Rocket wake effect on probe electric potential measurement for low angle plasma flow simulated using EMSES

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September 21, 2018

Abstract

Electric plasma fields in the ionosphere is often studied with probes connected to a sounding rocket by wire booms. These measurements might be affected by the electron depleted wake left by the rocket body. This wake is studied using EMSES particle in box simulations. We pay special attention to the effect of small-angle changes in the wakes direction. The results show a small, but very consistent change in the measured electric field values, comparing to the theoretical case. We find an unexpected small yet outside margin of error deviation from the emerging pattern. We are unable to replicate any low-angle noise (as seen in experimental measurements presented in Figure 9a in [1]). We conclude that the rocket body wake alone is not the cause of this noise.

1 Introduction

Knowledge about the ionosphere is vital to a many industries around the world. It is important when sending radio signals around the world, and very important for rocket science. The ionosphere is the upper region of the atmosphere that has a significant portion of ionized particles. The electric field in the ionospheric plasma is of special interest. A method used to measure electric fields in the ionosphere is to use Langmuir probes attached to a sounding rocket. Typically a sounding rocket will have 2 or 4 probes connected to the rocket via booms. These Langmuir probes measure the electric potential, and by knowing the distance between them we can calculate the electric field in the ionospheric plasma. An issue that occurs in such a case is that the interaction between the rocket and the plasma flow can disturb the probe measurement. The Debye sheathe of the rocket has an excess of positive ions causing the electrons in the plasma flow to be deflected, creating an electrostatic imbalance wake behind the rocket. If a probe is inside the wake from the rocket, the potential measurements will be affected. When doing experiments, it is difficult to know if the measurements are disturbed by something unexpected. In simulations this is much easier to control. Doing so we can in greater detail study the wake effects caused by the probe, and how this changes the electric field measurements at the probes. In this study, we look into how the electric field measurements are affected by the wake coming from the rocket body. We do this while changing the angle of the plasma flow compared to the angle between the rocket and the probes. The electric field measured by the probes will be compared to the analytic floating point potential.

Put simply, a sounding rocket is composed of a rocket body and probes attached to booms. Simulations show that the charging of the booms enhance the wake left by the rocket [2]. This effect will not be taken into consideration in this paper. We will look at a more simplistic case of a cylinder rocket body and how this wake changes the electric potential measured between 2 probes.

In [1] Figure 9a shows an a wave that is almost sinusoidal, but with a bump when the field is around zero. We wish to explore whether the irregularities in the potential differences can be explained by introducing a rocket body in a plasma-flow simulation.

2 Methods

We wish to simulate how a rocket body placed between two probes will change the electric potential measurements when the plasma flow is such that one probe is downstream from the rocket. For out simulations we use the EMSES (Electro-Magnetic Spacecraft Environment Simulator) [3].

2.1 EMSES

For a detailed explanation of the EMSES method, see [3] or [2]. In short, EMSES uses particle in cell (PIC) methods to simulate plasma physics interaction with space bodies. EMSES can reproduce complicated plasma physics phenomena in three dimensional plasma space. In addition, EMSES is compatible with distributed memory parallelization using MPI, and it is possible to efficiently solve the interaction between the motion of plasma particles and the electromagnetic field in the space by using a super computer. EMSES updates particle position, electric field, magnetic field every step. EMSES fully incorporates all of Maxwells equations to accurately update electromagnetic fields. They are

$$\begin{aligned}\nabla \times E &= \frac{\partial B}{\partial t}\\ \nabla \times B &= \mu_0 J + \frac{1}{c^2}\frac{\partial E}{\partial t}\\ \nabla \cdot E &= \frac{\rho}{\varepsilon_0}\\ \nabla \cdot B &= 0.\end{aligned}$$

We use EMSES to simulate plasma flow for 10000 time steps. EMSES combines time series data into mean spacial data readily available for intuitive analysis.

