INSTRUMENT SIMULATIONS IN TENUOUS PLASMAS: WHAT TO LEARN FOR SPIS

Chris Cully

IRF-Uppsala

BACKGROUND

- 2005, developing the MMS radial boom concept
- Needed more quantitative tools
  - NASCAP: restricted to Americans
  - SPIS: not quite what we needed
- Developed own code
- Has been useful for us

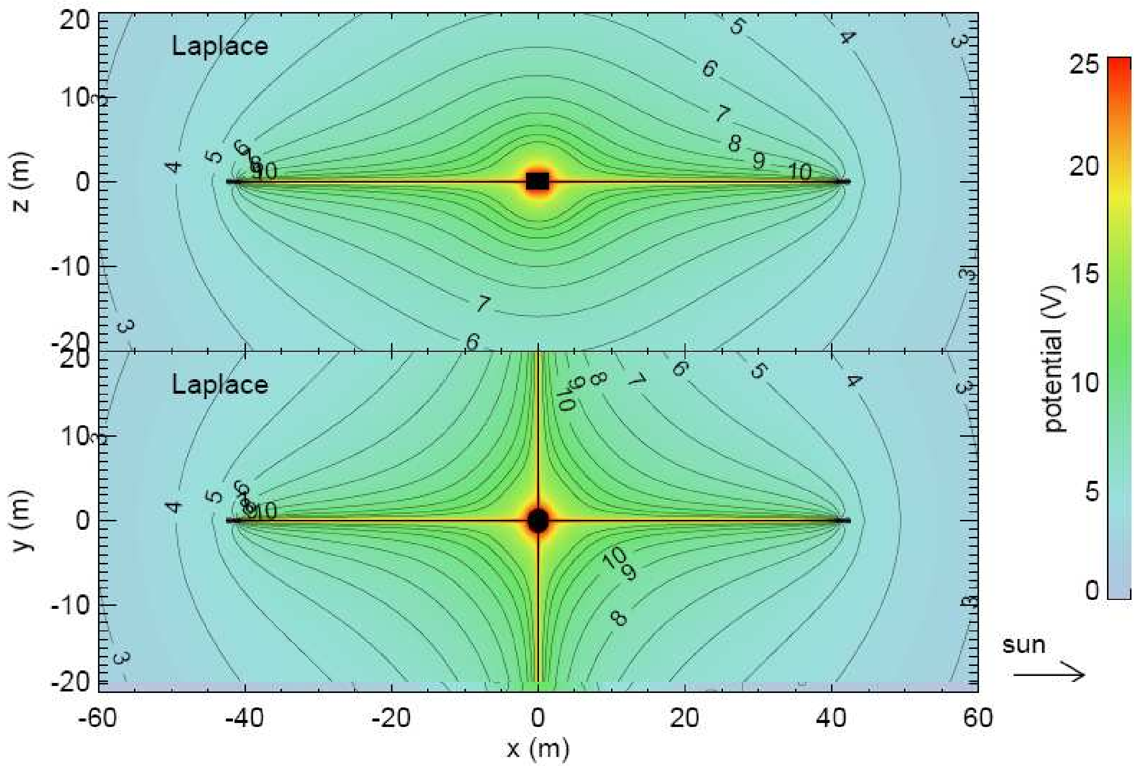
- <u>Can we refine SPIS to replace this code?</u>

OUTLINE

- What we usually want to model
- Our solution [Cully et al, JGR, 2007]
- Example applications
  - Advantages + disadvantages vs. SPIS
- How to include this functionality in SPIS?

