Current Developments in Three-Dimensional Electrostatic Detumble of Axi-Symmetric GEO Debris

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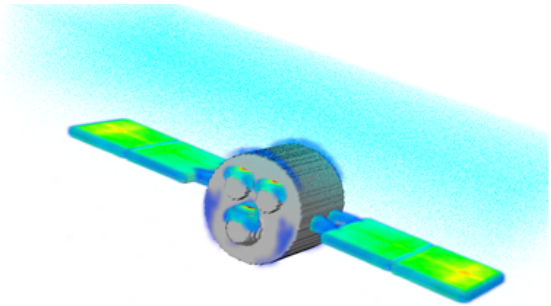
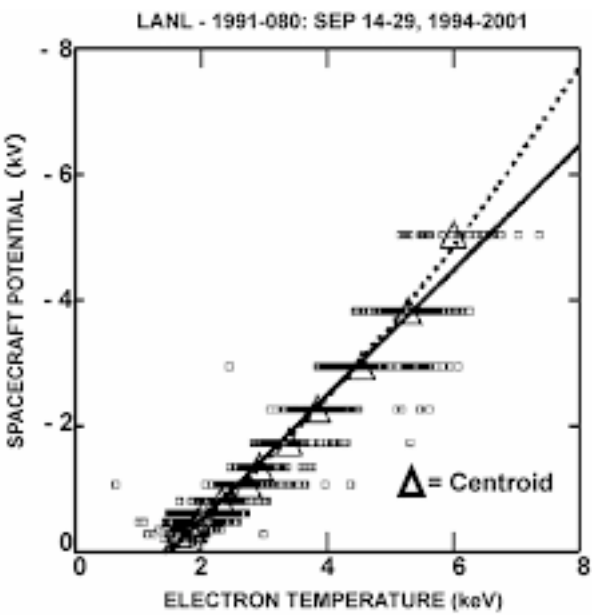
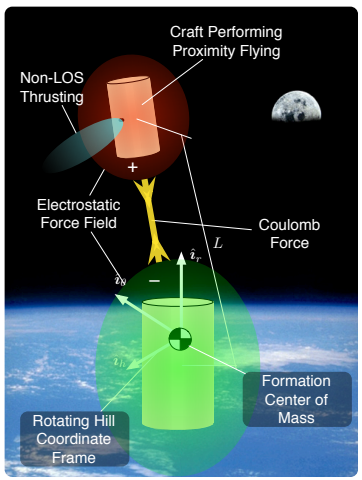
Motivation

