Kinetic modelling of particle distribution measurements in DEMETER

R. Marchand[1,2], J.-J. Berthelier[1]

[1] *CETP/CNRS, Saint-Maur-des-Fossés, France*

[2] *University of Alberta, Edmonton, Canada*

DEMETER was launched in June 2004 and placed on a nearly circular orbit around Earth with the main scientific objective of studying possible correlations between iononspheric disturbances, and geophysical phenomena such as earthquakes. The orbit is polar ($98^\circ inclination$) and quasi heliosynchronous, with dayside passage at approximately 10:30 local time over a broad range of latitudes, and a night side passage at approximately 22:30 local time. The instruments onboard DEMETER include electric and magnetic sensors, thermal ion and energetic particle analysers, and Langmuir probes. These have been described in [1], [2], [3] and references therein. IAP, located near a corner, on the upstream face of DEMETER, is used to measure ion particle distributions in the rammed ionospheric plasma. Given the orbital DEMETER velocity of $7500m/s$, and usual natural plasma flow velocities $\leq 200m/s$ at mid latitudes, deviations between the direction of the incident plasma flow and the direction of propagation are expected to be $\leq 2^\circ$. Yet, larger angles are frequently observed, as illustrated in Fig. 2. In the figure, the two angles ϕ and θ correspond to the horizontal and vertical directions respectively. In this example of observed large deviation angles, while the horizontal angle is typically less than 2° as expected, the vertical angle ranges typically between -5° and 8° along a single half orbit. If these angles corresponded to actual lateral plasma flows, the corresponding velocities would be in excess of $600m/s$, which is unlikely along DEMETER orbits. In addition to transverse plasma flows, which would account for only part of the observed phenomenon, a possible explanation would involve lensing and distortion of incident particle trajectories by the electrostatic sheath that surrounds the satellite. This possibility is examined in what follows, by calculating the interaction of DEMETER with the surrounding ionosphere for representative plasma conditions. For that purpose use is

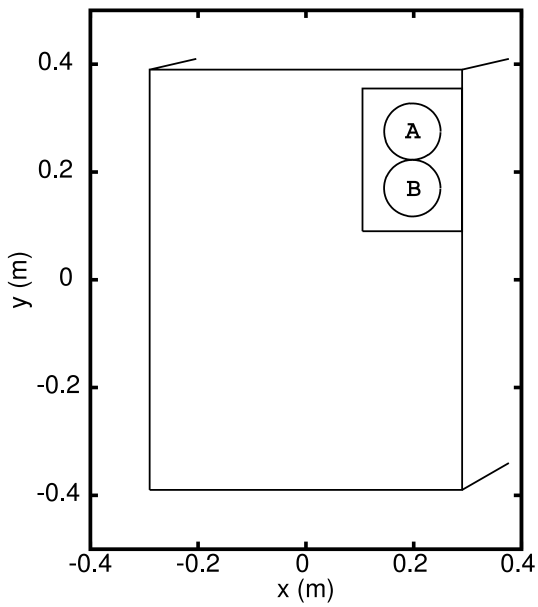

Figure 1: Illustration of IAP in the upper right corner of the ram face of DEMETER.

made of a 3D PIC code with an unstructured tetrahedral mesh capable of accurately representing the satellite geometry. The computed electrostatic field surrounding the satellite is then used as input in a test-kinetic code ([4], [5]) to calculate the ion distribution function at IAP. The resulting distributions are then integrated to obtain moments that can be compared directly with observations. In this first step in the analysis of sheath effects on measured particle distribution functions, the following simplifying assumptions are made: 1) The plasma is assumed to be unmagnetised, 2) Only O^+, which is the usual dominant ion species at DEMETER altitudes (see Fig. 2) is taken into account, 3) Both ions and electrons are assumed to have the same temperature and 4) The spacecraft is approximated by a single floating (with zero net current) rectangular prism. In particular, booms and differential biasing between their different elements are not taken into account. Despite these simplifications, the resulting analysis should provide insight into the possible effect of lensing and on the magnitude of the resulting distortions in the measured plasma flow. As usual, the plasma is assumed to be electrically neutral, with $n = n_e = n_{O^+}$ sufficiently far from the spacecraft.

