Development of Numerical Plasma Plume Analysis Module for Spacecraft Environment Simulator

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Abstract: A spacecraft charging analysis software called MUSCAT had been developed as a quantitative charging analysis tool in Japan. MUSCAT enables satellite engineers to simulate charging status of a spacecraft in Geosynchronous Orbit, Low Earth Orbit, and Polar Earth Orbit. In addition to the analysis of interaction between spacecraft and environmental plasma, MUSCAT has the optional module for plasma plume analysis for ion engine from a viewpoint of spacecraft contamination. Comparing with the experimental data validated the basic function of the analysis module. In this paper, we describe the concept of the plasma plume analysis for spacecraft charging, numerical model of the module, and fundamental validation of that is also shown.

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Nomenclature

n_b, n_n, n_{cex} = number density for the beam ions, the neutrals, and the charge exchange ions, respectively
n_{b0}, n_{n0}, $n_{\mathrm{cex}0}$ = number density for the beam ions, the neutrals, and the charge exchange ions at the thruster exit, respectively
n_0 = maximum number density of ions at the thruster exit
v_b = velocity of beam ions
σ_{cex} = cross section of charge exchange collision
ϕ = electric potential
T_e = electron temperature

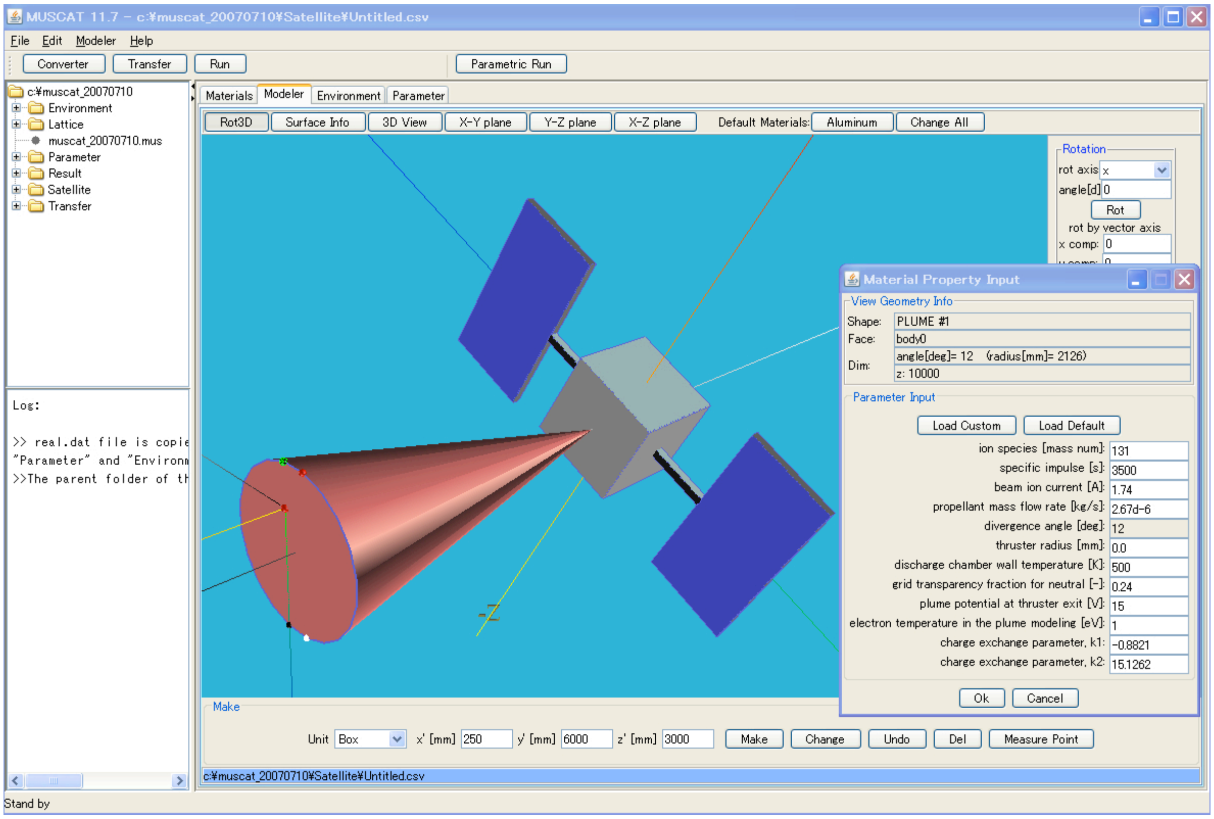
I. Introduction

SPACECRAFT-plasma interaction has become a crucial issue to a spacecraft operation during its lifetime because of charging-arcing problem. It is well studied that charging-arcing problem caused by the interaction between spacecraft and space environmental plasma brings about the degradation of spacecraft electric power. In Japan, the serious failure occurred to ADEOS-II, a large-scale Polar Earth Orbit satellite, in October, 2003. The satellite lost its total electric power in the accident, and the Japanese satellite engineers had found that the failure had been caused by charging-arcing problem afterwards.[1, 2] After the accident, development of a numerical software to analyze spacecraft charging qualitatively had been promoted by Japan Aerospace Exploration Agency. As a result, the software named Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT) [3-5] had been developed in March, 2007, as the next-generation charging analysis software in Japan. MUSCAT employs Graphical User Interface (GUI) for numerical input including three-dimensional satellite modeling. The MUSCAT solver can analyze spacecraft charging in Geosynchronous Orbit, Low Earth Orbit, and Polar Earth Orbit.[3-5] On the other hand, active plasma emission as ion engine thruster produce plasma environment around the spacecraft, and interactions between the spacecraft and the plasma have become much concern from a viewpoint of spacecraft contamination or charging. We decided to develop the optional module to analyze ion engine plasma plume behavior, and include it to MUSCAT. From the next section, the concept of the plasma plume analysis module of MUSCAT is described. The numerical model of the module and fundamental validation of the code are also shown.

II. Plasma Plume Analysis Module of MUSCAT

