Verification of Analysis Tool of Thruster Plume Interactions for Spacecraft

IEPC-2007-293

Presented at the 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007

Satoshi Hosoda[1]
Japan Aerospace Exploration Agency, Sagamihara, Kangagawa, 229-8510, Japan

Naomi Kurahara[2] and Mengu Cho[3]
Kyushu Institute of Technology, Kitakyushu, Fukuoka, 804-8550, Japan

Takanobu Muranaka[4] and Hitoshi Kuninaka[5]
Japan Aerospace Exploration Agency, Sagamihara, Kangagawa, 229-8510, Japan

Shinji Hatta[6] and Jeongho Kim[6]
MUSCAT Space Engineering Co. Ltd., Kitakyushu, Fukuoka, 804-8550, Japan

and

Hiroko O. Ueda[7], Kiyokazu Koga[8] and Tateo Goka[9]
Japan Aerospace Exploration Agency, Tsukuba, Ibaraki, 305-8505, Japan

Abstract: Multi-utility Spacecraft Charging Analysis Tool (MUSCAT), a spacecraft charging analysis software, has developed as a joint work of JAXA and KIT. The purpose of the present paper is to validate the accuracy of the MUSCAT solver experimentally. We measured the current collection characteristic and sheath formation on the wake side in flowing plasma environment to evaluate the PIC and Particle-Tracking solver. To produce a flowing plasma, we have used an Argon hall thruster. When negative voltage biased was applied to the collector plate, the similar sheath structures on the wake-side between experiment and simulation was confirmed. The current collection characteristic was well simulated to experiment result. These results support MUSCAT can simulate complicate absolute or differential charging in LEO or PEO environments.

Nomenclature

[1] Researcher, Institute of Space and Astronautical Science, hosoda@ep.isas.jaxa.jp.
[2] Graduate student, Dept. of Electrical engineering.
[3] Professor, Dept. of Electrical engineering.
[4] Researcher, JEDI center.
[5] Professor, Institute of Space and Astronautical Science.
[6] President, MUSCAT Space Engineering Co. Ltd.
[7] Researcher, JEDI center.
[8] Researcher, Institute of Aerospace Technology.
[9] Leader, Institute of Aerospace Technology.

e	=	elementally charge	ξ	=	normalized variable in space
M	=	ion molecular mass	ϕ	=	normalized potential
U_i	=	ion drift velocity	Ω	=	ion plasma frequency
V	=	potential			
x	=	variable in space			

I.Introduction

JAPAN Aerospace Exploration Agency (JAXA) determined that the total loss of ADEOS-II, a polar Earth orbit (PEO) satellite with bus voltage of fifty volt, attributed to interaction between the plasma environment and its multi layer insulation (MLI) around wire harness. During investigation process of the loss of ADEOS-II, it was revealed that charging of a polar satellite could cause serious failure including total loss.[1,2]

In order to prevent power system failure due to charging like what occurred on ADEOS-II, quantitative analysis from the viewpoint of charging-arcing issue from the early stage of satellite designing phase is necessary. Electric potential of satellite body with respect to ambient plasma and differential voltage of each surface component with respect to the satellite body potential are the most important elements to consider charging-arcing issue. Satellites in PEO are exposed to unique plasma environment including low energy (0.1~0.2 eV) ionospheric plasma and high-energy auroral zone particles. In low earth orbit (LEO) with a low inclination angle low energy particles are dominant. In geostationary orbit (GEO), on the other hand, high-energy particles are dominant. Therefore, an analyzing tool developed for PEO can be used both for LEO and GEO with minor modification. In Japan, Space Plasma Simulation Group promotes “Geospace Environment Simulator (GES)” project using the Earth Simulator, one of the fastest computer at present in the world.[3] A computer code for simulating plasma environment surrounding a satellite is under construction as a component of GES. As GES uses Particle-in-Cell (PIC) method for computation of environment around spacecraft, it requires long computation time even for the Earth Simulator.[4] Therefore, although GES is very powerful, it is not useful for easy use like parametric runs in spacecraft designing phase.

