Mitigation of Detrimental Electric Thruster Force Measurement Effects

IEPC-2017-162

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

A. Neumann[1], C. Volkmar[2], C. Geile[3] and K. Hannemann[4]

Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)
German Aerospace Center, Spacecraft Department
Bunsenstrasse 10, 37073 Goettingen, Germany

Abstract: DLR (German Aerospace Center) operates the test facility STG-ET for electric space propulsion in Goettingen, Germany. The STG-ET has been especially designed for electric space thruster testing with a vacuum chamber that measures 12.2 m in length and 5 m in diameter. Thrust measurement is a basic requirement for propulsion engine qualification. Ion and Hall effect space thrusters usually produce thrust levels in the milli newton range. A thrust measurement system used on these engines has to carry the weight of the thrusters which are of the order of several kg and measure these low force values. Within this paper, we analyze issues when using a thrust measurement device, and give some hints on how to mitigate these. Stability of the balance carrying structure, decent cable and fluid pipe routing, and good thermal conditioning are the most important points to take care of for minimizing issues.

I. Introduction

The implementation of electric space propulsion (EP), and especially ion thrusters is on a growing path, and this now includes orbit transfer besides attitude control and station keeping. For supporting this transition, DLR operates a space electric propulsion test facility at its site in Goettingen, Germany [1]. The central element of this facility is a 12 m long and 5 m diameter vacuum chamber. This facility is designed for investigations on electric propulsion thrusters in the range of roughly 100 W up to several tens of kW. This corresponds to thrust levels of a few mN up to about 1 N.

The investigations span from basic R&D and ignition tests, over component testing and beam diagnostics, up to qualification and long duration tests. Those lifetime tests have to prove wear resistance and reliability of these thrusters after very long testing times.

An electric space propulsion test facility needs a dedicated diagnostics package. This must include:

- Reliable pressure measurement
- Thrust balance with reliable calibration
- Ion current sensors (Faraday cups) on one or more dimensional scanners
- Ion energy analyzers (also called retarding potential analyzer, RPA)

[1] Head of Electric Propulsion Test Facility, a.neumann@dlr.de
[2] Electric Propulsion Research Engineer, chris.volkmar@dlr.de
[3] Electric Propulsion Technician, christopher.geile@dlr.de
[4] Head of Spacecraft Department, klaus.hannemann@dlr.de

- Mass spectrometer (gas analyzer)

Further instruments are desirable:
- Photo and video equipment
- Infrared monitoring for temperature measurement on critical components
- Energy selective mass spectrometer
- Microscope, tele microscope, for surface analysis inside vacuum chamber
- Profile scanner for off-site wear measurement
- Sputter targets

The focus in this paper is on thrust measurement. Different methods for electric propulsion thrust measurement have been described in many papers [2-11]. Nevertheless, each method has its own pros and cons, and thrust measurement always needs careful mounting and fine-tuning.

The next sections describe DLR's thrust balance and show issues and mitigation measures.

II. DLR Thrust Balance

A. General

DLR operates a thrust balance designed and built by the German company Advanced Space Technologies GmbH (AST). This thrust balance uses a mechanical design based on a double pendulum forming a parallelogram [12]. The parallelogram is made of two stiff girders supporting the thruster platform (see sketch in Fig. 1). The lower leg of the parallelogram carries a counterweight to balance out the weight of the upper platform and thruster. This design has several advantages, and is based on a design shown in Ref. 11. Figure 2 shows this thrust balance installed in the STG-ET.

The thrust balance main specifications are listed in Table 1. The nominal range is up to 250 mN, but based on tests we found that 350 mN is measurable without problems. For the calibration, two methods can be used. With a calibrated coil (voice coil), a well-known force can be applied onto the thruster platform. The second method is a calibration with a known weight. This weight pulls on a string which runs over a pulley to transform the vertical force into a horizontal one. This horizontal force is applied to the thruster platform. Both calibration methods can be activated in vacuum and give a high confidence in the measurement.

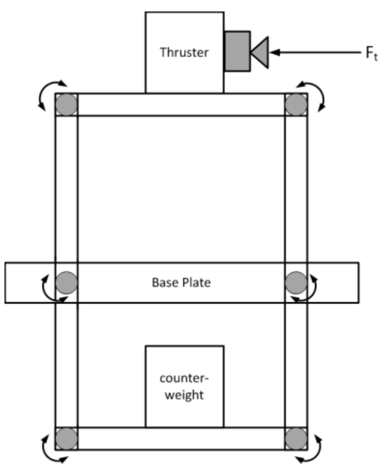

Figure 1 Schematics of the inverted double counterbalanced pendulum. The base plate is fixed to lab system.

