Identification of the principal characteristics of an Ionospheric LANGMUIR PROBE

for future satellite Space Missions

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Introduction

This study aims to model the response of a **Langmuir probe** in the **topside ionosphere** through **Particle-In-Cell (PIC)** simulations. Specifically, the research aims to characterize the perturbations induced by the spacecraft plasma sheath on Langmuir Probe measurements, with particular emphasis on the distortions affecting the **I-V characteristic curve** and the resulting biases in plasma parameter retrieval [1].

Plasma conditions representative of a **Super Solar Quiet** (**SSQ**) day were derived from the **International Reference Ionosphere** (**IRI**) model [2], selecting the "worst-case scenario" in terms of Debye length. Numerical simulations were performed using the **Spacecraft Plasma Interaction Software** (**SPIS**) framework [3].

Particular attention was devoted to the interdependence of input parameters. A **consistent hierarchy** was defined, identifying arbitrary variables and deriving both secondary plasma parameters and direct simulation inputs under physical and computational constraints.

This structured approach also highlighted the **limitations of the SPIS** code for high-resolution applications, notably the absence of **MPI-based multi-node parallelization**. As a consequence, the available computational resources set an upper limit on mesh refinement, constraining the resolution of the results.

Discussion and Conclusions

Despite the aforementioned computational constraints, the simulations produced physically consistent and interpretable results. Two geometries were considered: a **highly simplified configuration** and a semi-realistic representation of the **Langmuir probe onboard Swarm** spacecrafts, adapted from [4]. **Figure 2** shows that the electron distribution around the sensors is strongly perturbed by the expanding plasma sheath, which partially embeds the positively biased probe in an electron depletion region. **Figure 3** further demonstrates the resulting distortion of the I-V curve. Although spherical probes are adopted in both geometries, the corresponding I–V curves exhibit behavior more consistent with planar probe theory [5][6]. In particular, current in the electron saturation region reaches a plateau slightly below the theoretical value expected for a planar probe with an area of $2\pi r^2$.

These results suggest that **Orbital Motion Limited** theory (**OML**) conditions are not satisfied in this regime, as particle trajectories are disrupted by sheath effects and cannot complete full orbital motion. As a consequence, the collected current appears to be limited to the particles directly impacting the fraction of the probe surface not immersed in the depletion region. Although preliminary and constrained by the limitations of the numerical framework these findings provide a basis for further validation. Future work will focus on reproducing the simulations using **PTetra** [7], in order to assess the robustness of the results across different solvers.

