An Analytic Model for Estimating the First Contact Resistance Needed to Avoid Damaging ESD During Spacecraft Docking in GEO

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Introduction and Objective

NASA's Gateway program [1] will involve spacecraft (s/c) docking in the outer radiation belt in order to transfer Gateway elements between s/c for transport to lunar orbit. The charging of these s/c to different potentials prior to docking raises the possibility of a damaging electrostatic discharge (ESD) at the time of first contact between the s/c. A proposed mitigation strategy is for first contact to occur prior to docking through a resistor with resistance R that would lower the potential difference at an optimal rate to a sufficiently low value to prevent ESD damage. The coupling of s/c by a resistor can be modeled by SPIS [2], but for realistic two s/c models SPIS can take hours to simulate the evolution of the s/c surface charges and potentials to an equilibrium state. Our objective is to develop a simpler model of s/c resistive coupling that runs orders of magnitude faster while providing useful first design estimates of the time variation of the s/c potentials, current through the resistor, and how these vary with R and s/c configuration This configuration is defined by the relative separation and orientation of the s/c, and their solar illumination. The configuration and geometry of the s/c determine their capacitive coupling. The s/c capacitances are computed using Nascap-2K [3]. This poster presents the first version of such a model, and initial tests.

Model Equations

The equations relating the charges and voltages on two conductors [4] are combined with Ohm's law:

$$Q_1 = C_{11}V_1 + C_{12}V_2 \quad (1)$$
$$Q_2 = C_{21}V_1 + C_{22}V_2 \quad (2)$$
$$I_1 = \frac{dQ_1}{dt} \quad (3)$$
$$I_2 = \frac{dQ_2}{dt} \quad (4)$$
$$I_1 = \frac{(V_2 - V_1)}{R} \quad (5)$$
$$I_1 = -I_2 \quad (6)$$

Give initial conditions $V_1(0), V_2(0)$ or $Q_1(0), Q_2(0)$.

The model does not yet include photo-electron or plasma currents.

Solution to Model

Given the initial conditions the solution is:

$$V_1(t) = V_1(\infty) + (V_1(0) - V_1(\infty))\exp(-t/\tau)$$
$$V_1(t) - V_2(t) = (V_1(0) - V_2(0))\exp(-t/\tau)$$
$$I_1(t) = \frac{(V_2(0) - V_1(0))}{R}\exp(-t/\tau) \quad \text{where}$$

$$V_1(\infty) = \frac{(C_{11}+C_{21})V_1(0) + (C_{12}+C_{22})V_2(0)}{C_{11}+C_{22}+C_{12}+C_{21}}$$
$$\tau = \frac{R(C_{11}C_{22} - C_{12}C_{21})}{C_{11}+C_{22}+C_{12}+C_{21}} \equiv RC_{mutual}$$

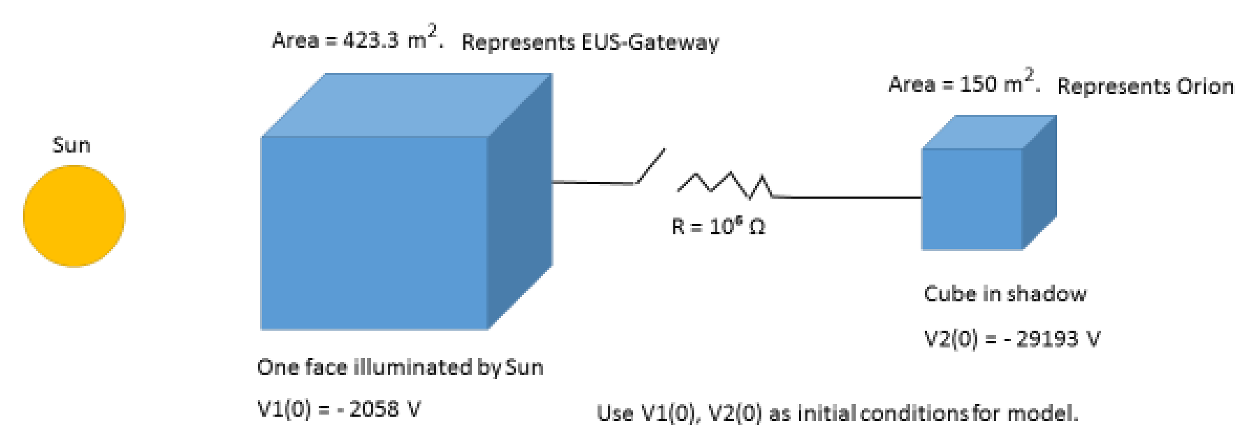
Determination of the C_{ij} and Initial Voltages