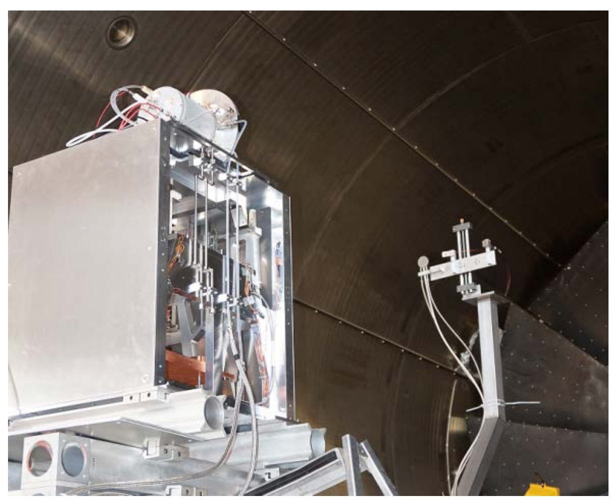

Figure 2 DLR thrust balance on pedestal in the STG-ET vacuum chamber, with side lids removed.

Table 1

Thrust range	0-250 mN (see text)
Accuracy	2.5 mN
Resolution	0.25 mN
Maximum vertical load	40 kg
Mass	130 kg
Calibration in vacuum	• voice coil • weight

A thrust balance measuring a horizontal force (this is the usual EP thruster arrangement) may be regarded as an inclination sensing device since tilting the balance with a load on the thruster platform will make it sensitive to gravity. The vector component along the balance sensitivity direction will become non-zero. The force value will depend on the mass distribution and torques on the thruster and counterweight platforms.

Therefore, it is very important to keep the supporting structure (base plate in Fig. 1) perfectly horizontal. This is not a trivial task as an EP balance has to work in a vacuum chamber which is not as solid as e.g. an optical table in a dedicated lab. Even slight temperature changes and thermal stress caused by these on foundation posts will lead to erroneous measurements. The impact of a changing plane will be shown in this paper.

Another issue is usually caused by cables and piping leading from the lab system up the moving platform of the thrust balance. Running electrical power through the cables may change their temperature and change the forces on the sensing system. In case of very high electrical currents magnetic fields may also have an impact. The same is valid for changes in fluid or gas supply. If the fluid temperature changes this may trigger a change in geometry and introduce forces.

Although usually several precautions are taken to minimize these effects there is still often room for improvement. This paper will show these issues and present a few measures to mitigate them.

B. Example of a Thrust Measurement

To demonstrate a thrust measurement at the lower sensitivity end of DLR's thrust balance a record is shown in Fig. 3. The ion source is a RIT with 37 grid holes. The thrust F can be calculated by equation (1)

$$F = \sqrt{\frac{2 \cdot m \cdot V}{e}} \cdot I \cdot \cos(\theta) \qquad (1)$$

With

m: *ion mass*
e: *electron charge*
V: *electric potential*
I: *beam current*
θ: *beam divergence*

Based on this equation and using the operational data ($V = 1800$ V, $I = 0.018$ A) the thrust can be calculated to be 1.26 mN. The measured thrust of 1.5 mN is very close to the calculated one, even more taking in to account the nominal manufacturer-given error of 2.5 mN. It should be mentioned that equation (1) does not include the thrust caused by neutral gas exiting the thruster. The design of the thrust balance was not based on engines with such low thrust, and therefore this is an extreme test case. It is shown here that a force measurement on a short time scale of minutes is possible with high accuracy.

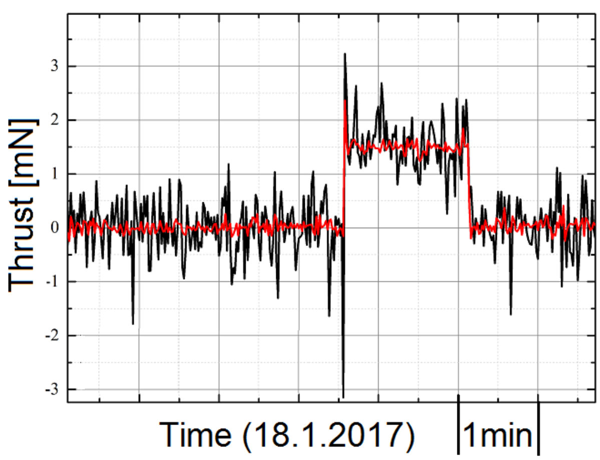

Figure 3 Thrust measurement on a RIT with 37 holes grid. This thruster produces about 1.26 mN, which is at the resolution limit of DLR's thrust balance.