In the situation mentioned above, JAXA decided to develop its own charging analysis tool that can calculate charging status of a polar orbiting satellite jointly with Kyushu Institute of Technology (KIT). The numerical tool is named Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT).[5] It will be used to evaluate the risk of charging in spacecraft design phase, to determine appropriate parameter settings of ground tests by calculating the worst-case charging potential, and to determine whether a given satellite failure is due to charging or not. Fundamental algorithm of MUSCAT is based on a two-dimensional electrostatic solver developed by Cho et al.[6] MUSCAT employs Particle-In-Cell (PIC) method and particle tracking (PT) method. PIC is used to obtain the steady state of sheath around spacecraft and the PT is used to obtain current flow into surface and to update surface potential. Detail specifications of MUSCAT, the frameworks, time table and basic algorithm, were described in Ref. 5 and 7.

The purpose of the present paper is to validate the accuracy of the MUSCAT solver experimentally. One of the advantages of MUSCAT is to be able to simulate complex charging phenomena in PEO plasma environment. The polar orbit is a peculiar orbit where low energy but dense ionospheric plasma and high energy but dilute aurora particles coexist. If the aurora electron current surpasses the current due to ionosphereic ions, the satellite body itself may be charged to a negative potential (Absolute charging)[8,9]. Also, aurora particles may lead to severe surface charging of the wake side (Differential charging)[10].

In case of LEO and PEO environments, spacecrafts must travel at a speed of 7~8 km/s through dense ionospheric plasma. To produce a flowing plasma, we have used an Argon hall thruster. It is very difficult to produce a flowing plasma with the orbital velocity of 8km/s while keeping the plasma parameters similar to the PEO condition. Therefore, we use a similarity law to simulate the flowing condition in PEO previously used in a laboratory experiment to simulate a plasma flow with around a high voltage solar array in ionospheric plasma[11]. They introduced the scaling law and identified two non-dimensional parameters that are important to apply the results of the laboratory simulation to the real interaction in orbit. To evaluate PEO simulation, we measured the current collection characteristic and sheath formation on the wake side in flowing plasma environment applying the scaling-law.

II.Experimental facilities

A. Experimental setup

The experiments for the code validation were done at the facility in ISAS/JAXA. The chamber is a cylinder which had 1.5m in diameter and 2.8m in length. The chamber is made of stainless steel and the body is electrically grounded. An oil-sealed rotary pump (Displacement: 7500 L/min) and a roots pump (40000 L/min), and two diffusion pumps (3700 L/sec) were attached as vacuum pumps. Plasma source and traverse units for Langmuir probe measurements were attached on the chamber door as shown in Fig. 2. Current collection sample was set at the 150mm downstream from plasma source. This sample plate was removed when plasma parameter measurements.

B. Plasma source

Figure 3 shows a picture of a hall thruster. In this experiment, the plasma flow is generated with a hall thruster.

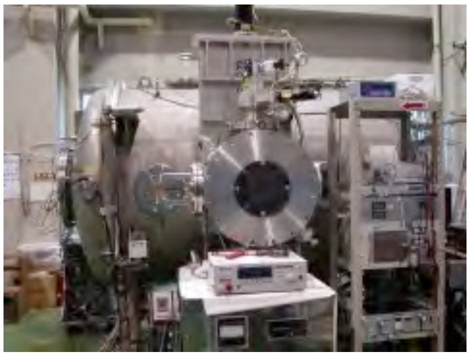


Figure 1. Vacuum chamber.

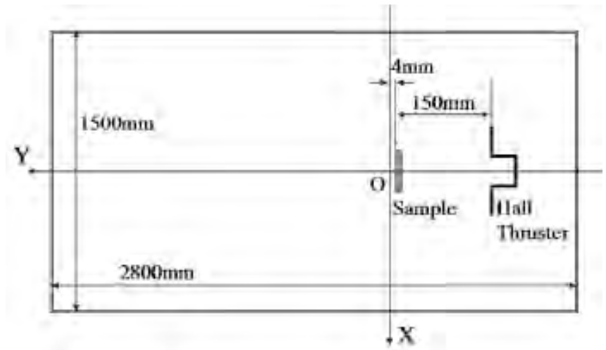


Figure 2. Setup configuration

Figure 4 shows the electrical circuit of the hall thruster. Magnetic field is created by coils. Cathodes were tungsten filament with carbonate paste. The operational conditions are shown in Table 1. Argon was used as a working gas. The chamber pressure during the experiment is $1.6\text{x}10^{-3}$ Pa at 28sccm.

