

Micronewton Balance Measurements at Onera and Application to the GAIA Mission

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Thrust measurements are essential to qualify thrusters for space missions, especially for new technologies. In the micronewton range, few thrust balances are available with the required accuracy. Onera has been developing a micronewton balance for 10 years, now achieving a thrust resolution $<0.1 \mu\text{N}$ and a range of 10 mN, with a thrust noise of $0.1 \mu\text{N}/\sqrt{\text{Hz}}$ in the range [0.02-1 Hz]. In view of its performances the Onera balance has been selected for the test of the 13 GAIA thrusters. The 13 newly-developed GAIA cold gas micronewton thrusters (CG-MT) from TAS-I were subjected to acceptance tests in order to measure their thrust noise and specific impulse curve. The calibration of the balance is presented, and the post-processing corrections leading to these performances are detailed. The specific impulse of the 13 CG-MT flight models has been measured for thrust levels in the range [0.2-1000 μN].

Nomenclature

C_b	=	backscattering correction factor, μN
C_p	=	pressure correction factor, μN
C_v	=	valve movement correction factor, μN
D	=	position of the calibration masses relative to the balance axis, mm
g	=	standard acceleration of gravity, m/s^2
I_{sp}	=	specific impulse, s
L	=	length of the balance arm, mm
PSD	=	power spectral density, $\mu\text{N}/\sqrt{\text{Hz}}$
Q_m	=	mass flow rate, $\mu\text{g/s}$
Q_v	=	volumetric flow rate, sccm
S	=	capacitive sensor signal, V
T	=	thrust, μN
T_{eq}	=	equivalent thrust, μN
W	=	weight of calibration masses, g
α	=	calibration factor of the balance, $\text{V}/\mu\text{N}$
σ	=	standard deviation
$\gamma_{//}$	=	projection of gravity
θ	=	angle of the pendulum, rad
Δl	=	linear displacement of the bottom of the pendulum, nm

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I. Introduction

The direct measurement of the thrust generated by the GAIA cold gas thrusters is a fundamental step in the validation of their performances for successful realization of GAIA mission. However, it is a challenging endeavor because of the requirements: very low minimum thrust levels ($<1 \mu\text{N}$), low noise ($<1 \mu\text{N}/\text{Hz}$), and large bandwidth (10^{-3} to 10 Hz). Several balances exist for micronewton thruster characterization: at ONERA [1,2], Thales Alenia Space Italia [3], Busek [4,5] (USA), NASA Goddard [6] (USA), Marotta [7] (UK), University of Southampton [8] (UK), and ESTEC [9] (Netherlands). But very few thrust balances are currently able to meet the most stringent space mission requirements in both resolution and bandwidth.

ONERA has been developing a micronewton balance since 1999 in order to fill the need for a micronewton thrust stand in Europe for scientific missions such as GAIA, Microscope, LISA, or Euclid. The balance has been successfully tested in the range $[1\text{-}20 \mu\text{N}]$ with an Indium FEEP thruster from Austrian Research Center at Seibeldorff (ARCS) [1], and in the range $[1\text{-}200 \mu\text{N}]$ with a cold gas thruster from Bradford Engineering [2]. Recent improvements of the balance design, under CNES funding, have enabled to extend thrust measurement to the range $[0.1\text{-}1000 \mu\text{N}]$, and to significantly reduce the noise [10]. A thrust measurement test on a prototype GAIA CG-MT from TAS was done in 2010 for Astrium. Following these performances improvement, the ONERA micronewton balance has been selected by ESA for thrust characterization of GAIA CG-MTs.

This paper presents the current configuration of the Onera micronewton balance, and the results of the thrust qualification campaign of the 13 flight-model cold gas thrusters manufactured by TAS-I that will be mounted on GAIA service module. The principle of the ONERA micronewton balance and the thrust calibration procedure are described, and the background noise and thrust noise performances are presented. A description of the thrust data post-treatment with all necessary corrections is provided. Finally, we present a synthesis of the thrust results and specific impulse (I_{sp}) obtained with all thrusters.

II. Micronewton Balance Description

A. Fluidic and vacuum system

The vacuum tank used for the measurements is 50 cm in diameter and 70 cm long and is mounted on a support structure that has a lowest resonant frequency of 25 Hz, which is of importance to avoid excitation of the main balance vibration mode at 17 Hz (Fig. 1). A turbomolecular pump with pumping speed 1000 l/s for N_2 yields a limit vacuum $<10^{-7}$ mbar. Typically, with a cold gas thruster of I_{sp} 50 s running with a thrust of 1 mN, the vacuum level, measured with a MKS 999 Quattro vacuum transducer, is about 1×10^{-3} mbar.

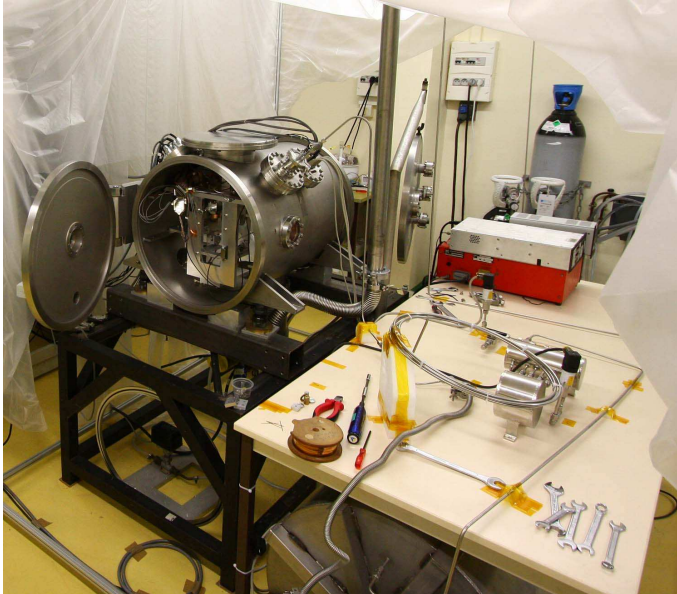


Fig. 1 Picture of the vacuum tank with the balance mounted in it.

Ten temperature sensors, with a resolution of 0.01 °C and an accuracy of 0.05 °C, are placed in different parts of the tank and balance assembly. They allow for monitoring the thermal stability of the balance, which is important to avoid a drift in the thrust signal. In particular an air conditioning system and a set of thermal shields acting as temperature low-pass filters damping the room temperature variations, have been installed in the laboratory (Fig. 2).



Fig. 2 Thermal shield installed in order to serve as a low-pass filter for the temperature variations of the room due to the pulsed air conditioning system.

B. Principle of the balance

The ONERA micronewton balance used for this campaign is a vertical pendulum (Fig. 3). In the basic configuration, the thruster applies a horizontal force on the pendulum, which then moves from its initial vertical position to a new, tilted equilibrium position. In this tilted position the torques of the thrust and of the weight of the pendulum cancel each other. The angle of the pendulum is then a linear measure of the thrust, given that the angle is usually very small ($\ll 1^\circ$).

A vertical pendulum has two advantages compared to other balance types (torsion and weight balance):

- the frictionless pivot and equilibration is technically simple;
- thrust calibration can be done in an absolute manner with calibrated weights; this will be described in a later section.

Displacement sensors are placed on the pendulum to measure the angle and two different types of sensors are used. One is an accelerometer (Honeywell QA 2000) whose axis measures the projection $\gamma_{//}$ of gravity when the pendulum tilts. It is also used as a vertical reference. The other sensor is a capacitive sensor (Fogale, MC900), which measures the linear movement of the bottom of the pendulum. The capacitive sensor is the one used for actual thrust measurement because of its higher signal-to-noise ratio, while the accelerometer is used as a vertical reference and for redundancy.

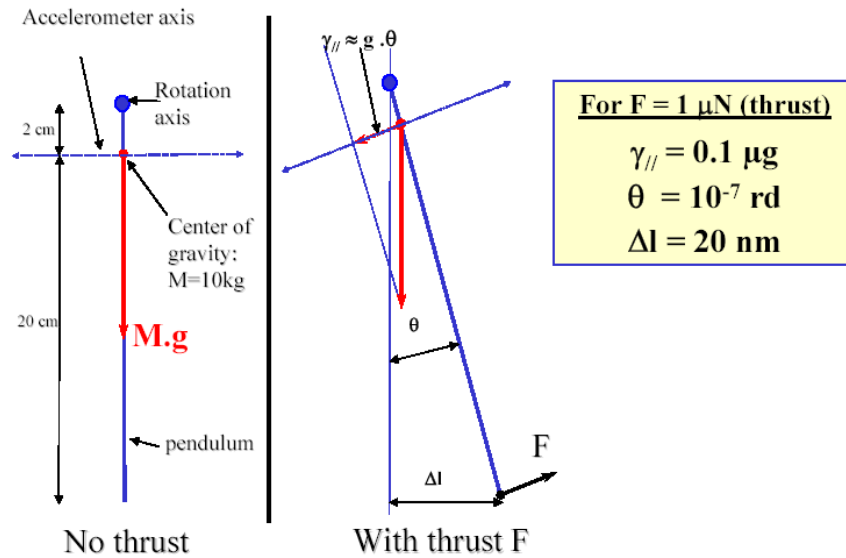


Fig. 3 Principle of the ONERA micronewton balance, and order of magnitudes of characteristic displacements.

A more detailed schematic of the balance is shown in Fig. 4. All the displacement sensors are shown:

- two accelerometers: one on the pendulum for tilt measurement, one on the balance support to measure the tilt of the vacuum tank due to ground and structure vibration.
- one capacitive sensor on the pendulum arm.

The pendulum is of the compound type, where a moving counterweight is used to change the position of the center of gravity of the system, thus changing the sensitivity and natural frequency of the balance. Typically the natural frequency used in experiments is around 0.3 Hz. Note that the time response of the balance is not limited to this value, because its frequency transfer function is very well known and can be used to recover a much higher time response, at the expense of a larger floor noise, as will be shown below.

At the bottom of the pendulum two actuators are placed. The first one is a copper plate close to a permanent magnet: this is the frictionless Foucault current damping system, which allows the pendulum to be near optimum damping. The second one is a coil moving also near a permanent magnet on the vacuum tank. By making a current flow through the coil, a force is applied on the balance: this is the coil actuator. One of the characteristics is its linearity: because the movement of the coil is frictionless and is very small, ($<1 \mu\text{m}$) compared to the gradient of the magnetic field of the permanent magnet, the force is very much proportional to the current.

