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Electric dipole in small biased probe sub-payloads and its effect on spacecraft-plasma interaction

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Abstract

A small sub-payload with a biased needle-probe is simulated to investigate floating potential and spacecraft-plasma interaction's effect on electron current measurements. Typically, the probe bias' effect on the space-craft charge is negligible, but for small sub-payloads with relatively large probes this is no longer the case. We found that a 10V bias results in a roughly even charge distribution for a sub-payload with 10 cm diameter, with resulting probe potential +5V and body potential -5V. The resulting dipole effect further complicates the spacecraft-plasma interaction, disrupting the typical flow and gyration of particles, and increases the current collected with a magnetic field.

1 Introduction

The ionosphere is a complex and dynamic system characterized by turbulence, irregularities and structuring. Small structures and irregulatires are studied with in-situ missions, where a variety of instruments measure different plasma parameters. Multi-Needle Langmuir Probe (m-NLP) measure currents with a high sample rate, resulting in sufficient spacial resolution for small scale structures[1, 2, 3] which combined with probe theory is used to infer plasma density. However, m-NLP systems on sounding rockets only provide data along the trajectory of the rocket. Having multiple subpayloads deployed from the sounding rocket increases the number of simultaneous data points in space, allowing for a more detailed picture of small scale structures.

However, subpayloads provide their own challenges as a result of having a quite different size and shape from a sounding rocket. Particularly, biasing a probe in order to attract more electrons assumes sufficient surface area on the rocket to effectively absorb the redistributed charged particles. In the case of a small needle probe and a large sounding rocket, this assumption holds. However, in the case of small subpayloads this might no longer be the case, leading to a dipole effect. Further, assumptions about the rocket being larger than gyro-radii might also change.

Further, the actual bias will be relative to the rocket body's floating potential, where the floating potential is when the sum currents I of species ℓ is zero

$$\sum_{\ell} I_{\ell}\left(\phi_{\text{fl}}\right) = \frac{\mathrm{d}Q}{\mathrm{d}t} = 0, \tag{1}$$

where Q is the charge. However, the probe bias effects the probe currents, which in turn effects the charge redistribution, which in turn effects the probe bias, which all effects the respective reference floating potential. As a result, the potentials and resulting electric fields can be hard to predict when the spacecraft body's non-zero floating potential is variable and non-negligible.

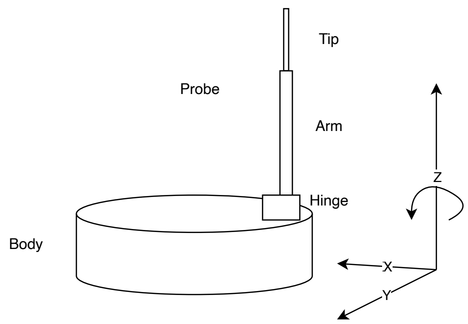

Figure 1. The subpayload body and probe. The subpayload carries angular momentum about the z-axis from the main rocket. The probe is slightly shorter than the diameter of the body at around 9.5 cm

The theory of Langmuir probes are often based on Orbital-Motion-Limited theory [4], where a positively biased cylindrical probe's electron current is given by

$$I_e = A n_e q_e \sqrt{\frac{k_b T_e}{2\pi m_e}} \sqrt{1+\chi} \tag{2}$$

Where $\chi = q_e\phi/(k_b T_e)$, A is the area of the probe, T_e is the electron temperature, q_e is the electron charge, m_e is the electron mass, n_e is the number density and k_b is Boltzmann's constant. OML is used in probe theory to infer and approximate plasma parameters from probe currents [1, 3, 5]. However, OML neglects collisions, assumes uniform sheath expansion, assumes a stationary plasma, neglects magnetic fields and assumes that the local Maxwellian distribution close to the probe is the same as the rest of the plasma [4].

As a result, simple physics based models of probe currents are not sufficient, particularly for intricate geometries with overlapping opposite electric fields such as a small subpayload with a biased probe. Hence, first principle simulations such as particle-in-cell simulations are typically used to investigate the plasma-spacecraft-probe interaction.

