Simultaneous Measurement of Impulse Bits and Mass Shots of Electrothermal Pulsed Plasma Thruster

IEPC-2017-456

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

T. Yoshikawa[1]
The University of Tokyo, Bunkyo-ku, Tokyo, 113-8654, Japan

H. Kuninaka[2] and K. Nishiyama[3]
Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, 252-5210, Japan

Abstract: A pulsed plasma thruster (PPT) is one of the electric propulsions for small satellites less than 100 kg. Though some kinds of thrust stands can measure impulse bits, there are few examples that mass shots of PPTs have been measured by thrust stands. In this study, a seesaw type thrust stand have been developed in order to conduct real-time and simultaneous measurement for PPT's impulse bits and mass shot. Calibrations of impulse bits and mass shots were accomplished and a measurement of electrothermal PPT's performance was conducted.

Nomenclature

I_{bit}	=	impulse bit
ΔM	=	mass shot
I_{SP}	=	specific impulse
μ	=	thrust efficiency
g	=	acceleration due to gravity
E	=	input energy
M_{i}	=	propellant mass before PPT's N shots operation
M_{f}	=	propellant mass after PPT's N shots operation
N	=	shot counts of PPT
L_{PPT}	=	distance between flexure pivots and point where PPT is applied
ω_{n}	=	natural frequency
ζ	=	damping coefficient
K	=	spring constant
I	=	moment of inertia
C	=	damping constant
M_{CW}	=	mass of movable counter weight
Δx	=	displacement of movable counter weight
$\Delta\theta$	=	angular displacement

[1] Graduate Student, The University of Tokyo, t-yoshi@ep.isas.jaxa.jp
[2] Professor, Institute of Space and Astronautical Science , kuninaka@isas.jaxa.jp
[3] Associate Professor, Institute of Space and Astronautical Science , nishiyama@ep.isas.jaxa.jp

I. Introduction

Recently there is a trend of space development with small satellites less than 100 kg. In this trend, pulsed plasma thrusters (PPTs) have attracted attention as its thruster for these small satellites. A PPT (Figure.1) is small and has a simple structure. Therefore its manufacturing cost is also lower than other electric propulsions. Besides its power consumption is about 1 to 100 W, which is also less than other electric propulsions. Above all, a particularly noteworthy feature is using polytetrafluoroethylene (PTFE; Teflon®) as a solid propellant. This is non-toxic material so that it is easy to handle. In addition, high pressure tanks and valves are not required. For this reason, a PPT system is advantageous for small satellites when launching as piggyback satellites. PPTs generate thrust by pulse operation. For this reason, its thrust is evaluated by the impulse bits (I_{bit}), which is the momentum change generated by the PPT per 1 pulse. In this research, electrothermal PPTs are focused. Electrothermal PPTs have higher I_{bit} and lower specific impulse (I_{SP}) than electromagnetic PPTs.

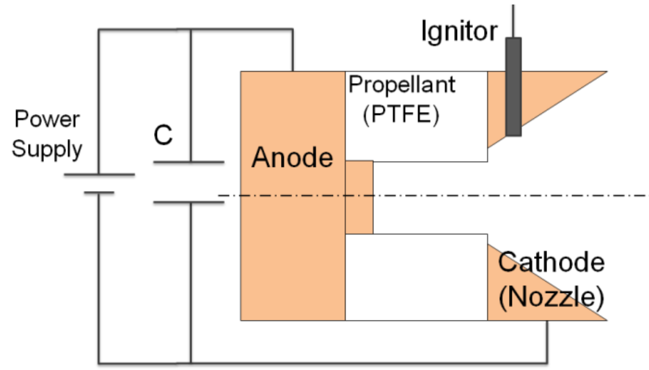

Figure.1 Electrothermal PPT

Generally, the I_{bit} of PPTs has been measured mainly by three kinds of thrust stands. The first is a "pendulum thrust stand (Figure.2)" [1]. In this case, a PPT is hanged as a pendulum. Then, I_{bit} of the PPT is measured from the amplitude of the pendulum at the time when the PPT generates an impulse. The second type is "target thrust stand (Figure.3)" [2]. In this type, a thrust target is hanged as a pendulum, and the PPT is set outside the stand toward the target. When the PPT generates its impulse, the pendulum with the target vibrates by the PPT's plume and then I_{bit} is measured from this amplitude. Lastly, it is a "torsional balance thrust stand (Figure.4)" [3]. This stand consists of the PPT, counterweight, damper mounted on the arm oscillating horizontally. In addition, torsion springs are applied at the center of oscillation of the arm. At the occurrence of PPT's impulse, the arm oscillates damping toward the balance point, and then I_{bit} is measured from the value of the first peak of the waveform etc.

