Interpretation of Langmuir probe data obtained close to a spacecraft

A. I. Eriksson, T. Nilsson, J.-E. Wahlund

Swedish Institute of Space Physics, Uppsala

We use the Spacecraft Plasma Interaction System (SPIS) simulation code to gain insight in the measurements by the Langmuir probe (LP) on Cassini. SPIS is an open source code, sponsored by the European Space Agency (ESA) and available at `http://www.spis.org`. SPIS includes modules to first model a spacecraft of any geometry, then to iteratively simulate its interaction with the space plasma by calculating the plasma flow around it with a particle-in-cell approach, computing the charging of the spacecraft surfaces and solving the Poisson equation for the potential around it, and finally to post-process and visualize the result [1].

The Cassini LP forms part of the Radio and Plasma Wave Science instrument [2]. Since the Cassini arrival at Saturn in 2004, the LP has been used to explore plasmas varying by more than six orders of magnitude in density, from a few times 10^{-3} cm^{-3} in the magnetotail lobes to a few times 10^3 cm^{-3} in the densest regions of Titan's ionosphere [3]. Cassini is a big spacecraft, some 6.8 m in height, with the spherical LP (diameter 5 cm) mounted on a 1.5 m boom, so some influence from the spacecraft on the LP measurements is inevitable. We use SPIS (version 4.3.1) to explore some consequences of this for a stationary unmagnetized plasma.

At left in Figure 1 is an example LP bias voltage sweep of a type sometimes observed in dense plasmas. This particular example is from the plasma disk just outside the orbit of Enceladus [3]. As the bias voltage U_{bias} increases from zero, the measured current to the probe, I_{p}, mainly due to electron collection, increases moderately up to about 13 V bias, then with a steeper slope at higher bias voltage. Such two-stage behaviour is not found from simple theory of a spherical probe in a homogeneous plasma, but may be expected in the vicinity of a negative (electron repelling) spacecraft [4, 5]. When negative with respect to its close surroundings, I_{p} increases exponentially with voltage: this can be seen in the $\frac{\mathrm{d}I}{\mathrm{d}U}$ plot below about +3 V bias, signifying that the potential in space at the position of the probe is about 3 V more positive than the spacecraft. The spacecraft is thus negatively charged with respect to the surrounding plasma, as expected in a dense plasma. Between about 3 and 13 V, $\frac{\mathrm{d}I}{\mathrm{d}U}$ first grows slowly, then faster, to finally level out at an approximately constant value at higher bias voltages. This can be due to the potential structure from the probe, now positive with respect to its immediate neighbourhood but not to infinity because of the potential field from the spacecraft, gradually opening a breach in the barrier raised by the electron repelling spacecraft potential as illustrated in the cartoons at right in Figure 1. Finally, above about 13 V, electrons from the surrounding plasma are more or less

