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

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## 1. Introduction & Objective

NASA's Gateway program [1] is to 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 a damaging ESD. The coupling of s/c by a resistor can be modeled by SPIS (Spacecraft Plasma Interaction System) [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 abstract and the associated poster describe the first version of such a model, and initial tests.

## 2. Model Equations

The model provides simple analytic expressions for the time dependence of the charges and frame voltages (potentials) $(Q_i, V_i\ (i = 1, 2))$ on the s/c, and the current through the resistor connecting the s/c beginning at the time of first contact. The model provides an $RC$ time constant that determines the exponential time variation of these quantities.

The s/c are modeled as two perfect conductors in vacuum, so there are no photo-electron or plasma currents. The equations relating $Q_i, V_i\ (i = 1, 2)$ on the conductors are (e.g., [4]-[5]):

$$Q_1 = C_{11}V_1 + C_{12}V_2 \tag{1}$$

$$Q_2 = C_{21}V_1 + C_{22}V_2 \tag{2}$$

The $C_{ij}$ are capacitances. They describe the electrical coupling of the s/c through their electric fields. As the separation of the s/c increases, $C_{ij} \to 0$ for $i \neq j$. Although the model predicts the total s/c charges $Q_i$, it cannot predict the surface charge distributions.

For a given geometrical configuration of the s/c, the $C_{ij}$ are constant (independent of time $t$). Here they are determined by running Nascap-2K as follows. One fixes the frame potentials $(V_1, V_2)$ at $(1, 0)$, and then run Nascap-2K to equilibrium. Then $C_{11} = Q_1, C_{21} = Q_2$, where the $Q_i$ are given by Nascap-2K as the surface average over the entire s/c of the normal component of the electric field times the total area of the s/c. One then runs Nascap-2K again with $(V_1, V_2) = (0, 1)$. Then $C_{12} = Q_1, C_{22} = Q_2$. As a check on these numerically determined capacitances, they must satisfy the exact relations [5]: $C_{ii} > 0, C_{ij} < 0 (i \neq j), C_{ii}C_{jj} - C_{ij}C_{ji} > 0, C_{ij} = C_{ji}$, and $C_{ii} + C_{jj} + C_{ij} + C_{ji} > 0$. These relations guarantee that the $RC$ time constant $\tau$ defined in Eq. (8) is positive.

At the time $t = 0$ of first contact, the s/c are connected through the resistor. It is assumed that the current through the resistor obeys the Ohm's law $I_1(t) = (V_2(t) - V_1(t))/R$, where $I_1 = dQ_1/dt$ and $I_2(t) = -I_1(t)$.

Once the $C_{ij}$ are determined, SPIS is run for the same s/c configuration using chosen initial s/c frame potentials to obtain equilibrium values of $V_i$. These are the initial conditions $V_i(0)$ for the model. SPIS is used because it can model two s/c connected by a resistor, while the current version of Nascap-2K cannot.

### 3. Analytic Solution of the Model

Given the capacitances and initial conditions, the solution is:

$$V_1(t) = V_1(\infty) + (V_1(0) - V_1(\infty)) \exp(-t/\tau) \tag{3}$$

$$V_1(t) - V_2(t) = (V_1(0) - V_2(0)) \exp(-t/\tau) \tag{4}$$

$$I_1(t) = \frac{(V_2(0) - V_1(0))}{R} \exp(-t/\tau) \quad \text{where} \tag{5}$$

$$V_1(\infty) = \frac{(C_{11} + C_{21})V_1(0) + (C_{12} + C_{22})V_2(0)}{C_{11} + C_{22} + C_{12} + C_{21}} \tag{6}$$

$$\tau = \frac{R(C_{11}C_{22} - C_{12}C_{21})}{C_{11} + C_{22} + C_{12} + C_{21}} \tag{7}$$

$$\equiv RC_{mutual}. \tag{8}$$

Here $\tau$ is the effective $RC$ time constant.

The outline of the procedure for solving the model may be summarized as follows:
1. Choose a s/c configuration.
2. Run Nascap-2K to determine the $C_{ij}$: Run it once with $(V_1, V_2)$ fixed at $(0, 1)$, and again with them fixed at $(1, 0)$.
3. Run SPIS using chosen initial values for the $V_i$. Use the resulting equilibrium values of $V_i$ as the initial conditions $V_i(0)$ in the model.
4. Specify a range of $R$, and evaluate the analytic solution. Equivalently, using equation (5), specify ranges of the maximum magnitude of $I_1 (= |I_1(0)| \propto 1/R)$, or specify ranges of the maximum magnitude of $dI_1/dt (= |I_1(0)|/\tau \propto 1/R^2)$, and then solve for the corresponding range of $R$.

