Performance verification of the µNRIT-2.5 thruster on the Nanobalance facility

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Abstract: This paper reports the results from the direct thrust measurements of the miniaturised RIT thruster µNRIT-2.5 on the TASI Nanobalance facility. The test, performed by Thales Alenia Space Italia and University of Giessen under ESA contract, allowed for the first time a complete characterization of the performance of this actuator, especially in the µN and sub-µN-level force regime.

I. Introduction

GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) is on orbit since March 17th 2009. Employing an ultra-sensitive gradiometer on a very low altitude orbit in along-track drag-free condition, GOCE has already provided in about 2 years a global model of the Earth's gravity field and of the geoid to an unprecedented spatial resolution and accuracy.

The objectives of a "Next-Generation Gravity Mission" (NGGM) are to provide the temporal variations of the Earth's gravity field over a time span of several years with high spatial resolution (i.e. ~100 km, comparable to that provided by GOCE, while it is about ~500 km in GRACE) and higher temporal resolution than GRACE (which is limited to ~1 month interval between successive gravity field maps). Such a mission will significantly improve our understanding on ice sheet and glaciers melting trends, continental water cycles, ocean masses dynamics, solid-earth deformations and other geophysical phenomena through the mass transportation (and the consequent temporal variations of the gravity field) produced within the Earth system. Preparatory studies suggest that the NGGM ought to be based on Low-Low Satellite-to-Satellite Tracking (LL-SST). This technique exploits the satellites themselves

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as “proof masses” immersed in the Earth gravity field. The satellites fly in a loose formation in which they are free to move under the action of the gravity field within a measurement band with a typical lower bound <1 mHz. Since the altitude of the satellite must be low (around 350 km or less) to increase the sensitivity to the higher harmonics of the Earth gravity field, the relative motion between the satellites will be perturbed by aerodynamic forces (air drag) too. The distance variation between their centres of mass (Δd, produced by both gravitational and non-gravitational forces together) is measured with high resolution by a distance metrology set-up. The achievement of the mission objectives calls for a relative error in the distance measurement of the order of 10^{-13} m/√Hz, for a typical inter-satellite distance of 100 km: this implies the use of a laser interferometer. The drag accelerations produced by the aerodynamic forces on the satellites are separately measured by means of accelerometers. The proper operation of the accelerometers requires a “drag-free” control in order to reduce the level of the linear and angular non-gravitational accelerations of each satellite below 10^{-8} m/s^2/√Hz and 10^{-8} rad/s^2/√Hz respectively.

In the preparatory studies carried out by Thales Alenia Space Italia (TAS-I), the miniaturized version of the Radiofrequency Ion Thruster (or MiniRIT) under development at the University of Giessen [1] has been identified as a promising actuator for the NGGM satellites. Thanks to its scalability, this thruster can perform all the MicroPropulsion tasks in this mission: orbit altitude maintenance, drag compensation, fine attitude control and laser beam pointing. Indeed, it seems possible to implement the RIT thrusters in the required two typologies:

- Main RIT thrusters for the along-track drag force compensation, orbit and formation control
- Lateral MiniRIT thrusters for the lateral drag force compensation and the attitude/laser beam control.

During the last years, Thales Alenia Space Italia has also implemented, under ESA contract, a test facility, the Nanobalance (NB), for the direct measurement of force and noise of μN-thrusters.

Towards the end of 2009, ESA has awarded a study contract to Thales Alenia Space Italia and University of Giessen with the objective of characterise the performance of a breadboard MiniRIT (μNRIT-2.5) on the Nanobalance. The test was performed in 2010. The MiniRIT thruster was characterised in terms of resolution, noise, linearity, rise/fall time, in the range from 50μN to 1mN. The measured noise, very likely limited by the NB operational performance in these test conditions, is however below the mission requirement. This together with the results of the other tests leads to confirm the MiniRIT as a good candidate actuator for a future gravimetric mission.

