

# Direct Thrust and Thrust Noise Measurements on the LISA Pathfinder Field Emission Thruster

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**Abstract:** The paper presents the first exhaustive thrust measurement campaign on the field emission thruster system (or FEEP system) developed for the LISA Pathfinder spacecraft. LISA Pathfinder is the first demonstration spacecraft of the joint ESA/NASA LISA (Laser Interferometer Space Antenna) mission. LISA Pathfinder is built by ESA and will fly as a payload the NASA Disturbance Reduction System. The core technologies under development at ESA and to be verified in orbit are the inertial sensor and the field emission thrusters. The thrust stand developed for these measurements is based on a dual pendulum force sensor where the pendulum deflection is measured by an interferometer. The thrust stand is installed on a multi-stage active-passive isolation system. The thruster tested was a flight-like LISA Pathfinder FEEP thruster driven by its flight-standard electronics. All performance parameters were measured and carefully characterized including noise down to sub-mHz frequencies.

## Nomenclature

$T$	=	thrust
$I_{beam}$	=	beam current
$\eta_{div}$	=	divergence efficiency
$V_{beam}$	=	beam voltage
$K_{beam}$	=	thrust coefficient
$m_{Cs}$	=	Cesium ion mass
$q$	=	electron charge

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## I. Introduction

LISA Pathfinder is an experiment to demonstrate Einstein's geodesic motion in space more than two orders of magnitude better than any past, present, or planned experiment, except for LISA. LISA Pathfinder's experiment concept is to prove geodesic motion by tracking two test-masses nominally in free-fall through laser interferometry with picometer distance resolution. LISA Pathfinder will show that the relative parasitic acceleration between the masses, at frequencies around 1 mHz, is at least two orders of magnitudes smaller than the value demonstrated so far.

The basic elements to achieve and prove geodesic motion are to have free floating test masses equipped with motion sensors in all degrees of freedom and free of dynamical disturbances ( $< 3 \times 10^{-14} \text{ m/s}^2 \sqrt{\text{Hz}}$  at 1 mHz). This can be achieved only with very low thrust ( $\sim 10 \text{ } \mu\text{N}$ ), very low noise ( $\leq 0.1 \text{ } \mu\text{N} / \sqrt{\text{Hz}}$ ) proportional thrusters to push the spacecraft to follow the test masses.

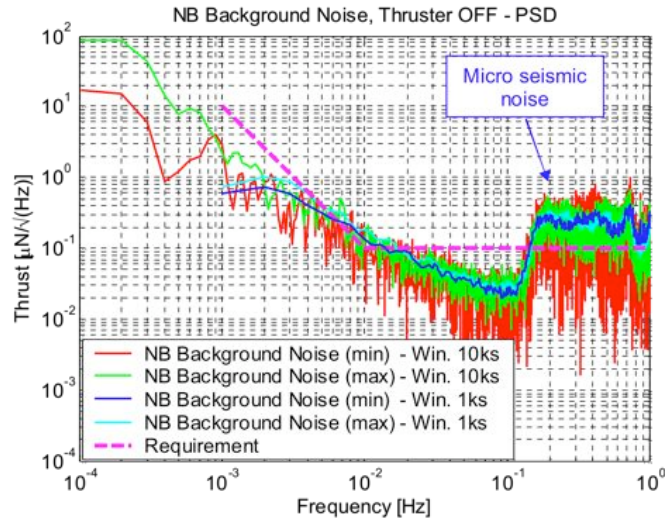
The thrusters are one of the enabling technologies needed to make this possible. The extremely stringent propulsion requirements need to be verified by direct measurement. A dedicated thrust stand facility was developed in the frame of the program to validate the thruster subsystem performance. The extreme performance of the thruster posed severe challenges on the measurement system to be able to measure it on ground. In fact the complex facility developed, one of the most advanced of its kind, is just sufficient to guarantee that mission can meet its performance goal, indeed not being able to measure the full scale performance of the FEPP thruster system.

LISA Pathfinder hardware is designed for use on LISA. However, it is obvious that many other possibilities are opened by the results of LISA Pathfinder. LISA Pathfinder is indeed at once a mission in General Relativity and in Precision Metrology and will open the ground for an entirely new generation of missions not just in General Relativity, but in Fundamental Physics at large and in Earth Observation.

## II. Propulsion requirements

The demanding residual acceleration requirement of LISA Pathfinder translates via the drag-free control system into the challenging propulsion requirements at the basis of both the field emission thruster and the thrust stand design. High thrust ratio and bandwidth, extreme accuracy and resolution, excellent linearity and response time, all while producing a very low noise are key to the mission success.

