Impacts of Cislunar Plasma on Electrostatic Tractor Potentials

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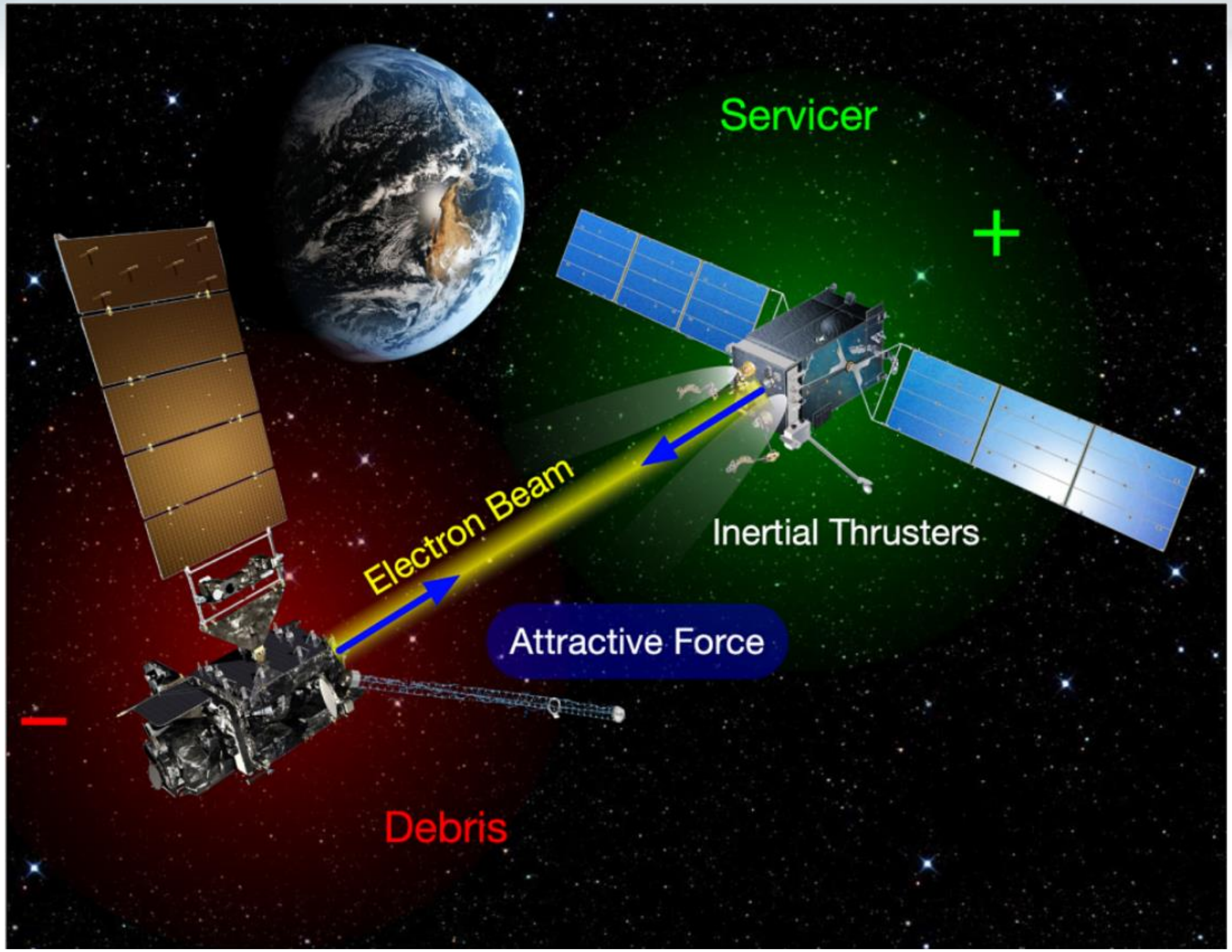
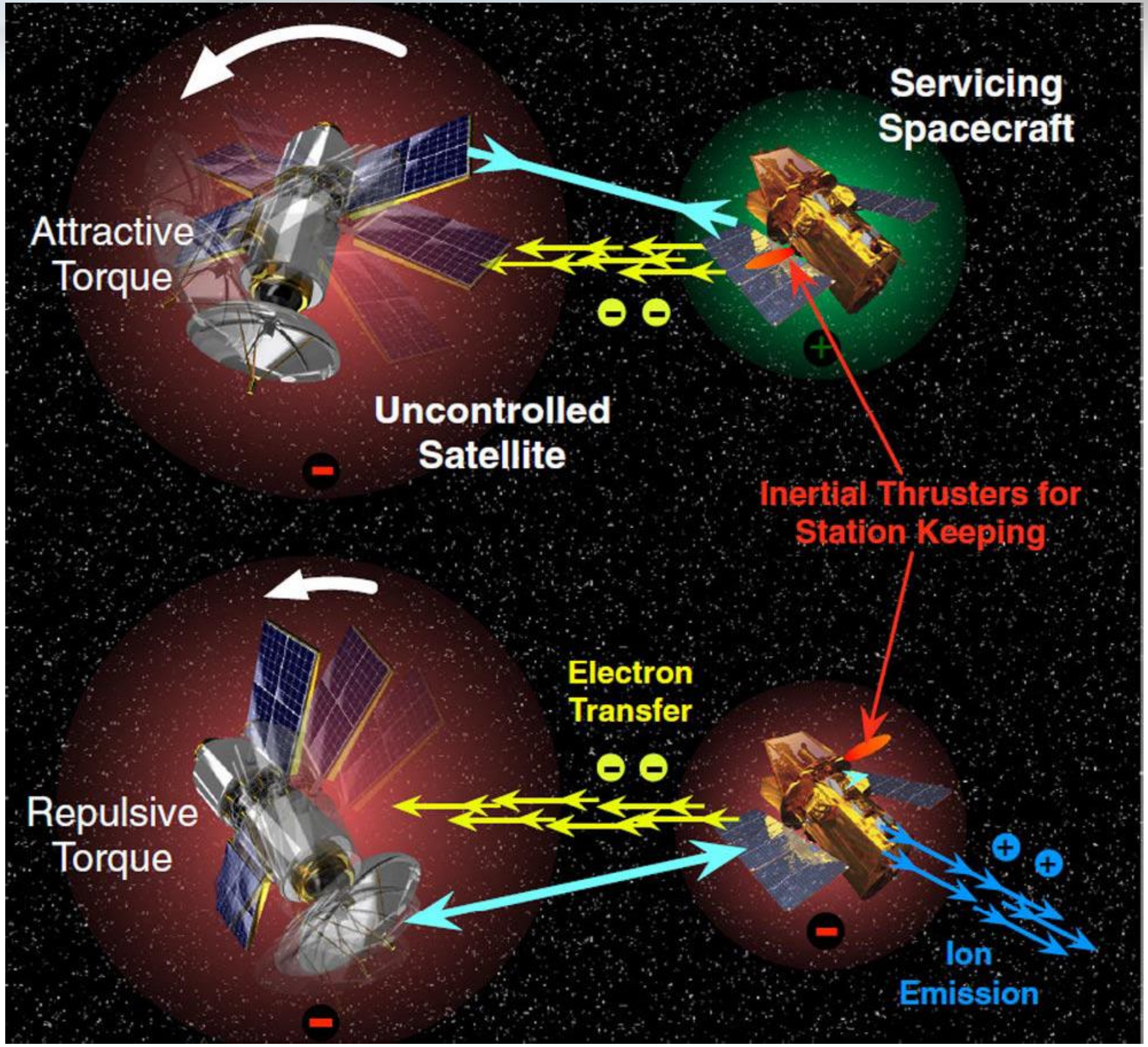
Introduction and Motivation

Electrostatic tractor



Hammerl and Schaub, “Effects of Electric Potential Uncertainty on Electrostatic Tractor Relative Motion Control Equilibria”, Journal of Spacecraft and Rockets, 59(2), 2022

