Plasma Simulations at ESA for Spacecraft Plasma Interactions

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- Problems to solve.
- PicUp3D
- SPIS
- Examples of applications

Problems to solve

Terms to compute:
- Charged particle current
  - ion, electron
  - photo-electron
  - secondary electron emission
  - active emission
- self-consistent potential distribution
  - In material for deep dielectric charging.
  - Outside material for surface interactions.
- Multi-physics problems
- Very small community in Europe (~5 man*Y/Y)
Simulation Methods

Essential features of tools available from www.spis.org:

- 3D Kinetic model of all particle species transport for ‘large’ $\lambda_D$ (Boltzmann equilibrium of electrons otherwise).
- PIC method for particle transport and density calculation.
- Poisson solver, e.g., finite difference (PicUp3D) or FEM (SPIS).
- Spacecraft Equivalent electric circuit solver (SPIS).
- Surface physics modules (SPIS).

Plasma modelling with PicUp3D

- Vlasov-Poisson system:
  \[
  \begin{align*}
  \frac{\partial f(t, x, v)}{\partial t} + v \cdot \frac{\partial f(t, x, v)}{\partial x} + e \frac{\partial f(t, x, v)}{\partial v} &= 0 \\
  F &= q(E + v \times B) \\
  \nabla \cdot E &= \frac{\rho}{\varepsilon_0} \\
  \Delta \phi &= \frac{\rho_{tot}}{\varepsilon_0}
  \end{align*}
  \]

Particle-In-Cell code loop:
PicUp3D Simulation techniques

- PIC method for particle transport and density calculation.
- Poisson solver with finite difference on regular rectangular grid.
- Object defined with triangular surface mesh technique.
- BC on nearest object grid point.

Software Features

- Open source and freely available from: [www.spis.org](http://www.spis.org)
- OO and Java based.
- Supported by SPINE, ESA, IRF, CNES.
- In use since 2001 at ESA.
- ESA investment (r&d +dev): ~90 kEuro + ~1 man*year.
Validation of PicUp3D with uniform photo-emission

- Comparison TP-PicUp3D (100 cc, 1 eV)

Example of non-uniform photo-emission effect (*Thiébault et al., JGR, 2004*)

\[ T = 1 \text{ eV} \]
\[ N = 100 \text{ cm}^{-3} \]
Example: Cluster Electrostatic Sheath in large $\lambda_D$ regime

(Thiébault et al., sctc, 2003)

Sheath and photoelectron cloud structure and effects
- Ion plume neutralised and potential shielded in the near sheath region by photo-electrons
- Far sheath dominated by photo-electrons
- Possible effects on the electric field measurements (requires higher resolution)

PicUp3D current limitations
- Mesh/box limit to $\sim$100 on rectangular grid.
- Nearest Grid Point approximation.
- Needs optimisation of numerical solvers (in progress).
- No surface physics.
New Generation: SPIS

- Unstructured surface and volume mesh.
- Includes various modules (e.g., sources, 1D, 2D elements) and databases (e.g., for material properties).
- Spacecraft equivalent electric circuit solver.
- PIC/Boltzmann distributions
- Poisson solver (Conjugate gradient, linear/ non-linear)

SPIS software feature

- OO and Java based.
- Advanced framework for pre- and postprocessing and numerical schemes definition.
- Supported by SPINE (Onera, artenum, GolP), ESA, CNES.
- Open source and freely available on www.spis.org.
- ESA investment (r&d +dev): 600 kEuro+1 man*year.
Passive Sphere with plasma shielding effect

- Temperature: 1.0 eV
- Number density: 55 cm$^{-3}$
- Debye length: 1.0 m
- Sphere potential: -25 V
- Sphere radius: 1.0 m
- Tetrahedrons: ~50 000
- Simulation box size: 40 m
- Macro particles: 300,000

Emitting Sphere

- Ambient e- Temp.: 1.0 eV
- Photo e- Temp.: 2.5 eV
- Number density: 100 cm$^{-3}$
- Debye length: 0.74 m
- Sphere potential: [-1, 1] V
- Sphere radius: 1 m
- Tetrahedra: ~50 000
- Simulation box size: 40 m
- Macro particles: 300,000
Testing Thin Cylinder in OML regime

- Temperature: 1.0 eV
- Number density: 10 cm$^{-3}$
- Debye length: 2.4 m
- Potential: [0,12] V
- Cylinder radius: 0.25 m
- Length: 16 meter
- Central node0: 2 m
- Outer node1: 7+7 m
- Tetrahedrons: ~60,000
- Simulation box size: 20 m
- Macro particles: 300,000
Testing Thin Cylinder in OML regime

Application: SMART-1 Floating Potential
SPIS simulation of SMART-1

• Array facing:
  – ~16 V
  – ~$10^7$ cm$^{-3}$

SPIS simulation of SMART-1

• Array in wake:
  – ~7 V
  – ~$10^3$ cm$^{-3}$
Application: Cluster Probe

Cluster Probe

SPENVIS WORKSHOP, 3 Oct 2005,
Leuven-Louvain, Belgium
Cluster Probe

Current Coupling on Cluster Probe
SPIS current limitations

- Need validation (including experimental) and improvement of multi-time scale phenomenas for s/c charging application in industry.
- Detailed particle trajectories near surfaces should be optimised.
- Critical mass – Link with other communities?

Conclusion

- Spacecraft-plasma interactions have to be considered for spacecraft design, some instrument calibration, electric propulsion systems, power systems, etc.…
- Usually order of magnitude estimates can be made with simple formulas for basic charging state.
- Plasma simulation and detailed space-based observation for validation are necessary for refined estimates.
- PicUp3D and SPIS are open and free for these use.
- SPIS already operational after less than 2 Y development.
- www.spis.org
Back-up slides

Further reading

- Proceedings of the 9th Spacecraft Charging Technology Conference, Tsukuba, Japan, April, 2005.
- Info and free software: www.spis.org.