Particle-in-Cell Simulations on Interferometry Technique by a Single Spacecraft

Ibuki Fukasawa, Yohei Miyake, Hideyuki Usui, Koshiro Kusachi, Satoshi Kurita, and Hirotsugu Kojima

Abstract – Interferometry observations by a single spacecraft can be used to obtain the phase velocities of plasma waves in space. Such observations use the electric field waveforms picked up by two monopole electric field sensors. The phase velocity is obtained from the phase difference of waveforms received by these sensors. Here, we performed three-dimensional full particle-in-cell simulations to evaluate the interferometry technique applied to the Langmuir waves excited by bump-on-tail instability. The sensor elements in our simulations are simple conductive rods with a particular length. Although each element picks up plasma waves by its whole part, our simulation results showed that the phase difference between the waveforms received by the two monopole sensors is consistent with the phase difference at two points on the elements, with a distance that is almost equal to the sensor's center-to-center distance.

1. Introduction

To understand the generation and propagation of plasma waves in space, it is important to determine properties, such as phase velocities and wavenumber vectors. The interferometry technique is one of the methods to obtain such wave properties through spacecraft observations. Because interferometry provides the phase difference between target waves at different spatial points, the velocity of the wavefront can be calculated based on the distance between observation points. The interferometry observations in space are applicable for multipoint observations by a number of spacecraft, as well as observations by single spacecraft. Although the interferometry by multispacecraft is effective for plasma waves with long wavelengths, the technique by a single spacecraft can be applicable for plasma waves with relatively short wavelengths, such as electrostatic waves. Interferometry observations by a single spacecraft often use monopole electric field sensors [1–4]. Waveforms picked up by two monopole electric field sensors can be used to identify the phase difference between two observation points on each element of the sensors. The phase difference and distance between observation points provide the phase velocities of the target waves. However, the complexity of the electric field observations introduces uncertainty. For example, the distance between observation points depends on the type of electric field sensors, such as wire types or boom types. Furthermore, the existence of spacecraft bodies, as well as electric field sensors, could cause distortions of electric field wavefront. Evaluations based on realistic models of plasma environments that include the spacecraft body are important for obtaining precise phase velocities from observations.

Computer simulations are effective tools to simulate space environments considering realistic parameters. The present study shows the success in realizing the interferometry observations using a full-particle model, including electric field sensors in the simulation box. Two individual wire-type electric field sensors installed inside the simulation box pick up electric fields of beam-excited Langmuir waves. The results are very reasonable in the realistic model under the existence of electric field sensors. They show the features of the wavefront of the Langmuir waves around the sensors and determine the distance between two observation points on each sensor element by calculating phase differences of waveforms received by two monopole sensors.

2. Simulation Model

The present study uses the electromagnetic spacecraft environment simulator (EMSES) [5]. EMSES is a full-particle simulation code based on the three-dimensional particle-in-cell (PIC) method. Detailed specifications and features of EMSES are presented in previous articles [5, 6]. To simulate electric field sensors, we introduce a pair of two conductive solid bodies as sensor elements with inner boundaries. Electric fields are picked up by the individual elements. The waveforms received by each element can be used to obtain phase velocities by calculating the phase difference between them. The Langmuir waves excited by the bump-on-tail instability of electrons are used to evaluate the interferometry technique in the simulation model.

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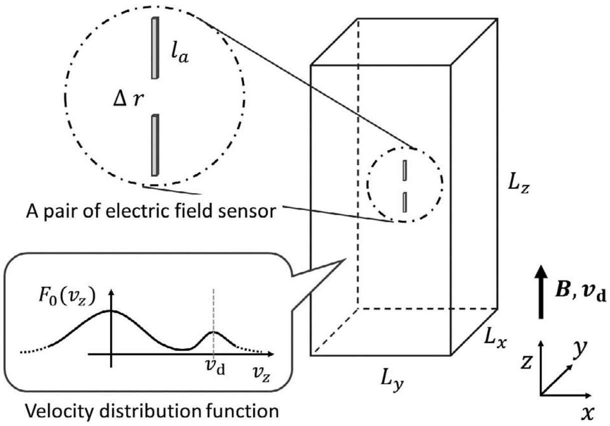

Figure 1. Three-dimensional simulation model used in the present analysis.

Figure 1 shows the simulation model. The boundary conditions at all six boundaries of the simulation box are periodic. Two individual conductive rods located in the center of the simulation box are equivalent to two monopole electric field sensor.

The two waveforms picked up by each monopole sensor provide the time difference (Δt_ϕ) as

$$\Delta t_\phi = \Delta\phi/(2\pi f) \tag{1}$$

where $\Delta\phi$ is the phase difference between two waveforms with fixed frequency f. From the time difference Δt_ϕ and the distance between the observation points L on the sensor elements, the phase velocity v_ϕ can be calculated as follows:

$$v_\phi = L/\Delta t_\phi \tag{2}$$

Note that the length L contains uncertainty in spacecraft observations, because it depends on the type of electric field sensors.