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Simulation Paremeters

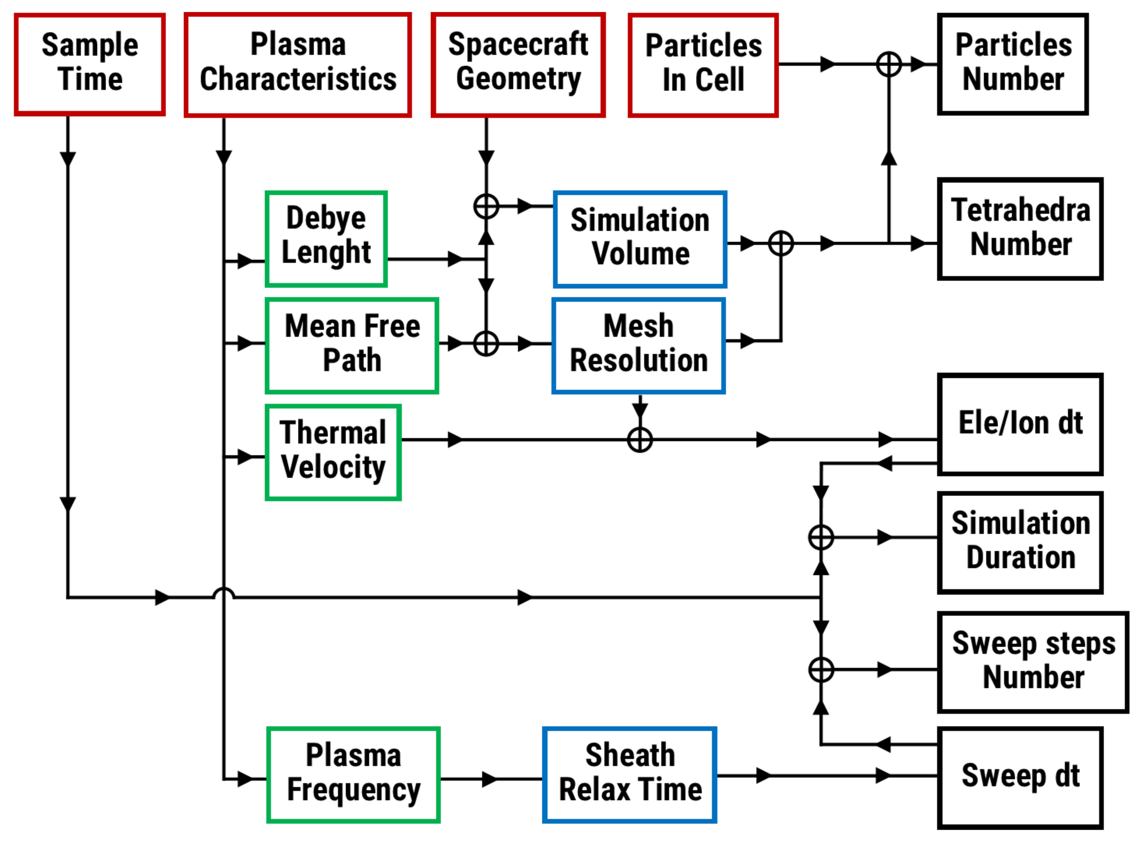

Figure 1. **Simulation parameters estimation scheme**. Red cells contain the starting parameters. Green cells contain the descriptive plasma parameter. Blue cells contain the secondary parameters. **Black** cells contain the final simulation input parameters.

Brief overview of the relationships among the parameters:

-> **Simulation Volume:** Must include the satellite geometry and extend several Debye lengths into the ambient plasma to minimize boundary effects.
-> **Mesh Resolution:** Defined to resolve both the Debye length and the mean free path.
-> **Sheath Relax Time:** Estimated as approximately four times the ion plasma period to ensure transient stability.

-> **Number of tetrahedra:** Determined by the discretization of the simulation volume at the chosen mesh resolution.
-> **Number of Particles:** Derived from the total number of tetrahedra and the required number of *particles per cell* (*PPC*) to minimize statistical noise.
-> **Electron/Ion Time Step:** Defined according to the *CFL* (*Courant-Friedrichs-Lewy*) condition, ensuring that particles do not traverse more than one cell per time step.
-> **Simulation Duration:** Set by the instrument sampling interval and the required temporal resolution.
-> **Sweep Time Step:** Must exceed the sheath relaxation time to ensure quasi-steady plasma conditions during measurements.
-> **Number of Sweep Steps:** Determined by the ratio between the total sweep duration and the sweep time step.

