Numerical Modelling of Spacecraft Charging and Sheath Formation Around BepiColombo Mio using SPIS

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Motivation

Spacecraft charging in the Mercury plasma environment

BepiColombo Mio operates in a variable plasma environment at Mercury where electron/ion collection, photoelectron emission and spacecraft geometry modify the plasma surrounding onboard sensors.

Implications for in-situ measurements

The resulting sheath perturbs the local density, potential and electric-field structure around boom-mounted probes. Active Measurement of Mercury's Plasma (AM2P) **[1]** onboard the Mio spacecraft uses active mutual-impedance measurements to retrieve local electron density and temperature. AM2P may therefore sample a spacecraft-modified plasma rather than the undisturbed ambient environment. **[2]**

Aim

This work combines Orbital Motion Limited (OML) current-balance estimates and 3D SPIS (Spacecraft Plasma Interaction Software **[3]**) simulations to identify representative charging regimes and quantify the near-probe perturbation relevant to AM2P interpretation.

The objective of this work is to quantify the spacecraft-modified near-probe plasma environment that must be accounted for when interpreting future AM2P mutual impedance measurements.

Modelling Approach

1. Analytical Charging Model

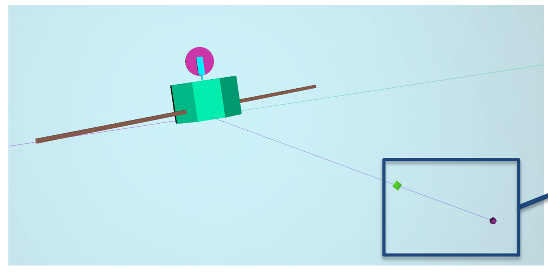
Inputs:
$n_e,\ T_e,\ n_i,\ T_i,\ J_{\mathrm{ph}}$

Model:
$I_e(\phi_{\mathrm{SC}}) = I_i(\phi_{\mathrm{SC}}) + I_{\mathrm{ph}}(\phi_{\mathrm{SC}}) + I_{\mathrm{SEE}}(\phi_{\mathrm{SC}})$

Output:
$\phi_{\mathrm{SC}} = \phi_{\mathrm{eq}}\left(n_e, T_e, n_i, T_i, J_{\mathrm{ph}}\right)$

An OML-based current-balance model **[4] [5]** is used to provide a first-order estimate of the equilibrium spacecraft potential before performing 3D SPIS simulations.

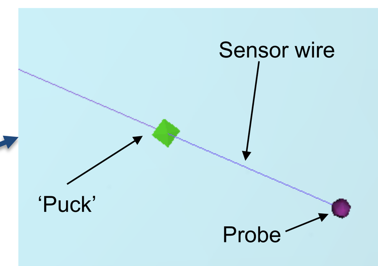
2. SPIS model of Mio and AM2P environment



Model of the Mio Spacecraft implemented in SPIS

A simplified model of the Mio spacecraft and probe environment is implemented in SPIS, a 3D spacecraft–plasma interaction simulation tool used to resolve charging, sheath formation and local plasma perturbations around the Mio geometry.

