DOI: 10.13009/EUCASS2025-239

Six-degrees-of-freedom cold gas propulsion system for the deep-space Milani mission

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Abstract

IANUS is a six-degrees-of-freedom cold gas propulsion system designed to enable the Milani CubeSat to perform proximity operations around the Didymos binary asteroid system along with reaction wheel desaturation manoeuvres, as part of the ESA-funded HERA mission, a planetary defence initiative launched in October 2024. IANUS propulsion system consists of two identical 0.5U modules, mounted on opposite sides of the spacecraft to ensure full system redundancy. Each module incorporates four independent nozzles, capable of achieving three degrees of freedom, along with an integrated tank, fluidic system, and electronic board. The synergic use of the two modules guarantees 6 degrees of freedom to the satellite. The tank serves as the primary structural element and, due to its 3D-printed design, houses the main fluidic components. The fluidic system comprises high-pressure and low-pressure stages, separated by a miniaturized pressure regulator. The high-pressure stage includes the tank, which supports propellant loading and unloading via the fill and drain port, and a phase separator that ensures the outlet flow consists solely of gaseous propellant (unitary vapor quality). The low-pressure stage features four thrusters per module, each with its own nozzle and its independently controlled flow control valve. Both stages are monitored by compact pressure and temperature sensors. The propellant used in IANUS is R134a: a non-explosive, non-toxic, non-flammable, and zero-ODP fluid. Its biphasic nature allows for relatively low pressures in the tank (e.g., below 20 bar) while minimizing the required propellant volume. The IANUS development program, funded by ESA, was completed within a rapid 10-month timeline, progressing from preliminary design to a successful qualification test campaign in Q3 2022. The aim of this paper is to provide an overview of IANUS main features and test results.

1. Introduction

The IANUS propulsion cold gas system was specifically developed for CubeSat platforms operating in deep space environments. Designed and realized by Technology for Propulsion and Innovation S.p.A. (T4i), IANUS has been integrated into the MILANI CubeSat, one of the two CubeSats embarked in the European Space Agency's (ESA) Hera mission. Hera is part of the Asteroid Impact and Deflection Assessment (AIDA) international cooperation, aimed at demonstrating and evaluating planetary defence techniques through the investigation of the binary asteroid system Didymos and its smaller companion, Dimorphos [1][2].

The Hera spacecraft was launched on October 7, 2024, aboard a SpaceX Falcon 9 launch vehicle and is expected to reach the Didymos system in 2027. Its mission objective is to carry out a detailed post-impact characterization of the system, following the DART (Double Asteroid Redirection Test) mission led by the National Aeronautics and Space Administration (NASA), which successfully impacted Dimorphos in 2022 [3]. Hera hosts two CubeSats, MILANI and Juventas, marking the first deployment of CubeSats by ESA in interplanetary space. MILANI, developed by Tyvak International S.r.l., carries a scientific payload including the ASPECT hyperspectral imager and the VISTA dust detector, designed to analyze the surface composition and particulate environment of the asteroid system [4].

IANUS meets this mission unique needs through a compact design and the use of R134a, a biphasic, non-toxic propellant that enables high-density storage and stable thrust regulation. This allows MILANI to execute a variety of

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mission-critical operations, including hyperbolic arcs, controlled flybys, and proximity manoeuvres at distances ranging from 10 km down to 2 km from the surface.

The development process of IANUS involved addressing several demanding technical requirements, which guided the overall design and implementation strategy. First, the system had to comply with stringent volume and mass constraints, typical of CubeSat architectures. Secondly, the deep-space mission profile introduced the need for extremely low leakage rates, with a target of 10^{-6} sccsHe, to preserve propellant mass over multi-year mission. Furthermore, the propulsion system had to deliver the required performance in terms of thrust, accuracy and repeatability, and thermal behaviour, under vacuum and thermal cycling conditions representative of interplanetary space at operative and non-operative conditions of the mission.

Another key challenge was the compressed development timeline: the IANUS system, from preliminary design through to full environmental qualification, was completed in less than 12 months. This included manufacturing, integration, and testing, all carried out in line with the growing interest in low-cost, rapid-development propulsion solutions for small spacecraft.

The system architecture was designed with an integrated approach involving all key subsystems — fluidic, mechanical, thermal, and electronic. The electronic subsystem was developed by Tyvak International, which oversaw the design, production, and functional validation of the flight boards.

The development of IANUS is consistent with the broader trend of employing CubeSats as independent deep-space platforms, capable of supporting scientific and exploration objectives traditionally reserved for larger spacecraft. The propulsion system's modular and autonomous configuration allows MILANI to operate independently from its carrier spacecraft, executing correction manoeuvres and trajectory adjustments as needed to fulfil its scientific objectives while avoiding potential hazards.