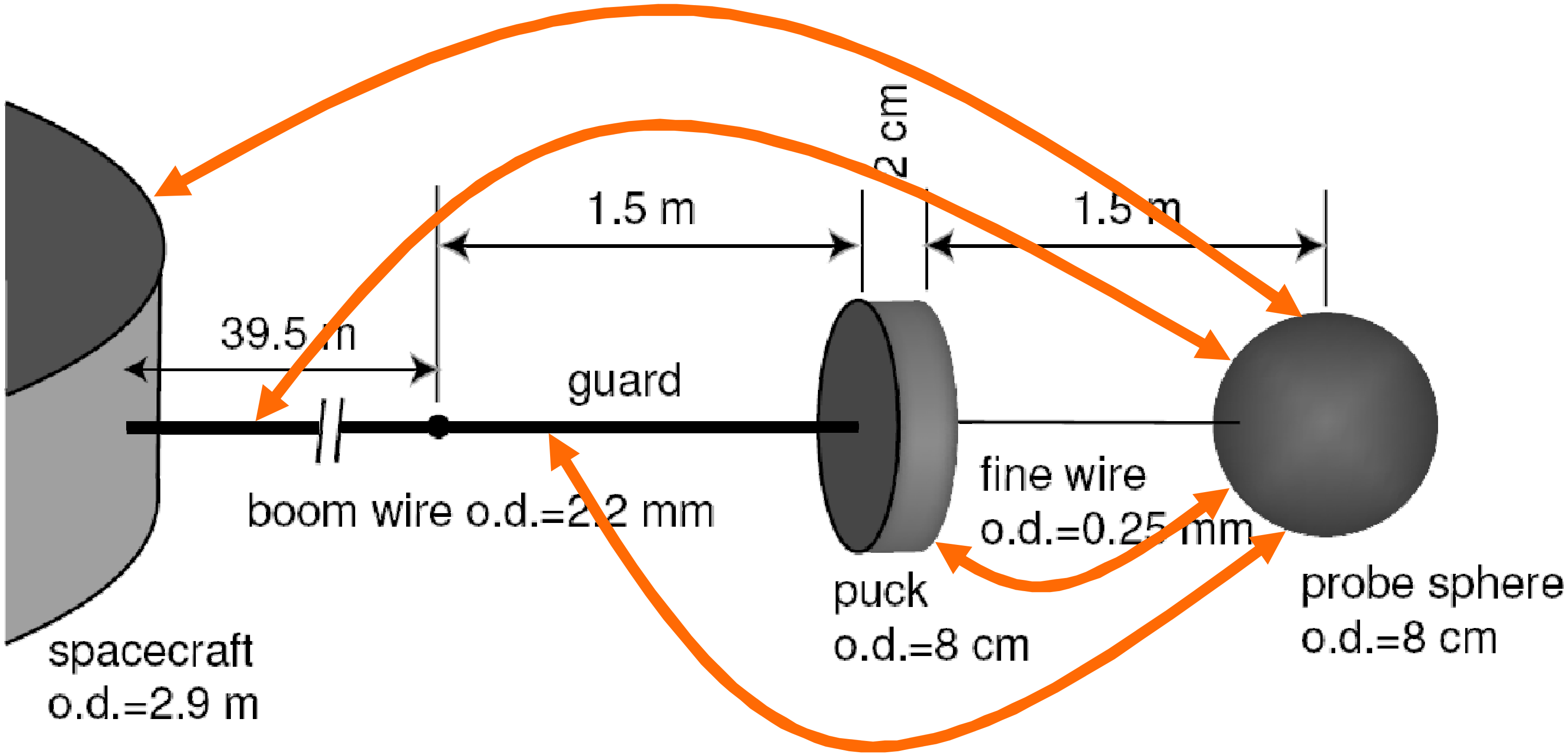
MODELLING REQUIREMENTS

1. Potential field near the spacecraft



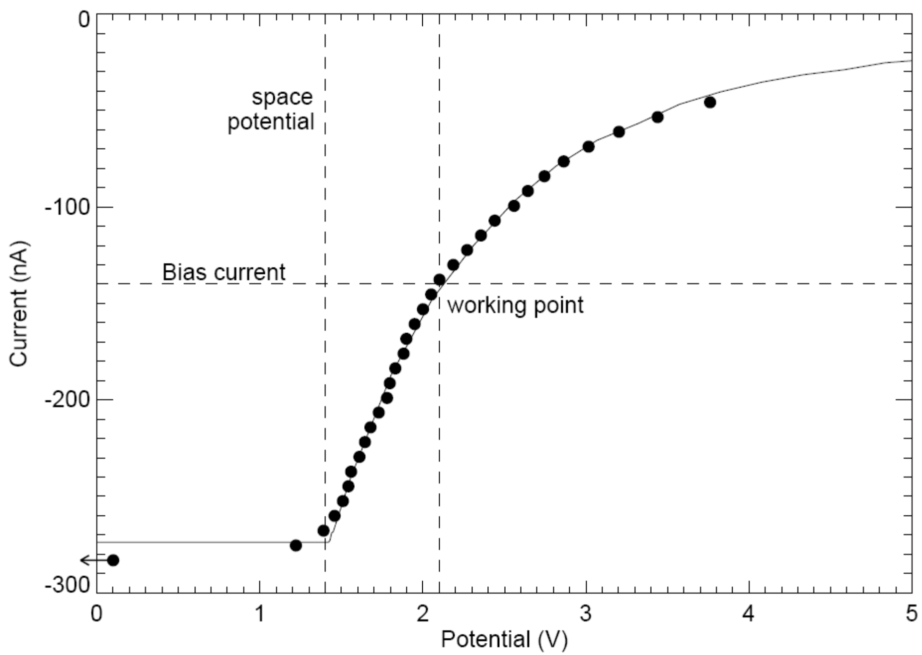
MODELLING REQUIREMENTS

1. Potential field near the spacecraft
2. Stray currents to the probe



MODELLING REQUIREMENTS

1. Potential field near the spacecraft
2. Stray currents to the probe
3. Probe-plasma interaction: current-voltage (I-V) curve



MODELLING CHALLENGES

- Few useful symmetries: fully 3D
- Thin wires are difficult to model
  - Smallest scale size is $\sim 10^{-6}$ box size
- Need to include photoelectrons
- Need to accurately compute currents
- Boundary conditions are specified at infinity

MODELLING SIMPLIFICATIONS

- Background plasma can often be assumed tenuous
  - Debye length > system size
  - Ambient plasma has little efffect on potentials
- Usually interested in the time-stationary solution

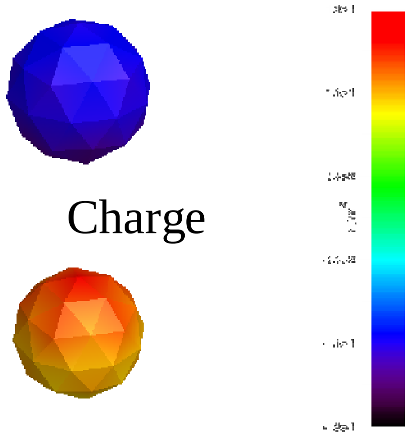
OUR SOLUTION

SOLVERS: OVERVIEW

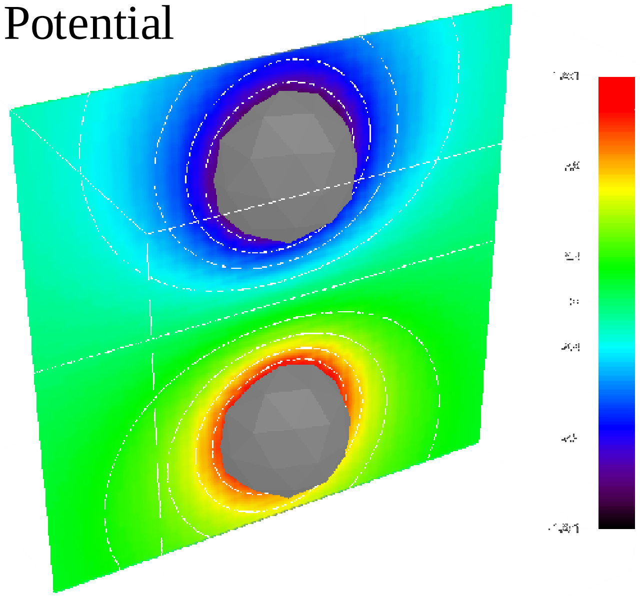
- Laplace solver: Boundary Element Method
  - Grid-free integral method
  - Circumvents scale separation problems
  - Often all that we use