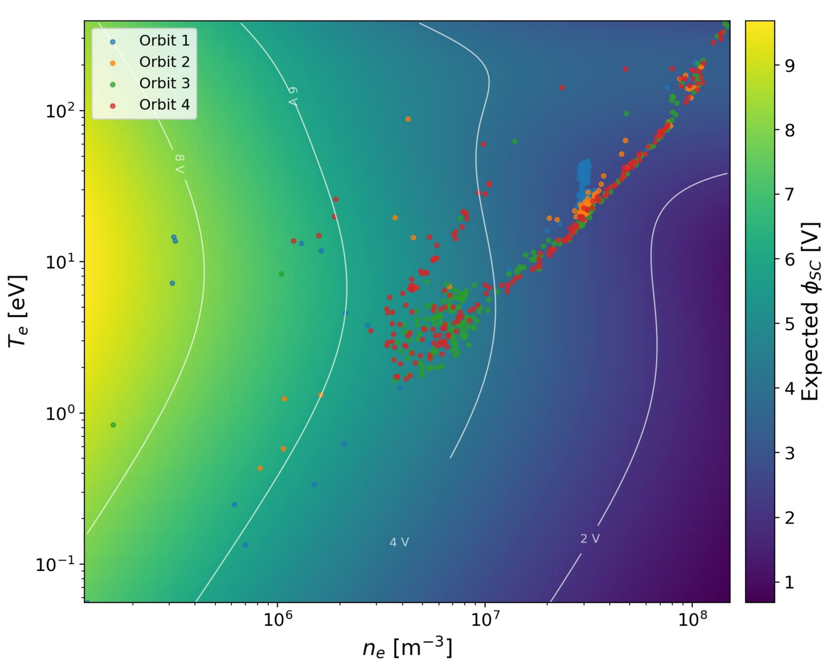
3. Near-probe electrostatic environment analysis



AM2P probe-region zoom: MEFISTO wire, puck and probe implemented in SPIS.

The resulting potential structure and plasma perturbations are analysed close to the AM2P sensors to assess how strongly the local environment differs from the ambient plasma.

Analytical Charging Model



Analytical charging regime map
Equilibrium Mio spacecraft potential from analytical OML current-balance model in (n_e, T_e) space, with representative Mio plasma conditions at Mercury overlaid.

Orbit	ϕ_{SC} range [V]	Median [V]	Eclipse [%]
O1	-6.9 to $+5.9$	$+2.9$	7.8
O2	$+2.6$ to $+6.5$	$+2.8$	0
O3	-7.1 to $+8.6$	$+3.1$	20.3
O4	$+2.5$ to $+6.7$	$+3.9$	0

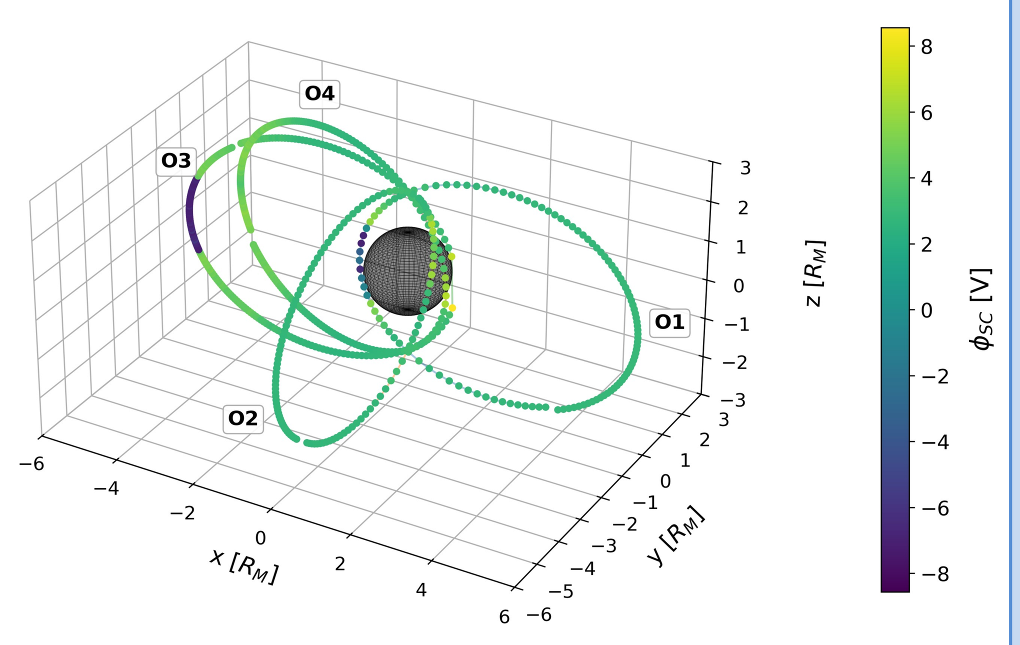
Analytical orbit summary
Sunlit samples remain weakly positive; negative analytical potentials occur only during eclipsing portions of O1 and O3.

