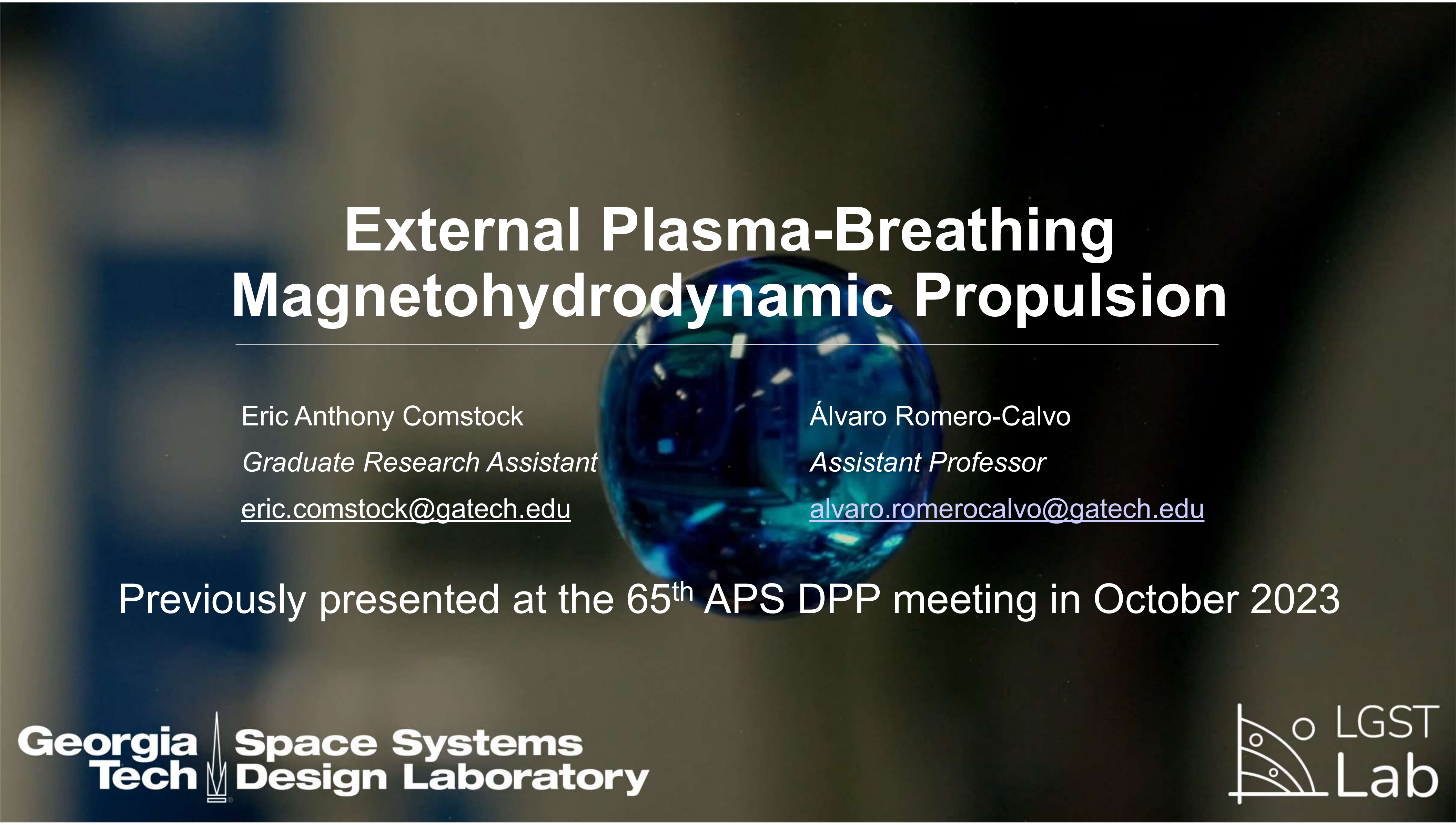

External Plasma-Breathing Magnetohydrodynamic Propulsion

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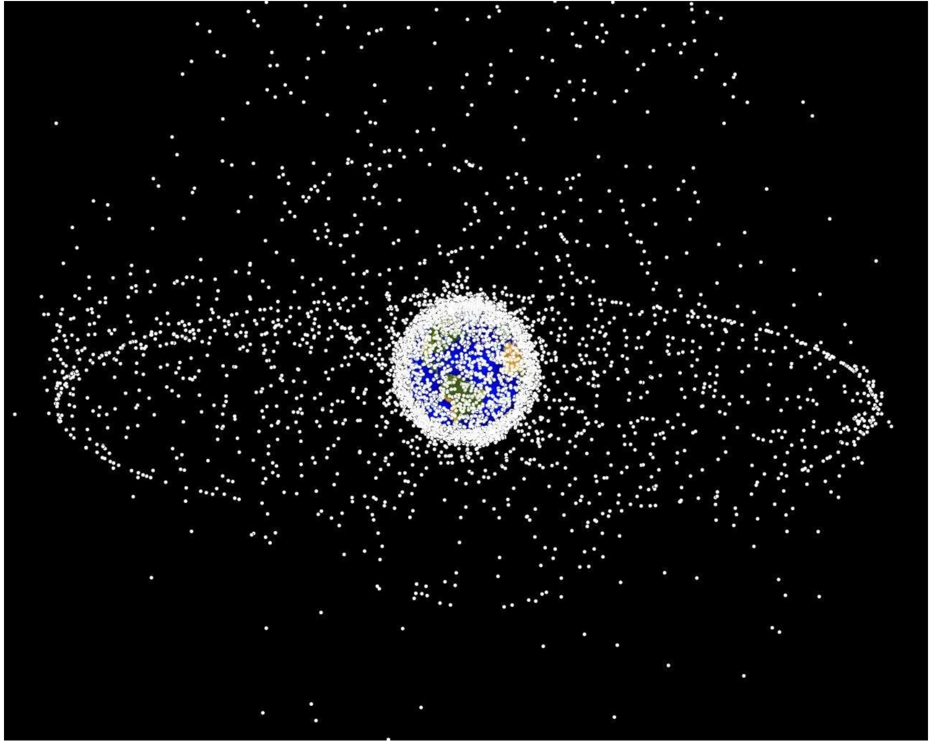
LGST Lab