The table on the right shows a subset of the primary propulsion requirements. Because of the dual role on the spacecraft, that is both drag-free actuations during the science mode and standard attitude and orbit control, the field emission thrusters have quite a stretched set of requirements compared to other propulsion.



**Figure 1. Thrust noise requirement.** For LISA Pathfinder the mission requirement is the pink dashed line. The other lines are the thrust-stand background noise with thruster installed.

Key Requirement Specification	FEPP
Thrust Range	0.3-150 $\mu\text{N}$
Thrust Precision	$< 0.1 \text{ } \mu\text{N}$
Thrust Noise	$< 0.1 \text{ } \mu\text{N}/\sqrt{\text{Hz}}$
Response Time	$< 340 \text{ ms}$
Specific Impulse	$> 4,000 \text{ sec}$
Cluster Power Consumption (4 thrusters @30mN)	55 W
Cluster Mass (4 thrusters, neutralizer and PCU)	13.7 kg
Lifetime (Thruster-ON)	250 days
Total Impulse	2,000 Ns

**Table 1. Key propulsion requirements on LISA Pathfinder.** On LISA Pathfinder the FEPPs are the only propulsion system once the transfer vehicle is released, so in addition to drag-free tasks they manage all the attitude and orbit control.

### III. The test item: the LISA Pathfinder FEFP

The tested equipment was a representative unit of the Cesium slit field emission thruster system to be flown on LISA Pathfinder. The system is composed of a set of slit thruster assemblies, which include the Cesium propellant tanks, neutralizers and their control and power electronics [1]. One thruster assembly and a single power and control unit were used for the measurements, without neutralizer being irrelevant for the thrust performance.

In particular the thruster assembly was a flight-like assembly with its own tank thermal shield and without the lid opening mechanism. The reason being the lid mechanism would have required re-calibration and re-balancing in air of the stand's plates once opened. Since the thruster can function nominally even without lid mechanism (i.e. the thruster can be exposed to atmosphere if the tank's rupture disk is sealed), and having no effect on the performance, it was deemed only an additional complication. The tank thermal shield instead is necessary to shield the radiated heat and electric field towards the thrust stand which both disturb the measurements, as discussed more in detail in the following pages.

The PCU (power conditioning unit) was an elegant breadboard, identical to the flight electronics except that it contained only one motherboard, one control board and one power board. The electronic unit was installed outside the vacuum vessel, and controlled via an on-board computer simulator. The PCU thrust loop controls constantly beam current and voltage to obtain the desired thrust via the equation:

$$T = \eta_{div} \cdot I_{beam} \cdot \sqrt{\frac{2 \cdot m_{Cs} \cdot V_{beam}}{q}} \text{ or simply } T = k_{beam} \cdot I_{beam} \cdot \sqrt{V_{beam}}$$

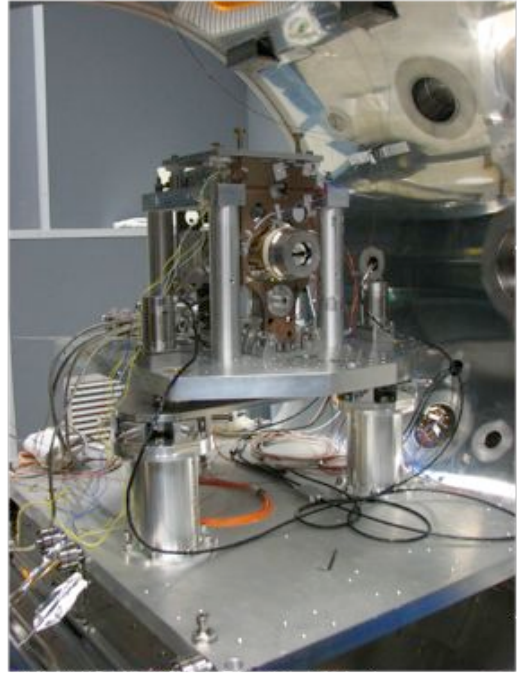
Most performance parameters as response time, accuracy, resolution, noise and others depend on this control. The correlation between computed thrust and real thrust is through the  $k_{beam}$  coefficient stored in look-up-tables that were re-calibrated during this test.

The activation by tank opening and assisted priming was performed in fully automatic mode as in flight via defined procedures.

### IV. The instrument: the Nanobalance thrust stand

The Nanobalance thrust stand [2] is composed by two vertical tilting plates connected by a flexible joint to a rigid block made of Zerodur, in a pendulum-like arrangement. The micro-thruster to be characterized is installed on one of the tilting plates. A counterweight is installed on the second tilting plate to ensure the same dynamics behavior of the first one and therefore the rejection of the common-mode environmental vibrations acting on the thrust stand.

