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Particle-In-Cell Modeling of CubeSat Interaction with Ionospheric Plasma

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Abstract. We numerically investigate the interaction between a nanosatllite CubeSat and surrounding plasma. The present study aims to elucidate particular issues related to nanosatllite-plasma interaction which affects the on-board instruments by using particle-in-cell simulations. The numerical results of the present study demonstrate the importance of several key physical processes in nanosatellites-plasma interaction. In particular, it is shown that plasma flow, ion composition, and the geomagnetic field have a strong impact on the Langmuir probes.

Keywords. CubeSat, particle-in-cell, nanosatellites

1. Introduction

The Dynamics Ionosphere CubeSat Experiment (DICE) mission funded by the National Science Foundation (NSF) and NASA Educational Launch of Nano-satellites (ELaNa) programs was launched on October 27, 2011. It consists of the two identical nanosatellites "CubeSats" which were released into an eccentric low Earth orbit. Each payload carries two identical Langmuir probes to measure in-situ ionospheric plasma parameters (Fish *et al.* 2014). For in situ measurements of space plasma, Langmuir probes have been extensively used on sounding rockets and satellites (Gurnett *et al.* 2004; Lebreton *et al.* 2006). Some numerical models have been presented to investigate the essential physical factors that are at play in the interpretation of the Langmuir probe data carried by the satellites (Imtiaz & Marchand 2015; Marchand 2016). For nanosatellites, Albarran (2015) employed the SPIS simulations to understand the interaction between the CubeSat and surrounding plasma. In this study the focus is on the importance of accurately accounting for the attitude and boom size in order to derive the ambient plasma density from spin-modulated Langmuir probe measurements on CubeSats. However, it does not account for the effect of the geomagnetic field and the ionic composition. The goal of the present study is to improve earlier approaches and enable a better interpretation of Langmuir probe measurements on CubeSats. This is accomplished by carrying out fully kinetic simulations of the interaction between a CubeSat and space environment, while accounting for the effects not included in previous studies, that is including the local geomagnetic field and ion composition. For this purpose we use the particle-in-cell simulation code 'PTetra' which is capable of simulating the time dependent interaction between a LEO satellites and plasma (Marchand 2012). PTetra computes the electrostatic sheath potential around the probes and the floating potential of the payload and booms under specified plasma conditions. In next section, we briefly explain the numerical approach along with the results and general discussion of our findings.

Table 1. Summary of the simulation parameters in reference case.

Physical parameter	Value
Flow velocity($\vec{v_d}$)	$(0, 7469, 0)m/s$
Plasma density(n_o)	$10^{10}\ m^{-3}$
Plasma temperature($T_e = T_i$)	$0.25eV$
Magnetic field ($\vec{B_o}$)	$(-4.66, -40.8, -8.72)\mu T$
Ionic composition	$24\%H^+$, $76\%O^+$
Debye Length(λ_D)	$0.02m$
ion thermal gyro radius(ρ_i)	$6.95m$
electron thermal gyro radius (ρ_e)	$0.037m$
Tetrahedral mesh resolution	$0.008m$
Number of tetrahedra	$1,739,343$
Macro-particles	$8,000,000$

Table 2. Summary of simulation cases to study CubeSat-plasma interaction.

Case	Physical conditions
a	Reference Case
b	$100\%H^+$
c	$100\%O^+$
d	$B_o = 0$
e	Stationary Plasma

2. Numerical Technique and Simulation Results

The idealized geometry of the $1.5U$ CubeSat consisting of the payload, booms and two spherical Langmuir probes is constructed with an open source mesh generator GMSH (Geuzaine & Remacle 2009) as illustrated in Figure 1. The payload/booms are at the floating potential (collecting zero net current) and the bias voltage of the two Langmuir probes ranges between $-4V$ to $+4V$. For each bias voltage considered, PTetra simulations are carried out forward in time until a steady state is reached. The current characteristics are obtained by applying the same potential to the dual Langmuir probes and calculating the current collected by each probe individually. There are number of physical processes which affect charging of the CubeSat in the Low Earth orbit ionosphere. For this purpose we considered the five cases as summarized in Table 2. The numerical results obtained in different simulation cases are analyzed to assess the effect of different physical conditions on CubeSat-plasma interaction both qualitatively and quantitatively. The interaction between CubeSat and surrounding plasma disturbs the local plasma environment. This in turn leads to the formation of the electrostatic plasma sheath and wake structures around the nanosatllite. Figure 2 illustrate the electrostatic sheaths formed around the CubeSat payload and probes due to charging of their surfaces inside the plasma for probe relative bias of $+2V$, obtained in different simulation cases. It is found that the electrostatic sheath profiles vary significantly with the physical conditions accounted for in the simulations.

