Development of a Highly Sensitive Micro-Newton Thrust Balance: current status and latest results

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In the context of investigations for a suitable attitude control thruster for future scientific space missions like LISA, or optical interferometrically coupled constellations, we have developed a thruster test facility which consists of a highly precise thrust balance coupled with plasma diagnostics. The setup allows a concurrent operation of all instruments and can also be used for different types of µN propulsion systems including cold gas thrusters. Especially, our unique double pendulum thrust balance design allows a highly accurate characterisation of micro-Newton thruster. The Balance has a proven resolution of less than 0.1 µN in bandwidth between 1 Hz and 10^{-3} Hz. We will give an overview of the current status of our experimentally performed micro-HEMPT development. Furthermore, the design, the present performance, and the future plans of the micro Newton thruster test facility will be presented.

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Nomenclature

GAIA	= Global Astrometric Interferometer for Astrophysics
LISA	= Laser Interferometer Space Antenna
AOCS	= Attitude and Orbit Control System
FEEP	= Field Electric Emission Propulsion
RIT	= Radio Frequency Ion Thruster
HEMPT	= High Efficiency Multistage Plasma Thruster
COTS	= Commercial Off the Shelf
OLV	= Oerlikon Leybold Vacuum
ESC	= Electro-Static Comb
PSD	= Power Spectral Density

I. Introduction

In the last decade, missions like the Global Astrometric Interferometer for Astrophysics (GAIA), Euclid, or the Laser Interferometer Space Antenna [3], [2], [1] have forced an acceleration of micro-thruster development.

The Euclid space telescope will require an Attitude and Orbit Control System (AOCS) with a thrust noise level bellow 1 µN in bandwidth between 10 Hz and 10^{-2} Hz [8].

The proposed space based gravitational wave observatory, LISA will form a three armed interferometer in space. The constellation shall consist of three satellites. The LISA AOCS requirements are almost one order of the magnitude bellow the Euclid specifications. Thus, the thrust noise level should be smaller than 0.1 µN in a bandwidth between 1 Hz and 10^{-3} Hz [3].

Beside the use of micro-Newton propulsion for future science missions, the technology is applicable for micro-satellites, as well. Small and efficient thruster could pave the way for cube sat formation flying [7].

Independent from the specific application and the targeted thruster principle is the fact that the propulsion system must be tested, characterised and qualified. Therefore, suitable thruster test facilities have to be available. Especially the propulsion system requirements of future scientific space mission, as mentioned above, are challenging to achieve and it is not trivial to characterise thrusters in this regime.

We developed a micro-Newton test facility which allows a detailed testing, characterisation and qualification of micro-Newton propulsion systems, with a focus on the needs of future scientific space missions.