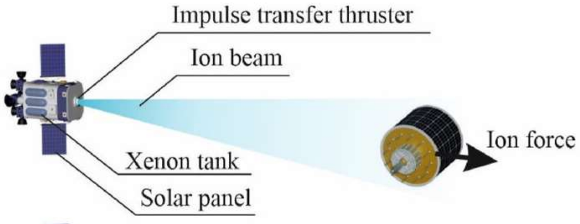
Space Debris and Current Mitigation Strategies



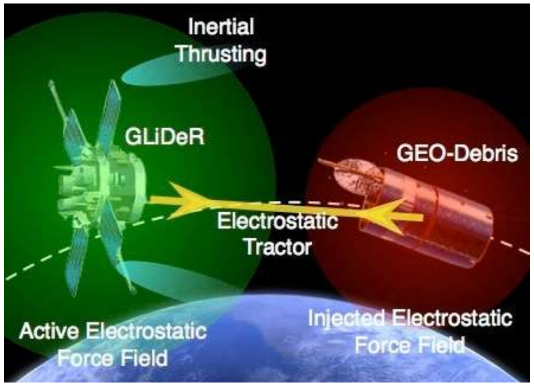
NASA Simulation of current space debris

The illustrations on the right are current mitigation technologies which are expensive and cumbersome to implement.

Trushlyakov, V & Yudintsev, Vadim. (2019). Rotating tethered system for active space debris removal. Journal of Physics: Conference Series. 1260. 112032. 10.1088/1742-6596/1260/11/112032.



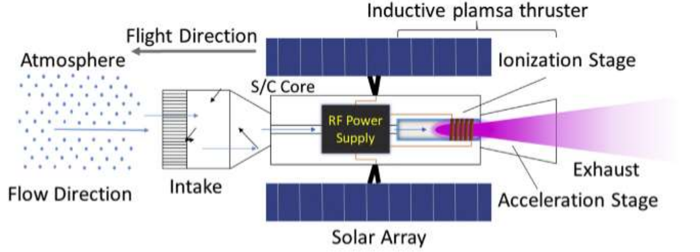
Alexander S. Ledkov, Vladimir S. Aslanov, Active space debris removal by ion multi -beam shepherd spacecraft, Acta Astronautica, Volume 205, 2023, Pages 247-257, ISSN 0094-5765, https://doi.org/10.1016/j.actaastro.2023.02.003.



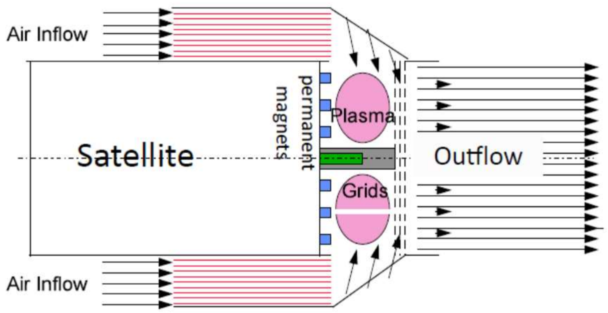
Mann, Adam. "Battling Space Junk with a Tractor Beam of Static Electricity." *Wired*, Conde Nast, 21 Oct. 2013, www.wired.com/2013/10/electrostatic-space-junk/.

Atmosphere-Breathing Electric Propulsion (ABEP)

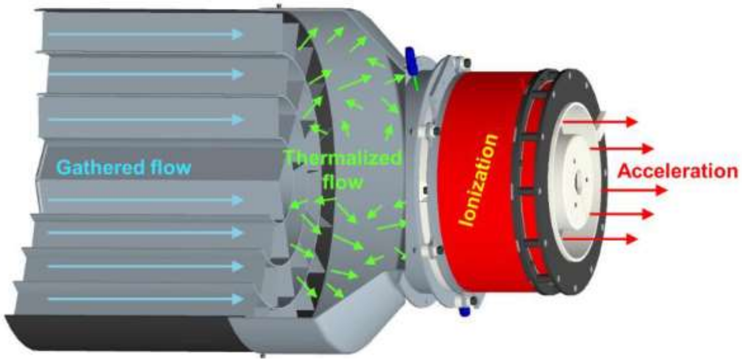
These are current ABEP technologies for mitigating orbital debris. They are high cost and high complexity.