III. Drift Caused by Temperature Variation

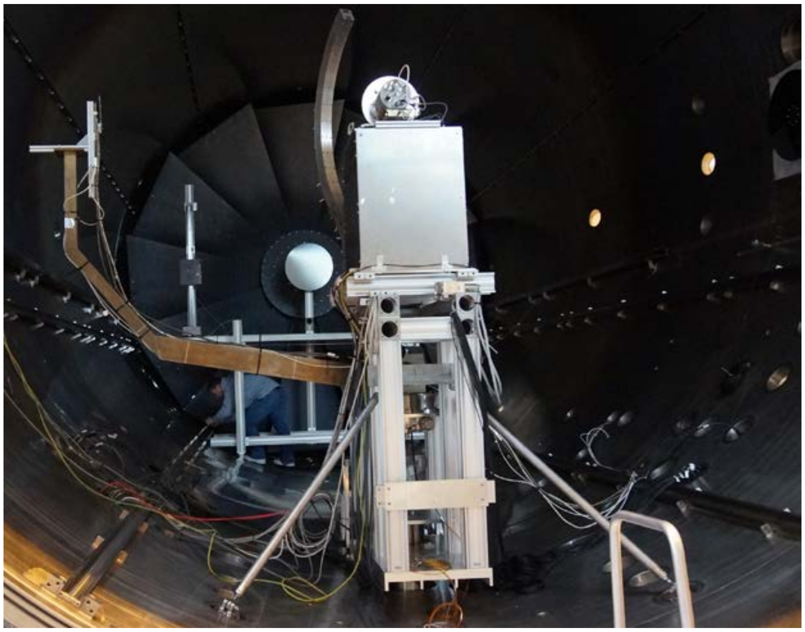

Figure 4 Rear view of the thrust balance on the thruster stand. The stand is stabilized by two additional diagonal members.

More challenging than an instantaneous measurement are long term measurements. It is known that EP thrust balances are often affected by drift effects.

In our case the thrust balance sits on a supporting structure which is decoupled from the chamber wall, as visible in Fig. 4.

Figure 5 shows the time profile of a thrust measurement (constant offset force) over several days after chamber closure and pump down. Furthermore, a temperature measurement taken at a location near the thrust balance is shown. It is obvious that the balance signal has a periodical pattern with a daily period. The diurnal thermal cycle influences the thrust balance signal. At first thought one might think of a temperature variation in the thrust balance structure itself. This may be excluded because this structure (the housing) is temperature controlled.

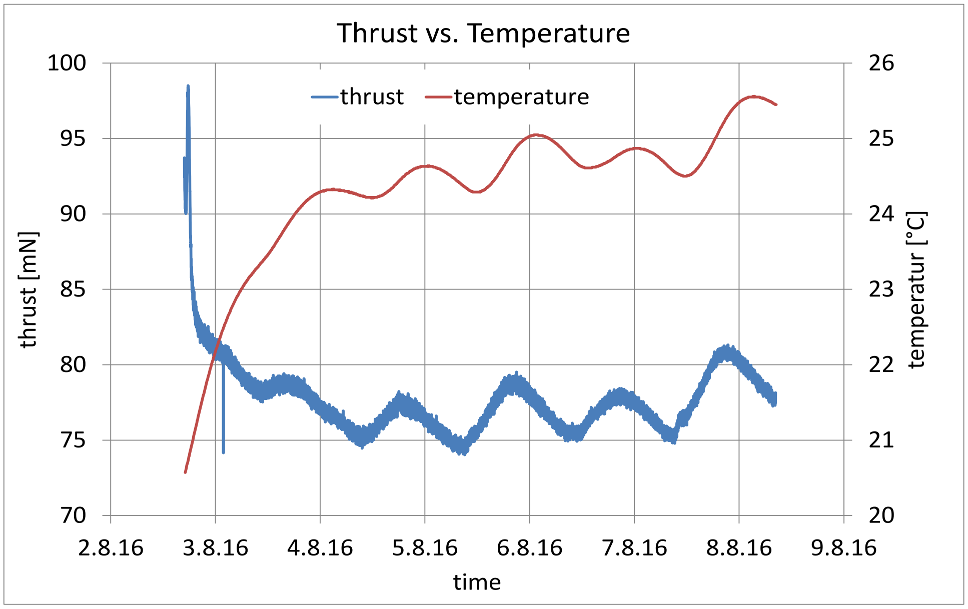

Figure 5 Fluctuations of thrust offset value and temperature measured at a point near to the thrust balance.