II. The NGGM MicroPropulsion requirements

The low-thrust electric propulsion with variable thrust is one of the key technologies for the realization of the NGGM. In particular, it allows:

- satellite orbit maintenance at its operational altitude;
- satellite formation control;
- implementation of the drag-free control at level of each satellite;
- attitude control of each satellite;
- laser beam pointing control.

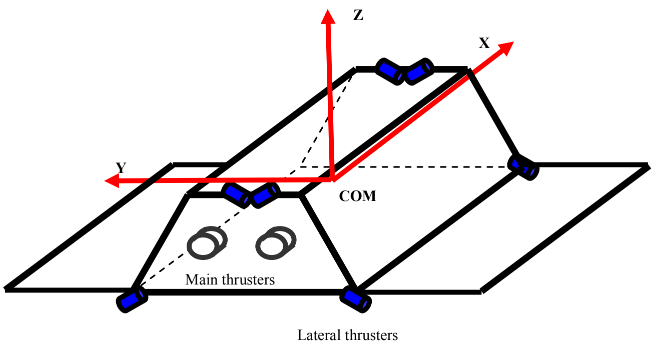

Figure 1: Arrangement of two main thrusters and eight lateral thrusters on the satellite for the NGGM

For the broad range of applications, more than one thruster typology is required, depending also on the satellite configuration and on the type of formation geometry. For the simplest in-line formation, in which the satellites chase each other along the same orbit and experience a main drag force always along the same axis, the need of two types of thrusters has been identified (main thrusters and lateral thrusters), arranged as shown in Figure 1 and with the preliminary requirements provided in **Figure 2** and **Figure 3**.

	Main Thrusters	Lateral Thrusters
Range	0.1 ÷ 6 mN	0.05 ÷ 1 mN
Resolution	4 μN	0.5 μN
Update command rate	10 Hz	10 Hz
Slew Rate	> 2 mNs	> 0.25 mNs

Figure 2: Preliminary requirements for the NGGM main and lateral thrusters

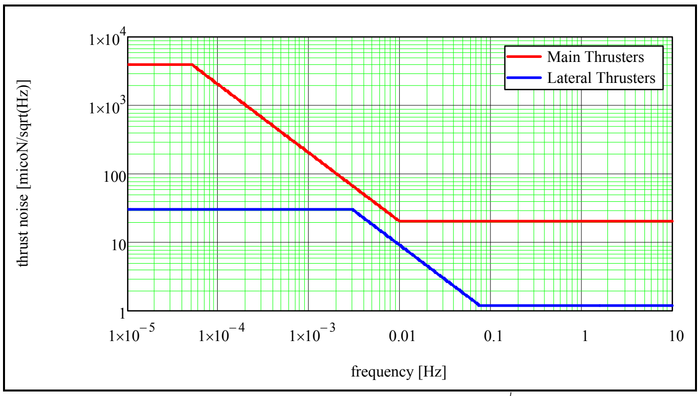

Figure 3: Preliminary requirements on the noise (µN/√Hz) of the main and lateral thrusters

Among the various electric propulsion technologies reviewed for this application, the Radio-Frequency Ion Thruster (RIT) appears very promising for the NGGM due to its “scalability”. Indeed, it seems possible to implement the RIT thrusters in the required two typologies:

- main RIT thrusters for the along-track drag force compensation, orbit and formation control;
- lateral MiniRIT thrusters for the lateral drag force compensation and the attitude/laser beam control.

The features of these thrusters are the dynamic range (a value > 40 is needed to cope with the large variation of the drag forces encountered in a long duration mission, especially in periods of high solar activity), the specific power for minimizing the solar panel surface, and the specific impulse for reducing propellant consumption.

III. MiniRIT technology for NGGM

Radio-frequency Ion Thrusters (RITs) generate thrust by the electrostatic acceleration of xenon ions. Since the middle of the 60th of the last century, RIT thrusters have been designed, built and qualified by Astrium Lampoldshausen (D) and University of Giessen (D). These thrusters cover the thrust range from 10mN to 250mN. RIT10 has been the first Western European ion thruster operated in space on EURECA (European Retrievable Carrier) mission. Since 2003, RIT-10 is flying in space onboard ARTEMIS satellite.

