

Development of a Highly Precise Micro-Newton Thrust Balance

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In this proceeding we present our ongoing micro-Newton thrust balance development, which fulfils the LISA requirements. In the context of the development of highly precise thrusters for attitude control of satellites for future space missions, the development of test facilities for the characterising and qualification of thrusters is performed contemporaneously. The presented thrust balance has a resolution of $0.1 \mu\text{N}$ in a bandwidth between 1 Hz and 10^{-3} Hz . As general measurement principle, we chose a pendulum balance. The setup consists of two pendulums to enable a common mode rejection. To suppress the eigenfrequency of the pendulums, a damping via an eddy current brake is part of the balance assembly. A heterodyne laserinterferometer is used as translation sensor. Different measurements were performed to investigate the noise performance of the pendulum. The results are presented and analysed. The measurement system was used to measure the neutral gas thrust of a micro-HEMP-T.

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Abbreviations

LISA	= Laser Interferometer Space Antenna
GAIA	= Global Astrometric Interferometer for Astrophysics
FEEP	= Field Electric Emission Propulsion
RIT	= Radio Frequency Ion Thruster
HEMP-T	= High Efficiency Multistage Plasma Thruster
DUT	= Device Under Test
DWS	= Differential Wavefront Sensing
FPGA	= Field Programmable Gate Array
DDS	= Direct Digital Synthesizer
CLK	= Reference Clock
Freq	= Frequency
PLL	= Phase Lock Loop
FIFO	= First In First Out Memory
ESC	= Electro-Static Comb
PSD	= Power Spectral Density

I. Introduction

IN the last decades, the need for highly precise attitude control of satellites became more and more important, because of two reasons. First, the growing number of small satellites with masses lower than 20 kg. In order to fulfil the challenging miniaturisation requirements for this small satellites, an electrical micro-Newton thruster is required. Second, different scientists have proposed future scientific space mission with a need for highly precise attitude control to achieve their mission goals. Possible mission examples are the Laser Interferometer Space Antenna (LISA), the Global Astrometric Interferometer for Astrophysics (GAIA), or the Darwin space telescope [1,2]. In reference to this, different micro-Newton thrusters are in development, e.g. Field Electric Emission Propulsion (FEEP), micro-Radiofrequency Ion Thruster (micro-RIT), micro-Highly Efficiency Multistage Plasma Thruster (micro-HEMP-T), or cold gas systems [3,4,5]. Challenging performance requirements are thrust level, accuracy, dynamic response and thrust noise. For instance, LISA requires a thrust range from 1 μN to 100 μN with a thrust resolution of 0.3 μN in a bandwidth from 1 Hz to 10^{-3} Hz [1,5]. Astrium Satellites Friedrichshafen started to develop the micro-HEMP-T in the context of the LISA mission study. In parallel to the development of a suitable thruster, the design and the development of a suitable test infrastructure is needed, too. Therefore, the development of a micro-Newton thrust balance was started. In this article the author describes the design and the testing of a micro-Newton thrust balance which fulfils the LISA requirements.

II. Micro-Newton Thrust Balance Setup

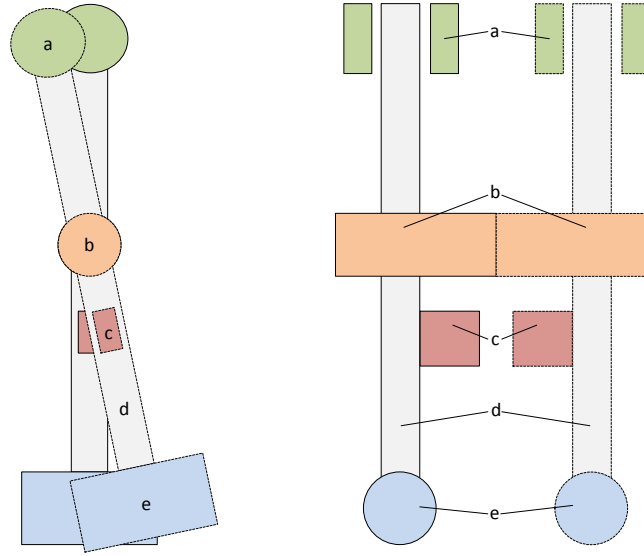


Figure 1. Simple sketch of the balance setup, a) is the damper, b) is the bearing, c) is the translation sensor, d) is the pendulum arm structure and e) is the thruster or device under test. The setup consists of two full symmetric pendulums. This enables a common mode rejection.

