Sheath effects on particle sensor measurements in DEMETER and Swarm

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Outline

Objective

1. Assess the effect of electrostatic sheath that surround a satellite and its instruments on:
    - measured ion flows,
    - measured particle distribution functions.
2. How? Model the interaction of satellites and their instruments with space plasmas with:
    - realistic Geometry,
    - representative plasma conditions,
    - sufficiently complete physics.
3. 3D PIC modelling with PTetra
    - Realistic mass ratios.
    - Multiple electron and ion species.
      Each species has its density, temperature and drift velocity.
      Ions species have their specific mass and charge.
4. Test-particle modelling combined with Liouville's theorem.

General features of PTetra

1. Written in Fortran 90.
2. The code does exclusively particle pushing for a given mesh (geometry) and set of boundary conditions.
3. Other tasks such as
   - mesh generation,
   - definition of boundaries and boundary conditions (material properties or "physicals",
   - visualisation and simulation analysis.

   Must be done separately with proprietary or open source software.

Mesh generation - boundaries

1. gmsh
   - open source,
   - easy to use,
   - produces “reasonable” meshes for simple geometries,
   - difficult to have good quality meshes with complex geometries or when very different spatial resolutions are required.
2. cubit
   - proprietary (Sandia National Lab, $300 US),
   - full GUI, requires non negligible learning,
   - good diagnostics and mesh improvement tools,
   - can require a lot of RAM (up to 17 GB on some Swarm problems).
3. In house mesh generator
   - useful for simple geometries (cubes rectangular prisms),
   - produces very regular meshes.

Visualisation

1. May be done as a simulation is running or after completion.
2. Requires geometry (mesh) and output files produced by the code (periodically or upon request).
3. No tight connection with a particular visualisation program.
   The only requirement is output files in the proper format (tecplot, vtk, ...). Those can easily be generated by the user.
4. Software used so far
   - paraview: Open source
   - Vu: proprietary, www.invisu.ca

Result analysis

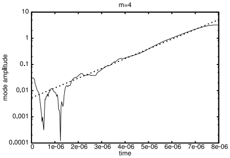
1. All analyses are done separately from PTetra.
2. The simplest ones consist of curve plotting.
   This is done from an output file listing standard parameters (voltage of surface elements, accumulated charges, currents, etc) as a function of time.
3. Backtracking test-particle code.
   Used to calculate distribution functions at precise positions in space without statistical errors associated with Monte Carlo simulations.

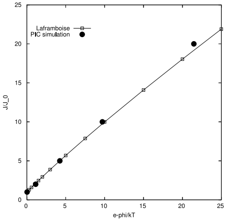
Other features

1. Plasma without satellite: useful for testing basic physics.
2. Photoelectrons:
   - Calculation of illumination of every surface element,
   - emission with empirical energy and angular distributions.
3. Option to generate a restart file.
4. Multiprocessor version using mpi.
5. Relative potential differences between surface elements may be specified, but the overall floating potential of the satellite must be calculated self-consistently from accumulated charges.
6. Missing:
   - secondary electrons,
   - magnetic field (coded, but tests are incomplete).

Validation - comparisons with other models

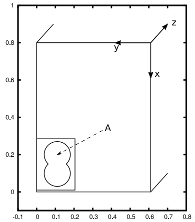
- Comparisons with SPIS.
- Two-stream instability in an empty box. Exponential growth was found up to two orders of magnitude, in agreement t with theoretical growth.
- Characteristic of spherical probes: comparison with calculations by Laframboise.

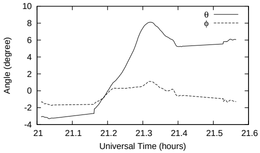




DEMETER - Rationale

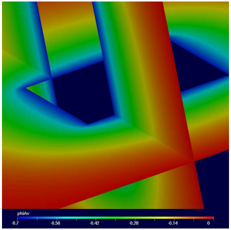
- The deviation of the incoming plasma flow from the ram direction, measured by the ion drift meter in IAP is anomalously large.
- We investigate the effect of the electrostatic sheath on the possible deflection of incoming ions.

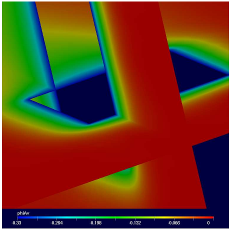




$n - T$ parameter space survey

- Simulate the sheath on a 9-point array in $n - T$ parameter space, with $n = 10^8$, 10^9, $10^{10} m^{-3}$, $T = 0.1$, 0.2, $0.5 eV$.
- Assume 20% H^+, 80% O^+ in all cases.
- Compute the distribution functions using test-particle back-tracking and Liouville's equation, and assuming flow velocities far from the sheath, exactly in the ram direction. Note that this is done separately from the PIC code.

