High Precision Thrust Vector Determination through Full Hemispherical RPA Measurements assisted by Angular Mapping of Ion Energy Charge State Distribution

IEPC-2013-284

Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013

B. van Reijen[1], S. Weis[2], A. Lazurenko[3], J. Haderspeck[4], A. Genovese.[5], and P. Holtmann[6]
Thales Electronic Systems GmbH, Ulm, 89077, Germany

K. Ruf[7] and N. Püttmann[8]
Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR) - Raumfahrt-Agentur, Bonn, 53227, Germany

Abstract: For the successful integration and design strategy on the satellite manufacturer's side electric propulsion ion beam characteristics are of vital importance in order to analyze and quantify the thruster ion beam impingement effect upon satellite surfaces, leading to degradation of optical surfaces or available solar array power. A high precision beam analysis can be used to measure the thrust vector, removing the need for a complex multi-axis thrust balance and enables the satellite integrator to fine-adjust the thruster's orientation w.r.t. the satellite center of mass, thus saving mass otherwise needed for momentum wheel offloading. The data for both these analyses are produced with the combination of measurements taken with retarding potential analyzers (RPA) for the energy specific ion current density and an energy selective mass spectrometer (ESMS) for the energy specific charge state. Thales is currently assembling a thrust vector scanner with 37 RPAs mounted to a boom, capable of rotation ±90° around the thruster exit. Additionally an ESMS can map the energy selective charge state along a quarter circle by rotating the thruster. Thales will, upon successful assembly, integration and verification, be the only manufacturer of commercial electric propulsion systems to provide beam data to such a detailed extend.

Nomenclature

Y = sputter yield: atoms target material per incident atom (-)
α^T = dimensionless constant based upon ion mass and target atom mass (-)
γ = dimensionless constant based upon ion mass and target atom mass (-)
M_{ion} = ion atomic mass (kg)
M_t = target material atomic mass (kg)
E = ion energy (eV)

---

[1] Components R&D Manager, Plasma Devices, benjamin.reijen@thalesgroup.com.
[2] System Engineering Manager, Plasma Devices, stefan.weis@thalesgroup.com.
[3] Testing Manager, Plasma Devices, alexey.lazurenko@thalesgroup.com.
[4] System Engineer, Plasma Devices, jens.haderspeck@thalesgroup.com.
[5] Testing Engineer, Plasma Devices, angelo.genovese@thalesgroup.com.
[6] Program Manager R&D, Plasma Devices, peter.holtmann@thalesgroup.com.
[7] Project Manager, Robotic Systems, klaus.ruf@dlr.de
[8] Head Systems for Satellites, Robotic Systems, norbert.puettmann@dlr.de

U_b = binding energy (eV)
$\vec{T}$ = thrust vector along the thruster axis (N)
m = mass (kg)
v = velocity (m/s)
t = time (s)
$\dot{m}$ = massflow (kg/s)
$\vec{v}$ = velocity vector along the thruster axis (m/s)
α_{eff} = effective angle (-)
I = thruster discharge current (A)
e = elementary charge (C)
Q = ion charge state (-)
U_i = ion acceleration potential (V)
ρ = ion current density (A/m^2)
α = ion exhaust angle w.r.t. the thruster axis (rad)
φ = azimuth angle (rad)
Φ = energy specific ion current density (A/eVm^2)
U_{acc} = acceleration potential (V)
E_i = ion energy (eV)

I. Introduction

Thales has developed a novel type of ion propulsion system based upon the HEMP-Thruster. The successive qualification is performed in course of the HEMP-TIS program for the SmallGEO satellite and includes ground qualification and in orbit verification. A total of two Engineering Models, two Qualification Models and four Flight Models have been manufactured and are currently undergoing qualification and verification testing[1]. These tests are performed in the ULAN test facility and incorporate End-to-End, mechanical, thermo-vacuum and performance testing. During the performance test the thrust is measured by a thrust balance and the ion beam is characterized by retarding potential analyzers (RPA) and an energy selective mass spectrometer (ESMS).