The values of the floating potential computed for the CubeSat payload and Langmuir probes in different plasma conditions are given in Table 3. The variation in the floating potential depends on the charged particle fluxes to the spacecraft and hence on the charge collected by the spacecraft surface. In the reference case, the plasma consists of 24% lighter H^+ and 76% heavy O^+ ions. The thermal gyro-radii of these ions are much larger than the size of the payload and instrument. The ions are therefore practically

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Table 3. Floating potentials (in *volts*) of Payload (V_{pl}), wake(V_{Lpw}) and ram(V_{Lpr}) probes.

Cases	V_{pl}	V_{Lpw} and V_{Lpr}
Reference Case	−0.49	−0.55, −0.48
Pure Hydrogen plasma	−0.37	−0.41, −0.40
Pure Oxygen plasma	−0.59	−0.59, −0.50
$B_o = 0$	−0.67	−0.61, −0.55
Stationary plasma	−0.56	−0.55, −0.55

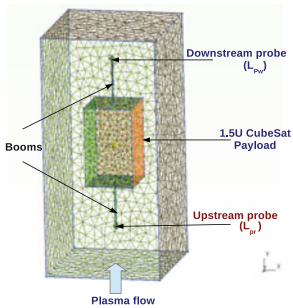

Figure 1. Simulation domain of 1.5U CubeSat payload.

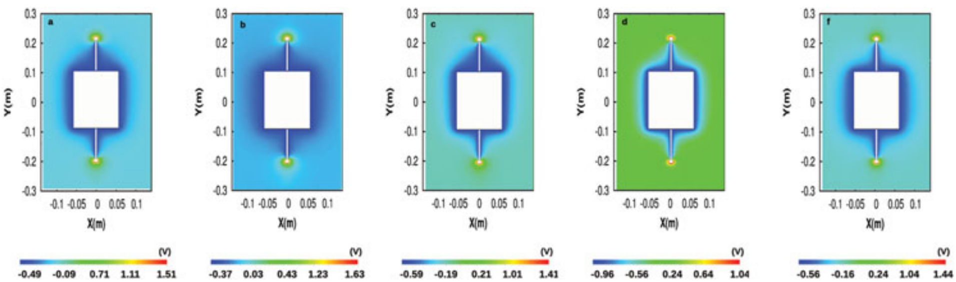

Figure 2. Sheath potential profiles around the CubeSat's payload/Langmuir probes.

unmagnetized and their current is not affected by the ambient magnetic field. On the other hand, the gyro-radius of the electron is comparable of the scale lengths of the system and therefore, electrons are strongly magnetized. The strong magnetization of electrons makes their dynamics restricted and only electrons contained in the magnetic flux tube of radius of the order of two thermal gyro-radii contribute to the collected electron current. Therefore, in order to balance the electron and ion currents such that the net collected current becomes zero, the floating potential has to be less negative when a magnetic field is accounted for in the simulations. In a plasma with 100%O^+ ions, the floating potential is strongly negative compared to the reference case. This behavior arises due to the higher mobility of electrons compared to the heavier O^+ ions. In order to balance the electron and ion fluxes, the potential barrier opposing the electron current should be larger than the reference case. However, in a 100% H^+ ionic plasma, the thermal speed of H^+ ion is 4 times larger than the O^+ thermal speed. The relatively high mobility of a lighter H^+ ion leads to the higher ion flux incident on the spacecraft surface compared to the reference and heavy ion cases. In order to achieve the balance between the ion and electron fluxes, a weaker electron repulsion is required. This in turn leads to the less negative floating potential. It can be seen that a strongly negative floating potential is obtained in case without magnetic field. This behavior arises due to unrestricted motion

