ISO17025 Accreditation of the ESA Micro-Newton Thrust Balance

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Abstract: **Some future European scientific missions (Microscope, LISA, EUCLID) are foreseen to have very stringent requirements on thrust accuracy and thrust noise. With the aim of providing a tool for qualification of micro-thrusters needed for these mission profiles, the European Space Agency (ESA), in close collaboration with the National Physical Laboratory (UK), has developed a balance capable to measure thrust in the micro-Newton range. Since 2011 the development of the ESA uNTB has been improved leading to its accreditation for steady state direct thrust measurement in the first half of 2014. In this paper, the balance and its test setup are described and the accreditation test procedures and results are presented. In addition, the uncertainty budget calculation process is exposed along with its compliance to ISO GUM standards.**

Nomenclature

V_a	=	command of the Force Actuator
y	=	displacement of the pendulum
T_{FA}	=	thrust produced by the Force Actuator
u	=	standard uncertainty
u_c	=	combined uncertainty
τ	=	noise associated to the signal
k	=	coverage factor
σ	=	confidence level
MBA	=	measurement balance assembly
TCA	=	tilt compensation assembly
μNTB	=	micro-Newton thrust balance
PID	=	proportional-integral-derivative (controller)
CoG	=	center of gravity
ESA	=	European Space Agency
MPT	=	micro proportional thruster
RMS	=	root mean square

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I. Introduction

EUROPEAN scientists are pursuing a number of unique science missions which require extremely high performance micro-propulsion systems to perform precision attitude control to meet their challenging scientific goals. These missions include planned and possible missions such as LISA Pathfinder[1], Microscope[2] and Euclid[3].

Verification of performance of potential thruster candidates by test is challenging due to the magnitude of the thrust noise requirements of the stated missions, which is close to the limit of available measurement devices. Aside from common practicalities of testing thrusters in vacuum, disturbances due to external effects such as background vibrations and thermal drifts are magnified due to the low thrust levels to be measured.

Two other measurement facilities were already identified in the past within European industry, one at Thales Alenia Space[4] and one at ONERA[5]. The latter has recently been used for the acceptance of GAIA CG-MT thrusters manufactures by TAS-I, but they both have limitations in performance (particularly in terms of measurement bandwidth).

The ESA and the ESA Propulsion Laboratory (EPL) started in 2009 the development of a Micro-Newton Thrust Balance (µNTB)[6] to improve measurement coverage of the mission requirements and to offer measurements accredited to ISO 17025 in the µN range with traceability to international standards with rigorous uncertainty evaluation. An accredited measurement, including an ISO GUM (Guide to the expression of uncertainty in measurement) compliant uncertainty budget, was considered vital considering the difficulty of such measurements.

For several years the ESA has been working on the µNTB project with the National Physical Laboratory (NPL), the UK's national measurement institute. Since 2011[7], the development of the ESA uNTB has been improved leading to its accreditation for steady-state direct thrust measurement of a cold-gas thruster under ISO17025 standards. Upgrades include the addition of background vibration isolation systems, definition of a standard measurement and signal post-processing methods, and consolidation of the uncertainty budget calculation proceedure. The present paper will describe the activities performed leading to the accreditation of the uNTB for ISO17025 steady-state direct-thrust measurement of a cold-gas thruster, detailing the set-up of the device in the EPL, the test procedures and the results.

II. Micro-Newton Thrust Balance System

The Micro Newton Thrust Balance (µNTB) is a direct thrust measurement device developed by the EPL in close collaboration with the NPL (UK). The measurement of static thrust on cold-gas thrusters with the Micro Newton Thrust Balance is accredited for the range of [1 – 500] µN with an uncertainty of ± 1 µN. In Table 1 is listed the confirmed performance of the uNTB.

A. uNTB System Description

The system is composed of two nominally identical null-displacement balances, the Measurement Balance Assembly (MBA) and the Tilt Compensation Assembly (TCA). Both balances are built in the form of a monolithic folded pendulum. A capacitive displacement sensor (MTI ASP-5-PCR, amplified by Accumeasure 5000) measures the thrust induced displacement of the pendulum. A force actuator integrated in a feedback servo system applies a force to the pendulum so that its displacement is held at zero (null displacement). The force actuators were specifically designed and manufactured by NPL for the µNTB. The actuators are voice coil actuators including a Maxwell pair solenoid assembly and a permanent magnet mounted in a holder. They are powered by a specially designed precision current source with a ±100 mA range per actuator. The concept of the measurement is presented in Figure 1.

