Simulation of Space Platform Charging in Very Low Earth Orbit with Particle Methods

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This contribution aims to explore the physics of the interaction between spacecraft and charged particles in the ionosphere, specifically within Very Low Earth Orbit (VLEO). Employing particle methods, the primary objective is to simulate and comprehend the charging processes on spacecraft surfaces, concurrently revealing the resulting electric potential structure around the spacecraft. In addressing the VLEO conditions, particle methods are prominent for their accuracy, but also computationally most demanding.

VLEOs are essentially placed within the ionosphere, a region comprised of charged particles from atmospheric species such as oxygen ions O^+ and nitric oxide ions NO^+ [1]. The presence of these particles is a result of atmosphere gas ionization from solar radiation, with charge particle density distribution dependent on current solar activity [2, 3, 4]. It is essential to note that in VLEO and LEO conditions, drag caused by neutral particles becomes also highly significant.

To simulate spacecraft-plasma interaction physics, we employ PANTERA [5], a specialized numerical software developed in-house at the von Karman Institute. PANTERA utilizes Particle-In-Cell (PIC) plasma modeling [6] coupled with Monte Carlo collisions [7]. Spacecraft geometry, whether in 2D or 3D, is reconstructed on finite grids, particularly unstructured grids, representing the physical domain for numerical simulation. GMSH [8], a powerful open-source mesh generator, is instrumental in generating such geometries. This software allows for the creation of high-quality unstructured meshes, offering flexibility and accuracy in representing complex geometrical structures.

A common numerical simulation consists of a sphere interacting with plasma in the ionosphere at given altitude. An example result of such simulation is shown in Figure 1. The physical domain is represented in 2D axisymmetry to simulate a flow of oxygen ions O^+ and electrons e^- being injected from left boundary with velocity given by the orbit speed of the sphere. The important distributions are found, such as the electric potential shown in a) which shows the resulting floating potential on the sphere orignating from the plasma-spacecraft interaction.

Despite the establishment of theoretical backgrounds and experiments, the interaction between the charged particles and the spacecraft remains not completely understood. Numerical simulations utilizing particle methods, where individual charged particles of the ionosphere are simulated independently, are crucial for understanding the fundamental process of space platform charging [9]. However, in current scientific simulations, electrons in the ionosphere are often treated as a fluid using *the Boltzmann electron fluid model* for the sake of the improvement of computational efficiency.

This contribution aims to investigate accuracy and limitations of the Boltzmann electron fluid model through a direct comparison between full particle and particle (ions)-fluid (electrons) representations. Particular focus will be aimed on simulations of a specific phenomenon known as ionospheric drag: enhanced drag on the charged spacecraft caused by the direct interaction with ionospheric plasma.

[1] J. A. Bittencourt, *Fundamentals of Plasma Physics*, (2004), DOI: 10.1007/978-1-4757-4030-1

[2] C. T. Russell, J. G. Luhmann, and R. J. Strangeway, *Space Physics: An introduction*, (2016), University of California, ISBN: 9781107098824

[3] D. Bilitza, M. Pezzopane, V. Truhlik, D. Altadill, B. W. Reinisch, and A. Pignalberi, *The International Reference Ionosphere Model: A Review and Description of an Ionospheric Benchmark*, Reviews of Geophysics **60 4**, (2022), DOI: 10.1029/2022RG000792