Ion beam characterization is important to the satellite integrator for two reasons: ion impingement prediction for satellite structures and determination for off-axis thrust deviation. For this reason Thales is currently preparing a thrust vector scanner (TVS) for integration into the ULAN test facility.

II. Ion Impingement

Ions are charged particles, which in case of current commercial ion propulsion systems have been electrostatically accelerated towards high velocities. When exiting the thruster along its central axis these ions provide a maximum of impulse to the satellite in the opposite direction, depending on the electric field geometry inside the thruster and thruster plume characteristics however, ions can be expelled at high angles and thus cause them to impact the satellite structure, instruments, antennae or solar panels. When ions of sufficient energy impact such a surface their impulse knocks atoms from the lattice structure of the impacted material, see Fig.1, this is a complex process, the extend of this effect depends upon the ion atomic mass, target material atomic mass (both combined in the dimensionless constant α^T), ion kinetic energy, impact angle and base material properties such as the binding energy and atomic structure, see eq.(1)[2]. Also different types of reaction mechanisms within the target material are possible. Incident ion energy below a threshold value will not induce sputtering, above which however increasing ion energy non-linearly increases the sputter rate. The sputter rate is at nominal value at an incidence angle of 0° and increases to the maximum at an angle of 60° after which it decreases to zero at 90°.

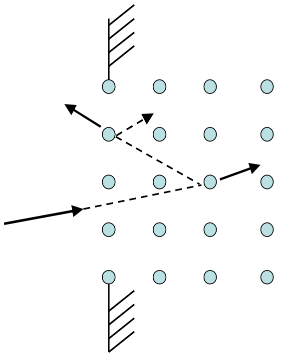

Figure 1. Single knockon elastic collision sputter effect

$$Y(E) = \frac{3}{4\pi^2} \alpha^T (M_{ion}, M_t) \cdot \frac{\gamma E}{U_b} \tag{1}$$

Especially in the case of solar arrays the silver interconnectors are sensitive to this sputtering effect due to the low sputter threshold of silver and their thickness of only a few microns. Separation of these interconnectors causes multiple rows of solar cells to be cut-off, therefore the available power to the satellite suffers. Knowledge of where critical sputter rates can be expected provides the opportunity to adapt the satellite configuration to minimize such effects.

Giving a known material combination of impacting ions and the base material the sputter rate can be deduced by theory or empirical sputter yields when the angle resolved data of the incident ion energy is known. This information is provided by beam characterization where the angle resolved ion current, potential and charge state is measured.

III. Thrust Vector

The purpose of an ion propulsion system is to provide directional thrust, the direction however is rarely exactly along the thruster axis, manufacturing tolerances, structural parts or neutralizer positions change the ion acceleration direction away from the axis. Any error of the thrust vector not passing through the satellite center of mass adds to a build-up of rotational momentum which needs to be countermanded by reaction wheels and ultimately by a propulsion system requiring propellant mass. In order to reduce the unwanted propellant mass for momentum wheel offloading it is desirably to know the exact thrust vector of all thrusters and adapt their mechanical interface to such an extent that their thrust vector points through the satellite center of mass.

Although the thrust of an ion propulsion system can be readily measured by a thrust balance the thrust vector deviation would require a highly complex multi-axis thrust balance. As an alternative ion beam characterization enables the use of measurement data to calculate the thrust vector of the equipment under testing. Most thrust vector ion beam measurements are performed by a rotating boom equipped with faraday probes; such a system however provides the current vector instead of the thrust vector. For thrust vector determination the angular and energy specific charge state needs to be measured and then be combined with the angular energy spectrum and integrated over the thruster hemisphere. Thales is currently integrating a TVS based upon RPAs and an ESMS, capable of measuring the thrust vector.