This paper provides a detailed overview of the IANUS propulsion system, covering its design rationale, subsystem integration, qualification testing. The discussion highlights how the system architecture addresses the specific challenges of deep-space CubeSat missions and explores its potential role in future small satellite applications for planetary defence and interplanetary science.

2. System description

IANUS is an advanced cold gas propulsion system that comprises two identical 0.5U modules (Figure 1), symmetrically integrated into the MILANI spacecraft. Each module has a fully integrated design with a wet mass below 600 g and occupies a compact volume of 100 × 95 × 60 mm.

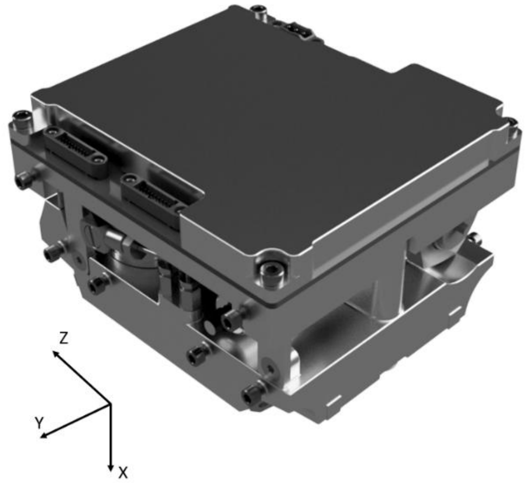

Figure 1 IANUS single module

Together, the two modules provide a total impulse of 76 Ns (38 Ns per module), supporting precise and responsive manoeuvres across all six degrees of freedom (6 D.o.F.). The system can deliver thrust levels of about 9, 11, and 27 mN along the spacecraft's primary axes, ensuring fine control for both translational and rotational motions. Table 1 summarizes the key performance characteristics and technical specifications of the IANUS propulsion system.

Table 1 IANUS main features

Feature	Value	Notes
Thrust [mN]	9/11/27	Per two modules
Torque [mN*m]	0.6/2.9/1	Per two modules
Power [W]	<60 peak per two modules	<40 firing per two modules
Volume [U]	0.5	Per module
Voltage [V]	12	Unregulated
Totak Impulse [Ns]	38	Per module
Leak rate [sccsHe]	$< 10^{-6}$	
Operating Temperatures [°C]	-10/50	-30/60 non-operative
Communication [-]	RS422 protocol HDLC-like	

The system architecture, depicted in the fluidic schematic of Figure 2, is organized into three primary subsystems: structural, fluidic, and electronic.

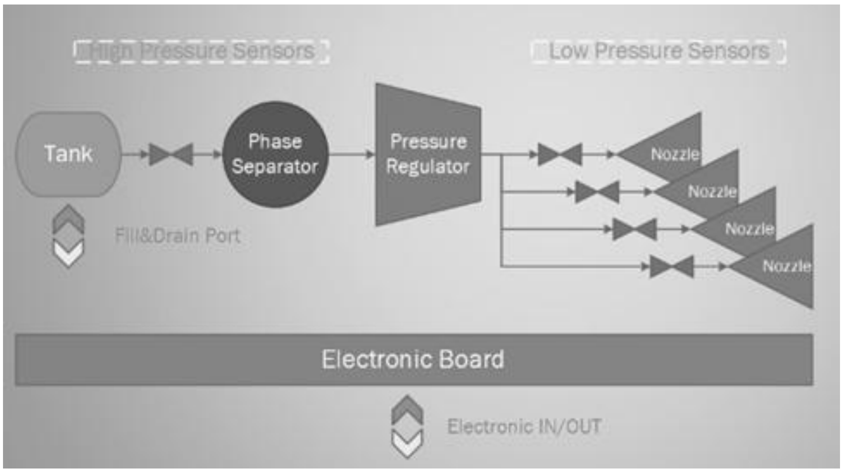

Figure 2 IANUS single module line

- **Structural Subsystem**: Built using high-resistance aluminum alloys and advanced additive manufacturing techniques, the main structure is free from welded parts, allowing for integrated fluidic channels and reduced potential leakage paths. This design approach also ensures robustness while maintaining mass and volume constraints.
- **Fluidic Subsystem**: The propulsion cycle begins with the storage of R134a propellant in a tank under biphasic (liquid-gas) conditions. A propellant management device ensures the delivery of gaseous phase only to the downstream components. The fluid then passes through a precision pressure regulator, which reduces the high storage pressure to a stable low-pressure line feeding four miniature nozzles. Each nozzle is independently actuated, enabling fine vectoring and thrust modulation. All high-pressure interfaces are protected with double-barrier sealing, and critical components are carefully selected from high-reliability COTS (Commercial Off-The-Shelf) sources to ensure long-term system integrity.
- **Electronic Subsystem**: Each IANUS module incorporates fully independent control and actuation electronics. This modularity enhances fault tolerance by reducing single points of failure and enables flexible integration into a variety of satellite bus architectures. The system is capable of rapid readiness, typically requiring less than 5 minutes from power-up to firing, with a maximum warm-up time of 30 minutes as requirement.