The axis of rotation is a frictionless pivot: the pendulum is suspended with four blades.

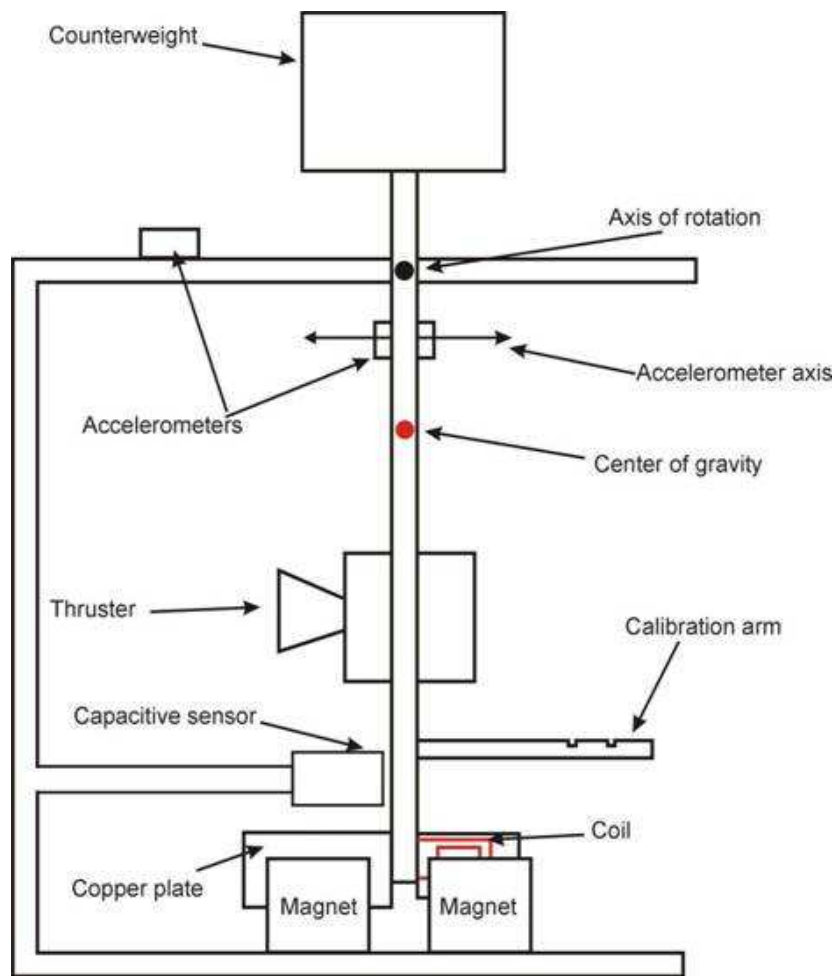


Fig. 4 Configuration of the balance.

The electrical connections to the balance arm are made with thin enameled copper wire. The fluid connections to the balance is made with a 1/16" plastic tubing 3 cm long.

Finally, two balance configurations can be used:

- the horizontal configuration: it is the one described so far, where the thrust vector is horizontal (Fig. 5, left); this configuration is best for electric propulsion (e.g. FEEP thrusters [1]).
- the vertical configuration: the thruster is mounted on an horizontal arm, and the thrust vector is vertical (Fig. 5, right); this configuration is best for cold gas thrusters.

The reason for the use of the vertical configuration lies in the internal, longitudinal valve movement of cold gas thrusters. In the horizontal configuration, the valve shift (when it is opened or closed) changes the mass distribution of the pendulum, and thus creates a tilt of the pendulum. This tilt can be confused with the action of a thrust. In contrast, in the vertical configuration the longitudinal position of the valve is not important for the equilibrium of the pendulum, and thus only a thrust can affect the pendulum (as long as the valve does not have "side" movements). In this case, only residual second-order side movements of internal parts in the thruster create a perturbation of the thrust measurement, and this small remaining effect can be somewhat compensated by careful calibration, as will be explained. It is noteworthy that this small unbalance should be taken into account for thrust measurement calibration, but it is not a thrust error in flight.

In the vertical configuration, if the length of the horizontal arm is the same as the length of the vertical arm (170 mm in our case), and if we neglect the added mass of the arm, the thrust sensitivity will be the same in both configurations because the torque created by the thrust is the same in both cases ($T \cdot L$ in Fig. 5; T =thrust, L =arm length).

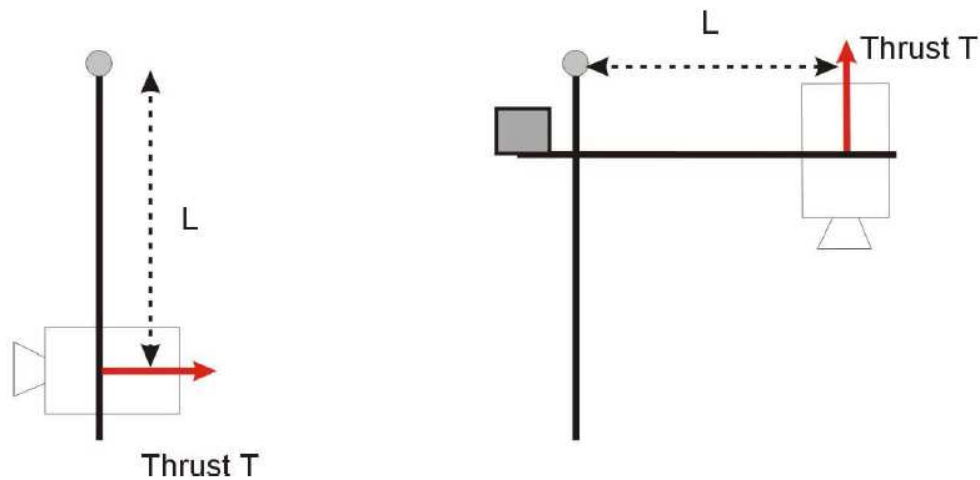


Fig. 5 The two balance configurations: horizontal configuration (left) and vertical configuration (right).

C. Electrical equipment

The data acquisition system is comprised of a 16 channel, 18 bit, 500 kHz, National Instrument DAQ board connected to a computer where a Labview program runs the acquisition. Anti-aliasing low-pass filters are used on nearly all channels, especially those where the frequency content is important (such as the capacitive sensor channel). The filters are of the Butterworth type with 24 dB/octave slope. The data acquisition is done at 40 Hz sampling with 20 Hz (cutoff frequency) filters. For noise measurements the bandwidth is used up to 10 Hz. For thrust measurement, in order to reduce the noise, further averaging is done during post-processing, reducing the bandwidth to about 0.1 Hz, which is appropriate for thrust steps 30 s long as used.

D. Thrust calibration

One of the advantages of a pendulum balance is that it allows for an absolute and precise thrust calibration. The principle is to deposit masses on a small horizontal arm attached to the pendulum. The calibration arm schematic is visible in Fig. 4 and is shown in more detail in Fig. 6. The weights of small masses are calibrated very precisely with a Mettler Toledo balance precise to 0.01 mg. These masses are placed on a vertical, vacuum-rated translation stage. The calibration can thus be operated in vacuum, in the same exact conditions as the thrust measurements. For calibration, different masses can be sequentially deposited on the calibration arm, thus imposing calibrated torques on the balance.

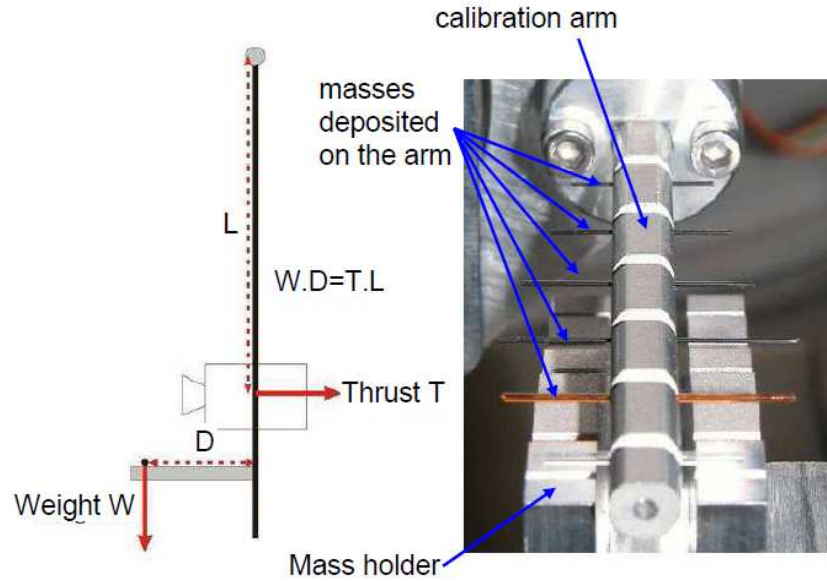


Fig. 6 Principle of thrust calibration (left) and image of six masses deposited on the calibration arm (right).

Following the notations on Fig. 6, if the measured signal is S for a weight W , we obtain a calibration factor $\alpha = S/(W.D)$ in $V/(N.m)$. Then, during the measurement of a thrust T with signal S_t , we deduce the torque of the thrust S_t/α and since it is equal to $T.L$, we deduce T . In order to check for linearity over the whole range of the balance, we can use several calibrated masses that are deposited sequentially at different positions on the calibration arm (Fig. 6, right). Table 1 presents the six masses used for calibration with their position relative to the balance axis, and the cumulated equivalent thrust produced T_{eq} .

Table 1 Calibration masses used

Mass (mg)	Position (mm)	T_{eq} (μN)
6.20	20.5	7.33
9.26	25.5	20.96
18.67	30.5	53.81
45.57	40.5	160.30
109.92	45.5	448.87
194.70	50.5	1016.20

For the lower ($< 7 \mu N$) thrust range it is not practical to use masses for calibration. We then use the coil actuator, which has a linear behavior. The calibration from the coil is matched to the absolute masses calibration in the $[7.33-1016.2 \mu N]$ thrust range, and it allows us to calibrate and check linearity down to $0.1 \mu N$. This is a straightforward procedure and does not a priori involve any uncertainty. In fact the calibration does not have any assumption besides the linearity of the actuator which is trivial. A typical calibration curve obtained in this manner is shown in Fig. 7. The error bars correspond to:

- for the masses (see error budget): 0.5% (error on mass determination) plus $0.02 \mu N$ (measurement error due to balance noise);
- for the coil : 1% (estimate on coil current uncertainty) plus $0.02 \mu N$ (measurement error due to balance noise).