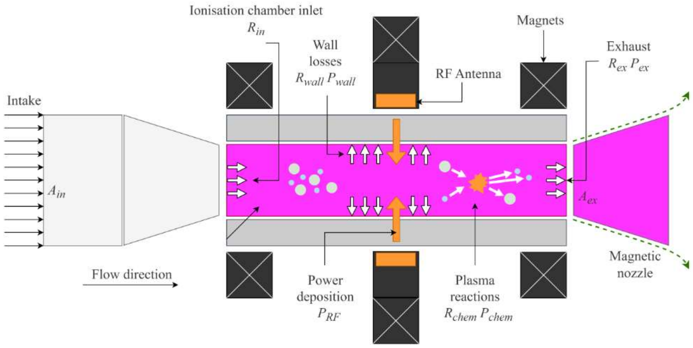
Romano, F., et al., “System analysis and test-bed for an atmosphere-breathing electric propulsion system using an inductive plasma thruster,” Acta Astronautica, Vol. 147, 2018, pp. 114–126. https://doi.org/10.1016/j.actaastro.2018.03.031.



Jackson, S. W., “Design of an Air-Breathing Electric Thruster for CubeSat Applications by Faculty of the Graduate School of the University of Colorado in partial fulfillment of the requirements for the,” University of Colorado, 2017. https://doi.org/10.13140/RG.2.2.34587.57124



Andreussi, T., Cifali, G., Giannetti, V., Piragino, A., Ferrato, E., Rossodivita, A., Andrenucci, M., Longo, J., and Walpot, L., “Development and Experimental Validation of a Hall Effect Thruster RAM-EP Concept,” 35th International Electric Propulsion Conference, 2017, pp. IEPC–2017–377. URL https://iepc2017.org/sites/default/files/speaker-papers/iepc-2017-377_ram_final.pdf.

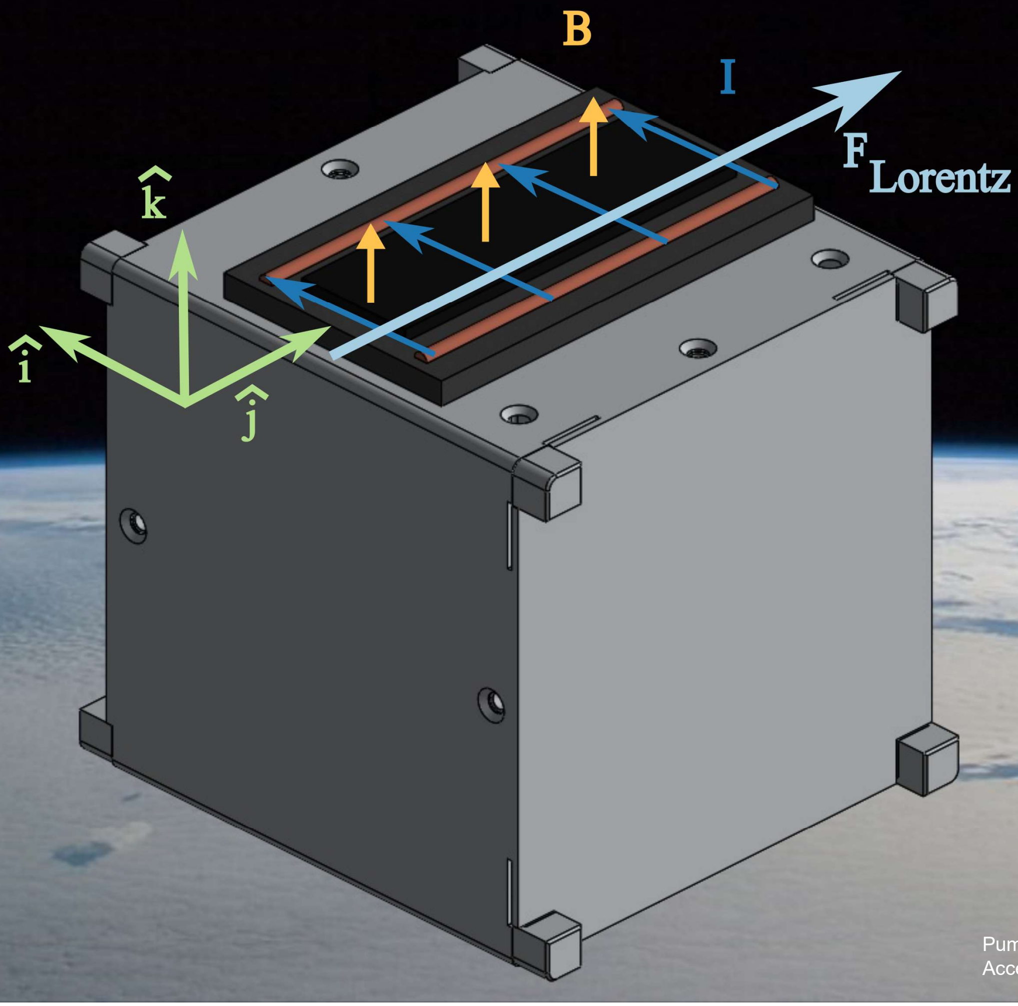


Souhair, N., Magarotto, M., Andriulli, R., and Ponti, F., “Prediction of the Propulsive Performance of an Atmosphere-Breathing Electric Propulsion System on Cathode-Less Plasma Thruster,” Aerospace, Vol. 10, 2023. https://doi.org/10.3390/aerospace10020100.