- Poisson solver:
  - Spacecraft: Boundary Element Method
  - Plasma: Fast Multipole Method
- Particle push: adaptive (4^{th} order Runge-Kutta)
- Iterative self-consistent solver
  - Laplace → Vlasov → Poisson

BOUNDARY ELEMENT METHOD



Potential

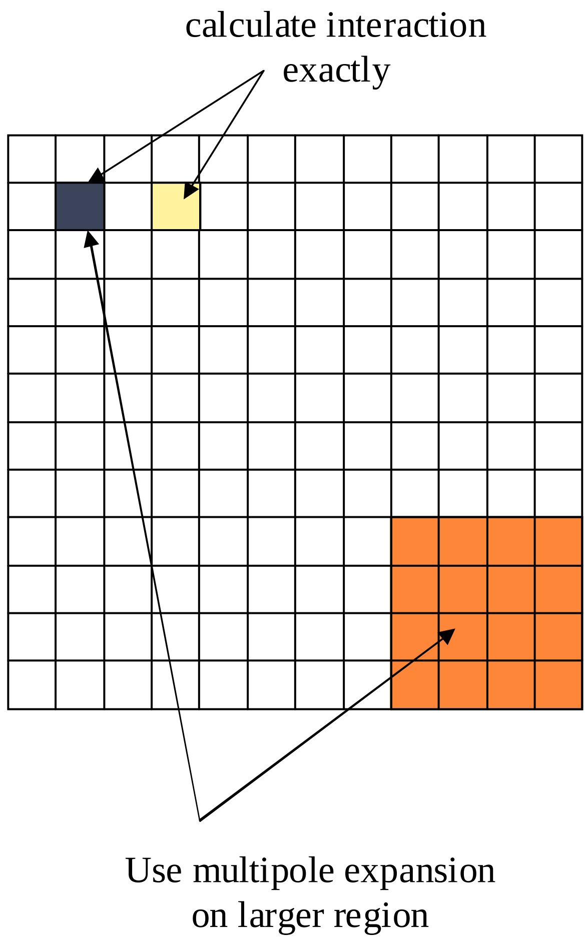


- Problem: gridding the space is prohibitively expensive
  - Solution: Don’t grid the space
- Boundary Element Method:
  - Divide the boundary (i.e. the spacecraft) into panels of (unknown) constant charge density
  - Solve for charge density on the boundary (inverse integral eq.)
  - Once all the charges are known, the potential is uniquely determined

$$\Phi = \frac{1}{4\pi\varepsilon_0} \sum_{elements} \iint \frac{\sigma(x', y')}{r} dx' dy'$$

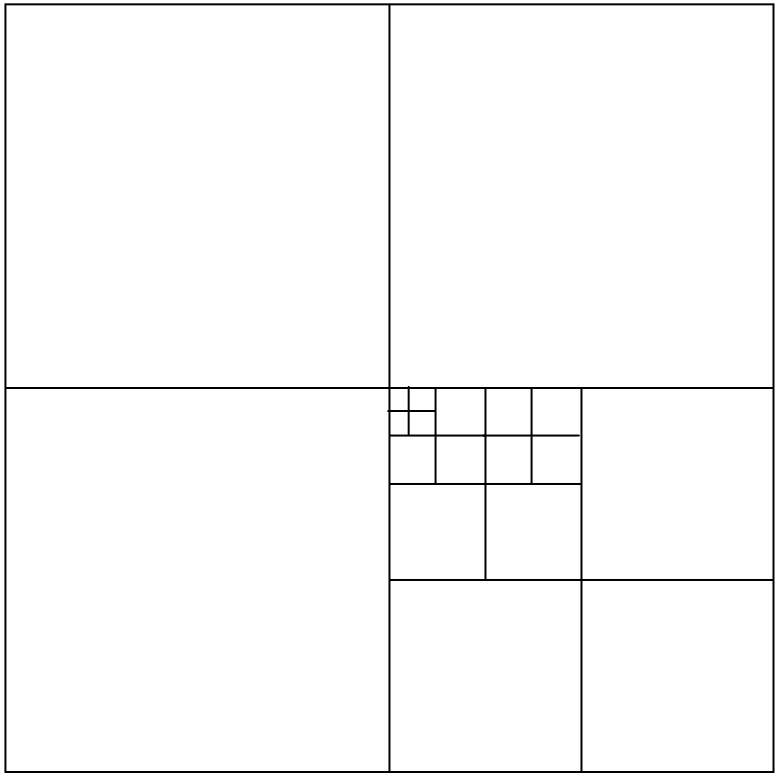
FAST MULTIPOLE METHOD (FMM)

- Basic idea: use multipole expansion to compute long-range forces
  - Trade precision for speed
- 2 “flavours”:
  - n*log(n) hard
    - Relatively simple
  - n hard
    - “True” FMM
    - Faster in theory, but requires many spherical harmonic manipulations
- Greengard + Rokhlin 1987