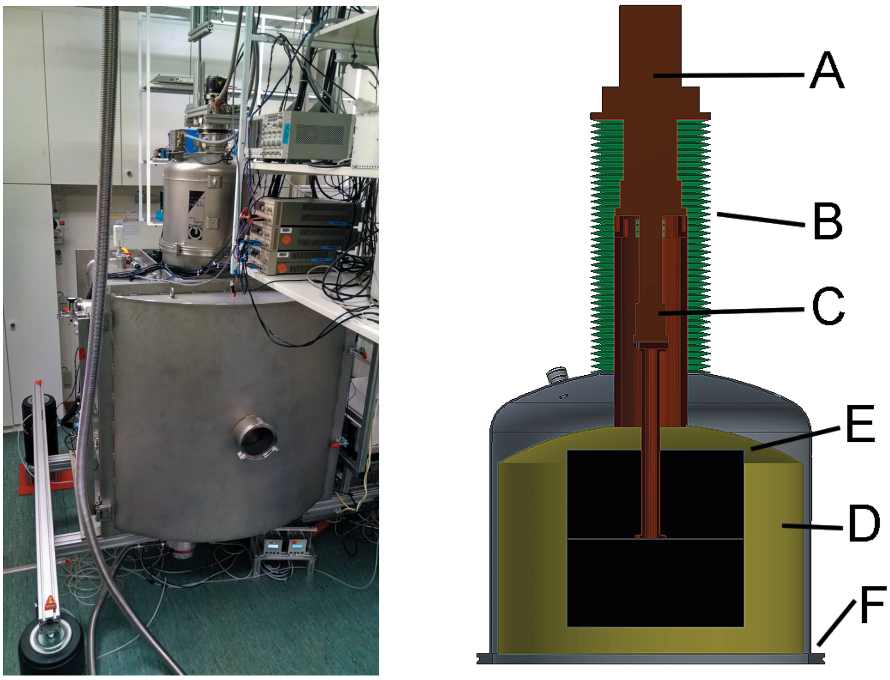
To generate reliable information of the AOCS pointing control error, the characterisation of the thrust noise produced by the AOCS system is necessary. But as far as we know, the available thrust balances were not long term stable enough to characterise micro-Newton thruster in the complete LISA measurement bandwidth. Therefore, we developed a highly precise and highly stable micro-Newton thrust balance which fulfils the LISA requirements, especially in point of thrust noise. The design and the performance of the balance were presented at the IEPC 2013 [5]. The micro-balance is part of the micro-Newton thruster test facility, now. In addition to the direct thrust measurement setup, a set of plasma diagnostic is integrated as well. The simultaneous operation of the instruments allow a concurrent direct and indirect thrust measurement, which is leading to a detailed characterisation of the thruster under test and a deeper understanding of the thruster physics.

II. Micro-Newton Thruster Test Facility

The micro-Newton Thruster Test Facility consists of a 1500 L vacuum tank. The size of the cubic chamber is 1200 mm x 1200 mm x 880 mm. The tank has two doors, one on each side. This enables an easy access to every instrument which is inside the chamber. The whole assembly is decoupled via four isolator feet from ground to reduce seismic noise. An image of the facility is shown in figure 1 a.

A. Pumping System

For a reliable thruster testing a sufficient measurement environment is necessary. For electric propulsion tests the background pressure is from special interest because of the direct coupling between the neutral



(a) (b)

Figure 1. Figure a) shows an image of the micro-Newton thruster test facility. Figure b) presents a cross sectional snapshot of the pump assembly. The cold head (A) is connected to the standard COOLVAC (CV) 10000 CL cryo surfaces (E and D) via a set of cooper adapters (C). The assembly is connected via the membrane bellow (B) to the vacuum chamber