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3. Qualification test campaign

To verify the readiness of the IANUS propulsion system for deep space conditions, an environmental qualification test campaign was carried out at the Space Qualification Laboratory of CIRA (Capua, Italy) from September 5 to 16, 2022. The campaign was conducted in accordance with the ESA standard ECSS-E-ST-10-03C and involved a single Engineering Qualification Model (EQM) of the propulsion module. The objective was to assess the system's mechanical strength, structural integrity, leak tightness, and functional performance under simulated launch and space environment conditions.

3.1 Test Setup and Methodology

The device under testing consisted of a single IANUS module mounted on a dedicated interface plate with lateral brackets. During the mechanical vibration tests, IANUS single module remained in a non-operational state, while during the thermal-vacuum cycles it was activated to verify its functionality within both operational and non-operational temperature ranges. The sequence of testing was designed and executed as follows:

- Initial inspection and functional test,
- Sine sweep vibration tests before and after each major mechanical test,
- Sine vibration tests along X, Y, and Z axes,
- Random vibration tests along all three axes,
- Mechanical shock tests along X, Y, and Z axes,
- Thermal vacuum (TVAC) testing, including bakeout and multiple thermal cycles,
- Post-test inspection and final functional verification.

The sine-sweep measurements were conducted to identify the system's natural frequencies. Any shift in these frequencies was used as an indicator of possible structural modifications or degradation resulting from the applied test conditions.

3.2 Vibration Testing

Vibration qualification tests were conducted to replicate the mechanical loads associated with launch conditions. Both sine and random vibration profiles were applied using electrodynamic shakers (Figure 3).

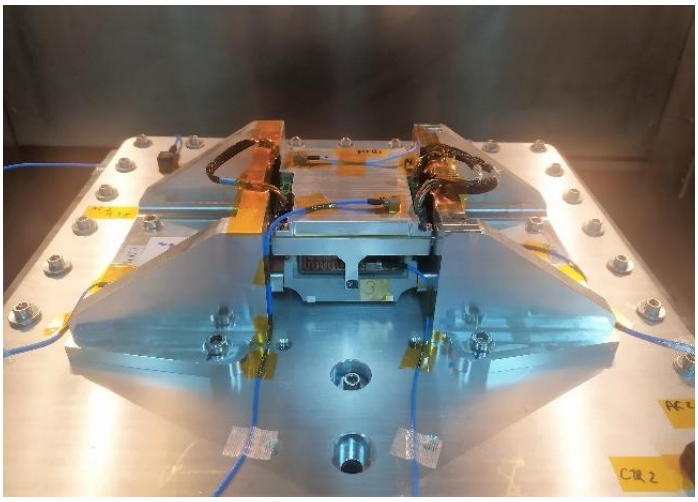

Figure 3 IANUS vibrations test setup

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For sine vibration testing (Table 2), frequency sweeps were performed along the X, Y, and Z axes. The X and Y axes were tested from 5 Hz to 100 Hz, with a maximum acceleration level of 8 g between 13 Hz and 100 Hz. The Z axis was subjected to the same frequency range, with a peak level of 12 g between 18 Hz and 100 Hz. All sweeps were executed at a rate of 2 octaves per minute, with a duration of 120 s per axis.

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Table 2 Sine vibration test levels

Load condition	**Frequency [Hz]**	**Qualification level [g]**
X – axis	5	1
	13	8
	100	8
Y – axis	5	1
	13	8
	100	8
Z – axis	5	1
	18	12
	100	12
Sweep rate	2 Oct/min	
Duration	120 s	

Random vibration testing (Table 3) was conducted along all three axes using a spectrum characterized by a flat acceleration spectral density of 0.16 g^2/Hz between 50 Hz and 800 Hz, tapering to 0.026 g^2/Hz at 20 Hz and 2000 Hz. The tests were performed for 120 s per axis, with an overall root mean square (RMS) acceleration of 14 g.

Table 3 Random vibration test levels

Load condition	**Frequency [Hz]**	**Qualification level [g]**
All directions	20	0.026
	50-800	0.16
	2000	0.026
Duration(s) / axis	120	
Acceleration grms (g)	14	

Each axis was tested sequentially, and detailed acceleration control and response measurements confirmed that all test levels were successfully achieved. Post-vibration sine sweeps showed no significant deviations in frequency response, confirming structural resilience, as reported in Figure 4 and Figure 5 as examples on X axis.