Electrostatic detumbling

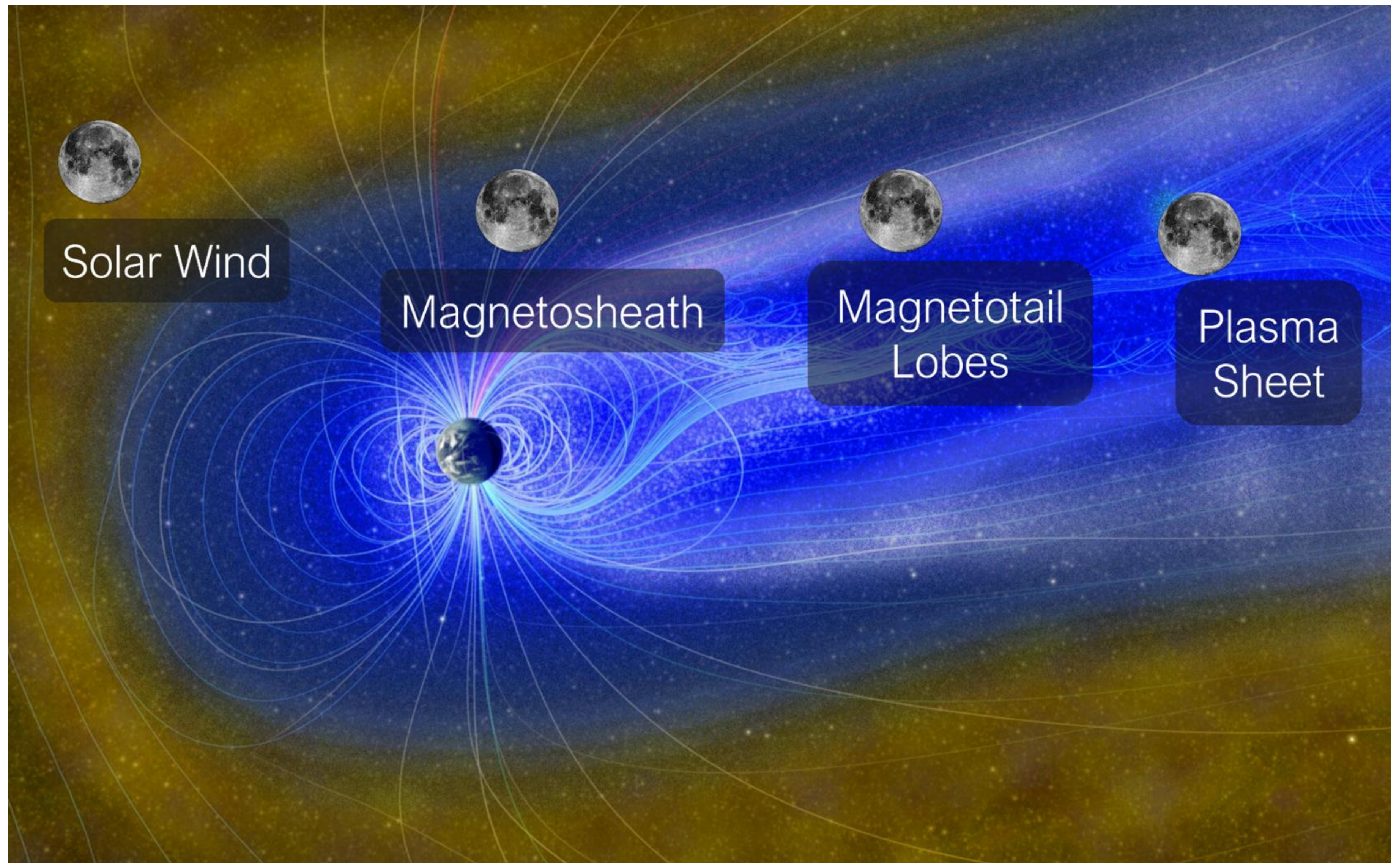


Casale, Schaub, and Biggs “Lyapunov Optimal Touchless Electrostatic Detumbling of Geostationary Debris Using Surface Multisphere Models”, Journal of Spacecraft and Rockets, 58(3), 2021

Expansion to Cislunar Space

- Electrostatic tractor previously investigated in GEO
  - Debye length typically on the order of hundreds of meters
- Cislunar environment presents new environmental challenges
  - Moon orbits through and outside magnetosphere
  - Debye length varies from several meters to hundreds of meters
  - Spacecraft wakes
- **Different charging levels and forces expected in cislunar space**

Cislunar plasma environment regions



Spherical Spacecraft Charging Model

- **Incident particles (electrons and ions)**

$$I_e(\phi) = \begin{cases} -\frac{Aq_0 n_e w_e}{4} e^{\phi/T_e} & \text{if} \quad \phi \leq 0 \\ -\frac{Aq_0 n_e w_e}{4} \left(1 + \frac{\phi}{T_e}\right) & \text{if} \quad \phi > 0 \end{cases}, \qquad I_i(\phi) = \begin{cases} \frac{Aq_0 n_i w_i}{4} \left(1 - \frac{\phi}{T_i}\right) & \text{if} \quad \phi \leq 0 \\ \frac{Aq_0 n_i w_i}{4} e^{-\phi/T_i} & \text{if} \quad \phi > 0 \end{cases} \qquad w = \sqrt{8T_{e/i}/(m_{e/p}\pi)}$$

- **Photoelectrons**

$$I_{ph}(\phi) = \begin{cases} j_{ph,0} A_{ph} & \text{if} \quad \phi \leq 0 \\ j_{ph,0} A_{ph} e^{-\phi/T_{ph}} & \text{if} \quad \phi > 0 \end{cases} \qquad \begin{aligned} j_{ph,0} &= 20\ \mu\text{A/m}^2 \\ T_{ph} &= 2\ \text{eV} \end{aligned}$$

- **Secondary electrons due to electrons and ions** – from NASCAP-2k scientific documentation

$$Y_{ee}(E,\psi) = c_1 \int_0^R \left|\frac{\mathrm{dE}}{\mathrm{dx}}\right| \mathrm{e}^{-c_2 x \cos\psi}\, \mathrm{dx} \qquad \frac{\mathrm{dE}}{\mathrm{dx}} = \left(\frac{\mathrm{dR}}{\mathrm{dE}}\right)^{-1} + \left(\frac{\mathrm{d^2R}}{\mathrm{dE^2}}\right)\left(\frac{\mathrm{dR}}{\mathrm{dE}}\right)^{-3} x, \qquad Y_{SEE,i}(E) = 2\frac{\beta E^{1/2}}{1 + E/E_{max,i}}$$

$$R = b_1 E^{q_1} + b_2 E^{q_2}$$

- **Backscattered electrons** – from NASCAP-2k scientific documentation

$$Y_B(E) = \left(\frac{H(1-E)H(E-0.05)\log(E/0.05)}{\log 20} + H(E-1)\right) \cdot \left(\frac{\exp(-E/5)}{10} + A_{0/I}\right)$$

$$A_0 = 1 - \left(\frac{2}{e}\right)^a \qquad A_I = 2\frac{1 - A_0(1 - \log A_0)}{(\log A_0)^2}$$

$$a = 0.0375Z$$

Electron Beam Currents

- **Servicer beam current**

$$I_{EB,S}(\phi_S) = \begin{cases} I_{EB} & \text{if} \quad E_{EB} > \phi_S \\ 0 & \text{if} \quad E_{EB} \le \phi_S \end{cases}$$

- **Target beam current**

$$I_{EB,T}(\phi_T, \phi_S) = \begin{cases} -\alpha_{EB} I_{EB} & \text{if} \quad E_{EB} > \phi_S - \phi_T \\ 0 & \text{if} \quad E_{EB} \le \phi_S - \phi_T \end{cases}$$

$$I_{SEE/B,EB}(\phi_T, \phi_S) = Y_{SEE,e/B}(E_{\text{eff}}) \cdot I_{EB,T}(\phi_T, \phi_S)$$