SPIS input set

O1 provides the first detailed analytical/SPIS comparison case. O2 and O4 act as sunlit weak-positive reference cases. O3 samples the strongest eclipse-driven negative-potential regime.

Screening outcome

The OML map reduces the Mio plasma samples to a small set of representative charging regimes. Most sunlit cases remain weakly positive, while eclipsing portions of O1 and O3 provide negative-potential cases. These selected orbital samples define the input conditions for the detailed 3D SPIS simulations.



Representative orbital charging cases
Analytical estimate of equilibrium spacecraft potential along selected Mio orbital cases with Mercury shown at the centre.

AM2P Measurement Implications and PEPSO Validation

AM2P Measurement Implications

- AM2P samples the plasma response in the near-spacecraft environment, which may differ from the undisturbed ambient plasma.
- SPIS predicts electron depletion and sheath formation around the spacecraft and boom-mounted sensors.
- These spacecraft-induced perturbations should be accounted for when interpreting future AM2P mutual impedance measurements.

PEPSO Validation

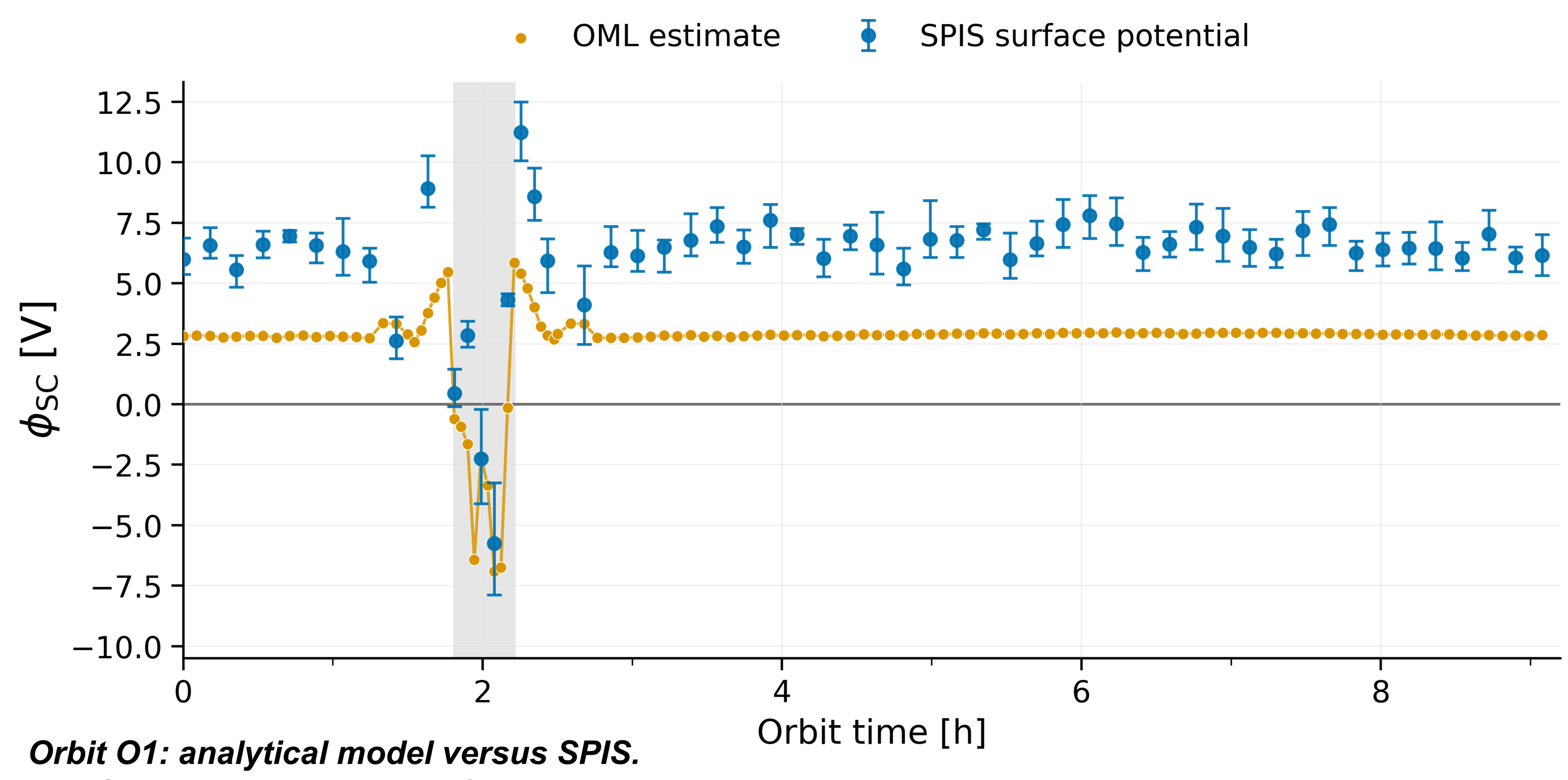
- PEPSO provides a controlled laboratory counterpart for testing the modelling approach.
- Chamber simulations can be compared with experimental measurements before applying the model to Mio in-flight conditions.