Presently, only a few micro-Newton thrust balances are in development or operational [6]. The predominant measurement principle is that a force F generated from the device (usually a Thruster) under test (DUT) deflects the measurement assembly, the deflection is called Δx . By known spring rate k of the setup, F can be calculated by

$$F = k \cdot \Delta x \quad . \quad (1)$$

The general measurement principle is following the same rules for different balance configurations. Common configurations are a torsional balance or a pendulum balance. Both concepts have specific advantages and disadvantages. In reference to our reputation in the field of highly precise metrology [7,8], we decided to build up a highly symmetrical pendulum balance with a heterodyne laser interferometer as optical read out. A simple sketch of the mechanical balance setup is shown in figure 1. The assembly consists of two pendulums, a reference pendulum and a measurement pendulum. On the pendulum structure (d) the DUT

and a dummy are mounted (e). The physical properties of the dummy and the DUT are equal. The bearing (b) consists of four leaf springs per pendulum. The springs operate as frictionless pivot. Furthermore, they can be used as power or data connection for the DUT as well. In reference to this, the balance spring rate k consists of the spring rate of the bearing, $k_{bearing}$, and the spring rate caused by the force of inertia. Therefore, k is given by

$$k = k_{bearing} + \frac{m^2 \cdot g_0 \cdot l_{CG}}{I_{pendulum}}, \quad (2)$$

where m is the pendulum mass, g_0 is the gravitational constant, l_{CG} is the distance between the bearing and the centre of gravity of the pendulum and $I_{pendulum}$ is the torque of inertia of one pendulum. The advantages of the chosen balance configuration is a variable measurement resolution, in respect of the use of calibration weights. The symmetrical setup enables a common mode rejection. This is important to fulfil the requirements in point of long term stability. A general disadvantage of a pendulum balance is the sensitivity to seismic noise. Random stimuli generates a motion of the pendulum at the first eigenfrequency. A damper (a) is implemented to avoid this. In reference to the aimed measurement bandwidth, an eddy current brake was chosen as damper. The damper assembly consists of two permanent magnets which are mounted on the pendulum support structure. Aluminium plates are mounted on the pendulum arm to increase the effect of the damper. The distance between the pendulum and the permanent magnets is variable. Therefore, the damping coefficient is variable and can be adapted to different boundary conditions, e.g. sensitivity. Each pendulum has an own damper. A dielectric mirror is mounted on the pendulum arm as sensor for the optical readout. The used laser interferometer system allows a translation readout down to pico meter level. Therefore, the read out have no influence on the balance performance. The whole pendulum balance