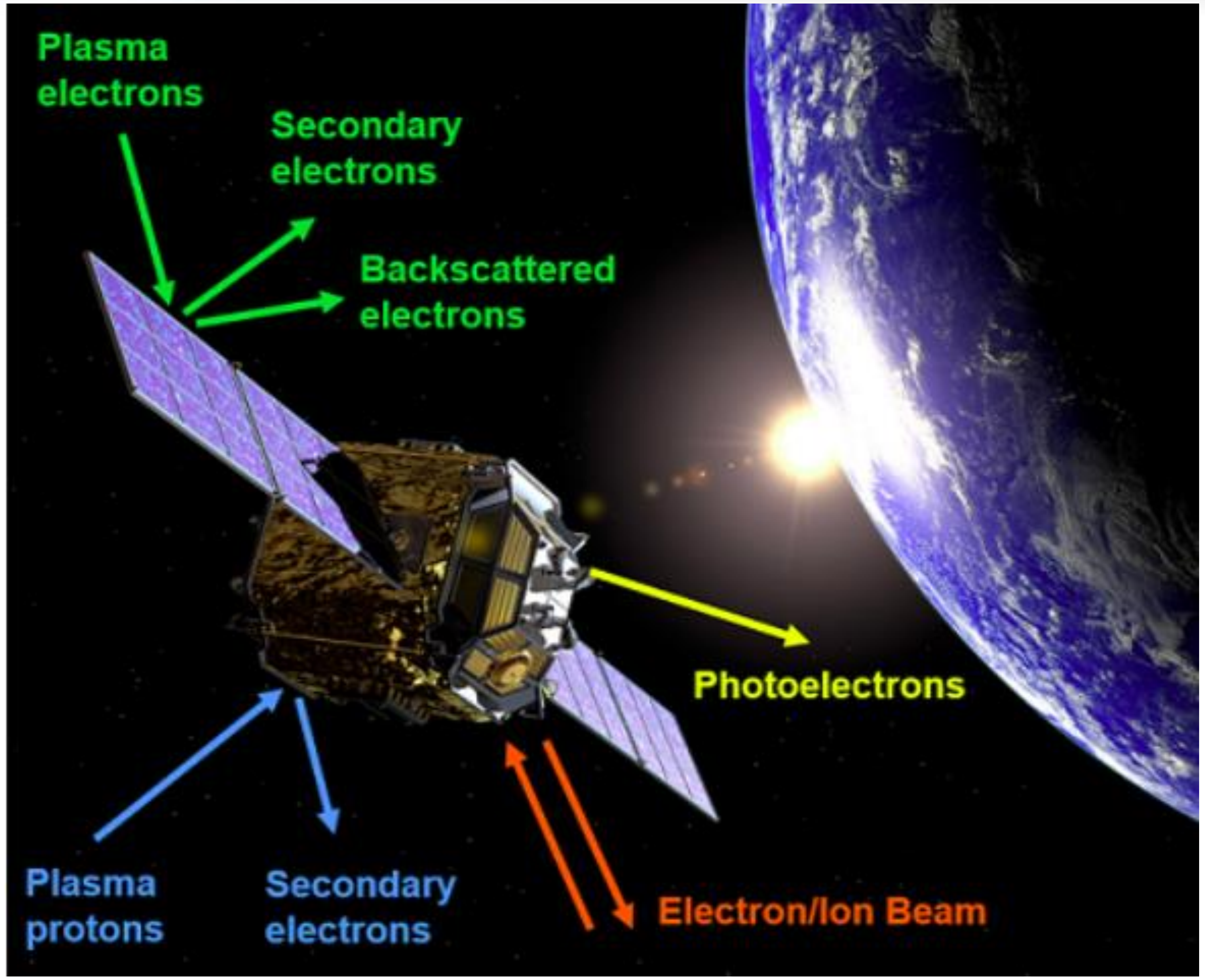
$$E_{\text{eff}} = E_{EB} - \phi_S + \phi_T$$

- **Total Currents**

$$I_{\text{tot},S}(\phi_S) = I_e(\phi_S)(1 - Y_{SEE,e}(\phi_S) - Y_B(\phi_S)) + I_i(\phi_S)(1 - Y_{SEE,i}(\phi_S)) + I_{ph}(\phi_S) + I_{EB,S}(\phi_S)$$

$$I_{\text{tot},T}(\phi_T, \phi_S) = I_e(\phi_T)(1 - Y_{SEE,e}(\phi_T) - Y_B(\phi_T)) + I_i(\phi_T)(1 - Y_{SEE,i}(\phi_T)) + I_{EB}(\phi_T)(1 - Y_{EB,T}(\phi_T, \phi_S) - Y_{SEE,EB}(\phi_T, \phi_S)) + I_{ph}(\phi_T)$$

Spacecraft charging physics

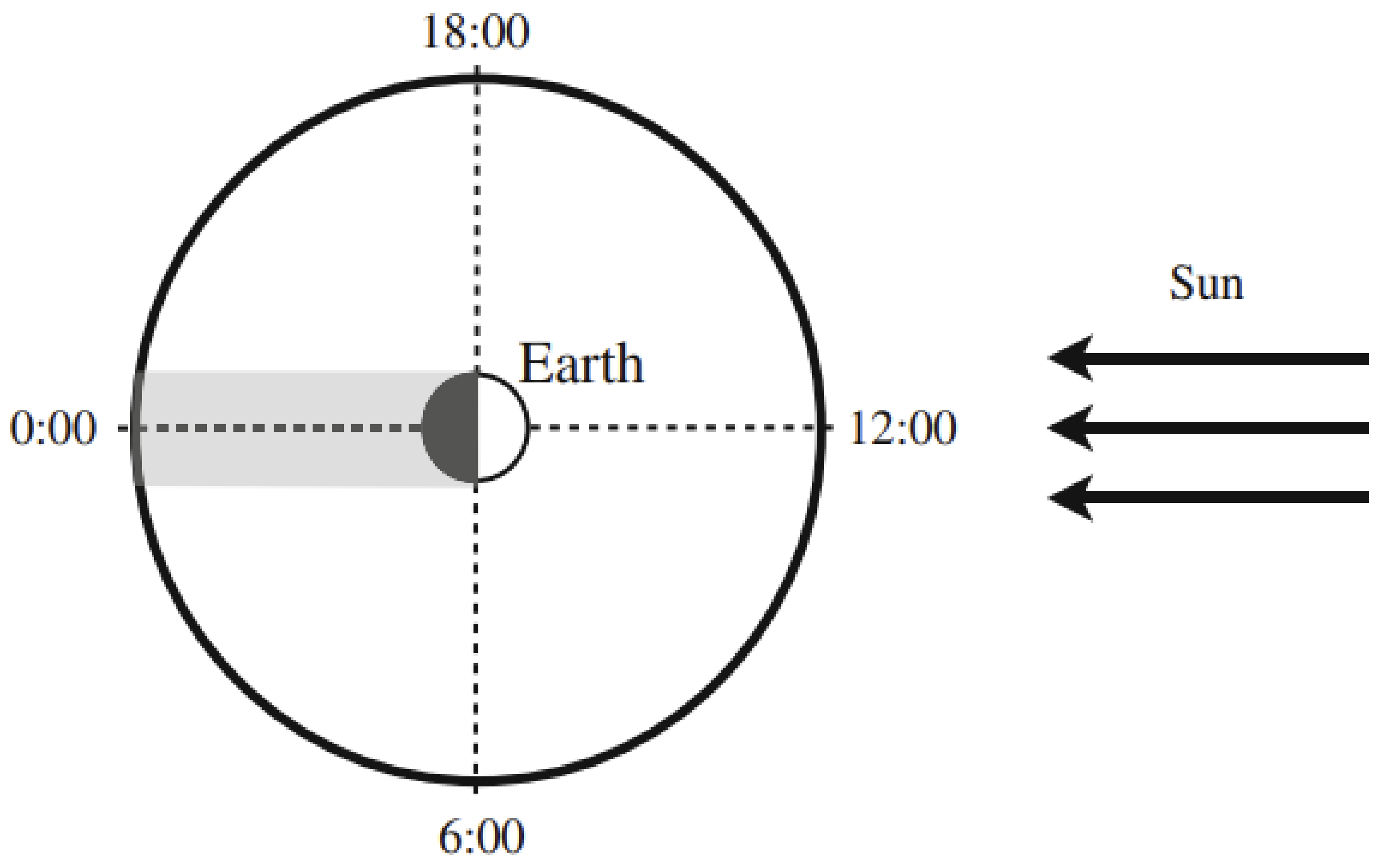


Bengtson., "Electron Method for Touchless Electrostatic Potential Sensing of Neighboring Spacecraft," Ph.D. Dissertation, 2020

Problem Definition

- Two spherical spacecraft composed of Aluminum
  - Servicer radius of 2m
  - Target radius of 0.975m
- Beam energy of 40 keV, varied current
  - Highest potential difference between servicer and target ($\emptyset_S - \emptyset_T$) is 40 keV
- Potentials investigated in GEO and cislunar regions
  - Quiet, moderate, and severe storm conditions at 3:00 local time in GEO
  - Mean parameters in each cislunar environment

Local time at GEO



Hogan, Erik A., and Hanspeter Schaub. "Space weather influence on relative motion control using the touchless electrostatic tractor." The Journal of the Astronautical Sciences 63 (2016): 237-262.