Parameter	Confirmed performance
Measurement Range	500 µN
Measurement Uncertainty	+/- 1 µN (2 sigma confidence level)
Measurement Resolution	0.2 µN
Measurement Bandwidth	Mass dependent • Best achieved: 10 Hz • With cold gas thruster: 4 Hz
Measurement Noise Floor (µN/√Hz)	Mass dependent • Best achieved: ≤ 0.1 (10^{-2} – 10 Hz) • Best with cold gas thruster: ≤ 1 (10^{-2} – 10 Hz)

Table 1. µNTB confirmed performance.

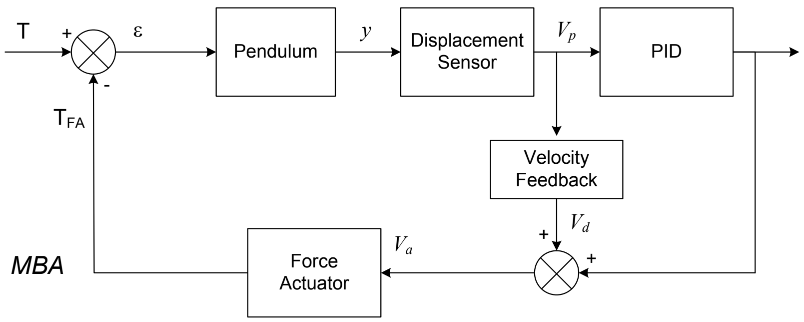

Figure 1. Schematic of the µNTB measurement concept (MBA only).

B. Physical Setup

The µNTB complete setup includes the physical measurement device and the supports and platforms that form the complete assembly. As stated in the previous paragraph, the physical setup of the balance assemblies (MBA or TCA) include a monolithic folded pendulum, a MTI displacement sensor and a force actuator developed by NPL. All these items are installed on a harness with electric and gas feedthroughs, and are presented in Figure 2.

Each of the harness assemblies is installed on a separate aluminium tilt adjustment platform. Each platform has three points of support: two fixed pins from the aluminium platforms and the micrometer tip. The micrometers are used to level the balances independently. The micrometers are motorized so that the balances can also be levelled once in vacuum.

Both aluminium tilt adjustment platforms sit on an aluminium baseplate. The baseplate surface is etched with two slits and two holes, (one slit and one hole for each tilt adjustment platform) which serve as kinematic locations for the correct alignment of the platforms.

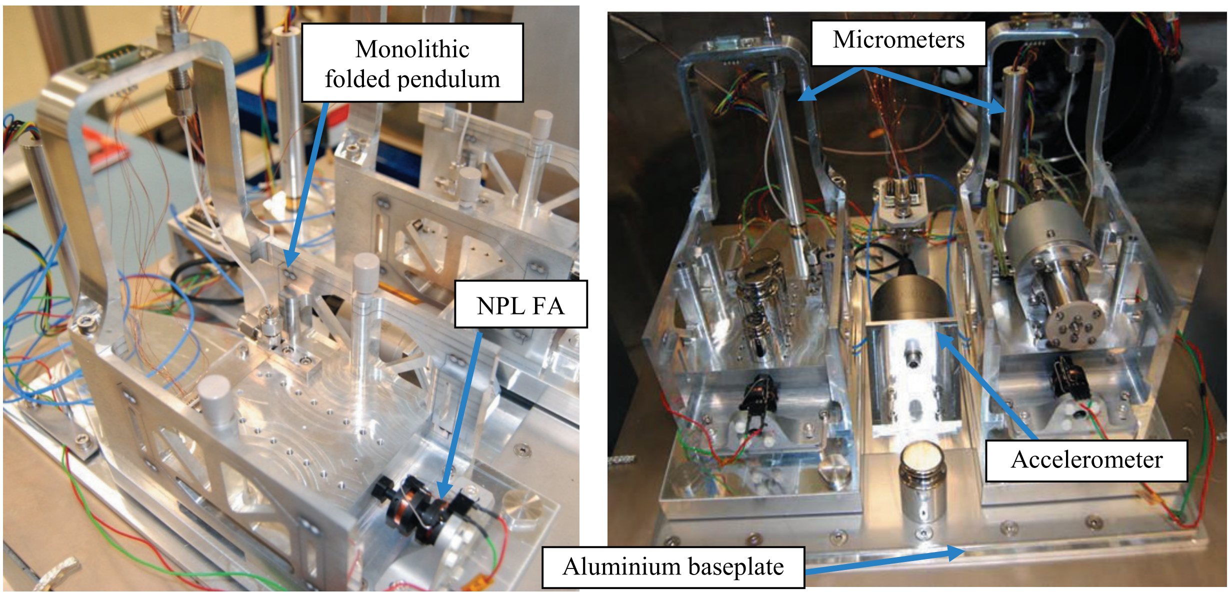

Figure 2. Micro-Newton Thrust Balance assembly on its harness (left) and µNTB MBA and TCA assemblies installed on the aluminium base plate.