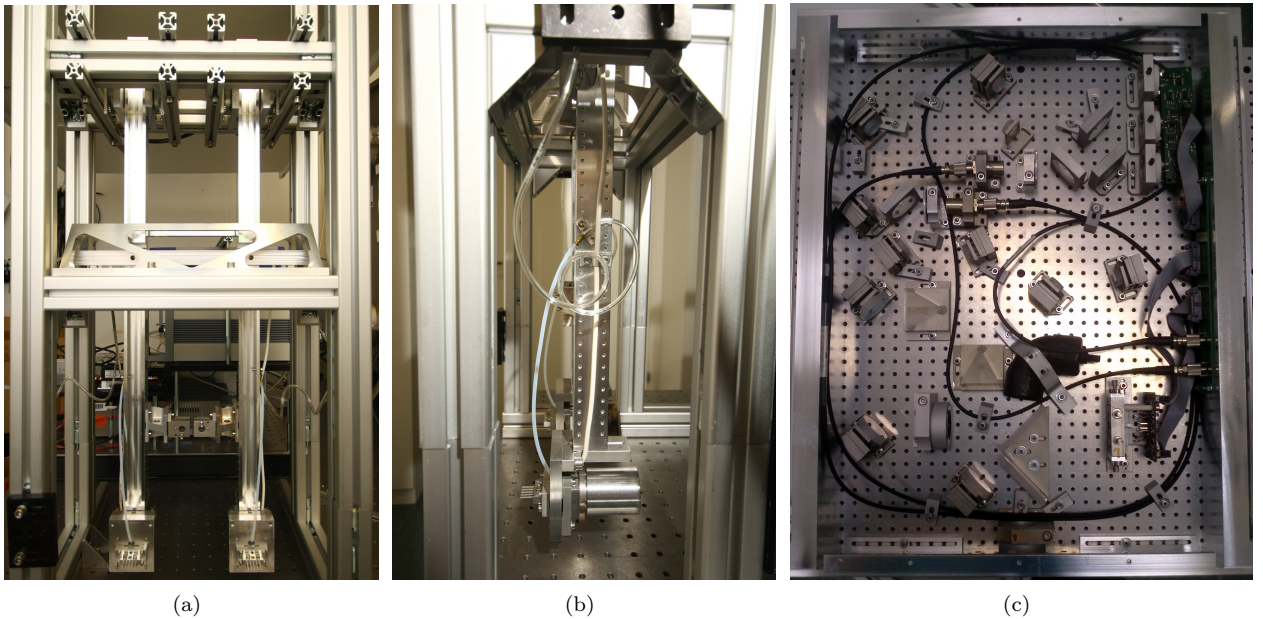


Figure 2. Picture of the whole pendulum balance assembly, outside of the vacuum chamber. Picture a) shows the assembly from the back, b) shows the assembly in side view. The key component of the optical read out, the laser interferometer head, is shown in c).

assembly is shown in picture 2 a) and b). The pictures show the balance in back view and in side view. The pendulum arm itself is made of aluminium. A thread grid allows variable mounting of all needed components. The support structure which connects the balance with the vacuum chamber consists of item profiles. The simple item profile construction combines a flexible handling with a stiff structure. At the top of each pendulum, the eddy current brake assembly is visible. The side view shows the thruster, the power and the gas connection as well. The gas supply tube is laying in circles. Therefore, the tube has a well defined length and a minimised influence on the balance spring rate. The thruster power control cable is connected to the power supply unit via a leaf spring. The key component of the optical read out, the laser interferometer head, is shown in picture 2 c). The laser head is a redesign of the actual Astrium heterodyne

interferometer generation [7,8], with a wider beam distance and a pig tailed optical fiber input. The use of two quadrant photodiodes allows a differential wavefront sensing (DWS). The DWS enables the read out of both pendulum angles, in a nano-rad resolution, beside the usual translation measurement. In contrast to the translation measurement, the result of the DWS measurement is independent for each pendulum.