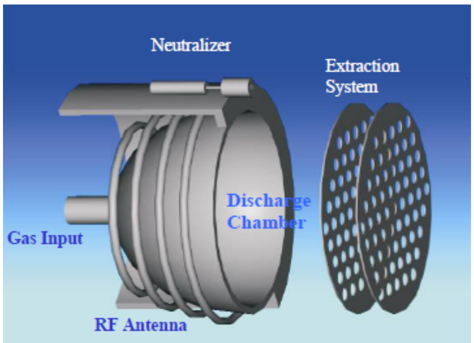

Figure 4: Functional principle of RIT

The development of the miniRIT thruster, initiated in 2005, bases on the heritage in design, development, test and space operation of RIT10. Since 2005 several miniRIT breadboard have been built and tested to respond to the need of MicroPropulsion systems capable of providing precise thrust modulation in the µN to low mN regime.

For its operation the thruster requires propellant (xenon) and electric power. Neutral xenon gas is injected into the thruster’s ionisation unit via an integrated insulator and gas distributor. The ionisation occurs in a vessel made by an insulating material (discharge chamber) and surrounded by the induction coil (RF Antenna) that is part of the resonance circuit of a radio frequency generator (RFG). The induced electric eddy-field accelerates electrons and generates a self-sustaining, electrodeless gas-discharge. From this plasma the ions are extracted, focused, and accelerated by a two-grid system made of Molybdenum and Graphite, ultimately generating thrust.

The thrust produced by the RIT thrusters depends on the mass of the propellant coming out of the thruster (ion current) and on the velocity of these ions (ion acceleration voltage), through the expression:

$$T = J * \eta_{\mathrm{hom}} * \eta_{\mathrm{hom}} * \sqrt{2 * \frac{m_{ion}}{q_{ion}} * U_{beam}}$$

Where J is the ion beam current and U_{beam} the extraction/acceleration voltage. To change the thrust (T), it can be changed the U_{beam}, which provides a very small thrust dynamics or the J by regulating either the RF power or the propellant mass flow, as:

$$J = \dot{m} * P_{RF}$$

The thrust control of the MiniRIT is performed by the beam current controller. **Figure 5** shows a block diagram of this closed loop system. The extracted ion current from the thruster is measured by a high precision resistor. This signal is used for a PID regulator, which controls the radio frequency power fed into the plasma. Using this concept, the beam current is kept constant.

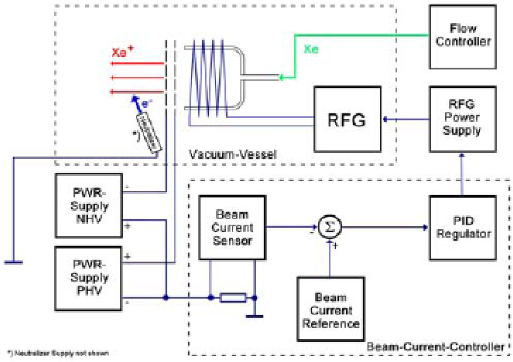

Figure 5: Block diagram of beam current control loop

Test performed in the past on several MiniRIT thrusters showed the ability of this type of thrusters to provide very precise thrust modulation. However, the performance test had still to show that the application requirements of NGGM like thrust noise, thrust accuracy and stepping, power and propellant consumption, engine mass, etc. could be fulfilled.
Following the R&D work by Giessen University and Astrium, the μNRIT-2.5 MiniRIT thruster prototype was designed, built and tested at Giessen [1]. The μNRIT-2.5 has a nominal thrusting range between 50 μN and 500 μN, an RF-power consumption of less than 15 W at maximum thrust level, and a mass of only 210 g.