The first case considered is for a plasma with density $n = 10^{10} m^{-3}$, and temperature $T = 0.2eV$, corresponding to a Debye length $\lambda_D \approx 3cm$. The outer boundary of the simulation domain is a rectangular prism from where the distribution function of the incoming plasma is imposed, and on which the electrostatic potential is set to zero. The outer boundary is sufficiently far from the satellite ($\sim 1m$) for the solution near the satellite to be approximately independent of its exact position. The mesh used is generated with the public domain mesh generator gmsh [6]. The scalar potential ϕ is obtained at each time step by solving Poisson's equation using the method of finite elements and a GMRES iterative solver, with Sahad's incomplete LU preconditioning [7]. In our calculations we used a mesh with 66433 nodes, 397643 tetrahedral elements, and the number of particles (ions or electrons) ranged between 0.95 and 1.3 millions. The simulation is carried forward in time until a steady state is reached.

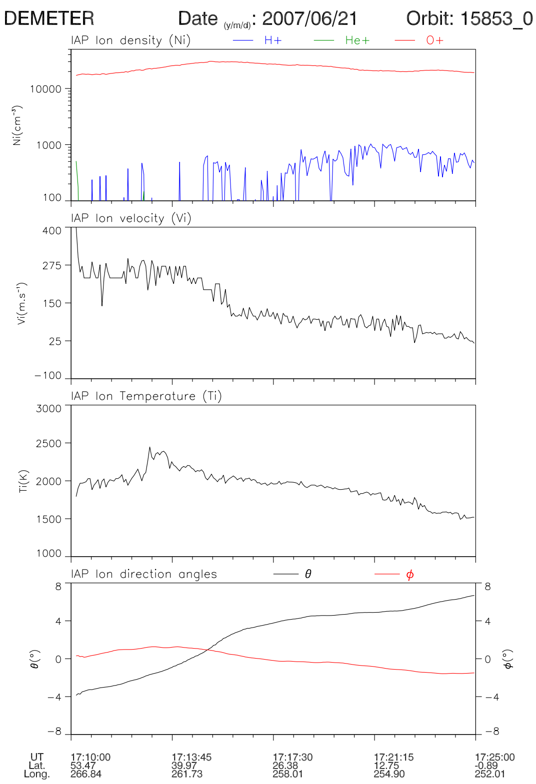

Figure 2: Example of ionospheric plasma parameters along a dayside DEMETER orbit.

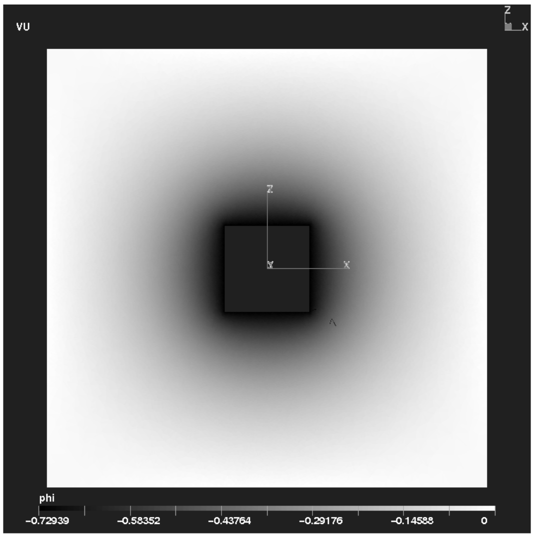

Figure 3: Profile of the scalar potential ϕ computed with density $n = 10^{10} m^{-3}$.