A second source of error may be the thrust balance supporting structure.

IV. Stability of Base Structure

The thrust balance in the STG-ET is mounted on a post made of multipurpose aluminum rails (Fig. 4). As mentioned above, this post is anchored in the building foundation and disconnected from the chamber wall. Diagonal cross members give more stiffness against vibration and heavy load deformation. The thrust balance is a sensitive inclinometer in its measurement direction.

The daily fluctuation and some longer trends are shown in Fig. 5. What would happen if the balance would be rotated by 90 degrees around its vertical axis so that the active direction is not pointing along the chamber axis but perpendicular to it (see Fig. 6, red arrow)? The result is shown in Fig. 7 where the 90 degrees measurement is compared to the thrust measurement shown in Figure 5. The 90 degree data were time-shifted in order to start at the same date and time. The periodical amplitude of about 4 mN in the original 0 degree position is reduced to less than one mN if the balance is mounted in the 90 degree position.

In conclusion, we can attribute the periodical signal offset to the base structure that has a change in geometry (tilt angle) cause by temperature change, and with this modifies the thrust balance offset.

Some measures for reducing these effects may be:

- Very stiff supporting structure
- Temperature control on supporting structure
- Offset measurement with a very similar load and load distribution over several days before a test with a real thruster begins

Further investigations may reveal more measures for lowering this test stand geometry change.

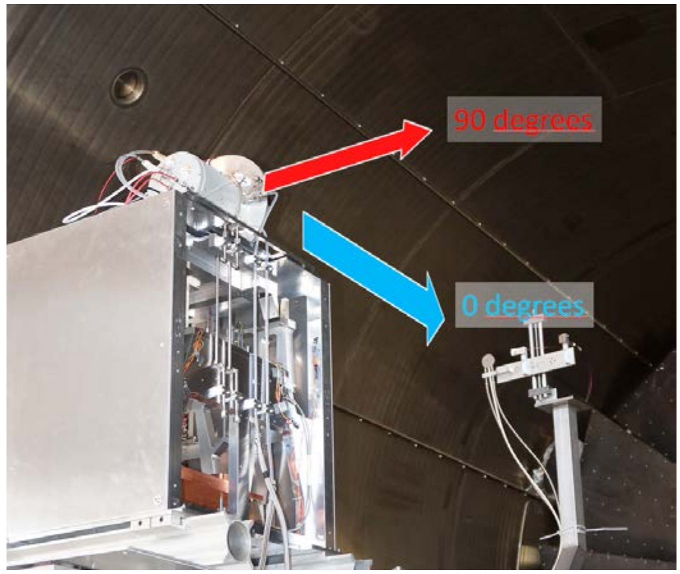

Figure 6. Normal orientation of thrust balance is with thrust vector pointing along vacuum chamber axis (blue, 0 degrees). For comparison, in this test the thrust balance was rotated so that its thrust axis pointed perpendicular to the chamber axis (red, 90 degrees).

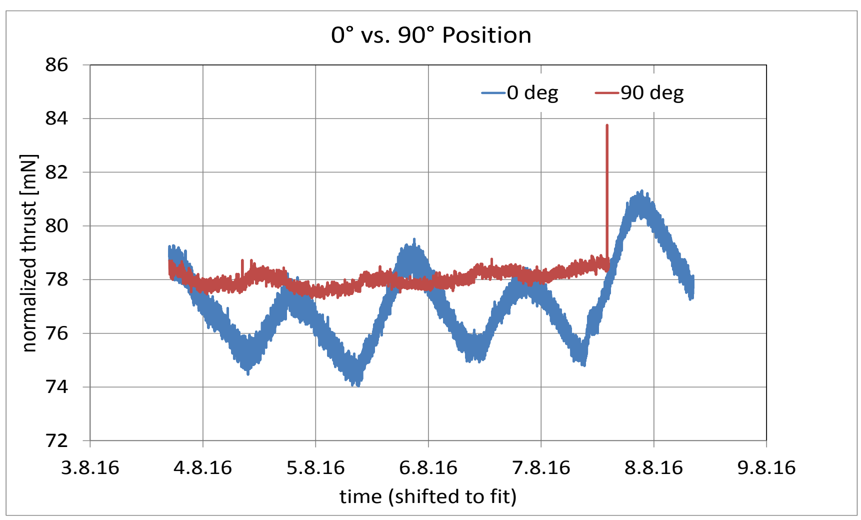

Figure 7. Comparison of periodic measurement drift for the thrust balance in normal position (0deg) and positioned under 90 degrees (see text).