2.2 Parameters

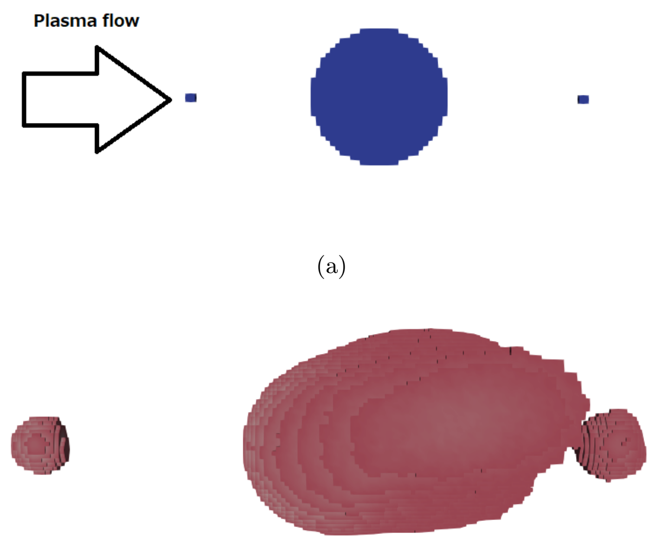
Our plasma parameters are set to mimic the real ionosphere, they are presented in Table 1. If the ions are only protons, then the real ratio m_i/m_e is 1836. In reality, there are also heavier ions like oxygen present. The real ratio is much higher. Heavy ions do however strongly increase the number of time steps needed to get good results. With this in consideration, the ratio is set to 500.

Table 1: Parameters used for simulations

Electron temperature [K]	3000
Ion temperature [K]	2000
Magnetic field [μT]	50
m_I/m_e	500
Debye length λ_D [cm]	0.845
Electron gyro radius [cm]	2.425
Ion gyro radius [cm]	44.270
Mach number	3.5

2.3 Boundary conditions

The EMSES code does not use periodic boundary conditions, instead new particles are injected to induce plasma flow, and particles that exit the simulation cell are deleted by the program. Some plasma particles are injected from the other sides corresponding to plasma fluctuations following a Maxwell distribution. To avoid boundary conditions affecting the measured result we need to make sure to have sufficient space in our simulation cell. We impose some vital conditions on the boundary effects:



(a)

(b)

Figure 1: This diagram show how the project is set up. The plasma flow is going from left to right in the y direction. (a) The rocket is represented by cylinder and placed at (32,96,24) with two probes on its side with the coordinates (32,26,24) and (32,166,24). (b) Shows an example wake in the ion density when the plasma flow is tilted to 12 degrees.

1. The probes need to be several Debye lengths from the simulation edge
2. The rocket body must be smaller than the ion gyration radius but much larger than the electron gyration radius
3. The distance between the probes and the rocket body must be multiple Debye lengths to avoid sheathe interaction

2.4 Simulation setup

When placing our probes and rocket we make sure to have enough space to avoid boundary conditions. In addition we wish to limit the size of the simulation box to speed up simulations. Doing so, we choose our simulation box to be rectangular, with the plasma flow moving in the largest direction. It is of size 64x196x48 grid cells.

Taking the boundary conditions into account while considering the plasma parameters in Table 1, we placed the probes at locations (32, 26, 24) and (32, 166, 24). The probes have a radii of 4 EMSES grid units. The probes are $16\lambda_D$, $13\lambda_D$ and $11\lambda_D$ from the x, y and z boundaries respectively. The rocket is represented by a cylinder that is placed at (32, 96, 24). It stretches in the z-direction from $z = 10$ to $z = 38$. The radii of the rocket is 16 EMSES grid units. The rocket is about 6.5 electron gyration radii, and about 0.36 ion gyration radii. The distance between the edge of the rocket and the edge of the probe is now 25 cm, or almost $30\lambda_D$. An image of the setup is presented in Fig. 1a. The 2 probes are placed symmetrically on either side of the rocket. Fig. 1b shows an example of what the wake looks like in simulations. It

In real experiments, the sounding rocket has a diameter of 40 cm, and the distance between the Langmuir probes is 17.4 cm. The ratio between these numbers is 4.35. These are the two parameters we would expect to affect the magnitude of the wake interaction. Therefore in our simulations we use distances and sizes to replicate this ratio. We use a rocket diameter of 16 cm and a probe separation of 70 cm. The simulation ratio is 4.375. The hope is that using this ratio our results will be realistic.

When using the EMSES code, we can set the number of particles used in the simulation. This number of particles is not related to the plasma density set by the simulation. The number of particles controls the accuracy of the code. Taking this into consideration we use 2^{28} simulation electrons and ions. The ion and electron density in our simulation cell is $n = 3.57 * 10^9\ m^{-1}$.