IV. The TASI Nanobalance Facility

The Nanobalance (NB) is a complete test system for the direct measurement of the force provided by a micro-thruster (MT) along its thrust axis [2]. Developed within a contract of the European Space Agency by Thales Alenia Space Italia in co-operation with the Italian National Metrology Institute and Politecnico di Torino (I), the Nanobalance is supporting the development and testing of MicroPropulsion technologies for major European space programmes like LISA Pathfinder [3], LISA, GAIA, Microscope and NGGM.
The Nanobalance thrust stand is essentially composed by two vertical "tilting plates", made in Copper Beryllium alloy, connected by a flexible joint to a rigid block, made of Zerodur®, in a pendulum-like arrangement (**Figure 6**).
The micro-thruster under characterization is installed on one of the tilting plates, the so called "*active tilting plate*". A second, passive MT (or a dummy MT) is installed on the second tilting plate, called "*passive tilting plate*", to ensure the same dynamics behaviour of the active one. Tilting plate balancing must be assured also for the rejection of the common-mode environmental vibrations acting on the thrust stand. Flexible joint stiffness, pendulum geometry and mass have been designed in order to provide each pendulum with a natural frequency $f \geq 10$ Hz (the natural frequency of the tilting plates is ≈13 Hz, without MT installed). The natural oscillation frequency of the two tilting plates shall be made as much identical as possible for thrust stand balancing purpose.
When the micro-thruster is switched on, it produces a displacement of one plate relatively to the other, measured by means of a Metrology System (MS) consisting of a Fabry-Perot (F-P) laser interferometer, whose reference spherical mirrors are mounted at the bottom of the tilting plates. The F-P interferometer is fed by an Nd:YAG source working at the wavelength λ = 532 nm (2^{nd} harmonic). The laser frequency is regulated so as to maintain it locked to the F-P resonator, since the relative distance between the two mirrors changes under the action of the MT (i.e. the laser frequency tracks the distance variation). The frequency of this laser (measurement laser) is measured against the frequency on an identical Nd:YAG laser (reference laser) stabilized on a Iodine molecular transition using the Pound-Drever technique. The beat frequency of these two lasers (reference and measurement laser) is measured by a

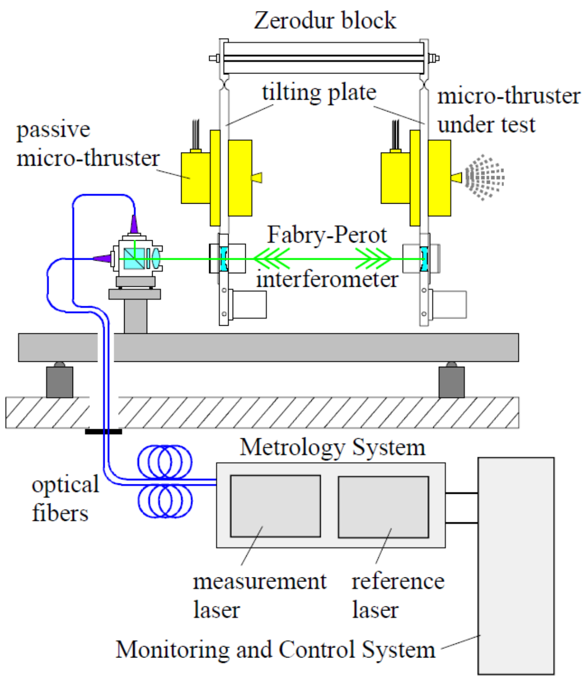

Figure 6: Block diagram of the Nanobalance

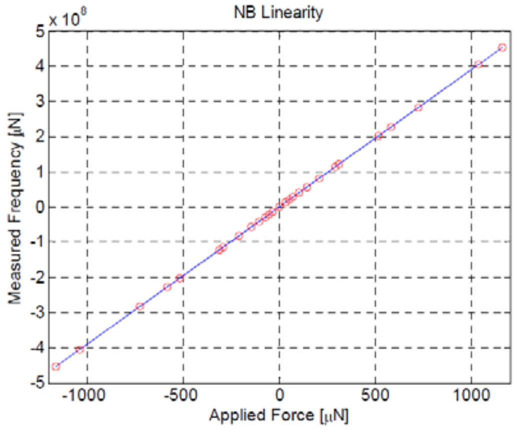

Figure 7: Relationship between applied force and measured frequency variations extended up to ≈±1 mN range

frequency-meter and converted in a force measurement using a calibration relationship (shown in **Figure 7**), verified by means of the voice coil actuator permanently installed on the active tilting plate and operable even during the test campaign.