Severe vibration noise coming from the ground is known to significantly contribute to the uncertainty of the balance measurement. To minimise noise transmission from the environment to the balance assemblies, two isolation systems have been incorporated to the setup, the Minus-K platform and the isolation tower harness.

The Minus-K vibration isolation platform is a six degrees-of-freedom mechanical low pass filter based on negative stiffness[8]. The aluminium baseplate holding the measurement system is placed on the Minus-K platform in order to place the CoG of the setup as close as possible to the geometrical centre of the platform with the help of two alignment pins.

The isolation harness tower consists of a baseplate support for the Minus-K isolation system (on which sits the balance) and two columns coupled by a joist which allocates the electrical and feeding system interfaces. It also includes electrical and gas interface. Thin, low stiffness cables and tubes are used to connect the balance setup to these interfaces in order to limit ground noise transmission. This leads to a standard setup configuration, ameliorating measurement repeatability and minimises vibration transmission from environment to the balance assemblies through cabling and piping.

III. Test Set-up

The thrust measurements were performed in vacuum in the GALILEO facility at the ESA Propulsion Laboratory. GALILEO is a 1.2 m high 1 m diameter chamber. Its pumping system includes primary pumps, a turbomolecular pump and a cryopump. Cryopumps/cryoheads are very noisy and were not used during µNTB testing activities to reduce their contribution on the balance signal uncertainty. The turbomolecular pump has a pumping speed of 450 L/s of N_2.

Figure 3. GALILEO Vacuum Facility

The balance assemblies were installed in GALILEO using the isolation harness tower. Gas was fed through a dedicated feeding system (including pressure regulator, mass flow sensor and pressure transducer). Seismic disturbances, temperature and background pressure were monitored during the test.

All instruments were connected to a single Data Acquisition System and were controlled by their respective drivers. The balance was controlled by a validated software provided by NPL. Balance data was recorded at 128 Hz.

The reference thruster used for this test was the MPT EM01, manufactured by MOOG UK and property of the EPL. It is a cold gas (Nitrogen) thruster producing 0 – 1000 µN of thrust, which is proportional to its command input. A validated software provided by the manufacturer was used to operate the thruster. Closed loop control of the thruster was achieved with an embedded PID controller and an internal pressure transducer.

IV. Test Procedures

The test was performed following an internally developed procedure for steady-state direct thrust measurement of a cold-gas thruster with the ESA uNTB. Following a step by step approach, the procedures had been defined to obtain and reproduce the thrust measurements independently of the environment and test item. The set of actions were result of an iterating process after several experimental campaigns. The aim of this test was to accredit the test procedures based on ISO17025 standards.

First, a list of preliminary checks were performed to sort out any possible defect or damage on the balance or thruster, and to confirm the suitability of the test setup. These included visual inspections, feedline leak checks, electrical checks, and verification of the balance transfer functions. Regular checks were performed for every step of the gradual assembly of the test setup, allowing the rapid identification of a potential problem. The test setup was considered completed when the ESA uNTB was installed inside the GALILEO VF, in stable configuration, with high vacuum conditions, no leaks on the feedlines, and the MPT installed on the MBA. For this test, a dummy weight with the same mass as the MPT was installed on the TCA. Then, different measurement procedures were performed to identify potential systematic effects on the balance output signal during the thruster activation, e.g. variation of the background pressure and the gas feedline pressure or displacement of the thruster piezo valve. The procedures had been previously defined to reproduce the desired effects without actually firing the thruster. Non-negligible results on these tests had to be characterised and accounted in the final thrust measurement, and, if applicable, in the uncertainty budget calculation.

Finally, the thrust measurement sequence was carried out. This sequence started with the measurement of the balance transfer functions (both the MBA and the TCA), and continued with the characterization of the feedline pressure effects. At last, the thrust measurement is performed by sequential thruster on/off steps interspersed with FA steps of the same order of magnitude. Noise measurements were also performed regularly during the test. The thruster setpoints were defined at the beginning of the test campaign and commanded as closed-loop pressure transducer voltage targets (in mV).

V. Test Results

A. Balance health checks

The transfer function of each balance (MBA and TCA) was measured before each thrust measurement sequence. A known stimulus was applied with the balance force actuator and the balance output was recorded. Output/Input was fitted to a predefined model in which some of the terms are known and others have to be determined. This result was always validated by applying twice the same stimulus.