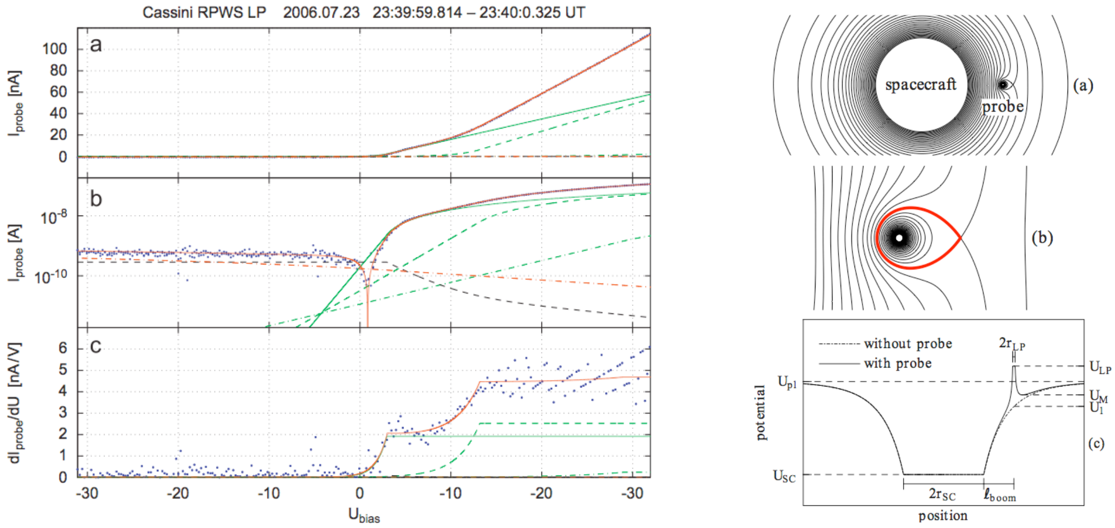

Figure 1: *Left*: A Cassini RPWS-LP probe bias sweep. Data plotted as blue dots, a model fit in solid red, and various partial currents of this model as dashed curves. Top plot is lin-lin, centre plot is lin-log, and lowest plot shows the derivative. From [3]. *Right*: Illustration of mechanism of electron barrier formation and opening around a negative spacecraft. From [5].

freely collected, resulting in a constant slope of the probe characteristic.

Due to the disparate size of the two objects, full SPIS simulations of the Cassini LP and the Cassini s/c are impractical until the improved SPIS-Science code, now under development, is completed and released [6]. However, the essential physics of this situation is captured by an idealization of the spacecraft and the probe as separate spheres. For this situation, there is an analytical model by Olson et al. [5], assuming collection of electrons with energy above the last close equipotential (red in Figure 1, right column, plot (b), denoted U_M) as if from a homogeneous infinite plasma of density $\exp(eU_M/KT_e)$ times the ambient density, thus ignoring effects of particle absorption on the spheres. To find U_M and U_1, the potential at the location of the small probe had it not been there, a simple Debye law, $\exp(-r/\lambda_D)/r$, is used in [5].

We set the sphere radii to 0.15 and 0.4 m, electron temperature $T_e = 0.33$ eV and large sphere potential $V_s = -1$ eV. We have simulated four densities, equivalent to Debye lengths λ_D of 1.22, 1.98, 2.73 and 4.21 m, and four distances d between the sphere centres: 0.70, 0.85, 1.00 and 1.50 m. For each combination, simulations were done for several potentials of the small sphere, to provide a probe characteristic.

The parametric dependence found in the simulations is summarized in Figure 2, showing the ratio of the actual slope $\frac{dI}{dU}$ at large positive bias potential (the region above 13 V at left in Figure 1) to what it should have been if the large sphere did not perturb the plasma. This also becomes the ratio of observed to real density if the sweep is analyzed with standard OML theory [3]. In the corner of shortest λ_D and largest d, the ratio is nearly one, meaning that the full current expected for a free probe is sampled. As expected, I_p decays with increasing λ_D and with decreasing d.

Figure 3 shows probe characteristics for the small sphere from two simulations. The left plots shows I_p practically undisturbed by the large sphere outside its Debye sphere, with good agreement between all curves. At right, we find a significant decrease in I_p inside the sheath of the big sphere. The model from [5] is clearly better than the single-sphere OML model, though it differs quantitatively from the simulation. To see if this is due to the crude assumption of a Debye law for the potential (see above), we replaced the value of U_M obtained in that way by [5] by the actual value of this minimum potential extracted from our SPIS simulations. As can be seen, this has very small impact on the result. We conclude that the quantitative problems of the model in [5] are not caused by the Debye potential, but more likely the assumption of free collection from a reservoir at potential U_M, or the simplified density suppression by a Boltzmann factor not taking absorption by the large sphere into account [4]. This points to possible directions for improving the model.

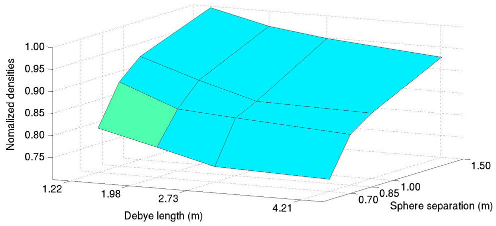

Figure 2: Normalized inferred electron density from simulated probe sweeps, if interpreted by OML theory [3], as function of λ_D and d.

Comparing Figures 3 and 1, the simulations show no sign of the quite clear two-slope behaviour of the probe characteristic seen in data. When the improved SPIS-Science code becomes available [6], it will be interesting to see if a realistic ratio between s/c and probe sizes will give better agreement.