Table 1. Operational condition of the hall thruster

Discharge voltage	110 V
Discharge current	2 A
Coil current	10 A
Input power of cathode	20W
Argon flow rate	28 sccm

Figure 3. Hall thruster.

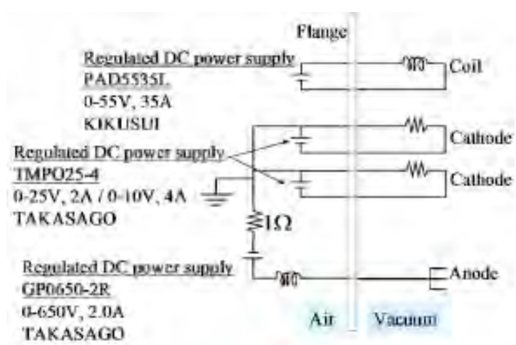


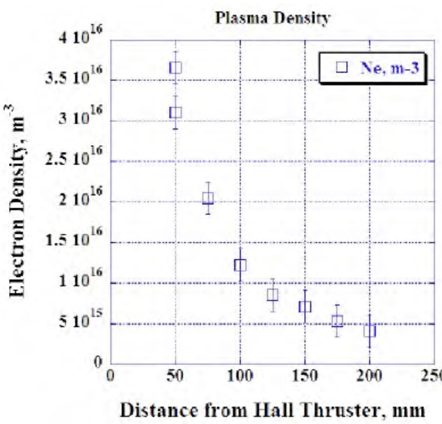
Figure 4. Electrical circuit of hall thruster.

III. Plasma plume diagnostics

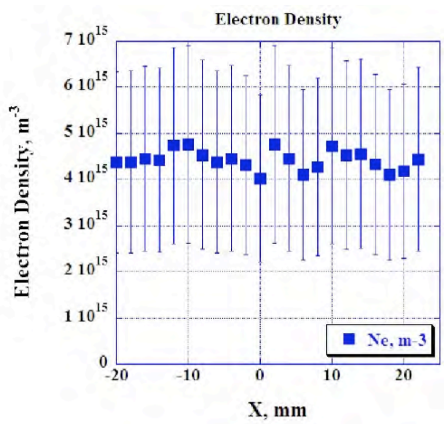
A. Langmuir probe measurements

Plasma parameters generated by the hall thruster were measured with a langmuir probe. The characteristics of the plasma parameters against the distance from the hall thruster surface are shown as follows. Figure 5-a and 5-b show the density variations in parallel and perpendicular to the flow direction, respectively. Uniform density distribution was evaluated within the 20mm radius between 120mm and 200mm downstream. Figure 5 shows the plasma density characteristics, Figure 6 shows the electron temperature and Figure 6 shows the plasma potential with respect to the chamber wall potential. These parameters were also evaluated with good uniformity.

We determined as a test section from 120mm to 200mm downstream. Typical temperature, density and plasma potential with respect to chamber wall potential were 5eV, 8×10^{15} m^{-3} and 20 V, respectively.



(a) Parallel to the flow direction



(b) perpendicular to the flow direction. 200mm downstream from plasma source

Figure 5. Plasma density distribution.

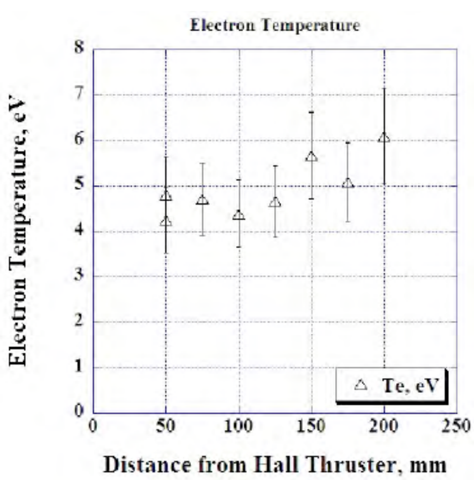


Figure 6. Electron temperature.