2.5 Floating point potential

We need to have a theoretical result to compare our results with. Our simulations neglect photo emission from the space craft so the total current is $I = I_e + I_i = 0$. The floating point potential is then

$$\Delta V = -\frac{kT_e}{e} \ln \left(\frac{\sqrt{\frac{kT_e}{2\pi m_e}}}{\sqrt{\frac{kT_i}{2\pi m_i} + \frac{v^2}{16}}} \right). \tag{1}$$

In our simulations we are using a set of parameters (complete list presented in Table 1) used to define the plasma and calculate the floating point potential. The electric potential at a probe is found as $V_{probe} = \Delta V + V_p$, where $V_p = yv|B|$. The electric field between the two probes is the potential difference divided by the length between them,

$$|E| = \frac{V_{probe2} - V_{probe1}}{L} \tag{2}$$

The value of the electric field should follow a sine function when changing the angle of the plasma flow. Therefore we have

$$|E(\theta)| = \sin\theta |E|. \tag{3}$$

Using the set of parameters we list in Table 1, and using Eqs. 1 and 2, we calculate $|E| = 1.67$ V/m.

3 Results

The measured potential at the left and right probes for each flow angle is noted in Table 2. The electric field is calculated using $E = \Delta V/L$, where $L = 0.70$ m is the distance between the probes. The probe potential is converted from EMSES units to SI units before calculations.

Table 2: Measured potential at 1st and 2nd probes for a spectrum of angles. The electric field is calculated $E = \Delta V/L$. The units for the probe potential is in EMSES units. The potential is measured by taking the mean of the last 4000 time steps. The error is the standard deviation of this data.

Flow angle [deg]	**1st probe**	**2nd probe**	**E-field** [V/m]
-2	-111.5 ± 0.1	-125.6 ± 0.3	-0.103 $\pm$ 0.002
0	-115.4 ± 0.1	-121.5 ± 0.3	-0.045 $\pm$ 0.002
2	-119.4 ± 0.1	-117.5 ± 0.2	0.014 ± 0.002
4	-123.4 ± 0.1	-113.5 ± 0.2	0.072 ± 0.002
6	-127.4 ± 0.1	-109.5 ± 0.2	0.131 ± 0.002
8	-131.4 ± 0.1	-105.5 ± 0.2	0.189 ± 0.002
10	-135.3 ± 0.1	-101.7 ± 0.2	0.245 ± 0.002
12	-139.2 ± 0.2	-97.9 ± 0.3	0.301 ± 0.003
14	-143.1 ± 0.2	-94.1 ± 0.2	0.358 ± 0.002
16	-146.9 ± 0.1	-90.4 ± 0.2	0.412 ± 0.002
18	-150.6 ± 0.1	-86.6 ± 0.1	0.467 ± 0.001
20	-154.5 ± 0.2	-83.0 ± 0.2	0.522 ± 0.002

Fig. 2 shows the potential measured in the simulation box along a line starting at (32,0,24) and ending at (32, 192, 24). This line goes through the center of both probes and the rocket body, as seen by the flat areas in the curves. We see that the when increasing the flow angle, the potential at the 1st (left) probe decreases and the potential at the 2nd (right) probe increases. The potential inside the rocket is unchanged.