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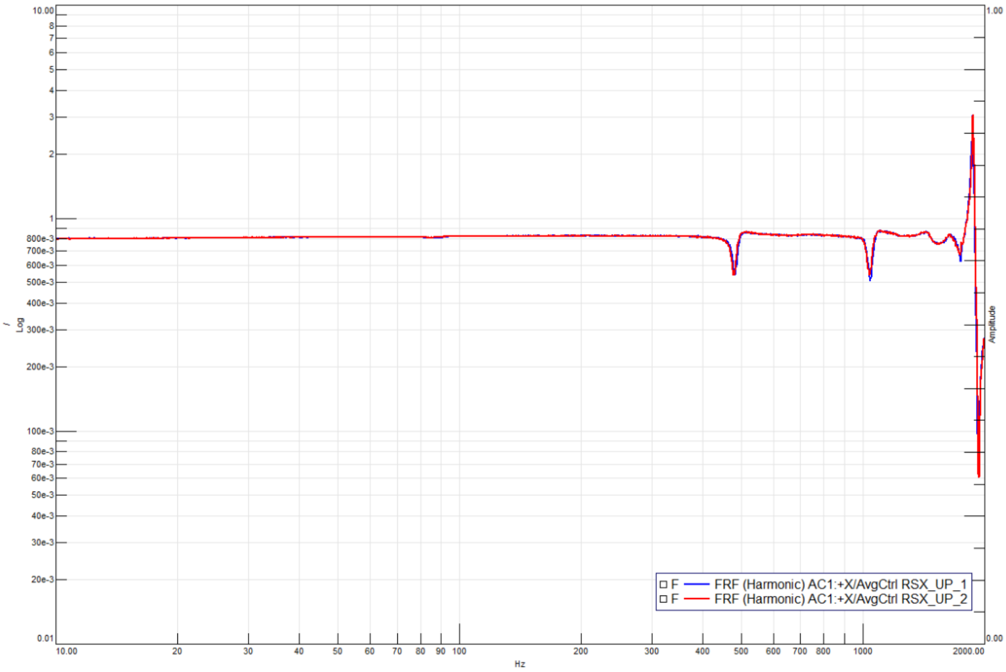

Figure 4 Sine sweep before and after sine vibration on X axis

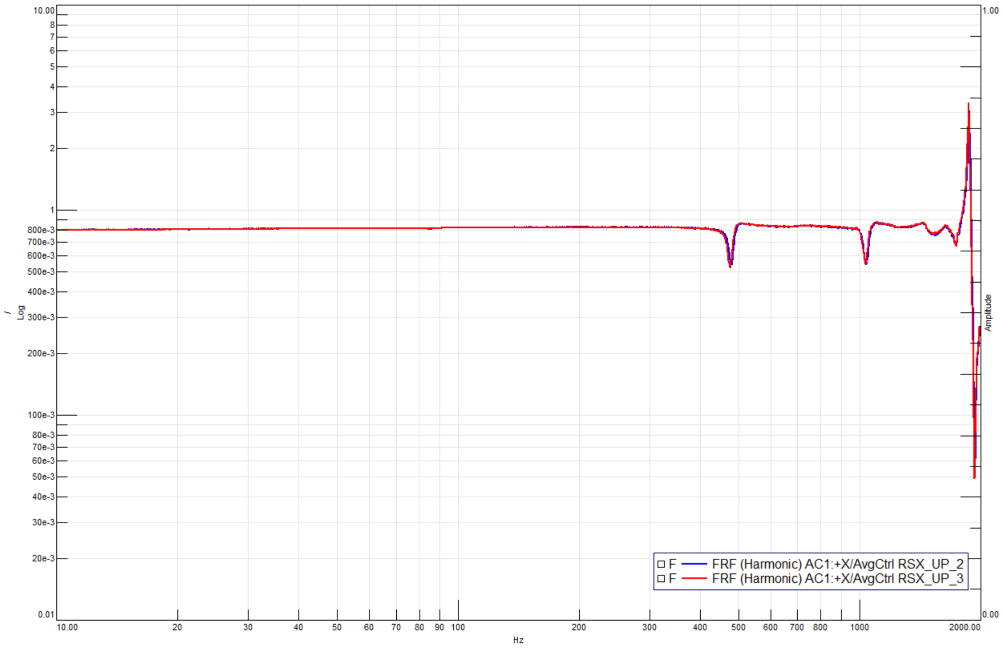

Figure 5 Sine sweep before and after random vibration on X axis

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3.3 Mechanical Shock Testing

Mechanical shock tests were conducted to reproduce the high-G loads associated with events such as spacecraft separation and deployment. Two shock events were applied along each of the X, Y, and Z axes using a hammer-anvil setup equipped with ringing plates (Figure *6*).