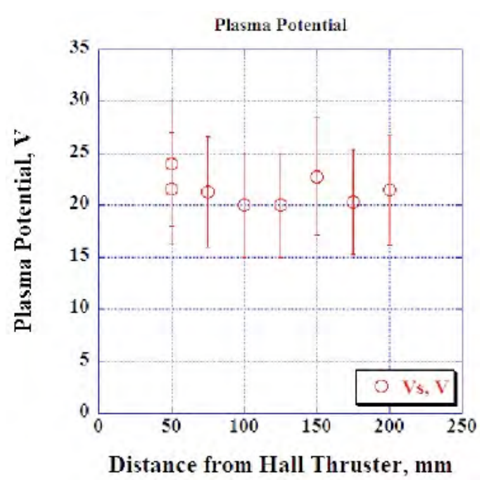


Figure 7. Plasma potential with respect to the chamber wall.

B. Ion drift energy measurement

High energy and speed particles are included in the plasma flow generated by the hall thruster. The ion energy distribution was measured with a Retarding Potential Analyzer (RPA). Figure 8 shows the picture and schematic structure of the RPA. The RPA is composed of an ion collector which has a negative potential and an energy analysis grid (G2) which has a positive potential. Only the ion which has higher energy than the energy analysis grid can go through the gird. The grid set in front of the ion collector (G3) reflect the secondary electrons from ion collector. The ion energy distribution is shown in Figure 9. As shown in the graph the ion energy peak of the ion flux was about 45eV (=15km/s).

In case of LEO and PEO environments, spacecrafts must travel at a speed of 7~8 km/s through dense ionospheric plasma. We use a similarity law to simulate the flowing condition in PEO. A non-dimensional length ξ and non-dimensional potential ϕ were defined by,

$$\xi = \frac{x}{U_i / \Omega} \tag{1}$$

and,

$$\phi = \frac{eV}{\frac{1}{2} M U_i} \tag{2}$$

Using the scaling law, the plate corresponds to 7.6m in PEO plasma with density of $2.0\times10^{10}\mathrm{m}^{-3}$, whose density is corresponds to 690km PEO plasma condition[10]. The bias voltage of -1kV corresponds to -75V in PEO. This plasma plume can provide a PEO plasma simulation condition.

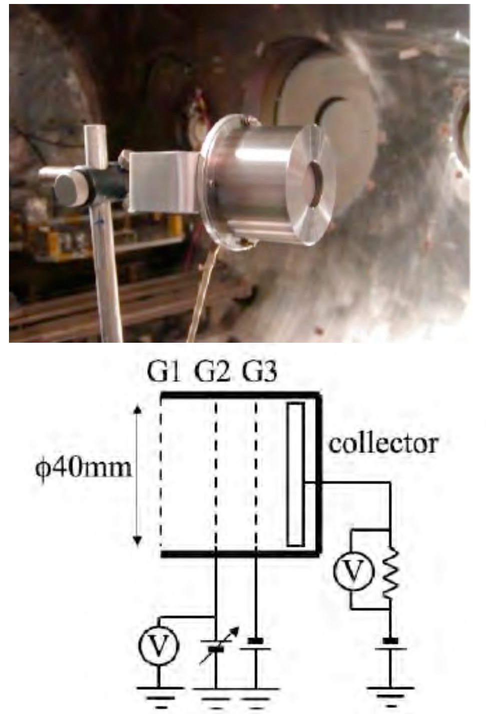


Figure 8. Retarding Potential Analyzer.

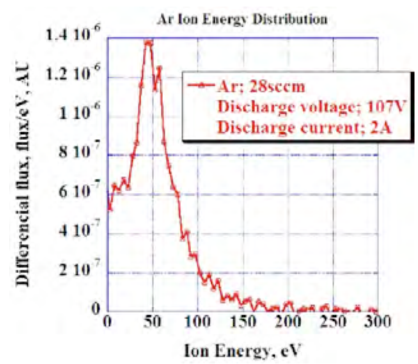


Figure 9. Ion energy distribution.

IV. Current collection and plasma potential distribution

An ion collector sample simulating solar array paddle was shown in Fig. 10. Ion collector side is a conductor plate (molybdenum, 44x44x0.5mm), and the other side is an insulator (boron, 44x44x1mm). This sample was attached a stepping motor via alumina rod. Rotating this motor, the angle of attack can be changed.