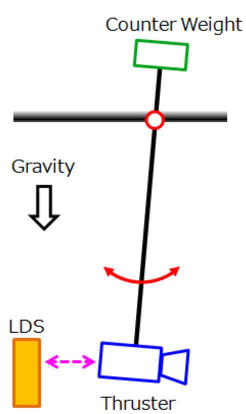

Figure.2 Pendulum thrust stand

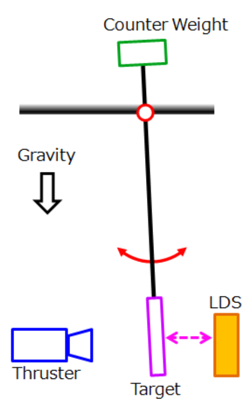

Figure.3 Target thrust stand

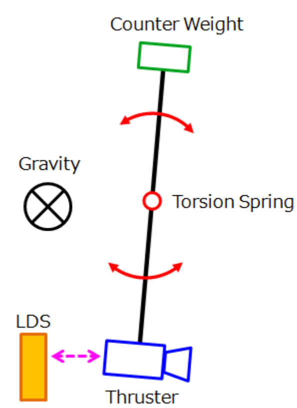

Figure.4 Torsion balance thrust stand

II. Thrust stand for measurement of mass shot

A. Conventional method of measurement of mass shot

Another important performance is the mass shot (ΔM), which is a propellant mass used per 1 impulse. This performance and the impulse bit determine the PPT's specific impulse (I_{SP}) and thrust efficiency (μ). Equation (1) and (2) show calculation formulas for the specific impulse and thrust efficiency of PPT, respectively.

$$I_{\mathrm{SP}} = \frac{I_{\mathrm{bit}}}{g \cdot \Delta M} \tag{1}$$

$$\mu = \frac{{I_{\mathrm{bit}}}^2}{2 \cdot E \cdot \Delta M} \tag{2}$$

Mass shots are generally measured by electronic balances. First, the propellant mass before an N shots operation is measured as an initial mass (M_{i}). Subsequently, after the operation, the final propellant mass M_{f} is measured. Then the mass shot is gained as an average value by dividing the mass difference (Mi - M_{f}) by the PPT's shot counts (N) as shown in Equation (3).

$$\Delta M = \frac{M_{\mathrm{i}} - M_{\mathrm{f}}}{N} \tag{3}$$

However, the above method has the following problems.

1) Pressure release is required for every measurement
2) Solid propellant can be affected by pressure release
3) It is difficult to increase the measurement frequency due to 1) and 2)

Thus, a device which can measure mass shots in vacuum is needed.

B. Thrust stand for measurement mass shot

In order to measure PPT's specific impulse with measuring mass shots, "thrust stand micro-mass balance (Figure.5)" had been developed by T.C.Lilly et al[4,5]. The stand has a structure such as a seesaw and consists of torsion springs, dampers and so on, as with the torsional balance thrust stand. Besides, a method of measuring impulse bits is the same as the torsional balance.

The most important feature of the stand is that the balance point of the stand arm is displaced by a change of the mass of the PPT due to the mass shots. Thus, measurement of mass shots can be made possible by getting a relation between the amount of the PPT's mass loss due to the mass shot and the displacement of the stand arm.

In this study, a "seesaw type thrust stand" have been manufactured and developed in order to measure performances of electrothermal PPT.