In this investigation, we have performed such particle-in-cell simulations to study the plasma-subpayload interaction, and it's effect on measurements. Specifically, the ICI-5 subpayload has been modelled, which can be seen in Figure 1, and put in a stationary plasma with and without a background magnetic field. We compare the floating and fixed potential methods to investigate whether the floating potential effect is negligible or not.

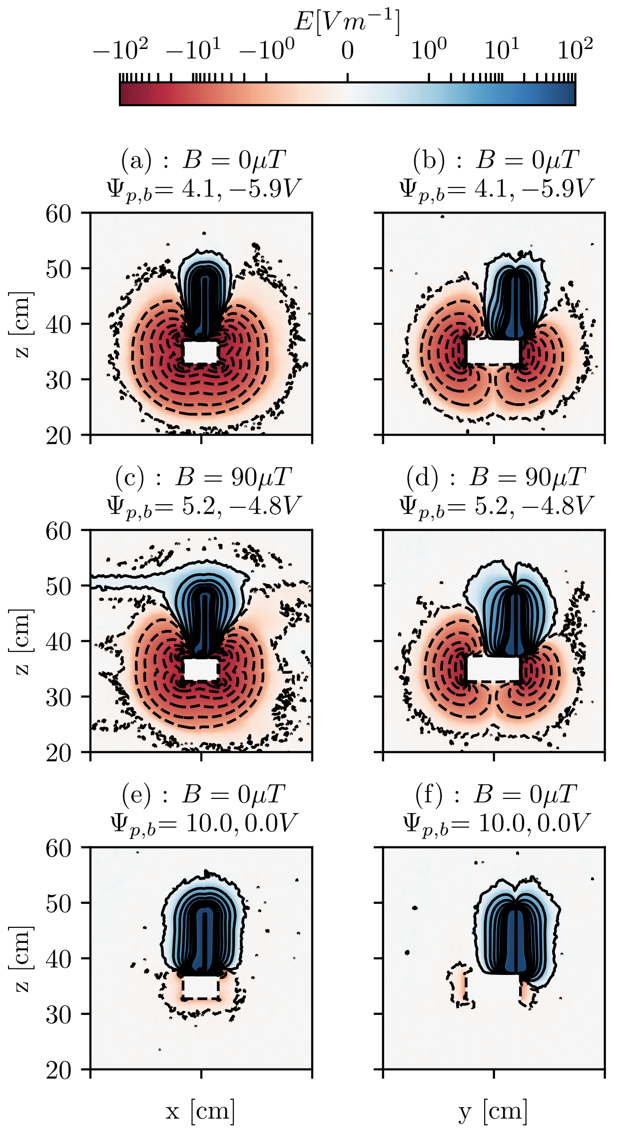

Figure 2. The electric field E and equipotential lines. The color indicates the force felt by a positive test charge away (blue) or towards (red) the object surface. Subscript p,b refers to the probe and body potential, respectively. B indicates the strength of the magnetic field on the x-direction. Here, (e) and (f) has a fixed probe bias at 10V with body at 0V neglecting floating potential effects seen in (a) - (d). The slices intersect the probe tip.

Table 1. Input parameters for the simulations. A subgrid is used for the probe, resulting in higher spatial resolution around the objects. ω refers to plasma frequency, B is the magnetic field, and Δx and Δt are space and time resolution, respectively.

Δx	0.25 cm
Δt	1.667 ns
ω_{pe}	17.83 MHz
ω_{pi}	0.564 MHz
T_e	1000K
T_i	750K
n_e	1e5 /cc
B	90μT
$\frac{m_i}{m_e}$	1000
Probe tip width	1Δx
Probe tip length	28Δx
Probe bias	+10V
Box dimensions x,y,z	80,80,80 cm

2 Method

The simulations are carried out with the three-dimensional particle-in-cell (PIC) code EMSES (Electro-Magnetic Spacecraft Environment Simulator). The EMSES code models plasma using "superparticles"; a collection of plasma particles gathered into a single volume [6]. Charge currents are collected on the object surfaces and redistributed according to the probe bias through a discretized capacitance matrix. We used the supercomputer facilities at Kobe University to run a series of simulations of subpayloads.