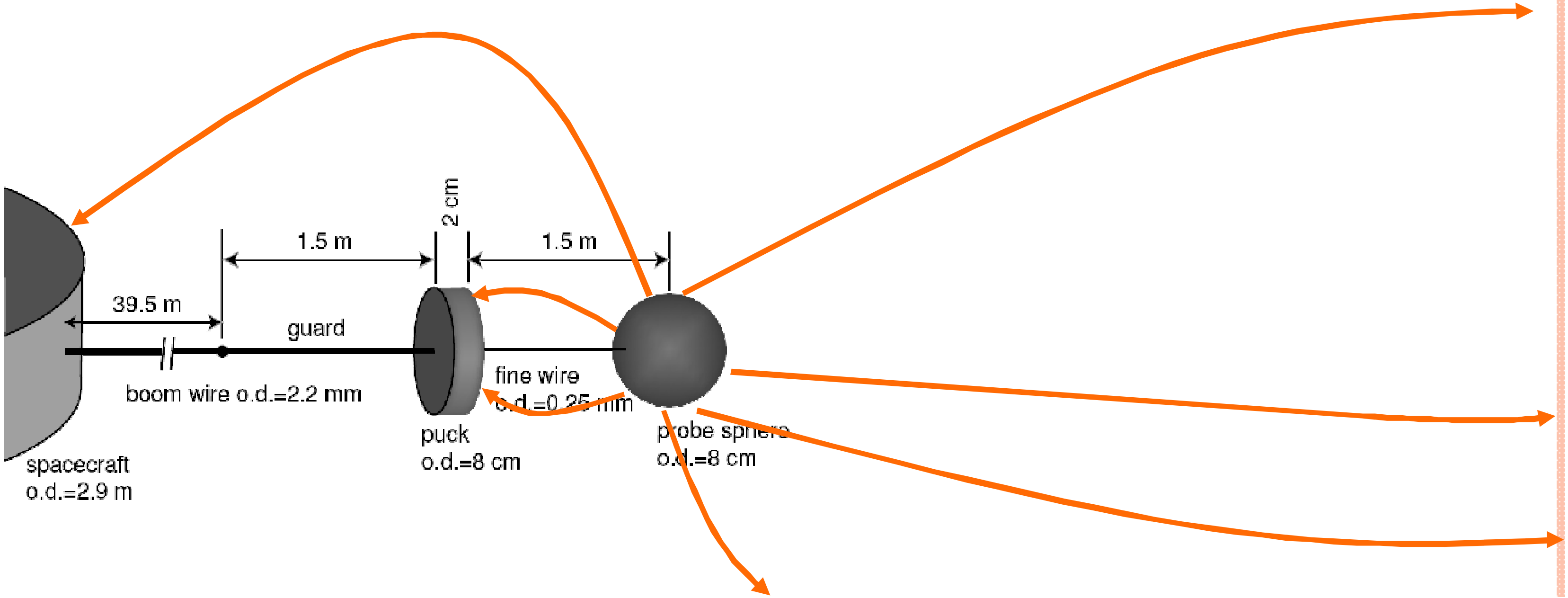
MULTIGRID REPRESENTATION

- Resolution can be different in different areas of the domain.
  - Allows the storage of grids that would otherwise be prohibitively large
- Fits easily with FMM



CALCULATING CURRENTS

- Particles are traced back in time starting at the surface at which the current is to be calculated
  - Current found using Liouville's theorem