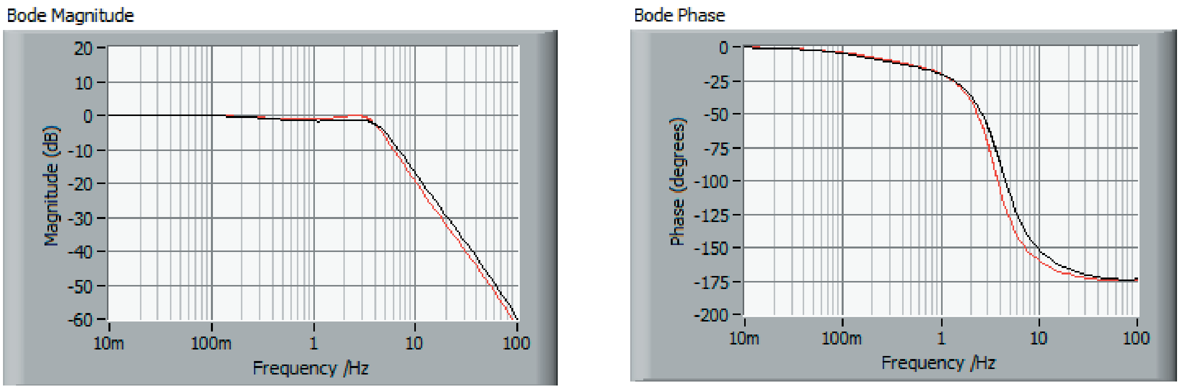

Figure 4: Bode plots (left: amplitude, right: phase) of the MBA (black) and TCA (red) transfer functions measured during system identification

The results indicated a nominal performance of both balance assemblies and the transfer functions were used to deconvolve the thrust output from the balance. Results showed a bandwidth of 3.5 Hz in this setup. Bandwidth is directly correlated with the weight installed on the balance.

B. Seismic and Thrust Noise

Background vibration noise was recorded by accelerometers for all tests placed on the ground of EPL close to the GALILEO VF, on the GALILEO VF structure (on air) and on the Minus-k top plate. In parallel, dedicated thrust noise measurements were carried out with the balance at the beginning and end of the test and regularly between steps of each thrust measurement sequence. Noise spectral density of the signals recorded by the accelerometers showed high background noise levels on frequencies larger than 10 Hz. This is compensated by the effective vibration damping by the Minus-K isolation platform above 1 Hz. On the other side, the MBA and TCA signals match up to 10 Hz, and therefore the tilt compensation mechanism (MBA-TCA) is efficient (Figure 5).

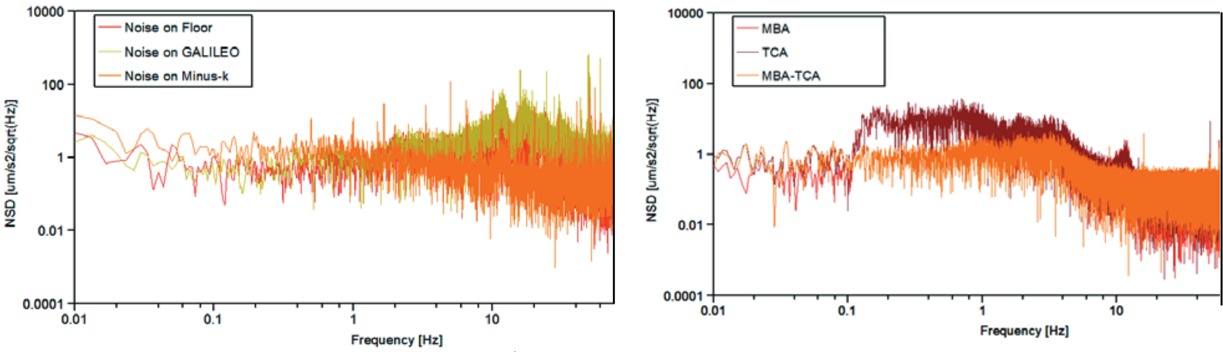

Figure 5: Noise spectral density (NSD, µm/s²/√Hz) for accelerometers on the floor of the EPL, GALILEO and Minus-K (left) and Thrust noise spectral density (NSD, µN/√Hz) for MBA, TCA and the difference between both (right)

C. Thruster health checks

The correct functioning of the MPT was checked by applying a triangle command voltage in open loop, in accordance with the manufacturer procedures. This was repeated three times taking as reference the two internal measurement devices (pressure transducer and strain gauge). All three tests presented similar results, and the behaviour of the MPT was in accordance with results from previous tests. Results showed expected hysteresis in open loop mode and repeatable response (Figure 6).