IV. Thrust Vector Determination

The thrust of an ion thruster upon its spacecraft is defined by the time rate change of momentum, see eq. (2).

$$\vec{T} = \frac{dmv}{dt} = \frac{dm}{dt} v = \dot{m}\vec{v} = \dot{m}v \cdot \cos\alpha_{eff} \tag{2}$$

$$\dot{m} = \frac{I \cdot M_{ion}}{e \cdot q} \tag{3}$$

$$\frac{1}{2} M_{ion} v^2 = E_{ion} = q \cdot U_{acc} \cdot e \tag{4}$$

$$v = \sqrt{\frac{2q \cdot U_{acc} \cdot e}{M_{ion}}} \tag{5}$$

$$\vec{T} = \frac{I \cdot M_{ion}}{e \cdot q} \sqrt{\frac{2q \cdot U_{acc} \cdot e}{M_{ion}}} \cos\alpha = I \sqrt{\frac{2U_{acc} \cdot M_{ion}}{q \cdot e}} \cos\alpha_{eff} \tag{6}$$

Deducing eq.(5) from eq.(4) and combining eq.(3) and eq.(5) with eq.(2) leads to eq.(6), with I as defined in eq.(7).

$$I = \int_0^{2\pi} \int_0^{\frac{\pi}{2}} \rho_{\alpha,\varphi} \sin\alpha d\alpha d\phi \quad (7)$$

From eq.(6) it is seen that the thrust is a function of the ion atomic mass M divided by the elementary charge e, this proportion is defined by the choice of propellant. The acceleration voltage U is defined by the anode potential and the location of the ionization regions within or outside of the thruster. The thrust vector magnitude in direction of the thruster axis is reduced by the cosine of the angle of the ions as they traverse the acceleration field, the integrated value is defined as α, the particle flow angle in the free expansion region of the ion beam with respect to the thruster axis. The total thrust is constructed from these ion properties integrated with the ion current over the thruster hemisphere as shown in eq.(7).

The measurement approach of setting the current vector equal to the thrust vector limits the analysis to the Icosα components of eq.(7), thus ignoring the thrust vector variations due to non-cylindrical acceleration voltage and charge state distributions. These distributions can be measured by a combination of 2 devices, the ion energy over charge spectrum, or rather the ion acceleration potential U is directly deducible from RPA measurements. The charge state can only be measured by an ESMS, which measures the energy specific charge state distribution, which can be mapped with the ion potential distribution from the RPA measurements.

V. Retarding Potential Analyzer

RPAs function on the principle of a retarding electrostatic field to act as a high pass filter for incident ions. Those ions capable of passing the field are collected and their neutralization current measured as a voltage drop over a resistor. Increasing the retarding field from zero to a value larger than the highest ion potential results in a graph, starting at the maximum current where all ions are detected, reducing to zero when the retarding field blocks all ions. The negative differential of the collector current over the ion potential divided by the collector surface and elementary charge e results in the energy specific ion current density[3], see eq.(8). It is noted that the retarding electric field measures the ion energy $U_i e$ in eV, which is equal to the thruster acceleration potential $U_{acc} e$ and the ion energy E divided by the ion charge state q, see eq.(9).

$$\Phi = -\frac{dI_{coll}}{dU_i \cdot A_{coll} \cdot e} \quad (8)$$

$$U_i \cdot e = U_{acc} \cdot e = \frac{E_i}{q} \quad (9)$$

In the past, Thales has put a great deal of effort into the understanding, simulation and development of RPAs. Simulations were used to anticipate the lens effect of consecutive electrostatic fields, and validate the transmission properties of electrode systems as used in RPAs. This resulted in a state-of-the-art high resolution single orifice RPA design which will be implemented on the Thales TVS. The main interfaces to the Thales RPA, see Fig.2, are a sensor cable for the collector current and three high voltage lines to the electrode system. In-house developed electronics, combined with in-house developed software controls the applied voltages, performs high-precision current measurements and fully automatically scans and evaluates the ion beam data.

Figure 2. Thales RPA

Since the RPA cannot distinguish between double charged 2keV ions and 1keV single charged ions this ion property needs to be measured by an ESMS.