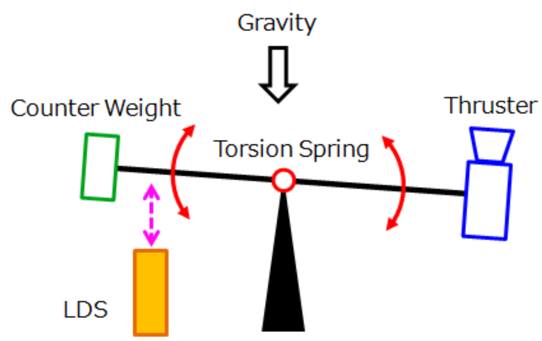

Figure.5 Schematic of seesaw type thrust stand

C. Objective of this study

When using this stand, calibration is necessary. This stand has three factors (K, C, I). These factors can be estimated by moving the movable counterweight. Based on the estimation, impulse bits and mass shots can be written by equation (4, 5).

$$I_{\mathrm{bit}} = \frac{\sqrt{KI}}{L_{\mathrm{PPT}} \cdot \sqrt{1-\varsigma^2} \cdot \exp\left(-\frac{\varsigma \operatorname{Cos}^{-1}\varsigma}{\sqrt{1-\varsigma^2}}\right)} \Delta\theta_{\mathrm{MAX}} \tag{4}$$

$$\Delta M = \frac{K}{\mathrm{g} \cdot L_{\mathrm{PPT}}} \Delta\theta \tag{5}$$

However, this method is not effective. This is because a maximum of 30% error occurred in the mass shot measurement. As an error factor, the mass of the movable counterweight cannot be accurately measured.

As calibration methods for impulse bits and thrusts, there are few methods. For example, impact hammer and electronic comb. Although these methods have been well developed, handling is not easy because it is necessary to calibrate this device itself.

The objective of this study is to establish a simple calibration method. Specifically, impulse calibration using collision of steel balls, calibrations for mass shot and PPT's average thrust using known weight were performed.

III. Calibration methods

The seesaw type thrust stand is shown in Figure.6. The stand mainly consists of a couple of torsion springs, a magnetic damper, a movable counter weight and a laser displacement sensor (LDS) . In this study, three calibration systems for I_{bit}, ΔM and F_{ave} were mounted additionally.

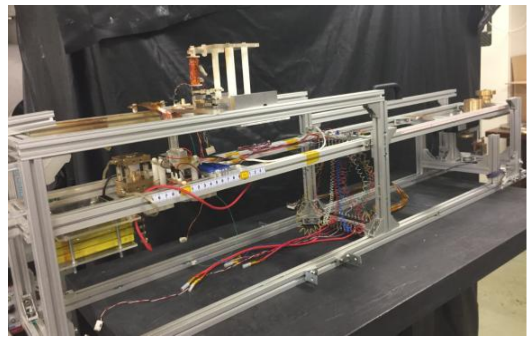

Figure.6 Seesaw type thrust stand

A. ΔM Calibration

Calibration for ΔM measurement of PPT was conducted by releasing a known weight from a certain position on the thrust stand in vacuum in order to simulate mass losses. The structure of the mass shot calibrator is shown in Figure. The mass shot calibrator is made up of a disk (rotating disk) that rotates by a cylinder / servomotor that stores a known weight, and a fixed disk (fixed disk) located just below it. A specific calibration method is shown below (Figure.7).

1) Store known weights in the cylinder.
2) Rotate the rotating disc by 90 ° and catch one tooth in the cylinder.
3) Then rotate the rotating disk by -90 deg and release the caught weight out outside the stand through the fixed disk.

The above method was carried out when the output of LDS was about 4V. After that, the change of the LDS output due to the release of the weight was returned to 4V by the movable counterweight. The displacement of the counterweight can be controlled by a computer. The output for the known mass loss was defined as the movement of this counterweight.

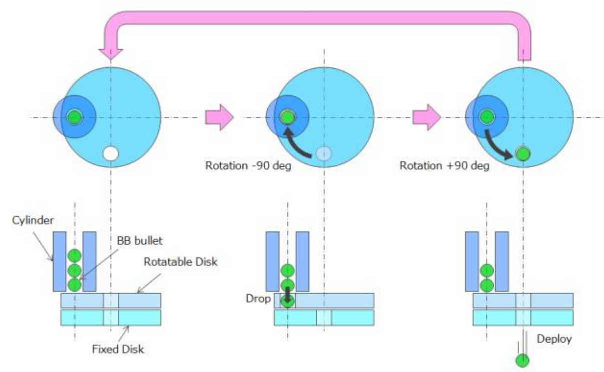

Figure.7 Method of ΔM calibration

B. I_{bit} Calibration

The vibration waveform of the stand when a PPT generated I_{bit} can be regarded as almost an impulse response. This is because the ΔM is so small that the step response due to ΔM can be almost ignored.