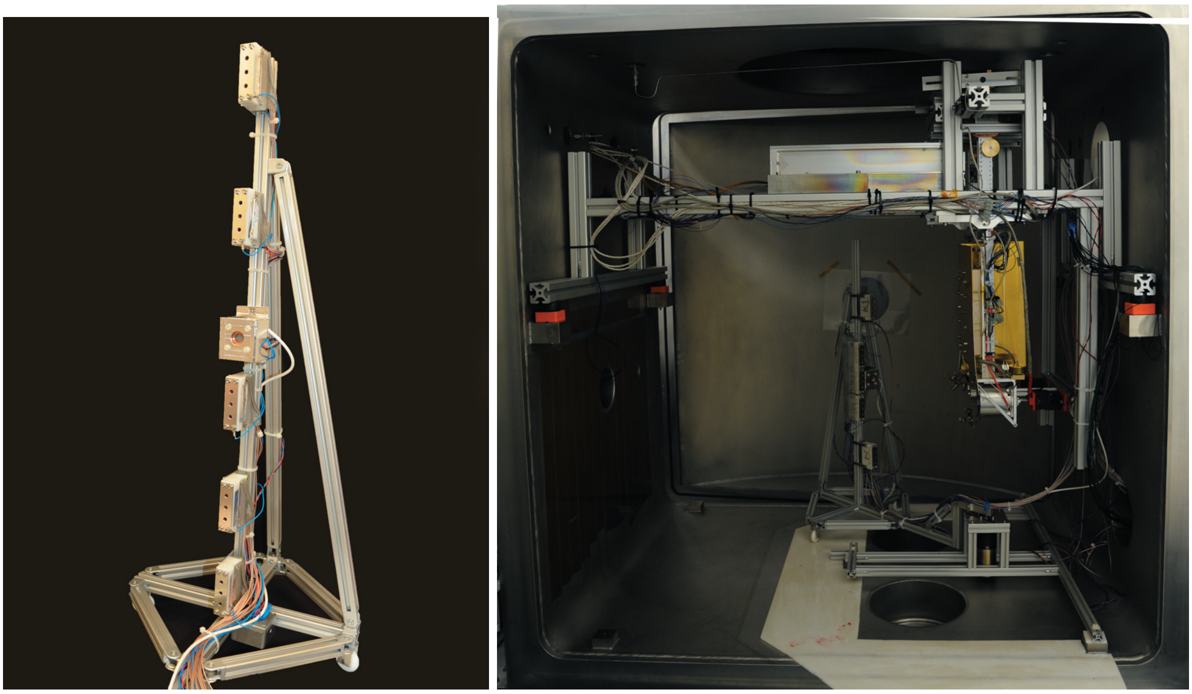
gas particles and the thruster operation. As good practice for EP testing a pressure level in the 10^{-6} mbar regime should be the standard. To maintain this pressure level, a three stage pumping system is installed. As first stage a 20 L/s rotary vane pump is used. Two turbo molecular pumps, with together 1400 L/s pumping speed, are forming the second stage. The third stage is a 10000 L/s cryo pump. All pumps must be mechanically decoupled from the vacuum chamber because the thrust balance is sensitive to seismic noise.

The fore stage pump is decouple via a 7 m long corrugated tube. The pump is placed in a separated container in front of the laboratory building to avoided acoustic noise coupling. The turbo pumps are decoupled from the vacuum chamber via a Commercial Off the Shelf (COTS) pump damper. To maintain the background pressure level of 10^{-6} mBar with running thruster (gas ballast up to 0.5 sccm), a pumping speed in the 10^4 L/s regime is required. In order to provide such a large pumping speed with a single pump, a cryo pump is part of the system.

We modified a COTS COOLVAC (CV) 10000 CL cryo pump from Oerlikon Leybold Vacuum (OLV) to get a reliable, cost efficient and mature pumping system with the advantage of reduced seismic noise. Based on the work of Gerd Jakob [6], we replaced the pneumatically driven Gifford-McMahon cold head COOLPOWER (CP) 5/100 with the mechanically driven OLV cold head CP 10 MD. The CP 10 MD has special properties like high cooling power, low vibrations compared to other coolers [6] and a flexible rotation speed. Moreover, we isolated the cryo pump system from the vacuum tank via a 50 stage membrane bellow. A cross sectional snapshot of the pump assembly is presented in figure 1 b. The cold head (A) is connected to the standard CV 10000 CL cryo surfaces (E and D) via a set of cooper adapters (C). The cold head, the adapters and the cryo surfaces are building the pump assembly. It is connected via the 50 stage membrane bellow (B) to the vacuum chamber, i.e. the pump assembly has no direct contact to the chamber.