The ideal balance should be linear (i.e. have a constant calibration factor). In this example, a calibration factor of $6.13 mV/\mu N$ is a good value at all thrust levels. A calibration of the balance was performed before all thrust sequences and correction factors measurements.

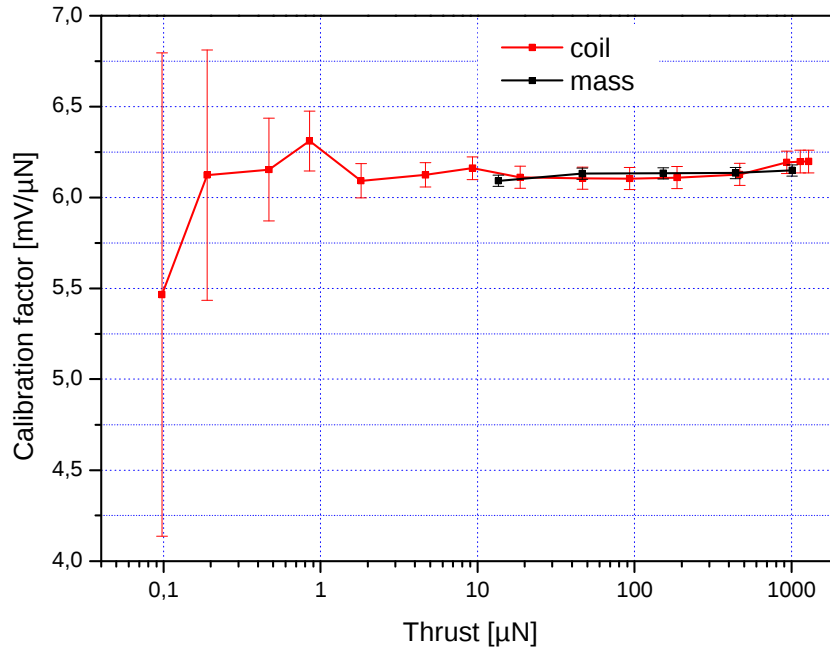


Fig. 7 Typical calibration factor curve obtained with the masses and with the coil actuator. The error bars correspond to $1\% + 0.05 \mu\text{N}$.

III. Setup specific to GAIA measurements

The fluidic set up description is shown in Fig. 8. The MT is located inside the vacuum chamber mounted on the balance arm. The nitrogen gas is fed from an ultra-high purity (99.9999%) Alphagaz 2 cylinder through a dedicated fluidic pipe line. A lab pressure regulator produces a pressure slightly above 1 bar (~ 1.05 bar). A large buffer tank (400 L) has been added downstream from the regulator to limit pressure variations during thruster firing, because the mechanical regulator cannot maintain the pressure with enough accuracy. Two Kistler pressure transducers are used, one upstream the vacuum chamber (PT1) and the other just upstream the plenum (PT2). A Honeywell pressure transducer (PT3) is placed on the piping attached to the balance arm before the MT. A $2 \mu\text{m}$ filter inside the vacuum tank prevents particles from entering the thruster. The primary pump was displaced in another room in order to reduce vibrations and heat perturbation on the system.

To ensure that pure nitrogen is fed to the thruster, any fluidic element exposed to air is either pumped down and filled again, or purged by a flow of nitrogen. In particular at the beginning of the campaign the whole fluidic system up to the tank valve, including the large buffer, is pumped down to 5×10^{-4} mbar using an auxiliary turbopump, and then filled with nitrogen. A particule counter (Met Oner HHPC-6) is used, before each run, in the room and at the exit of the piping connected to the MT-FM, in order to check the cleanness of the gas.

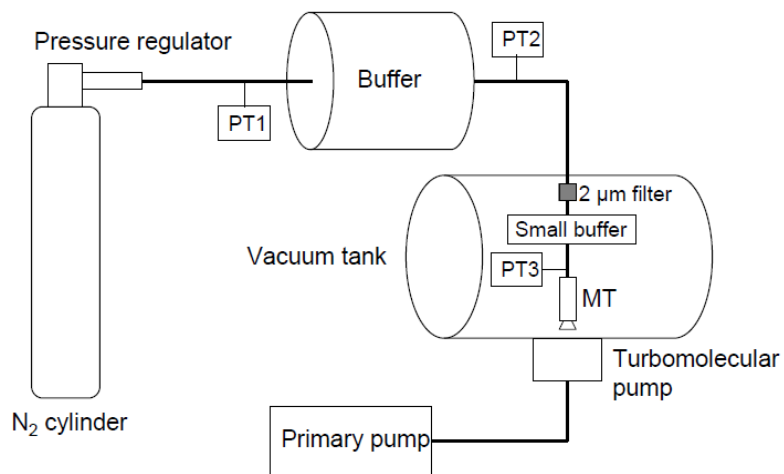


Fig. 8 Fluidic setup schematic. PT1, PT2 and PT3 are pressure transducers.

An image of a cold gas MT-FM mounted on the balance in vertical configuration inside the vacuum chamber is shown in Fig. 9.

The Electronic Ground Support Equipment (EGSE) of the MT-FM is used to control and deliver power to the MT (supplied by TAS-I).

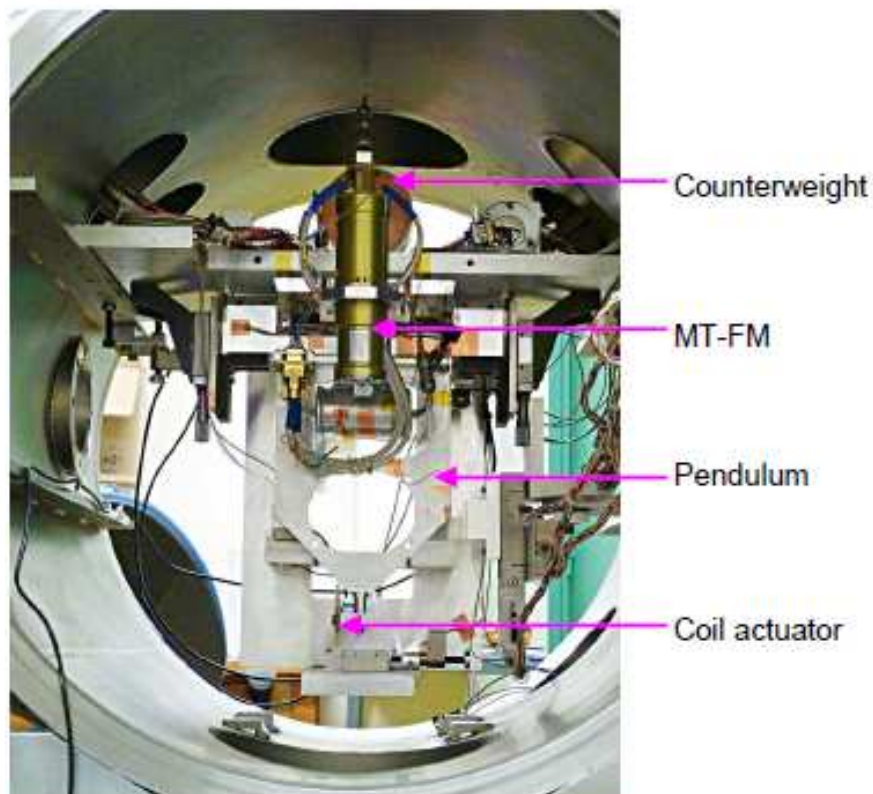


Fig. 9 Picture of ONERA microneutron balance with an MT-FM inside the vacuum tank.

IV. Balance performance

The performance of the balance depends in large part on the data acquisition system and post-treatment procedure. The 18 bit DAQ board and the anti-aliasing filters allow to remove the noise outside of the measurement bandwidth and to have a large measurement dynamic, which is essential for signal recovery in the frequency domain. In order to process the signal in frequency-domain measurements, one has to know the frequency behavior of the balance. Since the performance of the balance is sensitive to the mass on the arm, the measurements are performed with a MT –FM mounted on the arm (but with no thrust applied).

A. Noise

The frequency response of the balance was determined using swept-sine analysis with a dynamic signal analyzer (Agilent 35670A). A variable frequency sine wave signal is supplied to the coil actuator, which provides a thrust on the balance. The amplitude of the balance movement is measured with the capacitor sensor as a function of the frequency, and the transfer function is then calculated taking into account the calibration factor of the sensor (in V of signal per μN of thrust exerted on the balance) and the calibration factor of the coil (in μN of thrust produced per ampere of current applied). The frequency response of the balance is shown in Fig. 10.

The movement of the arm of the balance follows the dynamic of a pendulum that can be modeled with a second order system whose response is attenuated above its natural frequency at 0.42 Hz.

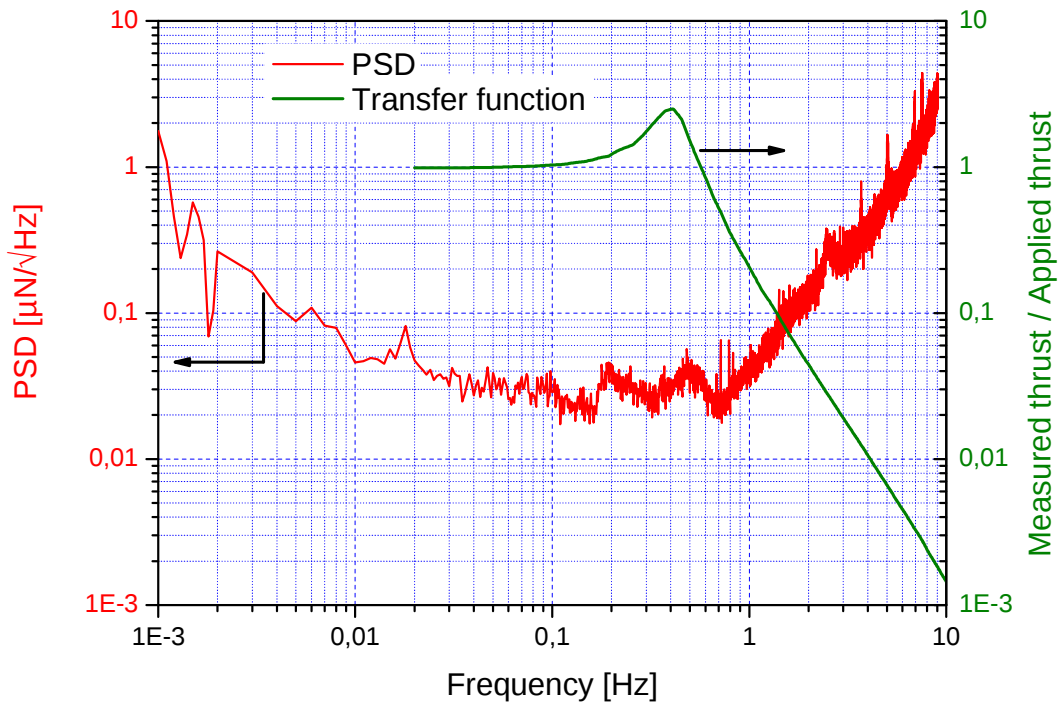


Fig. 10 Frequency response of the balance of the balance (transfer function) and PSD of the background noise.