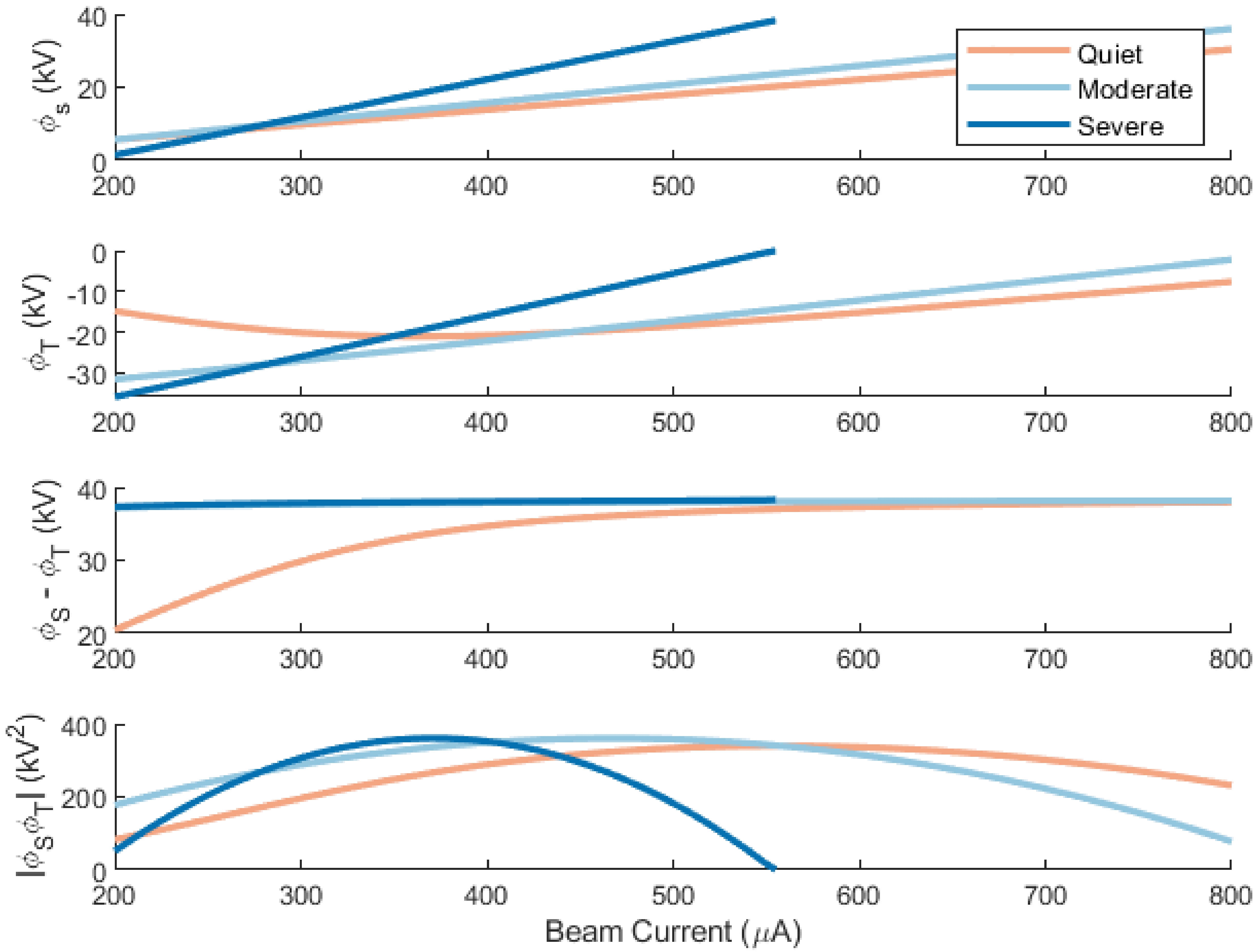
GEO Results

GEO plasma characteristics (Denton et al., 2005)

Storm Level	n_e (m^{-3})	T_e (eV)	n_i (m^{-3})	T_i (eV)	λ_D (m)
Quiet (K_P=1.5)	9.25E5	2640	3.05E6	50	397.1
Moderate (K_P =6)	1E6	4700	1E6	15000	509.6
Severe (K_P = 8-9)	1E6	20000	1E6	20000	1051.2

- Product of potentials shown instead of force
  - Provides insight into electrostatic force trends
- Geomagnetic storms may be considered helpful for the electrostatic tractor
  - Less current required to achieve maximum potential difference and product of potentials

Electrostatic tractor cislunar results



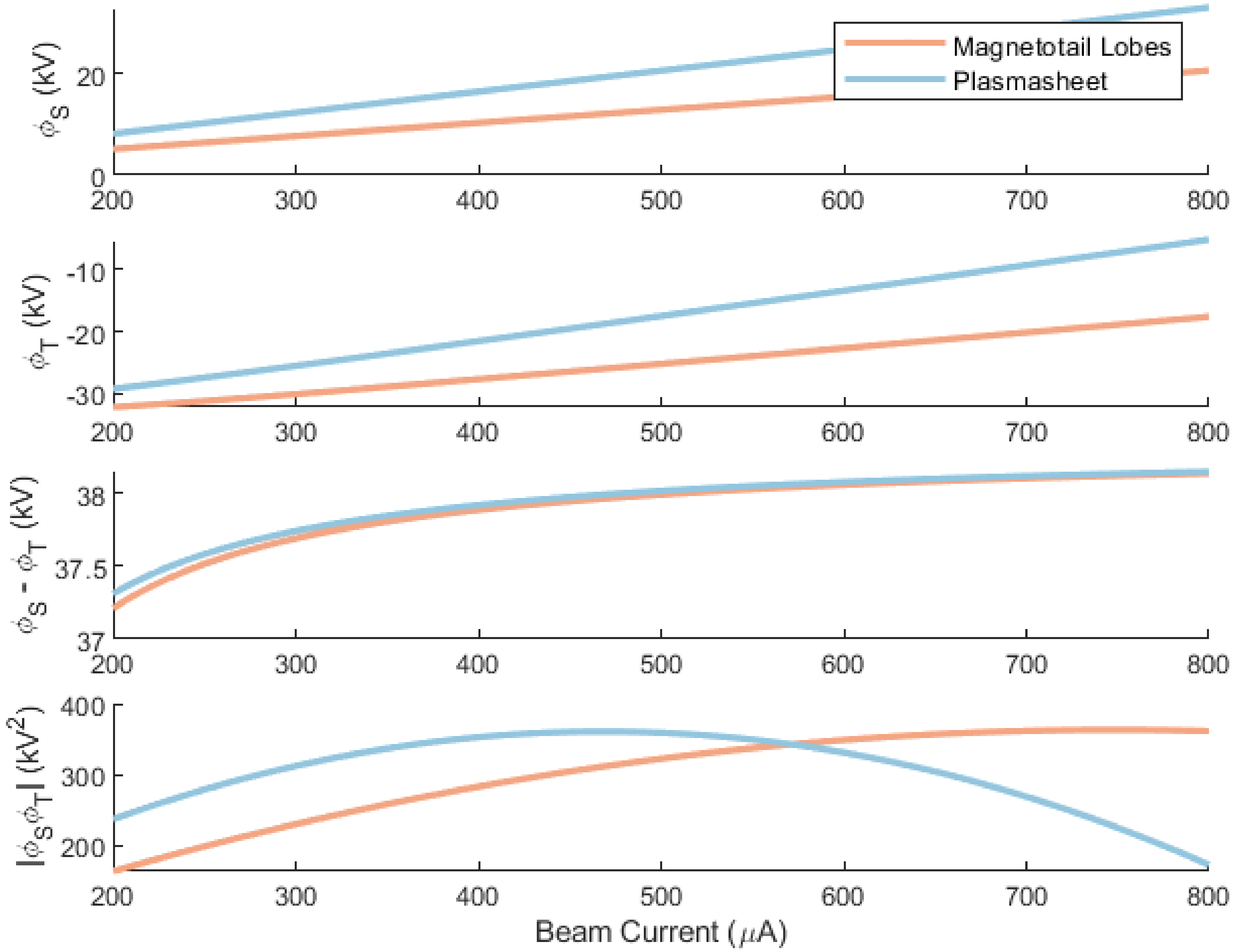
Cislunar Regions with Large Debye Lengths

Mean plasma characteristics

Region	n_e (m^{-3})	T_e (eV)	n_i (m^{-3})	T_i (eV)	λ_D (m)
Magnetotail Lobes	2E5	48	2E5	290	115.2
Plasmasheet	2.2E5	150	2E5	780	194.1

- More severe ambient plasma environment (plasmasheet) may again be considered helpful
- Comparable to the quiet to moderate GEO environments