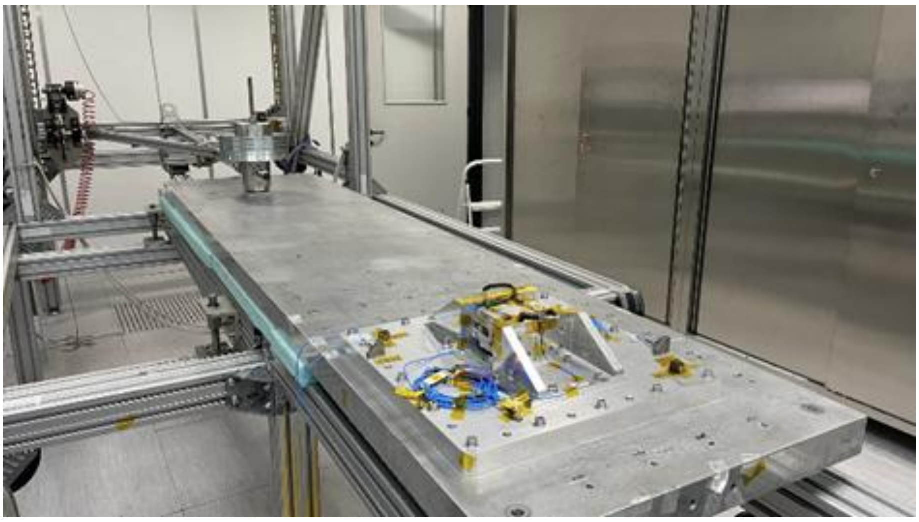

Figure 6 IANUS shock test setup

The target Shock Response Spectrum (SRS) peaked at 1200 g around 10 kHz (shock levels in Table *4*). SRS compliance was measured using dual accelerometers. Results showed that for X-axis 91–92% of the SRS magnitude exceeded the specification (Figure 7), whereas for the Y-axis and Z-axis the percentage were 99–100% and 95%, respectively.

Table 4 Shock test levels

Load condition	**Frequency [Hz]**	**Qualification level SRS Q=10 (g)**
All directions	100	40
	1100	350
	10000	1200

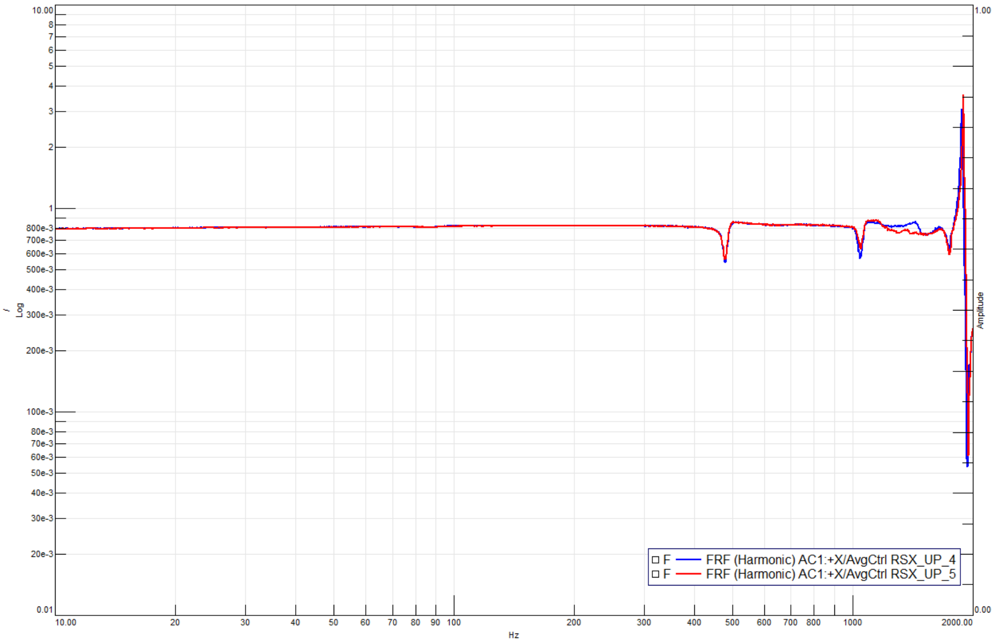

Figure 7 Sine sweep before and after shock test on X axis

3.4 Thermal Vacuum Testing

Thermal vacuum testing was performed to assess the module’s functionality under vacuum and temperature conditions representative of the space environment. The unit was mounted on PTFE supports inside an Angelantoni HVT2000 vacuum chamber (Figure *8*Figure *8*), with pressure levels maintained below 10^{-6} Pa. The thermal profile included one bake-out cycle in the non-operational qualification range (from –40 °C to +70 °C) followed by seven thermal cycles within the operational qualification range (–20 °C to +60 °C) (Figure 9). Six PT100 resistance temperature detectors were positioned at selected locations on the module to monitor thermal response. Functional tests were executed during thermal plateaus, as well as at the beginning and end of the test campaign.