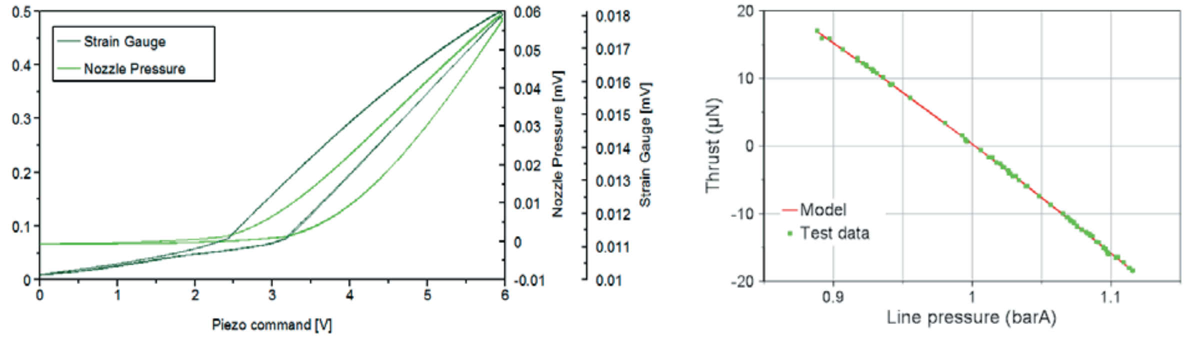

Figure 6: MPT heath check results: nozzle pressure set point (light green, mV) and strain gauge (dark green, mV) recorded during three separate triangle commands (left). Raw command (blue, V) and thrust (grey, µN) data recorded during a thruster activation cycle with steps of 1 V from 2 to 7 V (right)

D. Thruster activation effects

Thruster activation effects were characterized by activating the piezo valve of the MPT with no gas in the line. Each step command was interspersed with off-command steps of the same length (Figure 6). The RMS of the means for a given command are in the order of the resolution of the balance. There was no measurable effect of piezo activation on thrust for steady state measurements. Therefore, no correction was applied to thrust.

E. Gas line pressure effect characterization

Gas line pressure effects on the balance were characterised by applying falling pressure steps in the thruster feedline with the piezo valve closed. The test was repeated before and after each thrust measurement sequence. The mean pressure and measured thrust for each step were recorded for the duration of this test and are presented in Figure 7.

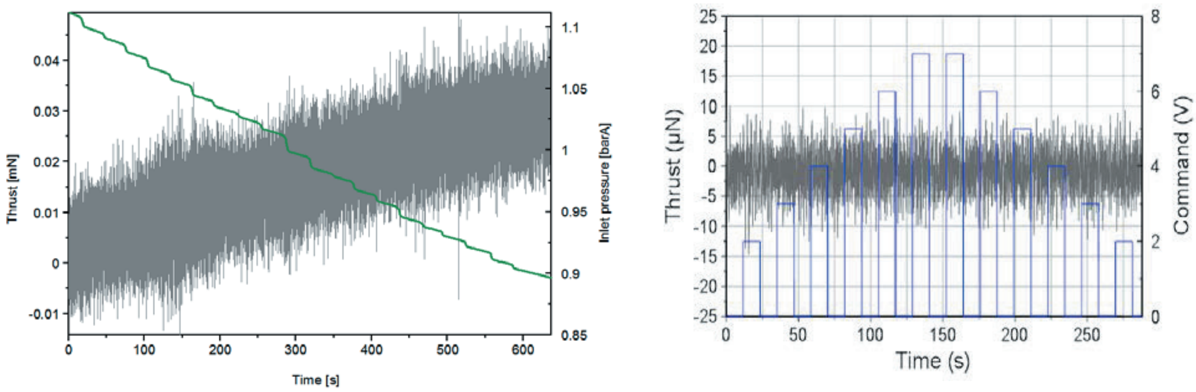

Figure 7: Pressure effects characterization showing that Thrust (grey, µN) varies with line pressure (green, barA) (left). Mean thrust (µN) versus line pressure (barA) data points recorded (green) and best second order polynominal fit (red) (right).

A second order polynomial is fitted to this data:

$$f_{press}(P) = aP^2 + bP + c$$

Where f_{press} is the force measured by the balance during the line pressure effects characterisation tests and P is the pressure of the feedline. This best fit gives the correction model to be used for each thrust measurement. The uncertainty on the correction is given by the RMSE of the fit.

F. Thrust measurements

Fifty MPT thrust steps were recorded for each nozzle pressure set point. Real thrust steps were always interspersed with simulated force actuator steps. A thrust step can be simulated with the calibrated force actuator by applying a known input voltage. This is used to assess the uncertainty of the measurement and to validate the post-processing method. Each step was 30 seconds long.