It should be noted that a balance hysteresis effect exists, characterized by a small drift of the signal after a thrust change. Its effect is on the order of 1% of the thrust for a 30 s step. Although the effect is reproducible, the associated uncertainty was conservatively estimated also at 1% of the thrust.

The noise of the signal was measured during a 3 hour acquisition. After FFT treatment and correction by the frequency response of the balance, one obtains the power spectral density (PSD) of the signals in Fig. 10. The

background noise is relatively flat from 0.02 to 1 Hz, with a PSD close to $0.03 \mu\text{N}/\sqrt{\text{Hz}}$. In the frequency range $[10^{-3}-5 \text{ Hz}]$, PSD levels of the background noise remain below $1 \mu\text{N}/\sqrt{\text{Hz}}$.

The RMS noise (N_{RMS}) as a function of the cut-off frequency of low-pass filters (f_c) is then obtained by integration of the PSD:

$$N_{\text{RMS}}(f_c) = \sqrt{\int_{f_0}^{f_c} (\text{PSD}(f'))^2 df'}$$

The RMS noise of background is shown in Fig 11. For a thrust measurement bandwidth of 2 Hz and 6 Hz, the RMS noise of the signal is, respectively, $0.1 \mu\text{N}$ and $1 \mu\text{N}$.

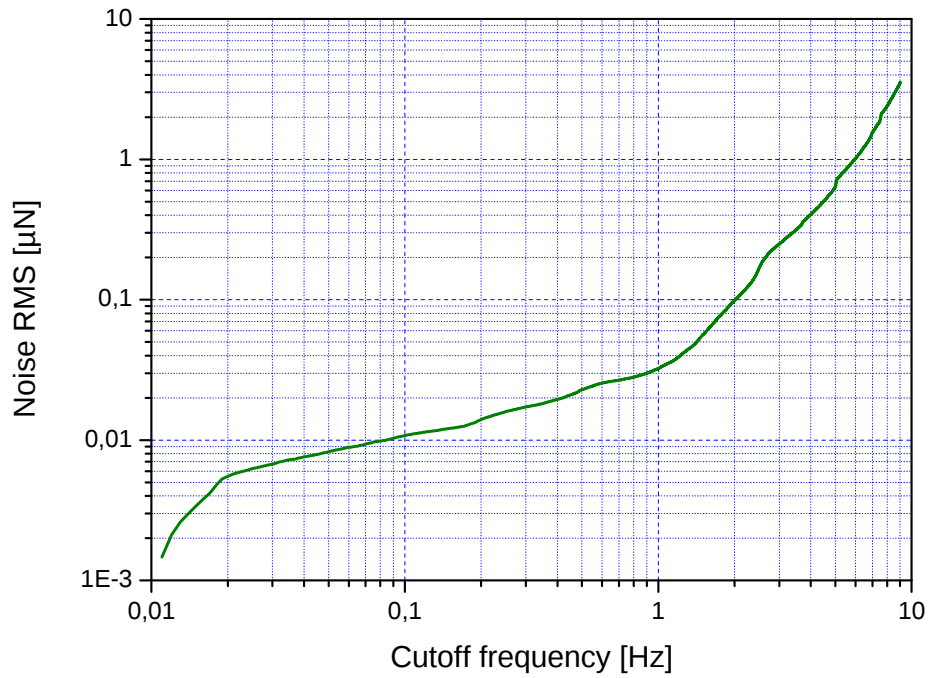


Fig 11 RMS noise of the balance signal as a function of the cutoff frequency (*i.e.* bandwidth).

B. Thrust resolution

The thrust resolution of the balance is assessed using the coil actuator. From the balance calibration, one can deduce the current to be supplied to the coil to produce small steps of equivalent thrusts of 0.1 and $1 \mu\text{N}$. The signal of the capacitive sensor for three successive steps is presented in Fig. 12. Equivalent thrust steps of $0.1 \mu\text{N}$ amplitude stand out clearly amid the background noise. One can notice the good repeatability of the $0.1 \mu\text{N}$ and $1 \mu\text{N}$ equivalent thrusts over three steps. Thrust steps of 20 nN (nanonewton) would still be visible.

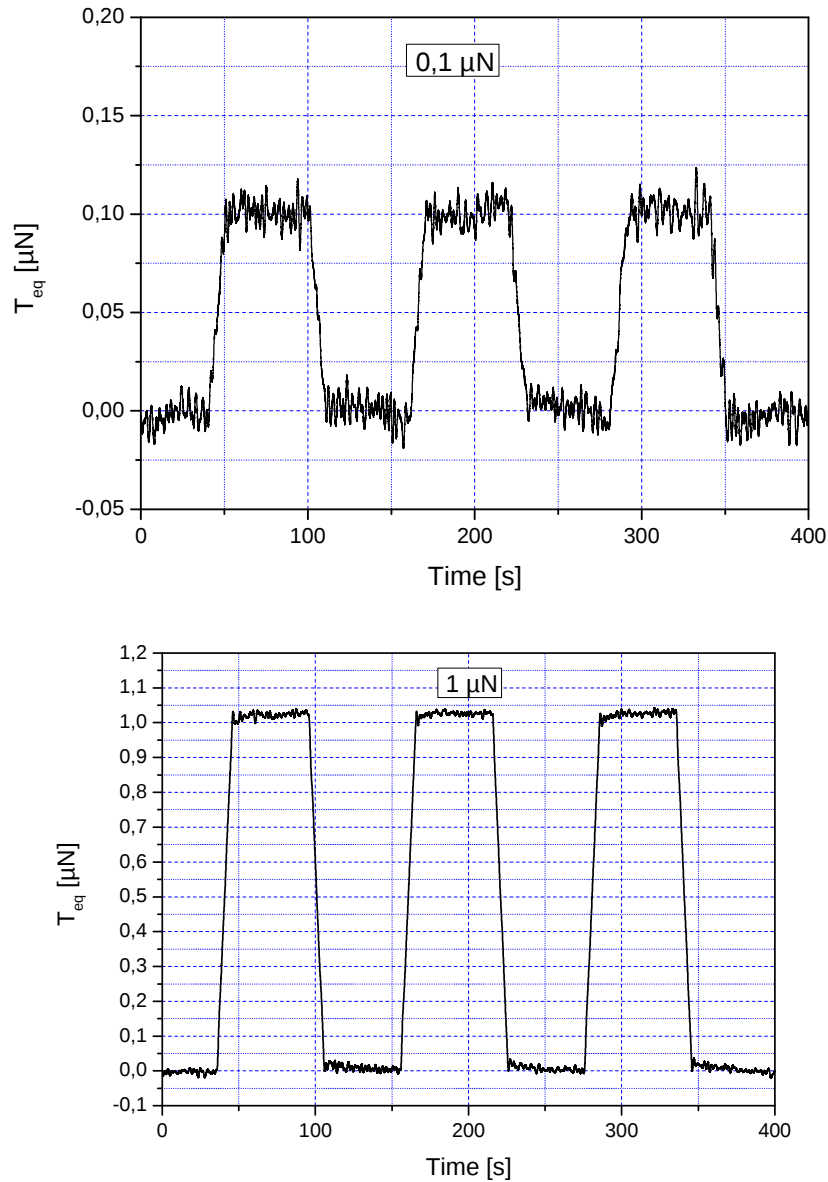


Fig. 12 Typical balance signal for 1 minute steps of equivalent thrust $0.1 \mu\text{N}$ (top) and $1 \mu\text{N}$ (bottom) obtained with the coil actuator and with the thruster mounted on the balance. Only straight-line detrending and low-pass filtering (0.1 Hz) have been applied to the raw data.

C. Balance range

The thrust range of the balance with a single capacitive sensor is [$< 0.1 \mu\text{N}$, 1.5 mN]. Using a second sensor, the range can go up to 10 mN . For a cold gas thruster, the upper limit of the thrust range is limited to 2 mN due to the pumping speed of the tank.

D. Error budget

The error budget, as a function of the measured thrust, has been obtained by evaluating all the sources of errors in the measurements. The I_{sp} uncertainty presented relates only to the thrusters measurement uncertainty. The flowrate measurement uncertainty (by the thruster MFS), which was not included in the I_{sp} uncertainty, is less than 0.5% as given by the manufacturer.

The different sources of error are detailed and quantified in **Table 2**. The acceleration of gravity was measured to be 9.8089 at the site of the ONERA balance (Palaiseau, France) by the team of A. Bresson using a cold-atom gravimeter, hence the corresponding low uncertainty. The backscattering, valve movement and pressure effect correction terms will be detailed in section V-B.

Table 2. Error budget of the Onera balance with a TAS-I thruster (V_b is in mV and T_{raw} in μN)

Standard deviation σ_X	Origin	Value σ_X	Relative standard deviation $\frac{\sigma_X}{X}$
σ_{V_B}	Balance output voltage noise	0.13 mV (about 0.02 μN)	$\frac{0.13}{V_B} = \frac{0.02}{T_{raw}}$
σ_m	Mass calibration	0.5% of mass m (kg)	5×10^{-3}
σ_g	Standard acceleration of gravity uncertainty	$< 10^{-4} \text{ m.s}^{-2}$	$< 10^{-5} \Rightarrow \text{Negligible}$
σ_{L_m}	Leverage calibration	1% of L_m (m)	10^{-2}
σ_{V_C}	Balance output voltage noise during calibration	0.13 mV (about 0.02 μN)	$\frac{0.13}{V_B} = \frac{0.02}{T_{raw}}$
σ_{L_T}	Thruster leverage uncertainty	0.15 % of L_T (m)	1.5×10^{-3}
σ_{C_B}	Backscattering correction uncertainty	10% of C_B	0.1
σ_{C_V}	Valve movement correction uncertainty	0.05 μN	$\frac{0.05}{T_{raw}}$
σ_{C_P}	Pressure effect correction uncertainty	0.005 μN	$\frac{0.005}{T_{raw}}$
σ_{C_H}	Balance hysteresis correction uncertainty	1% of T_{raw}	0.01

The standard deviations of all the terms are added quadratically to obtain the global standard deviation (the terms are assumed independent). In the end it leads to a formulation in the form:

$$\frac{\sigma_{Thrust}}{Thrust} = \sqrt{\sum_{i=1}^N \left(\frac{\sigma_{X_i}}{X_i} \right)^2}$$

The 3σ uncertainty can be fitted, using in the first order the asymptotic values A (at low thrust) and B (at high thrust) that can be read on Fig. 13. At low thrust $A=0.18\mu\text{N}$ and at high thrust $B=4.5\%$.