### 4. Test Case: Aluminum Cubes

Two Al cubes were created in SPIS. The cube configuration is shown in Figure 1. The cubes have their centers on the line normal to two faces of each cube. The cubes have their closest faces 1 m apart. The areas of the cubes are the approximate areas of the EUS-DSG s/c (cube 1)[1], and the Orion s/c (cube 2). One face of cube 1 is illuminated by the Sun, and so is a source of photoemission. Cube 2 is entirely in the shadow of cube 1. The cubes are connected by a resistor. SPIS was first run to equilibrium including all photo-electron and plasma currents, but without the resistor connecting the cubes. The resulting equilibrium potentials of the cubes, which are the initial potentials for the model for cubes 1 and 2 were $V_1(0) = -2058$ V, and $V_2(0) = -29193$ V. The same cube configuration was created in Nascap-2K to compute the capacitances shown in Figure 1.

SPIS was then run to equilibrium with the cubes connected by the resistor, and using these initial potentials. This was done for three environments for $t > 0$: (1) Without photo-electron or plasma currents. (2) Without photo-electron currents, but with plasma currents. (3) With photo-electron and plasma currents. The model solution for the potentials of cubes 1 and 2, and their difference, was compared with the SPIS results. The results for these three cases are presented in Figure 2, and briefly summarized in §6.

### 5. Other Results for a Pending Test Case

A preliminary CAD (Computer Aided Design) model of the EUS-DSG and Orion s/c was constructed in Nascap-2K (a similar construction is being done in SPIS). This model includes a preliminary choice of dielectric and conducting materials bonded to the conducting s/c frames. A configuration was chosen for which the s/c are close to docked, with a minimum separation of 1 m. The capacitances for this configuration are $C_{11}$ = 5.1e-10 F, $C_{22}$ = 7.558e-10 F, $C_{12}$ = −2.58e-10 F, and $C_{21}$ = −2.67e-10 F,

[1]EUS-DSG = Exploration Upper Stage-Deep Space Gateway. EUS, the DSG component, and Orion are to be launched together. In the outer radiation belt, Orion is to detach from EUS, turn around, dock with the DSG component on EUS, extract it, and transport it to lunar orbit.

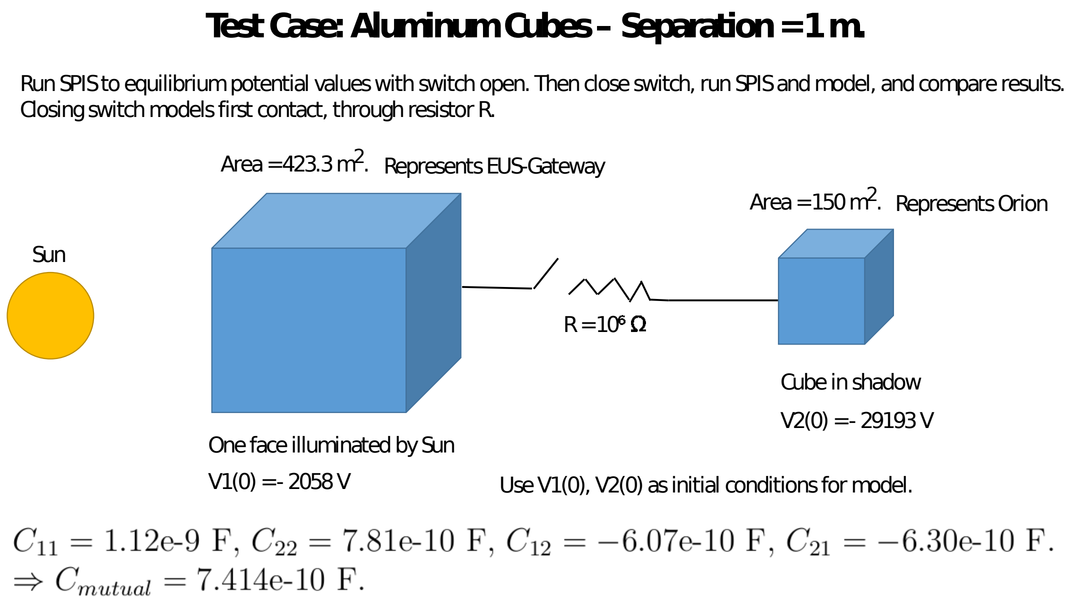


Figure 1. Al Cubes Test Case.

which gives $C_{mutual} = 4.273\text{e-}10$ F. Here the subscripts 1 and 2 refer to Orion and EUS-DSG, respectively. Nascap-2K was run to equilibrium for this configuration. The final frame potentials are $V_1 = -6854$ V and $V_2 = -7906$ V. Using these values as initial conditions in the analytic model, and assuming $R = 10^9\ \Omega$, the model predicts that both frame potentials converge to $-7560.9$ V in $\sim 2$ sec, and an $RC$ time constant of 0.4273 sec. If $R$ is reduced to $10^6\ \Omega$, the convergence time decreases to $\sim 2$ ms since $\tau \propto R$. Once the SPIS CAD model is complete, SPIS will be run with the s/c connected by the resistor to obtain equilibrium frame potentials for the two s/c for comparison with the model prediction of $-7560.9$ V.