B. Plasma Diagnostics

For the characterisation of micro-Newton thrusters a minimum set of instruments is required. Besides the measurement of the thruster parameters such as voltage, current, massflow, the nature of the thruster plume



(a) (b)

Figure 2. In figure a) the plasma diagnostic is shown. All instruments are mounted on a rotatable jib arm. Figure b) presents the inner view of the vacuum tank. On the top the micro-Newton thrust balance is visible. The jib arm is viewable in the middle.

is of special interests. Therefore, a set of plasma diagnostics is part of the facility. To measure the ion current and the shape of the plasma plume, 15 faraday cups are used. A retarding potential analyser is part of the system for a simultaneously measurement of the ion energy. All instruments are mounted on a rotatable jib arm. The setup is presented in figure 2 a). The in house developed instruments have a generic and flexible design. Thus, the position of each probe can be adapted on the specific needs of the thruster under investigation e.g. for a gridded ion thruster the distance between the faraday cups should be minimal because of the small beam divergence of the plume. For a µ-HEMPT the distance between the cups should be wider because of the bigger plume divergence. The faraday probes and the retarding potential analyser are custom designs. The diagnostics were calibrated with a highly precise Keithley ampere meter. The estimated relative error due to the electronic design and the calibration is smaller than 5 % .

C. Thrust Balance

Facility Key Parameters	Specific Value
Thrust range	0.1 µN to 1000 µN
Measurement bandwidth	$10\,\mathrm{Hz}$ to $2 \cdot 10^{-3}\,\mathrm{Hz}$
Thrust noise sensitivity	$0.1\,\mu\mathrm{N}/\sqrt{\mathrm{Hz}}$
Maximum device under investigation weight	5 kg
Vacuum chamber dimensions	1200 mm x 1200 mm x 880 mm
Pumping speed	11400 L/s
Background pressure without gas ballast	$2 \cdot 10^{-7}$ mbar
Background pressure with gas ballast (1 *sccm*)	$3 \cdot 10^{-6}$ mbar

Table 1. Summary of the facility key parameters.

The main instrument of the thruster test facility is our unique micro-Newton thrust balance. The balance is shown in 2 b). The balance consists of two hanging pendulums. The thrust detection is performed by a differential translation measurement between the pendulums via an optical read out. 20 leaf springs are used as a quasi frictionless bearing. The leaf springs are used as power and data connection as well to minimise the influence of power and sensing signal harness on the balance spring constant. Both pendulums are damped by a tunable eddy current brake. The thrust balance is able to operate in open- and closed-loop. In open-loop the measured translation is directly converted (multiplication with the specific pendulum spring constant) into the measured thrust. In closed-loop operation the pendulums are held in zero position with the force generated by one voice-coil per pendulum. Therefore, the thrust is measured by the differential of the applied forces from the actuators. An Electro Static Comb (ESC) assembly is used to calibrate the thrust balance. The thrust balance has a demonstrated resolution of less than 0.1^{-6} N in a measurement bandwidth from 10 Hz to $2 \cdot 10^{-3}$ Hz. The key parameters of the balance assembly are presented in tabular 1. A detailed description of the balance is given in [4].

III. Measurement Results and Analysis

So far, we performed several measurements with different thrusters in our micro-Newton thruster test facility to demonstrated the performance of the facility and to characterise the thrusters. Up to now, we tested the µ-HEMPT and the RITµX. A detailed report of all performed measurements would go beyond the scope of this proceeding. That is why, this chapter will only wrap up the performed RITµX tests. In figure 2 b) the used test setup is shown. We performend direct thrust measurements, thrust noise measurements and plasma diagnostics measurements.

A representative of a faraday cup measurement is given in figure 3. On the x-axis the elevation position of the faraday cups in degree is given, the y-axis represents the azimuth position in degree. The ion-beam current density is ploted on the z-axis. The plot illustrates the almost Gaussian plume of the RITµX with a divergence angle smaller than 20 % . The result of the integration of the presented current density is 1.808 mA. The measured beam current was 1.8 mA. The measurement is in agreement with the expected value and inside the estimated maximum error of the plasma diagnostic.