MUSCAT, a spacecraft charging analysis software in Japan, has an optional analysis module for ion engine plasma plume, which is independent of the main solver for charging analysis. This module is developed to analyze spacecraft contamination by plasma plume, in other words, to solve motion of slow charge-exchange (CEX) ions generated near a plasma thruster exit rather than that of fast beam ions. CEX collisions between fast beam ions and thermal slow neutrals of a propellant gas near a thruster exit produce slow CEX ions. The CEX ions tend to diffuse toward a spacecraft because of the electric potential gradient between a spacecraft and ion beam resulting in spacecraft contamination. Due to ambipolar diffusion of the CEX ions and the neutralized electrons, the spacecraft is surrounded by a plasma as dense as Low Earth Orbit.[6] In such a case, the parasitic power leakage from the solar array circuit to the plasma may become an issue. This optional solver enable satellite engineers to make quantitative analysis on spacecraft contamination and the power leakage. An additional GUI tool has been developed in the MUSCAT GUI tool to help the users to input the simulation parameters assuming an ion thruster as shown in Fig. 1. At present, the optional solver can treat only one thruster. In the GUI tool, the users specify the typical parameters for the ion thruster operation, such as ion mass number, specific impulse, beam ion current, propellant mass flow rate, beam divergence angle, etc.

Numerical simulation is performed for the CEX ions using an electrostatic PIC method [7] to solve particle position and electric potential in self-consistent manner. Beam ions and neutrals are treated as steady background particles, where spatial distributions of them are analytically described as functions of the distance from each virtual center of divergence and divergence angle.[8] The accelerator grid is assumed to be a spherical shell in the formulations.[8] The neutralizer electrons are modeled by the Boltzmann distribution.



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ion species [mass num]:	131
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thruster radius [mm]:	0.0
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grid transparency fraction for neutral [-]:	0.24
plume potential at thruster exit [V]:	15
electron temperature in the plume modeling [eV]:	1
charge exchange parameter, k1:	-0.8821
charge exchange parameter, k2:	15.1262

Unit: Box
x' [mm]: 250
y' [mm]: 6000
z' [mm]: 3000

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Figure 1. Additional GUI tool in the MUSCAT GUI tool for plasma plume analysis. *A cone-shaped plasma plume from a thruster exit is determined by the parameters of the location of the thruster, the diameter of the thruster, and the beam divergence angle.*

III. Numerical Model

The plasma plume solver aims to analyze slow CEX ions that participate in spacecraft contamination as mentioned above. Numerical simulation is performed for the CEX ions using an electrostatic Particle-In-Cell (PIC) method to solve particle position and electric potential in self-consistent manner. Beam ions and neutrals are treated as steady background particles, where spatial distributions of them are analytically described as functions of the distance from each virtual center of divergence and divergence angle.[8] Accel grid is assumed to be a spherical shell in the formulations.[8]