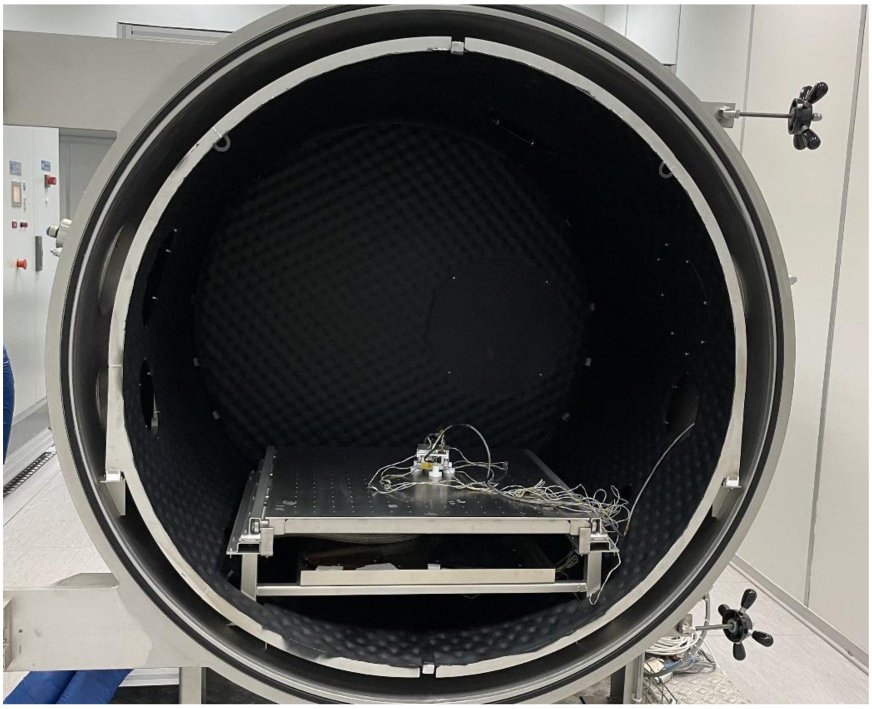

Figure 8 IANUS in TVAC

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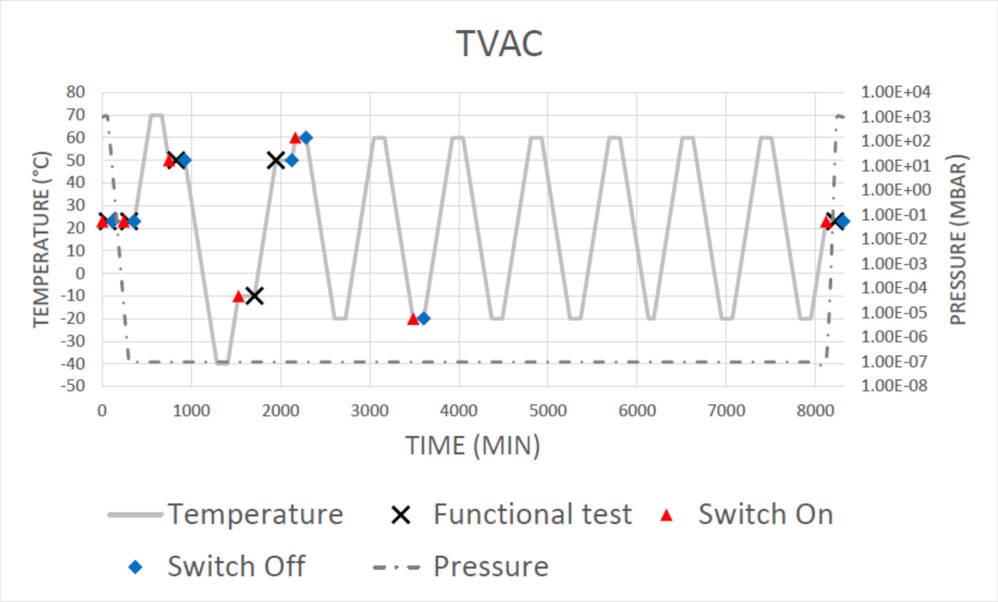

Figure 9 TVAC cycles profile

A slight pressure decrease was observed in the thruster's low-pressure stage during the thermal phase; however, subsequent functional verifications identified a manufacturing defect in the pressure regulator as the root cause. Specifically, the presence of a non-nominal metallic chip within the regulator, confirmed through inspections at the manufacturer's facility, accounted for the performance deviation. This finding provided a conclusive explanation for the observed variation and confirmed that the deviation was not attributable to the IANUS system itself.