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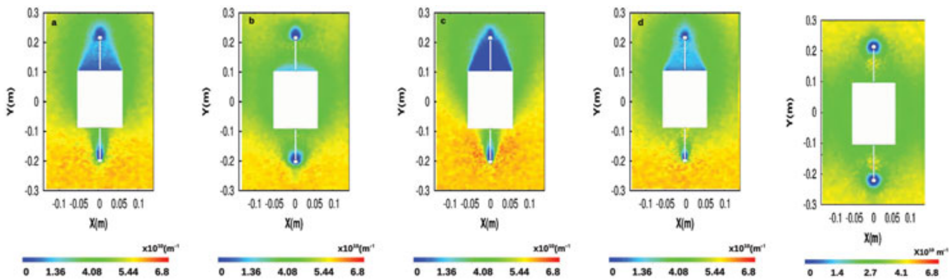

Figure 3. Wake structures behind the CubeSat's payload obtained in different cases.

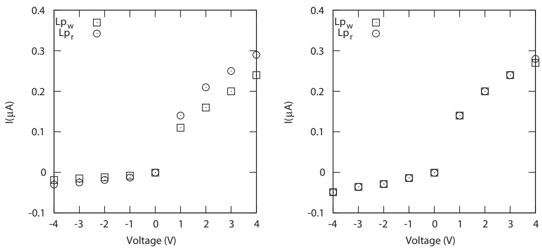

Figure 4. IV-curves of the Langmuir probes in flowing (left) and stationary (right) plasmas.

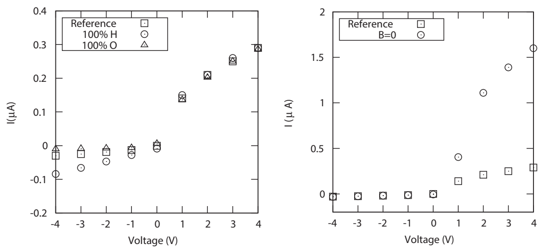

Figure 5. IV-curves of upstream L_{pr} for ionic composition (left), and magnetic field (right).

of the electrons which leads to the higher electron flux to the spacecraft. In order to ensure the net collected current to be zero, a strong potential barrier is required to repel the electrons. Therefore, the value of the floating potential is slightly more negative than its value in the reference case.

The supersonic motion of the CubeSat through a plasma modifies the plasma density and velocity distributions around it. This is manifest from a significant depletion in the ion density in the wake region. The properties of the wake structure depends sensitively on the plasma flow and ionic composition as illustrated in Figure 3. It is found that an enhanced ion density depletion wake is formed in a high Mach plasma ($M = 4$); i.e., with 100% O^+ compared to that in the a low Mach number plasma ($M = 1$); i.e., with 100% H^+, as shown in Figure 3. Of course, there is no wake formation in the stationary plasma case (with $M = 0$).

The current characteristics of the upstream/downstream spherical Langmuir probes in the range bias voltages between $-4V$ to$+4V$ have been computed for different plasma conditions. As expected, in all cases with plasma flow, the probe in the upstream(ram) region collects large current as compared to that in the downstream (wake) region as shown in Figure 4. This assymetry is a direct consequence of the plasma density depletion in the wake, and the resulting reduction in particle fluxes to the probe located in that region.

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The impact of the heavy and light ions on the current collection is illustrated in Figure 5a. It can be seen that the probes collect twice as much current in the presence of the lighter ions. Finally, Figure 5b, shows the impact of the magnetic field on the IV-curves of the Langmuir probes. A significant increase in the electron current is found in the absence of the ambient magnetic field. The variation in the current collection of the Langmuir probes under different plasma conditions also affect the plasma parameters determined from the IV-curves. It is beyond the scope of the present study to provide a detailed prescription to infer plasma parameters from probe measurements under actual ionospheric conditions. It is clear from our results, that the measurement of plasma density and temperature must account for several effects such as the geometry and location of the probes with respect to the satellite body, the ion composition, and the strength and direction of the geomagnetic field. This remark is particularly important in view of the fact that Langmuir probe measurements are often based on simple analytic models (e.g., OML) in which these effects are not included.

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