Analysis of Receiving Antenna Characteristics in Space Plasma Environment via Particle-In-Cell Simulation

***Yohei Miyake*[1], *Hideyuki Usui*[1], *Hirotsugu Kojima*[1], *Yoshiharu Omura*[1]**

[1]Research Institute for Sustainable Humanosphere, Kyoto University. Gokasho, Uji, Kyoto 611-0011, JAPAN.
E-mail: y-miyake@rish.kyoto-u.ac.jp

Abstract

For investigation of receiving antenna behaviors in space plasma, inhomogeneous plasma environment resulting from antenna-plasma interactions should be taken into consideration. To include effects of such inhomogeneity in self-consistent manner, we applied the electromagnetic Particle-In-Cell simulations to the analysis of receiving antenna characteristics. In the analysis, we set up external waves in a simulation region and receive them with the antenna placed in the simulation region. Using this method, we evaluated the effective length of antennas aboard scientific spacecraft. We particularly focused on effects of an ion sheath and a photoelectron cloud created around the antennas.

1. Introduction

Understanding of electric field antenna characteristics (e.g., effective length and impedance) in plasma environment is important because electric field measurement using electric field antennas is very common in plasma wave investigations with scientific spacecraft [1]. However, due to complex behavior of the surrounding plasma, it is often difficult to apply theoretical approaches to the analysis of practical antenna characteristics including effects of the plasma kinetics. One of the important points to be considered is the inhomogeneous plasma distribution around the antenna. In many previous works (e.g., [2]), an antenna is assumed to be an ideal thin conductive wire, totally transparent to the fluid plasma medium. However, an antenna is made of a solid body and plasma particles which impinge the body are absorbed and contribute to the antenna charging, which leads to the formation of an ion sheath.

In the current study, we applied the electromagnetic Particle-In-Cell (EM-PIC) plasma simulation to the complex antenna analysis in space plasma [3, 4]. By using the PIC modeling, we can self-consistently consider the plasma kinetics. This enables us to automatically include effects of inhomogeneous plasma environment such as a sheath created around the antenna. We particularly modeled situations of electrostatic/electromagnetic-wave reception by an antenna aboard scientific spacecraft. By using this model, we examined the effective length of the antenna.

2. EM-PIC Simulation Tool for Antenna Analysis

We have developed a numerical tool for the analyses of antenna characteristics in plasma environment by making the most use of the EM-PIC plasma simulations [4]. In the tool, Maxwell's equations for fields and equations of motion for charged particles are solved as basic equations. By this treatment, plasma kinetic effects are reflected in the field evolution in a self-consistent manner. To analyze the antenna characteristics, we have introduced the numerical model of solid bodies corresponding to the antenna and the spacecraft as inner boundaries in the simulation system. In the present code, we can treat body surfaces made of perfect conductors, in which the electric field should be zero. To obtain an equipotential solution over the conductive surfaces, we redistribute the surface charge by using Capacity Matrix method [5] and correct the electrostatic field by solving Poisson's equation in consideration with the modified surface charge. We also implemented a function that handles electron emission from the conducting surfaces in order to simulate photoelectron emission [3].

The developed method was validated by evaluating the impedance of a dipole antenna under a simple condition that the plasma is homogeneous and unmagnetized, and the Debye length is smaller than the antenna length. Fig. 1 shows an example of an impedance result for a case of $L_a = 24\lambda_D$, where L_a and λ_D represent the antenna total-length and the local Debye length, respectively. We confirmed impedance resonance near ω_p, where ω_p represents the electron plasma frequency. Finite resistance and increased capacitance values were also confirmed below ω_p. These behaviors are basically consistent with past theoretical results [2]. From these basic properties, we confirmed that the present code can correctly reproduce the plasma dynamics in the vicinity of the conductive antenna with the evolution of electromagnetic field.