V. Cables and Pipes

Usually, the thruster unit is not fully autonomous as one might think by looking at Figure 1, and there is a need for having power cables, propellant supply hoses, and data lines connecting the unit to the laboratory or test facility infrastructure. Those supplies have to be connected on one side to the thruster on the moving part of the balance, and on the other side to the lab (or vacuum chamber). These supply lines may introduce forces that depend on

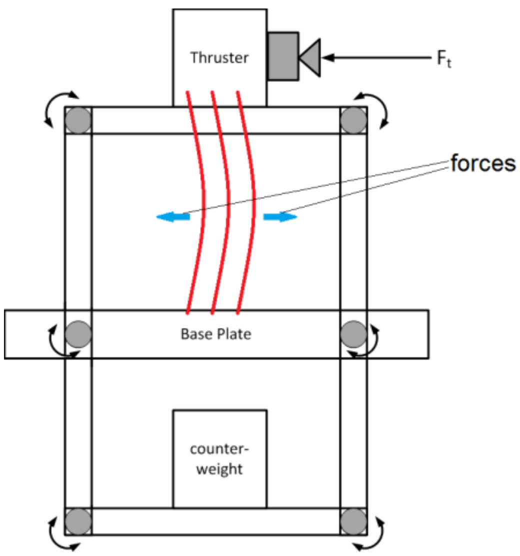

Figure 8 The thruster must be connected to the lab system via cables and piping, indicated in red. These connections may introduce forces.

electrical current, temperature, and media flow. Figure 9 shows this in a schematic way for the cables and fluid supply lines. Changes in length or curvature will produce forces onto the thruster platform.

In a real setup, those lines may occupy quite a lot of space, as can be seen in one of DLR's test configurations in Fig. 9. Cabling is show in the left part of the picture, and fluid lines in the right part.

As an example of the above mentioned forces Figure 10 displays a screen shot of the thrust balance offset value if cables or pipes are activated. This test was performed in air, chamber open, for better access. Heating the electrical cables with a heat gun produced a spike of more than 20 mN, with a thermal relaxation after removing the heat source. Switching on the cooling water flow (cooling water above ambient) led to decreasing thrust levels, even into negative forces. Setting the water temperature to 40° C led to a signal of -17 mN, setting well below ambient to 10° C gave +20 mN. This documents the impact of cooling water flow and pipe stress onto thrust measurement. Cooling water effects may be reduced by letting the cooling fluid flow ahead of a test campaign and by a precise temperature control, and compensating for any offset.

Also during measurement campaigns, the impact of changes in current through cables was definitely seen. The allowable current range for electrical cables is about 1-10 A/mm², according to standard usage. But this is for electrical installations based on thermal boundary conditions and not on slight cable geometry changes.

For an assessment of such effects two experiments were conducted in order to see changes in typical cables. The question was if a typical current load on a cable that we use for EP testing would lead to noticeable effects on forces. Figure 11 shows the two setups that were tested. Both should give an idea of a change in cable length. On the left, a 2 mm diameter cable with a length of 0.42 m was held horizontally between fixed points. A weight was attached at its center. This assembly was positioned on a scale so that the latter displayed a fraction of the attached true weight. If an elongation of the cable would take place, the scale should indicate a larger weight. The cable was then fed with a current of 3 A, which corresponds to approximately to 1 A/mm². This is a value at the lower end of typical current densities. The dissipated power was 31 mW. Figure 12 shows the scale value for a current switch-on and off every 300 s. The apparent weight changed by about 0.12 g which corresponds to about 1.2 mN.

On the right part of Fig. 11 the setup was changed, for comparison, to a vertical cable and a weight attached to its lower end. The same 3 A current steps with a 300 s duration were applied here. The cable had a length of 0.42 m, which leads to a power dissipation of 28 mW. Figure 13 shows the change of the apparent weight. Here we have a change of almost 1 g, which corresponds to about 10 mN. Such a force is non-negligible compared to typical EP thrust.

The result of these experiments is that using cables under typical electrical design conditions may lead to unexpected forces. Even in the design used for our cable routing, which was supposed to be insensitive to cable stress, we saw issues with on/off current flow. In conclusion, it can be said that the cable setup as seen Fig. 9 is not as insensitive to errors as expected. A better solution is actually under test and may be published soon.