Electrostatic tractor cislunar results



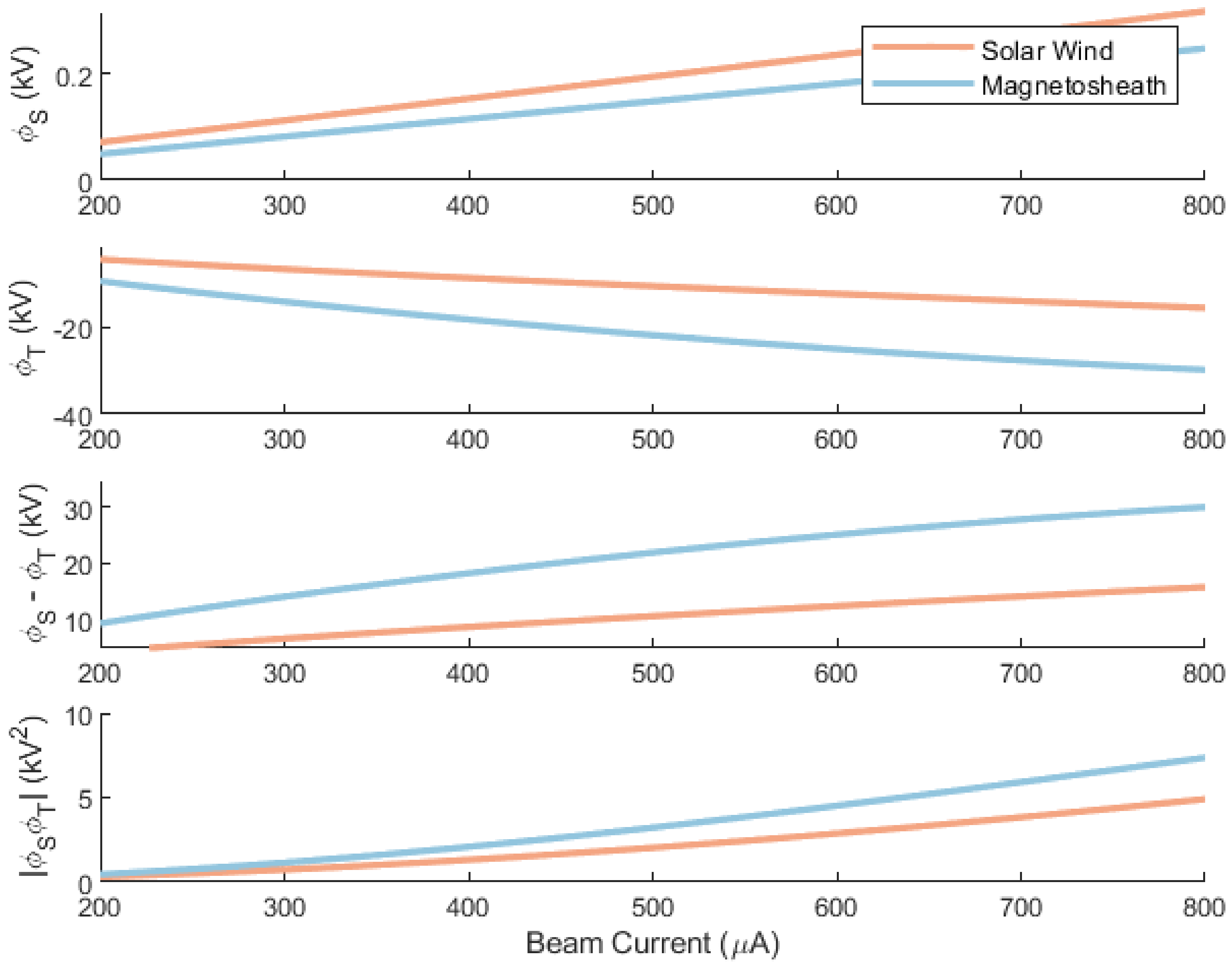
Cislunar Regions with Short Debye Lengths (Analytic)

Mean plasma characteristics

Region	n_e (m^{-3})	T_e (eV)	v_i (km/s)	n_i (m^{-3})	T_i (eV)	λ_D (m)
Solar Wind	6E6	11	420	6E6	7	10.1
Magnetosheath	9.5E6	18	350	8E6	94	10.2

- Servicer potential is two orders of magnitude smaller than previously presented environments
- Less severe ambient plasma parameters again show to require larger currents for comparable spacecraft potentials
  - Maximum potential difference and product of potentials is not achieved in evaluated range
  - Product of potentials is an order of magnitude smaller
- Results do not account for spacecraft wake effects

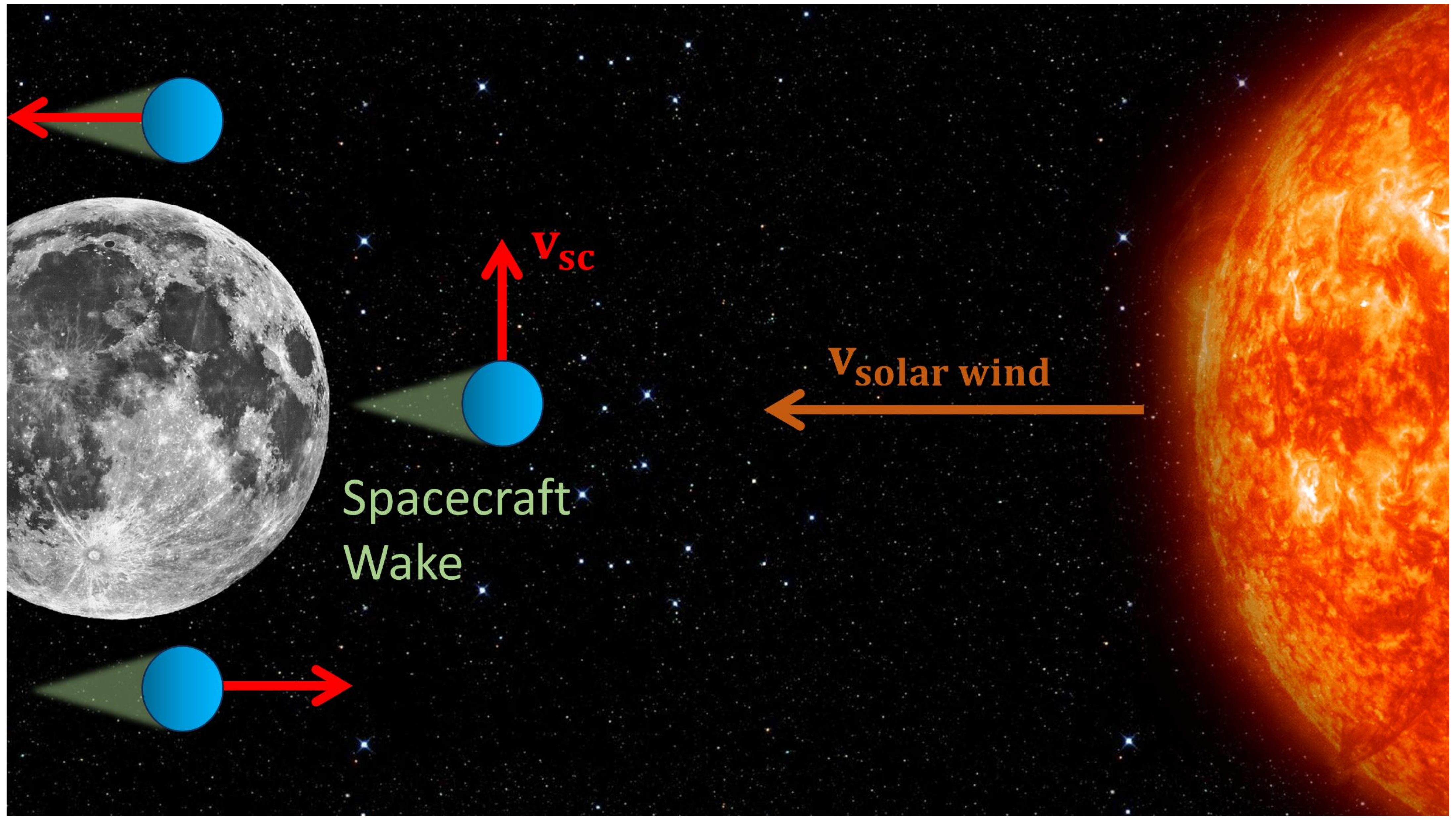
Electrostatic tractor cislunar results



Spacecraft Wakes

- Spacecraft wakes occur when plasma is mesothermal, or the thermal velocity of the ions is less than the velocity of the spacecraft with respect to the plasma, which is less than the thermal velocity of the electrons ($v_i < v_{SC} < v_e$)
  - Particles are pushed out of the way of the spacecraft => electrons can catch back up, but ions can't
  - Net negative charge prevents electrons from entering wake region
- Wakes found to occur in the solar wind and magnetosheath regions
- Solar wind velocity (100s of km/s) is significantly greater than lunar orbiting spacecraft velocity (~1 km/s)
  - Spacecraft wake forms on eclipse side of spacecraft