Visual inspections and functional verifications were systematically performed at key stages of the Environmental Verification Testing (EVT) campaign:

- Prior to the shipment of the propulsion module to the test facility,
- Upon receipt at the facility, following unpacking,
- After each axis-specific vibration and shock test,
- Before and after thermal vacuum (TVAC) cycling,
- During the final post-campaign inspection at T4i premises.

All fasteners remained secure, with no evidence of epoxy staking delamination. Electronic subsystems operated nominally, and functional tests consistently met predefined criteria. The qualification campaign demonstrated the IANUS EQM's ability to withstand the combined mechanical and thermal loads associated with launch and space environments. No structural failures, performance degradation, or significant deviations in dynamic response were observed. The module preserved full functionality under shock and thermal conditions, confirming the robustness of its design and manufacturing. These results support the assignment of Technology Readiness Level 8 (TRL8), indicating readiness for integration on MILANI and subsequent deployment in the HERA deep-space mission.

4. Performance tests results

Performance testing focused on verifying the actual thrust output, specific impulse, repeatability, and accuracy of the propulsion system, following the test plan in Table 5.

Table 5 IANUS test plan

Test description	**Component**

Proof pressure test	Tank
Proof pressure test	Assembled system
Leakage assessment with Helium	Assembled system
Filling	Assembled system
Performance	Assembled system
EVT campaign	Assembled system
Leakage assessment with Helium post EVT	Assembled system
Performance test post EVT	Assembled system
Burst pressure test	Tank

Key outcomes include:

- **Thrust Measurement**: Each nozzle was tested for thrust generation, along with groups of nozzles to simulate maneuvers (Figure 10 and Figure 11). Thrust repeatability and accuracy were both evaluated and resulted to be less than 5% and 10%, respectively.
- **Responsiveness**: Valve actuation tests confirmed the ability to achieve target rise and decay times under 50 ms, ensuring agility for navigation maneuvers and precise control.
- **Leakage**: Leakage test with helium detector confirmed the ability to withstand the strict requirement of the interplanetary mission (Figure 12 and Figure 13).
- **System proof pressure**: The proof pressure test was carried out both at the tank level and at the assembled system level. At the system level, test pressure was limited to 20 barA due to the constraints of the selected isolation valve. In contrast, the tank-level proof and burst tests were conducted in accordance with ECSS standards, at 30 barA and 36 barA, respectively.

All performance characteristics were confirmed both before and after the environmental test campaign, proving the reliability and resilience of the propulsion system.