VI. Energy Selective Mass Spectrometer

Thales procured a Balzers/Inficon quadrupole plasma process monitor PPM422 energy selective mass spectrometer ESMS, see Fig.3, with a mass range of 512 amu, an energy resolution of 0.3eV and an energy range of ±512eV. Since the energy range is insufficient for the HEMP-Thruster, which accelerates ions with a typical energy of 1keV the PPM422 was galvanically separated from the vacuum vessel such that the base potential can be altered up to 1kV. This modification required an adaptation to the vacuum-side of the mass spectrometer, shielding it from the plasma environment, without disturbing the ion influx into the PPM orifice. This was done by a shield grid and focusing electrode stack, which focusses the ions of a specific energy, which are currently being scanned, into the PPM. Thus, through control of the PPM ground potential the whole ion energy range from the HEMP-Thruster can be detected and their energy specific charge state measured[3]. The weight, dimensions and electronics of the PPM prevent it from being used inside the vacuum chamber, therefore it is flanged to the vacuum chamber at the opposite end from the thruster. Rotation of the thruster around the vertical axis through its exit plane enables the ESMS to scan one quarter orbit. Through the assumption of rotational symmetry the ion charge property of the ion beam is known.

Figure 3. Thales ESMS mounted to the vacuum chamber

VII. Thrust Vector Scanner

The Thales thrust vector scanner is currently undergoing assembly and consists of the following components: a hollow square profiled tube construction forms the basis for a stiff mounting frame. Upon this frame bent rails permit rotation of a separate baseplate around a virtual axis, this virtual axis coincides with the thruster exit plane, when the thruster is mounted upon the thrust balance which is positioned upon the rotatable baseplate. This configuration makes sure the whole thruster hemisphere is free from obstructions and the ion beam can freely expand until it reaches the chamber wall. A vacuum motor with a planetary gear drives the rotation of the thrust balance and thus the thruster. The virtual axis for the rotation of the thruster coincides with the rotational axis of a semicircle U-profile which is attached at two pivot points on the main mounting frame, one is a pivot bearing, the other is a vacuum motor which drives the rotation of the semicircle around the thruster exit. The semicircle, or boom, is two meters in diameter and high-precision machined to be equipped with 37 Thales RPAs, equally spaced every 5°, resulting in a 180° view angle. With the capability to rotate the boom to ±90° from the thruster axis the RPAs cover the full thruster hemisphere for energy selective current density measurements, see Fig.4. The RPAs are positioned at a radial distance of one meter from the thruster exit and due to their viewing angle can detect all ions escaping through the thruster exit.

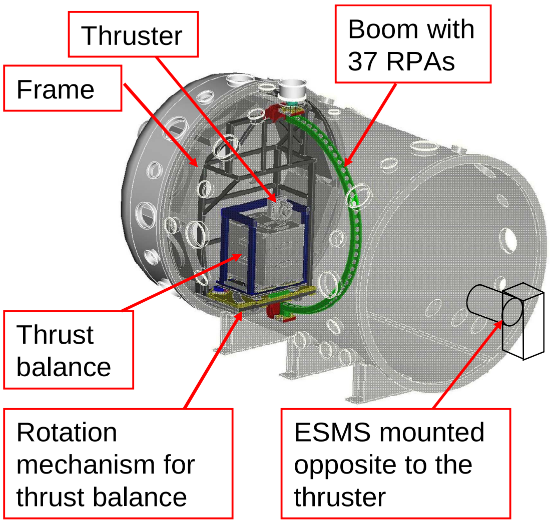

Figure 4. The Thales TVS installed within the ULAN vacuum chamber

A total of 40 cables are attached to the boom, 37 sensor cables for one collector per RPA and three high voltage lines for the RPA electrodes. The TVS electronics can monitor up to 40 sensor lines simultaneously and correlate these with the actual applied retarding voltage, thus the voltage can be ramped from zero to 1.3kV in 65 seconds, resulting in the simultaneous measurement of 37 RPAs every minute, and a full thruster characterization in about 45 minutes.

Rotation of the thrust balance around the vertical axis enables the ESMS to scan a quarter circle line on the thruster hemisphere and although the charge state information can be mapped upon the energy density distribution variation it is clear that under the assumption of cylindrical symmetry the charge state has no direct contribution to the thrust vector calculation. It is however used as an angle specific property applied as a scaling factor to the ion acceleration potential that may not be neglected due to an effect in the $\sqrt{2}$ magnitude.

