Thrust Measurements with the ONERA Micronewton Balance

IEPC-2009-185

Presented at the 31st International Electric Propulsion Conference,
University of Michigan • Ann Arbor, Michigan • USA
September 20 – 24, 2009

D. Packan[1] , J. Bonnet[2] and S. Rocca.[3]
ONERA, Palaiseau, 91120, France

Abstract: The micronewton thrust balance developed at ONERA is presented, and is applied to thrust measurements with a cold gas thruster. The principle of the balance and of the calibration is detailed, and the recent improvements in post-processing are presented, in particular the noise-subtracting method. Currently the noise performance of the balance is 1µN/√Hz in the frequency range [10^{-3} - 10 Hz] and 0.1µN/√Hz in the smaller frequency range [10^{-2} - 1 Hz].

I. Introduction

Several forthcoming space missions, such as MICROSCOPE (MICROSatellite with drag Control for the Observation of the Equivalence Principle), LISA (Laser Interferometer Space Antenna), LISA Pathfinder (a mission intended to demonstrate the key technologies for LISA) and Darwin (an infrared space interferometry mission), require very accurate satellite position and attitude control. The types of thruster deemed to satisfy these requirements are field effect electric propulsion (FEEP) thrusters, colloid thrusters, and cold gas thrusters. These technologies are still under development, and one of the aspects that require verification is their thrust performance: stability, reproducibility and noise level. The direct measurement of the thrust generated by these thrusters is a fundamental step in the validation of their technologies and for the successful realization of space missions. However it is a challenging endeavour because of the very low thrust levels (< 1 µN) that need to be measured over a large bandwidth ([10^{-3} Hz – 10 Hz]). To address this issue ONERA has developed during recent years a micro-newton balance dedicated to the measurement of thrust at µN levels (0.01- 1mN). Improvements of the balance design have been recently made regarding noise reduction by vibration subtraction.

The ONERA micro-newton balance is based on the pendulum principle. The thruster is positioned on a pendulum and, when it exerts a force, the pendulum moves from verticality. An accelerometer, used as an inclinometer, senses a component of the acceleration of gravity when the pendulum is displaced from verticality. Another accelerometer measures the movements of the supporting structure. Two capacitive sensors measure the movements of the pendulum with respect to the structure. The current version of the balance represents an improvement over the previous balance [1] which did not use the accelerometer sensing the structure vibrations. The absolute calibration of the thrust is performed in vacuum with small weights, and a coil in a magnetic field is used as a linearity control.

II. Principle of the balance

The ONERA micronewton balance is a vertical pendulum (Figure 1). In the basic configuration, the thruster applies a horizontal force on the pendulum, which then moves from its initial vertical position to a new, tilted

[1] Reasearch scientist, Physics and Sensing Department, denis.packan@onera.fr.
[2] Reasearch scientist, Physics and Sensing Department, jean.bonnet@onera.fr.
[3] Post-doctoral student, Physics and Sensing Department, simone.rocca@onera.fr.

equilibrium position. In this tilted position the torques of the thrust and of the weight of the pendulum cancel each other. The angle of the pendulum is then a linear measure of the thrust.

A vertical pendulum has two advantages compared to other balance types (torsion and weight balance):
- the frictionless pivot and equilibration is technically simple
- thrust calibration can be done in an absolute manner with calibrated weights; this will be described in a later section.

Displacement sensors are placed on the pendulum to measure the angle and two different types of sensors are used. One is an accelerometer (Honeywell QA 2000) whose axis measures the projection $\gamma_{//}$ of gravity when the pendulum tilts. It is also used as a verticality reference. The other sensor is a capacitive sensor (Fogale, MC900) which measures the linear movement of the bottom of the pendulum.