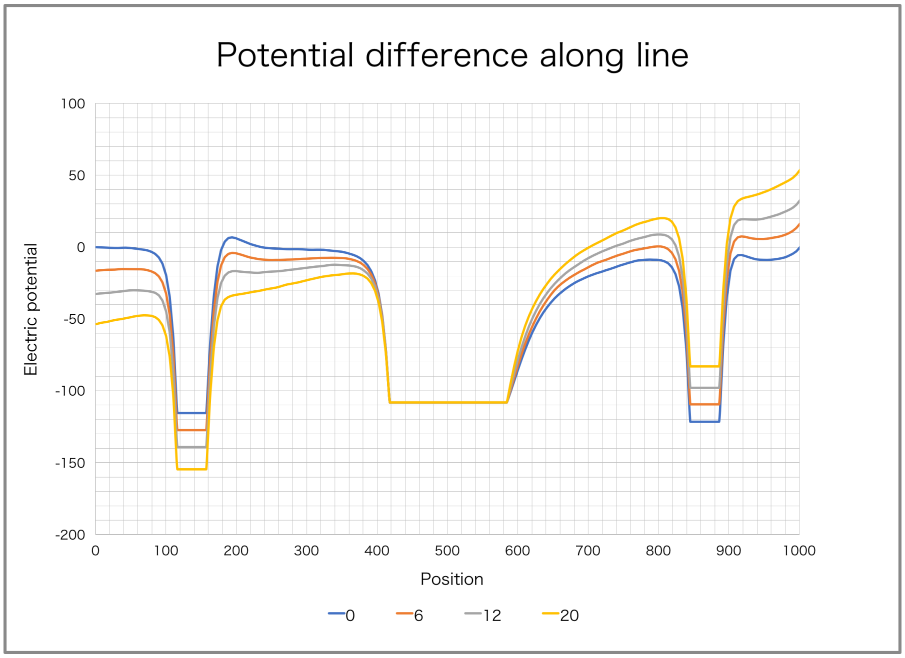


Figure 2: Potential along a straight line starting at (32,0,24) and ending at (32, 192, 24). This is a line going through the probes and the rocket body.

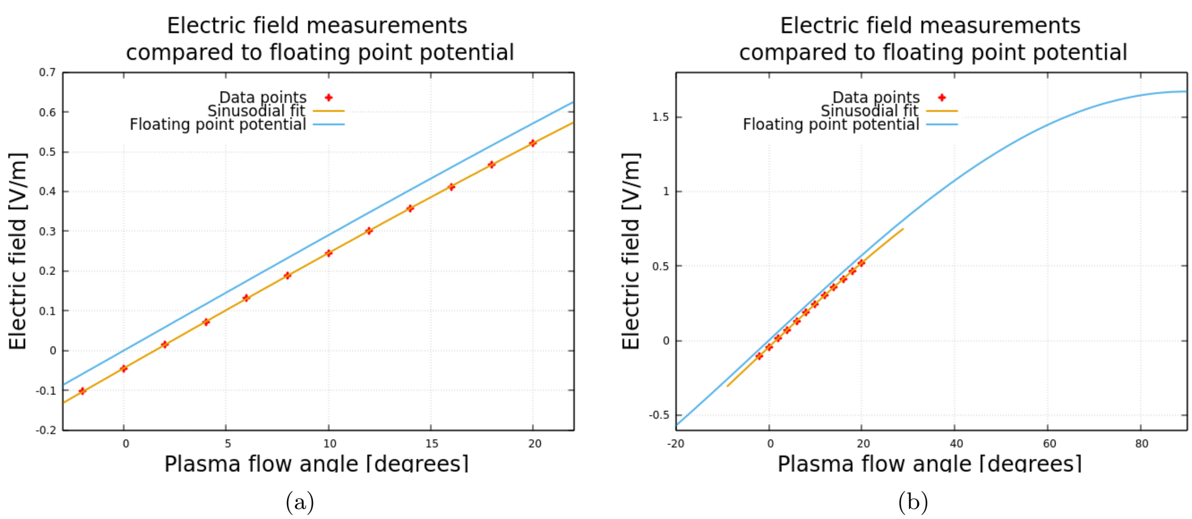


Figure 3: Electric field data points from Table 2 compared with the theoretical floating point potential Eq. 3. (a) shows how the points deviate by a constant deviation. (b) shows the larger scale model. The sine fit is removed for small and large x to demonstrate that we don't expect the trend to continue.

Figure 3a shows the electric field measured between the probes for different plasma flow angles (from Table 2). We can see that all the measured points are below the theoretical value at nearly equal intervals. The uncertainties in Table 1 are not big enough to be visible in this graph, so they are not included. Figure 3b shows the larger scale model of Figure 3a. We can see that it is along the sine wave within the measurement range. The sine fit curve is only included for a small spectrum of angles, this is because we don't expect the measured pattern to continue past this.

Fig. 4 shows the deviation between Eq. 3 and the measured electric field. The figure shows a mostly constant deviation at low angles and a slightly increased deviation at larger angles. The slight increase at higher angles is not much larger than the error.