When the thruster is switched on, it produces a displacement of one plate relative to the other, which is measured by means of a Fabry-Perot laser interferometer, which reference spherical mirrors are mounted on the tilting plates. The Fabry-Perot interferometer is fed by an Nd:YAG source working at the wavelength  $\lambda = 532$  nm. The laser frequency is regulated so as to maintain it locked to the F-P resonator as the relative distance between the two mirrors changes under the action of the thruster (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. This frequency measurement is



**Figure 2. Front view of the thruster during installation on the thrust stand.** *The stand's protective screen and calibration are still to be installed. The active isolation stage is visible below the thrust stand.*

converted in a force measurement using a calibration relationship, verified by means of a voice coil actuator permanently installed on the tilting plate and operable even during the test campaign on the micro-thruster.

The Nanobalance thrust stand is operated inside a vacuum chamber. Inside the chamber, the thrust stand is mounted on a horizontal basement which inclination is actively controlled to zero. The vacuum chamber is installed on six pneumatic isolators, rested on an anti-seismic block. The Nanobalance has been fully commissioned without thruster and with representative thrusters: it has a force resolution of  $0.1 \mu\text{N}$  and an intrinsic force measurement noise spectral density  $\leq 0.1 \mu\text{N}/\sqrt{\text{Hz}}$  between 0.01 and 1 Hz ( $\leq 1 \mu\text{N}/\sqrt{\text{Hz}}$  down to 1 mHz), over a measurement range of 1 mN.

Extensive calibration campaigns were performed prior to begin the measurements with and without the thruster installed. In particular high voltage capacitance effects, thermal stability and coupling between thruster and balance, vacuum quality, background noise with increasing mass and test complexity and so on. Given the amount of power lines and signals, even if limited to the minimum, particular care was taken in the routing and residual stiffness introduced.

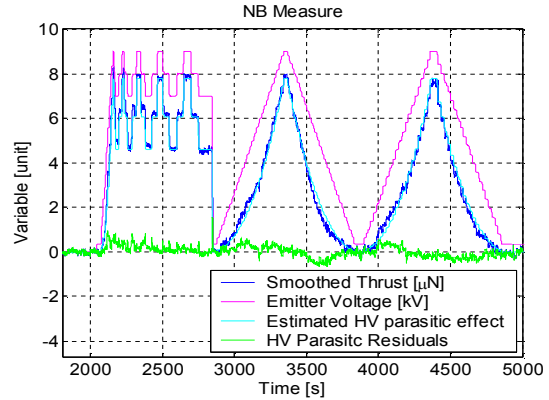
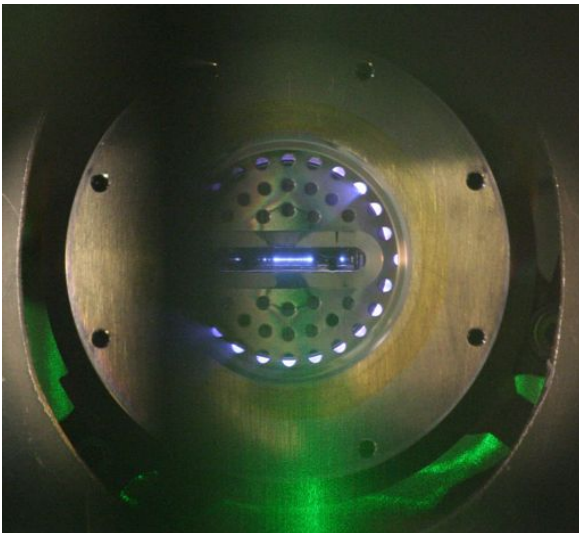


Figure 13: Estimated HV parasitic effect and residuals

**Figure 3. High voltage capacitive effect on the tilting plates.** *Though maximum care was taken into shielding all high voltage parts, the thruster frontal opening introduced parasitic effects removed later.*

## V. Results

In this paper we report only the main results of the measurements highlighting the key performance of the thrusters. Clearly a large set of data was collected during the one-month test campaign that encompasses a wide range of operating conditions, from simulating maneuvers and science mode profiles to verifying the limits of the design well beyond the mission requirements.



**Figure 4. Thruster view during test.** *The green light is the thrust stand laser metrology.*

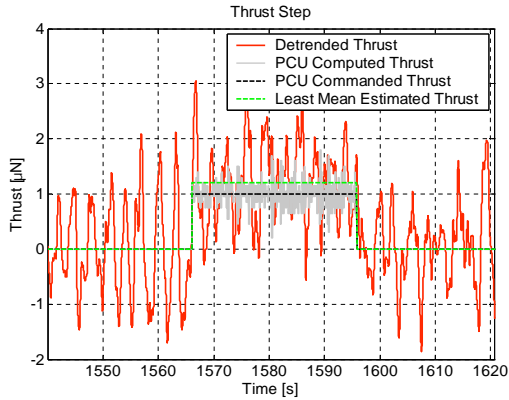
All along the measurement campaign, and prior to each set, the calibrated solenoid force actuator was used to give a reference calibration verifying the thrust stand's correct force magnitude output. Temperature measurements on the balance were acquired continuously. Subsequently the data were processed to remove most temperature and high voltage effects.