Figures 11 shows the video images taken during the experiment. Dark region appears near the bias electrode, showing the sheath boundary. In the wake mode (Fig.11-a) where the biased electrode is behind the plate, semi-spherical sheath expands toward the downstream. In the ram mode (Fig.11-b), planar sheath appears in front of the biased electrode.

Figure 12 shows the characteristic of the current collection. The circle symbols indicate the incident current at wake side. The triangle symbols indicate the current at ram side. The amount of the current collection in the wake mode is about one forth of that in the ram mode. The wake mode is more serious situation because the surface

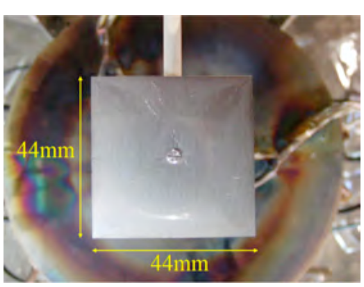


Figure 10. Ion collector.

(a) wake mode **(b) ram mode**

Figure 11. Video images of plate electrode during the experiments. The plasma flow is from the right to the left.

charging is hard to mitigate due to less current collection.

Figure 13 shows the potential distribution at the wake and ram mode measured by emissive probe. We can measure that the ion sheath in the wake mode is three times of that in the ram mode. Flowing ions captured by extended ion sheath.

MUSCAT simulation was carried out with the same plasma parameters as the experiment in the laboratory plasma generated by the hall thruster. Simulation domain was shown in Fig.14. One side of the plate is a conductor (44x44x1mm), and the other side is an insulator (44x44x5mm). Because it was hard to calculate a thin sample such as the laboratory sample, the thickness of the calculation sample was 6mm.

The current collection was compared between the result of the MUSCAT simulation and the laboratory experiment (Fig.15). Both results showed a good agreement.

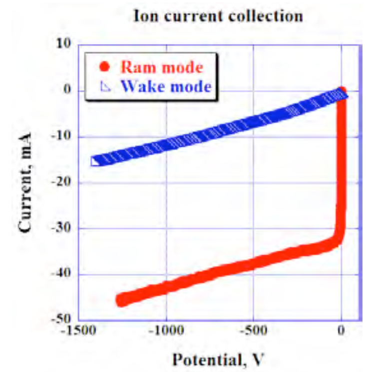
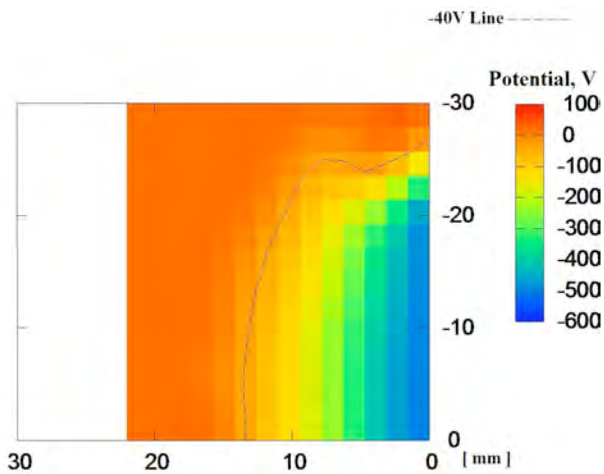
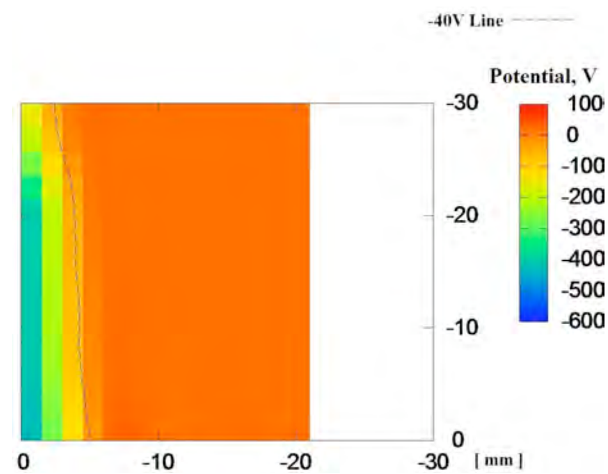


Figure 12. Ion current characteristics



(a) wake mode



(b) ram mode

Figure 13. Potential distribution measured by emissive probe. Horizontal axis indicates the distance from collector plate.