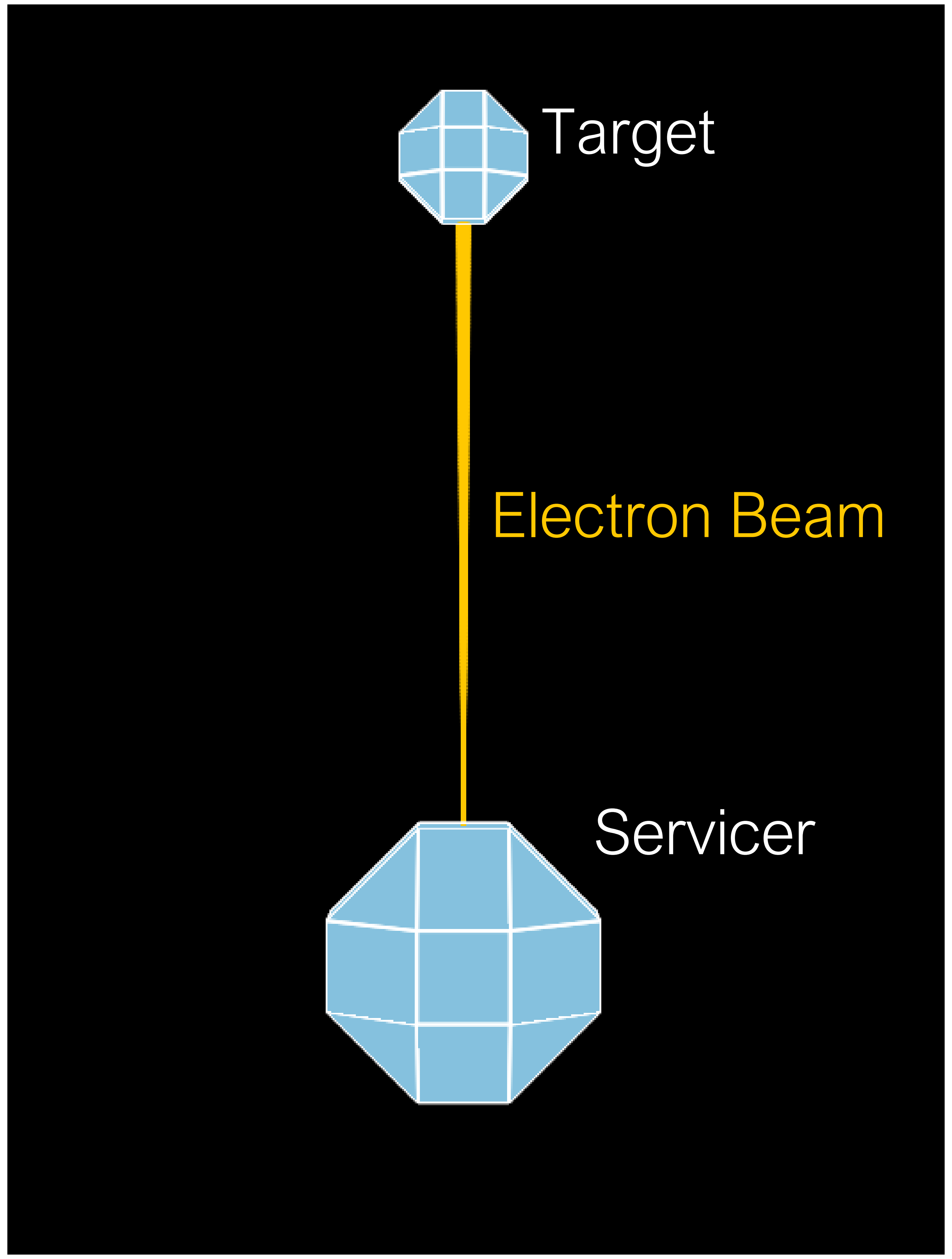
Cislunar wakes illustration



Spacecraft Wake Investigation

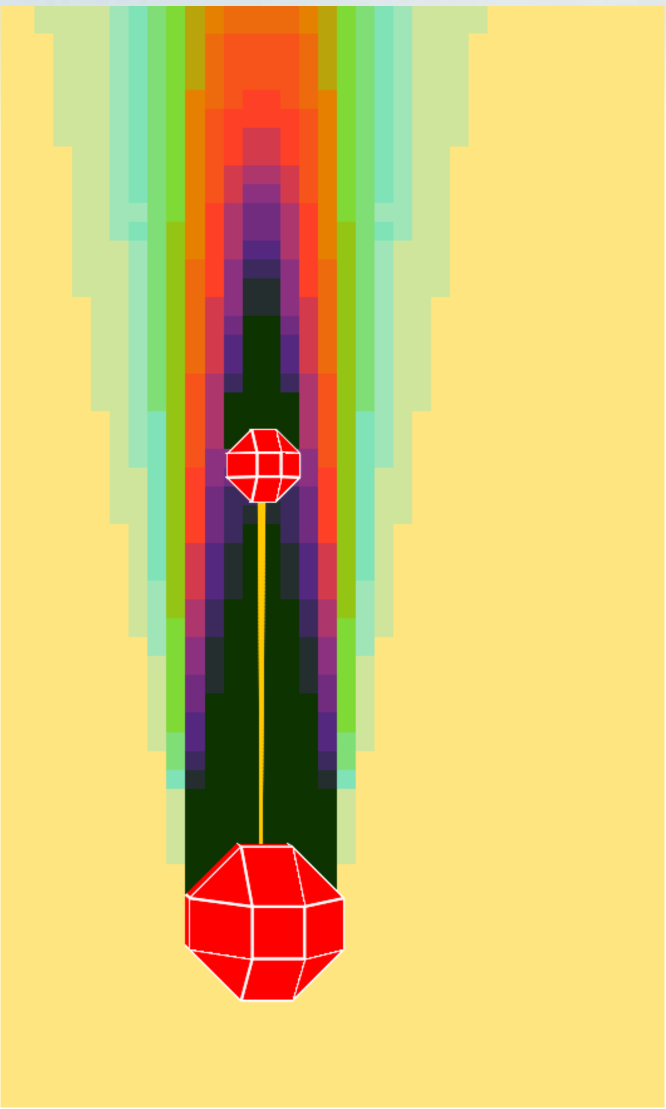
- Electrostatic tractor potentials in the presence of cislunar wakes investigated using NASCAP-2k
  - **NASCAP-2k**: 3D spacecraft charging and plasma interactions code developed as a collaboration between NASA and the Air Force Research Lab
- Sphere approximations used to represent the servicer and target
  - Separation distance of 12.5m
- Surface potential of the spacecraft determined using tracked particles
- Potentials in space determined using analytic nonlinear approximations
  - Interpolates between Debye screening at low potential and an accelerated distribution with particle convergence at high potentials