### A. Thrust range

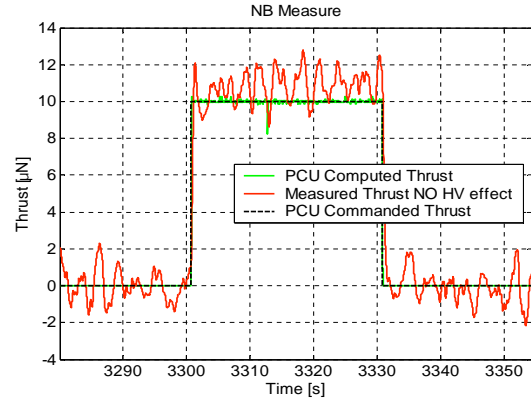
Thrust range was measured by increasing step-like responses to have always a zero-thrust reference in the data files. The complete range from  $0.1 \mu\text{N}$  to  $150 \mu\text{N}$  was applied, though the balance ultimately could detect only down to  $0.5 \mu\text{N}$  due to residual background noise. Concerning the upper-end, thrust levels up to  $200 \mu\text{N}$  (the flight electronics full scale thrust command) were successfully recorded.

The first set of thrust range measurements were used to update the look-up-tables in the control electronics that correlate the computed thrust and the actual delivered thrust. Once the tables were updated the accuracy was maintained all along the test

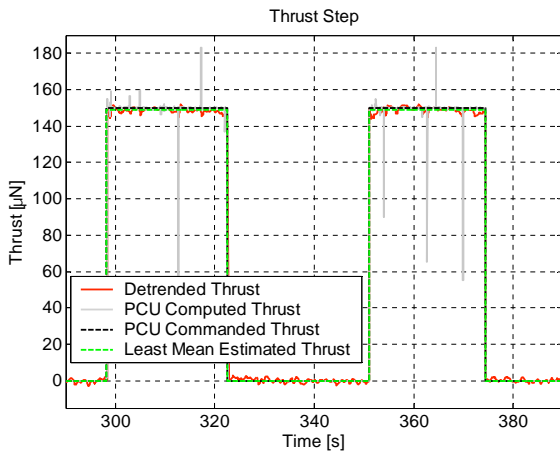
campaign. The correlation factors produced during this test will be uploaded on the flight hardware electronics and used as-is for the first part of the mission until further calibration is required in orbit.



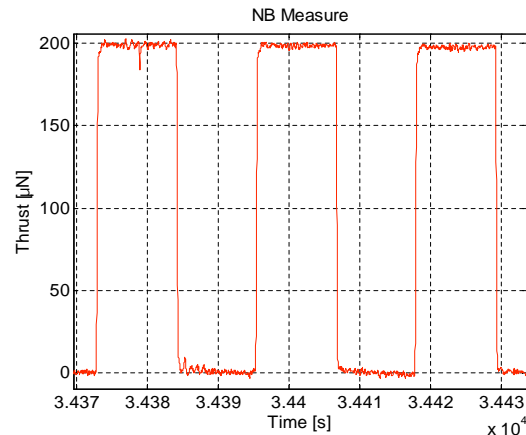
**Figure 5. 0 - 1  $\mu\text{N}$  thrust step.** The minimum thrust measured was 0.5  $\mu\text{N}$  due background noise, though 0.1  $\mu\text{N}$  is the minimum computed by the PCU



**Figure 6. 0 - 10  $\mu\text{N}$  thrust step.**



**Figure 7. 0 - 150  $\mu\text{N}$  thrust step.** LISA Pathfinder requires 100  $\mu\text{N}$ , with a target maximum up to 150  $\mu\text{N}$ .

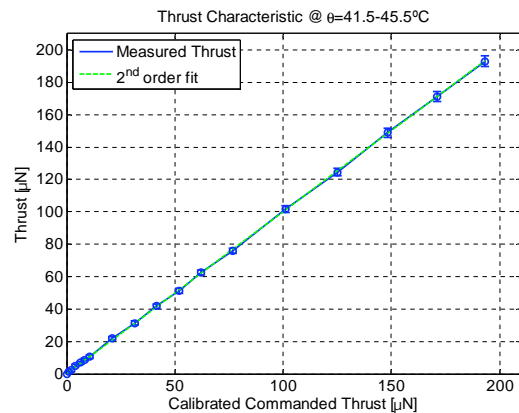


**Figure 8. 0 - 200  $\mu\text{N}$  thrust step.** The PCU is designed to operate up to 200  $\mu\text{N}$ . Maximum thrust on lab supplies was measured to be 350  $\mu\text{N}$  on this thruster.