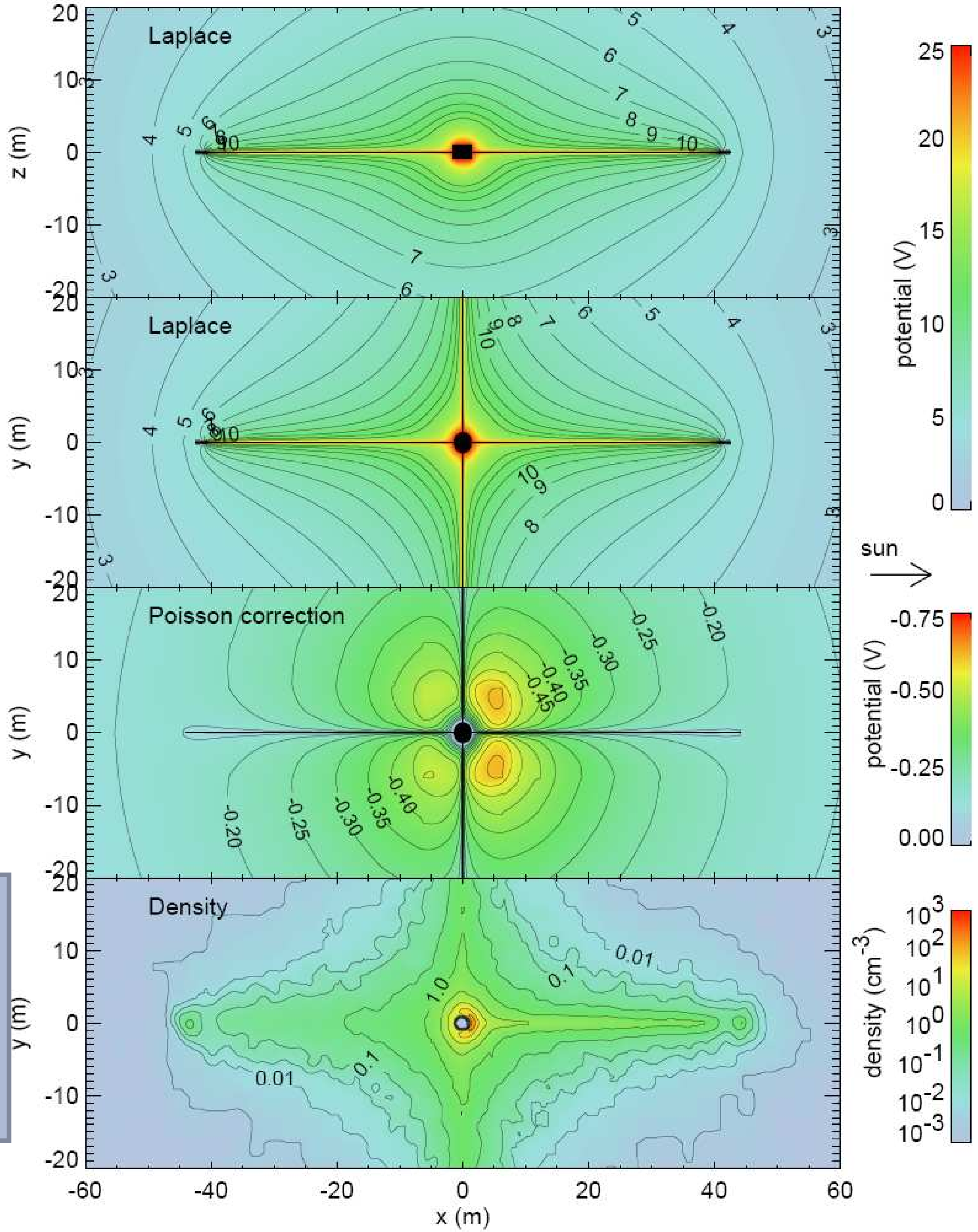


EXAMPLE APPLICATIONS

vs. SPIS:
Some advantages,
Some disadvantages

CLUSTER

- Self-consistent density and potential
- Boom "pulls" the spacecraft potential well with it
  - No 1/R falloff

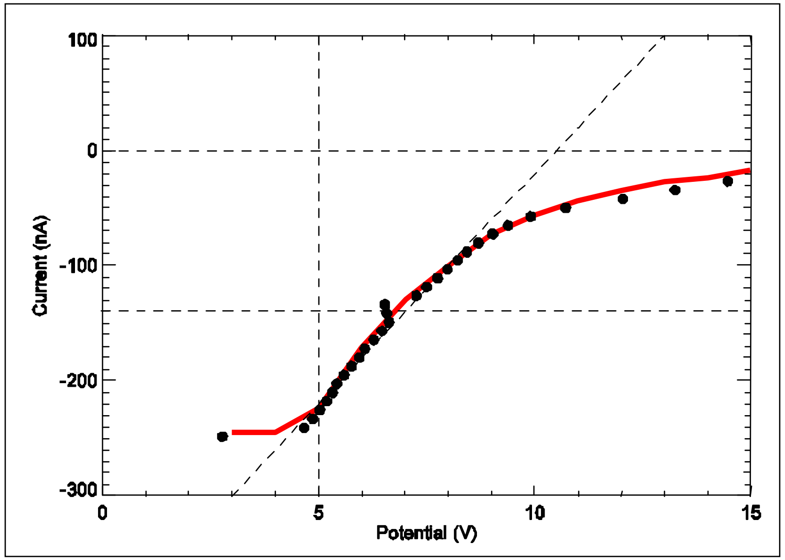


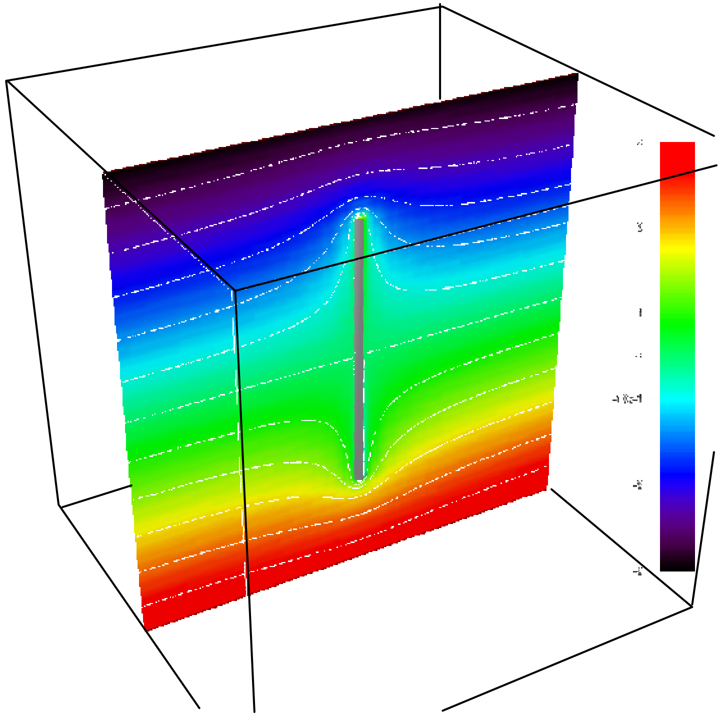
vs. SPIS:
Better treatment of wire booms
(in 2006...)
But, photoelectron cloud difficult and time-consuming to simulate.

CLUSTER (CONT.)

- Probe IV curve reproduced
- Electric field reduction ("boom shortening")
  - $E_{obs} = 0.87$ E
- Predicted relation between V_{sc} and V_{probe}
  - $V_{probe} = 0.19V_{sc}+0.7V$
- Mixed success in predicting sunward offset effects
  - At least partially due to puck-probe stray currents

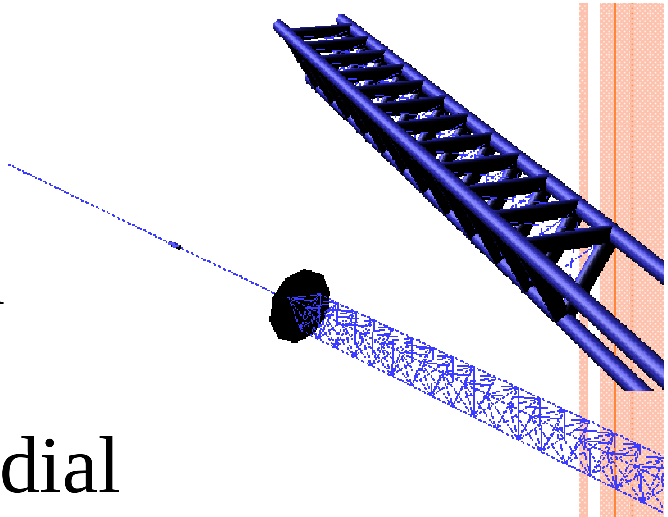
vs. SPIS:
Backtracking particles allows efficient computation of currents



