta Astronautica* 159:213–227
7. Krejci D, Lozano P (2018) Space propulsion technology for small spacecraft. *Proceed IEEE* 106(3):362–378
8. Marrese-Reading C, Anderson J, Jung-Kubiak C, Polk J, Singh V, Yee K et al (2016) Electrospray thruster performance with microfabricated emitter arrays and indium propellant, 2016–4738, In: Proceedings of the 52nd AIAA/SAE/ASEE joint propulsion conference, Salt Lake City
9. Jensen KL, Marrese-Reading CM (2003) Emission statistics and the characterization of array current. *J Vacuum Sci Technol B* 21:412
10. Ziemer JK (2009) Performance of electrospray thrusters, 31st international electric propulsion conference, IEPC-2009-242, 31st International Electric Propulsion Conference, Electric Rocket Propulsion Society, Ann Arbor
11. Gamero-Castano M, Hruby V (2001) Electrospray as a source of nanoparticles for efficient colloid thrusters. *J Propuls Power* 17(5):977–987
12. Ziemer J, Marrese-Reading C, Cutler C, Dunn C, Romero-Wolf A, Javidnia S (2018) In flight verification and validation of colloid microthruster performance, In: Proceedings of the 2018 AIAA propulsion and energy forum, Cincinnati
13. Lozano P, Martinez-Sanchez M (2005) Ionic liquid ion sources: characterization of externally wetted emitters. *J Colloid Interface Sci* 282(2):415–421
14. Krejci D, Mier-Hicks F, Thomas R, Haag T, Lozano P (2017) Emission characteristics of passively fed electrospray microthrusters with propellant reservoirs. *J Spacecraft Rockets* 54(2):447–458
15. Courtney DG, Wood Z, Gray S, Model J High-speed transient characterization of the Busek BET-300-P electrospray thruster, IEPC-2019-A-788, 36th international electric propulsion conference, Electric Rocket Propulsion Society, Vienna
16. Courtney DG, Wood Z, Fedkiw T. Reconstructing electrospray plume current spatial distributions using computed tomography, IEPC-2019-A-787, 36th international electric propulsion conference, Electric Rocket Propulsion Society, Vienna
17. Alexander MS, Stark J, Smith KL, Stevens B, Kent B (2006) Electrospray performance of microfabricated colloid thruster arrays. *J Propuls Power* 22(3):620–627
18. Cisquella-Serra A, Galobardes-Esteban M, Gamero-Castano M (2022) Scalable microfabrication of multi-emitter arrays in silicon for a compact microfluidic electrospray propulsion system. *ACS Appl Mater Interfaces* 14(38):43527–43537. <https://doi.org/10.1021/acsami.2c12716>
19. Courtney DG (2016) Dandavino, S., Shea, Herbert: comparing direct and indirect thrust measurements from passively fed ionic electrospray thrusters. *J Propuls Power* 32:392–407
20. Guo Y, Sun W, Sun Z, Wu Z, He J, Yang C, Wang N (2022) Direct thrust test and asymmetric performance of porous ionic liquid electrospray thruster, Chinese journal of aeronautics, In Press, <https://doi.org/10.1016/j.cja.2022.09.007>
21. Krejci D, Reissner A, Seifert B, Jelem D, Hörbe T, Plesescu F et al (2018) Demonstration of the IFM Nano FEEP thruster in low earth orbit. In: Proceedings of the 45 symposium 56, Sorrento
22. Seifert B, Buldrini N, Hörbe T, Plesescu F, Reissner A, Krejci D et al (2018) In-orbit demonstration of the indium-FEEP IFM Nano thruster, SPC2018–183. In: Proceedings of the 6th space propulsion conference, Seville
23. Krejci D, Reissner A, Schönherr T, Seifert B, Saleem Z, Alejos R (2019) Recent flight data from IFM Nano thrusters in a low earth orbit, 36th international electric propulsion conference, IEPC-2019-724. Electric Rocket Propulsion Society, Vienna
24. Schönherr T, Little B, Krejci D, Reissner A, Seifert B (2019) Development, production, and testing of the IFM Nano FEEP thruster, 36th international electric propulsion conference, IEPC-2019-362. Electric Rocket Propulsion Society, Vienna
25. Grimaud L, Krejci D, Reissner A, Seifert B (2019) The IFM Micro FEEP thruster: a modular design for smallsat propulsion, 36th international electric propulsion conference, IEPC-2019-675. Electric Rocket Propulsion Society, Vienna
