Space craft charging and electric sheath in a magnetised plasma

Outline

Model description

Benchmarking and validation

Example studies

Swarm

DEMETER

SIERRA - TED

Idealised cylindrical tether

Further developments

Space craft charging and electric sheath in a magnetised plasma

Richard Marchand
University of Alberta, Canada
Richard.Marchand@ualberta.ca
Canada

Special thanks to
Jean-Jacques Berthelier and David Knudsen
for valuable input

SPIS Workshop
Uppsala, January 17-19 2011

Outline

1. Model description
2. Benchmarking and validation
3. Example studies
   - Swarm
   - DEMETER
   - SIERRA - TED
   - Idealised cylindrical tether
4. Further developments

Model description

1. Objective
   - Compute sheath electric fields.
   - Compute particle distribution functions near instruments.
2. How?
   - 3D PIC simulations with
     - realistic geometry
     - “sufficiently” complete physics
   - Test-particle backtracking.

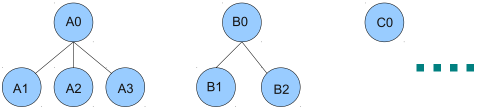
General features of PTetra

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"),
   - visualisation and simulation analysis.

   are done separately with proprietary or open source software.
5. The code is purely electrostatic.

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.

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.

Benchmarking and validation

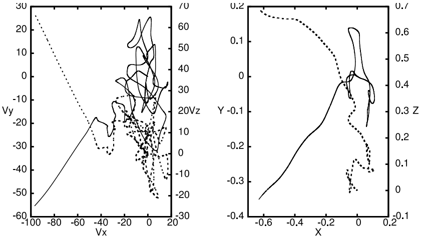
1. Numerics.
2. Basic plasma physics.
3. Comparison with other models.

Numerics: the self force

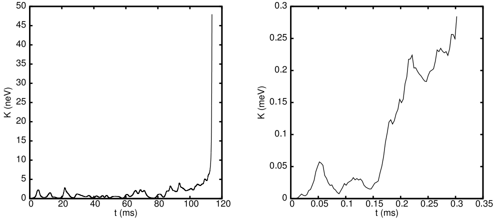
1. Self forces are easy to avoid on a regular grid. They can be suppressed in principle on an unstructured grid, but that would not be practical.
2. Self forces lead to motion akin to Brownian motion.
3. That is negligible provided that
   - The associated motion is less than that associated with interaction with other nearby particles.
   - The associated effective temperature is less than the physical temperature.

Self force in a sphere

Velocity and position.

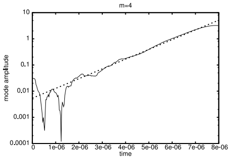


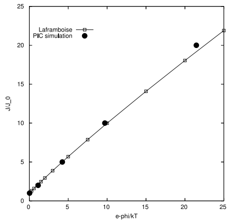
Kinetic energy without and with plasma.



Comparisons

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



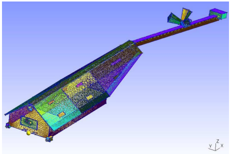


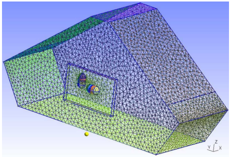
Example studies

- The following shows example results obtained for different spacecraft geometries and plasma conditions.
- These are presented to show the capability of the model and point to areas in need of possible improvements.
- The cases considered are for
  - Swarm (without magnetic field).
  - A simplified DEMETER geometry with and without magnetic field.
  - TED on the SIERRA payload.
  - Idealised tether in a magnetic field.

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.

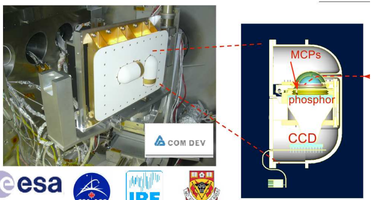




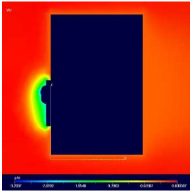
Ref.: Marchand, Burchill and Knudsen, Space Sci. Rev., in press.

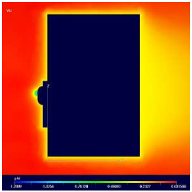
Three biasing scenarios

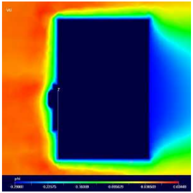
1. The bias of the face plate can be varied, with respect to the body of the spacecraft.
2. The contact potential of the gold ring surrounding the aperture of EFI also needs to be accounted for.



