Plasma Density Analysis of CubeSat Wakes in the Earth's Ionosphere

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Spinning or tumbling CubeSats with Langmuir probes deployed on booms will render spin-modulated plasma densities as the probes move in and out of the space wake. It is traditionally assumed that the lower density measurements from the spin-cycle are made in the spacecraft wake and the higher density measurements are outside the wake. Although this assumption is valid for larger spacecraft in the Earth’s ionosphere, this paper scrutinizes its relevance for CubeSats in similar conditions. Spacecraft-plasma interactions—surface charging, plasma sheaths and wakes—are less understood for CubeSats and the small CubeSat dimensions must be considered with respect to characteristic length scales of the space plasma environment, namely, the Debye length. A spacecraft charging tool, SPIS, is used to investigate CubeSat interactions with the meso-thermal plasma environment. For ionospheric densities, the CubeSat dimensions of \( b = 0.1 \) cm is comparable to the sheath thickness. Our simulations show that under such circumstances, a negatively charged CubeSat in meso-thermal ionospheric conditions creates an ion focus region in the far-wake. An independently written, first principles code in MATLAB verifies that this feature is a direct result of the CubeSat behaving like a Langmuir probe in the thick-sheath model. The work performed in this paper caution the community towards assuming CubeSats to have density depletion in their wakes, and stresses the necessity of having a more accurate altitude solution to derive ambient plasma densities from spin-modulated Langmuir probe measurements on CubeSats.

SPIS: CubeSat Charging in Non-Flowing Plasmas

If the dimension of conductor \( l \) is less than (or comparable to) the sheath thickness, \( l < \lambda_D \) for Debye length \( \lambda_D = (\pi n_0 e^2/k_B T_{\text{elect}})^{1/2} \) and \( n_0 < n \), then the thick sheath (obtained motion limited) model is appropriate. If the dimension of conductor is greater than the sheath thickness, \( l > \lambda_D \), then the thin sheath (space charge) model is appropriate. Larger spacecraft in the ionosphere abide by the thick sheath model of probe theory. It is shown here that CubeSat is in the ionosphere by the thick sheath model of probe theory.

**Figure 3:** SPIS simulations for non-flowing plasma. CubeSat charging potential \( \phi_c \) in a \( 1 \times 10^8 \text{ m}^{-3} \) density \( O \) CubeSat dominant LED plasma environment.

**Figure 4:** SPIS simulations for non-flowing plasma. CubeSat charging time \( \tau_c \) for \( n_0 = 1 \times 10^8 \text{ m}^{-3} \) (in blue) and \( n_0 = 1 \times 10^7 \text{ m}^{-3} \) (in red) as a function of plasma temperature. It is noted that \( \phi_c \approx (T, T) \) and \( \phi_c \approx (0, 0) \). Moreover, \( \phi(\alpha/\varepsilon| 0) \) and \( |\alpha| \approx (T, 0) \).

**Figure 5:** SPIS simulation for flowing plasma. The time of charging onset \( \tau_c \approx 5 \times 10^{-2} \) \text{ s} is defined as the time of maximum absolute net current. At \( \phi_c \), the flowing potential is \( \phi_c \approx -0.1 \text{ V} \). The simulation duration is \( 2 \times 10^{-1} \text{ s} \) with \( l = 1 \times 10^{-3} \text{ m} \) time-step.

**Figure 6:** SPIS simulation for flowing plasma. The \( O \) ion density charge along the spacecraft velocity \( v \). Ion densities are enhanced by \(-10^2 \) over \( n_0 \). The wake begins \( 21 \text{ cm} \) downstream and extends \( 68 \text{ cm} \) beyond \( 500 \text{ cm} \) quasi-neutral. Ion focusing distances \( 0 \text{ cm} \) (left) or, equivalently, \( \phi(0) \) for \( 1 \text{ cm} \) CubeSat dimension (parallel) to the direction of motion \( \phi(\varepsilon|x|) \).

**Figure 7:** SPIS simulation for flowing plasma. The electron charge density along the spacecraft velocity vector. Ambipolar effects are witnessed in the far-wake and an electron defect moves near the CubeSat charged at \( \phi_c \approx -0.1 \text{ V} \).

**Figure 8:** Plasma density and potential profiles along the velocity vector (along \( z \)-axis). The combined electrostatic wake and thermal wake are in red and blue, respectively. The combined electrostatic and thermal densities show an ion enhancement of \( 2 \) above background (black). The normalized SPIS density along the wake-axis (black dash-dot) agrees well.

**Figure 9:** MATLAB-rendered traditional view of the spacecraft wake in the ionosphere. Ion losses generate an ion density depletion in the near and far-wake for meso-thermal conditions, that is, \( \tau_c \approx 1 \text{ s} \) for electron (ion) thermal velocities \( v_{\text{electron}} \) and \( v_{\text{ion}} \). The thermal wake of an uncharged 1.5U CubeSat has \( \text{O} \) thermal velocities away from the wake-axis (red) and towards the wake-axis (blue). Quasi-neutral holds for all regions outside the Mach cone.

**Figure 10:** The electrostatic plasma wake of a charged sphere with flowing potential \( \phi_c \approx 0.2 \text{ V} \). Ions with thermal velocities towards the wake-axis are shown in blue and those with thermal components away from the wake-axis are shown in red. Attracted species generate a density enhancement directly downstream the on-axis Mach cone.

**Figure 11:** The distance from the charged spacecraft at \( \phi_c \) perpendicular to the flow and through the spacecraft center \( \phi_c = 0 \) as a function of effective focusing distance \( \varepsilon \). Focusing distances by electrostatic lithium \( \varepsilon = (\varepsilon|x| - \phi_c) \) converge to focusing distances by purely thermal motions \( \varepsilon = (\varepsilon|x| - \phi_c) \). MATLAB particle trajectory solutions, \( x_e \) and \( x_i \) are initial and final ion positions along the \( z \)-axis; \( x_c \) is initial ion position along \( x \) and \( y \) is the spherical radius.

**Figure 12:** Normalized densities along the wake-axis. The binned densities of the electrostatic wake and thermal wake are in red and blue, respectively. The combined electrostatic-thermal and thermal densities show an ion enhancement of \( 3 \) above background (black).

**MATLAB: Validation of Ion-Focus Region**

**Conclusion**

The rudimentary plasma dynamics modeled in the MATLAB code depict a focus region in the far-wake. An ion density enhancement of \( 30\% \) over background resides between \( 1 \text{ m} \) \( \leq x \leq 5 \text{ m} \) and \( 3 \text{ m} \leq z \leq 5 \text{ m} \) for effective downstream distance \( \varepsilon \). This is in close agreement to the \( \varepsilon = 0 \) ion density enhancement at \( 0 \text{ cm} \) downstream as rendered by the SPIS model. Attitude control is essential for Langmuir probe measurements aboard CubeSats in the Earth’s ionosphere as this study suggests the common presence of low density enhancements that exceed \( 30\% \) over background levels in the far-wake structure. For a rudimentary 1.5U CubeSat model, the ion focus region extends \( \tau_c = 7 \text{ cm} \) downstream for \( x_c = 15 \text{ cm} \). An independent code has successfully reproduced the ion focus region behind a CubeSat in the Earth’s ionosphere as generated by SPIS. The CubeSat plasma wake in LED occurs a level of complexity not seen for larger spacecraft. Correct attitude solutions are required when considering ion density enhancements during the design stage of CubeSat Langmuir probes. Similarly, wake structure should be considered carefully prior to data selection of wake-axis Langmuir probes.

**References**


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