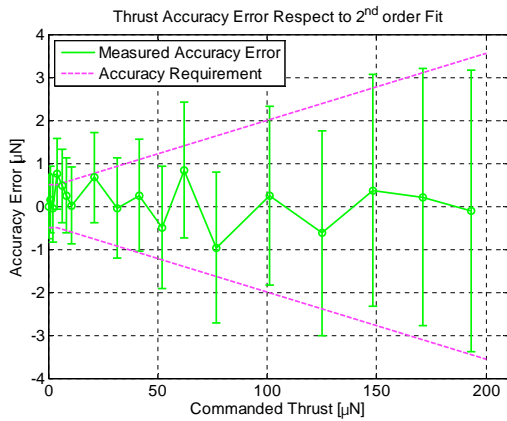
## B. Thrust accuracy

Thrust accuracy was derived after the measured thrust coefficient was uploaded in the control electronics, then verifying it remained unchanged for the duration of the test and in all conditions. The accuracy measured is obviously limited by the thrust stand's accuracy but is basically constant along the required thrust range (figure 8 and 9).

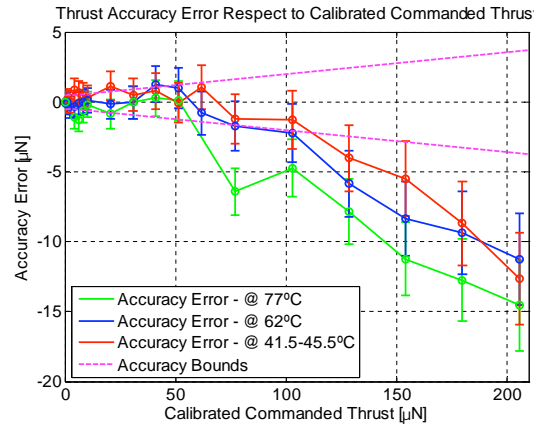
A dedicated thrust accuracy measurement was performed at high temperature since a small change of thrust coefficient was expected due to viscosity effects in the propellant ionization process (figure 10). In fact for a given command, the delivered thruster reduces as the temperature increases. This is considered to be due to a reduced number of cluster ions (like  $\text{Cs}_2^+$ ) which form during the field emission process due to the viscosity of the propellant. Thus at higher temperatures the ion beam fraction of singly charged ions should increase. The thruster thermal control keeps the emitter temperature in a narrow range of temperature such that this effect can be neglected.



**Figure 9. Thrust accuracy.** The accuracy measurement also confirms linearity.



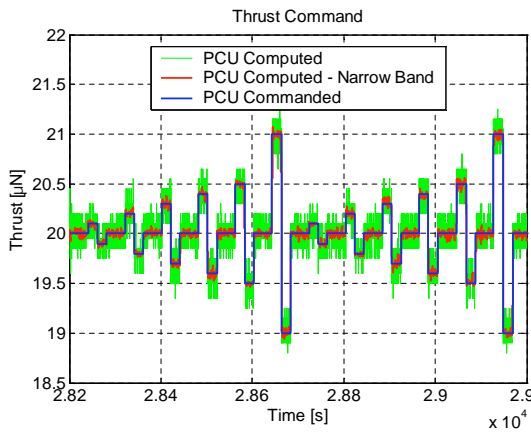
**Figure 10.** Thrust accuracy in terms of accuracy error at nominal temperature. The measurement accuracy is presented as error bars.



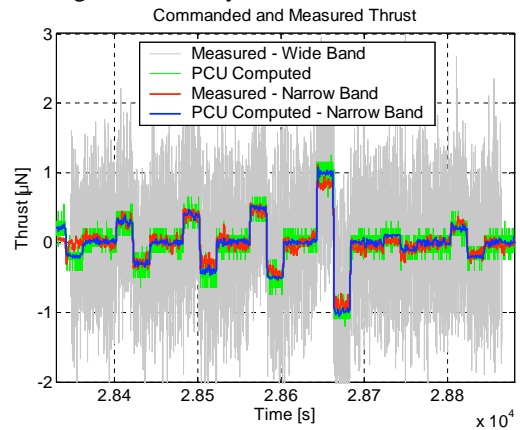
**Figure 11.** Thrust accuracy at high temperatures. The thrust coefficient becomes smaller at higher temperatures.