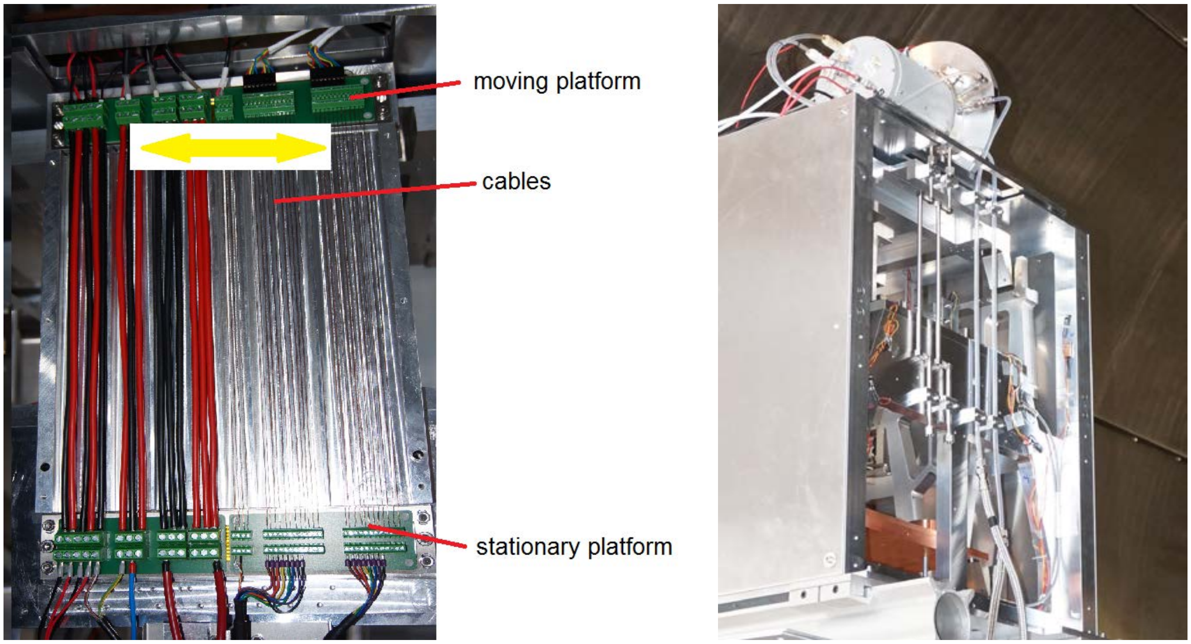

Figure 9 Cables feeding a thruster unit (left), and propellant gas and cooling water supplies (right) on the DLR thrust balance. It is important to minimize the forces on the upper moving platform.

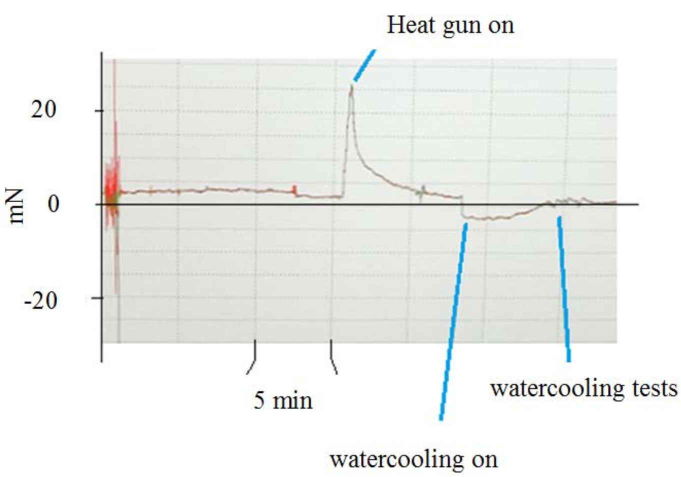

Figure 10 Screen shot of thrust balance measurement during offset tests. This included cable heating and cooling water switch on and off. Both have a pronounced impact on thrust measurement.

