PTetra: A Spacecraft Charging and Plasma Interaction Model

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Objective

1. Compute charging of spacecraft components and nearby electrostatic sheaths.
2. Compute particle distribution functions at or near spacecraft components.
3. Apply to:
    - compare with observations,
    - interpret measurements,
    - optimize geometry for *in situ* instruments.

How?

1. Model the interaction of satellites and their instruments with space plasmas Using PTetra:
   - 3D and realistic geometry using an unstructured adaptive tetrahedral mesh.
   - "sufficiently" complete physics.
   - Full PIC with physical mass ratios.
   - Multiple electron and ion species.
     Each species has its density, temperature and drift velocity.
     Ions species have their specific mass and charge.
2. Test-particle backtracking with computed electric fields.
   This produces particle distribution functions with minimal statistical errors (Marchand, Comm. Comput. Phys. **8**, pp. 471-83, 2010).

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. $<$ 6000 lines of code (Excluding the Poisson solver) $\rightarrow$ "easy" to modify and adapt.
4. Other tasks such as
   - mesh generation,
   - definition of boundaries and boundary conditions (material properties or "physicals"),
   - visualization and simulation analysis.

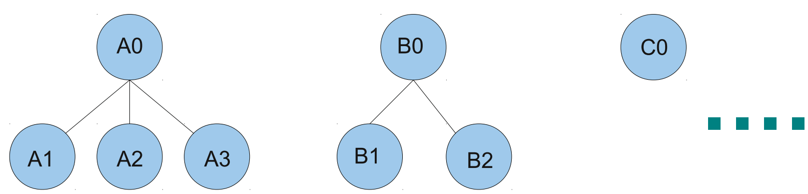
   are done separately with proprietary or open source software.
5. The code is purely electrostatic.
6. So far, it was tested and used without external magnetic fields.

Result analysis

1. All analyses are done separately from PTetra.
2. Needs output files produced periodically or upon request.
3. Backtracking test-particle code.
   Used to calculate distribution functions and their moments at precise positions in space without statistical errors.

Other features

1. Plasma without satellite: for testing basic plasma physics.
2. Photoelectrons:
   - Calculation of illumination of every surface element.
   - Emission with empirical energy and angular distributions.
3. Relative potential differences between groups of surface elements (circuits) may be specified.



4. Imposed collected current.
5. The overall floating potential of the satellite is calculated self-consistently from accumulated charges.
6. Option to generate a restart file.
7. Multiprocessor version using mpi.

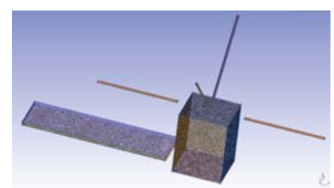
Benchmarking and validation

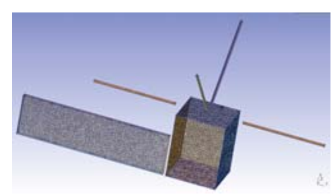
1. Numerics.
2. Basic plasma physics.
3. Comparison with other models.

Objective and modeling tools
Benchmarking and validation
Example studies
DEMETER
Swarm
Summary and conclusion

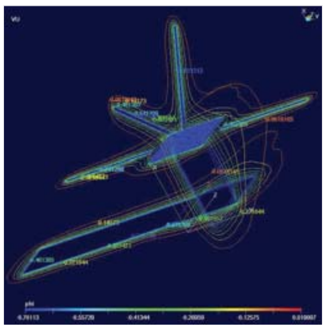
DEMETER - Rationale

1. The floating potential on some booms differ from what is expected.
2. Simulations are done with the four booms and the solar panel.
3. For simplicity, booms are truncated to 1m instead of 4m.
   Only two orientations of the solar panel are considered: parallel and perpendicular to the ram direction.
4. Computed electric fields are used to do particle backtracking and obtain particle fluxes on the booms.

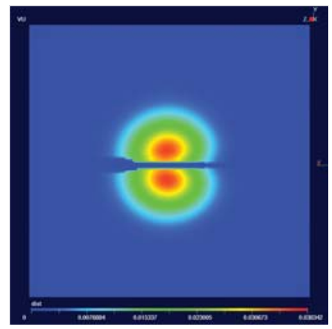




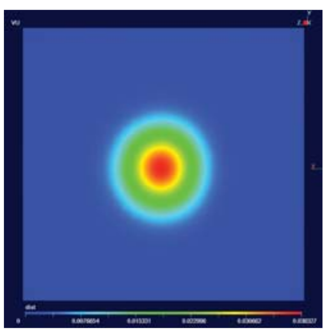
Computed electric fields are used to do particle backtracking and obtain particle fluxes on the booms.



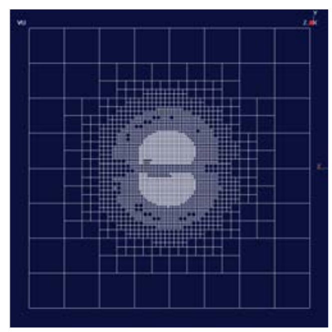
Potential contour lines in two cross sections.



f on the downstream boom.



f on the upstream boom.