I_{bit} calibration was conducted by free fall of steel balls whose weight is known from known height by using electromagnets in a vacuum. A known impulse was reproduced by collision between the ball and the arm of the stand. A gel material was set at the collision point, thereby non-perfect elastic collision was reproduced. Here, the problem is that a step response occurs due to the landing of the steel ball whose mass is several 100 mg on the arm. Therefore, the same device in order to

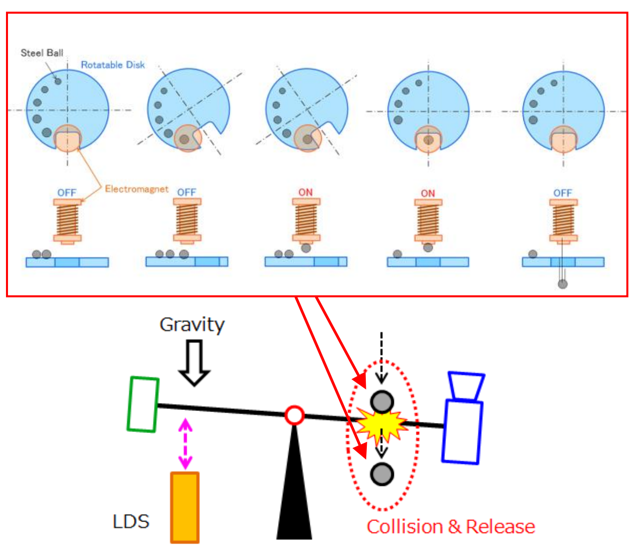

Figure.8 Method of I_{bit} calibration

release steel balls was mounted on the arm of the stand. This device can release steal balls that have the same mass by electromagnets as soon as the steel ball from the outside collides on the arm by program control. As a result, it was possible to cancel the drift due to the step response (Figure.8).

The output for the known impulse or actual I_{bit} was delivered as a difference ΔV_{LDS} corresponding to the displacement amount from the first peak value of the damped oscillation waveform of the arm displayed by LDS to the equilibrium position before occurrence of the impulse.

IV. Calibration results

A. Results of ΔM Calibration

Table.1 shows the conditions of known weights used the ΔM calibration.

Table.1 Conditions of known weights for ΔM calibration

Shape	Ball
Diameter	6 mm
Mass	0.1118 ± 0.0003 g

Figure.9 shows the result of the calibration. Linear relation between the known mass loss and the displacement of the movable counterweight was gained.

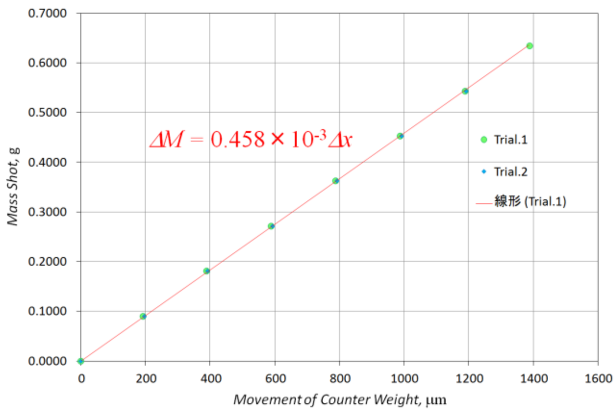

Figure.9 Result of ΔM calibration

B. Results of I_{bit} Calibration

Table.2 shows the conditions of steel balls for the I_{bit} calibration.

Table.2 Conditions of steel ball for I_{bit} calibration

No.	Diameter	Mass(±0.0005), g	Known Impulse, μNs
1	5.5	0.6785	1040
2	5.0	0.5097	780
3	4.5	0.3718	570
4	4.0	0.2610	400
5	3.5	0.1745	270

Figure.10 shows the waveform of output of the LDS at the time when the collision and release of two steel balls occurred. Impulse responses were almost reproduced.

The result of I_{bit} calibration is shown in FIgure.11. The relation between the known impulses and ΔV_{LDS} is gained as a linear relation.