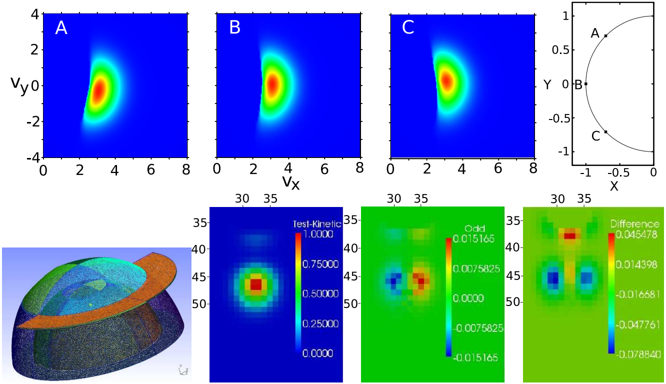
esa CSA ASC IRF Uppsala UNIVERSITY OF CALGARY







Sheath induced asymmetry



Moments are used to estimate plasma flow velocities:

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

Outline
Model description
Benchmarking and validation
Example studies
Swarm
DEMETER
SIERRA - TED
Idealised cylindrical tether
Further developments

Sheath aberration on 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.

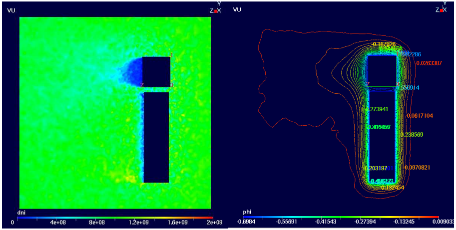
$T \backslash n$	$10^8 m^{-3}$	$10^9 m^{-3}$	$10^{10} m^{-3}$
$0.1 eV$	1.0, 0.5	0.9, -0.5	0.8, -1.7
$0.2 eV$	1.9, 1.0	2.3, -0.5	2.5, -2.1
$0.5 eV$	(4.3, 3.1)	(5.4, 2.2)	(6.1, -6.7)

Moments (hundredths of pixel) of the column indices calculated for the O^+ peak for left and right sensors.
From a thin sheath model: $v_{tr} = 546\bar{x}$.
$\rightarrow$ Aberration in transverse velocity < 36 m/s.

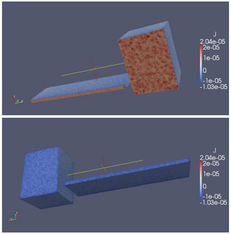
Outline
Model description
Benchmarking and validation
Example studies
Swarm
DEMETER
SIERRA - TED
Idealised cylindrical tether
Further developments

DEMETER, $\vec{B} = 0$

$n_e = 10^9 m^{-3}$, $T_e = T_i = 0.2eV$
$n_{H+} = 0.2 \times 10^9 m^{-3}$, $n_{O+} = 0.8 \times 10^9 m^{-3}$
$\vec{v} = (0., 0., 7500.) m/s$, $\vec{B} = 0.$



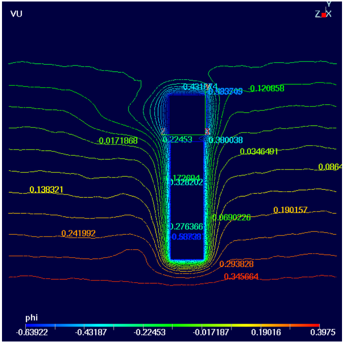
Cross sections of the density and potential profiles.



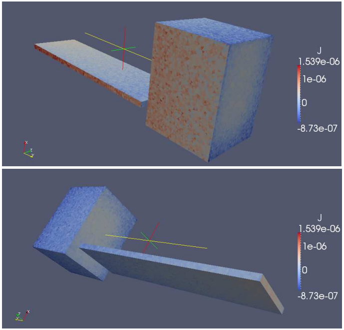
Net current collected per unit area.

DEMETER, $\vec{B} \neq 0$

Same plasma parameters as previously except for
$\vec{B} = (-2.12, 0., -2.12) \times 10^{-5} T \rightarrow \rho_e \simeq 3.6cm$



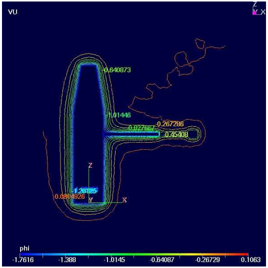
Cross sections of the density and potential profiles.