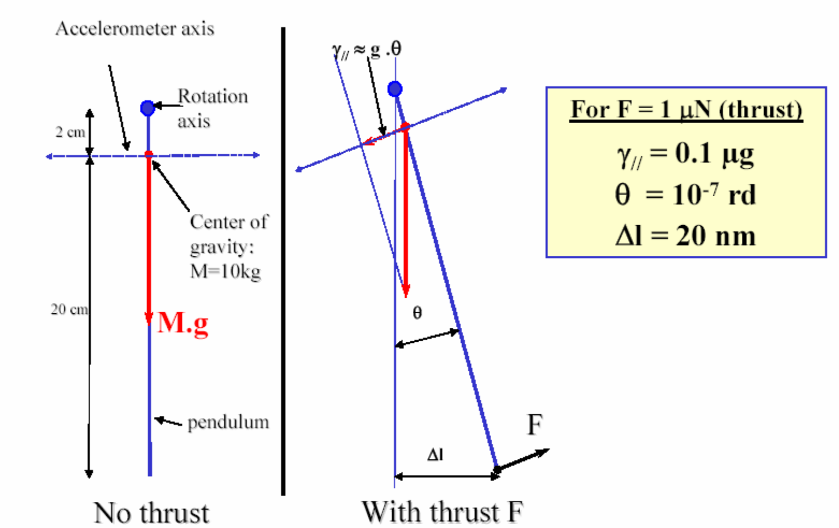

Figure 1. Principle of the ONERA micronewton balance.

A more detailed schematic of the balance is shown in Figure 2. All the displacement sensors are shown:
- two accelerometers: one on the pendulum for tilt measurement, one on the balance support to measure the tilt of the vacuum tank due to ground and structure vibration.
- two capacitive sensors on the pendulum arm (only one is represented).

The basic difference between the two types of sensor is the reference used for measurements: for the accelerometers it is the gravity, for the capacitive sensors it is the counter electrode attached to the structure of the vacuum tank.

Out of the four sensors, only one is theoretically needed to measure the tilt of the balance. But the use of different sensors, at varying places with different physical principles and reference proved very useful for the tune up of the balance and the observation of the vibrational modes of the pendulum and support structure. The main measurement sensor is currently a capacitive sensor.

The pendulum is of the compound type, where a moving counterweight is used to change the position of the centre of gravity of the system, thus changing the sensitivity and natural frequency of the balance. Typically the natural frequency used in experiments is 0.3 Hz.

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

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

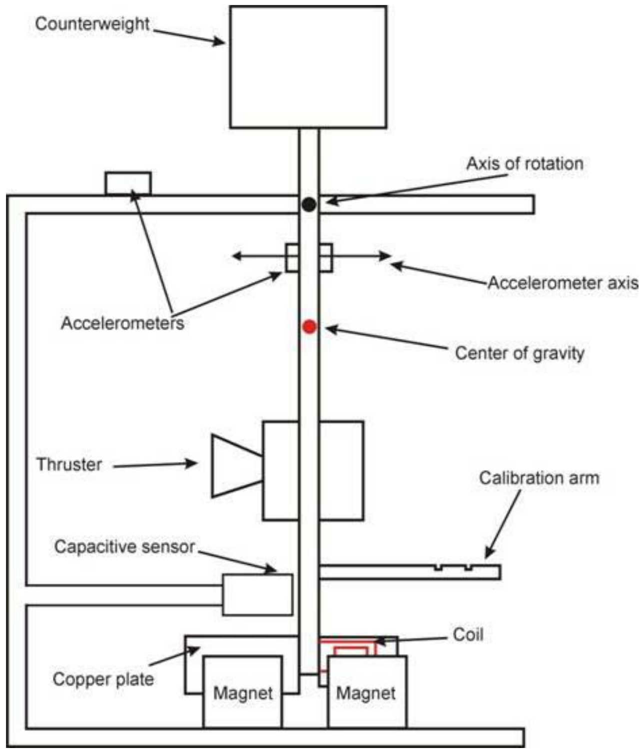

Figure 2. Configuration of the balance.