Concept Overview

This is an illustration of my device concept on a CubeSat (a cube satellite), along with the forces that it will generate.

It is low-cost and low-complexity, and can be scaled to any size satellite.



Pumpkin, Inc. "1U solid-wall structure." 3D Models of the CubeSat Kit, Accessed 7/3/2023, http://www.cubesatkit.com/content/design.html

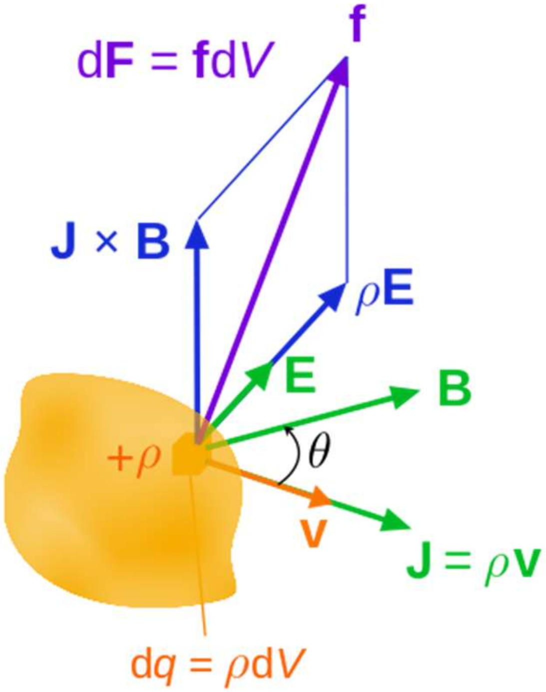
First-Order Analysis

E and B fields

Ohm’s law: $\mathbf{E} + \mathbf{v} \times \mathbf{B} = \frac{\mathbf{J}}{\sigma}$

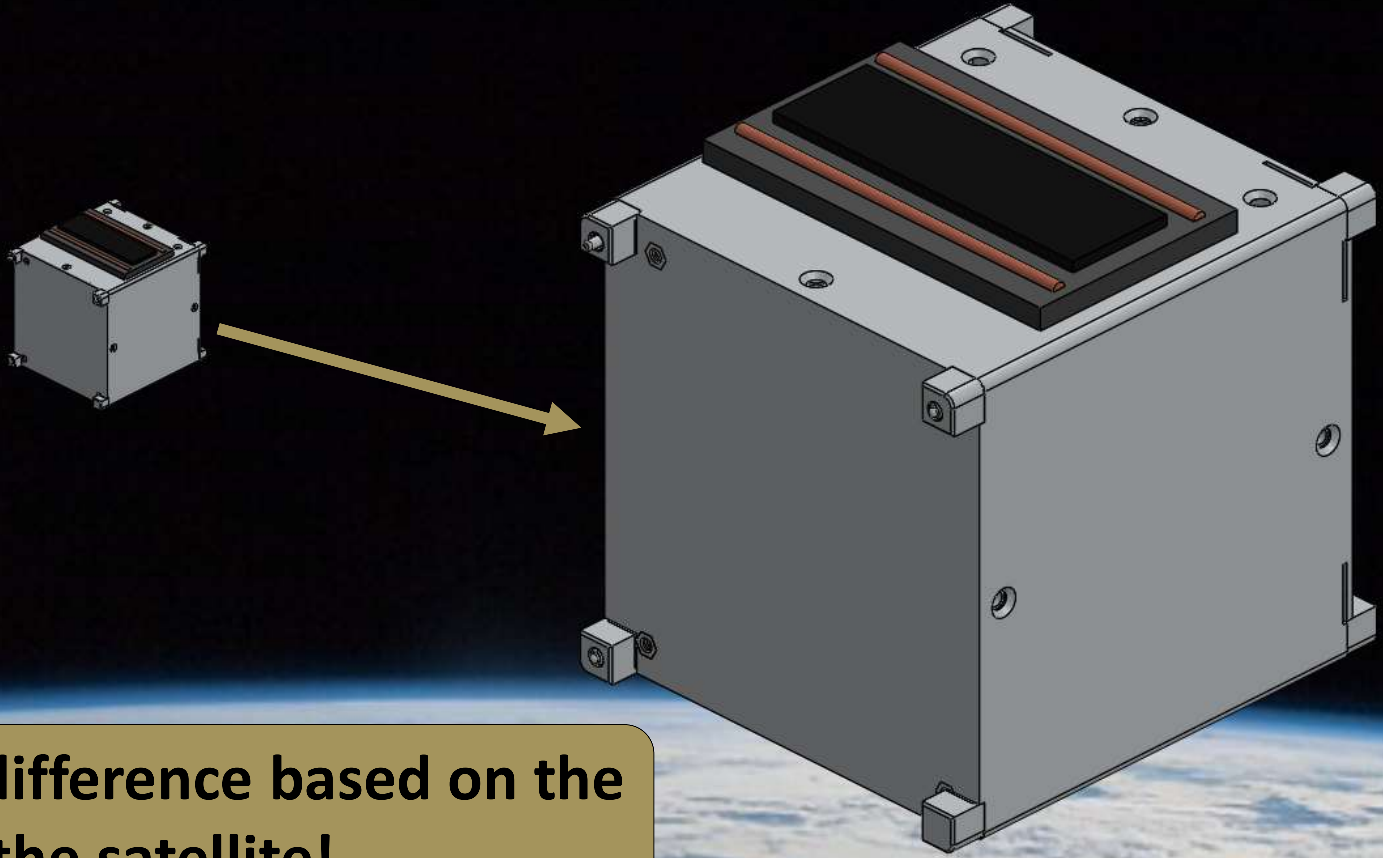
Lorentz Force: $\mathbf{f} = \mathbf{J} \times \mathbf{B}$