References

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Results

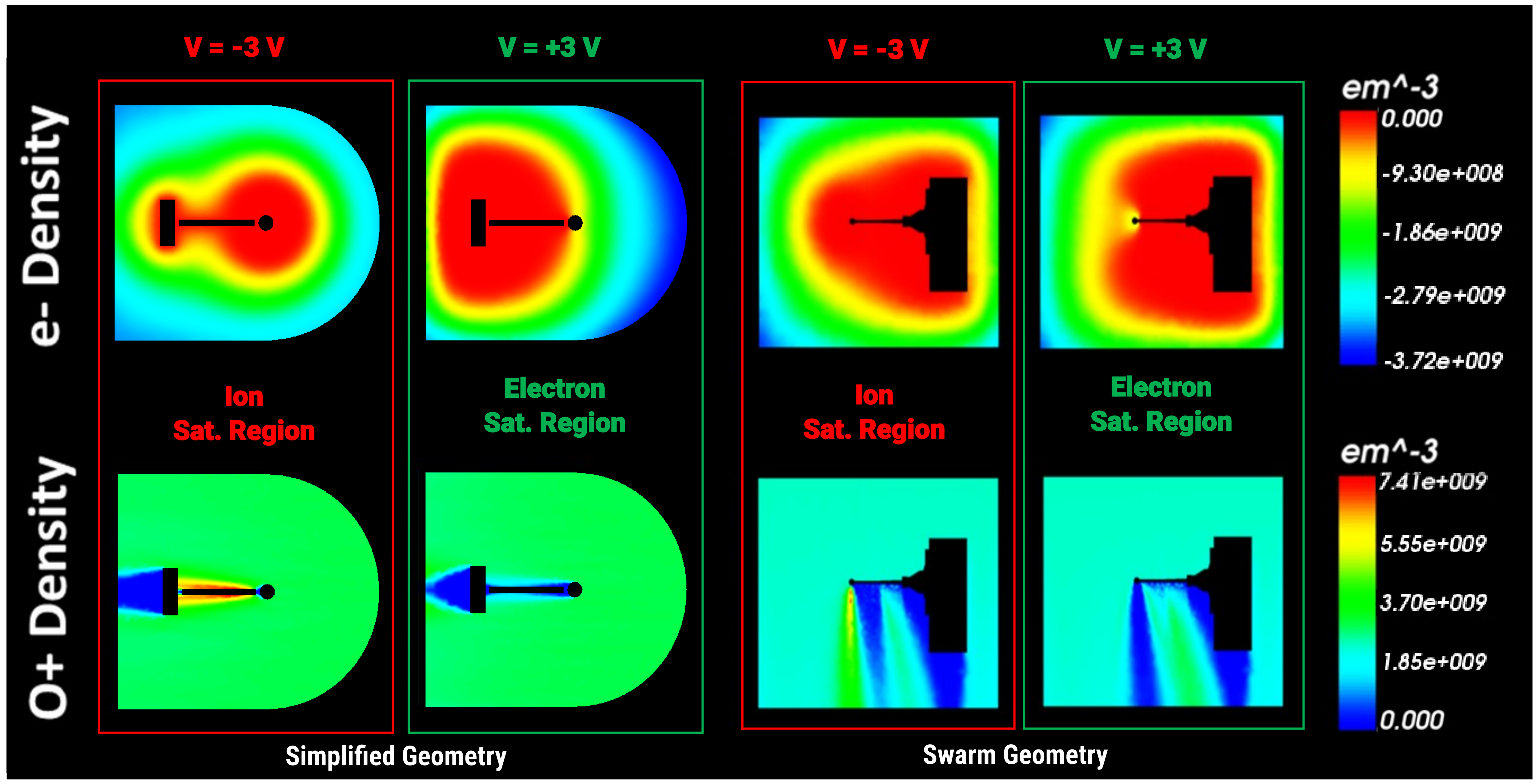

Figure 2. **Density distributions**, expressed in units of **elementary charge per cubic meter,** obtained from SPIS simulations of a simplified geometry (probe, boom, and spacecraft body, four panel on left) and Swarm-like geometry (four panel on right). The simulated electron density is shown in the first row and according to colorbar, **red** indicates the minimum electron density while **blue** represents the maximum. In the ion density, which is shown in second row, the color scale in the colorbar is reversed. Plots **framed in red boxes** correspond to negative probe bias, representing the ion saturation regime. Plots **framed in green boxes** correspond to positive probe bias, representing the electron saturation regime. In the four plots on the left, spacecraft is assumed to move **from left to right**, while in the four plots on the right, spacecraft is assumed to move **from bottom to top**.