Two measurement modes can be used:
- open loop : as described above, the pendulum is free to move
- closed loop: a feedback loop uses the coil actuator to maintain the pendulum vertical as the thrust is applied; the current through the actuator is then a measure of the thrust. This mode has one clear advantage: the movement of the pendulum becomes second order. This can be important if the movement of the pendulum is perturbed by nonlinear flexure phenomena (plastic deformation of cables, hysteresis, etc…), because these are dramatically reduced. In our case the perturbations create less than 5% error in open loop, thus closed loop operation does not seem mandatory.

Finally, two balance configurations can be used:
- the horizontal configuration: it is the one described so far, where the thrust vector is horizontal (Figure 3, left); this configuration is best for FEEP thrusters
- the vertical configuration: the thruster is mounted on an horizontal arm, and the thrust vector is vertical (Figure 3, right); this configuration is best for cold gas thrusters

The reason for the use of the vertical configuration lies in the internal, longitudinal valve movement of cold gas thrusters. In the horizontal configuration, the valve shift (when it is opened or closed) changes the mass distribution of the pendulum, and thus creates a tilt of the pendulum. This tilt can be confused with the action of a thrust. This problem is compounded by the fact that the movement of the valve is not easily predictable (hysteresis in piezo-actuated thrusters, heating in coil-actuated thrusters). In contrast, in the vertical configuration the longitudinal position of the valve is not important for the equilibrium of the pendulum, and thus only a thrust can affect the pendulum.

If the length of the horizontal arm is the same as the length of the vertical arm (170 mm in our case), and if we ignore the added mass of the arm, the thrust sensitivity will be the same in both configurations because the torque created by the thrust is the same in both cases (T.L in Figure 3 ; T=thrust, L=arm length).

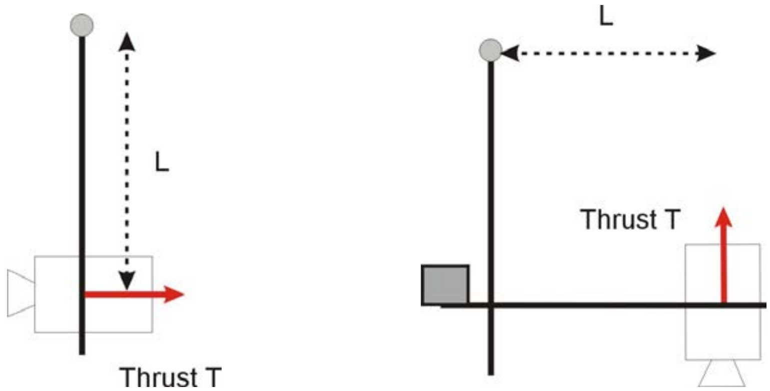

Figure 3. The two balance configurations: horizontal configuration (left) and vertical configuration (right).

III. Thrust calibration

One of the advantages of a pendulum balance is that it allows for an absolute and precise thrust calibration. The principle is to deposit masses on a small horizontal arm attached to the pendulum. The calibration arm schematic is visible in Figure 2 and is shown in more detail in Figure 4. Weights of small masses can be calibrated very precisely with a weight balance: 1% accuracy for a 10 mg mass, typical of the masses used, is easily achievable. These masses are placed on a vertical, vacuum-rated translation stage. The calibration can thus be operated in vacuum, in the same exact conditions as the thrust measurements, and often at various times during a thrust campaign. For calibration different masses can be sequentially deposited on the calibration arm, thus imposing calibrated torques on the balance.