The Nanobalance thrust stand is operated inside a vacuum chamber (see **Figure 8**) with an internal length of 2.5 m and an internal diameter of 1.2 m, provided with one primary pump, one turbo-molecular pump (with nominal pumping speed of N_2 = 2000 l/s) and two ion pumps (with nominal pumping speed of N_2 = 500 l/s each). The vacuum pumps are capable to maintain the pressure inside the chamber below $3.5 \cdot 10^{-5}$ mbar for mini-RIT firing up to 1mN.

The chamber has two large doors and can be split in two parts for a full access to the thrust stand. The vacuum chamber is installed on four pneumatic isolators placed on an anti-seismic block for minimizing the level of micro-vibrations reaching the thrust stand. Inside the vacuum chamber, the thrust stand is mounted on a horizontal basement which inclination is actively zeroed by a sub-microradian control system. The first level of the control stage is composed by a passive decoupling system to further reduce the horizontal accelerations of the NB thrust stand along the measurement direction. The thrust stand horizontality is then kept by means of the second control stage level composed by three piezoelectric motors installed on the NB basement, driven by a digital closed loop [4] which is fed by the measurement of a tilt-meter installed on top of the Zerodur® spacer.

The Nanobalance test facility is controlled by the Monitoring and Control System (MCS), which is in charge of controlling the MS and the thrust stand horizontality, monitoring the pressure of the vacuum chamber, the temperatures and inclination of the thrust stand and some telemetry data coming either from the thruster under test or from its control electronics. The MCS acquires also the output of the frequency-meter and converts it, in real time, into the thrust measurement. All the MCS parameters and measures are controlled and displayed in real-time by a Graphic User Interface (GUI).

Figure 8: Vacuum chamber hosting the Nanobalance thrust stand

The Nanobalance has been fully commissioned without thruster and with representative thrusters (pressurized micro-valve and ion source).

V. Test Plan

The aim of the tests was to verify the miniRIT Thruster performance compliancy to the preliminary performance requirements applicable to the ion thrusters for the NGGM. Specifically, main goals of the test are:

- provide functional and performance verification of the Thruster Unit in terms of the actual (measured) thrust,
- provide means for proper correlation of electrical parameters with real thrust data,
- provide measurement of thrust range, resolution, linearity, rise/fall time, slew-rate and noise.

Before proceeding with the measurements, a series of preparatory test were performed to evaluate the sensitivity of the Nanobalance Thrust Stand to the parasitic noise effect like as electrostatic force due to high voltage, RF generator and thruster working temperature and xenon plume impingement.

The sensitivity test provided the following information:

- 2.75 µN / kV is parasitic force measured by the Nanobalance due to electrostatic interaction between the thruster and the NB thrust stand caused by the application of High Voltage to the thruster grids
- 0.85 µN / sccm is the parasitic effect on the Nanobalance due to flow regulation
- RF generator water cooling system can not be used during the NB measurement session.
- Very large measurements drift was detected due to thermal dissipation, especially when RF power was applied to the thruster coil.

The first two issues were resolved using suitable test procedures and no parasitic errors were introduced on measurement.