First order analysis consists of modelling the electric and magnetic forces of the device to determine power requirements and scaling laws.



Maschen. “File:Lorentz Force Continuum.Svg.” *Wikimedia Commons*, 11 Sept. 2012, commons.wikimedia.org/wiki/File:Lorentz_force_continuum.svg.

Linear scaling results of Conductive MHD Patch



$M \sim L^3$

$F_a \sim L^3$ if $P/M \sim 1$

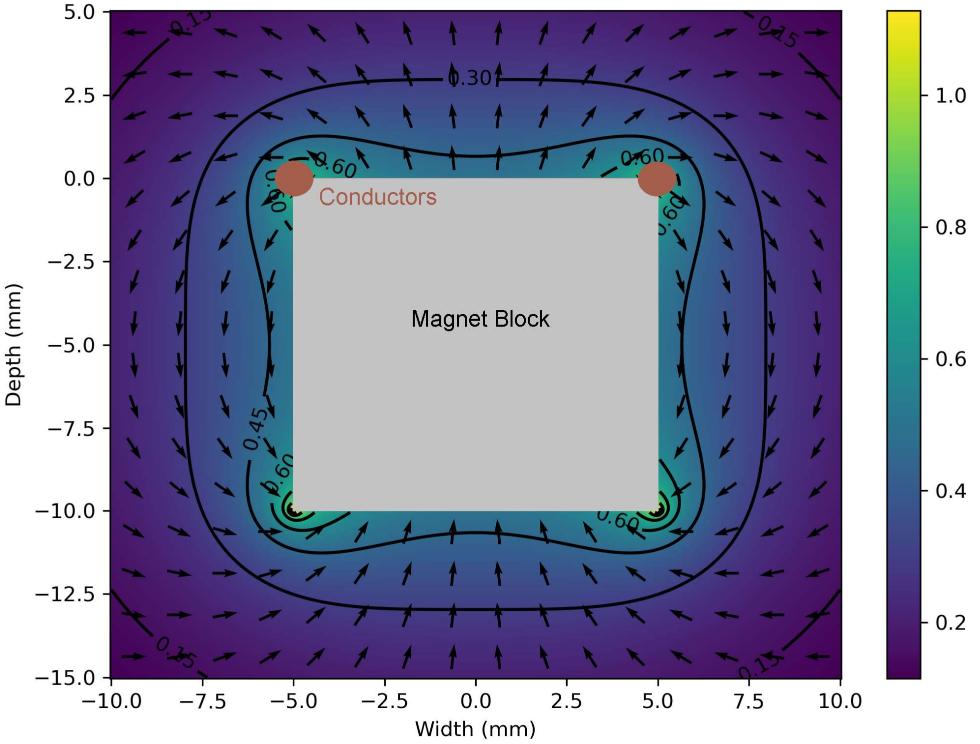
$F_p \sim L^3$

No performance difference based on the size of the satellite!

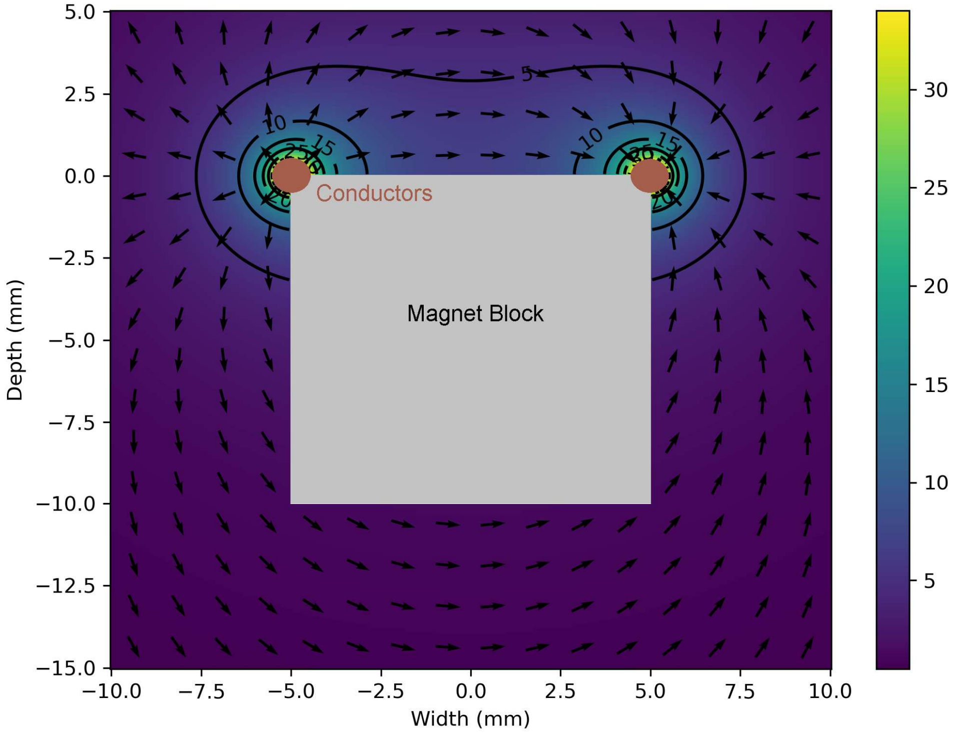
This can be scaled to any size satellite.