The probe is biased either with a fixed potential where the tip is fixed at the bias potential and the body has zero potential, or with a floating potential method. The floating potential works by redistributing the current collected in the tip, arm and hinge to the body, making sure their relative potential remains at the bias value, which is 10V in our case. The measured current is the current collected at the tip in Figure 1. We found, in test simulations, that a ratio $l/r \approx 50$ or larger, where l is tip length and r is tip radius, resulted in good agreement with OML theory for an isolated cylindrical probe. However, when combined with the rest of the subpayload geometry, currents did not result in the same agreement with OML.

2.1 Input paramameters

The input parameters can be found in Table 1, and represent approximate typical ionospheric conditions. In order to fit the ion gyroradius sufficiently inside the simulation box, the magnetic field strength is increased slightly above typical values of $25-60\mu$T [7], as increasing the simulation box' dimensions was too computationally expensive.

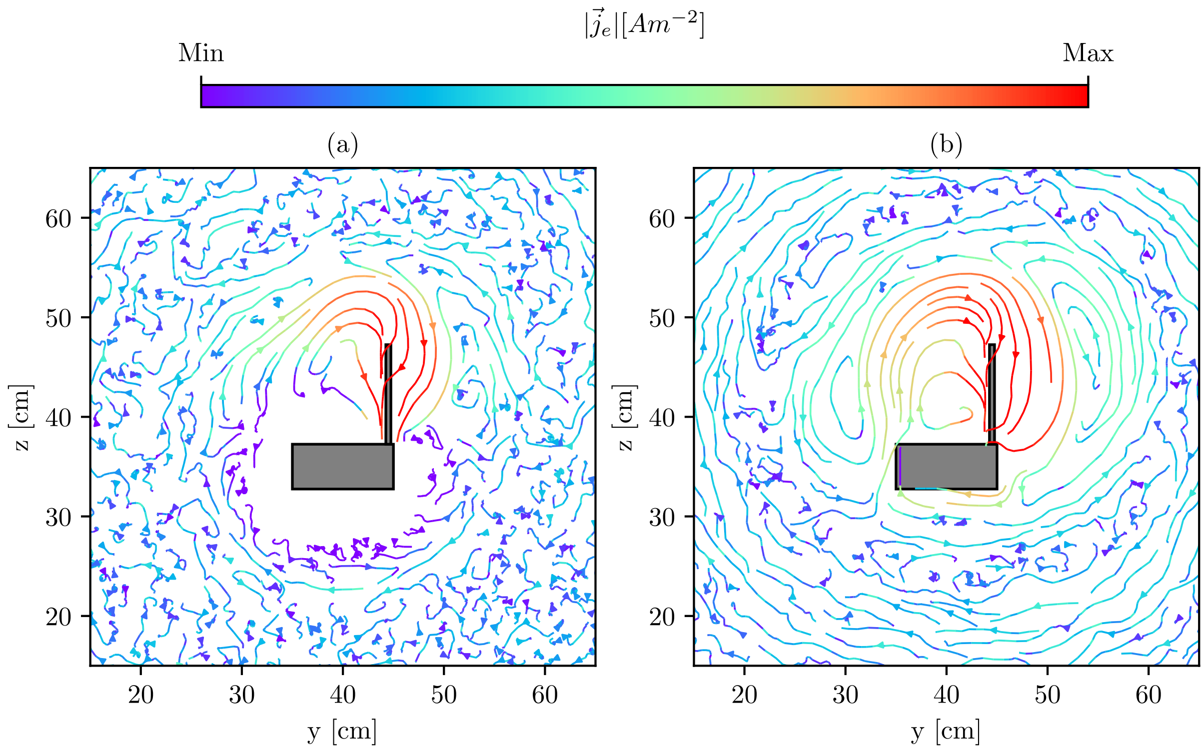

Figure 3. Electron current density for floating and fixed potential in (a) and (b) respectively with a probe biased at $10V$. The magnetic field strength is $B = 90\mu$T in the x-direction. The arrows point the direction the electrons are moving. The floating potential case is more chaotic, and collects more currents in the probe. The slices intersect the probe tip.

3 Results

In particular, we are interested in the extent of the dipole-like electric field, it's effect in currents and gyrating particles and how it impacts electron currents to the probe. As such, we have included some 2D slices of the current density $\vec{j}_x$ and electric field $\vec{E}$ as well as the corresponding current measurements from the probe. The slices intersect the probe tip in the xz and yz-plane.