Affine fit: We can write schematically $3 \sigma[\mu\text{N}]=A+B*Thrust[\mu\text{N}]$, i.e. $3\sigma=0.18+0.045*Thrust[\mu\text{N}]$.

The affine fit is plotted in Fig. 13 in dotted black line. One can see that it is not perfect, because the addition should be quadratic.

Quadratic fit: $3\sigma[\mu\text{N}] = \sqrt{A^2 + (B*Thrust[\mu\text{N}])^2}$. It is plotted in Fig. 13 in plain black line, and the agreement with the actual uncertainty is now very good. Note that it is not rigorously perfect because of the backscattering uncertainty which is not linear (it is neither fixed nor proportional).

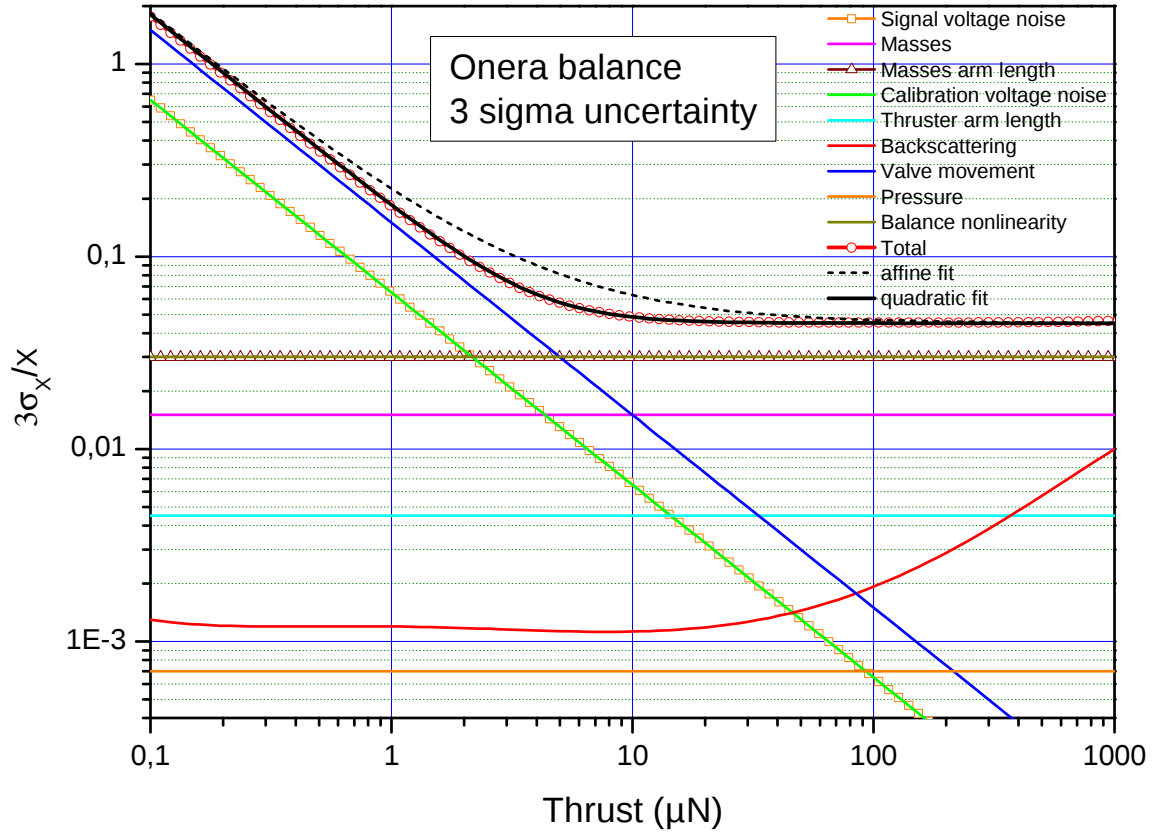


Fig. 13. 3σ error budget of the ONERA balance with a TAS-I thruster: contribution of most sources of error, total error (open red circles) and 2 fits of the total errors (solid and dotted black lines).

One may be interested in the relative uncertainty that characterizes the reproducibility of the results. Two cases can be looked at: between two measurements on one thruster (while the thruster is kept mounted on the arm), and between two thrusters. The relevant error terms are given in Table 3, and the error budget for the different cases is plotted in Fig. 14.. The balance non-linearity term is quite repeatable from step-to-step, and so it can be ignored for the step-to-step error, but it may create an uncertainty on the calibration process (due to the differences between the calibration steps and the thrust measurement steps), and since calibrations are done for each thruster, it must be kept in the thruster-to-thruster repeatability.

Table 3. Relevant error terms for repetitive thrust measurements

Standard deviation	Origin	Steps on one thruster	Thruster to thruster
σ_X			
σ_{V_B}	Signal voltage noise	X	X
σ_m	Masses		
σ_{L_m}	Masses arm length		
σ_{V_C}	Calibration voltage noise		X
σ_{L_T}	Thruster arm length		X
σ_{C_B}	Backscattering		X
σ_{C_V}	Valve movement	X	X
σ_{C_P}	Pressure	X	X
σ_{C_H}	Balance nonlinearity		X

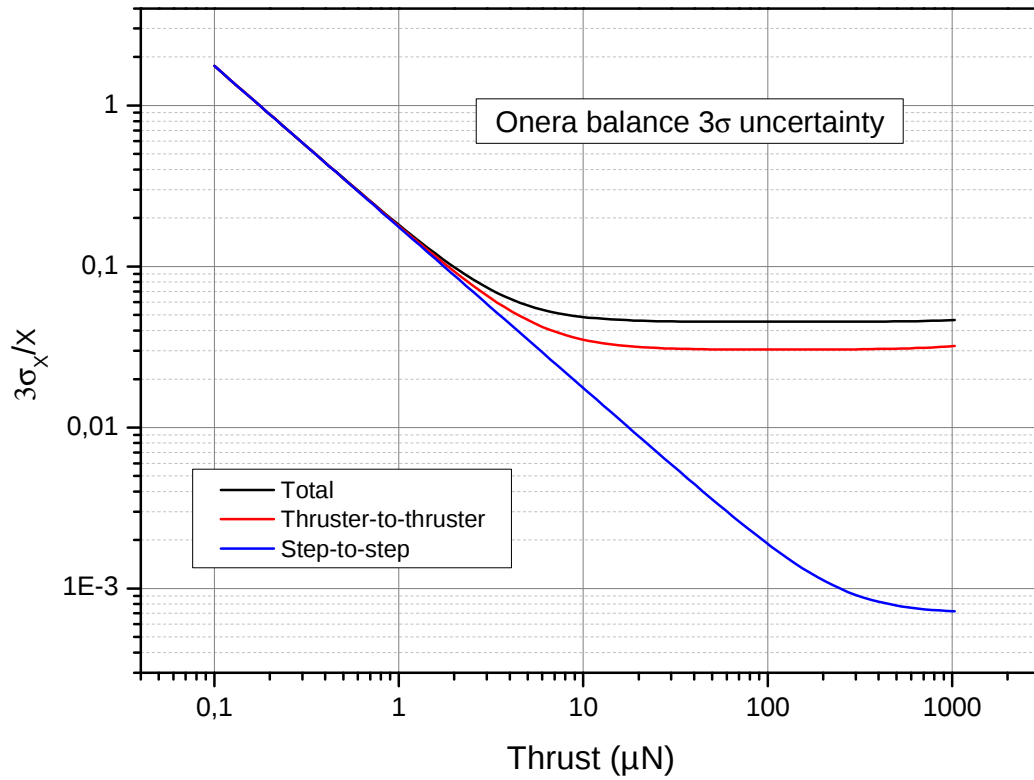


Fig. 14. Relative error budgets.

V. Thrust measurement procedure

Two types of test were performed:

- i. for all MT-FM (FM1 to FM13), an I_{sp} curve was measured with a steady-state sequence;
- ii. for FM3, a noise measurement was also performed.

A. Steady-state thrust sequence

For each thruster (FM1 to FM13) a sequence of pulses of constant thrust is applied to determine I_{sp} as a function of mass flow. The sequence consists of different mass flow setpoints, each setpoint being repeated 5 times with a 30 s duration and with 30 s at zero thrust between pulses. For FM1, FM2, FM3, and FM6, 36 different N_2 flow setpoints in the range [0.02-100 sccm] are applied, while the thrust measurement was limited to 16 setpoints in the range [0.1-100 sccm] for all other thrusters. The micro-thruster is operated in close loop mode: the piezo actuator voltage of the thruster valve is adjusted by the EGSE electronic in order to maintain the mass flowrate, measured with the thruster mass flow sensor (MFS), at a constant value.

Signals from the displacement sensors of the balance (capacitive sensors and accelerometers), thermocouples, and pressure transducers are acquired during the steady-state thrust sequence. Additional signals given by the MT-FM electrical equipment are acquired simultaneously: mass flow sensor (MFS) signal, mass flow set-point, piezo-driver monitor (*i.e.* the voltage supplied to the piezoelectric actuator to command MT valve movement during the regulation of mass flow), and nozzle and valve temperatures. The MFS signal is used for I_{sp} calculation, piezo-driver signal is used for valve movement corrections, and PT data are used for pressure corrections.

B. Correction factors

Three types of corrections are applied to the raw thrust data, corresponding to the most significant perturbations to the thrust measurement: backscattering (C_b), valve movement (C_v), and gas pressure inside the fluidic line (C_p).

$$T_{corrected} = T_{raw} - (C_b + C_v + C_p)$$

1. Backscattering effect

Backscattering effects are due to gas particles reflection on the vacuum tank walls and impinging the balance arm, which produces an additional force. The correction term C_b for backscattering was measured by attaching the MT-FM to the vacuum tank instead of the balance arm, thus removing the effect of the primary thrust. The thruster is however placed at nearly the same position (about 1 cm above) where it is on the balance arm during thrust measurements. Therefore, while the thrust force is not exerted on the balance, the effect of plume impingement and backscattering is nearly the same (neglecting the impact on the front face of thruster given its small area compared to the rest of the balance). During backscattering experiments the thrust produced by the MT is not measured (since it is attached to the vacuum tank). The backscattering effects lead to a movement of the balance which is registered as a thrust (in μN).