The number of CEX ions produced by collisions between beam ions and neutrals per unit time per unit volume is determined by the following equations.[9]

$$\frac{dn_{cex}}{dt} = n_b(x)n_n(x)v_b\sigma_{cex} = \frac{n_b(x)}{n_{b0}}\frac{n_n(x)}{n_{n0}}\left(\frac{dn_{cex0}}{dt}\right), \tag{1}$$

$$\frac{dn_{cex0}}{dt} = n_{b0}(x)n_{n0}(x)v_b\sigma_{cex}, \tag{2}$$

where n_b, n_n, n_{cex}, v_b, σ_{cex} mean the number density of beam ions, neutrals, and CEX ions, and the velocity of beam ions, the cross section of charge exchange collision between beam ions and neutrals, respectively. The parameters with suffix 0 stand for the same quantities at a thruster exit. The cross section of CEX collision is obtained by the following equation in m^2,

$$\sigma_{cex} = (k_1 \ln v_b + k_2)^2 \times 10^{-20}, \tag{3}$$

where k_1=-0.8821 and k_2=15.1262 for Xe-Xe$^+$ CEX collision.

Assuming the distribution of electrons to be Boltzmann distribution, the electric potential in the system is obtained by solving the following non-linear Poisson equation in iterative Newton-Rapson manner.

$$-\varepsilon_0 \nabla^2 \phi(x) = e\left(n_b(x) + n_{cex}(x) - n_0 \exp\left(\frac{e\phi(x)}{kT_e} \right) \right), \tag{4}$$

where e, ε_0, k, ϕ, n_0, T_e stand for elementary electric charge, vacuum permittivity, Boltzmann constant, electric potential, the maximum number density of ions at a thruster exit, the electron temperature, respectively. The electric potential on a satellite is fixed to be zero, and that at a thruster exit to be 15 V in the calculation, and Neuman condition is adopted as the boundary condition for the Poisson equation in this case.

IV. Numerical Result

As a validation of the plume analysis solver, numerical analysis was made for the T5 ion engine.[10] Table 1 shows the specifications of the T5 ion engine as input parameters. Typical Parameters were used for beam divergence angle and neutral permeability in addition to the experimental data. Numerical simulation was made for a simple cubic satellite model with the T5 ion engine. Figure 2 shows the numerical result of spatial distributions of CEX and beam ions for the T5 ion engine parameters. Diffusion of CEX ions around background beam ions was solved, and backflow of CEX ions to the spacecraft model was also recognized. Angular distributions of the ion density at distances of 30 cm and 60 cm from the thruster exit were compared between the numerical result and the experimental data shown in Fig. 3. Although envelope CEX ion densities are lower than experimental data, both were almost in good agreement with values of plasma density corresponding to beam ions and CEX ions.

Table 1. Specifications of the T5 ion engine.

Propellant Gas	Xe (M=130)
Thruster Diameter, cm	10
Mass Flow Rate, mg/s	0.808
Thrust, mN	27
Ionization Efficiency	0.77
Beam Ion Current, A	0.458
Avarage Exhaust Velocity, m/s	30940
Specific Impulse, s	3157
Beam Divergence Angle, deg	12
Neutral Permeability	0.24