In figure 4 two typical examples of the performed direct thrust measurements are given. Plot a) presents a 0.1 µN stepping performed by the RITµX on an absolute thrust level of 56 µN. The time (in s) is plotted versus the thrust (in µN). The blue curve presents the commanded thrust, the dotted blue curve illustrates the absolute error of the commanded thrust. The red plot represents the thrust which was measured by our micro-Newton thrust balance. The dotted red line represents the absolute error of the direct thrust measurement. The error of the commanded thrust is mainly driven by the used laboratory power supplies. The measured thrust is inside the estimated error interval. Figure 4 a) underlines the ability of the thrust balance to measure in a sub micro-Newton regime. The figure also demonstrates the ability of the tested RITµX to generate sub micro-Newton steps. This underlines the capability of the thruster for highly precise AOCS with an resolution smaller than 0.1 µN. The slow rising of the commanded thrust is driven by the chosen laboratory beam current controller. In general, the thrust balance as well as the RITµX have a much better thrust response to the command.

We also characterised the influence of the neutral gas flow on the commanded thrust. Figure 4 b) summarises the performed tests. The plot presents the massflow (in sccm) versus the measured thrust (in µN). The blue squares are the measurement points. Every point is the mean value of a 90 s long measurement step, or in other words the mean value of 1800 data points. The red bar is the absolute error of the used mass flow meter. The blue bar presents the error of the thrust balance. To estimate the produced thrust by the massflow, a linear fitting was performed. The green line represents the estimated fit. For all data points, the fit is inside the estimated errors. Therefore, the linear correlation between the massflow and the neutral gas thrust is a valid assumption. But a notable offset of the presented fit can be observed. Up to now, the physics behind the offset is not finally clarified. Possible reasons could be that the free molecular flow at low pressure or mass flow levels causes a none directional movement of the particles. Therefore, no direct force is produced. Leaking at some point of the thruster or at the gas feed line could also induce this effect. Moreover, unknown errors of the used laboratory massflow meter (operates at its lower limit) could also cause this effect. For a more detailed determination of this effect further measurements and an additional analysis is required e.g. the molecular flow through the grid could be simulated.

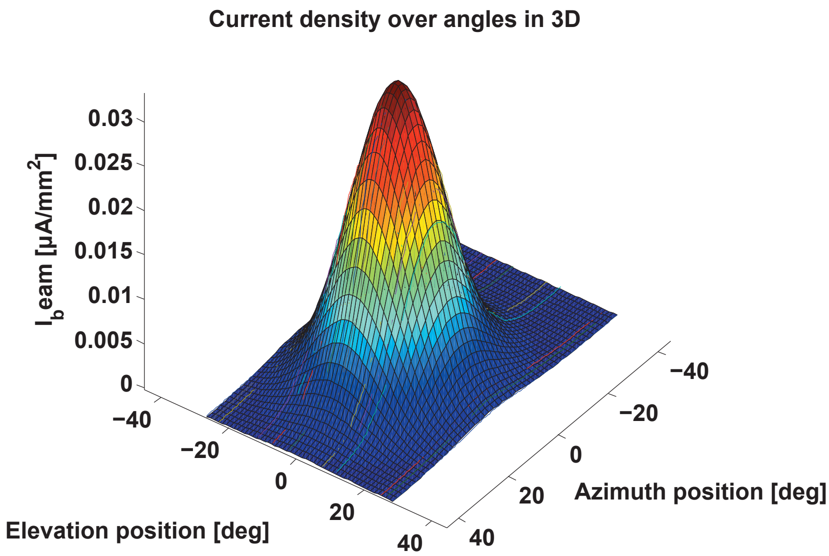
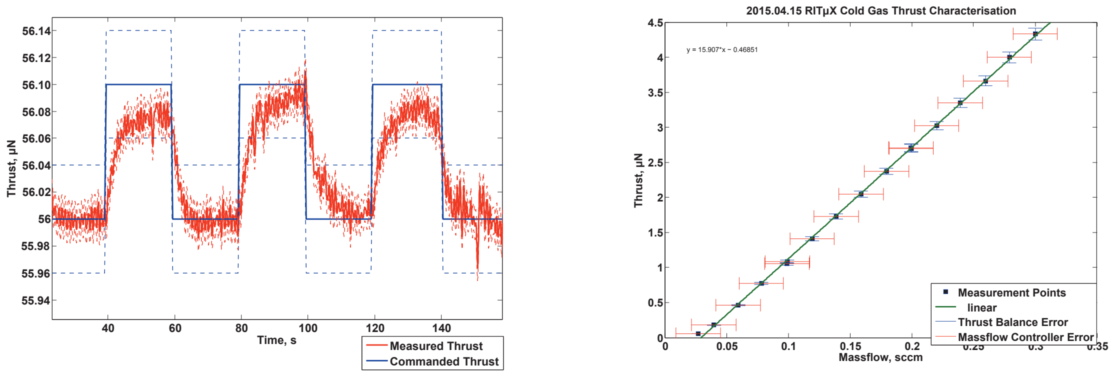