An example of backscattering correction factor C_b is shown in Fig. 15 as a function of N_2 flowrate. The uncertainty on backscattering correction is conservatively taken as 10% of the correction value.

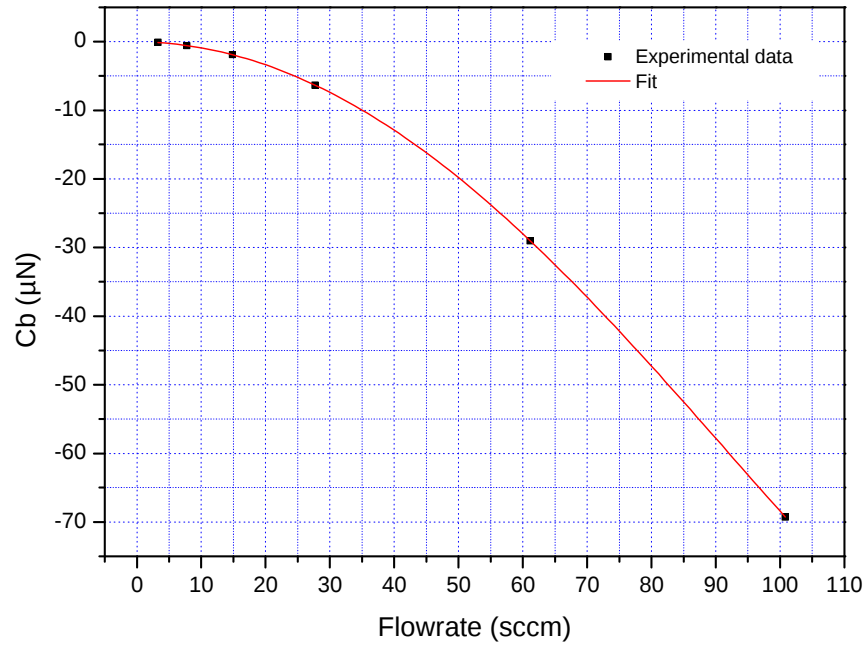


Fig. 15 Backscattering correction C_b as a function of nitrogen flowrate.

2. Valve movement

Since the micro-thruster is in vertical position, the valve movement is also vertical and should not, in theory, affect the static balance equilibrium. However, small deviations were noticed, probably from side movements inside the thruster. The method used to correct this effect is based on the assumption that the valve movement can be reproduced by applying the same voltage trace to the piezo-electric actuator as the signal registered during the steady-state thrust sequence. After a steady-state sequence, and in order to measure the valve movement alone, the gas is first evacuated from the MT by opening the valve, and after waiting for complete evacuation, the piezo-driver signal measured during the steady-state sequence is applied to the valve in open loop. The effect of the valve movement alone on the balance is recorded (red curve in Fig. 16), and then subtracted from raw thrust signal.

The uncertainty on the valve movement depends on the repeatability of the piezo-electric actuator movement. A previous study of repeatability has shown an uncertainty of $0.05 \mu\text{N}$ on C_V .

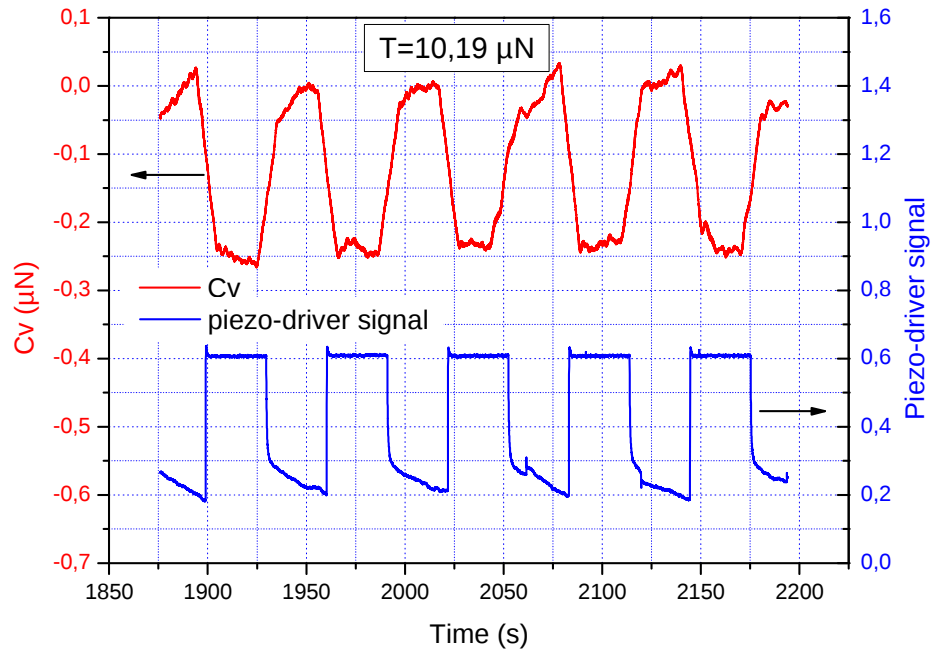


Fig. 16 Example of effect of valve movement on the balance (correction factor C_v) with the corresponding piezo-driver signal equivalent to five steps of thrust of $10.19 \mu\text{N}$ (flowrate : 0.9453 sccm).

3. Pressure effect

The balance was found to be sensitive to nitrogen pressure in the fluid parts, as illustrated in Fig. 17. Small variations of the pressure at the inlet of the MT are observed on PT3 trace during the steady-state thrust sequence. The global decrease is due to imperfect regulation of mechanical pressure regulator (accuracy $\pm 10\%$). This decrease is limited by the presence of the buffer tank. The steps of pressure are due to pressure drops in the capillary parts of the tubing during nitrogen flow (*i.e.* during a thrust step). Pressure corrections C_p (determined from Fig. 17) were applied to raw thrust data using PT3 signals registered during the sequence. It was also checked that the balance calibration is independent of the pressure.

The uncertainty on the pressure correction, which is itself a small correction, was estimated at about $0.005 \mu\text{N}$.

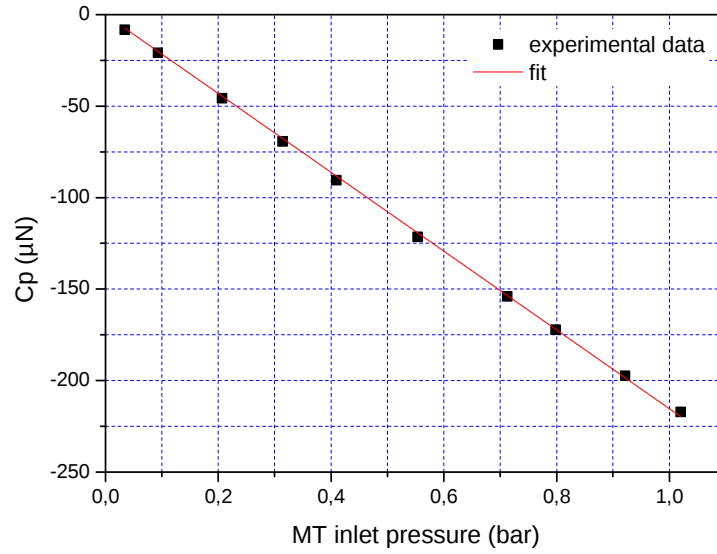


Fig. 17 Pressure correction factor C_p as a function of the pressure at the inlet of MT-FM.

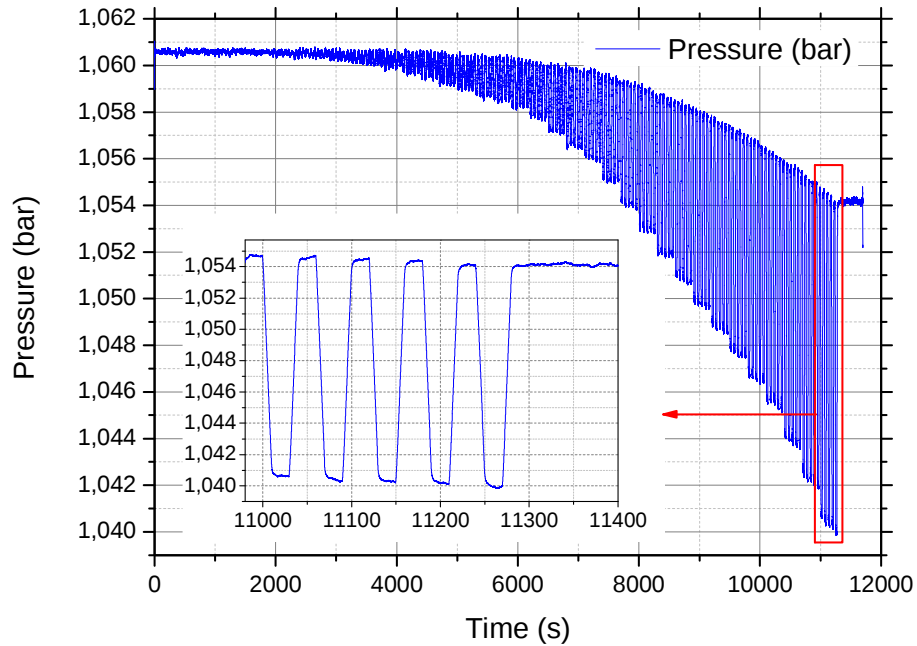


Fig. 18 Pressure variations at the inlet of MT during a steady-state thrust sequence.

4. Overview of corrections

In order to have an overall rough view of the ranges of predominance of the different correction factors, the approximate level of corrections, as a fraction of thrust, versus thrust are shown in Fig. 19. The correction factor C_v due to the valve movement predominates at low thrust levels (more than 10% of the thrust value below 1 μN , and close to the thrust value at 0.1 μN). C_v effects steadily decrease when increasing the thrust, whereas the correction factor C_b corresponding to backscattering effects is by far the most significant for high thrust levels ($>100 \mu\text{N}$).

From 2 μN to 1 mN, the corrections to apply to the raw thrust data correspond to between 1% and 10% of the thrust. The corresponding uncertainties are even lower (see the error budget section).