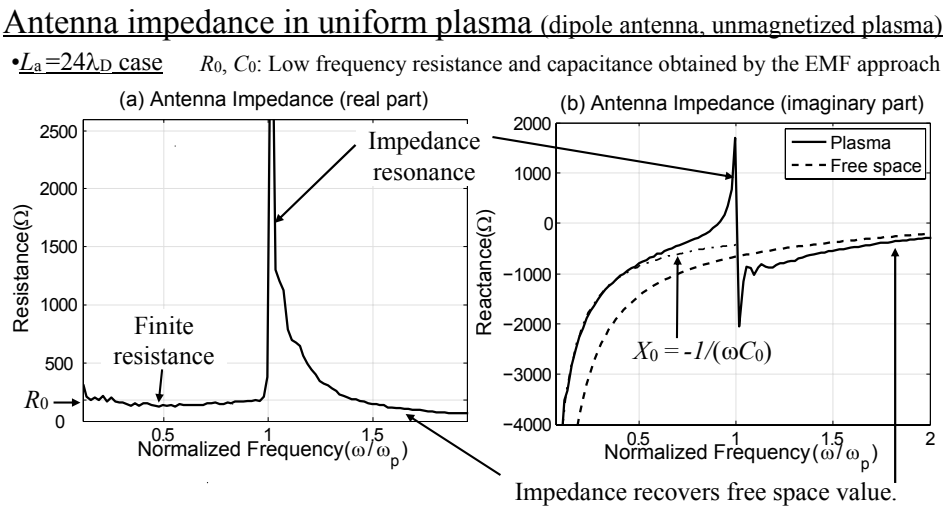
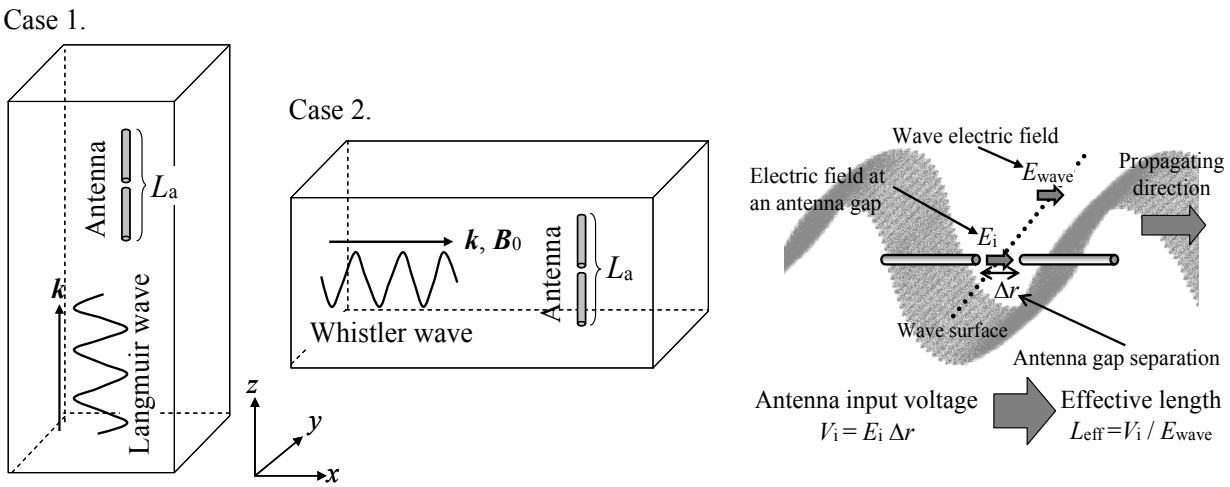


Figure 1. Code check by evaluating the antenna impedance in unmagnetized, homogeneous plasma.

3. Simulation Model

Fig. 2 shows the model of the current analysis. In the model, we initially set up external plane waves that propagate in the 3-dimensional simulation region. We also placed a wire dipole antenna in the center of the simulation region. In the current study, we examined the effective lengths in receiving the Langmuir and Whistler waves as electrostatic and electromagnetic wave modes, respectively. For the Langmuir wave setting, we initially modulated density and velocities of background electrons contained in the simulation region, so that a sinusoidal profile of electrostatic potential is created. In the current study, we set the Langmuir wave with a long wavelength $\lambda = \sim 21.3L_a$. The antenna was aligned with the wave number vector of the Langmuir wave. An observation frequency is obtained from the wavelength λ by using the dispersion relation of the Langmuir mode. For the Whistler wave setting, we initially set the static magnetic field $\boldsymbol{B}_0$ along the propagation direction and wave electric/magnetic fields. We also modulated electron velocities sinusoidally. Also in case of Whistler wave, we treated a long wavelength $\lambda = \sim 21.3L_a$. As shown in the middle panel of Fig.2, the antenna axis was set vertically with respect to the wave number vector for the reception of the Whistler wave. For both cases, the background plasma was composed of electrons and protons, and λ_D was set to 0.25 L_a. In each simulation run, we observed values of the wave electric field E_{wave} and the electric field E_i induced at a gap between two antenna-body elements. The input voltage V_i at the antenna gap can be calculated as $E_i \Delta r$, where Δr represents the spatial grid width. The effective length L_{eff} is obtained as the ratio V_i / E_{wave}.