Because the phase velocity v_ϕ for the excited Langmuir waves and the time difference Δt_ϕ can be obtained from computer simulations, the equivalent distance L_eq can be calculated from the simulation results as

$$L_\mathrm{eq} = v_\phi \Delta t_\phi \tag{3}$$

Table 1. Simulation parameters

Parameter	Explanation	Value
Δt	Time step	$0.03\omega_\mathrm{pe}^{-1}$
Δx	Grid spacing	$0.006c\omega_\mathrm{pe}^{-1}$
L_x, L_y, L_z	System dimensions	$8\ \lambda_\mathrm{D}$, $8\ \lambda_\mathrm{D}$, $64\ \lambda_\mathrm{D}$
$m_\mathrm{i}/m_\mathrm{e}$	Mass ratio	1836
Ω_ce	Electron cyclotron frequency	$0.33\omega_\mathrm{pe}$
v_the	Electron thermal velocity	$0.024c$
v_d	Electron beam velocity	$0.4c$
$n_\mathrm{b}/n_\mathrm{e}$	Density ratio of beams to background electrons	0.005
l_a	Sensor length	$1.5\lambda_\mathrm{D}$
Δl_w	Sensor width in x and y directions	$0.125\lambda_\mathrm{D}$
Δr	Distance from one end of sensor to other	$0.5\lambda_\mathrm{D}$

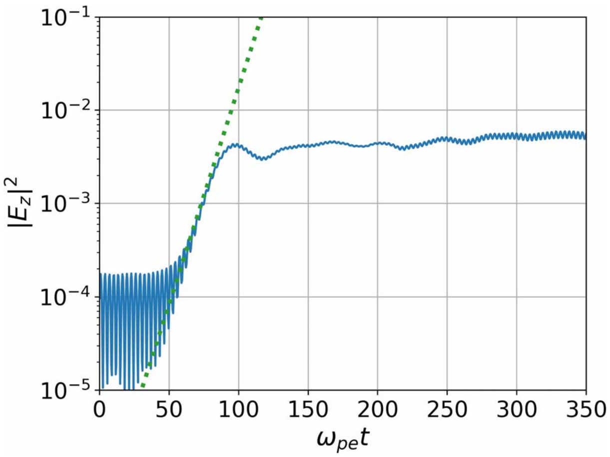

Figure 2. Time evolution of electric field energy for the Langmuir wave mode for $n_\mathrm{b}/n_\mathrm{e} = 0.005$. The dotted line represents the linear growth rate.

Table 1 lists the parameters used in the present simulation. All frequencies are normalized by the electron plasma frequency $\omega_\mathrm{pe} = (n_\mathrm{e}e^2/m_\mathrm{e}\varepsilon_0)^{1/2}$, where n_e is the electron number density, e is the elementary charge, and m_e is the electron mass, respectively. The simulation uses the realistic mass ratio of ions to electrons. The grid spacing is $\Delta x = 0.006c\omega_\mathrm{pe}^{-1}$, where c is the speed of light. The simulations ran for a total of 120,000 steps with $\Delta t = 0.03\omega_\mathrm{pe}^{-1}$. We define the length of one sensor element as l_a. The system length in the z direction is $L_z = 64\lambda_\mathrm{D}$, where λ_D is the Debye length.

The ambient magnetic field lies along the z direction. Langmuir waves are generated by the bump-on-tail instability, with a weak electron beam along the z direction. The background plasma and the electron beam are described by isotropic Maxwell and shifted Maxwell velocity distribution functions, respectively. The electron drift velocity is $v_\mathrm{d} = 16.67v_\mathrm{the}$. The density ratio of the beams to background electrons is given by $n_\mathrm{b}/n_\mathrm{e} = 0.005$, where n_b is the electron beam density.

3. Simulation Results and Discussion

The implementation of Langmuir waves in the simulation was checked by comparing the time evolution of the wave electric fields and the linear growth rate of the bump-on-tail instability of the Langmuir waves. Figure 2 shows the time evolution of the electric field energy for $|E_z|^2$. Note that there is no electric field sensor inside the simulation box in this case. The increase of the wave energy in the simulation agrees well with the linear growth rate shown by the dotted line. The phase velocity of the Langmuir wave in this simulation was calculated to be $v_\phi = 0.28c$. The wavelength of the Langmuir wave is about 50 times longer than the sensor element length. As shown in Figure 2, the linear growth almost stops around $\omega_\mathrm{pe}t =$

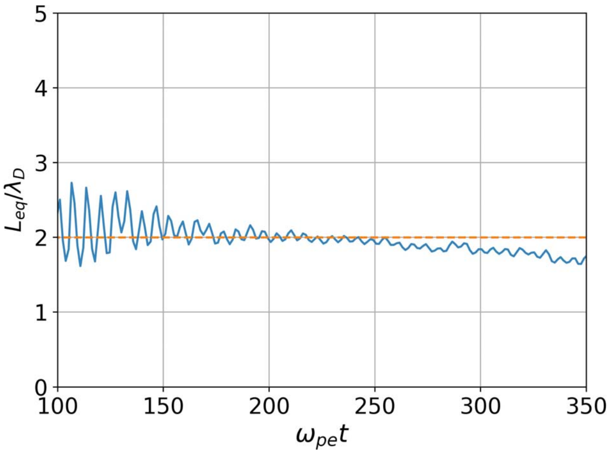

Figure 3. Time variation of L_{eq}. The dashed line represents the sensor center-to-center distance.