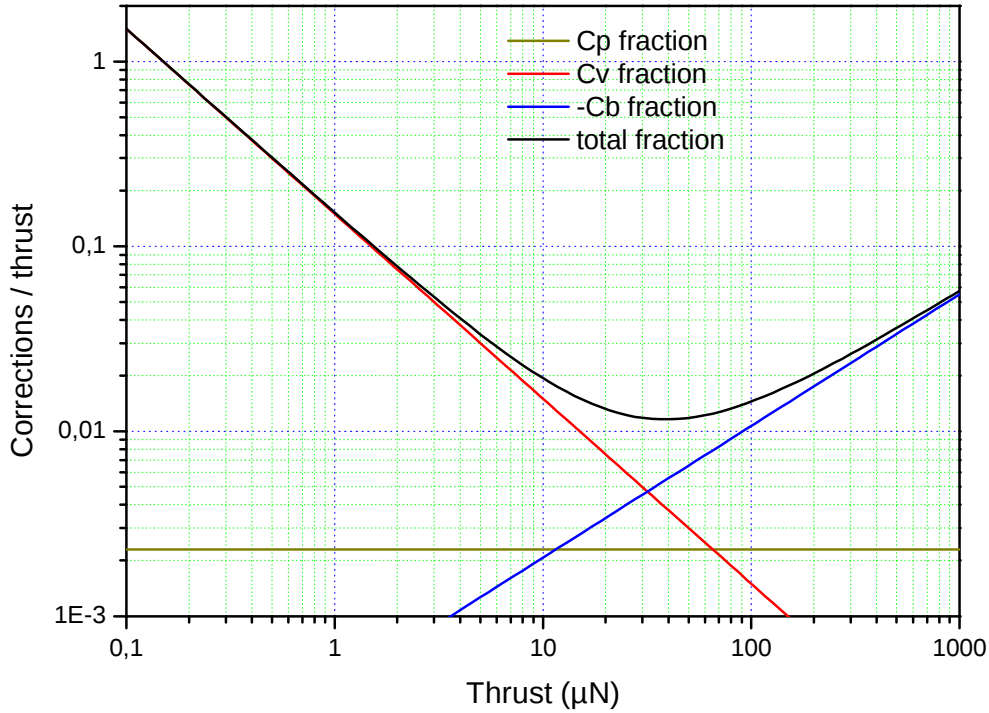


Fig. 19 Corrections as a fraction of thrust versus thrust.

C. Post-processing

After steady-state thrust sequence, the following procedure of post-treatment is applied to raw data:

- Adjacent-averaging of the raw data on 400 points (10 seconds). This is basically a low pass filter: the bandwidth of the raw data (20 Hz) is then decreased to 0.01 Hz, which reduced the balance background noise RMS to about 0.01 μN (0.02 μN is taken conservatively in the error budget).
- Straight line detrending in order to remove the thermal drift of the balance. No other detrending is necessary.
- Conversion to thrust using the calibration factor of the balance.
- Subtraction of correction factors to raw thrust signal

VI. Acceptance test results

A. Thrust noise

The cold gas thruster noise performance has been evaluated on FM3 in terms of PSD and noise RMS in Fig. 20. The MT-FM is operated with a constant thrust level of 500 μN . PSD levels of the thrust noise remain below 1 μN in the frequency range [10^{-3} -1 Hz], *i.e.* in agreement with GAIA MT requirements.

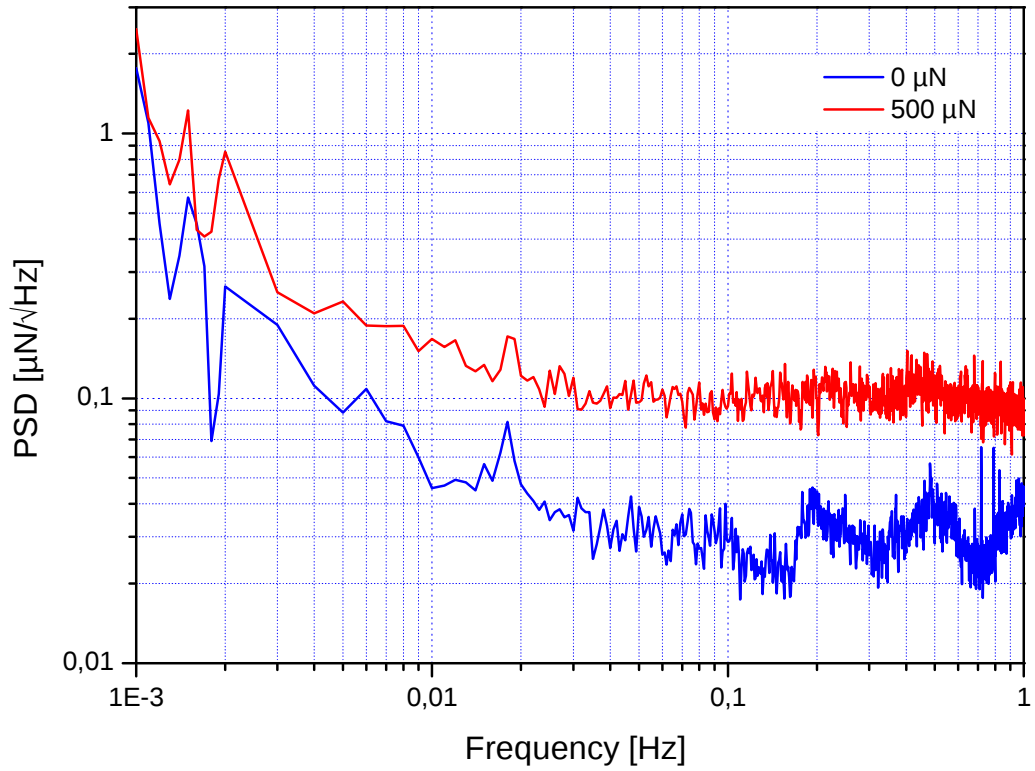


Fig. 20 PSD of FM3 thrust noise with a thrust level of 500 μN (red curve). The noise with no thrust from Fig. 10 and Fig 11 is also drawn for comparison (blue curve).

B. Thrust measurements and I_{sp} calculations

The results from the steady-state thrust sequence on the 13 MT-FM are presented here. Typical signals of the corrected thrust and the mass flow are shown in Fig. 21 for 5 steps at 4 different thrust levels. As can be seen, thrust as low as 0.1 μN can be detected and measured without noise perturbations. At every mass flow setpoint, the mean thrust and the mean mass flow is determined by averaging the value over the five steps.

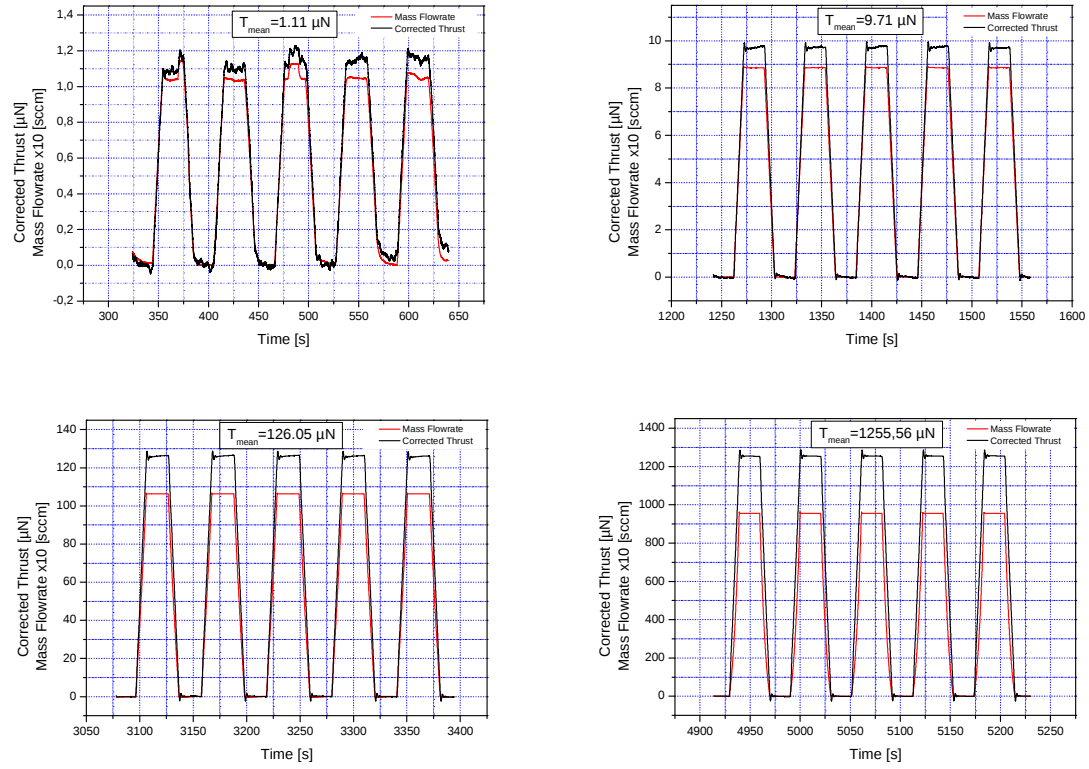


Fig. 21 Typical thrust and flowrate (FM7 data) from a steady-state thrust sequence for thrust levels of 1, 10, 126, and 1256 μN.

The I_{sp} is then calculated from mass flow measurements Q_m and corrected thrust for each step of the steady-state thrust sequence using:

$$I_{sp} = \frac{T_{corrected}}{Q_m(N_2) \times g}$$

A typical I_{sp} characteristics (*i.e.* the I_{sp} as a function of thrust) is presented in Fig. 22 for FM2. The I_{sp} calculated from each of the five steps and the mean I_{sp} are shown. The error bars of the 3σ error budget are much larger at low thrust levels, hence the dispersion of I_{sp} below 1 μN.