3-dimensional simulation region filled with background plasma Analysis of the effective length

Figure 2. Simulation model for the analysis of effective length.

4. Simulation Results

We here present several preliminary results. We first examined the effective length excluding effects of a sheath or a photoelectron cloud. For this aim, we used the "transparent" antenna modeling, in which plasma particles can pass through the antenna location. In the model, antenna charging and formation of an ion sheath do not occur automatically. By using the model, we run a simulation for an antenna with the length $L_a = 24$ measured in the simulation unit system. Fig. 3 shows a simulation result for a case of the Langmuir-wave reception. The left and right panels show the profiles of observed wave electric field E_{wave} and antenna input voltage V_i, respectively. Note that, in plotting profiles shown in Fig. 3, we used the synchronous detection technique in order to extract only a signal component at the wave frequency.

As shown in Fig. 3, a sinusoidal waveform is obtained as the antenna input voltage, which confirms that we successfully simulated the wave reception by the antenna. As the ratio between the amplitudes of E_{wave} and V_i, the effective length is obtained as $L_{eff} = 11.3 = 0.47L_a$, i.e., the effective length approximately coincides with the half of the dipole physical length. Although not shown in detail here, the same result was obtained for a case of the Whistler wave in absence of sheath or photoelectron effects. These results are basically consistent with past knowledge [6] as the effective length of the electrically short dipole antenna.

Because the electrostatic wave such as the Langmuir wave is described by the electrostatic potential, we can interpret the above result of the effective length from the potential profile. Fig. 4 shows the snapshot of the potential profile along the antenna axis. The left and right panels show the 1- and 2- dimensional profiles of the potential in the vicinity of the antenna. In the 1-dimensional profile, the solid and dashed lines represent profiles on the antenna axis and a position apart from the antenna location, respectively. The dashed line has a gradient that is caused by the

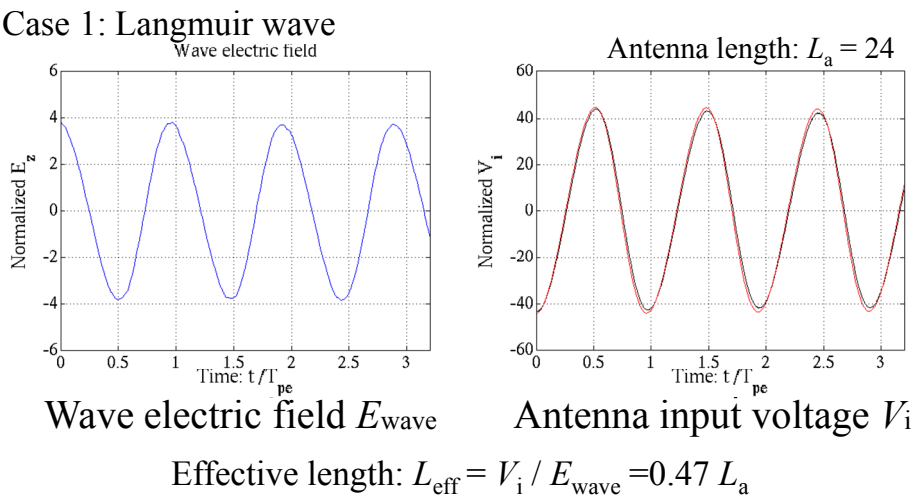


Figure 3. Time profiles of wave electric field (left panel) and antenna input voltage (right panel).