The acquisition and post-processing of data was performed by a software developed by NPL which included several steps. At first, the MBA and TCA transfer functions were calculated using system identification. This technique is applied to the balance's response to a sequence of stimulus. The calculated transfer functions were validated by comparing the predicted response of the balance with a second measurement of the response to the same stimulus. Data from thrust measurements was deconvolved using the inverse transfer function of the balance. Finally, the deconvolved data was cropped and processed to determine the height and associated uncertainty of each step.

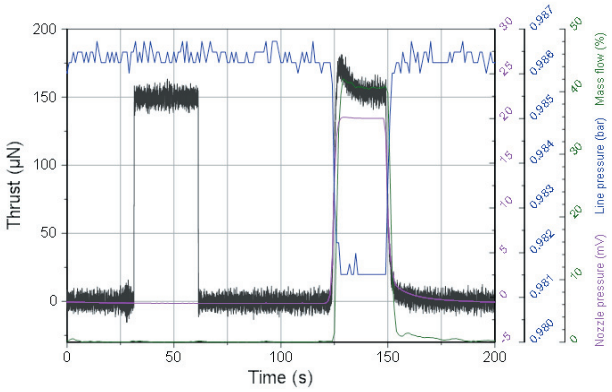

Figure 8: MBA force actuator step (150 µN) followed by MPT real step (20 mV). Are plotted: thrust (µN, grey), Nozzle pressure (mV, magenta), line pressure (bar, blue), mass flow (%max range, green).

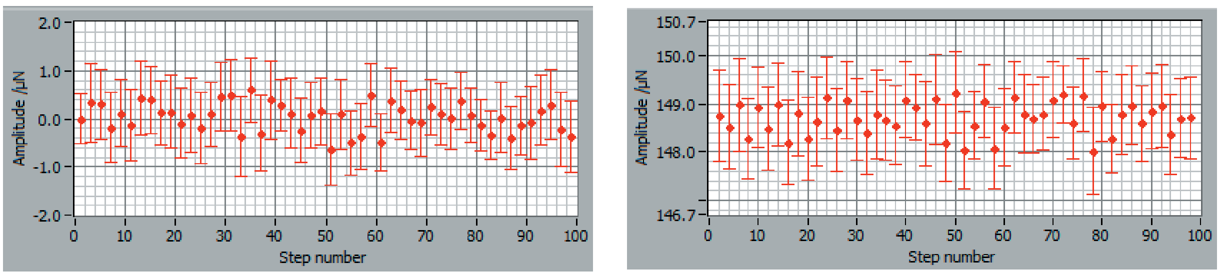

Figure 9: Thrust step height bias for force actuator steps (left) and real MPT steps (right) and associated uncertainty (k=2). 20 mV case.

Results confirmed that the standard deviation of the simulated steps and the mean uncertainty on the real thrust steps were in the same order of magnitude. Moreover, the difference between the simulated steps and measured thrust was within its associated uncertainty for at least 95% of the cases (k=2) in all measured setpoints. This validated all the post-processed results for this test.

VI. Uncertainty Budget Calculation

A standard way of determining measurement uncertainty was verified during this test[9]. The procedures are based on GUM standard[10] to evaluate the uncertainty. The steps are the following:

1. Identify each uncertainty source.
2. Quantify each uncertainty source and scale it to a Normal distribution ($k=1$), $u(\#)$. Where # can be substituted for a meaningful name.
3. Add all individual uncertainty terms in quadrature to give the Combined Uncertainty, $u_c(\#)$.
4. Apply a scale factor (k) to $u_c(\#)$ to get the Expanded Uncertainty, $U(\#)$, at the desired confidence level, usually 95 % corresponding to $k=2$.

A. Main sources of uncertainty

The main sources of uncertainty associated with the static thrust measurement using a pair of nominally identical balances are listed below.

Uncertainty Source	Comment
Force actuator	Contributions from both FAs
Calibration, $u(FA_{cal})$	Worst case from latest calibration.
Radial alignment, $u(FA_{rad})$	Constrained by design (0.005%)
Axial alignment, $u(FA_{ax})$	Constrained by design (0.015%)
Angular alignment, $u(FA_{ang})$	Constrained by design (0.005%)
Temperature change, $u(FA_T)$	Assume temperature of FA is known to 1 °C (0.03 %/°C)
Drift in sensitivity, $u(FA_d)$	Due to magnet & electronics.
$\boldsymbol{u_c(FA)}$ $_{MBA,TCA}$	Combination of the above. Not including $u(FA_d)$. One contribution per force actuator. (0.04% of the signal)
Data processing	
Extracting thrust signal from drift and noise, $\boldsymbol{u(T)}$	Based on **errors observed** in the Step Tests when processed with the modified model.
Compensation of systematic effects	
Thermal effects on pendulums, $u(D_T)$	Testing so far inconclusive. Depends on many factors e.g. gradients, rate of change... No thermal effects present in cold-gas thruster test
Compensation of harness induced drift, $u(D_h)$	Uncertainty in gas line pressure variation fitting
$\boldsymbol{u_c(Comp)}$	Combination of $u(D_T)$ and $u(D_h)$
Thruster alignment	
Alignment with measurement axis, $\boldsymbol{u(a)}$	For 1 ° misalignment. Cosine error (0.015 % of Thrust)
Balance uncertainty	
Difference signal uncertainty, $u_c(Diff)$	Combination of $u(T)$, $u_c(FA)_{MBA}$ and $u_c(FA)_{TCA}$. T is thrust signal magnitude, D is the TCA output signal (due to tilt). The MBA signal is subject to the same signal component.
Balance uncertainty, $\boldsymbol{U_c(B)}$	Combination of $u_c(Diff)$ and $u(a)$ and $u_c(Comp)$