Acknowledgments

The main SPIS sponsor is ESA, with most of the development done by ONERA in Toulouse and Artenum in Paris. We thank the Spacecraft-Plasma Interactions Network in Europe (SPINE) and the ISSI working group on interaction of satellites with the space environment for input and discussions, particularly L. Gayetsky (Dartmouth), A. Hilgers (ESA/ESTEC), J.-P. Lebreton (LPCE Orléans), R. Marchand (U. Alberta) and J.-C. Máteo-Vélez (ONERA).

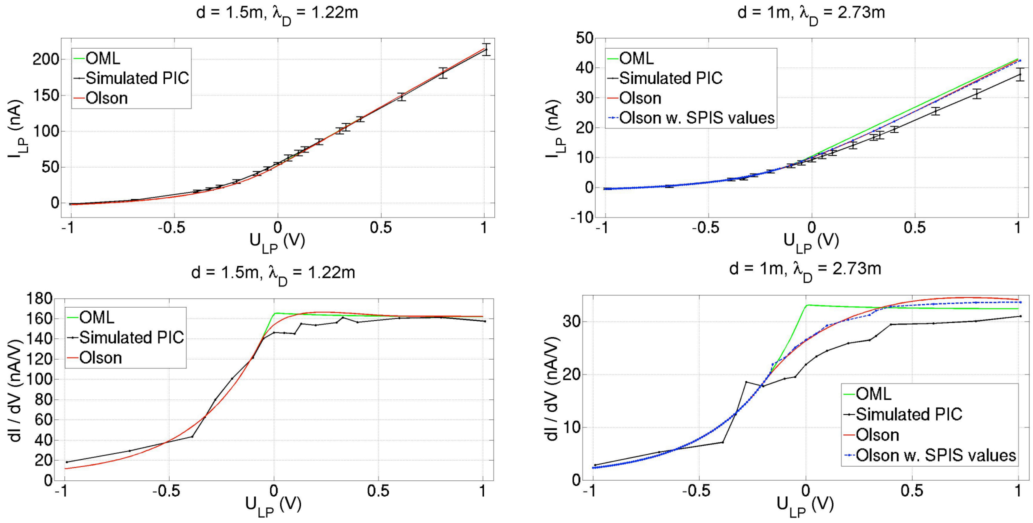

Figure 3: Simulated probe characteristics (top) and their derivatives (bottom) for the small sphere, for $\lambda_{\mathrm{D}} = 1.22$ m, $d = 1.5$ m (left) and $\lambda_{\mathrm{D}} = 2.73$ m, $d = 1.0$ m (right).

References

[1] J.-F. Roussel, F. Rogier, G. Dufour, J.-C. Mateo-Velez, J. Forest, A. Hilgers, D. Rodgers, L. Girard, and D. Payan, “SPIS Open-Source Code: Methods, Capabilities, Achievements, and Prospects,” *IEEE Trans. Plasma Sci.*, vol. 36, pp. 2360–2368, Oct. 2008.

[2] D. A. Gurnett et al., “The Cassini Radio and Plasma Wave Investigation,” *Space Sci. Rev.*, vol. 114, pp. 395–463, Sept. 2004.

[3] J.-E. Wahlund, M. Andre, A. Eriksson, M. Lundberg, M. Morooka, M. Shafiq, T. Averkamp, D. Gurnett, G. Hospodarsky, W. Kurth, K. Jacobsen, A. Pedersen, W. Farrell, S. Ratynskaia, and N. Piskunov, “Detection of dusty plasma near the E-ring of Saturn,” *Planet. Space Sci.*, vol. 57, pp. 1795–1806, 2009.

[4] J. G. Laframboise and R. Godard, “Perturbation of an electrostatic probe by a spacecraft at small speed ratios,” *Planet. Space Sci.*, vol. 22, pp. 1145–1155, 1974.

[5] J. Olson, N. Brenning, J. Wahlund, and H. Gunell, “On the interpretation of Langmuir probe data inside a spacecraft sheath,” *Rev. Sci. Instr.*, vol. 81, pp. 105106–+, Oct. 2010.

[6] J.-C. Matéo-Vélez, P. Sarrailh, B. Thiébault, J. Forest, A. Hilgers, J.-F. Roussel, G. Dufour, B. Rivière, V. Génot, S. Guillemant, A. Eriksson, C. Cully, and D. Rodgers, “SPIS Science: modelling spacecraft cleanliness for low-energy plasma measurement,” in *Proceedings of the 12th Spacecraft Charging Technology Conference (SCTC-12)*, JAXA, 2012.