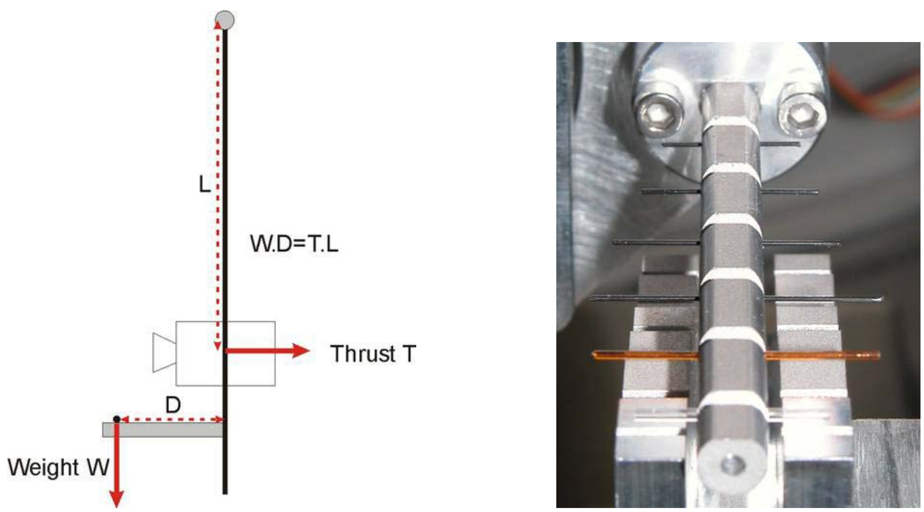

Figure 4. Principle of thrust calibration (top) and image of six masses deposited on the calibration arm (bottom).

If the measured signal is S for a weight W, we obtain a calibration factor α=S/(W.D) in Volt/(N.m). Then, during the measurement of a thrust T with signal St, we deduce the torque of the thrust St/α and since it is equal to T.L, we deduce T. In order to check for linearity over the whole range of the balance, we can use several calibrated masses that are deposited sequentially at different positions on the calibration arm (Figure 4, right). For the lower thrust range (< 10 µN), it is not practical to use masses for calibration. We then use the actuator coil, which has a linear behavior. The calibration from the coil is matched to the absolute masses calibration on the higher thrust range, and it allows us to calibrate and check linearity down to 0.1 µN. Another advantage of the coil is that it permits dynamic calibration like sweep sine or step input.

IV. Vacuum Facility

The vacuum tank used so far for the measurements is 50 cm in diameter and 70 cm long. A turbomolecular pump with pumping speed 1000 l/s for N_2 yields a limit vacuum < 10^{-6} mbar. Typically, with a cold gas thruster of Isp 50 running with a thrust of 500 µN, the vacuum is about 10^{-3} mbar. The four sensors of the balance (capacitive and accelerometric) are linked to vacuum-rated actuators allowing to zero the readings while the thrusters and balance are in vacuum.

Six temperature sensors are placed in different parts of the tank and balance assembly. They have a resolution of 0.01 °C and an accuracy of 0.05 °C. They allow checking the thermal stability of the balance, which is important to avoid a drift in the thrust signal. The balance is mounted on a support structure that has been recently stiffened in order to increase its resonant frequency from 10 Hz to 25 Hz.

A new, larger facility is now available for the micronewton balance (Figure 5). It is a vacuum tank 80cm in diameter and 2 meters long. The pumping speed of the turbopump is 2000 l/s for N_2. A cold trap 0.5 square meter in area can be cooled to -60°c and is an effective pump for condensable feed such as cesium, with an equivalent pumping speed of about 25000 l/s for Cesium and a limit vacuum < 10^{-7} mbar.

Figure 5. Small vacuum tank and balance mounted (left) and new B09 facility (right).

V. Postprocessing and noise cancellation

The performance of the balance depends in large part on the data acquisition system and post-treatment procedure. The data acquisition system involves effective anti-aliasing filters and 18bit A/D acquisition card. This allows to remove the noise outside of the measurement bandwidth and to have a large measurement dynamic, which is essential for signal recovery in the frequency domain. In order to process the signal, one has to know the frequency behavior of the balance through mechanical modeling calibrated by actual measurements of the balance characteristics.