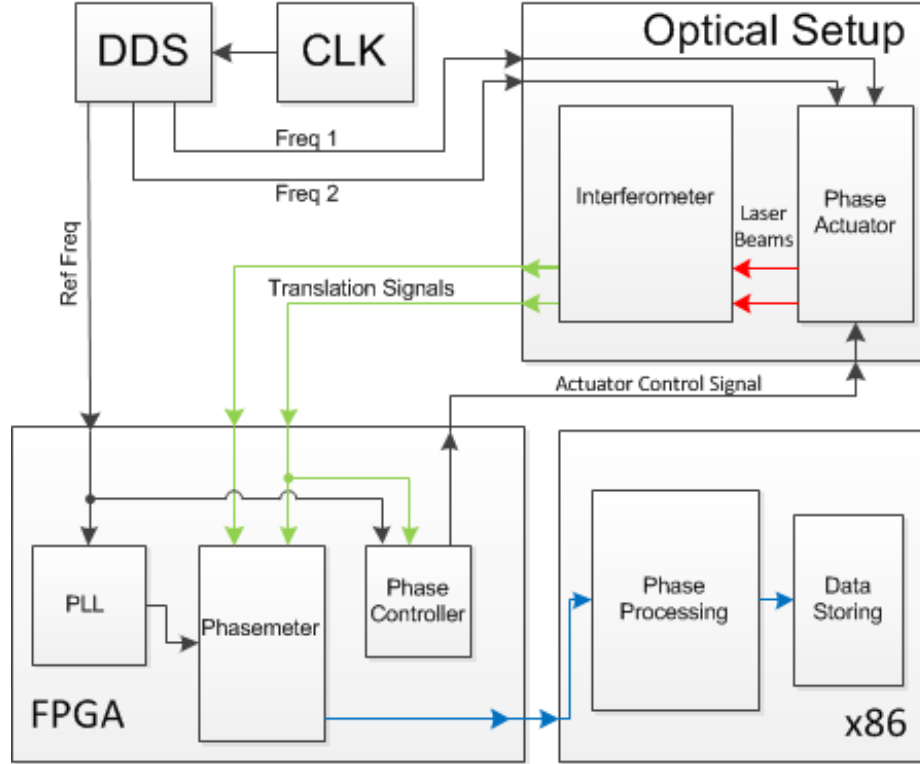


Figure 3. Flow chart of the read out and data acquisition. The system consists of a master clock (CLK), a direct digital frequency synthesiser (DDS), an optical setup, a FPGA-Board and a workstation with x86 architecture.

An FPGA board is used to acquire the measurement signal. Figure 3 gives an overview about the data handling and acquisition. To generate the required frequencies, a Direct Digital Synthesiser (DDS) is used. To enhance the performance of the DDS, it is locked to a reference clock (CLK). The DDS generates three frequencies. Frequency 1 (Freq 1) and Frequency 2 (Freq 2) as input for the laser interferometer and a Reference Frequency (Ref Freq) as phase reference for the phasemeter and the phase controller. The value of heterodyne frequency is 10 kHz. The acquired translations signals (measurement and reference signal) get processed in the phasemeter, in real time, with a sampling frequency of 200 kHz. The phase controller and the phase lock loop (PLL) working with 200 kHz, too. A down sampling to 400 Hz is processed as last step of the data handling on the FPGA. To reduce the needed FPGA resources to a minimum, a workstation with an x86 architecture is used for more complex data operations. The data is transferred via a FIFO to the x86 system to avoid errors from timing violations. On the x86 system all further data operation, like thrust calculation or data storing, is processed. The x86 system includes an analog data acquisition board which allows the control of the DUT and other needed components.

To calibrate the balance assembly an Electro-Static Comb (ESC) is used. One part of the comb is shown in picture 2 a) and b). The ESC assembly consists of a comb pair, one is on the pendulum and the other one is mounted on the support structure. Johnson and Warne presented that the calibration error is minimised, because of the symmetric design of the combs. In reference to this results no further calibration of the ESC was performed [9,10]. The used comb configuration (in respect of the used power supply) has a rang from 0 to 3181 μN with an relative error of 0.27 %.

The pendulum assembly is placed in a 600l vacuum chamber. To evacuate the vacuum tank, two 700l/s turbo pumps are used. With a gas load of 1 sccm the pressure is around $5 \cdot 10^{-5}$ mbar. To uncouple the

balance from pump noise, the pumps are connected via a damper to the chamber. Moreover, the assembly is placed on a damped optical desk, which shields the assembly from seismic noise, too.

III. Measurement Results and Analysis

Figure 4 presents the balance performance in different configurations. The shown Power Spectral Density (PSD), where the thrust (in μN), normalised to the frequency (in $\sqrt{\text{Hz}}$), is plotted logarithmically versus the frequency, gives an overview of the noise level at specific frequencies. The black plot presents the LISA requirement. The blue curve presents the first noise measurement of the thrust balance. We measured a single undamped pendulum versus a fixed mirror. Therefore, no common mode rejection occurs. The observed eigenfrequency of the pendulum is 0.77 Hz, this is close to the estimated eigenfrequency of 0.8 Hz. The amplitude of the swinging pendulum is the dominant noise term of the measurement resolution. Down to lower frequencies pink noise occurs and limits the resolution in point of long term stability. Possible reasons are thermal drifts and the movement of the optical table. This movements are in a nanometre regime, which cause a permanent phase drift of the measurement signal.