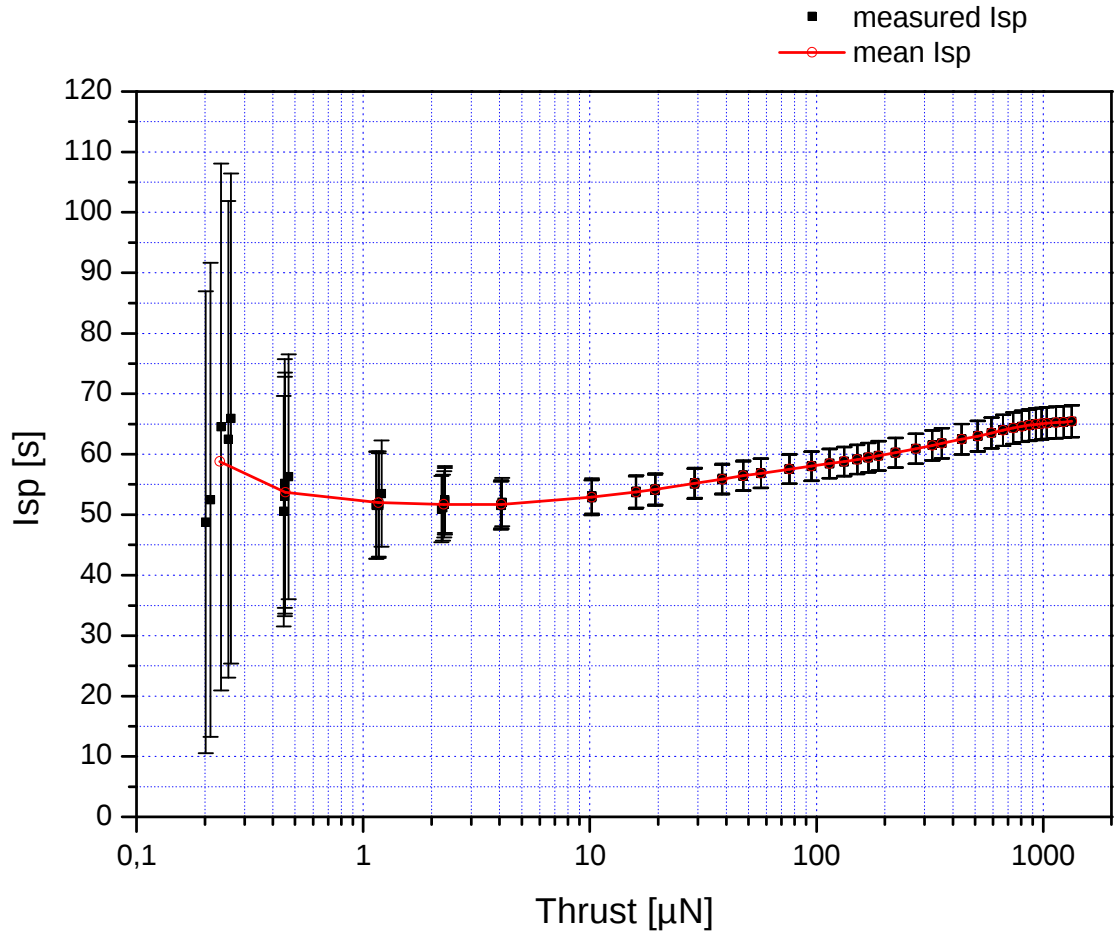


Fig. 22 Example of I_{sp} versus thrust for all measurement points with the error bars corresponding to the 3σ error budget, and mean I_{sp} of each flowrate setpoint, for FM2.

A summary of all MT-FM results is presented in Fig. 23 and Fig. 24. The mean I_{sp} is actually not constant over the whole thrust range: it tends to increase from around 50 s at 1 μN thrust level to a value close to 63 s at 1 mN. The presentation of the mean I_{sp} of the 13 MT-FM with the error bar envelopes in Fig. 24 shows that the different I_{sp} values are in agreement with the 3σ error budget.

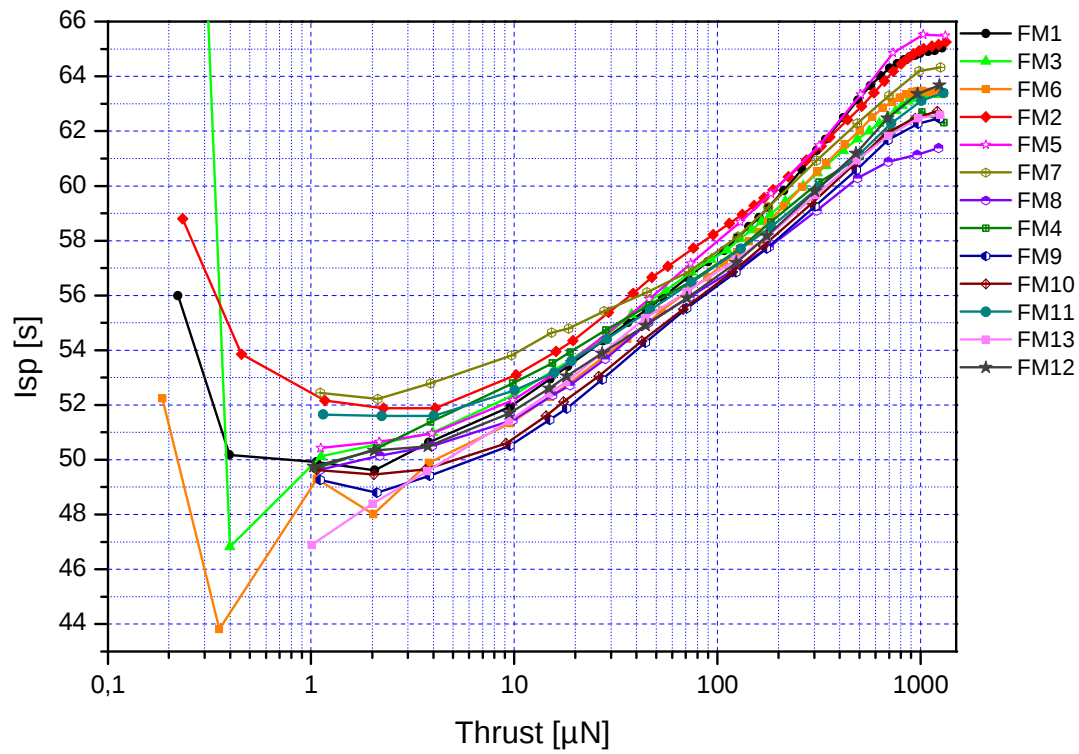


Fig. 23 Mean values of I_{sp} versus thrust for all GAIA Micro-Thruster Flight Models.

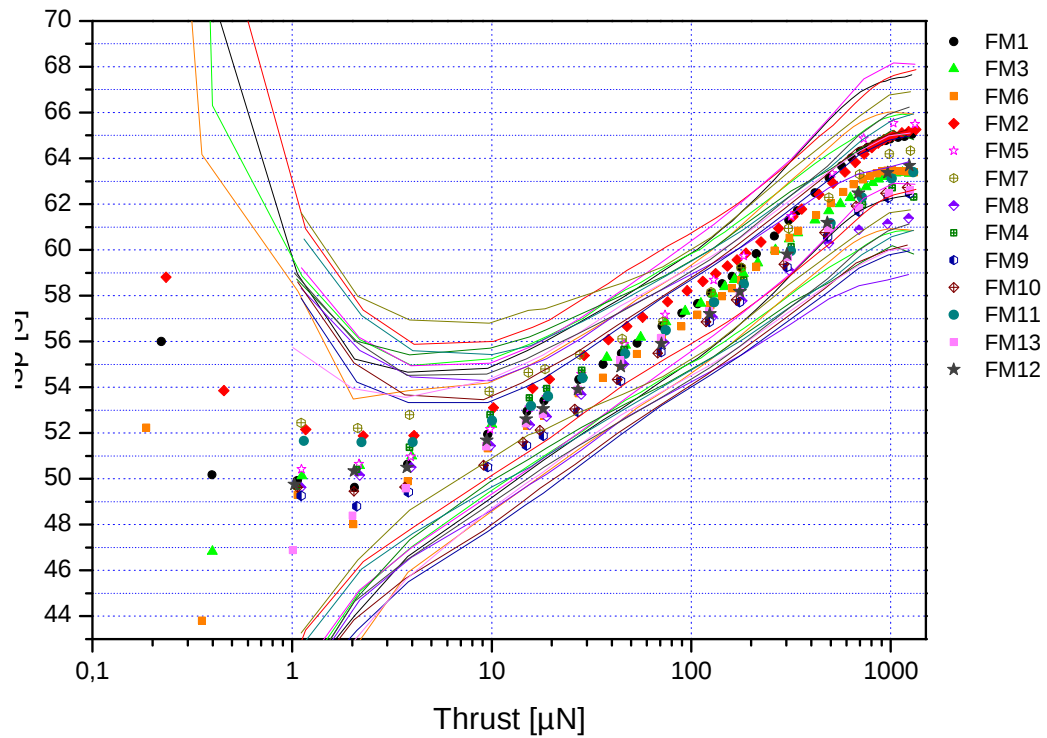


Fig. 24 Mean values of I_{sp} (symbols) versus thrust with the error bar envelopes (lines) corresponding to the 3σ error budget.

VII. Conclusion

The performance of the Onera micronewton balance was presented in the framework of the acceptance test of the cold gas Micro-Thruster Flight Models of GAIA mission. In the test conditions used, the thrust resolution of the balance was evaluated at $0.02\ \mu\text{N}$, and its RMS noise was evaluated at $0.01\ \mu\text{N}$.

The Isp of the 13 GAIA thrusters is also presented. The effect on the balance signal of the backscattering, of the pressure inside the MT and the fluidic line, and of the valve movement during mass flow regulation were assessed. Correction factors have been calibrated and applied to the raw thrust signal to remove these perturbations. An error budget was calculated.

Thrust measurements were performed in the range $0.2\text{--}1000\ \mu\text{N}$. The specific impulse has been determined as a function of thrust in this range for all micro-thrusters, showing an increase from about 50 s at $1\ \mu\text{N}$ to about 63 s at $1000\ \mu\text{N}$. Post-analysis of the I_{sp} results on the 13 MT indicates a good repeatability of the thrust measurements and the MT performances.

The contribution of the different factors to the error budget has been assessed as a function of the thrust level. On the low thrust side ($<10\ \mu\text{N}$) the main contribution comes from the valve movement of the thruster. The next contributor would be voltage noise, but it would have then to be reassessed, as it has been conservatively estimated so far. Indeed, the contribution on Fig. 13 at $0.1\ \mu\text{N}$ is 80% error 3σ for voltage noise, while the signal in Fig. 12 points to a much better actual figure.

On the high thrust side ($>10\ \mu\text{N}$), the first contribution to the error budget comes from the calibration: masses and masses arm length. Improved weighing and improved assessment of balance verticality would greatly reduce this factor. The next factor is balance nonlinearity, and can be due to wire passages, blades or plastic tubing. A dedicated set of tests could be done to test this factor and propose solutions.

Acknowledgments

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