A. Modeling

The movement of the arm of the balance follows the dynamics of a pendulum that can be modeled with a second order system whose response to thrust is attenuated after its natural frequency (Figure 6). The response of the capacitive sensor to thrust is proportional to the angle of deflection of the pendulum whereas the response of the accelerometer is a function of the angle of deflection and of its acceleration. In both cases, the sensitivity to thrust is not constant with frequency.

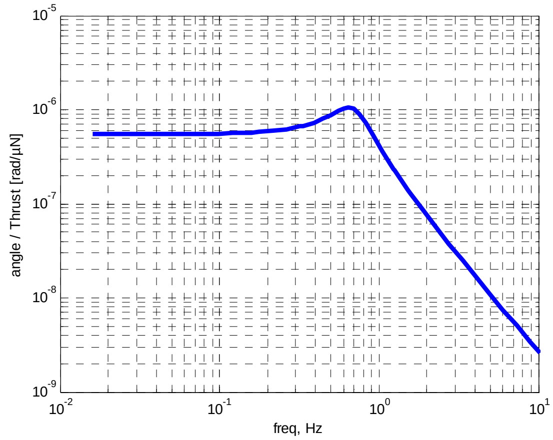

Figure 6. Typical frequency response of the pendulum to thrust.

The modeling of these relations and a dynamic calibration make it possible to define the sensor sensitivity as a function of frequency and thus to convert the sensors response into a force measurement.
During post processing in the frequency domain, the actual data is divided by the curve in Figure 6. In this way, the signals that are at a frequency larger than the natural frequency of the balance and thus that have been attenuated by the inertia of the arm are "lifted" back to their original strength in a very accurate way. That is where the 18 bit A/D is very important. This operation makes it possible to perform measurements at frequencies that are higher than the natural frequency of the pendulum. The results of this postprocessing is illustrated in Figure 7 (right) by looking at the difference between the blue curve (raw data) and the green curve (recovered data).

B. Noise compensation

A further postprocessing procedure has been recently implemented, and concerns the vibration of the balance support. The ground vibrations induce a movement of the pendulum and thus a response of the sensors. It is possible to measure those vibrations with an accelerometer on the support structure of the balance. If the transfer function beween this accelerometer and the balance signal is known (it was measured experimentally) then one can subtract the effect of the vibrations from the response of the sensors. A significant noise reduction is achievable by applying this operation (Figure 7). In these conditions the noise floor is due to the sensors.

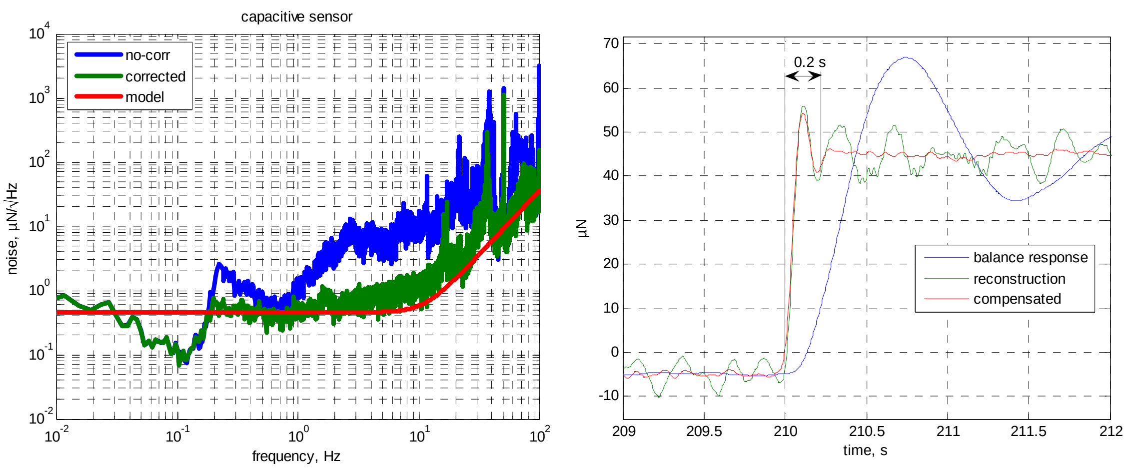

Figure 7. Effect of noise compensation on the PSD of the noise (left) and on a step response (right).