1. Fix all potentials on each s/c: $(V_1, V_2) = (1, 0)$. Run Nascap. Then $C_{11} = Q_1, C_{21} = Q_2$.
2. Run Nascap with $(V_1, V_2) = (0, 1)$. Then $C_{12} = Q_1, C_{22} = Q_2$.
3. Run Nascap without fixed potentials to obtain $V_1(0), V_2(0)$.

As a check on the numerically determined capacitances, they must satisfy the relations [5]:
$C_{ii} > 0, C_{ij} < 0 (i \neq j), C_{ii}C_{jj} - C_{ij}^2 > 0, C_{ii} + C_{jj} + 2C_{ij} > 0.$

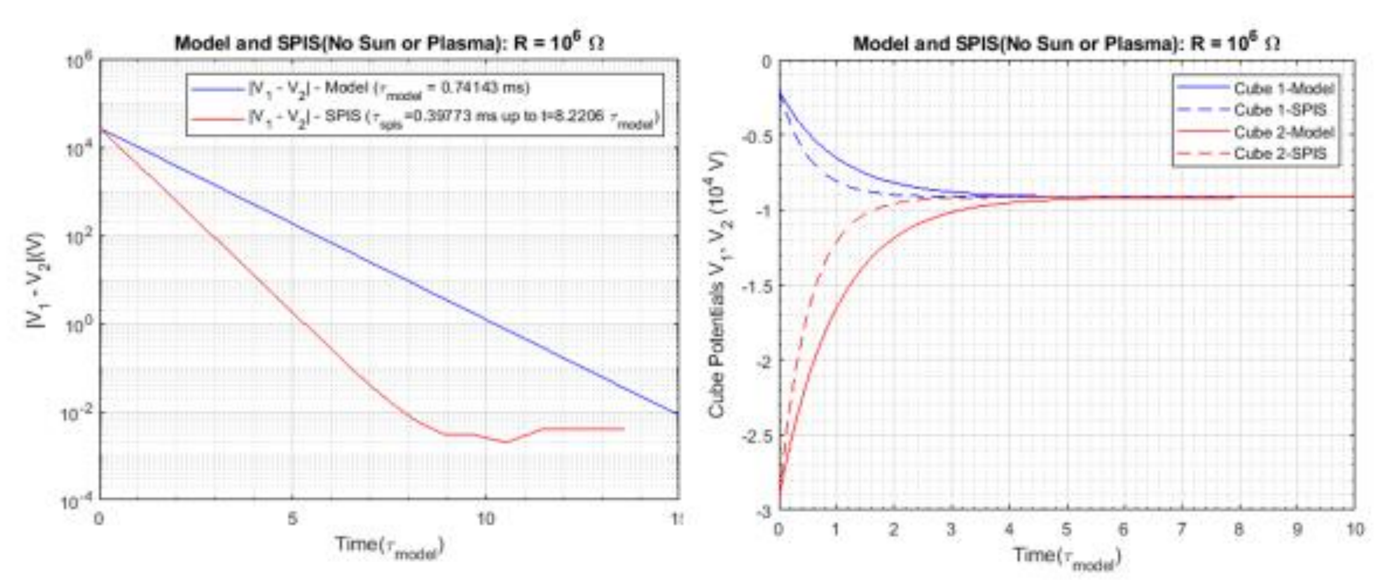
Test Case: Aluminum Cubes – Separation = 1 m.