3.1 Electric field and dipole

We observe a clear dipole effect as a result of the floating potential bias method in the electric field in Figure 2 (a)-(d). Here, the resulting potential is approximately equal in magnitude, however the body is much larger, so it's electric field is more dominant. Comparing the cases with and without magnetic fields, we observe a less symmetric electric field with the magnetic field. With the fixed bias we see some electron buildup on the neutral body, which is to be expected, however the body itself remains at a fixed zero potential.

Comparing the fixed and floating potential bias we see that the dipole effect is definitely not negligible.

3.2 Current density vector field

In Figure 3 (a) we observe the electric dipole disrupt the gyration around the magnetic field lines seen in a magnetized plasma. In (b) however, with the fixed bias, the electron gyration around the magnetic field is largely undisturbed by the subpayload's body. As magnetic fields are known to affect probe measurements beyond simple OML theory, disrupting it can be beneficial for probe performance.

3.3 Probe measurements

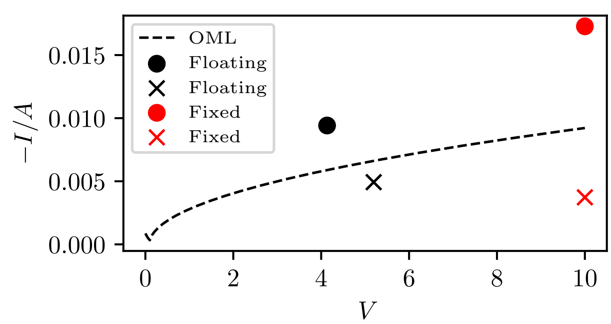

Figure 4. Currents collected at the tip, or needle probe, where red is fixed potential and black is floating potential. The X indicates a magnetic field $B = 90\mu T$, while dots have no magnetic field. The probe is biased to 10V in all cases.

Lastly, we consider the electric dipole's effect on the probe current measurement. First, we observe that neither of the measurements adhere to OML in Figure 4.

Next, we observe that with a magnetized plasma, the electric dipole disrupts the current-lowering effect of the magnetic field, which agrees with the disruption seen in Figure 3 (a). Here, the OML theory used to infer plasma parameters from current measurements assumes an unmagnetized Maxwellian distribution. As such, the electric dipole's disruption brings our magnetized case closer to the unmagnetized Maxwellian case.

4 Discussion

The importance of floating potential, and charging through bias in m-NLP systems, have been shown in Ref. [5], where charging events occurred in 2 of 3 rockets. In Ref. [3], the floating potential for the Norsat-1 satellite is estimated to $\approx -2V$. Particularly, Ref. [5] stresses that platforms with a single biased Langmuir probe needs a second device to measure the floating potential. In our case, the main rocket will have such a device, however, as shown in this investigation, the small subpayload will have very different potential.

Particularly, our platform's floating potential goes as low as $-5.9V$, such that the effective bias relative to a neutral plasma is only $4.1V$, compared to the expected $\approx 10V$. If we assumed that our floating potential was comparable to that of NorSat-1, or higher for a larger rocket, our resulting IV-characteristics would be very misleading. As such, it is crucial, as shown with our results, to investigate the floating potential resulting from probe bias to understand data from subpayload missions with biased probes.

Further, as the magnitude of our floating potential is larger, and the platform is smaller, the effects of the electric field resulting from the floating potential will extend further into the plasma. As such, our platform have a much larger relative electric field footprint, which is expected to effect currents and the background plasma more than already seen in Refs. [5, 3].

Lastly, we have used a stationary plasma, whereas the actual platform will have drift velocities of about one kilometer per second. However, the effect of plasma drift is outside the scope of this paper and is therefore not included.

5 Summary

We have found an electric dipole effect for the small subpayload configuration, where the potential distributes approximately equally, where in some cases the body has a greater absolute potential. The resulting currents collected at the cylindrical probe are higher than what OML predicts in the un-magnetized case, and lower in the magnetized case.

In the magnetized case we observe the dipole disrupting the gyration around the field lines, resulting in a reduction of the magnetic fields current-lowering effect.

6 Acknowledgements

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