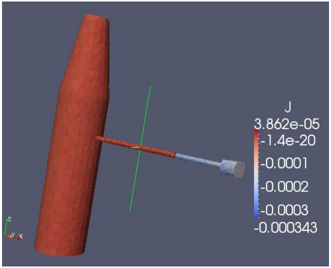
Net current collected per unit area.

SIERRA - TED (MacDonald et al. JGR 2006)

$n_e = n_{O+} = 10^{10} m^{-3}, T_e = T_i = 0.4eV$
$\vec{v} = (-1585, 0., -742) m/s, \vec{B} = (0, 0.5, 0) \times 10^{-5} T$
End of boom + TED: biased to $+1V$ with respect to payload.



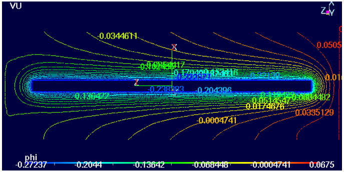
Cross sections of the potential profile.



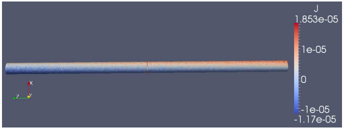
Net current collected per unit area.

Idealised cylindrical tether

$$r = 1cm, l = 50cm,\ n_e = n_{H+} = 10^{10} m^{-3},\ T_e = T_i = 0.1eV$$
$$\vec{v} = (-7500, 0, 0),\ \vec{B} = (0, 3 \times 10^{-5}, 0)\,T$$



Potential profile in the $y = 0$ cross section.



Net current collected per unit area.

Further developments - Physics

- Magnetic fields.
- Inclusion of SC internal components.
- Deep dielectric charging, material interaction with energetic particles.
- Option for specifying absolute collected currents (instead of bias or absolute voltages) from different components.
- Electron with drifts, including beams.
- Relativistic electrons.
- Combination of Maxwellian and non Maxwellian distribution functions (e.g. kappa distributions).
- Sputtering.
- Plasma neutral collisions.

Further developments - numerics

- Post-processing test-particle module.
- Multiprocessor version.
- Ability to read meshes generated by other programs (cubit, gambit, custom).
- Ability to read geometrical structures generated with AutoCAD as a guide to construct 3D meshes.
- Adaptive mesh refinement.
- Option for creating and using restart files.
- Mesh and field export facility. This would be useful for doing test-particle simulations from SPIS output.
- Option to run read or export a text (no GUI) input file.

Example PTetra input file

```
//Input file for picTetra

//-----------------------------------------
//  PLASMA PARAMETERS
//-----------------------------------------
//nepop: number of electron populations
//nipop: number of ion populations
//magfield: .true. (.false.) when there is (no) magnetic field
//b_field: cartesian components of the background magnetic field
&plasmaparameters
 nepop=1
 nipop=1
 magfield=.true.
 b_field=0. 3.e-5 0.
/

//The code will create as many species as are specified below
//N.B.: electron species must be specified first.
//ne: density of a given electron species
//te: temperature of a given electron species
//vexyz: velocity vector of a given electron species
//mi: mass (amu) of a given ion species
//qi: charge (e) of a given ion species
//ni: density of a given ion species
//ti: temperature of a given ion species
//vixyz: velociti vector of a given ion species
$begin plasmaparameters
  ne=1.0e10
  te=0.1
  vexyz=-7500.   0.  0.
  mi=1.
  qi=1.
  ni=1.0e10
  ti=0.1
  vixyz=-7500.  0.  0.
```

Further developments - Support

- A quick help service.
- E-mail notification to a subscribers' list when a question is posted.
- E-mail notification to the author (and interested subscribers) when answers are posted.
- Updated tutorial and general documentation.
- Standard tests and benchmarks with sample and documented input and output.
- Means for users who might have developed special modules, to follow the development of new versions and retain their custom made changes in future versions.
- Involve development team to ensure that custom made changes will be maintainable in future versions.

Needed beyond development

- Estimates of uncertainties (floating potential, currents,).
- Accurate and detailed design specifications are often difficult to obtain:
  - Geometry, including dimensions and positions of components in a consistent system of coordinates.
  - material properties (conductivities, photo- and secondary-electron emissivities)
  - Mutual capacitances (inductances for time dependent studies) of components.
  - ...
- Ensure that measurements and information needed for modelling will be collected and made available before satellites are launched.