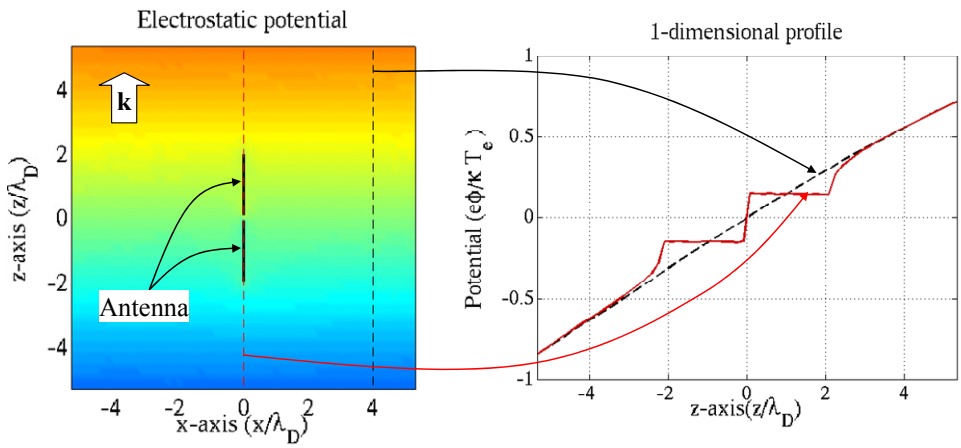


Figure 4. Snapshot of the electrostatic potential in the vicinity of the antenna.

Langmuir wave potential. For the solid line, since the antenna consists of two perfect conductive bodies, the equipotential values are measured on the location of each antenna body. On the other hand, the gap between two conductive bodies is electrically insulated, and thus each body can have an independent potential value. The observed V_i equals to the potential difference between two antenna bodies. By comparing the solid and dashed lines, we can find that each antenna body picks up the wave potential at nearly the midpoint of the body. From this, we can understand the result that the effective length coincides with the half of the antenna total length.

5. Summary

We successfully developed the method for the evaluation of the antenna effective length by using the EM-PIC plasma simulation technique. In the simulation, we set incident plasma waves propagating in the simulation region, and then the antenna placed in the center of the region receives the wave. As a preliminary result, we confirmed that the effective length coincides with the half of the dipole physical length in absence of sheath and photoelectron effects. We need further analysis for propagation near the Whistler resonance cone, because the effective length has been reported to become much different from the half of the dipole physical length in the situation [1]. We have started the analysis on the influence of an ion sheath and a photoelectron cloud that are created in the vicinity of the antenna. For this aim, we treated the antenna as solid bodies, which absorb impinging particles and emit photoelectrons, and implemented the numerical model of the antenna charging. It was confirmed that an ion sheath and a photoelectron cloud are successfully created in the self-consistent manner for cases in absence and presence of photoelectron emission, respectively. The effects of such inhomogeneous plasma environment on the antenna characteristics will be reported. We will also report results for not only simple dipoles but also antennas with complex structure such as MEFISTO, which is an electric field instrument for BepiColombo/MMO [7].

6. 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. The work was supported by Grant-in-Aid for Research Fellows of the Japan Society for the Promotion of Science (JSPS).

6. References

1. H. G. James, “Dipole Measurements of Waves in the Ionosphere,” *Lect. Notes Phys.*, **687**, 2006, pp. 191-210.

2. M. L. Schiff, “Impedance of a Short Dipole Antenna in a Warm Isotropic Plasma,” *Radio Sci.*, **5**, 1970, pp. 1489-1496.

3. H. Usui, Y. Miyake, M. Okada, Y. Omura, T. Sugiyama, K. T. Murata, D. Matsuoka, and H. O. Ueda, “Development and Application of Geospace Environment Simulator for the Analysis of Spacecraft-Plasma Interactions,” *IEEE Trans. Plasma Sci.*, **34-5**, 2006, pp. 2094-2102.

4. Y. Miyake, H. Usui, H. Kojima, Y. Omura, and H. Matsumoto, “Electromagnetic Particle-In-Cell Simulation on the Impedance of a Dipole Antenna Surrounded by an Ion Sheath,” submitted to *Radio Sci.*, 2007.

5. R. W. Hockney and J. W. Eastwood, *Computer Simulation Using Particles*, New York, McGraw-Hill, 1981.

6. D. A. Gurnett, “Principles of Space Plasma Wave Instrument Design,” *AGU Geophys. Monograph*, **103**, 1998, pp. 121-136.

7. L. G. Blomberg, H. Matsumoto, J.-L. Bougeret, H. Kojima, S. Yagitani, J. A. Cumnock, A. I. Eriksson, G. T. Marklund, J.-E. Wahlund, L. Bylander, L. Åhlén, J. A. Holtet, K. Ishisaka, E. Kallio, Y. Kasaba, A. Matsuoka, M. Moncuquet, K. Mursula, Y. Omura, and J. G. Trotignon, “MEFISTO – An Electric Field Instrument for BepiColombo/MMO,” *Adv. Space Res.*, **38**, 2006, pp. 672-679.