Electromagnetic Characterization

B-field (T)

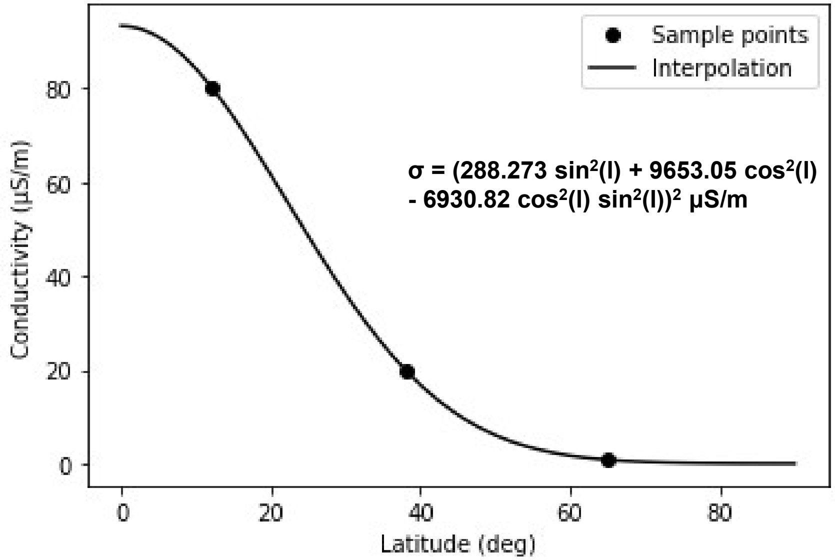


E-field (kV/m)

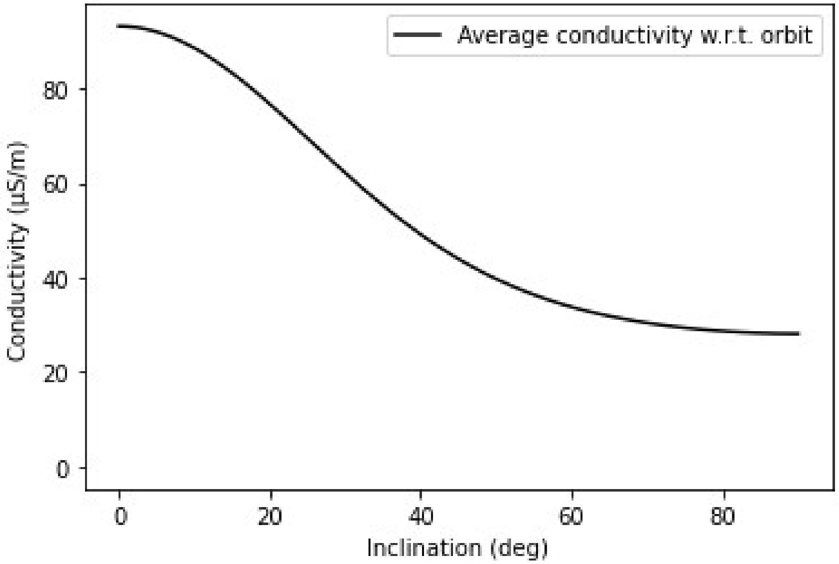


Above are the simulations of the electric and magnetic fields generated by an example propulsion device. This allows the Lorentz force to be computed, leading to the thrust.

Plasma conductivity



$$\sigma = (288.273 \sin^2(I) + 9653.05 \cos^2(I) - 6930.82 \cos^2(I) \sin^2(I))^2 \ \mu S/m$$