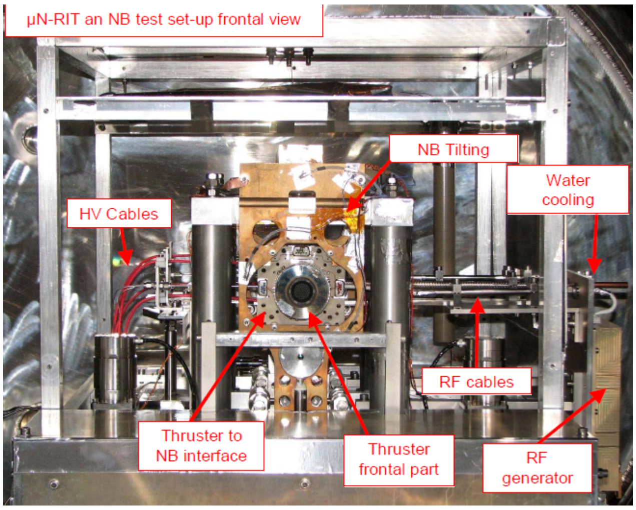

Figure 9: Test set up

The last two issues, instead, resulted in a limit in the NB continuous measurement time and, as consequence, in the data segments length used for Noise PSD computation.

The test setup is depicted in **Figure 9.** The thruster is fixed adiabatically to the Nanobalance tilting plate and a dummy thruster (with dummy piping and RF and HV cables) is installed on the passive Nanobalance tilting plate for balancing purpose. RF generator water cooling system is installed to avoid that the RF generator temperature achieve critical temperature (~ 40 ºC) during it operation. The water cooling system consists in a copper plate connected to the RF generator basement on top of which is welded a copper serpentine. Inside the serpentine it is possible to flush water using two pipes, connected trough a vacuum feedthrough to the laboratory water services.

VI. Test Results

The thrust range has been measured up to 1 mN as planned. As expected, the thrust throttling from 50 µN up to 1 mN can not be performed modulating only the RF power injected into the thruster RF coil. To achieve the required throttling the voltage applied to the thruster grids and/or to the Xenon flow rate injected into the thruster discharge chamber must be modulated together with the thruster RF power. Even if the prototype model of thruster control unit used during the tests not allowed the modulation of the above thruster parameters in a synchronous way, it is expected that the flight thruster control unit will permit, at least, the synchronous modulation of the RF power and of the voltage grids. In that case there will no problems to change the thrust level from 50 µN to 1 mN even in a single step, if needed.

The Nanobalance measured thrust versus the nominal one (that computed by the MiniRIT Control Unit, which is equal to the commanded thrust within 0.1µN due to the Control Unit ADC/DAC quantization) is shown in **Figure 11**. The scale factor between the measured thrust and the computed (commanded) thrust deviates from the unity by 3.05% over the full thrust range of 50 µN to 1 mN. This discrepancy could be introduced by the Nanobalance measurement drift during the test. In any case, a difference of 3.05% (and probably up to 5%) between the commanded and the achieved thrust is acceptable for the NGGM application, in which the thrusters are utilized in a closed-loop control system. Moreover, if necessary, this scale factor can be calibrated and corrected.

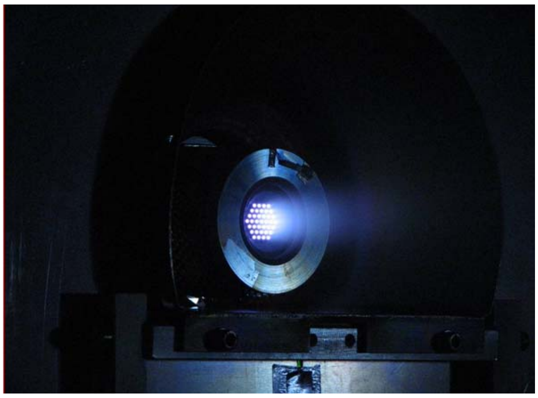
Figure 10: Thruster firing during test

Thrust resolution tests results shown that the current MiniRIT prototype and control electronics can be commanded with a resolution of about 0.1 µN. This is confirmed by the thrust computed from the thruster parameters. The Nanobalance excessive background noise in the test conditions prevented the direct verification of this resolution. The minimum steps