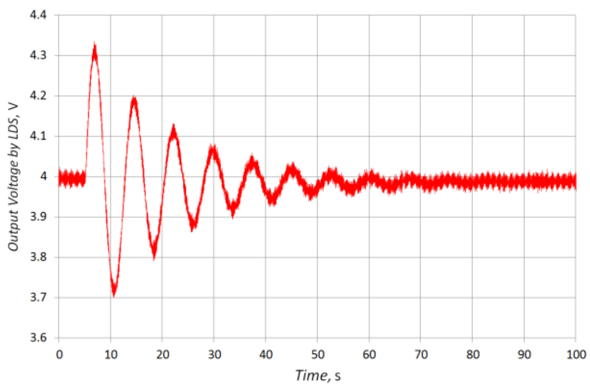

Figure.10 Waveform of the stand at the time of I_{bit} calibration

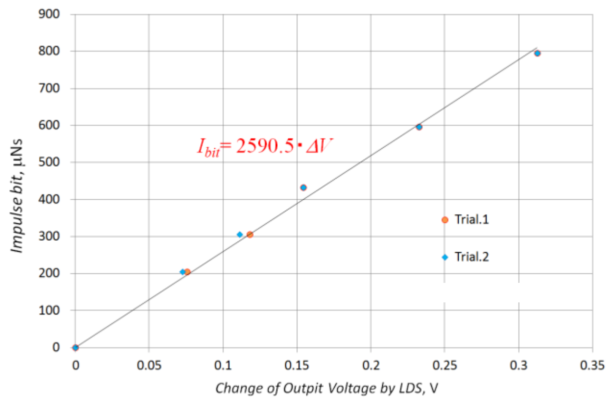

Figure.11 Relation between known impulses and ΔV_{LDS}

V. I_{bit}, ΔM measurement and Discussion

A. Results of measurement

Based on the above calibration results, measurement of performances of an electrothermal PPT was conducted. Table.3 shows conditions of the PPT.

Table.3 Conditions of electrothermal PPT

Cavity Diameter	3.5 mm
Cavity Length	10 mm
Input Energy	9.8 J
Operation Frequency	1 Hz
Number of PPT shots	10,000 shots

Figure.12 and 13 shows results of the measurement of ΔM and I_{bit} respectively. In Figure.13, green plots indicate the total mass shot at the each shots, orange plots indicate the average mass shots, and blue plots are actual mass loss measured by electronic balance.

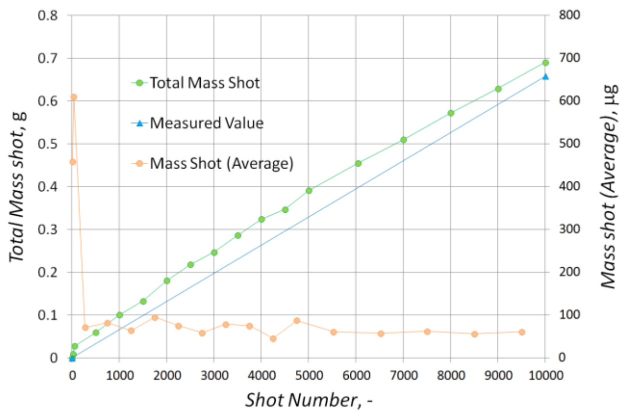

Figure.12 Result of ΔM measurement

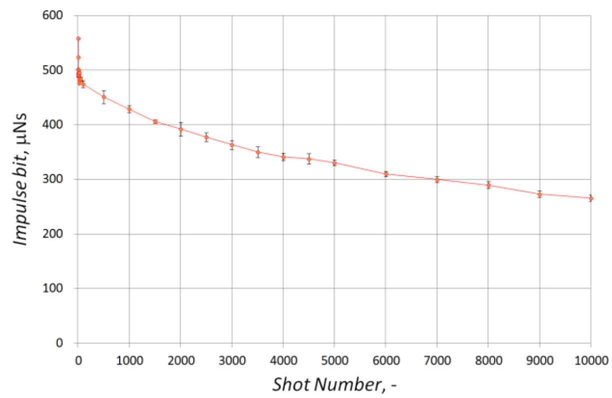

Figure.13 Result of I_{bit} measurement

B. Discussion

In Figure.12, when the total ΔM (0.691 g) measured by the thrust stand after 10,000 shots is compared with the actually measured value (0.658 g) by the electronic balance, the error was about 5.0%. As a major factor of the error, drift of the thrust stand as shown in Figure.14 is considered. This is because the center of gravity position of the arm of the thrust stand changes due to influence of outgases. However, this phenomenon occurs conspicuous immediately after evacuation, however the gradient of the displacement becomes slow with the passage of time. For this reason, this effect can be mitigated if sufficient time is given after evacuation to a sufficiently low pressure (less than 10 mPa). The reason why the ΔM measurement was achieved in this experiment with about 5% error is considered to be because the influence of drift was suppressed by placing sufficient time after evacuation as described above.