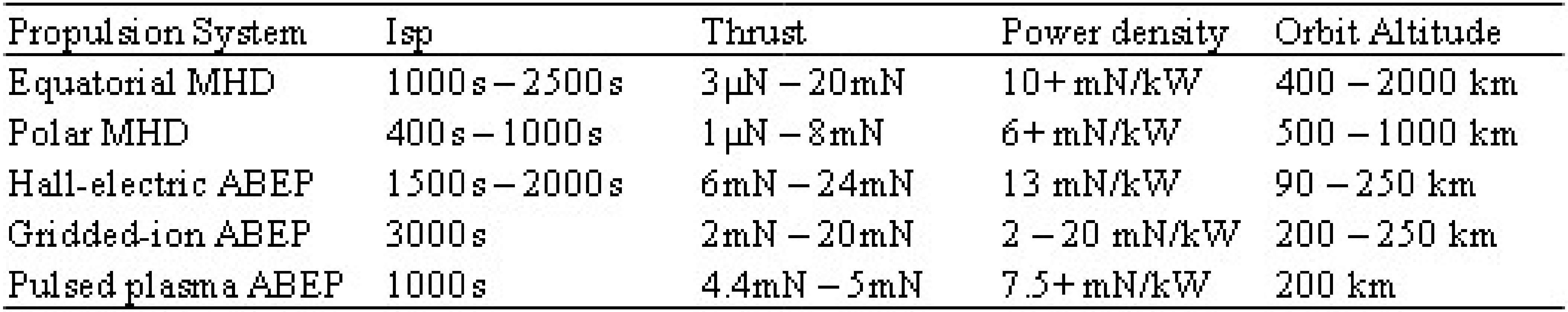
Conductivity vs latitude

- All orbits intersect the equator.
- Conductivity is highest near the equator, and lower at the poles*.

By interpolating these results, a conductivity model of the ionosphere is produced. Conductivity is also found to be altitude independent.

* - Pfaff, R. F., "The Near-Earth Plasma Environment," Space Science Reviews, Vol. 168, 2012, pp. 23–112

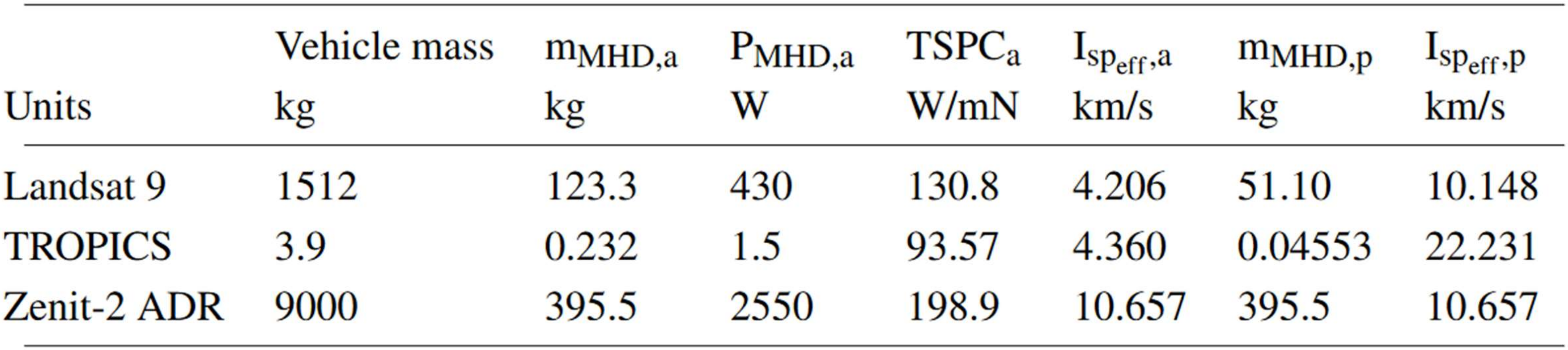
Performance



Propulsion System	Isp	Thrust	Power density	Orbit Altitude
Equatorial MHD	1000 s – 2500 s	3 µN – 20 mN	10+ mN/kW	400 – 2000 km
Polar MHD	400 s – 1000 s	1 µN – 8 mN	6+ mN/kW	500 – 1000 km
Hall-electric ABEP	1500 s – 2000 s	6 mN – 24 mN	13 mN/kW	90 – 250 km
Gridded-ion ABEP	3000 s	2 mN – 20 mN	2 – 20 mN/kW	200 – 250 km
Pulsed plasma ABEP	1000 s	4.4 mN – 5 mN	7.5+ mN/kW	200 km

MHD propulsion has similar specific impulses (efficiencies) to other ABEP options, and a similar power density, but can operate at much higher altitudes.

Examples

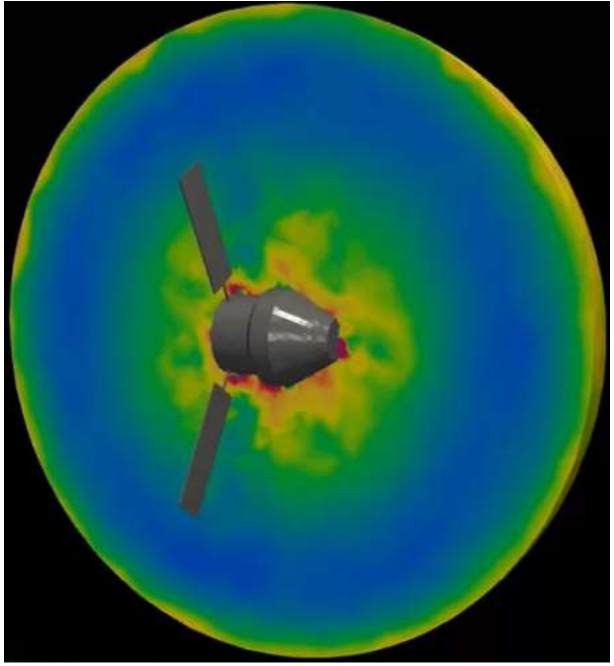


	Vehicle mass	$m_{\mathrm{MHD,a}}$	$P_{\mathrm{MHD,a}}$	$\mathrm{TSPC_a}$	$I_{sp_{eff},a}$	$m_{\mathrm{MHD,p}}$	$I_{sp_{eff},p}$
Units	kg	kg	W	W/mN	km/s	kg	km/s
Landsat 9	1512	123.3	430	130.8	4.206	51.10	10.148
TROPICS	3.9	0.232	1.5	93.57	4.360	0.04553	22.231
Zenit-2 ADR	9000	395.5	2550	198.9	10.657	395.5	10.657