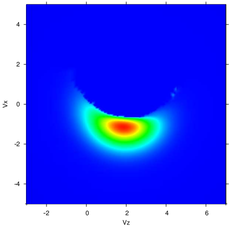


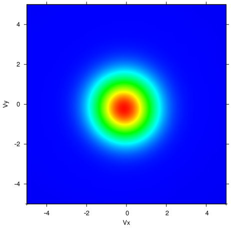


Ion distribution functions

- Example distribution functions f of H^+ in two cut planes in velocity space.
  These were computed at the centre of the ion drift meter aperture (arrow A in the figure above).
- Compute the first moments of f to get the ion flow $\vec{\Gamma}_i$ for each species i.
- Compute the deflection angles from

$$\tan\phi = \frac{\Gamma_y}{\Gamma_z} \quad \text{and} \quad \tan\theta = \frac{\Gamma_x}{\Gamma_z}.$$





Deflection angles

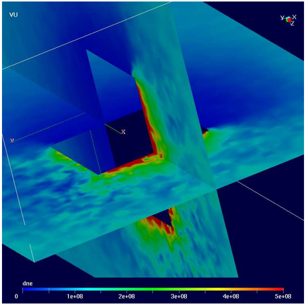
Table: Calculated deflection angles

$T \backslash n$	$10^8 m^{-3}$	$10^9 m^{-3}$	$10^{10} m^{-3}$
$0.1eV$	$\theta = -0.40°$ $\phi = -0.63°$	$-0.22°$ $-0.31°$	$-0.20°$ $-0.01°$
$0.2eV$	$\theta = -0.85°$ $\phi = -1.28°$	$-0.48°$ $-0.86°$	$-0.25°$ $-0.13°$
$0.5eV$	$\theta = -1.91°$ $\phi = -2.65°$	$-1.36°$ $-2.19°$	$-0.41°$ $-0.94°$

These angles don't add up to the large ($> 2°$) measured values.

Photoelectron effects

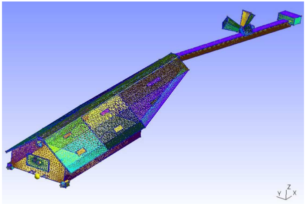
- Simulations were repeated with solar radiation from various angles.
- Differences in the electron volume charge density were found, but the net effect on deflection angles was small.

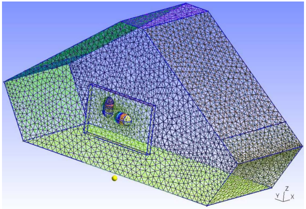


- For $n = 10^8 m^{-3}$, $T = 0.2eV$, the deflection angles are $\theta = -1.05°$, $\phi = -1.55°$.
- Without photoelectron effects, we found $\theta = -0.85°$ and $\phi = -1.28°$.
  This corresponds to a difference of less that 25%.

Swarm - rationale

- EFI will provide detailed 3D measurements of ion distribution functions and bulk flow.
- We consider possible distortion effects related to the sheath surrounding the instrument.
- The vicinity of EFI is modelled using a simplified Swarm geometry.





Biasing scenarios

- The bias of the face plate can be varied, with respect to the body of the spacecraft.
- The contact potential of the gold ring surrounding the aperture of EFI also needs to be accounted for.

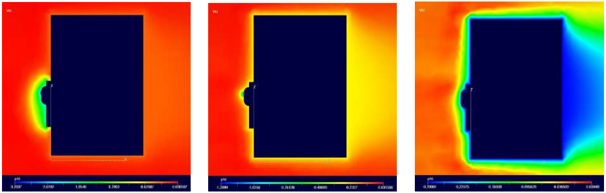
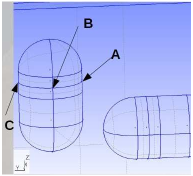
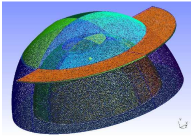


Figure: Potential profile near EFI for three relative biasing scenarios: $V_{FP} = -2V$, $V_{AU} = -3V$ (left), $V_{FP} = 0V$, $V_{AU} = -1V$ (left), $V_{FP} = 0V$, $V_{AU} = -0V$ (left).

Ion distribution functions around the slits

- The test-particle code is used to compute O^+ and H^+ distribution functions at several points around the entrance of the sensors.
- These are then interpolated and used to track particles inside the detector, down to the sensor plates.

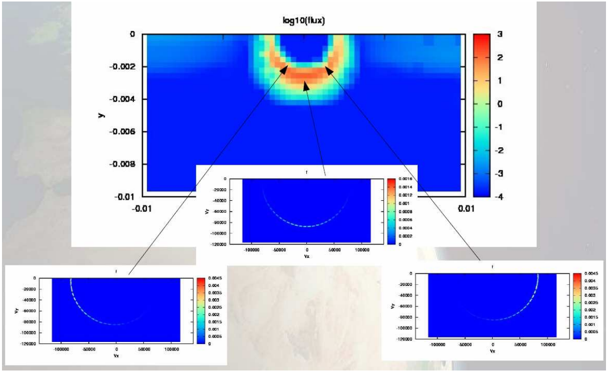




Ion fluxes and distributions (H^+)

From particle tracking and Liouville's theorem, we calculate

- fluxes on each pixel of the sensor plate (top figure),
- particle distribution functions in a cut plane of velocity plate in each pixel (lower figures).



Summary and conclusion

- Electrostatic sheaths can deflect ions in their approach to particle sensors.
- This will impact measurements of ion flow made with ion drift meters or distribution functions made with instruments such as EFI on Swarm.
- Calculated deflections cannot account for the large anomalies observed with the DEMETER drift meter.
- Photoelectrons have a relatively small effect with plasma parameters representative of DEMETER orbits.
- Magnetic fields, in particular, in combination with photoelectrons might have a more significant impact. This is currently under development.