Considering the case where the ion energy and current distributions are not rotational symmetric, where the energy distribution is a spectrum broader than a single mono-energetic peak and the charge state distribution is a function of the ion energy and angle α, eq.(6) and eq.(7) need to be adjusted into the combined eq.(10).

$$\vec{T} = \int_0^{2\pi}\int_0^{\frac{\pi}{2}}\int_0^{U_{\max}} \sqrt{\frac{2M_{ion}}{e}} \cdot \rho(\alpha,\varphi,U) \cdot \sqrt{\frac{U(\alpha,\varphi)}{q(\alpha,\varphi,U)}} \cos\alpha \sin\alpha dU d\alpha d\varphi \qquad (10)$$

For the HEMP-Thruster the current contribution due to double and triple charged ions may reach up to 60% of the total discharge current in a specific angle, therefore the error induced by the absence of complete hemispherical measurements is smaller compared to the case where no information is present at all. It may be clear that the additional information which is gained through RPA measurements instead of faraday cups is most helpful in cases where the acceleration potential of the ions is rather a broad spectrum instead of a defined peak in the energy spectrum. The high precision with which the thrust vector must be defined, in the 0.1° order of magnitude, drives the need for such extensive measurement equipment.

VIII. Conclusion

Ion thruster beam sputtering causes degradation of satellite surfaces, such as optical elements or solar arrays. The magnitude of this effect, for a given ion-target material combination, depends on the ion energy and angle. The ion energy in case of a non-mono-energetic beam is a distribution consisting of energy specific currents, directly related to the acceleration potential each ion is subjected to. The ion energy is defined by the acceleration potential multiplied by the ion electrical charge, which depends upon the ion charge state. For this reason the ion acceleration potential and charge state are vital parameters for thruster impingement analysis. The former can be measured by an RPA whereas the latter required an ESMS.

Manufacturing tolerances, magnetic and electrical disturbances to the plasma plume due to surfaces or cathodes cause deviations in the rotational symmetry of the free expanding ion beam. These deviations result in a thrust vector which is not perfectly in line with the thruster axis. Although thrusters are integrated onto the satellite such that their thrust vector goes through the satellite center of mass, if the exact thrust vector is unknown the alignment error will cause a rotational momentum when the thruster if firing. This momentum is nullified by the attitude control system, requiring additional propellant mass. Mechanical measurement of the thrust vector would require a complex multi-axis thrust balance, therefore Thales has chosen to analyze and calculate the thrust vector from beam characterization measurements. For this purpose a thrust vector scanner is currently under assembly, combining full hemispherical RPA measurements with 37 RPAs mounted to one meter distance on a rotating ±90° boom. The energy specific ion current, combined with the ion energy specific charge state distribution from measurements with an energy selective mass spectrometer, through the rotation of the thruster around its vertical axis, enable thrust mapping over the full thruster beam and makes the thrust vector available to a precision of an order of magnitude of 0.1°.

The construction of the TVS provides Thales with the unique ability of thrust vector analysis through ion beam characterization. Once the next steps of assembly, integration into the vacuum chamber and validation are completed this measurement equipment will be the first of its kind worldwide.

Acknowledgments

HEMP-TIS is supported by the Federal Ministry of Economics and Technology through German Aerospace Center DLR, Space Administration, under contract number 50RS0803.

References

[1] Lazurenko, A., et al., “Progress in Testing of QM and FM HEMP Thruster Modules”, *33rd International Electric Propulsion Conference,* IEPC-2013-274, Washington, D.C., USA, 2013.

[2] Behrisch, R. *Sputtering by Particle Bombardmen I, Physical Sputtering of Single-Element Solids,* Topics in Applied Physics Volume 47, Springer-Verlag, Berlin Heidelberg, 1981, Chap. 2.

[3] van Reijen, B., et al., “High Precision Beam Diagnostics for Ion Thrusters”, *32nd International Electric Propulsion Conference,* IEPC-2011-132, Wiesbaden, Germany, 2011.