VI. Performance of the balance

The current performance of the balance is shown in Figure 8 and is illustrated in Figure 9.

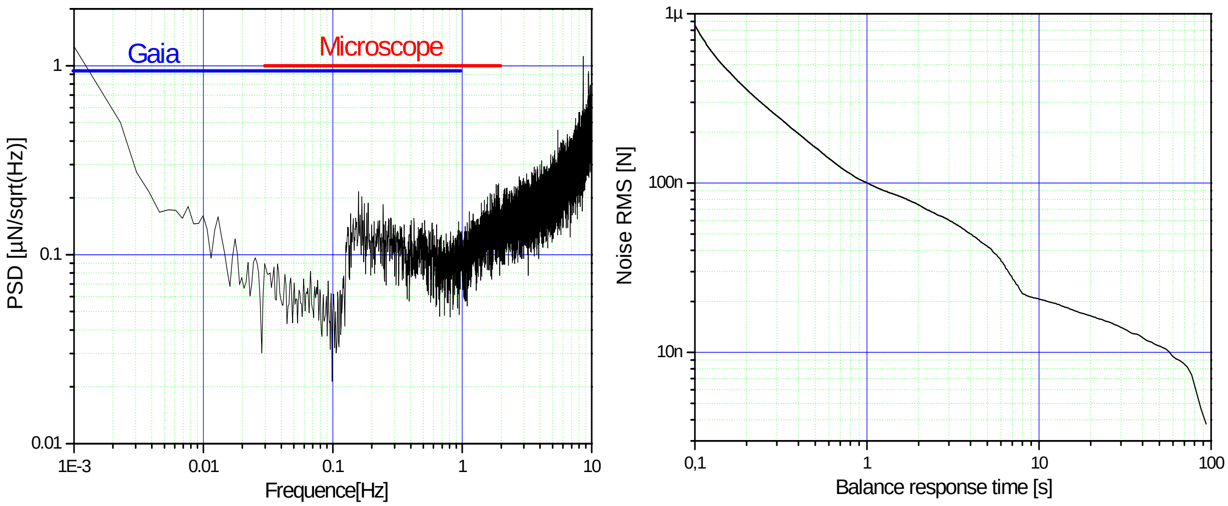

Figure 8. Performance of the balance in terms of PSD (left) and noise RMS (right).

In order to show the effect of varying post-treatment bandwidth, a step of thrust has been applied to the balance with the actuator coil, and the response of the balance is acquired and processed. This is shown in Figure 9.

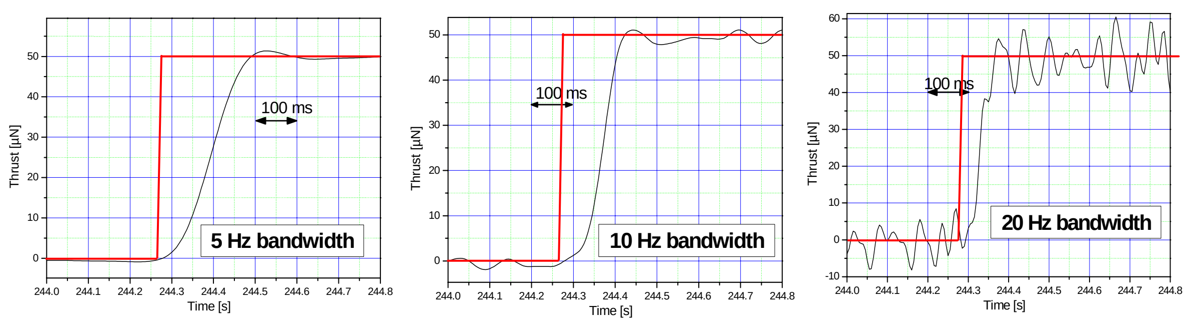

Figure 9. Performance of the balance: PSD of the noise (top left), RMS noise (top right) and illustration with a 50 µN step respponse shown with different processing bandwidths (5 Hz, 10 Hz and 20 Hz). The red curve is thrust step applied to the balance.