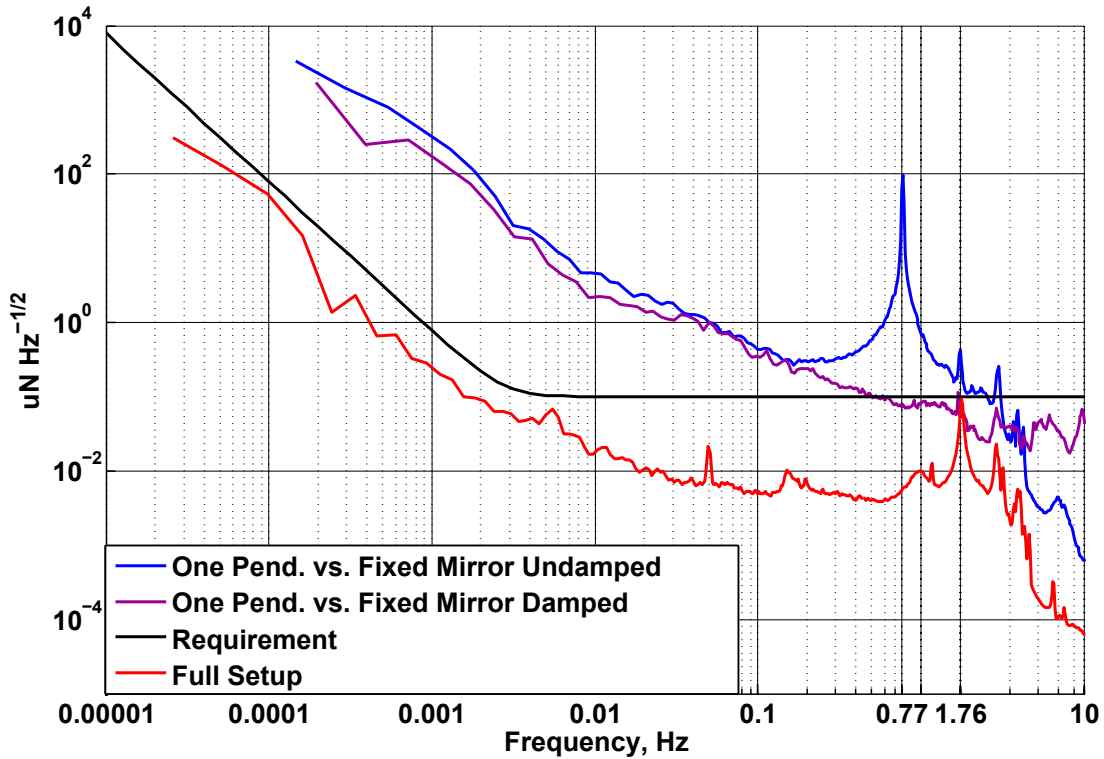


Figure 4. Summary of the balance performance. The blue plot presents the performance of one undamped pendulum. The purple plot shows the performance of a damped pendulum. The Black curve is the requirement. The red plot shows the performance of the full balance setup with active common mode rejection.

The purple plot presents the performance of one damped pendulum versus a fixed mirror (no common mode rejection). The damper suppresses the eigenfrequency. Therefore, at higher frequencies the noise level decreases on 1.5 order of the magnitudes. At lower frequencies pink noise dominates the PSD as in the blue curve. The noise measurement of the whole setup, which means two damped pendulums, is shown as the red plot. The noise level decreases of one order of the magnitude, down to lower frequencies the rise of the noise level is reduced, the assembly is stable enough to fulfil the requirement. At higher frequencies the resolution is limited because of a peak at 1.76 Hz. Measurements with different sample frequencies make clear that the peak is not an aliasing effect. Possible reasons are mechanical vibrations of the support structure or other external noise. Furthermore, it could be possible that the peak causes from asymmetries between the two pendulums. Therefore, the eigenfrequency of the pendulums are not equal. This effects that the common mode rejection do not applie at the eigenfrequencies. By reason that we measure one pendulum versus the

other pendulum, the doubled eigenfrequency should be visible in the PSD. But we observed a peak by 1.76 Hz which is 0.22 Hz away from the doubled eigenfrequency. All in all, further investigations are needed to find the reason of the 1.76 Hz peak.