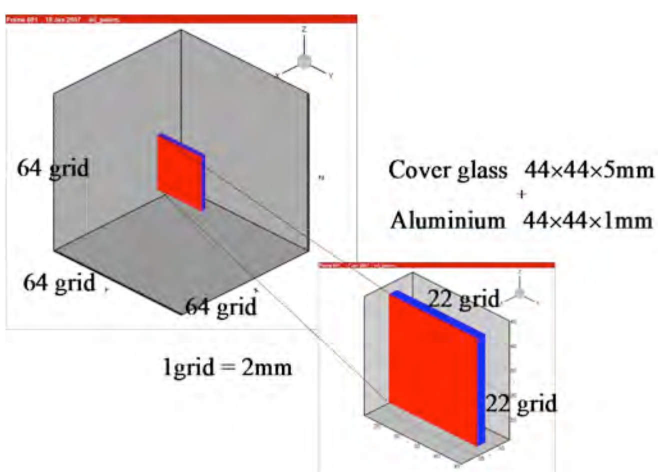


Figure 14. MUSCAT simulation domain

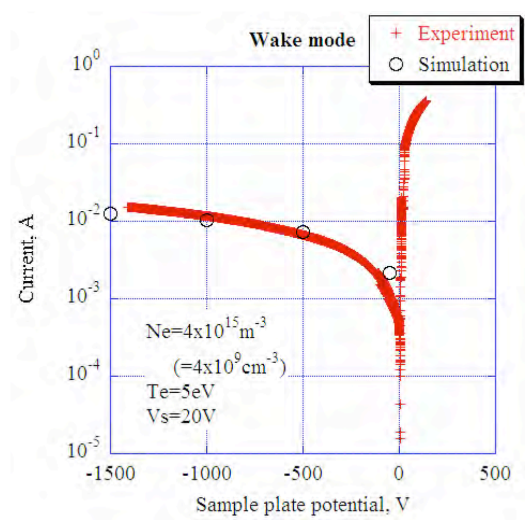


Figure 15. Comparison of current collection.

Figure 16 shows a potential distribution which was calculated with MUSCAT. The potential of the sample surface is -500V. The result of the MUSCAT simulation is very similar to the result of the laboratory experiment. The thickness of the sheath was almost equal. The plasma potential on the vertical line at the center of the sample was compared between the MUSCAT simulation and the laboratory experiment. Both plot curves agreed very well. Therefore it can be concluded that MUSCAT can calculate the basic plasma interaction with a spacecraft.

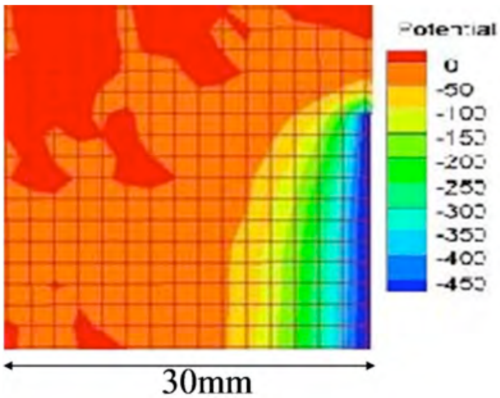


Figure 16. Calculated potential distribution.

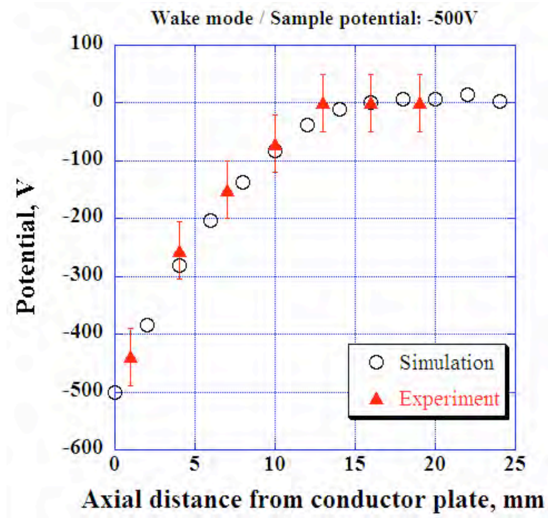


Figure 17. Comparison of plasma potential along the collector normal direction.