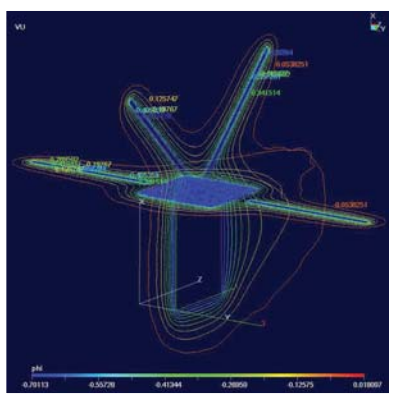
Unstructured mesh in velocity space.

Collected ion currents

Collected ion currents (nA/m) in the middle of each boom obtained for plasma parameters

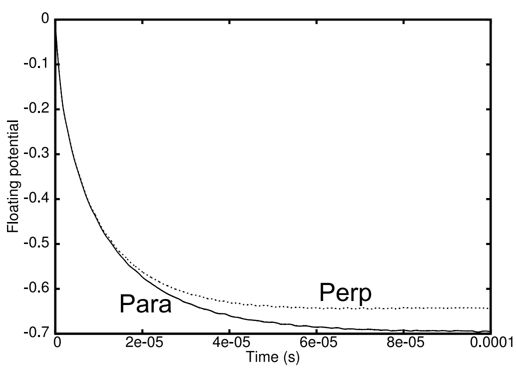
$$n_e = 10^9 m^{-3}, T = 0.2eV, n_{H+}/n_{O+} = 0.2, v_{ram} = 7500m/s.$$

	Boom 1	Boom 2	Boom 3	Boom 4
H^+	12.9	14.0	11.5	6.1
O^+	32.0	31.9	15.3	11.8
Total	44.9	45.9	26.8	17.9

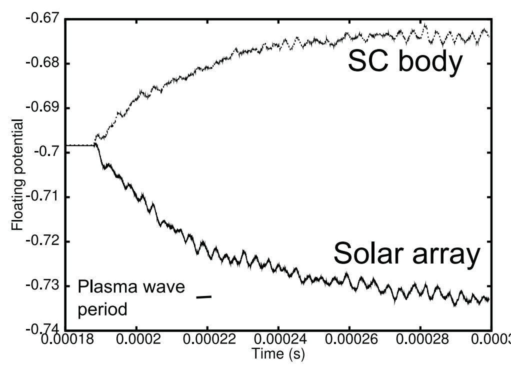


Example use of a restart

$$n_e = 10^9 m^{-3},\ T = 0.2eV,\ v_{ram} = 7500 m/s.$$



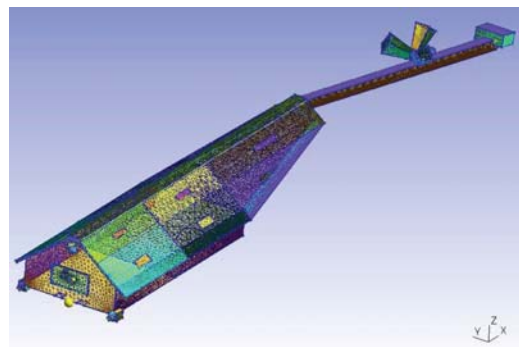
Floating potential for an equipotential SC. The solar panel is parallel or perpendicular to the ram velocity.

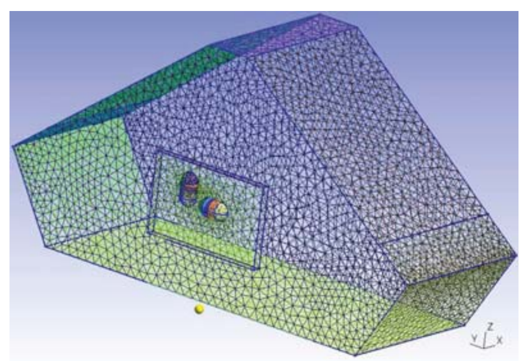


Computed potentials of the SC body and the (parallel) solar panel when these two are electrically insulated.

Swarm - rationale

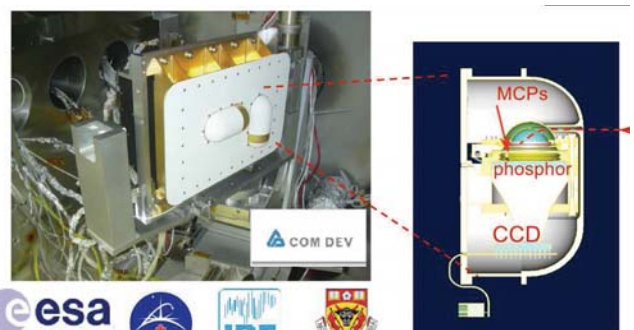
1. EFI will provide detailed 3D measurements of ion distribution functions and bulk flow.
2. We consider possible distortion effects related to the sheath surrounding the instrument.
3. The vicinity of EFI is modeled using a simplified Swarm geometry.