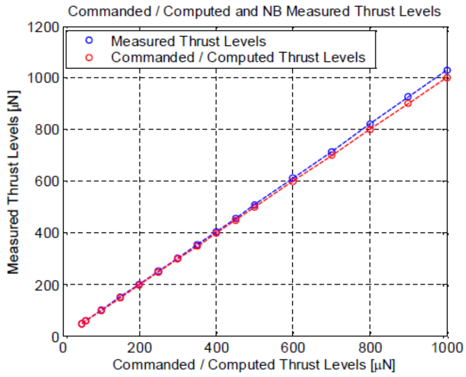

Figure 11: Nanobalance measured whole thrust characteristic vs. commanded / computed thrust

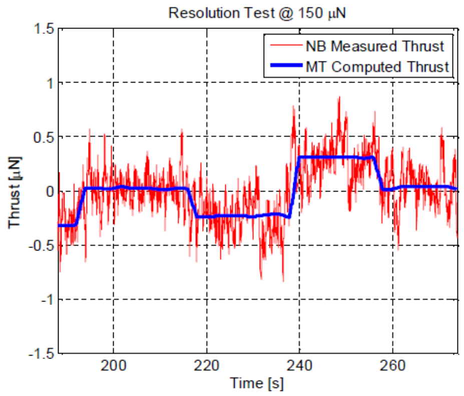

Figure 12: Thrust resolution

detectable from the Nanobalance measurements were ±0.3 μN, anyway compliant with the NGGM requirement (**Figure 12**).

From the results collected in all tests, it can be concluded that the thruster deviation from a linear behaviour is lower than ±2% (specification) from 50 μN to 1 mN.

The measure of the rise/fall time is limited by the response of the NB measurement filter. As visible in Figure 13 in the red plot (measure of the thrust filtered by the Nanobalance tilting plates beat) the thrust rise and fall in ≈ 100 ms whichever is the amplitude of the thrust step. This is the rise/fall time limits of the Nanobalance measurement filter. Filtering the Nanobalance measure with filter with higher bandwidth (and unfortunately introducing more noise on the Nanobalance measure) the measured rising and falling time is less than 50 ms. It is not possible to exactly measure the thruster intrinsic rise/fall time but it is possible to confirm that it is less than 50 ms.

The thruster noise has been measured at different thrust levels up to 650 μN. Above this level the test was not possible due to the temperature problems affecting the behaviour of the Nanobalance and the thruster itself, as the thruster is mounted adiabatically. The measured thrust noise is dominated by the Nanobalance background noise in test conditions, which is itself very close to the measurement requirement. In all tests, the measured noise is very close to the NB background noise which therefore represents an upper limit to the actual thrust noise. From 0.1 to 1 Hz, the measured thrust noise is always under the requirement and below 0.1 Hz it is very close to the requirement, as the NB background noise is. The thrust noise computed by the MTCU using the thruster parameter is, as expected, always much lower than the requirement (**Figure 13**), [5].