### C. Thrust resolution

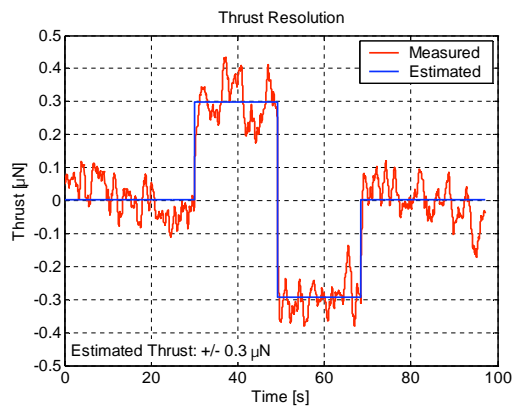
Thrust resolution was derived by commanding small increasing variations of thrust level starting from the target resolution of 0.1  $\mu\text{N}$ . The test was repeated at most thrust levels starting from the very low thrust to the maximum.



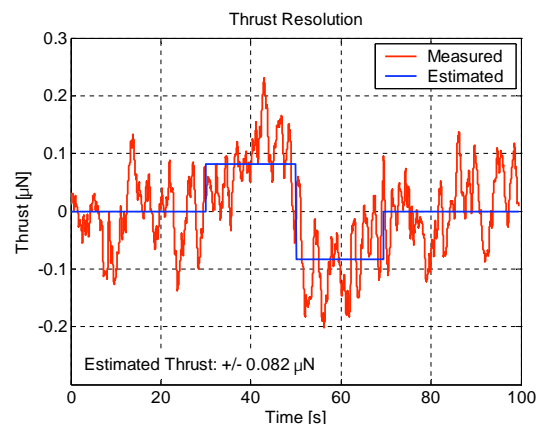
**Figure 12.** Thrust resolution profile. The resolution steps are 0.1, 0.2, 0.3, 0.4, 0.5, 1  $\mu\text{N}$ .



**Figure 13.** Thrust resolution measured. Measured down to 0.1  $\mu\text{N}$  at all thrust levels.



**Figure 14.** 0.3  $\mu\text{N}$  resolution. The LISA Pathfinder required resolution is 0.3  $\mu\text{N}$ .

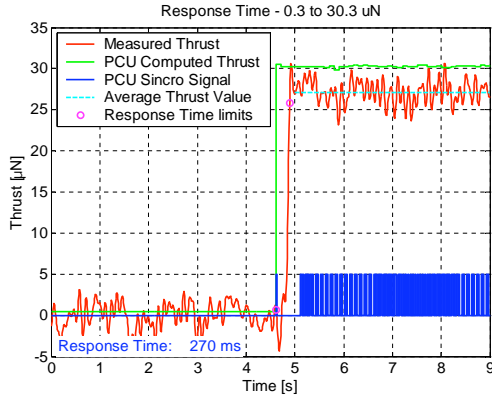


**Figure 15.** 0.1  $\mu\text{N}$  resolution.

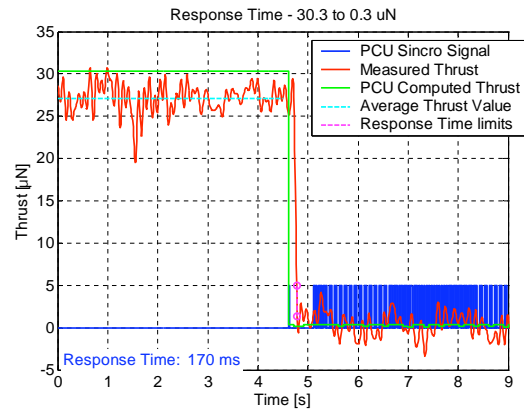
#### D. Response time

The thrust response time was measured by applying step changes and recording with the oscilloscope the balance output. Response time also limited by the thrust stand so values are normally 60 ms higher than what they actually are. Rise-time when starting from 0  $\mu\text{N}$  is always slower than fall-time due the nature of the process which requires passing through the emission threshold.

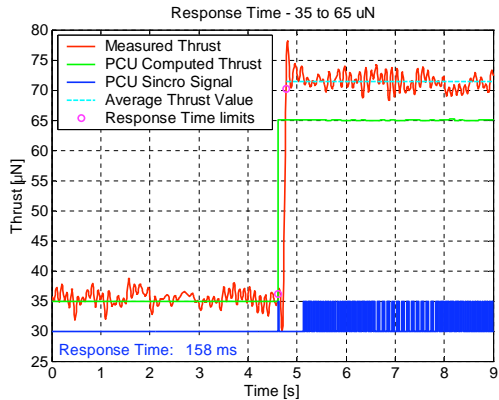
The requirement for LISA pathfinder is specified for a thrust step of maximum 30  $\mu\text{N}$  and the response is met in nearly all cases.