Table 2. Uncertainty sources associated with static thrust measurement.

B. Calculating the combined and expanded uncertainty

The uncertainty contributions for the force actuator have been combined by adding them in quadrature to give a combined uncertainty associated with each force actuator.

$$u_c(FA) = \sqrt{u(FA_{cal})^2 + u(FA_{rad})^2 + u(FA_{ax})^2 + u(FA_{ang})^2 + u(FA_T)^2 u(FA_d)^2}$$

The signals from the two balances are combined by subtracting the TCA signal from the MBA signal to compensate for low frequency drift and common-mode vibration. The resulting signal is further processed by the NPL software to calculate the thrust step magnitude and an uncertainty contribution due to noise on the signals. The model equation for this process is as follows:

$$\mathrm{F}_{\text{balance reading}} = D_{MBA} S_{FA}^{MBA} - D_{TCA} S_{FA}^{TCA} + \tau$$

Where D_{MBA} and D_{TCA} are the un-scaled (digital) outputs from the MBA and TCA respectively, S_{FA}^{MBA} and S_{FA}^{TCA} are the sensitivities of the MBA and TCA force actuators (taken from their calibration certificates), and τ represents noise on the combined signal and therefore includes variance in D_{MBA} and D_{TCA}. τ has an expectation value of zero and a standard deviation of $u(\tau)$.

The combined uncertainty for the processed difference signal, $u_c(F_{balance\ reading})$, is then obtained by adding in quadrature, contribution from the force actuators, $u(FA)_{MBA}$ and $u(FA)_{TCA}$, and the uncertainty due to noise taken from the NPL data processing, $u(T)$. Note that the uncertainty associated with the TCA force actuator contributes an uncertainty in tilt compensation.

$$u_c\left(F_{balance\ reading}\right) = \sqrt{D_{MBA}u\left(FA\right)_{MBA}^2 + D_{TCA}u\left(FA\right)_{TCA}^2 + u\left(\tau\right)^2}$$

Standard uncertainties for real thrust steps were between 0.4 µN and 0.9 µN in the worst case. Mean thrust values are presented in Table 2. These values are the height of the measured steps and have not been corrected for systematic effects.

Case	Definition	20 mV	5 mV	0.5 mV
SD_{FA}	Standard deviation of the FA steps	0.300	0.250	0.300
$\bar{u}_{FA}$	Uncertainty associated to the FA steps	0.343	0.309	0.433
SD_{MPT}	Standard deviation of the thruster steps	0.328	0.967	0.674
$\bar{u}_{MPT}$	Uncertainty associated to the thruster steps	**0.409**	**0.859**	**0.541**
$\bar{T}_{MPT}$	Mean measured thrust signal	**148.705**	**31.757**	**3.669**

Table 2. Standard deviations and mean standard uncertainties for force actuator and MPT steps for all thrust measurement sequences. The last line gives the MPT mean thrust step height. All values are in µN.

The final thrust value is given by:

$$F_{thrust} = (F_{balance reading} + \Delta F_{press} + \Delta F_{thermal} + \Delta F_{activation}) \times \left(1 + \delta \cos\right)$$

Each contribution to the final thrust measurement is detailed here:

$F_{balance\ reading}$: This value is the thrust step height and its associated uncertainty. It is taken as direct output of NPL's post processing software, which calculates the uncertainty contribution due to noise only.

ΔF_{press}: This is the correction due to the pressure changes in the gas line during the firing of the thruster.

$\Delta F_{activation}$: Correction due to activation of the thruster without gas. This correction includes voltage, current and change of CoG effects. There was no measurable effect on the balance during thruster activation.

$\Delta F_{athermal}$: Correction due to the thermal sensitivity of the balance. All temperatures were constant during the test. The MPT does not produce any thermal loads on the balance.