Run SPIS to equilibrium potential values with switch open. Then close switch, run SPIS and model, and compare results. Closing switch models first contact, through resistor R.

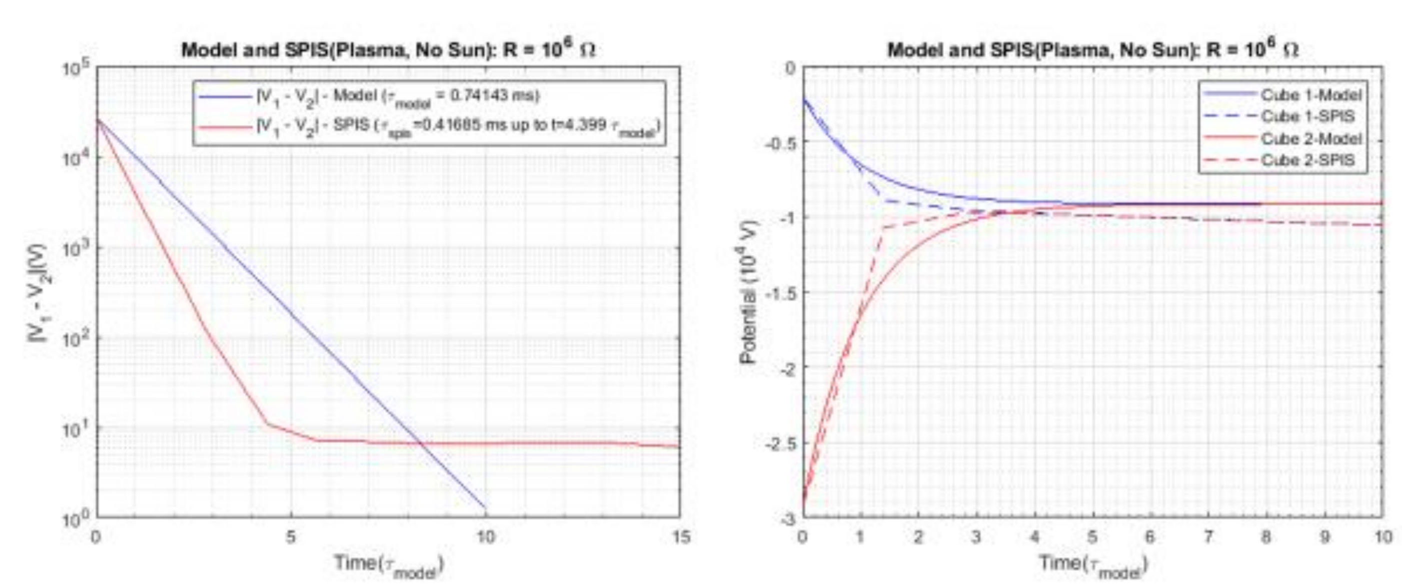


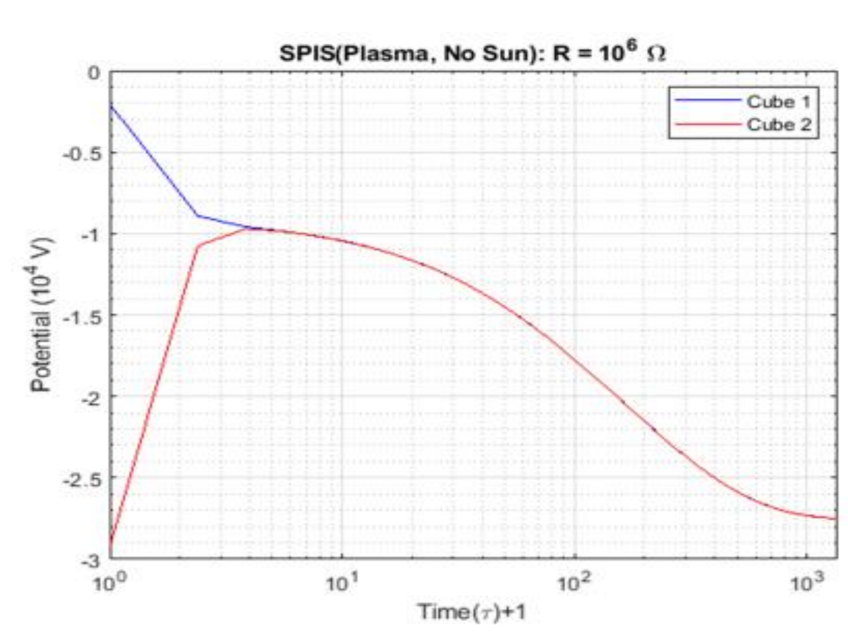
$C_{11} = 1.12\text{e-}9$ F, $C_{22} = 7.81\text{e-}10$ F, $C_{12} = -6.07\text{e-}10$ F, $C_{21} = -6.30\text{e-}10$ F.
$\Rightarrow C_{mutual} = 7.414\text{e-}10$ F.

Results for SPIS without Sun or Plasma (direct, secondary, and backscattered electrons, and ions)