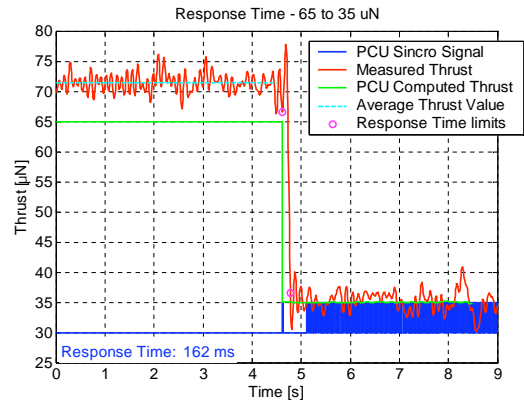
**Figure 16.** 30  $\mu\text{N}$  increase step response time. From 0.3  $\mu\text{N}$  to 30.3  $\mu\text{N}$  – 270ms.



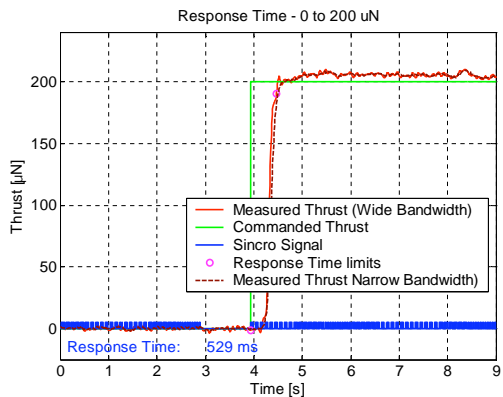
**Figure 17.** 30  $\mu\text{N}$  decrease step response time. From 30.3  $\mu\text{N}$  to 0.3  $\mu\text{N}$  – 170ms.



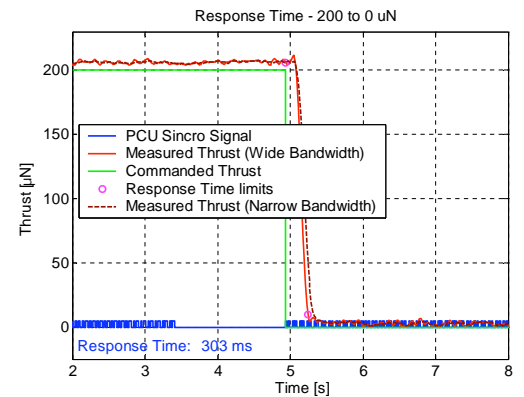
**Figure 18.** 30  $\mu\text{N}$  increase step response time. From 35  $\mu\text{N}$  to 65  $\mu\text{N}$  – 158ms.



**Figure 19.** 30  $\mu\text{N}$  decrease step response time. From 65  $\mu\text{N}$  to 35  $\mu\text{N}$  – 162ms.



**Figure 20.** Full-scale increase step response time. From 0  $\mu\text{N}$  to 200  $\mu\text{N}$  – 529ms.



**Figure 21.** Full-scale decrease step response time. From 200  $\mu\text{N}$  to 0  $\mu\text{N}$  – 303ms.

### E. Thrust noise

The thrust noise is the most complex to achieve at these extremely low levels due to number of disturbing factors including thermal noise and seismic noise. By just installing the thruster on the stand the noise floor immediately increases. The typical noise floor with thruster installed is shown in figure 21, light blue line. Just by activating the thruster thermal control, the thrust stand immediately picks up the thermal noise and the noise floor increases to the gray line. Buy firing the thruster the noise floor remains unchanged (red line) meaning that the noise generated by the thrust production is lower. For reference the noise computed from the PCU is shown in the blue line.

The noise measurements power spectral densities include any noise effect due to arcing.

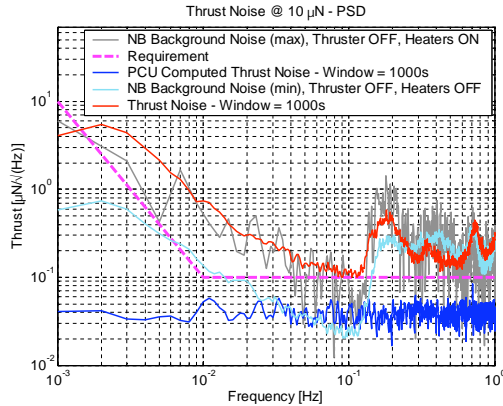


Figure 22. Thrust noise at 10  $\mu\text{N}$ . Noise floor with thruster firing or not is unchanged.