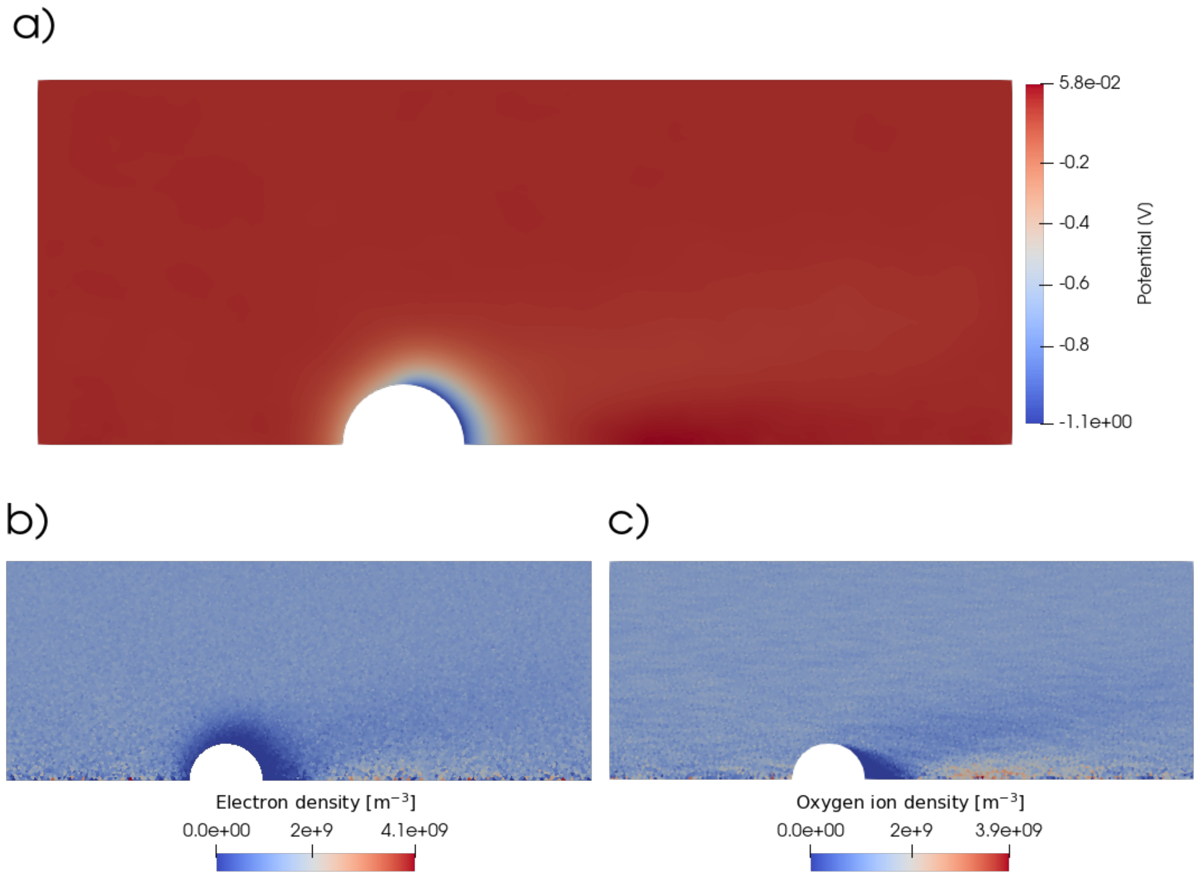

Fig. 1: Simulation of a sphere in 2D axisymmetry in orbit at altitude $h = 200$ km (flight direction is to the left). Here a) is the electric potential, b) is the electron density and c) the oxygen ion density.

[4] J. M. Picone, A. E. Hedin, D. P. Drob, and A. C. Aikin, *NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues*, Journal of Geophysical Research: Space Physics **107 A12**, (2002), DOI: 10.1029/2002JA009430

[5] P. Parodi, D. Le Quang, G. Lapenta and T. Magin, *Particle-in-Cell simulation of the VKI DRAG-ON facility*, AIAA 2024-2710, (2024), DOI: 10.2514/6.2024-2710

[6] G. Lapenta, *Particle In Cell Method: A brief description of the PIC method*, Katholieke Universiteit Leuven

[7] C. K. Birdsall and A. B. Langdon, *Plasma physics via computer simulation*, (1991)

[8] C. Geuzaine and J.-F. Remacle, *Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities*, International Journal for Numerical Methods in Engineering **79(11)**, (2009)

[9] R. Marchand and P. A. Resendiz Lira, *Kinetic Simulation of Spacecraft–Environment Interaction*, IEEE Transactions on Plasma Science **45 4**, (2017), DOI: 10.1109/TPS.2017.2682229