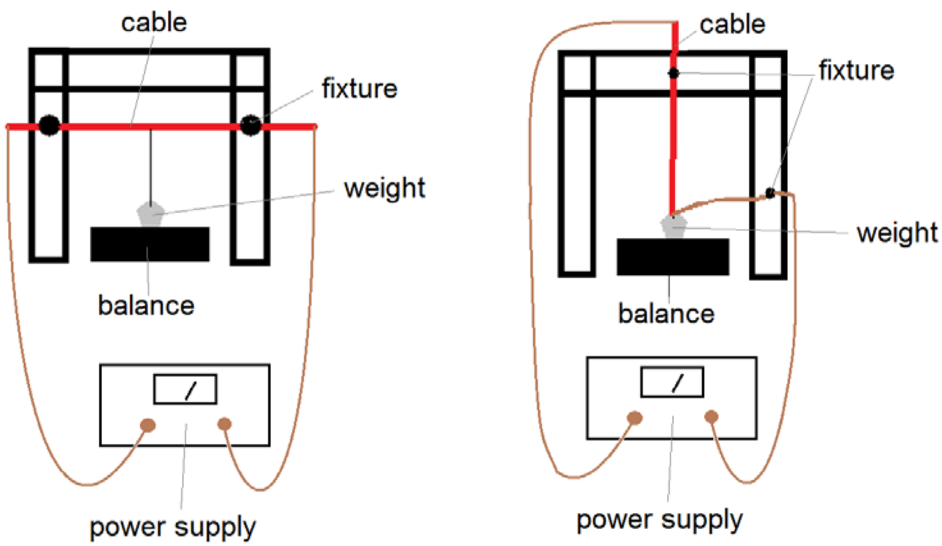

Figure 11 **Schematics of the setup for investigating the behaviour of cables carrying a current. Left: test cable in horizontal arrangement. Right: test cable in vertical arrangement. The signal of the lab balance is recorded depending on the electrical current flowing through the test cable.**

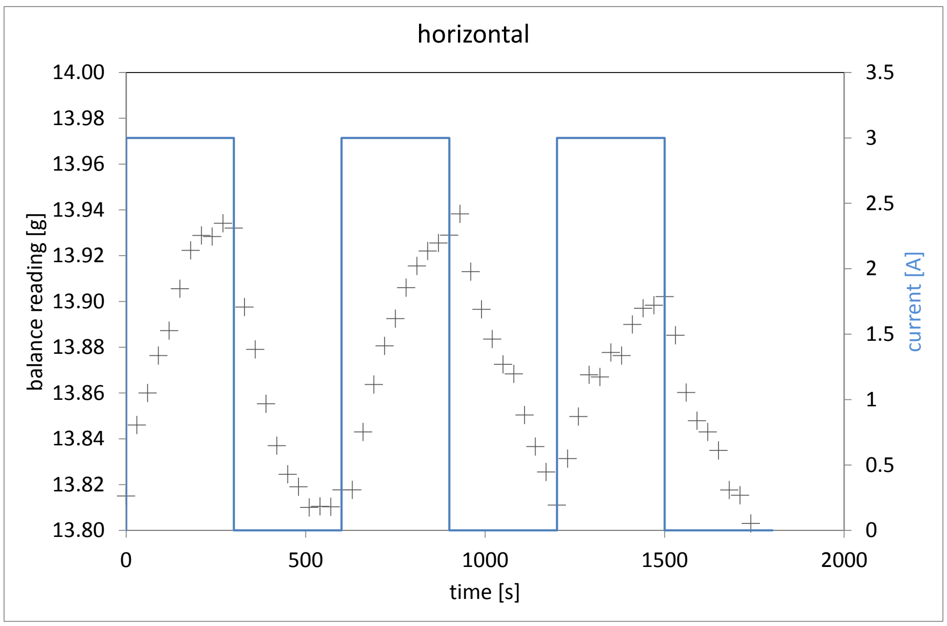

Figure 12 **Balance reading in the horizontal cable arrangement for current steps 0-3-0 A. Current switch-on duration is 300 s.**