Electrostatic tractor in NASCAP-2k

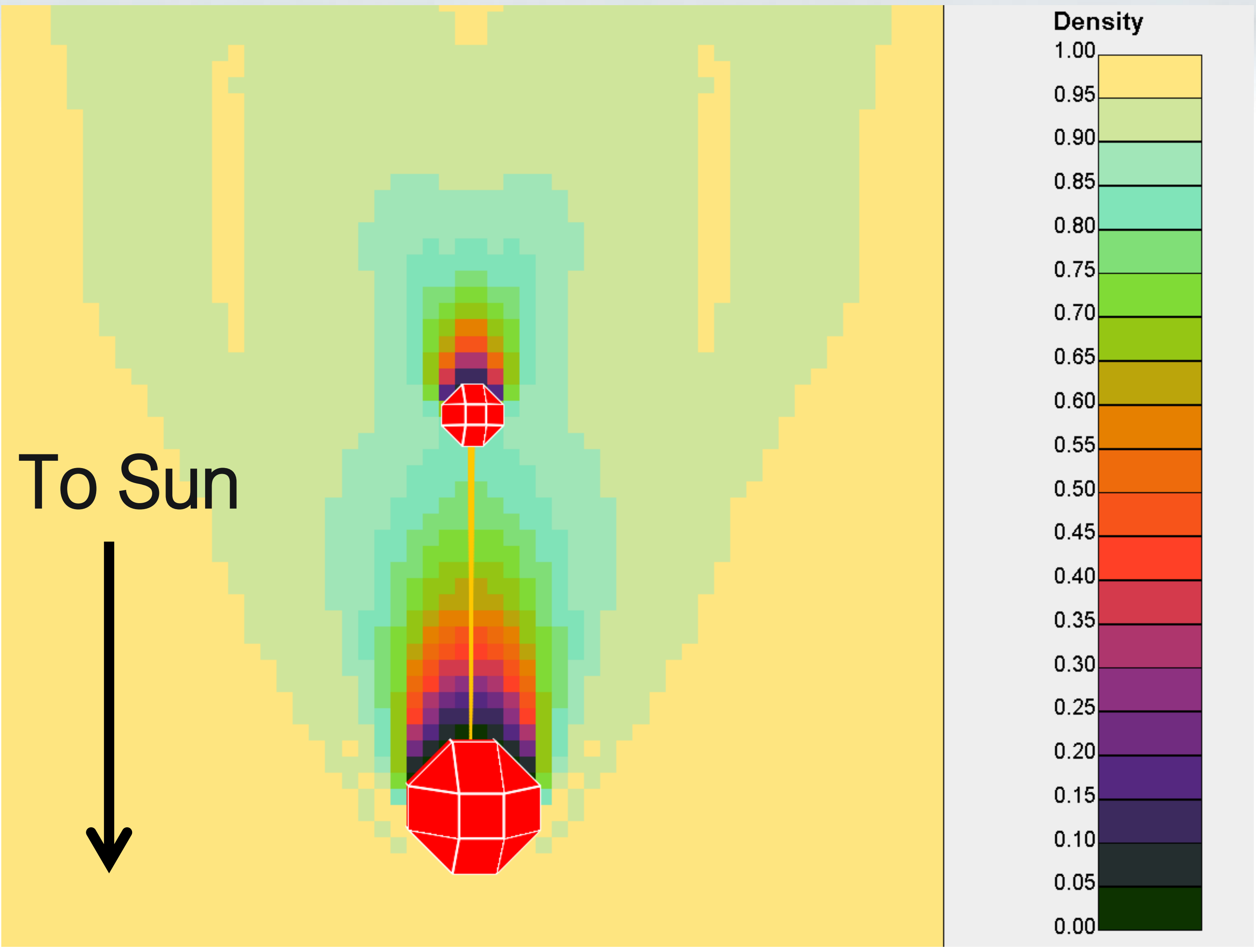


Servicer at 12:00 NASCAP-2k Results

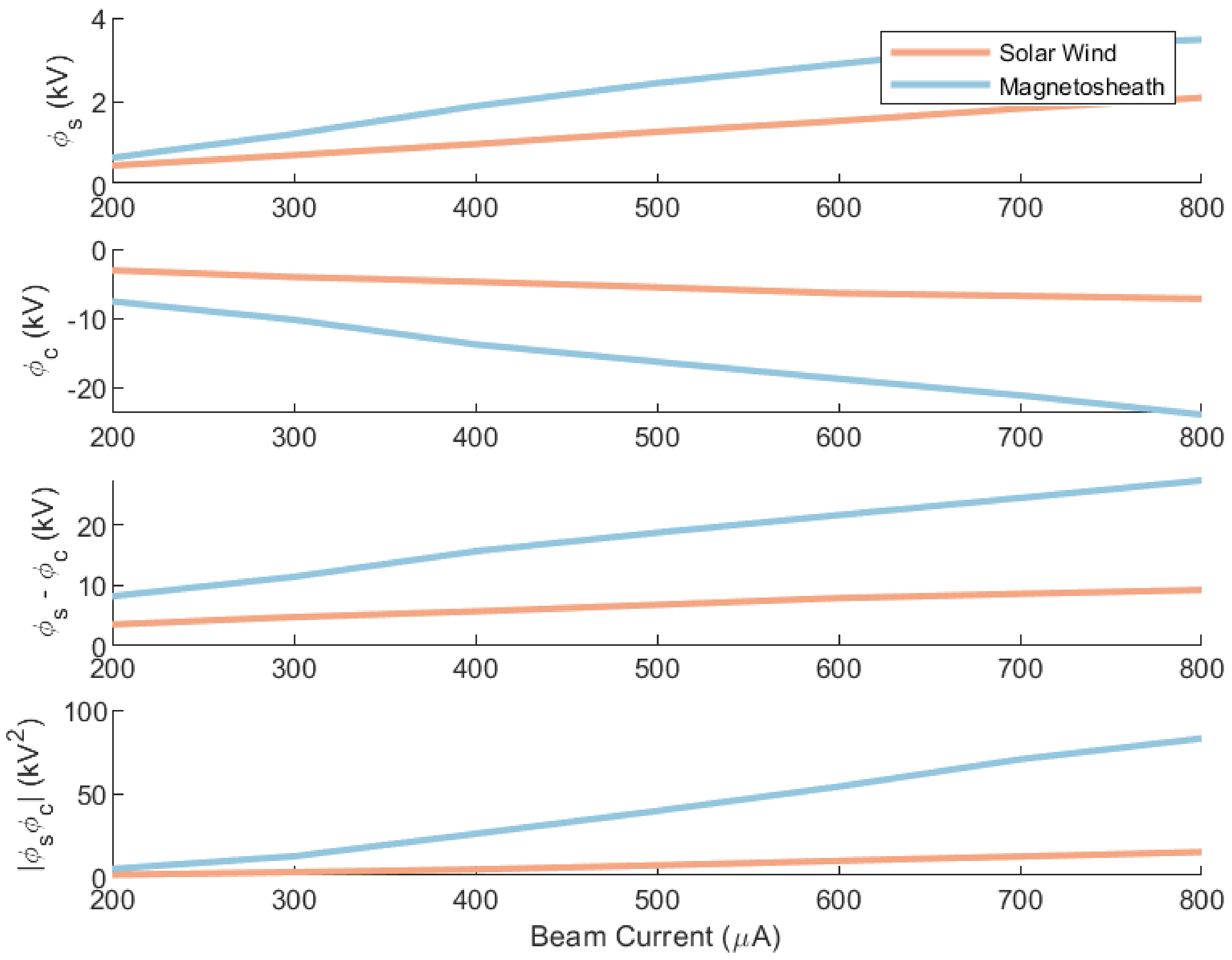
Solar Wind



Magnetosheath



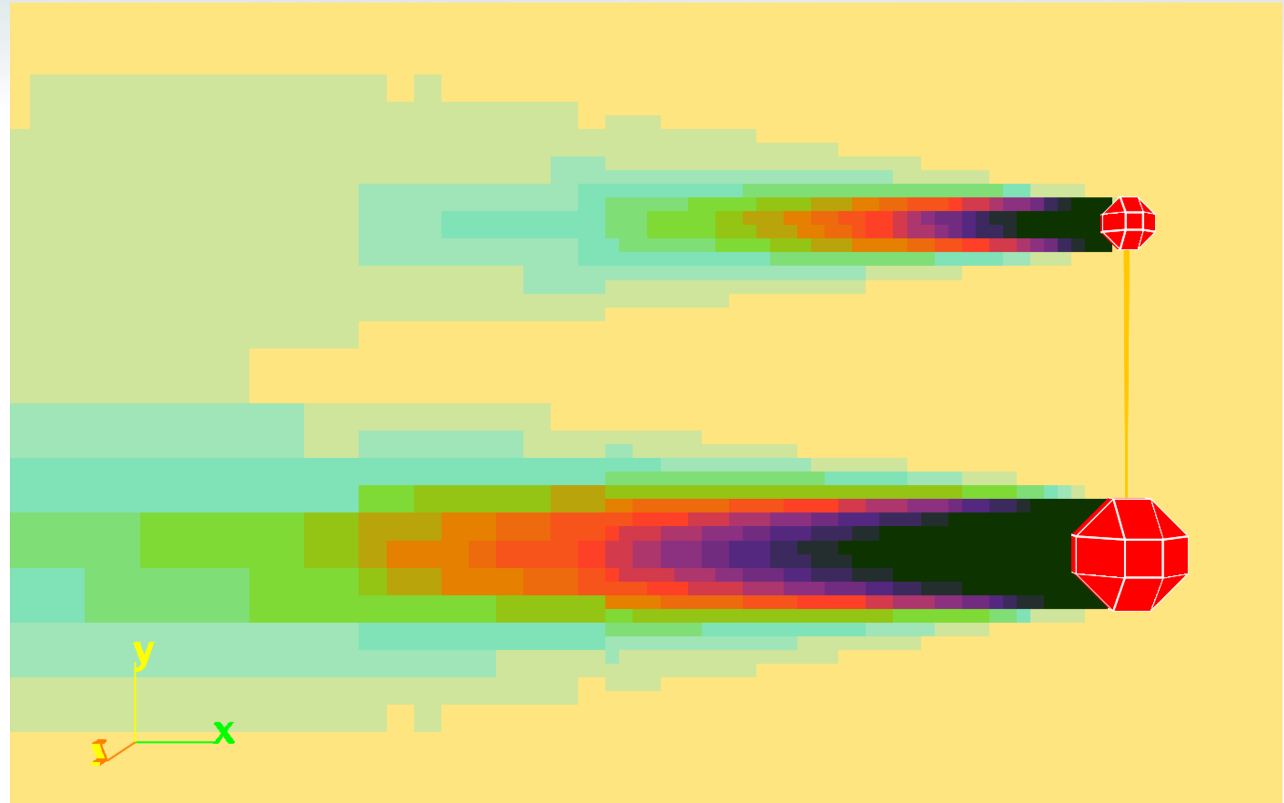
NASCAP-2k electrostatic tractor cislunar results