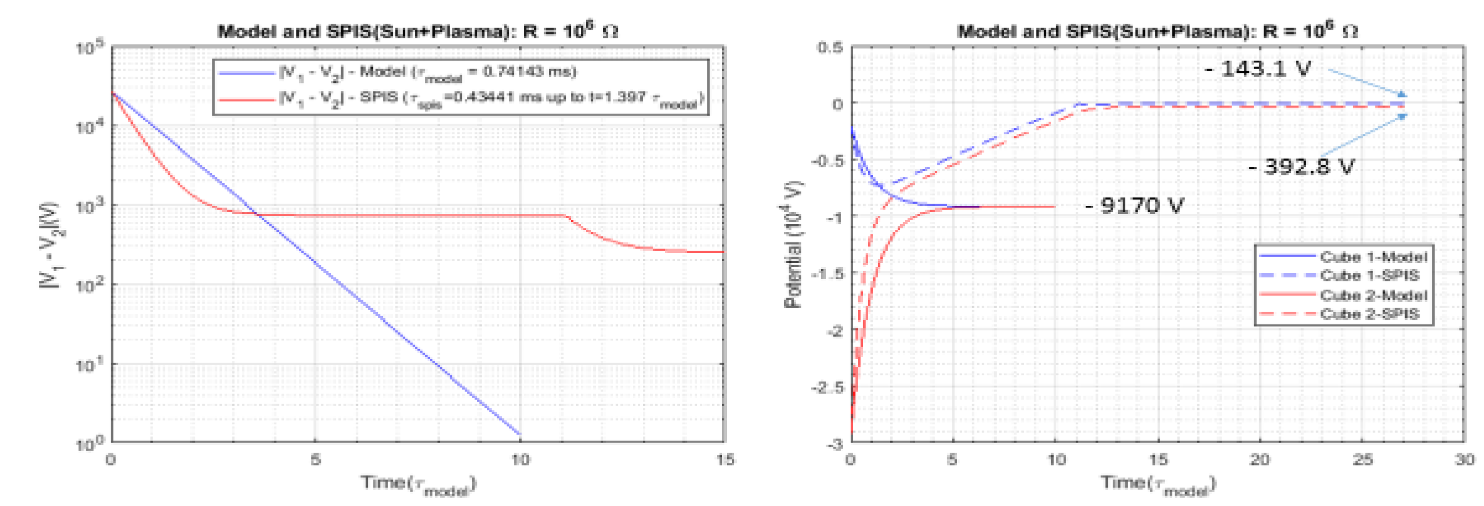


Results for SPIS with Plasma, no Sun

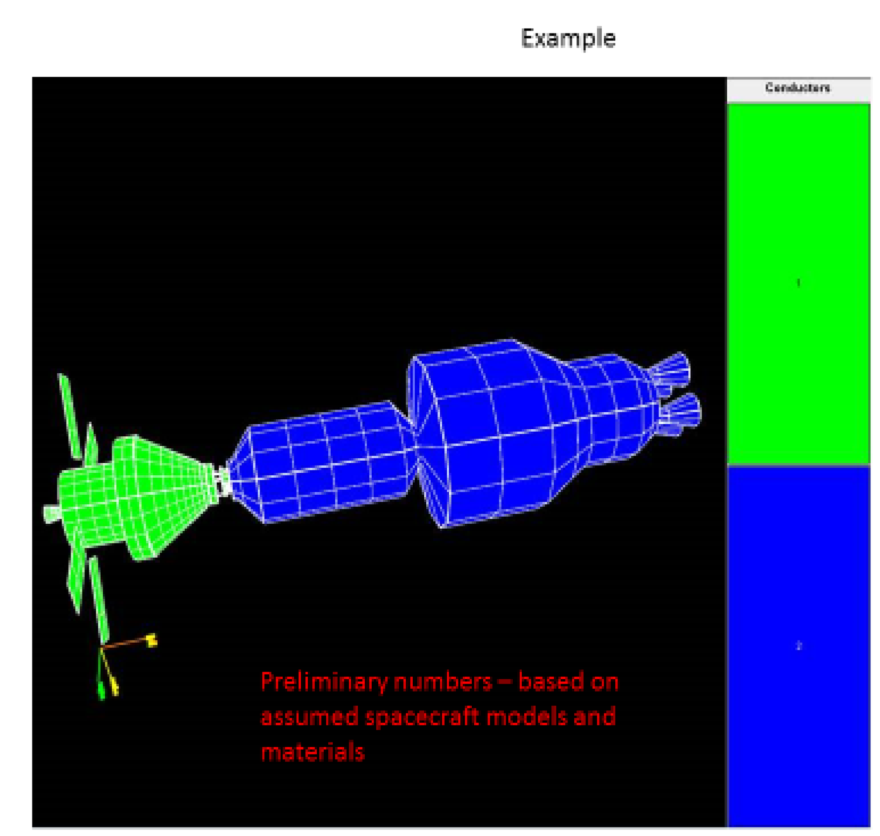




Results for SPIS with Plasma & Sun



Example Using a Realistic s/c Model



Minimum separation = 1 m.
Model Runtime = 1 ms.

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C11 = 5.1000e-10 F
C22 = 7.5580e-10 F
C12 = -2.5800e-10 F
C21 = -2.6700e-10 F