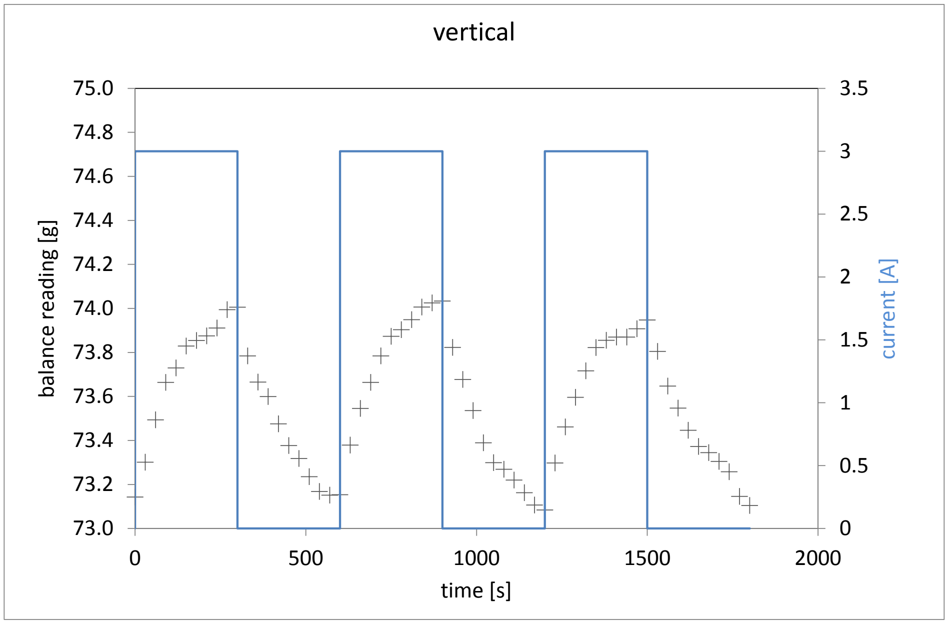

Figure 13 Balance reading in the vertical cable arrangement for current steps 0-3-0 A. Current switch-on duration is 300 s.

VI. Conclusion

This paper showed how thrust is measured at DLR's EP test facility STG-ET. The thrust balance was developed by the company AST, and is based on the double pendulum design. This device has a high sensitivity, but its supporting structure and the routing of cables and fluid lines is very critical. The balance acting as a device perfectly measuring inclination it is primordial to install a very stiff supporting structure, or even temperature control the supporting structure. On the other hand, a decent startup phase with the test object mounted may reveal offsets and regular periodic patterns in the measurements.

Cable routing is the other source of unforeseen forces. Here, current densities should be as low as possible. Thrust measurement on electric space propulsion engines is still a challenging task and optimization is very important for this special measurement application.

Acknowledgments

We would like to thank Tobias Molkentin, student at the Justus-Liebig-University Giessen, Germany, for performing investigations concerning heating of cables during an internship at DLR in 2015.

References

[1] Neumann, A., "Update on diagnostics for DLR's Electric Propulsion Test Facility", *Procedia Engineering* 185 (2017) 47–52.

[2] Nagao, N., Yokota, S., Komurasaki, K., and Arakawa, Y., "Development of a two-dimensional dual pendulum thrust stand for Hall thrusters," *Rev Sci Instrum.*, Vol 78, 115108, 2007.

[3] Y.-X. Yang, L.-C. Tu, S.-Q. Yang, and J. Luo, "A torsion balance for impulse and thrust measurements of micro-Newton thrusters," *Rev. Sci. Instrum.*, Vol. 83, 015105, 2012.

[4] Gamero-Castaño, M., "A torsional balance for the characterization of microNewton thrusters," *Rev. Sci. Instrum.*, 74(10), 2003, pp. 4509–4514.

[5] Murakami, H., Hirata, M., Kudo, I., "Thrust Measurement of an Ion Engine System," *J. Spacecraft*, Vol. 21, No. 1, 1984, pp. 96-100.

[6] Banetta, S., Falorni, R., and Biagioni, L., "Development of a two-axes thrust stand for electric thrusters," *Proc. 4th Int. Spacecraft Propulsion Conference, Cagliari, Sardinia, Italy*, 2-4 June, 2004.
[7] Boccaletto, L., and d'Agostino, L., "Design and Testing of a Micro-Newton Thrust Stand for FEEP," 36th *Joint Propulsion Conference, 17-19 July 2000, Huntsville, AL, USA*, AIAA-2000-3268, 2000.
[8] Stephen, R. J., Rajanna, K., Dhar, V., Kalyan Kumar, K. G., and Nagabushanam, S., "Thin-Film Strain Gauge Sensors for Ion Thrust Measurement," *IEEE Sensors Journal*, Vol. 4, No. 3, 2004, pp. 373-377.
[9] Kodys, A. D., Murray, R., Cassady, L., and Choueiri, E. Y, "An Inverted-Pendulum Thrust Stand for High-Power Electric Thrusters," *42nd Joint Propulsion Conference & Exhibit*, 9-12 July 2006, Sacramento, California, AIAA 2006-4821, 2006.
[10] Haag, T. W., "Thrust stand for high power electric propulsion devices," *Rev. Sci. Instrum.*, Vol. 62, No.5, 1991, pp. 1186–1191.
[11] Harmann, H.-P., Koch, Norbert, and Kornfeld, Guenter, "The ULAN Test Station and its Diagnostic Package for Thruster Characterization," *International Electric Propulsion Conference*, IEPC-2007-119, September 17-20, 2007.
[12] Neumann, A., Sinske, J., and Harmann, H.-P., "The 250mN Thrust Balance for the DLR Goettingen EP Test Facility", Proceedings of the 33rd International Electric Propulsion Conference, IEPC-2013-211, Washington, D.C., USA, October 6 – 10, 2013.