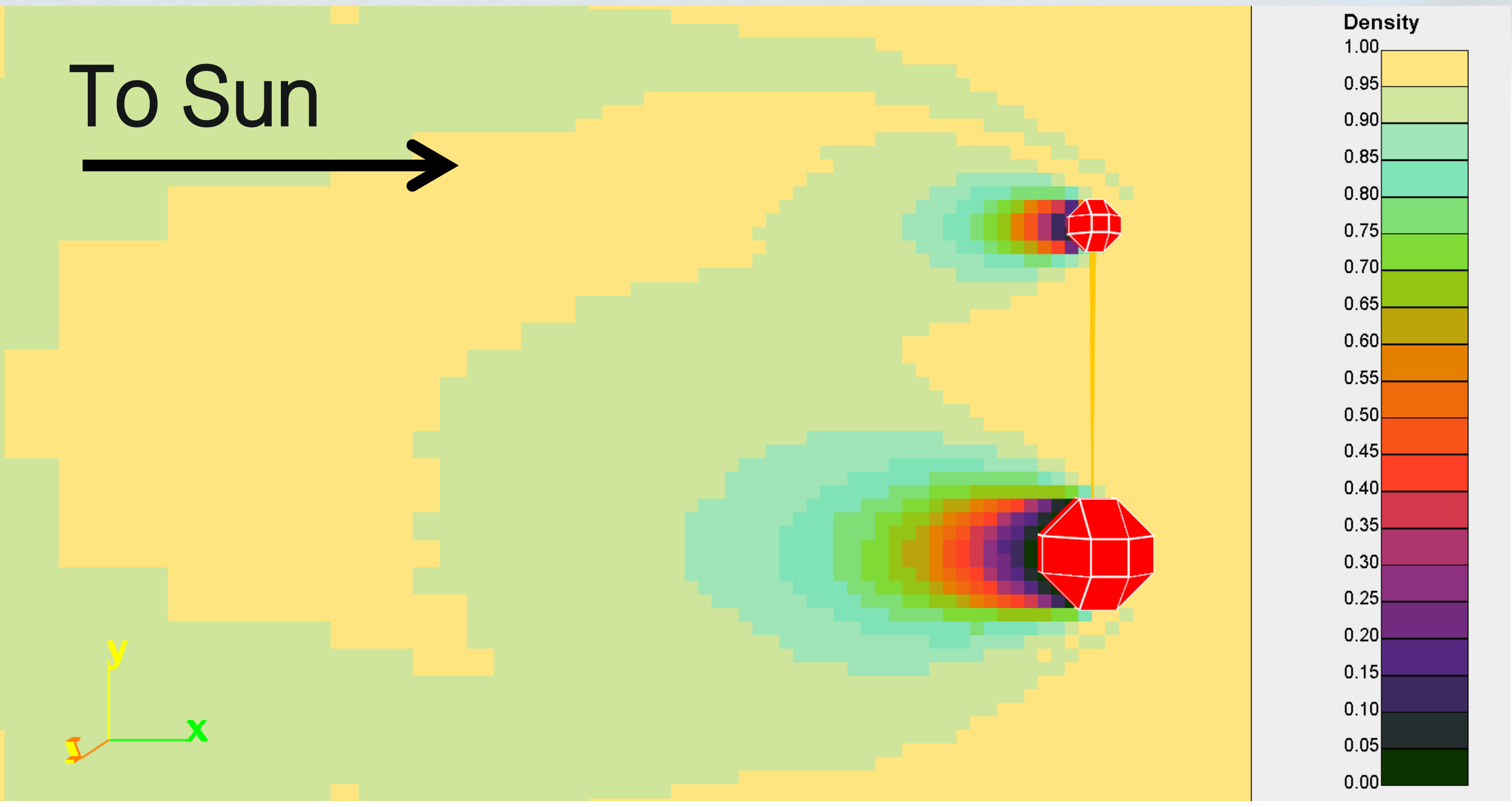
- Trends similar to analytic results
  - Maximum potential difference and product not achieved
- Magnitudes differ from analytic results
  - Servicer potential is an order of magnitude larger
  - Target potentials are slightly smaller

Servicer at 6:00/18:00 NASCAP-2k Results

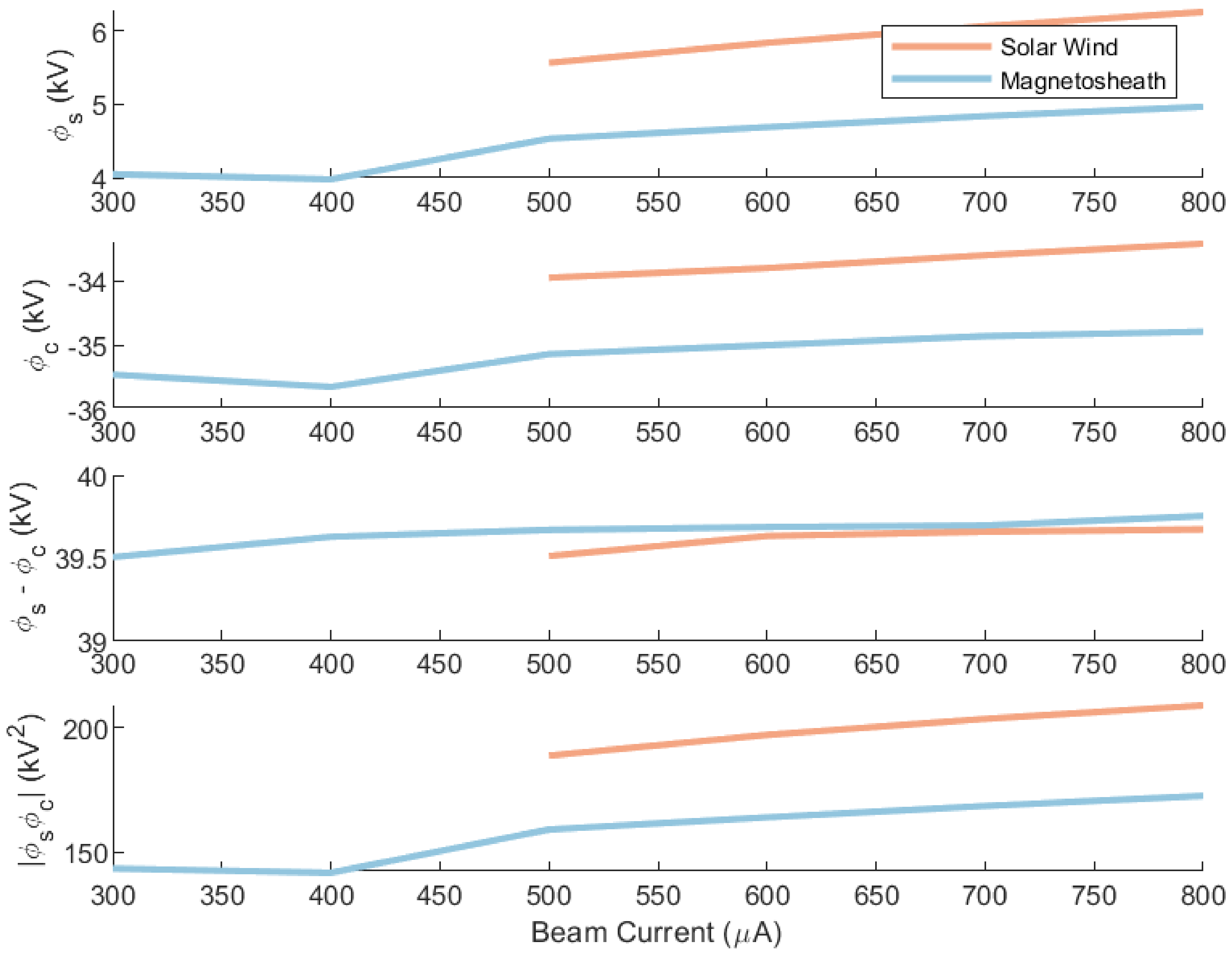
Solar Wind



Magnetosheath



NASCAP-2k electrostatic tractor cislunar results



- Significantly different from analytic and servicer at 12:00
  - Maximum potential difference approximately achieved
  - Target potentials **significantly** higher in magnitude
  - May be contributed to coupled charging between spacecraft not accounted for in analytic equations

Conclusions and Future Work

- **Conclusion**
  - More severe plasma environments are optimal for achieving larger potentials with smaller electron beam currents
  - Coupled charging effects between spacecraft should not be neglected in cislunar regions
- **Future work**
  - Determine electrostatic tractor potentials when servicer is at 0:00, or in the target’s wake
  - Investigate forces in cislunar solar wind and magnetosheath environments

Questions?

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