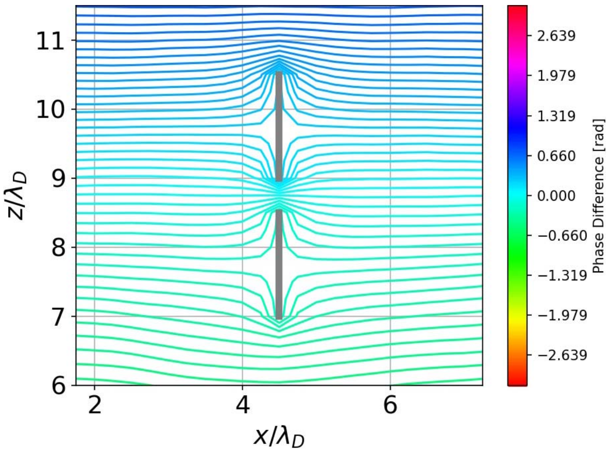

Figure 4. Wavefront lines for Langmuir waves at $\omega_{\mathrm{pe}}t = 225$.

100. Therefore, in the present analysis, we use the data in the time period after $\omega_{\mathrm{pe}}t = 100$.

Calculations of the time difference between the waveforms picked up by the two monopole sensors were conducted using the short-time Fourier transform (STFT). First, the STFT was applied to the waveforms of the voltages induced on each sensor rod, and the phase difference $\Delta\phi_{\mathrm{s}}$ was calculated from the Fourier spectra. The time difference was calculated from the phase difference and the angular frequency of the target wave using (1). By using the STFT, the phase difference can be determined in frequency space. The phase velocity of the Langmuir wave is obtained from electric field data at two spatial points separated by grids near the sensors. We obtained the equivalent length L_{eq} by (3).

Figure 3 shows the time variation of L_{eq} calculated from the phase difference between the Langmuir waveforms picked up by the two monopole sensors for the time period from $\omega_{\mathrm{pe}}t = 100$ to 350. The dashed line in Figure 3 represents the sensor's center-to-center distance. As shown in Figure 3, L_{eq} fluctuates from $\omega_{\mathrm{pe}}t = 100$ to 150. The fluctuations could be due to the unsteady state of the wavefront in the exited Langmuir waves. However, the time variation focuses around the sensor's center-to-center distance after $\omega_{\mathrm{pe}}t = 150$.

To interpret this result, we show a snapshot of the equiphase surface, which is equivalent to wavefront, of the Langmuir waves at $\omega_{\mathrm{pe}}t = 225$ in Figure 4. The two thick gray line segments in the center of the figure along the z-axis represent the sensor position. From Figure 4, it is evident that the equiphase surfaces in each element are line symmetric with respect to a straight line (not shown in the figure) along the x direction through the midpoint of each element. This result is consistent with Figure 3, which demonstrates that the equivalent length (L_{eq}) is almost equal to the sensor's center-to-center distance.

Figure 3 also shows a gradual decrease in L_{eq}. The reason for this trend is still unclear. It might be caused by the interaction between plasmas and sensor elements. However, explaining this trend is important in precisely interpreting the observation results of spacecraft. Detailed simulations are required to clarify this decreasing trend of the equivalent length.

4. Conclusions

In the present study, we performed three-dimensional full PIC simulations to evaluate the interferometry technique by a single spacecraft. For interferometry observations by a single spacecraft conducted with two monopole sensors, there is uncertainty in the distance between the points, where each sensor element detects the phases of the target waves. Our simulations deal with two monopole electric field sensors in the presence of beam-excited Langmuir waves. The simulation results show that the equivalent length for observing the Langmuir waves is almost equal to the sensor's center-to-center distance. The feature of equiphase surfaces around each sensor element is consistent with the estimated equivalent length.

Our study regarding the interferometry technique started with the simple sensor model to examine the validity of the simulation models. The EMSES simulation code used in the present study has the capability to deal with spacecraft bodies inside the simulation box. Our next goal in the simulation is to unveil the effects of spacecraft bodies to the equivalent length. Furthermore, in real spacecraft observations, the spacecraft may be spinning, and the wavefront is not always perpendicular to the sensors. We will also examine these realistic situations. Another important goal is to clarify the dependence of the equivalent length on the relation between the sensor element length and the wavelength of target waves because the length of an electric field sensor could be comparable to electrostatic waves in space.

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