Figure 3. A representative of a faraday cup measurement is given in the figure. On the x-axis the elevation position of the faraday cups in degree is given, the y-axis represents the azimuth position in degree. The ion-beam current density is ploted on the z-axis.

Thrust noise measurements of the RITµX were also performed. The micro-Newton thrust balance which is designed for high stability and especially to perform thrust noise measurements allows measurements in the whole LISA bandwidth. The Power Spectral Density PSD shown in Figure 5 presents the results of the performed measurements. The frequency in Hz is logarithmically plotted versus the logarithmically plotted thrust, which is normalised to the frequency, in $\mu N/\sqrt{Hz}$. The PSD provides an overview of the noise level at specific frequencies. The Euclid AOCS thrust noise requirement is plotted in blue. It is from special importance because the investigated RITµX is considered as suitable AOCS thruster design for the Euclid spacecraft. The black plot presents the LISA requirement (see chapter I), which is given by the required thrust level combined with the typical LISA allocation. The performance of the thrust balance is shown as green plot. The green PSD was generated from a 20 h measurement, with a Blackman-Harris 92 window. A linear detrend was also performed. The red plot presents the performance of the RITµX. To generate the PSD, an 11 h long measurement and a Blackman-Harris 92 window with linear detrend was used. At frequencies between 1 Hz and $8 \cdot 10^{-3}$ Hz the thrust noise of the thruster is bellow 0.1 µN. This can be also observed in the time domain data which are presented in figure 4 a). In respect to the error budget of the thruster assembly, the noise level is defined by the used power supplies and in particular by the resolution (0.001 mA, or 0.0404 µN at the specific operation point) of the used ampere meter for the beam current controller. The thrust noise level increases at frequencies bellow $8 \cdot 10^{-3}$ Hz typically with a $1/f$ shape caused by thermal drifting of the used electronic and thermo mechanical drifting as well. Bellow $1 \cdot 10^{-3}$ Hz the plot of the thruster noise level is almost equal to the thrust balance noise level plot, i.e. at this measurement points no statements of the thruster performance can be given.

The measured thruster demonstrated over the whole measurement bandwidth a noise level which is more than one order of magnitude bellow the Euclid requirement for what it is designed for. Moreover, the thruster almost fulfilled the LISA requirement. Only between $2 \cdot 10^{-3}$ Hz and $8 \cdot 10^{-3}$ Hz the noise level was above the requirement. Considering the limitations of the used power supplies it seems to be feasible to fulfil the requirement within the use of an electronic which is specially designed for the LISA mission application..



(a) (b)

Figure 4. Figure a) presents a $0.1\,\mu\text{N}$ stepping performed by the RITµX on an absolute thrust level of $56\,\mu\text{N}$. Figure b) summarises the performed neutral gas thrust measurements. It presents the massflow (in sccm) versus the measured thrust (in µN).

IV. Conclusion and Outlook

The micro-Newton thruster test facility of AirbusDS in Friedrichshafen is fully operational. It consists of a plasma diagnostic setup and a highly precise micro-Newton thrust balance. The instruments are placed in a 1500 L vacuum tank.