PEPSO Plasma Chamber at LPC2E in Orléans

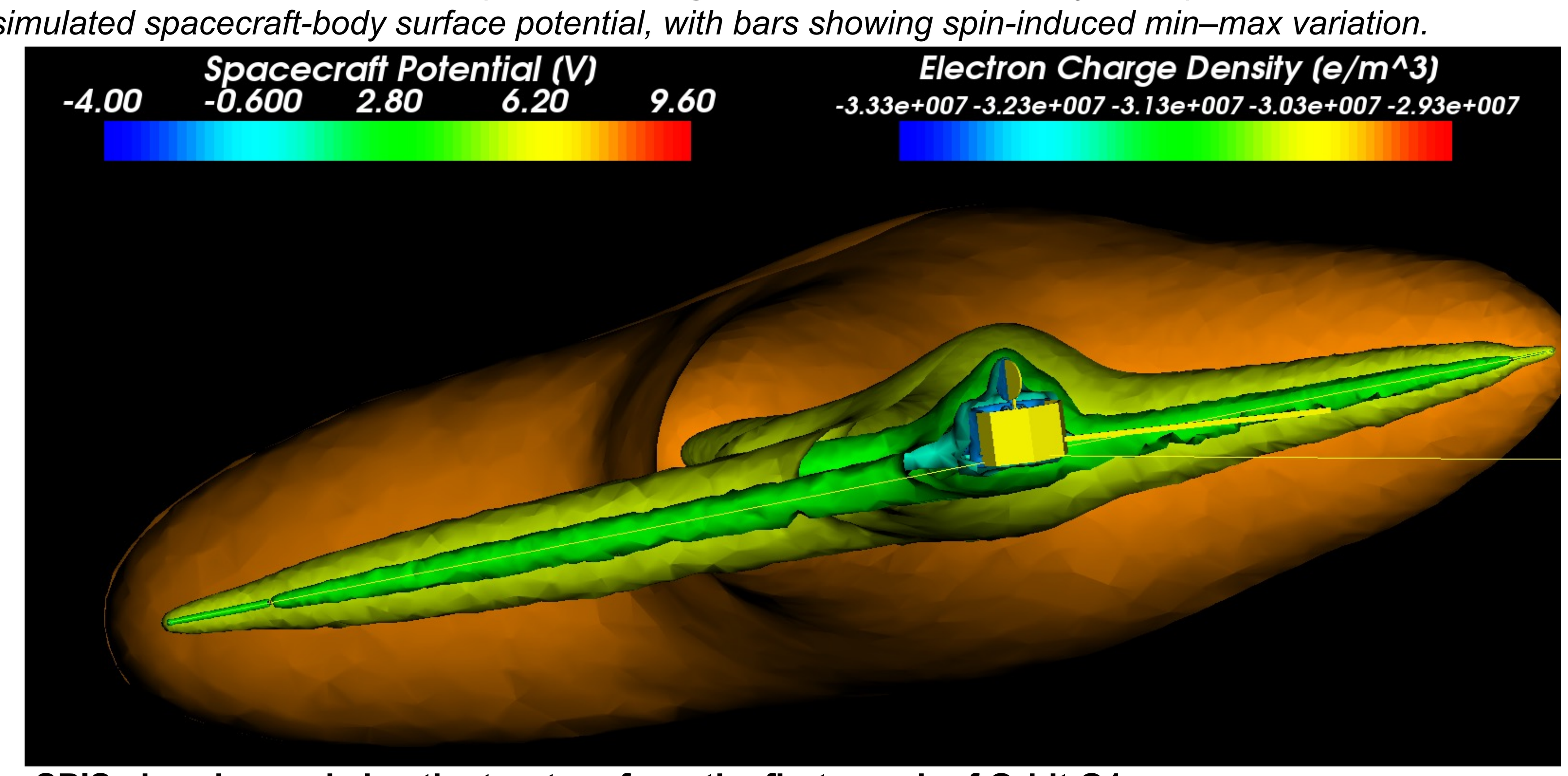
Conclusions

- Analytical regime screening identifies representative Mio plasma conditions for detailed SPIS simulations.
- Initial SPIS cases reproduce the broad OML charging trend but reveal stronger full-3D variability near the spacecraft.
- Electron depletion near the spacecraft and boom-mounted sensors suggests that AM2P measurements may be affected by spacecraft-modified plasma conditions.
- Future work will extract AM2P response metrics and compare the modelling approach against PEPSO chamber measurements.

Mio Spinning Spacecraft SPIS Results



Orbit O1: analytical model versus SPIS.
The OML model captures the first-order positive charging trend, with negative excursions during eclipse. SPIS follows the broad trend but predicts stronger case-to-case variability. Blue points show the median simulated spacecraft-body surface potential, with bars showing spin-induced min–max variation.



SPIS charging and sheath structure from the first epoch of Orbit O1
Electron depletion highlights the formation of an extended sheath around the spacecraft and boom-mounted sensors, indicating a strong perturbation of the local plasma environment.

Key observations

- Most selected Orbit O1 cases remain weakly positive, with the analytical model giving a median $\phi_{SC} \approx 2.8$ V and sunlit values $> 2.6\ V$.