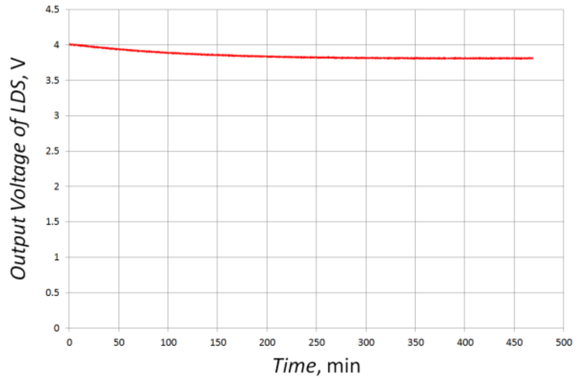

Figure.14 Balance point drift of the stand arm

The measurement result of I_{bit} in Fig.14 agrees with the trend of I_{bit} and the I_{bit} -E ratio reported by other institutes [6-8]. As the above result, a validity of the measurement for electrothermal PPTs based on the I_{bit} calibration method using the thrust stand is proved. Besides the results also indicate that not only I_{bit} measurement but also ΔM measurement could be performed in real time by the thrust stand.

VI. Conclusion

A seesaw type thrust stand was developed in order to measure I_{bit} & ΔM of electrothermal PPT simultaneously. ΔM and I_{bit} calibration methods using known weights and steel balls were proposed and the calibration results were obtained as a linear relation. Based on the calibration result, performance measurement of electrothermal PPT was conducted. As a result of the measurement, ΔM measurement with about 5% error from the actual value was achieved, and measured I_{bit} agreed with the results of other institutes.

References

[1] Egami, N., Inoue, Y., Nakano, S., Ikeda, T., and Tahara, H., “Research and Development of Nano-Satellite PROITERES with Electric Rocket Engines at Osaka Institute of Technology”, 2012 IEEE Vehicle Power and Propulsion Conference, 2012, pp. 523-528.

[2] Ryoji Yanagi, Itsuro Kimura. "New Type of Target for the Measurement of Impulse Bits of Pulsed Plasma Thrusters", Journal of Spacecraft and Rockets, Vol. 19, No. 3 (1982), pp. 246-249.

[3] William J. O'Neill, Dongju Lee, Anthony G. Cofer, and Alina Alexeenko. "Dynamic Modeling and Experimental Validation of Thrust-stand for Micropropulsion Testing", 51st AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2015-4186)

[4] Andrew D. Ketsdever, Brian C. D'Souza, and Riki H. Lee. "Thrust Stand Micromass Balance for the Direct Measurement of Specific Impulse", Journal of Propulsion and Power, Vol. 24, No. 6 (2008), pp. 1376-1381.

[5] Taylor C. Lilly, Andrew Ketsdever, Anthony P. Pancotti, and Marcus Young. "Development of a Specific Impulse Balance for Capillary Discharge Pulsed Plasma Thrusters", Journal of Propulsion and Power, Vol. 25, No. 3 (2009), pp. 823-826.

[6] Keita Kanaoka and Hirokazu Tahara. "Research and Development of a High-Power Electrothermal Pulsed Plasma Thruster System onboard Osaka Institute of Technology 2nd PROITERES Nano-Satellite", 52nd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2016-4844)

[7] Takuya Kamimura and Hirokazu Tahara. "R&D, Launch and Initial Operation of the Osaka Institute of Technology 1st PROITERES Nano-Satellite with Electrothermal Pulsed Plasma Thrusters and Development of the 2nd and 3rd Satellites", 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2014-3609)

[8] Junichiro Aoyagi, Masayuki Mukai, Yukiya Kamishima, Tsubasa Sasaki, Kouhei Shintani, Haruki Takegahara, Takashi Wakizono, Mitsuteru Sugiki. "Total impulse improvement of coaxial pulsed plasma thruster for small satellite", Vacuum 83 (2009), 72–76