Use cases

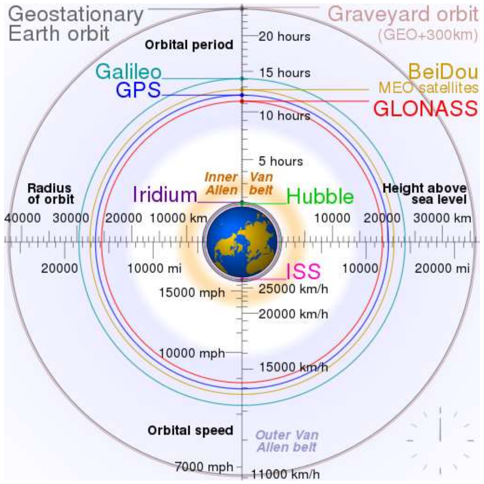
Use case scenarios were analyzed with favorable results showing that MHD propulsion is relevant on large and small satellites, as well as active debris removal.

Further research

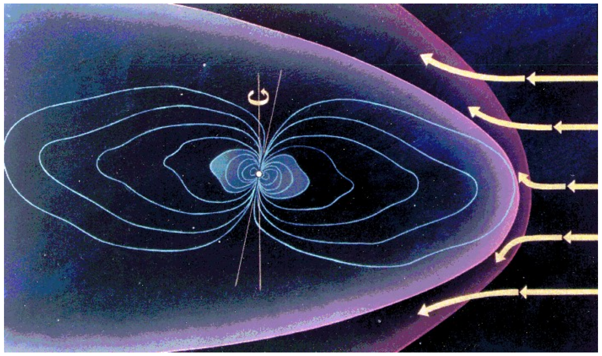


Ansys Blog. “EMA3D Charge and Its Particle-in-Cell Solver - Ansys.” Ansys, Ansys Inc., 23 Sept. 2022, www.ansys.com/blog/ema3d-charge-particle-in-cell-solver.

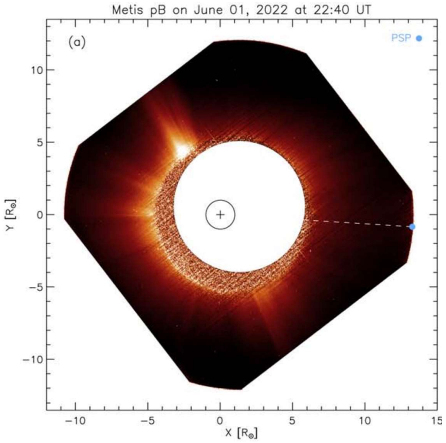
Further research for particle in cell (PIC) simulations include investigating magnetospheric drag effects, electromagnet usage, and use in high Earth orbit and other plasma environments.



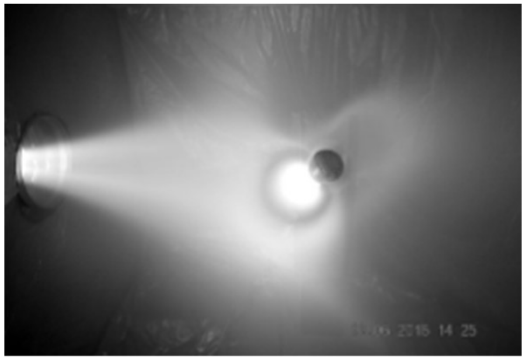
cmglee. “File:Comparison Satellite Navigation Orbits.Svg.” *Wikipedia*, Wikimedia Foundation, 5 Aug. 2020, en.wikipedia.org/wiki/File:Comparison_satellite_navigation_orbits.svg.



“Galileo Project: Jupiter’s Interior.” *NASA*, NASA, 1 Oct. 2001, www2.jpl.nasa.gov/galileo/jupiter/interior.html.



Telloni, Daniele et al. (2023). Coronal Heating Rate in the Slow Solar Wind. The Astrophysical Journal Letters. 955. L4. 10.3847/2041-8213/ace112.



Shuvalov et al., “Control of the drag on a spacecraft in the earth’s ionosphere using the spacecraft’s magnetic field”, Acta Astronautica, Vol. 151, 2018, pp. 717-725, doi: 10.1016/j.actaastro.2018.06.038.

Conclusion

Problem – Space debris

Solution – MHD

First-order simulations are used for preliminary analysis.

Conductivity varies with latitude, but not altitude.

MHD has good performance vs. chemical rockets & EP

PIC can be used to improve simulations, add additional effects, and explore alternate use cases.

Thank you for your time and consideration.

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More information available at lowgravitylab.ae.gatech.edu