- Negative analytical potentials occur during eclipse conditions, reaching approximately -6.9 V for Orbit O1.
- SPIS reproduces the broad positive-charging trend but predicts stronger case-to-case and spin-induced variability.
- Electron depletion around the spacecraft indicates that AM2P sensors may sample a spacecraft-modified plasma environment.

Preliminary SPIS simulations indicate that Mio develops a spacecraft-modified sheath environment near the spacecraft and boom-mounted sensors, with charging behaviour broadly consistent with OML estimates but more variable in full 3D.

References

[1] Y. Kasaba et al., "Plasma Wave Investigation (PWI) aboard BepiColombo Mio on the trip to the first measurement of electric fields, electromagnetic waves, and radio waves around Mercury," *Space Science Reviews*, vol. 216, article 65, 2020, doi: 10.1007/s11214-020-00692-9.
[2] R. L. Stenzel, "Mutual-impedance techniques for space plasma measurements," Measurement Techniques in Space Plasmas: Fields, 103, pp. 155–160, 1998.
[3] B. Thiébault, B. Jeanty-Ruard, P. Souquet, N. Balcon, J.-C. Matéo-Vélez, J. Forest, et al., "SPIS 5.1: An innovative approach for spacecraft plasma modeling," IEEE Transactions on Plasma Science, vol. 43, no. 9, pp. 2782–2788, 2015.
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[5] F. L. Johansson, A. I. Eriksson, N. Gilet, P. Henri, G. Wattieaux, M. G. G. T. Taylor, et al., "A charging model for the Rosetta spacecraft," Astronomy & Astrophysics, vol. 642, p. A43, 2020.