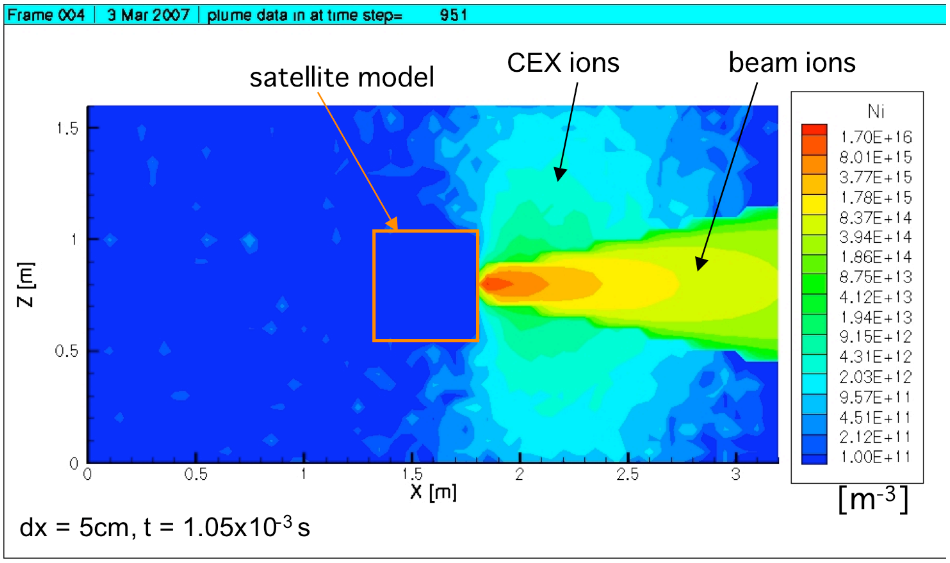

Figure 2. Numerical results of densities of CEX and beam ions. *Diffusion of CEX ions was recognized. Numerical domain was 64x32x32 grids, and satellite model was 10x10x10 grids. The result shows ion density including beam and CEX ions at 1.05 ms after the simulation started. The spatial width of the simulation is 5 cm.*

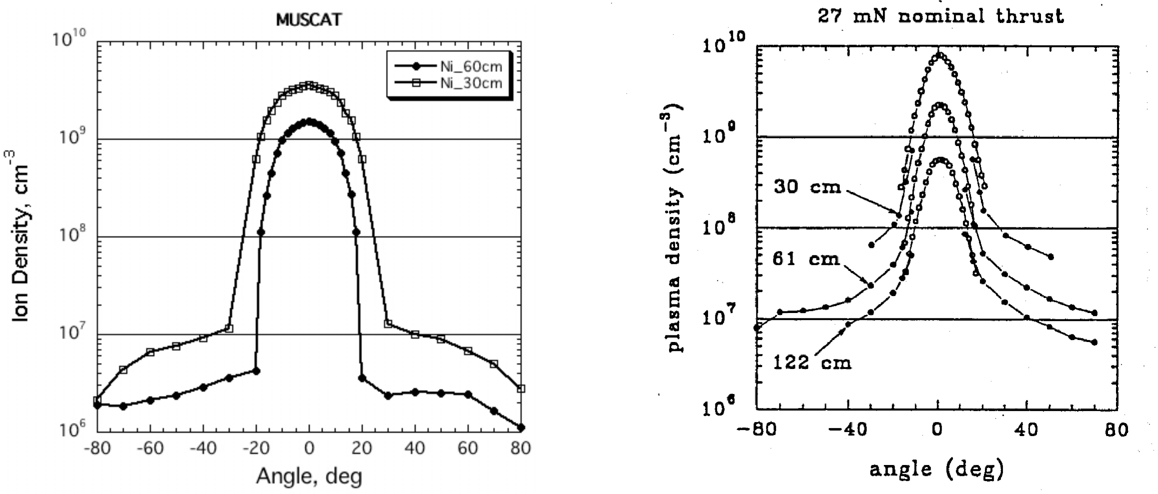

Figure 3. Comparison of plasma density between numerical result and experimental data at distances of 30cm and 60 cm from the thruster exit. (a) Numerical result of MUSCAT (left). (b) Reference experimental data of the T5 ion engine. Open symbols represent ion density, and closed symbols electron density (right).[10]

V. Conclusion

A plasma plume analysis code had been developed as the optional module for a spacecraft charging analysis tool, MUSCAT. An ion engine thruster generates plasma as dense as Low Earth Orbit around the spacecraft. Because of that, it is necessary to consider the influence of ion engine plasma plume on spacecraft environment.

The module can solve the motion of slow CEX ions that is crucial to spacecraft contamination or charging. The numerical function was validated by comparing the experimental result. Diffusion and backflow of the CEX ions were recognized in the simulation. Angular dependences for ion density at distances of 30 cm and 60 cm were compared with the experimental results. They were almost in good agreements in magnitude.

As a future work after the development of this module of MUSCAT, a three-dimensional full PIC code is being developed as a spacecraft environment simulator based on the large-scale PIC simulation code[11], which solves not only ions as a particle but also electrons. For plasma plume analysis, solving electrons as a particle enables us to simulate rapid electron response to a spacecraft potential and power leakage from the electric circuit of the solar arrays.

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