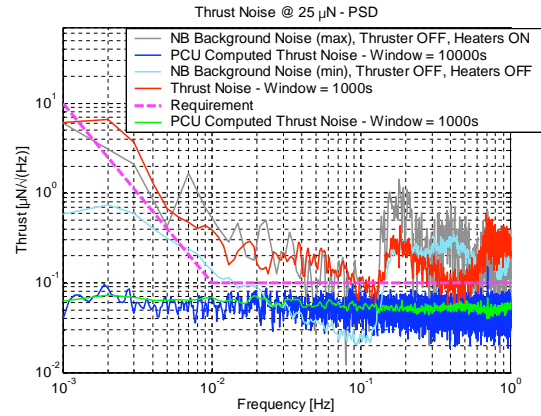


Figure 23. Thrust noise at 25  $\mu\text{N}$ .

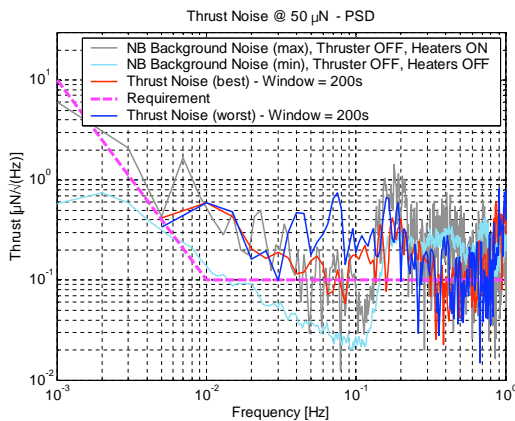


Figure 24. Thrust noise at 50  $\mu\text{N}$ .

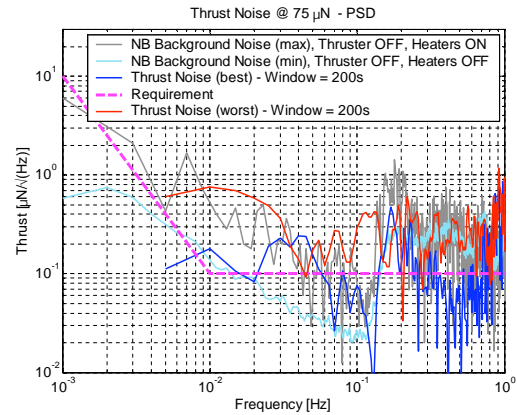


Figure 25. Thrust noise at 75  $\mu\text{N}$ .

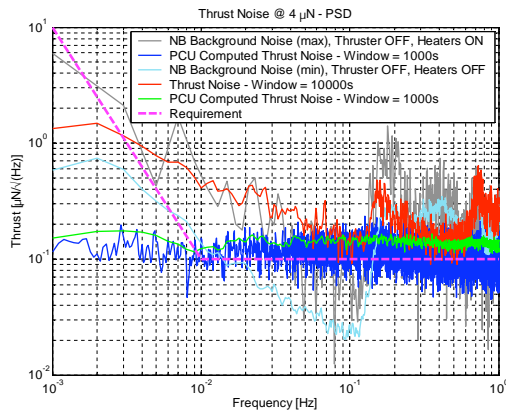


Figure 26. Thrust noise at 4  $\mu\text{N}$ .

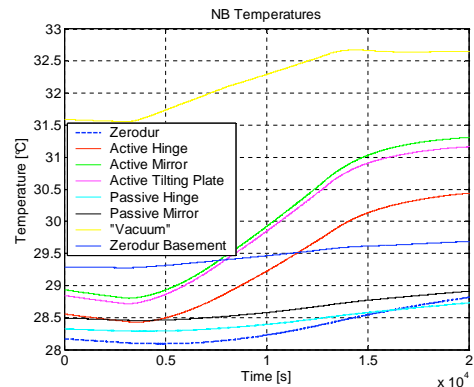


Figure 27. Temperatures of the Nanobalance. Example plot heat dissipated effect.



## VI. Conclusions

The most comprehensive set of measurements on a flight representative field emission thruster were performed in the frame LISA Pathfinder on the ad-hoc developed thrust stand and facility. The challenging test included operating this alkali metal high voltage ion source on an extremely sensitive piece of equipment operating with an interferometer. The results confirm the compliance of the FEEP thruster to the challenging requirements of LISA like missions. On the small scale, the Cesium slit FEEP thruster coupled with its control electronics has proven to be one of the most performing thrusters available ready for flight.

## Acknowledgments

The authors would like to thank all the people who work in the LISA Pathfinder FEEP project in ESA and Industry for their valuable contribution to the success of the program.

## References

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