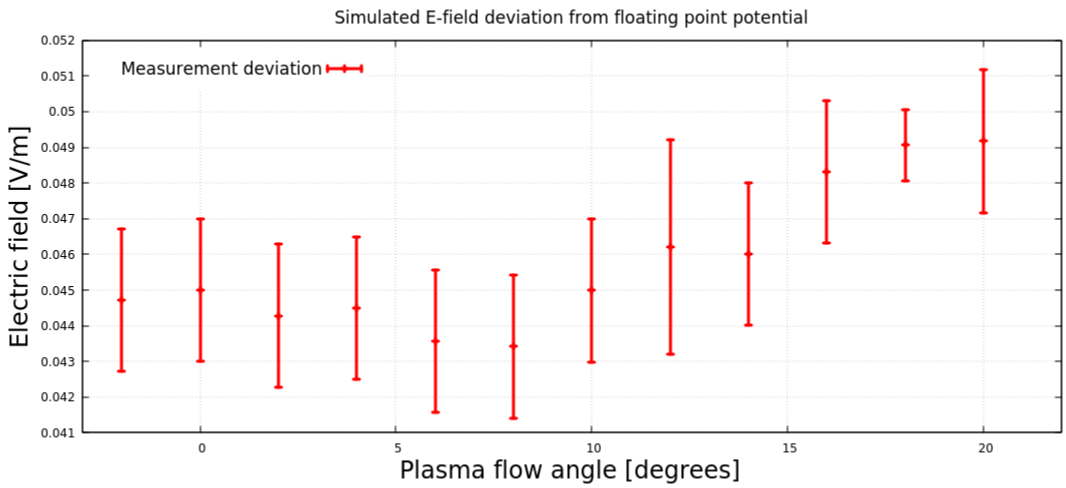


Figure 4: Difference between floating point electric field (Eq. 3) and simulated electric field. There are small fluctuations in the deviation, but they are not significant enough compared to the error to be of importance.

Figure 5 shows the ion and electron density in a line perpendicular to the plasma flow. The figure shows that the ion and electron density is very similar inside the center of wake. There is little change in electron and ion asymmetry. There is a slight dip in the electron density seen at 300 data points and 600 data points. This is roughly symmetric about the center of the wake. The differences at the edge are either coming from the end of the wake or boundary effects.

4 Discussion

The deviation from the floating point potential in Figure 3a is caused by the wake of the rocket changing the electric potential at 2nd probe. The effect of the wake seems to be approximately constant for the range of simulated plasma flow angles. This is seen in Figure 4. The deviation has a slight tendency to increase for larger angles, but the increase is only by ~0.004 which is outside the margin of error for some of the points. From Figure 5, we see that there is little difference between the ion and electron density in the middle of the wake. It might be that for angles -2 to 8, we are inside the middle of the wake in which there is little difference when moving around. So the deviation is approximately constant.

As the angles are increased from 10 to 20, the deviation increases. Why this is, is not apparent from any of our research. The relative size of the error compared to the size of the increase makes it difficult to tell if the increase is significant or not. The bumps in the electron density seen in Fig. 5 should make the potential more positive, and therefore increase the E field more than normal. This is not seen and instead the E field is slightly lower than expected. This means that maybe our simulated angles don't reach the dip seen in Fig. 5.