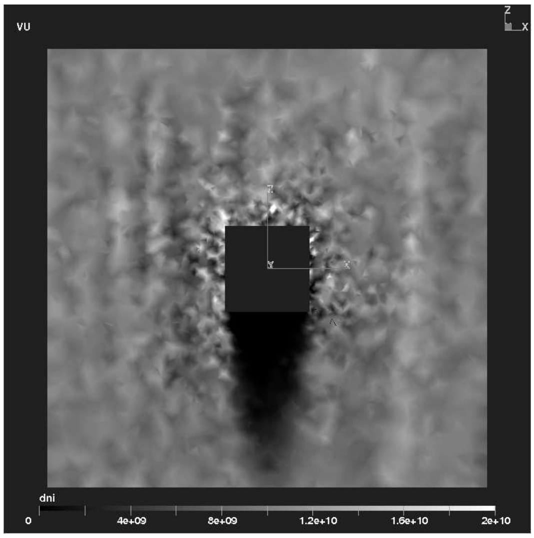

Figure 4: Profile of the oxygen ion density computed with density $n = 10^{10} m^{-3}$.

A useful diagnostic for recognising a near steady state is provided by the time evolution of the number of particles in the simulation domain, and the satellite floating potential. In these simulations, a steady state is reached within $0.6ms$, when the spacecraft floating potential becomes $\phi_{sc} \sim -0.73V \sim 3.6k_BT$, which is in good agreement with Langmuir Probe theory. The resulting potential and ion density profiles in a cut plane parallel to the incoming plasma flow are illustrated in Figs. 3 and 4. The electrostatic field surrounding the satellite affects the distribution function in two ways. First, incident ions are energized, and second, their trajectories are deflected on average, due to the fact the surfaces of constant ϕ are not orthogonal to the mean incident velocity. The induced asymmetry is conveniently parametrised in terms of the angles ϕ and θ which measure deflection in the x and y directions respectively. Thus, making use of the fact that $v_x, v_y \ll v_z$, ϕ and θ are defined as $v_x = v_z sin(\phi)$ and $v_y = v_z sin(\theta)$, where v_x, v_y and v_z are the x, y, z components of the average flow velocity obtained from moments of the distribution function. Computing these angles at positions A, and B in Fig. 1, we find respectively $(7.1^\circ, 7.6^\circ)$ and $(7.3^\circ, 0.4^\circ)$, for (ϕ, θ). As expected from the profile of the electrostatic potential around the satellite, the average velocity of particles striking near the edge of the ram face, have a transverse component directed toward the centre of the plate. At point A, both angles ϕ and θ are of the same magnitude (Point A is nearly equidistant from the top and right edges). In contrast to θ, which decreases as the distance from the top edge increases, ϕ remains approximately unchanged at points B. A second case was also considered for a density $n = 10^9 m^{-3}$, all other parameters being the same as in case 1. The corresponding Debye length $\lambda_D \sim 0.11m$ is a little larger, and the electrostatic sheath extends correspondingly farther from the satellite. The results are otherwise similar to those obtained with the higher density. In particular, the distribution functions computed at points A and B (see Fig. 1) yield deflection angles that are comparable to those found in the first case.

In summary, plasma-satellite interaction is studied with a a 3D PIC simulation code, combined with a test-kinetic approach based on particle back-tracking and the use of Liouville's theorem. The 3D PIC method is capable of describing detailed satellite geometry while accounting for effects such as mutual capacitances, relative biasing, and currents emitted or collected by different spacecraft components. Our results show that, under ionospheric plasma conditions representative of dayside DEMETER orbits, electrostatic sheath effects may be responsible for deflections that are comparable, in magnitude, with those observed with IAP. In particular, deviation angles in the direction of the incoming ion flux ranging from 4° to 7° are calculated at the location of IAP. The calculated deviation angles, however, are always positive, consistently with the curvature of the computed equipotential surfaces near IAP. This is in contrast with observations, where both positive and negative deviation angles are measured. Observed horizontal deviations (ϕ) are typically smaller than vertical deviations (θ) while, from our calculations, both ϕ and θ are comparable in magnitude. In conclusion, it should be noted that a number of physical effects are simplified or neglected in this analysis. In addition to the approximations already stated, biasing of the relative spacecraft components, the resulting currents collected and emitted, and the variable solar illumination of the spacecraft should be mentioned. Given the discrepancies between model predictions and observations, it appears that a more complete analysis including such effects is required in order to fully understand IAP measurements.

References

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