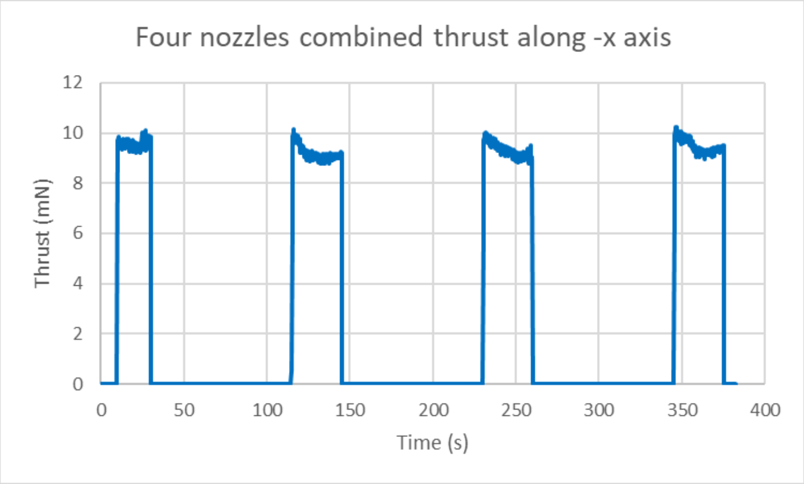

Figure 10 Four nozzles thrust on X axis pre-EVT

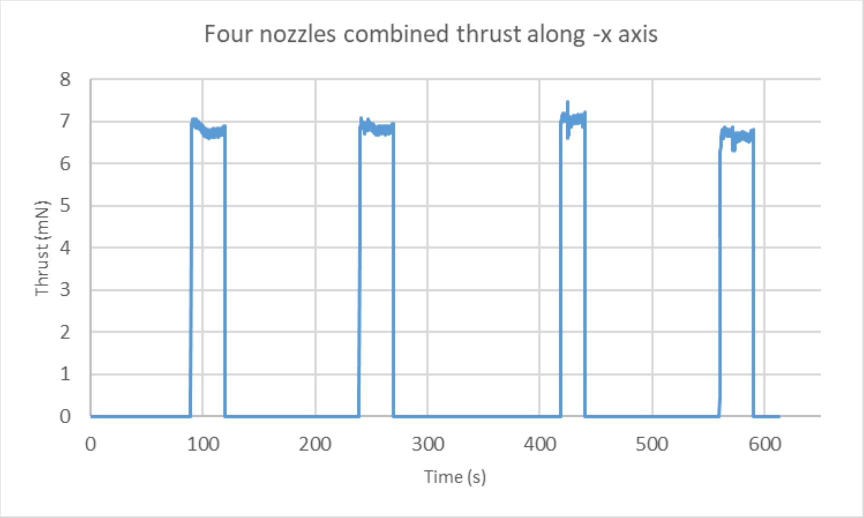

Figure 11 Four nozzles thrust on X axis post-EVT

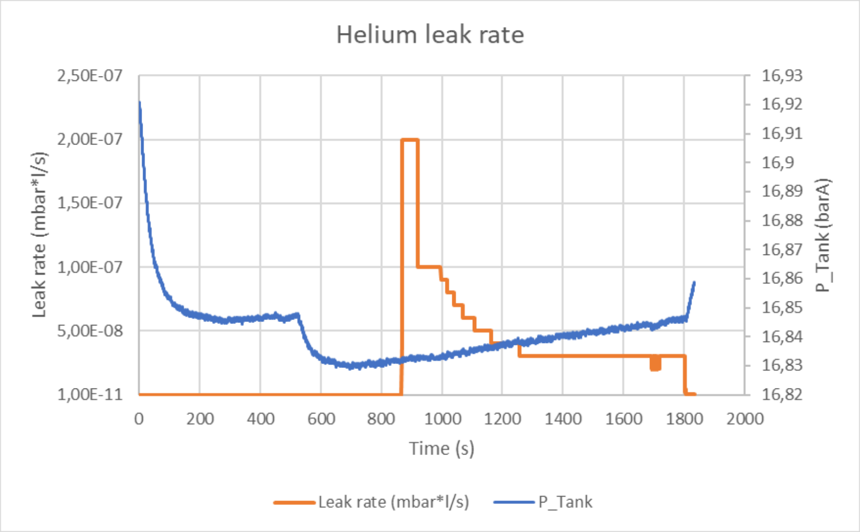

Figure 12 Helium test pre-EVT

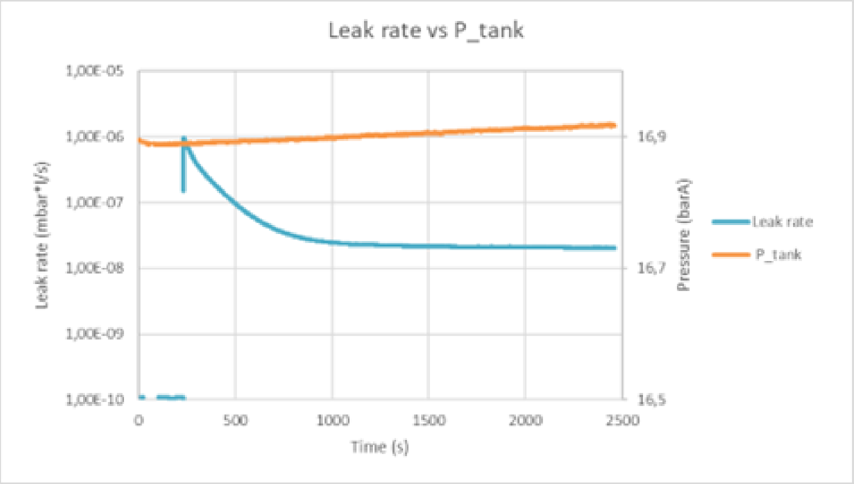

Figure 13 Helium test post-EVT

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5. Conclusions

The IANUS propulsion system constitutes a notable advancement in CubeSat propulsion technologies, providing a compact, efficient, and environmentally compliant solution designed for deep space applications. Over a 12-month development cycle, the system successfully achieved full qualification (TRL8) through a comprehensive campaign of structural, thermal, vibrational, and functional testing. In fact, the only deviation assessed was due to a manufacturing defect and not to the propulsion system itself.

Its modular architecture and additive-manufactured design minimize potential leak paths and optimize internal volume, while ensuring reliable performance. The integration of advanced propellant management, precise electronic control, and flight-qualified COTS components supports its suitability for future interplanetary CubeSat missions.

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