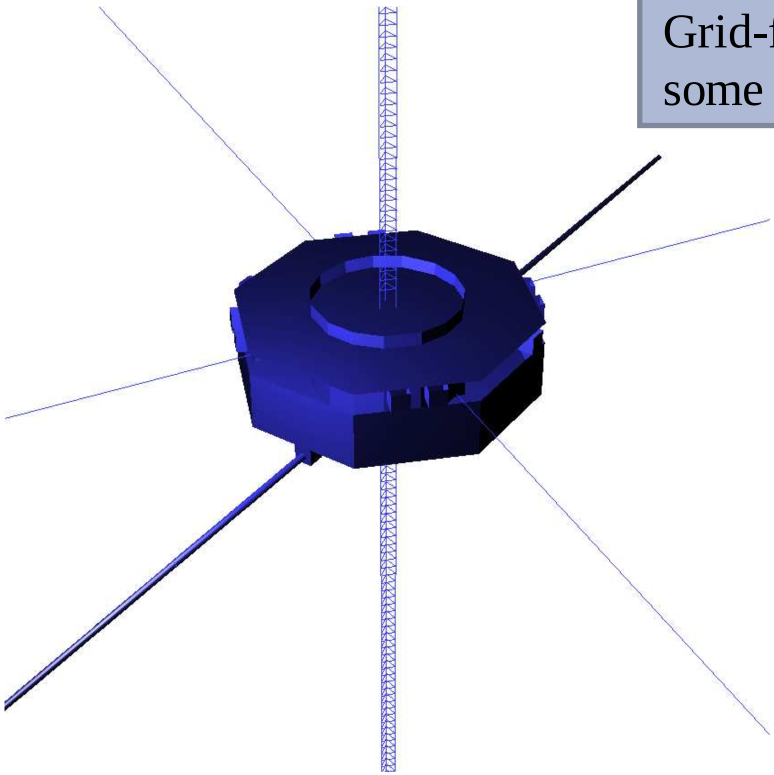


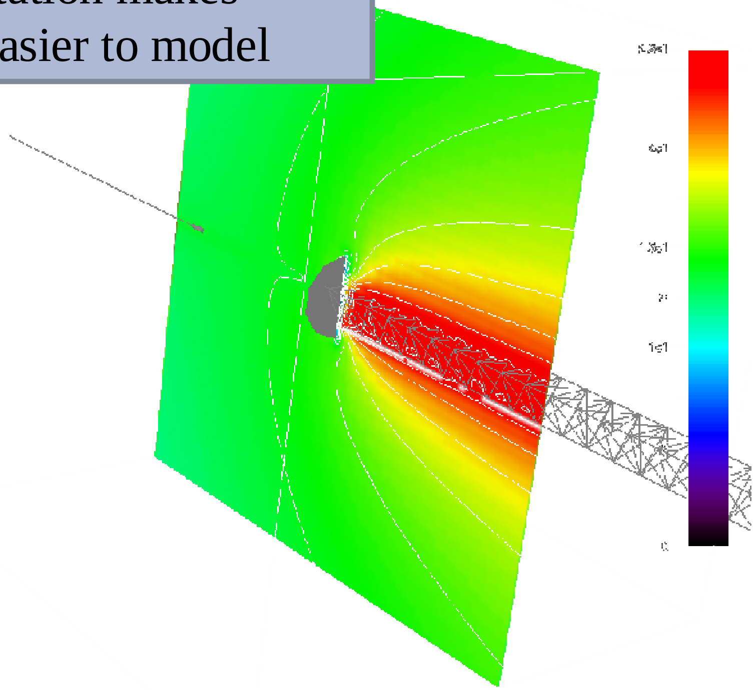
MMS

- Evaluated different axial and radial boom designs
- Evaluated various placements of radial booms



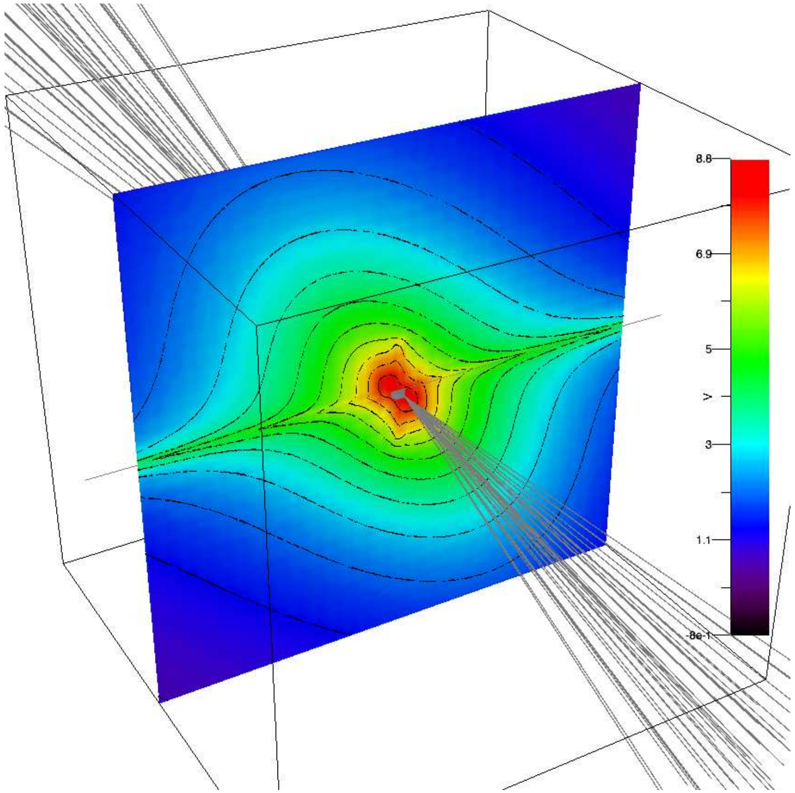
vs. SPIS:
Grid-free representation makes some geometries easier to model