26. Krejci D, Grimaud L, Schönherr T, Little B, Hugonnaud V, Koch Q (2021) NANO and MICRO propulsion systems: development and testing, AIAA02021–3420, In: Proceedings of the AIAA propulsion and energy forum, virtual event
27. The Indium Corporation of America: Indium Safety Data Sheet, SDS-IN 001, 7.12.2016
28. Krejci D, Reissner A, Weihrauch D (2019) IFM Nano thruster electric space propulsion: from first Cubesat demonstration to the first 100 thrusters produced, SSC19-XII-07. In: Proceedings of the 35th annual small satellite conference, Logan
29. Krejci D, Hugonnaud V, Schönherr T, Little B, Reissner A, Seifert B, Koch Q, Bosch-Borràs E, Gonzalez del Amo J (2019) Full Performance Mapping of the IFM Nano Thruster including Direct Thrust Measurements. *J Small Satellites* 8(2):881–893
30. Seifert B, Engel W, Genger J, Koch Q, Schönherr T, Krejci D (2022) direct thrust measurement of the NANO R3 propulsion system on FOTEC'S thrust test stand, SPC2022–053. In: Proceedings of the 8th space propulsion conference, Estoril
31. Krejci D, Reissner A (2022) 138 propulsion units launched in 4 years: a review and lessons learnt, SSC22-S1–12. In: Proceedings of the 36th annual small satellite conference, Logan
32. Krejci D, Reissner A (2022) The first 100 FEEP propulsion systems in space: a statistical view and lessons learnt of 4 years of ENPULSION, IEPC-2022-199, 37th International Electric Propulsion Conference 2022. Electric Rocket Propulsion Society, Cambridge
33. 18th Space Defense Squadron: <https://www.space-track.org/> (Accessed 27 Apr 2022)
34. Uchizono N, Wright P, Collins A, Wirz R (2022) Electrospray thruster facility effects, AIAA2022–1361. In: Proceedings of the AIAA SciTech Forum, San Diego

35. Mühlich N, Seifert B, Aumayer F (2021) IFM Nano thruster performance studies by experiments and numerical simulations. *J Phys D Appl Phys* 54:095203:12
36. Mühlich N, Seifert B, Aumayer F (2021) Verification of simulation model based on beam diagnostics measurements of the IFM Nano Thruster, IAC-21,C4,6,14,x64221. In: Proceedings of the 72nd International Astronautical Congress, Dubai
37. Hugonnaud V, Mazouffre S, Krejci D Faraday cup sizing for electric propulsion ion beam study: Case of a field-emission-electric propulsion thruster. *Rev Scientif Instruments*. 92(8):084502
38. Reissner A, Buldrini N, Seifert B, Hörbe T, Plesescu F, Gonzalez del Amo J et al (2016) 10 000 h lifetime testing of the mN-FEEP thruster, AIAA2016–5045, 52nd AIAA/SAE/ASEE Joint propulsion conference, Salt Lake City
39. Massotti L, Gonzalez del Amo J, P Silvestrin, Krejci D, Reissner R, Seifert B (2022) The Next Generation Gravity Mission and the qualification of the indium-fed mN-FEEP thruster, *CEAS Space J* 14(1):109–124
40. Schönherr T, Grimaud L, Vogel T, Krejci D, Reissner A, Seifert B (2022) Qualification status of the field-emission electric propulsion (FEEP) systems NANO R3 and MICRO R3, SP2022–192, In: Proceedings of the 8th space propulsion conference, Estoril
41. Grimaud L, Schönherr T, Vogel T, Reissner A, Krejci D, Mühlich N, Seifert B (2022) Qualification status update of the MICRO R³ and NANO R³ FEEP thrusters, IEPC-2022-200, 37th international electric propulsion conference 2022. Electric Rocket Propulsion Society, Cambridge
42. Koch Q, Schönherr T, Krejci D, Mühlich N, Seifert B (2022) Verification of the thrust vectoring capability of a FEEP thruster using spatial plasma plume diagnostic measurements, IEPC-2022-201, 37th international electric propulsion conference 2022. Electric Rocket Propulsion Society, Cambridge
43. Eizinger M, Gonzalez del Amo J, Bianchi L, Di Cara D, Koch Q, Krejci D et al (2022) Testing of the NANO AR3 FEEP cubesat electric propulsion system at ESA propulsion laboratory, SPC2022–266, In: Proceedings of the 8th space propulsion conference, Estoril

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