VII. Thrust measurements

Indium FEEP thruster

Thrust measurements on a preliminary version of the balance are presented for a FEEP thruster and a cold gas thruster. The Indium FEEP thruster is from ARCS (Austrian Research Center Seibersdoff), and has a maximum thrust of 20 µN for a measured current of 200 µA. These early measurements (made in 2001) as a function of the FEEP thruster current are shown in Figure 10.

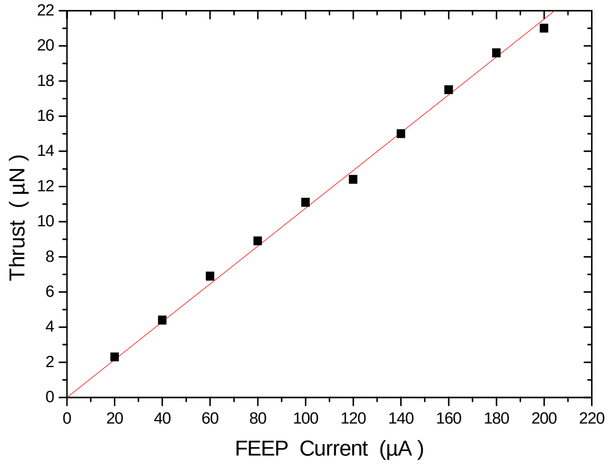

Figure 10. Thrust measurement on an Indium FEEP by ARCS (Austrian Research Center Seibersdoff) with the ONERA micronewton balance.

MTA cold gas thruster
A thrust measurement made with a cold gas thruster (MTA) by Bradford Engineering on the vertical balance configuration (Figure 3), as a function of the nitrogen flowrate is presented in Figure 11.

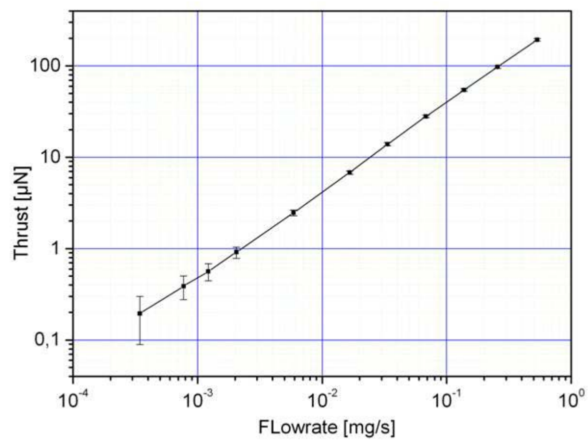

Figure 11. Thrust measurement on a Bradford Engineering cold gas thruster (MTA).

The error bars correspond mainly to uncertainties due to the piezo-activated valve movement inside the thruster. When the valve moves, the hysteresis of the piezoelectric material prevents us to know its exact state, thus it is difficult to subtract accurately its contribution from the measured thrust at low thrust levels (typically the contribution of the valve movement can be larger than 10 µN). The vertical configuration of the balance is more interesting for cold gas thrusters because it is much less sensitive (by a factor larger than 10) to longitudinal mass movements. The error bars in Figure 11 are due to residual movement effects because the axis of the thruster was not perfectly vertical. Given the latest experiments, it seems possible to decrease the sensitivity to negligible levels.

