Particle-In-Cell Simulations on Electric Field Antenna Characteristics in Space Plasma

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We studied the electric field antenna characteristics by performing computer simulations. The characteristics of an electric field antenna immersed in space plasma are affected by complex plasma kinetic effects such as sheath formation and photoelectron emission. In order to include such plasma kinetic effects, we applied PIC (Particle-In-Cell) method to analyze the antenna characteristics. We particularly focused on the electric field antenna onboard future mission called SCOPE and considered the finite size of a conducting spacecraft body. We also considered the photoelectron emission from the electric field antenna or spacecraft body and investigated the dependence of antenna impedance characteristics on the photoelectron density profile around the antennas.

1. Introduction

The Solar Terrestrial Physics (STP) group in Japan has organized new magnetospheric mission named SCOPE (Scale COupling in Plasma universE) whose objective is to investigate the scale-coupling process of plasma dynamics in the Terrestrial magnetosphere. In the SCOPE mission, spin-axial electric field antennas are planned to be onboard in order to realize three-dimensional measurements of electric field. The spin-axial antennas need to be well short for the attitude stability and light weight. We have to investigate electric field antenna characteristics in space plasma considering spacecraft body effects for the design of such short antennas.

Antenna characteristics in plasma have been studied theoretically by many scientists (e.g. Balmain, 1964; Adachi et al., 1977; Kuehl et al., 1966). However, the analysis of the antenna characteristics is very complex because plasma is dispersive and anisotropic medium. In the previous theories, only simple dipole or monopole antenna model could be treated and approximations were hired in the current distribution or the sheath structure. Meanwhile, many scientists have investigated the antenna characteristics numerically with the FDTD (Finite Difference Time Domain) method. However, the FDTD method with a dielectric tensor obtained under the cold plasma approximation can not treat plasma kinetic effects.

To treat the plasma dynamics, we apply the PIC (Particle-In-Cell) method to the conventional FDTD method. In the PIC method, we solve equations of motion for each particle with the field components obtained at grid points. In the present paper, we will show preliminary results of antenna characteristics in the PIC simulations. We particularly focused on the electric field antennas including spacecraft body and investigated the photoelectron sheath effects on antenna impedance characteristics.

2. Simulations

2.1 Simulation Model

We use a three-dimensional electromagnetic particle code called KEMPO (e.g. Matsumoto and Omura, 1993). In three-dimensional simulation space we set electric field antennas and a spacecraft body as shown in Figure 1. We assume that the antennas and spacecraft body are pure conductors, which implies that electric field inside them is assumed to be zero. Meanwhile, joints between antennas and spacecraft body are assumed to be electrically insulated.

We perform two types of simulations. One is the ES (electrostatic) simulation focused on the photoelectron emission from the conducting bodies and the sheath formation around the antenna. In the simulation we solve a Poisson’s equation and equations of motion for charged particles. We emit electrons from sunlit surfaces of antennas and spacecraft body as shown in Figure 1. The emitted electrons are assumed to have a Maxwellian spectrum. In order to obtain the equipotential solution of the conducting bodies we correct the surface charge on the conducting bodies and electrostatic field corresponding to the charge correction by using Capacity Matrix Method (e.g. Hockney, 1970; Eastwood et al., 1979).

We run the simulation with sufficient time steps so that the amount of escaping and impinging photoelectron currents come to be balanced. The other is the EM (electromagnetic) simulation for antenna analysis, where we solve Maxwell’s equations and equations of motion. We use the photoelectron sheath environment created in the ES simulation and provide voltage of a Gaussian-type pulse at the two joints between antennas and spacecraft body. The induced current is obtained with the rotational field around the feed points. The antenna impedance is calculated as the ratio of the voltage to the current. To maintain the photoelectron environment in the EM simulation, we continue the electron emission and correction of the surface charge on the conducting bodies.
2.2 Photoelectron Sheath Formation

The left panels of Figure 2 show the density profiles of the photoelectron sheath around the antennas and spacecraft body obtained at the steady state of ES simulation. We assumed the arrival direction of sunlight as shown in Figure 1 and emit electrons from the upper antenna and the upper surface of spacecraft body. As clearly shown, photoelectron sheath is created around the upper antenna. We assumed that the photoelectron flux from the upper surface of spacecraft body is higher than the sides of upper antenna because sunlight arrives along z-axis. Therefore, the photoelectron density around the upper surface of spacecraft body is high compared with the density around the upper antenna.

2.3 Photoelectron Sheath Effect on the Antenna Impedance

We examined the antenna impedance for the created photoelectron environment. The right panel of Figure 2 shows the imaginary parts of the antenna impedance. The solid and dash-dotted lines correspond to the impedance of upper and lower antennas, respectively. The dashed line corresponds to the impedance for the vacuum case. As shown clearly, there is a large change of the impedance of the upper antenna. This change is caused by the enhancement of electron density by photoelectron sheath. We can find that the enhancement of impedance occurs around the characteristic frequency

\[
\omega_{ph} = \sqrt{\frac{n_{ph}e^2}{m_e\epsilon_0}}
\]

where \(n_{ph}\) represents the photoelectron number density at the surface of upper antenna. It is clearly shown that there is a change of the impedance below the characteristics frequency \(\omega_{ph}\), while there is little change above \(\omega_{ph}\) compared with the vacuum case. The photoelectrons can follow the time variation of electromagnetic field with frequency below \(\omega_{ph}\) and can interact with electromagnetic field, which results in the modification of antenna impedance. However, the photoelectron cannot follow the time variation of field with frequency above \(\omega_{ph}\) and cannot interact with electromagnetic field. Therefore, the impedance characteristics above \(\omega_{ph}\) are not affected by photoelectrons.

Meanwhile, there is also a slight difference of impedance of the lower antenna compared from the vacuum case. It is because of the presence of low density photoelectrons in the vicinity of the lower antenna.

3. Conclusions

We first applied three-dimensional electromagnetic PIC simulations to study the electric field antenna characteristics considering the spacecraft body. We particularly focused on the plasma kinetic effects on the antenna impedance such as photoelectron emission. We confirmed the photoelectron sheath formation around the sunlit antenna by performing the electrostatic simulation. Secondly we examined the photoelectron sheath effect on antenna impedance characteristics by performing the electromagnetic simulation. We could confirm the large change of impedance of upper antenna below the characteristic frequency. The characteristic frequency corresponds to the density of local photoelectrons, which implies that the change of impedance was caused by photoelectron sheath. Although the above results are preliminary, we confirm that the antenna analysis including spacecraft body or photoelectron sheath effect by performing electromagnetic PIC simulations basically works. We will be able to examine the antenna characteristics including the more realistic antenna configurations and plasma environments, which is left as a future work.

Acknowledgments. Computation in the present study was performed with the KDK system of Research Institute for Sustainable Humanosphere (RISH) at Kyoto University as a collaborative research project.

References