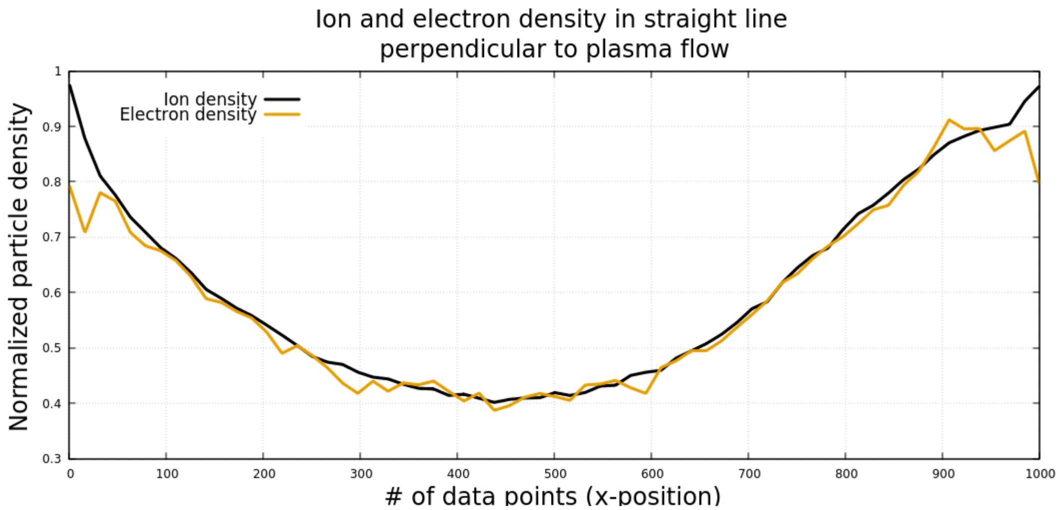


Figure 5: Ion and electron density inside the wake along a line moving from (0,125,24) to (64,125,24). For the data used in the graph, the plasma is flowing at a 0° angle. The figure demonstrates that the ion and electron density is approximately the same in the center of the wake. It is difficult to tell if deviations at high and low x-values come from wake symmetries or boundary effects.

Instead of the deviation increasing, we would have expected the effect of the wake to start to decrease once the plasma flow angle increased such that the probe was only in the edge of the wake. This is not seen, signaling that perhaps we need to go to higher angles to observe this. Perhaps the small increase is some other wake effect not seen in Fig. 5.

The simulated electric field's deviation is very systematic and in a similar shape to the sine curve. There is no bump or interesting effects coming from this deviation.

4.1 Validity of results

In our simulation setup, we placed the probes and rockets at positions such as to replicate real experiments. However, the code uses multiple approximations for speed and simplicity that change the simulations from reality. For example the ion to electron mass ratio is many times lower than in the ionosphere. This was not considered when designing the positions of the probes and rockets. With a real ion to mass ratio, the heavier ions are less affected by the wake and are able to penetrate further. Effectively enhancing the wake. This could have been simulated by moving the probes closer again. Therefore the effect of the wake in real experiments should be larger than what we have simulated.

The boundary effects likely do not disturb our measurements. The effect of having a narrow x-dimension is okay, because the plasma is not periodic and is not reflected by the boundary. Therefore it cannot interfere with the probe in the middle of the simulation box.

5 Conclusion

Through our simulations we have measured the electric field between two probes and looked at how the wake from the rocket affects the measurements when changing the angle of the incident plasma flow between -2 and 20 degrees. We found an almost constant lower electric field than the theoretical floating point potential if there's no wake. The deviation from the floating point potential increased slightly for larger angles. The reason for this is not clear. We expected the deviation to decrease for this range of angles. We still expect the deviation to decrease to zero for larger angles. This effect should be visible at least at 45 degrees and maybe as soon as 30 degrees.

Our data is not able to replicate the irregularities seen in Figure 9a in [1]. Therefore we are inclined to conclude that the wake from the rocket is not the cause of the data bump. If the probe was closer, then there shouldn't be that different to cause such a significant change. Perhaps if booms are introduced, from the rocket to the probes. This would enhance the potential difference in the wake [2]. In addition it would stretch the wake and make it less symmetric.

It would be interesting to simulate the electric fields for some larger angles and see if we can observe if the deviation in Figure 4 is going to zero. In addition, due to the relatively large uncertainty in the deviation, it would be useful to do several simulations for each angle. This way we could combine the data to lower the error so the data trend is more easily readable. There are other possible sources that could cause the measured bump in the electric field measurements. It could be that probes (in a sounding rocket with 4-probes, 1 in each direction) affect the one next to one another, and it is this that is responsible for changing the experimental result. It might also be that it is the combination of having multiple probes, booms and a rocket body that is the cause. Further and more precise simulations is required before any definite conclusions can be drawn about the matter.

References

[1] D. Darian, S. Marholm, J. J. P. Paulsson, Y. Miyake, H. Usui, M. Mortensen, and W. J. Miloch, "Numerical simulations of a sounding rocket in ionospheric plasma: Effects of magnetic field on the wake formation and rocket potential," *Journal of Geophysical Research: Space Physics*, vol. 122, no. 9, pp. 9603–9621, Sep. 2017.

[2] Y. Miyake, C. M. Cully, H. Usui, and H. Nakashima, "Plasma particle simulations of wake formation behind a spacecraft with thin wire booms," *Journal of Geophysical Research: Space Physics*, vol. 118, no. 9, pp. 5681–5694, Sep. 2013.

[3] Y. Miyake and H. Usui, "New electromagnetic particle simulation code for the analysis of spacecraft-plasma interactions," *Physics of Plasmas*, vol. 16, no. 6, p. 062904, 2009. [Online]. Available: https://doi.org/10.1063/1.3147922