## 6. Conclusions & Future Work

The model potentials agree reasonably well with those of 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 $\sim 0.40 - 0.43$ ms, to be compared with the model $RC$ time constant of $\sim 0.74$ ms. The results tentatively suggest that for values of $R$ not $\gg 10^6\ \Omega$ the $RC$ time-scale for discharge through the resistor is shorter than the time-scales for the photo-electron and plasma currents to significantly affect the cube potentials, but these currents have a large effect on these longer time-scales. Photo-electron and plasma currents will be included in future versions of the model, which will be tested against SPIS initially using simple structures such as cubes, and then using more realistic two s/c models in terms of geometry and material composition.

## References

[1] "Lunar Gateway." www.nasa.gov/mission_pages/station/main/index.html, National Aeronautics and Space Administration.
[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)

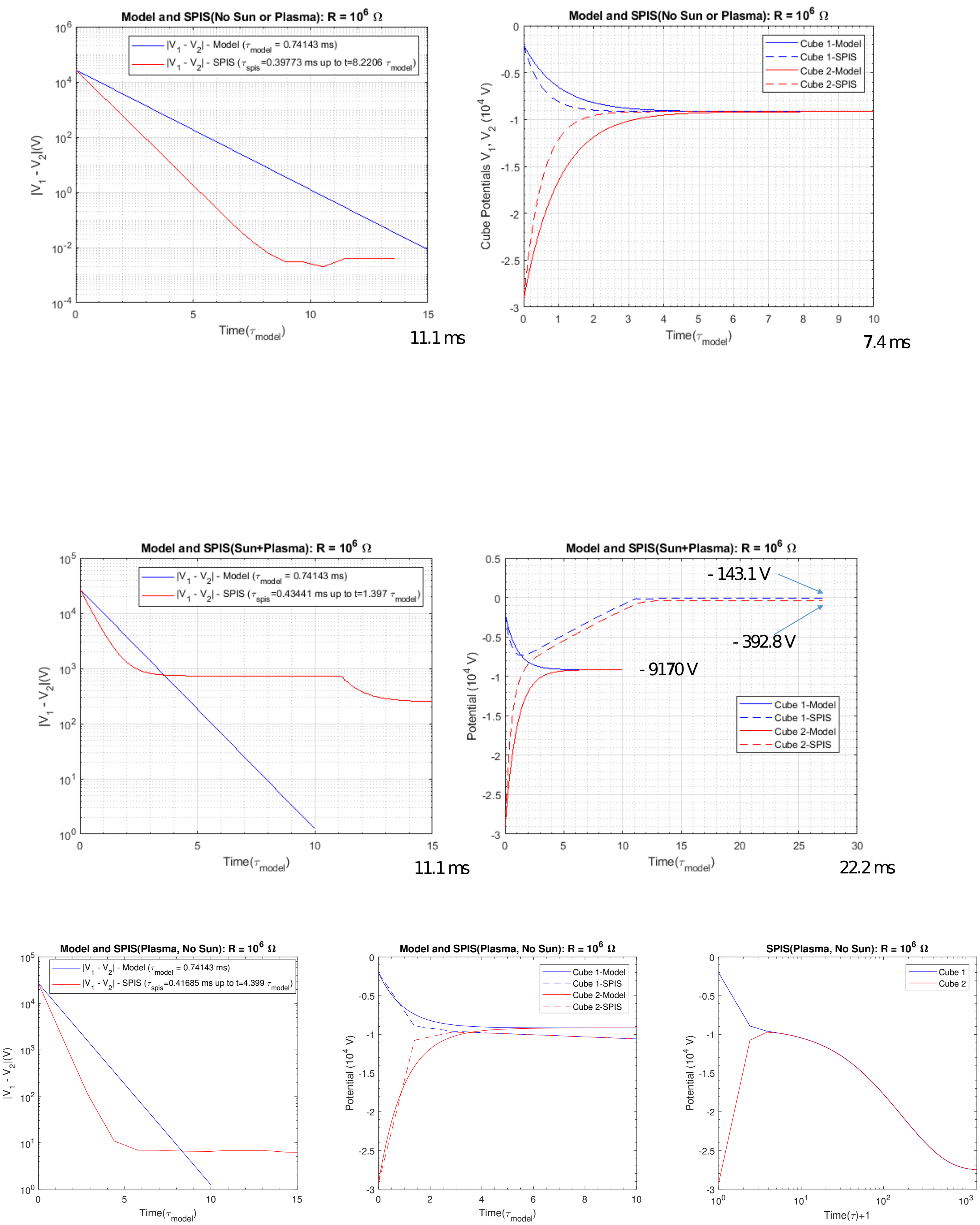


Figure 2. Al Cubes Test Case: Top - No photo-electron or plasma currents in SPIS. Middle - Photo-electron and plasma currents in SPIS. Bottom - Plasma currents, but no photo-electron currents in SPIS.