ΔF_{press}: This is the correction due to the pressure changes in the gas line during the firing of the thruster.

δcos: Uncertainty due to the alignment of the thruster with the MBA. Typically a 1° misalignment is assumed.

The uncertainty in the final output signal, $u_c(F_{thrust})$, is the quadrature sum of the difference signal uncertainty, $u_c(F_{balance\ reading})$, and the uncertainties in the compensation factors $\Delta F_{press}, \Delta F_{thermal}, \Delta F_{activation}$, and $\delta \cos$ multiplied by their respective sensitivity coefficients.

$$u_s(F_{thrust})^2 = \sum u_s(x_i)^2 \left(\frac{\partial F_{thrust}}{\partial x_i}\right)^2$$

where x_i are the uncertainty contributors in the model equation. In our case all the derivatives (sensitivity factors) were 1 except for δcos which is the sum of all the values of the other contributors. The sum of the equation above was determined using the GUM workbench software. The results for the 20 mV case are summarized in Table 3 below.

Quantity	Unit	Value	Expanded Uncertainty	Distribution Coverage factor	Standard Uncertainty	Sensitivity Coefficient	Index
$F_{balance\ reading}$	µN	148.705	0.41	normal (k=1)	0.409	1	89.5 %
δF_{FA}^{MBA}	µN	0.0	0.04	normal (k=1)	0.0404	1	0.9 %
δF_{FA}^{TCA}	µN	0.0	$1.4\cdot10^{-3}$	normal (k=1)	$1.4\cdot10^{-3}$	1	0.0 %
ΔF_{press}	µN	0.423	0.13	normal (k=1)	0.133	1	9.5 %
$\delta\cos$		0.0	$1.5\cdot10^{-4}$	rectangular (k=√3)	$86.6\cdot10^{-6}$	150	0.0 %
F_{thrust}	**µN**	**149.1**	**± 0.9 (k=2)**				

Table 3. Uncertainty calculation results for 20 mV case

Thrust measurements and their respective uncertainty are presented in the Table 4 for the three inspected setpoints. As the MPT thrust output has shown high dependency with the background pressure when firing, environmental conditions shall be specified for each measurement. The reported expanded uncertainties are based on a standard uncertainty multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95%.

Nozzle pressure set point (mV)	Thrust (µN)	Uncertainty (µN) (k=2)	Background pressure (mbar)	VF Temperature (˚C)
20	149.1	±0.9	(1.5±0.3)e-3	22.7 ± 0.1
5	31.9	±1.8	(4.3±0.9)e-4	22.7 ± 0.1
0.5	3.7	±1.1	(1.6±0.3)e-4	22.7 ± 0.1

Table 4. Corrected thrust and total uncertainty (k=2) for all nozzle pressure set points

VII. Conclusion

This paper presented the setup, procedures and results from the ISO17025 accreditation test of the ESA Micro-Newton Thrust Balance. Results showed that thrust was successfully measured with the uNTB for different commands of the MPT, a N_2 cold gas thruster, for thrusts in the range 3 - 149 µN under high vacuum conditions.

The test setup designed in the GALILEO vacuum chamber for the µNTB is adequate for ISO17025 accredited direct thrust measurements. The setup offers a repeatable way of measuring thrust and is flexible enough to be used with different cold gas thrusters. It also helps to minimise vibration noise transmission from the floor of the EPL to the balance. The Minus-K vibration isolation platform and the MBA/TCA tilt compensation approach both greatly improve thrust noise levels recorded in the EPL.

A test procedure was defined for ISO17025 accredited direct thrust measurements. The step by step approach encompasses all actions to be performed to obtain a validated measurement of the uNTB and to understand and characterize all effects that may influence the measurement.

Systematic errors were characterized before any thrust measurements and taken into account when necessary in the final uncertainty budgets. Activation of the thruster without gas in the line showed no effect on measured thrust. The effect of the variation of the line pressure was characterized before and after each thrust measurement sequence was accounted for in the individual uncertainty budgets.

An Uncertainty Budget Calculation was performed following GUM guidelines. Total uncertainty varies between 0.8 µN in the best case and 1.8 µN in the worst case (all with a 2σ confidence level) for each thruster setpoint; the uncertainty is mainly driven by the component associated to the extraction of thrust step height from raw data and by the correction due to pressure changes in the line. Both uncertainty terms are directly related to the background noise. Reducing vibration noise in the bandwidth of measurement would result in a decrease of uncertainty.

These results demonstrate good performance of the µNTB for static thrust measurements in the range 3 – 150 uN. This activity led to the accreditation of the EPL ISO17025 procedure for thrust measurement of a cold-gas thruster with the uNTB in steady-state conditions.

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