V.Conclusion

Development of MUSCAT, a spacecraft charging analysis software, started in November 2004 as a joint work of JAXA and KIT. Experiments for the code validation were made at ISAS/JAXA with hall thruster. We evaluate the charging in PEO plasma environment where low energy but dense ionospheric plasma and high energy but dilute aurora particles coexist. We measured the current collection characteristic and sheath formation on the wake side in flowing plasma environment. With respect to the wake charging experiments, similar sheath structures on the wake-side between experiment and simulation was confirmed. The current collection characteristic was well simulated to experiment result. These results support MUSCAT can simulate complicate absolute or differential charging in LEO, PEO or GEO environments.

After the development phase which was joint work by JAXA and KIT, MUSCAT has to be improved through practical use by satellite engineers. For the purpose, some of MUSCAT development team founded an enterprise named "MUSCAT Space Engineering Ltd" on September 2006. By the company, feed-backs from users are converged and MUSCAT is to be improved based on the feed-backs.

References

[1] Kawakita, S., Kusawake, H., Takahashi, M. et al., "Investigation of Operational anomaly of ADEOS-II Satellite," Proc. 9th Spacecraft Charging Technology Conf., Tsukuba, Japan, 4-8 April 2005.

[2]Nakamura, M., "Space Plasma Environment at the ADEOS-II anomaly," Proc. 9th Spacecraft Charging Technology Conf., Tsukuba, Japan, 4-8 April 2005.

[3]Usui, H., Omura, Y., Okada, M., Ogino, T., Terada, N., Murata, T., Sugiyama, T., Ueda, H., "Development of Geospace Environment Simulator," Proc. 9th Spacecraft Charging Technology Conf., Tsukuba, Japan, 4-8 April, 2005.

[4]Birdsall, C.K. and Langdon, A.B.: Plasma Physics via Computer Simulation, McGraw-Hill, New York, 1985.

[5]Muranaka, T., Hatta, S., Hosoda, S., Kim, J., Cho, M., Ueda, H., Koga, K., Goka, T., "Recent Progress of Development of Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT), " AIAA-2006-0408, 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, USA, 9-12 January 2006.

[6]Cho, M. and Hastings, D. E., "Dielectric Charging Processes and Arcing Rates of High Voltage Solar Arrays," J. Spacecraft and Rockets, Vol. 28, No.6, pp.698-706, 1991

[7]Muranaka, T., Hatta, S., Kim, J., Hosoda, S., Ikeda, K., Cho, M., Ueda, H., Koga, K., Goka, T., "FINAL VERSION OF

MULTI-UTILITY SPACECRAFT CHARGING ANALYSIS TOOL (MUSCAT)," 10th Spacecraft Charging Conference, Biarritz, France, 18-21 June 2007.

[8]Anderson, P.C., "A Survey of Surface Charging Events on the DMSP Spacecraft in LEO", Proceedings of 7th Spacecraft Charging Technology Conference, ESA, SP476, 2001, pp.331-336.

[9]Wahlund, J. E., Wedin, L., Carrozi, T., Eriksson, A. I, Holback, B., Anderson, L. and Laakso, H.,"Analysis of Freja Charging Events : Statistical Occurrence of Charging Events", ESA TECHNICAL NOTE, SPEE-WP130-TN, 1999.

[10]Mengu Cho, Jeongho Kim, Satoshi Hosoda, Yukishige Nozaki, Takeshi Miura and Takanori Iwata, "Electrostatic Discharge Ground Test of a Polar Orbit Satellite Solar Panel," IEEE Transactions of Plasma Science, Vol. 34, No. 5, pp.2011-2030, October, 2006.

[11]Kuninaka, H., "Space experiment on plasma interaction caused by high-voltage photovoltaic power generation," JOURNAL OF SPACECRAFT AND ROCKETS 1995, 0022-4650 vol.32 no.5 (894-898)