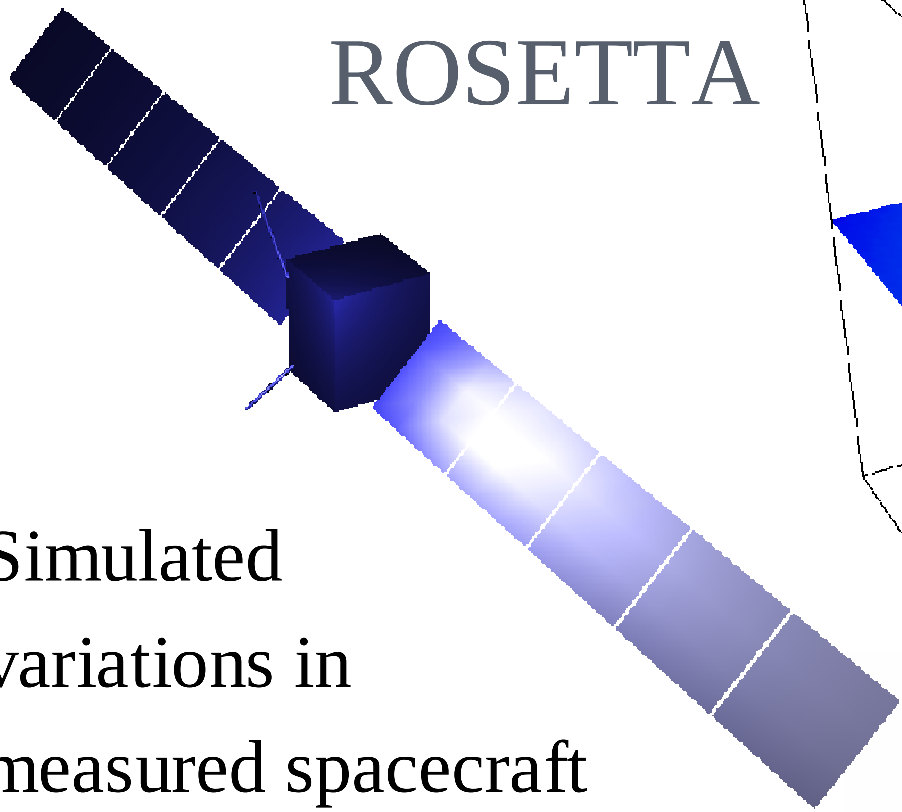
MMS

- Evaluated potential perturbations due to ASPOC ion emitter
  - Effect on electric field and EDI beams