Initial frame voltages:
V1(0) = -6854 V
V2(0) = -7906 V

Final frame voltage:
V1(∞) = -7.5609e+03 V

RC Time Constant:
τ = R*4.2734e-10 sec
R = 1.0e+09 Ohms ➔
τ = 0.4273 sec
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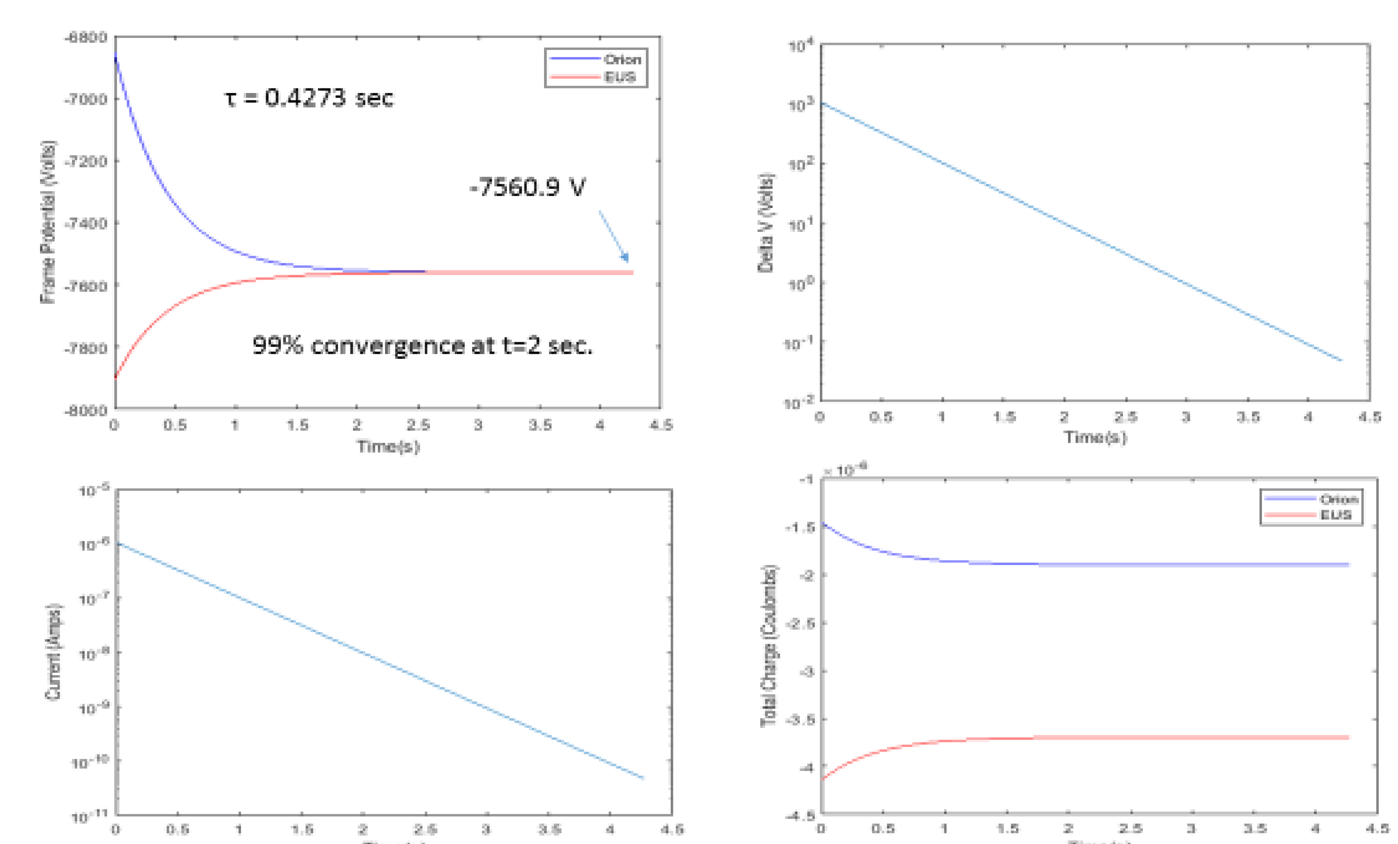

Conclusions & Future Work

The model agrees reasonably well with SPIS during resistive coupling of the cubes in the absence of photo-electron and plasma currents. In the presence of these currents in SPIS, the tendency of the cube potentials to equalize is dominated at early times by current flow through the resistor, with SPIS showing an initial exponential convergence of the potentials, characterized by an effective RC time constant ~ 0.40 – 0.43 ms, to be compared with the model RC time constant of 0.74 ms. Photo-electron and plasma currents due to primary, secondary, and backscattered electrons, and to ions will be included in future versions of the model.

References

[1] ``Lunar Gateway.'' www.nasa.gov/mission_pages/station/main/index.html, NASA
[2] SPIS (Spacecraft Plasma Interaction System), http://dev.spis.org/projects/spine/home/spis
[3] Mandell, Myron J., et al. "Nascap-2k spacecraft charging code overview." IEEE Transactions on Plasma Science 34.5 (2006): 2084-2093
[4] Jackson, J.D. 1999, ''Classical Electrodynamics'' (John Wiley & Sons)
[5] Landau, L.D. & Lifshitz, E.M. 1984, ''Electrodynamics of Continuous Media'' (Pergamon Press)