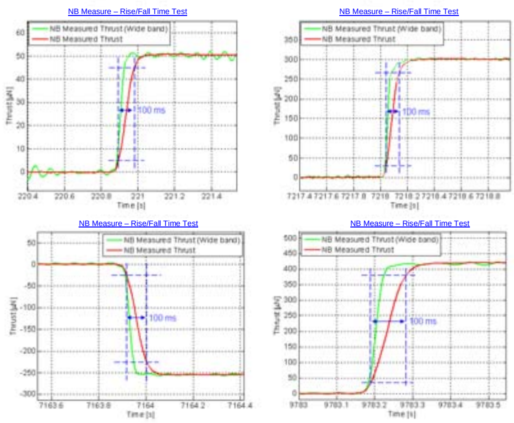

Figure 14: Thrust rise/fall time

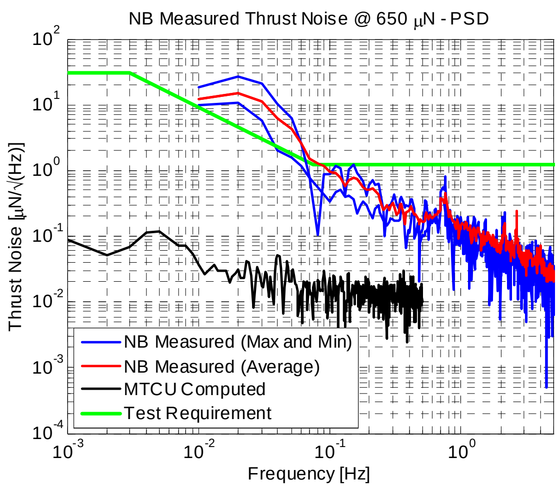

Figure 13: Thrust noise

VII. Conclusion

Globally the test results confirm the miniRIT as a good candidate actuator for the NGGM.
As result, the miniRIT MicroPropulsion system has been recommended for further development, especially in the version needed for the control of the lateral drag forces and of the satellite pointing, on the basis of the performance requirements preliminarily established in the NGGM study and with the objective of maximising the specific impulse and minimising the specific power across the whole thrust range.
The experience of this test campaign shall be also exploited for developing a new Thrust Stand and to improve the Nanobalance test set-up so to minimize the thermal disturbance coming from the thruster and the RF generator.
This development/improvement must be tailored to the accommodation of the qualification/flight version of the miniRIT, and shall lead to the availability of upgraded facility on time for repeating the performance tests on the qualification model of the thruster, and possibly for measuring also the specific impulse and power.
A possible evolution of the Nanobalance Thrust Stand for improving the thermal decoupling between the thruster and the measurement device has been already conceived by TAS-I and subject to a preliminary prototyping within an internally funded R&D activity.

Tested parameter	Requirement	Measured Values	Status
Thrust Range	The current prototype of the mini-RIT shall be able to provide continuous thrust with any value in the range 50 µN to 1 mN	From 50 µN up to 1mN.	Fully compliant.
Thrust Resolution	The mini-RIT shall be able to provide continuous thrust in the overall range (50 µN -1 mN) with a minimum resolution of 0.5 µN	Resolution of 0.5 µN, and in some cases of 0.3 µN, measured in the 50 – 550 µN range. Resolution not measurable above 550 µN due to operational constraints and excessive NB background noise.	Compliant in the tested range.
Thrust gain non linearity	The mini-RIT shall ensure that the gain non linearity of the delivered thrust respect to the commanded thrust shall differ by not more than the 2% throughout the whole thrust range.	< 2% from 100µN up to 1mN < 2% from 50 µN to 650 µN < 5.5% from 50µN up to 1mN, with maximum deviation (above 2%) only in the points at 50 µN and 60 µN.	Partially compliant over the full thrust range. Compliant on reduced ranges.
Rise/fall time	The mini-RIT rise/fall time (time required to switch from the 10% to the 90% of the final thrust step) shall be <50 ms.	Measured thrust rise/fall time < 50 ms over the full thrust range, for any thrust step from 50 µN to 400 µN.	Thrust rise/fall time fully compliant.
Slew rate	The mini-RIT shall be able to change the thrust value at a rate > 0.5 mN/s (50 µN step performed in 100 ms)	Slew rate >1 mN/s (derived from the rise/fall time measurement with a 50 µN step).	Thrust slew rate fully compliant.
Thrust Noise	The thrust noise of the mini-RIT shall be <1.2µN/√Hz for frequencies between 75 mHz and 1 Hz, and not exceed a 1/f increase between 75 mHz and 3 mHz.	Thrust noise measurements limited by the Nanobalance background Noise, but lower the requirement from 0.1 to 1 Hz, and close to the requirement from 0.01 to 0.1 Hz. Noise not measurable below 0.01 Hz due to excessive thermal drifts.	Compliant over the frequency range in which the measure was possible.

Figure 15: Summary of test results

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