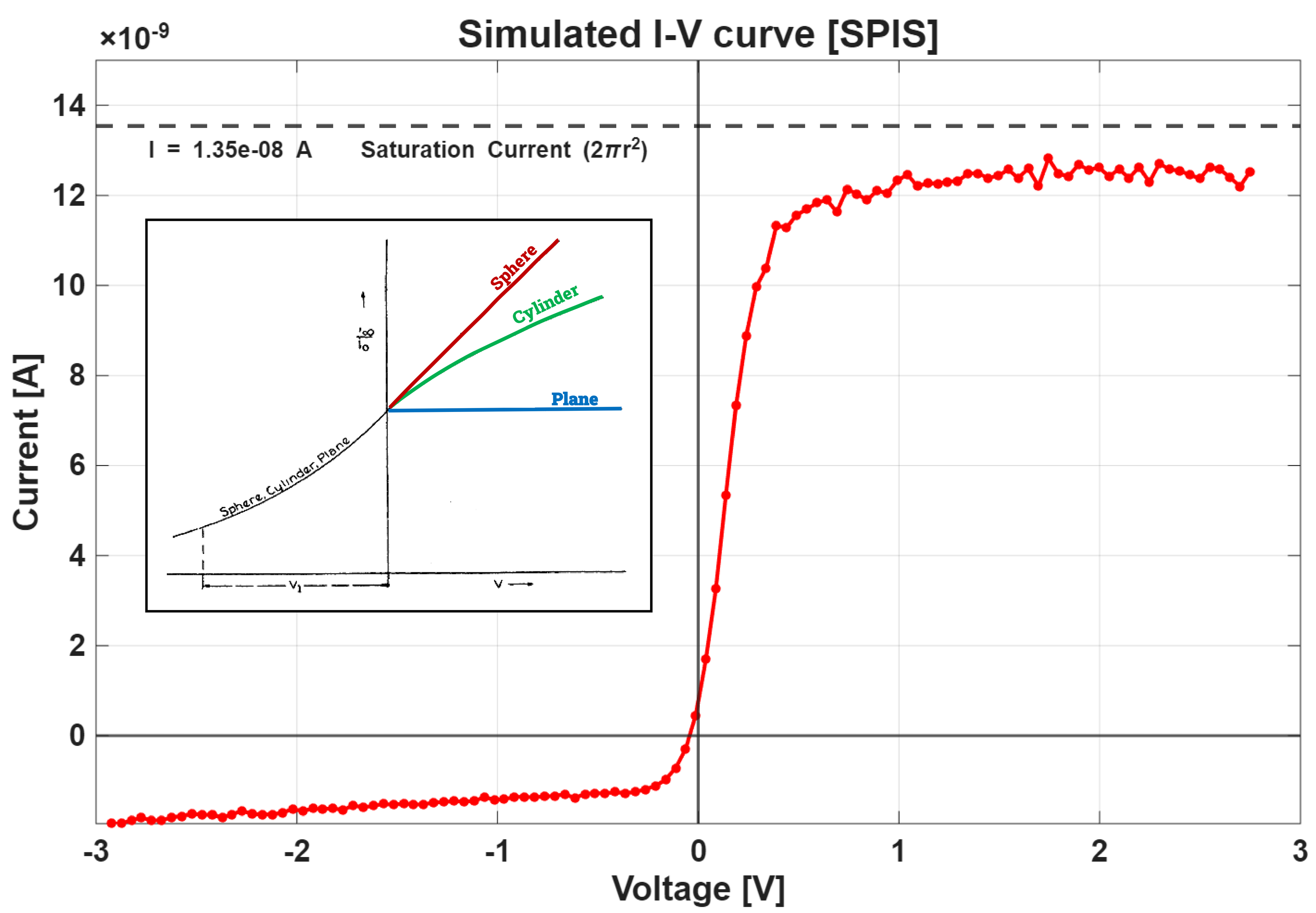

Figure 3. **Plasma characteristic I–V curve generated** by a SPIS simulation of the simplified geometry immersed in a topside ionosphere.

In the box, the **Plasma characteristic I–V curve** obtained by a **spherical** (red), **cylindrical** (green) and **planar** (blue) probe, considering a Maxwellian plasma.

In the table, the main plasma parameters identified as the worst-case scenario in terms of plasma sheath dimensions, corresponding to a super solar quiet day (01 December 2008).

Parameter	Value
Species	e^-, O^+
Electron density n_e	3.040E+9 m^{-3}
Ion density n_i	3.040E+9 m^{-3}
Electron temperature T_e	0.07 eV
Ion temperature T_i	0.07 eV
Magnetic Field B	-
Debye Length λ_D	0.03381 m