A calibration with the ESC was performed to estimate the spring rate of the balance assembly and to investigate the differences of the two pendulums. The result is presented in figure 5. The force (in N) is plotted versus the translation (in m). The red scatterplot shows the result of the calibration for the measurement pendulum and the blue scatterplot presents result for the reference pendulum. The slope of the scatterplots is equal to the spring rate. A linear interpolation was performed for each scatterplots to estimate the spring rates. The measurement pendulum has a spring rate of $15.7 \pm 0.2 \text{ N/m}$ and the reference pendulum has a spring rate of $18.12 \pm 0.2 \text{ N/m}$. The results and figure 5 indicate, that each pendulum has a different spring rate. That implies, the pendulums are not fully symmetric. A possible reason is that the fabrication and integration tolerances of the assembly causes differences in the weight and in the mass distribution of the pendulum. A tuning of the spring rate with calibration weights is in progress.

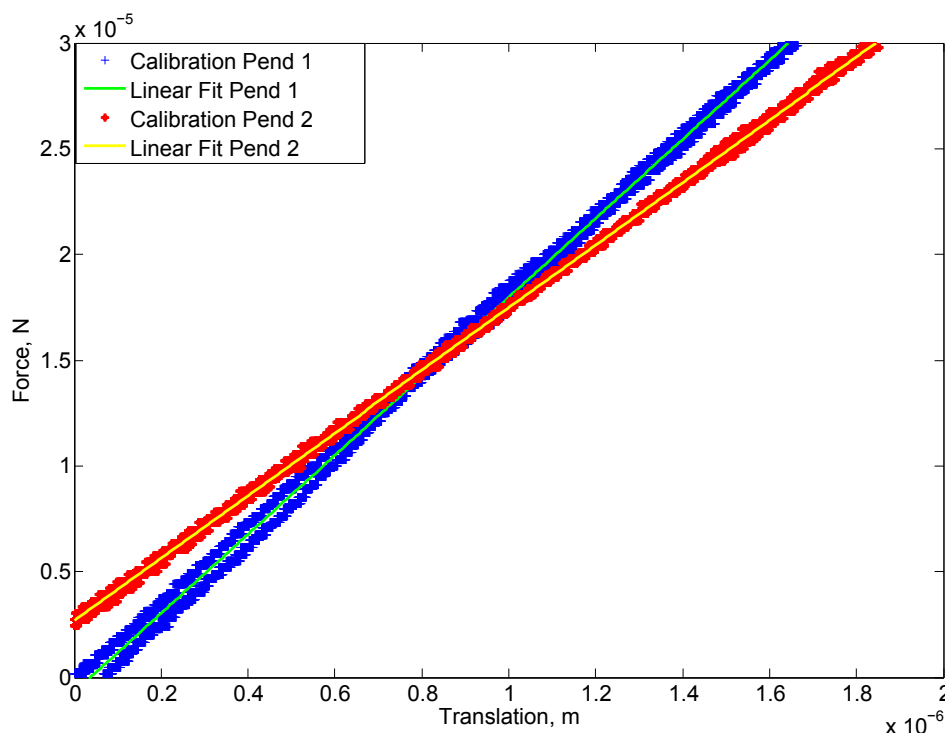


Figure 5. Result of the calibration for both pendulum. The force (in N) is plotted versus the translation (in m). The red scatterplot shows the result of the calibration for the measurement pendulum and the blue scatterplot presents result for the reference pendulum.