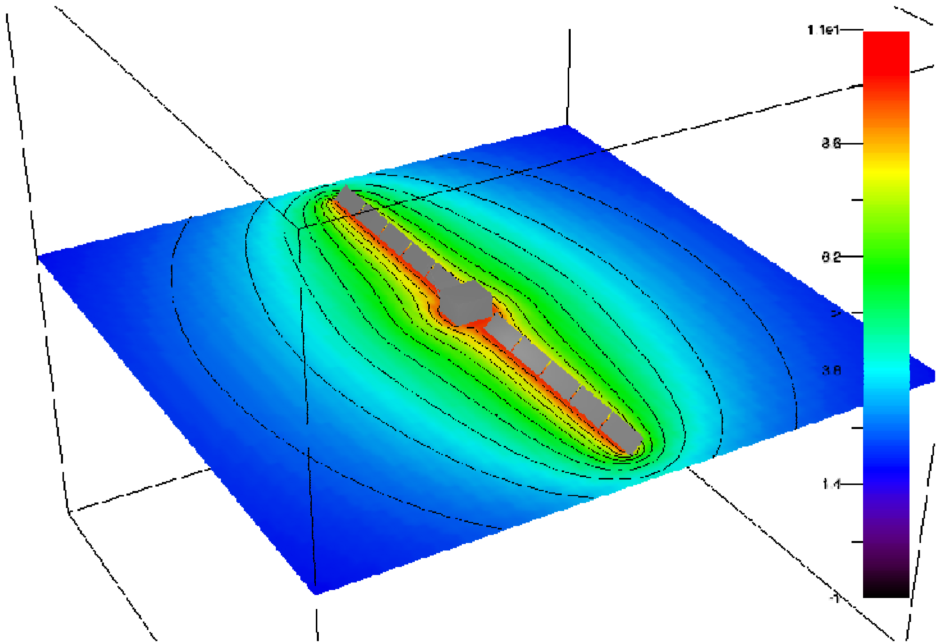


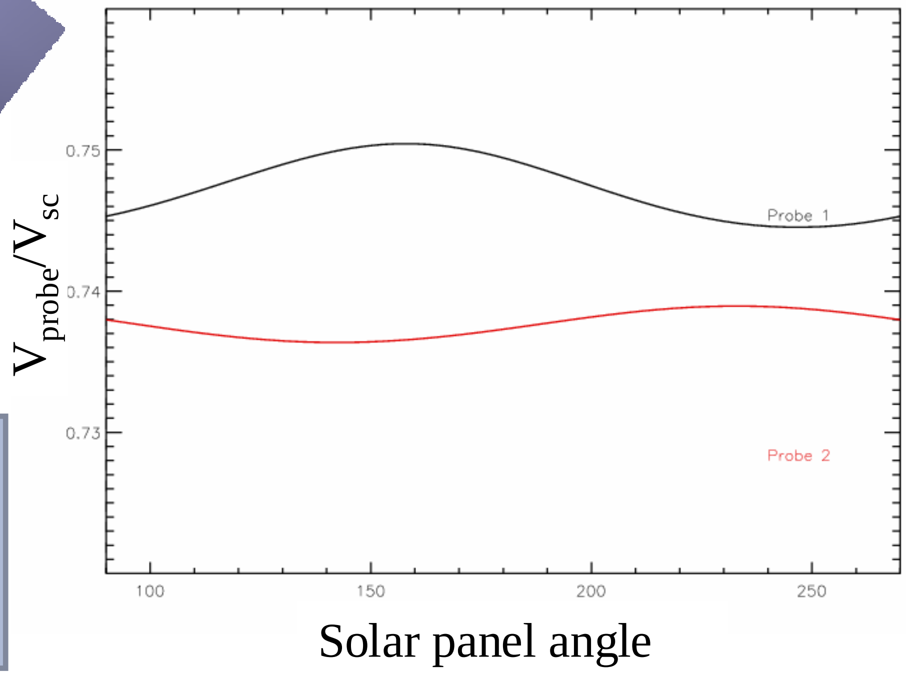
vs. SPIS:
Quick and easy.
PIC is really more appropriate.

ROSETTA



Simulated variations in measured spacecraft potential as the solar panels rotate





vs. SPIS:
Don’t need to remesh; less noise.
But, photoelectron cloud difficult and time-consuming to simulate.

IDEAS FOR INCORPORATING THIS INTO SPIS

COMPARISON TO SPIS

- Designed for a different sort of problem
  - Specialized for thin booms, tenuous plasmas
- Disadvantages
  - Limited background plasma
    - Can’t handle: wakes, dense plasmas, ...
  - No ability to handle time-varying problems
- 3 Perceived advantages
  - Particle backtracking for currents
  - Fast, easy-to-use Laplace solver
  - Good support for thin wires

PARTICLE BACKTRACKING

- Essential for finding currents
  - Otherwise, need to wait for sufficient number of particles to strike the probe
- Don't need full time dependence
  - Could trace through instantaneous field at $t=t_0$
- User interface is difficult to design
  - My GUI design failed; script-driven from IDL
- Need ability to label surfaces
  - Calculate currents
- Built-in weighting by exponential, Gaussian would be useful

GRID-FREE LAPLACE SOLVER

- Grid-free vacuum simulations have been surprisingly useful for us
  - Fast and accurate
  - Easy to change geometry
- Probably difficult to incorporate into SPIS
- Although, source code (and developer) available

THIN WIRES

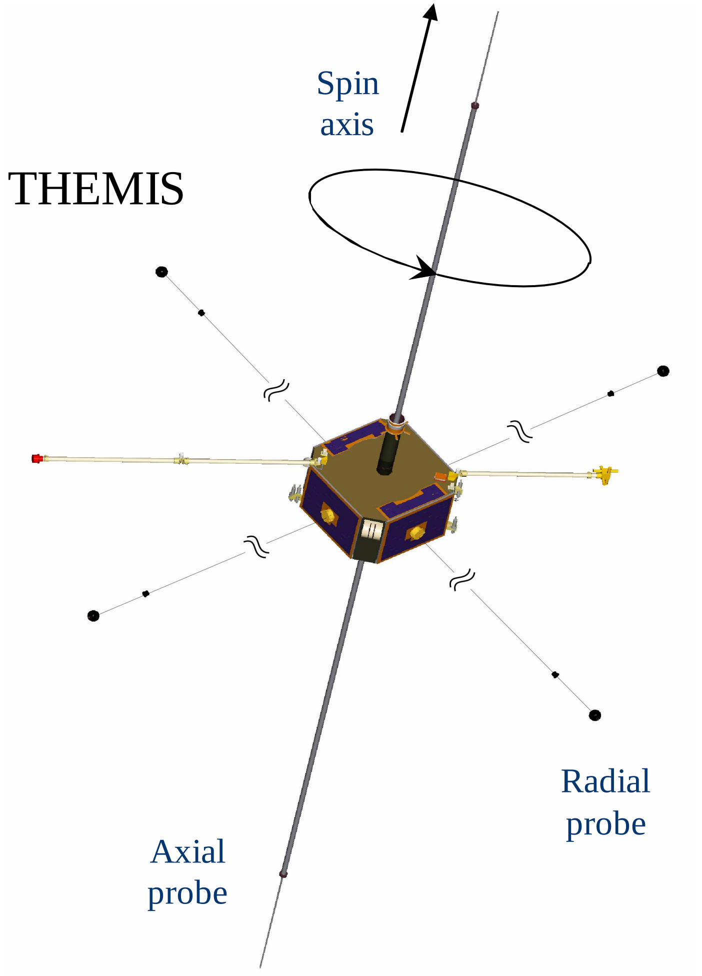
- Thin wire booms are important for some problems (e.g. BepiColombo)
- SPIS already has support for thin wires
  - Should perhaps cross-validate

CONCLUSIONS

- **Backtracking particles** would be very useful in SPIS
  - Need to think carefully about the interface
- Grid-free Laplace solver has proven valuable
  - Probably difficult to incorporate, but source code and expertise is available
- Modelling thin wires is important for electric field instruments
  - Should consider cross-validation

EXTRA SLIDES

TYPICAL DOUBLE PROBE ELECTRIC FIELD INSTRUMENT



(roughly to scale)

- Spinning satellite
- Measure potential differences between pairs of probe spheres
- 4 Radial probes on flexible wires
  - 50m-100m tip to tip
  - Held out centrifugally
- 2 Axial probes on rigid booms
  - 5m-25m tip to tip

ELECTROSTATIC CONTROLS

- Desire: isolate the probe sphere as much as possible from the spacecraft
  - Minimize perturbation in potential
  - Minimize stray currents