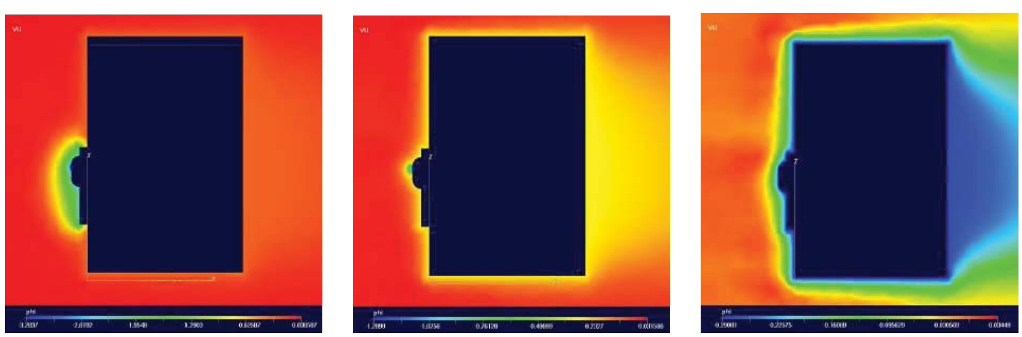




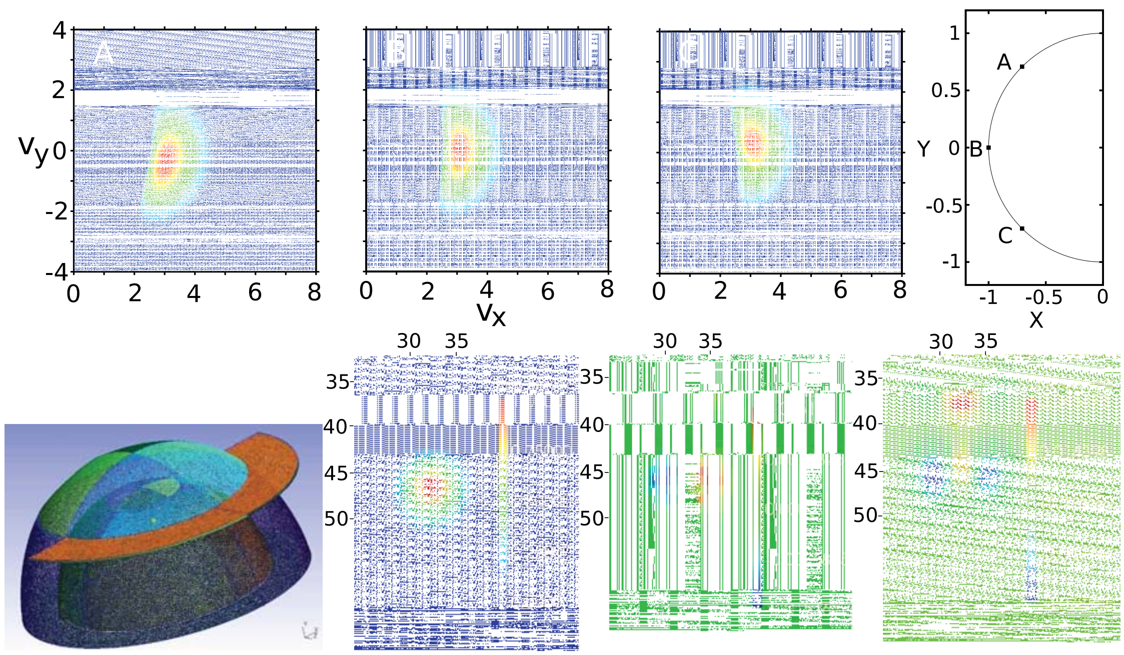
Three biasing scenarios

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





Sheath induced asymmetry



Moments are used to estimate plasma flow velocities:

$$\bar{x} = \sum_{k,l} F(k,l)(l-32.5) \Big/ \sum_{k,l} F(k,l).$$

Sheath effects on estimated flow velocities

1. Moments of particle on the MCP are used to estimate plasma flow velocities.
2. Asymmetric deflections in the sheath produce moments similar to transverse flows.

$T \backslash n$	$10^8 m^{-3}$	$10^9 m^{-3}$	$10^{10} m^{-3}$
$0.1eV$	1.0, 0.5	0.9, -0.5	0.8, -1.7
$0.2eV$	1.9, 1.0	2.3, -0.5	2.5, -2.1
$0.5eV$	(4.3, 3.1)	(5.4, 2.2)	(6.1, -6.7)

Moments (hundredths of pixel) of the column indices calculated for the O^+ peak for left and right sensors. From a thin sheath model: $v_{tr} = 546\bar{x}$.

Summary and conclusion

1. PTetra is used to model spacecraft-plasma interaction with unstructured tetrahedral mesh.
2. Coupled to particle backtracking, this is used to compute particle distribution functions and their moments with minimal statistical noise.
3. Realistic geometry and satellite components can be described accurately.
4. DEMETER simulations show that wake effects on boom ion collected currents can be significant.
5. Swarm simulations show that sheath aberrations on EFI measured plasma flows are likely within acceptable uncertainties ($< 15 m/s$).
6. Further improvements are being planned.
   This is a work in progress.