Three different kinds of pumps (Rotary vane pump, turbo pump, cryo pump) are used to evacuate the chamber. The custom cryo pump design leads to a quite noise floor and enables sub-micro-Newton thrust measurements.

The plasma diagnostic setup consists of 15 faraday cups and one Retarding Potential Analyser (RPA). The probes are placed on a rotatable jib arm which allows 180° 2D plume characterisation.

To perform direct thrust and thrust noise measurements, the micro-Newton thrust balance can be used. The balance has a proven resolution of less than $0.1 \cdot 10^{-6}\,\text{N}$ in a measurement bandwidth from 10 Hz to $2 \cdot 10^{-3}\,\text{Hz}$. The balance has a dynamic range from $0.1\,\mu\text{N}$ to $1000\,\mu\text{N}$. Maximum measurable force can be increased by the use of the calibrations weights. A concurrent operation of all instruments is possible.

We used the facility to characterise different thrusters e.g. the µ-HEMPTs, the RITµX. In particular, measurements examples of the performed RITµX were given. The results underlines the thruster characterisation and test capabilities of the micro-Newton thruster test facility. This leads to a deeper understanding of the tested thruster. It emphasises the capabilities of our micro-Newton thruster test facility to work with different thruster technologies because of the generic and adaptable design.

We also demonstrated the unique capabilities of the RITµX as possible AOCS Thruster candidate for Euclid or LISA.

In the next month, the facility will be used for further thruster tests campaigns. Improvements of minor parts of the facility like electronic components will also be realised. Moreover, we will start to offer the facility to external costumers. For any further informations about our services and capabilities please contact the author of this proceeding.

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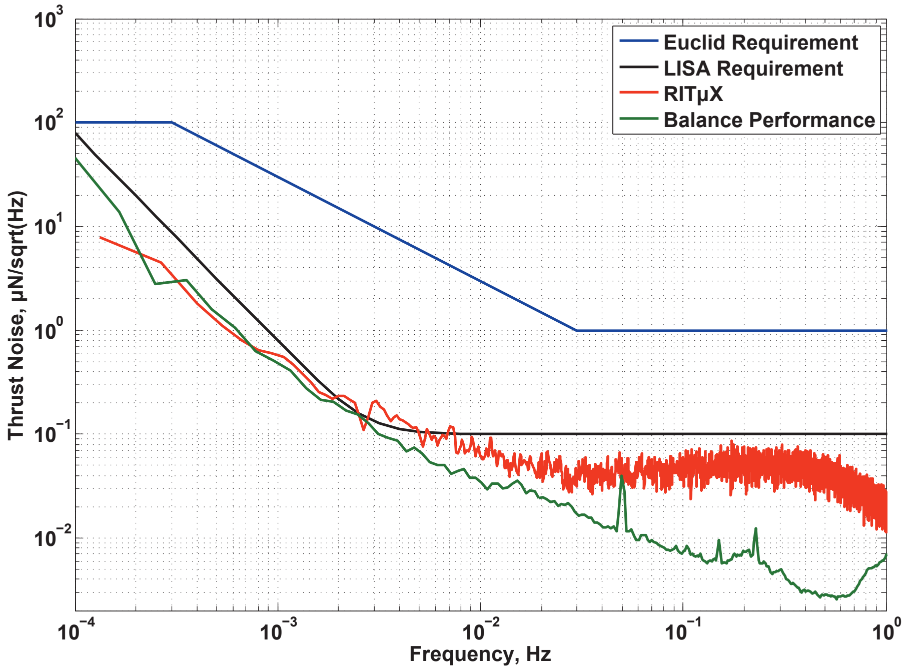

Figure 5. The PSD provides an overview of the noise level at specific frequencies. The frequency in Hz is logarithmically plotted versus the logarithmically plotted thrust, which is normalised to the frequency, in µN/$\sqrt{\text{Hz}}$.

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