PMT cold gas thruster
A test campaign was done in December 2007 on the Bradford Engineering coil-actuated cold gas Proportional Micro Thruster (PMT). The purpose of the campaign was to characterize the thruster in terms of thrust range, I_{SP} and thrust noise. Figure 12 shows the measurement of specific impulse obtained on the balance with the vertical thrust configuration compared with DSMC simulations. The uncertainties on the measurements are due mainly to two causes:
- as for the MTA thruster there is a residual movement of mass because the thruster is not perfectly vertical

- the magnetic field of the solenoid interacts with the magnetic metal parts on the vacuum chamber and creates a parasitic force.

These effects are not easily separable and are not reproducible due to coil heating, thus resulting in the uncertainties on the measurements visible on Figure 12. However, as shown in the figure, the measurements seem to match numerical simulations performed previously and independently.

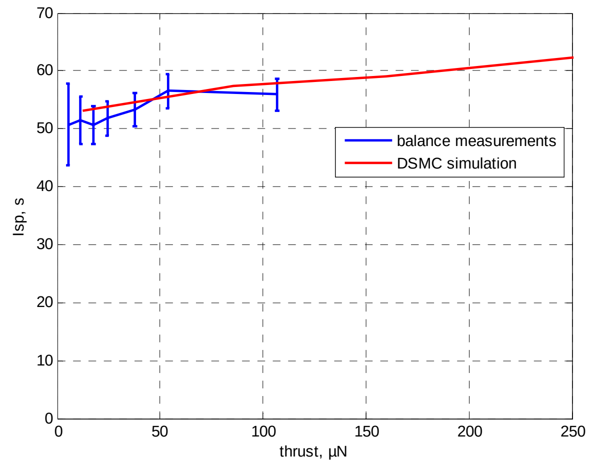

Figure 12. Isp measurements for the PMT cold gas thruster. The uncertainties are mainly due to the coil actuator.

VIII. Conclusion

After implementation of the new post-treatment procedures, the noise performance of the balance is 1μN/√Hz in the frequency range [10^{-3} - 10 Hz] and 0.1μN/√Hz in the smaller frequency range [10^{-2} - 1 Hz]. In the low frequency side, the noise is due to thermal drift, and a study is ongoing to model and propose solutions to limit this effect. On the high frequency side, the remaining noise is due to residual seismic noise and sensor noise. If needed, better sensors and a better cancellation procedure could be used. Beside, the use of an accelerometer can extend the measurement bandwidth much beyond 20 Hz, but then parasitic blade vibration could com into play.

The balance can be used with other thruster types, and can also be used in conjunction with diagnostics techniques to characterize the plume [2]. In particular for cold gas thrusters, techniques have been developed (Laser Induced fluorescence combined with Electron Beam Fluorescence) in order to measure non-intrusively the map of absolute number density and velocity in the cold gas plume[3].

IX. Acknowledgments

This study was done in the frame of CNES contract n° 4500025893. The authors acknowledge the support of E. Chesta and D. Arrat from CNES.

X. References

[1] "Thrust Measurements with the Onera Micronewton Balance", Jean Bonnet, Denis Packan, Simone Rocca, *30th International Electric Propulsion Conference*, Florence, Italy, September 17-20, 2007

[2] “Three-component LIF Doppler Velocimetry to measure the neutral cesium flow rate from a cesium-fed FEEP thruster”, IEPC-2009-173, P.Q. Elias, D. Packan, J. Bonnet, *31st International Electric Propulsion Conference,* University of Michigan, Ann Arbor, Michigan, USA, September 20 – 24, 2009

[3] “Number Density and Velocity Measurement in the Plume of a Micronewton Cold Gas Thruster by Electron Beam Fluorescence and Laser Induced Fluorescence”, IEPC-2009-184, D. Packan, J. Bonnet, S. Rocca, *31st International Electric Propulsion Conference,* University of Michigan, Ann Arbor, Michigan, USA, September 20 – 24, 2009