Figure 6 a) presents a calibration run of the pendulum. The translation (in nm) of the balance (blue curve and scale) is plotted versus the time. In comparison on this, the applied force (in μN , green curve) is plotted versus the time, too. The force was applied via the ESC. Every step was $0.5 \mu\text{N}$ high and 5 s long. A full calibration cycle is shown. The translation of the balance followed the applied force instantly. The figure illustrates the repeatability and the drift of the balance. At the displayed time scale, the drift is smaller than $0.1 \mu\text{N}$. This underlines the result of the noise measurement shown in figure 4. The plot demonstrates that the balance can measure in sub-micro-Newton range and fulfils the required stability.

As first real thrust measurement we investigated the neutral gas thrust of a micro-HEMP-T. The result is presented in figure 6 b). On the x-axis the time is plotted versus the thrust (left, in μN) and the mass flow (right, in sccm). The measurement started at 0.5 sccm, every step is 0.025 sccm high and 20 s long. Every mass flow step generates a thrust of $0.42 \pm 0.08 \mu\text{N}$. In this case, the balance shows a good reproducibility and a good stability as well. The achieved absolute value of the neutral gas thrust is close to approximated thrust. Further investigations have to show if these measurements are trustable.

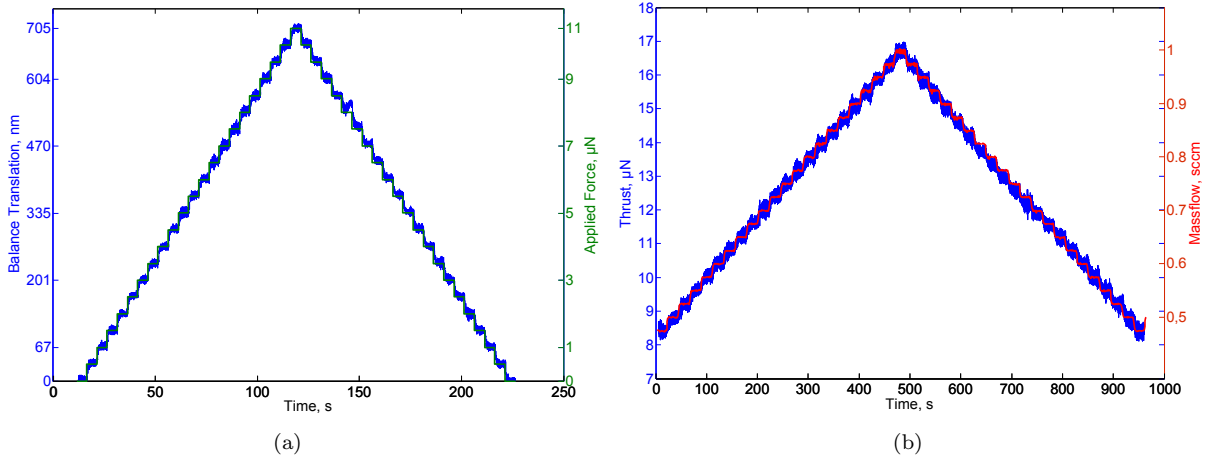


Figure 6. Figure a) shows a calibration of the balance. The time is presented versus the balance translation (in blue) and the applied force. Figure b) presents the measurement of the neutral gas flow of the micro-HEMP-T. The time is plotted versus the thrust (in blue) and the mass flow (in red).

IV. Conclusion and Outlook

The micro-Newton thrust balance at Astrium is able to measure sub-micro-Newton thrust and fulfils the LISA requirement. The calibration of the balance was performed with an ESC. The balance assembly has a measurement resolution of $0.1 \mu\text{N}/\sqrt{\text{Hz}}$ in a frequency range from 10 to $2 \cdot 10^{-3} \text{ Hz}$. This allows to characterise possible thruster candidates for LISA. First tests with an active thruster was performed. To get a deeper understanding of the observed effects and to identify possible measurement limitations, further tests are in progress.

In the next months the balance will be upgraded with an electromagnetic actuator to enable a close loop measurement. Furthermore, the whole assembly will be moved to a new vacuum infrastructure with higher pump capacities for more meaningful measurement results. Moreover, this allows the integration of other metrology equipment next to the balance. It is planned to install a faraday-array and a retarding potential analyser. After the completed integration in the new facility it is planned to test the balance with different thruster types.

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