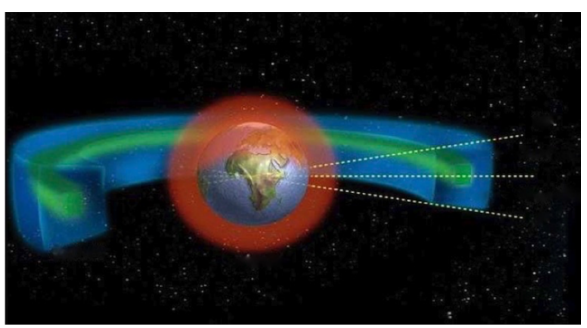
Spacecraft Charging



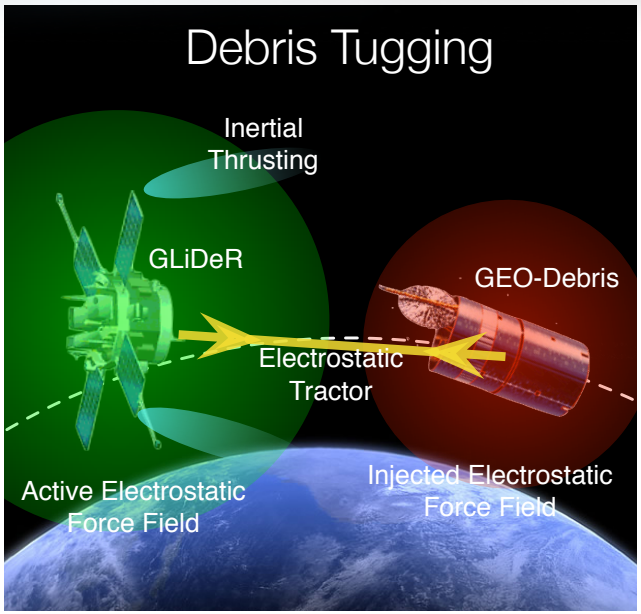


Coulomb Formation Flying

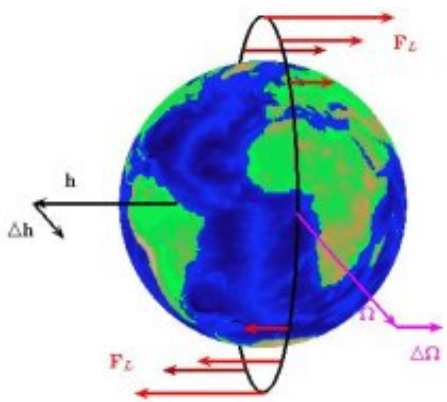




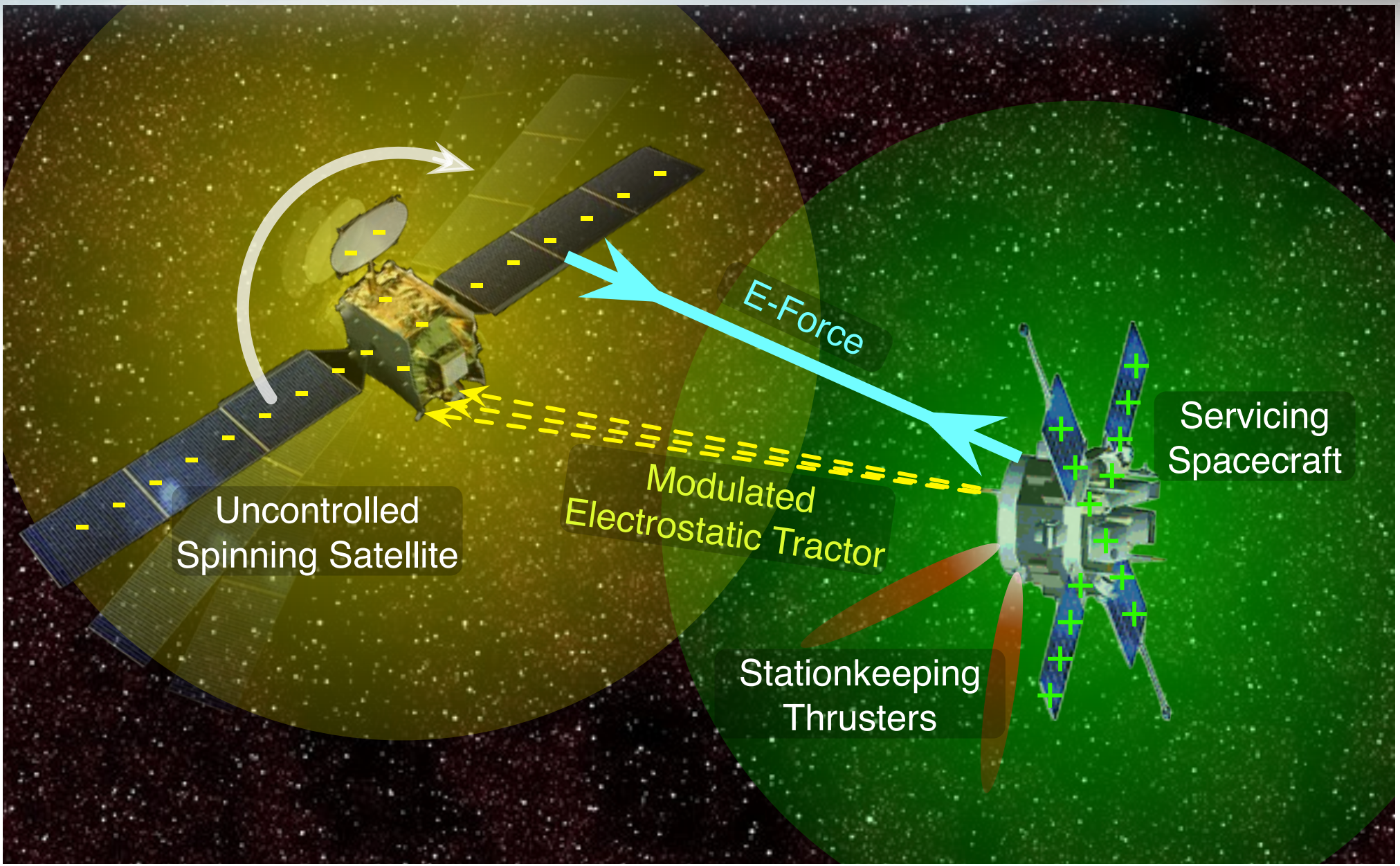
Debris Tugging



Lorentz Augmented Orbits

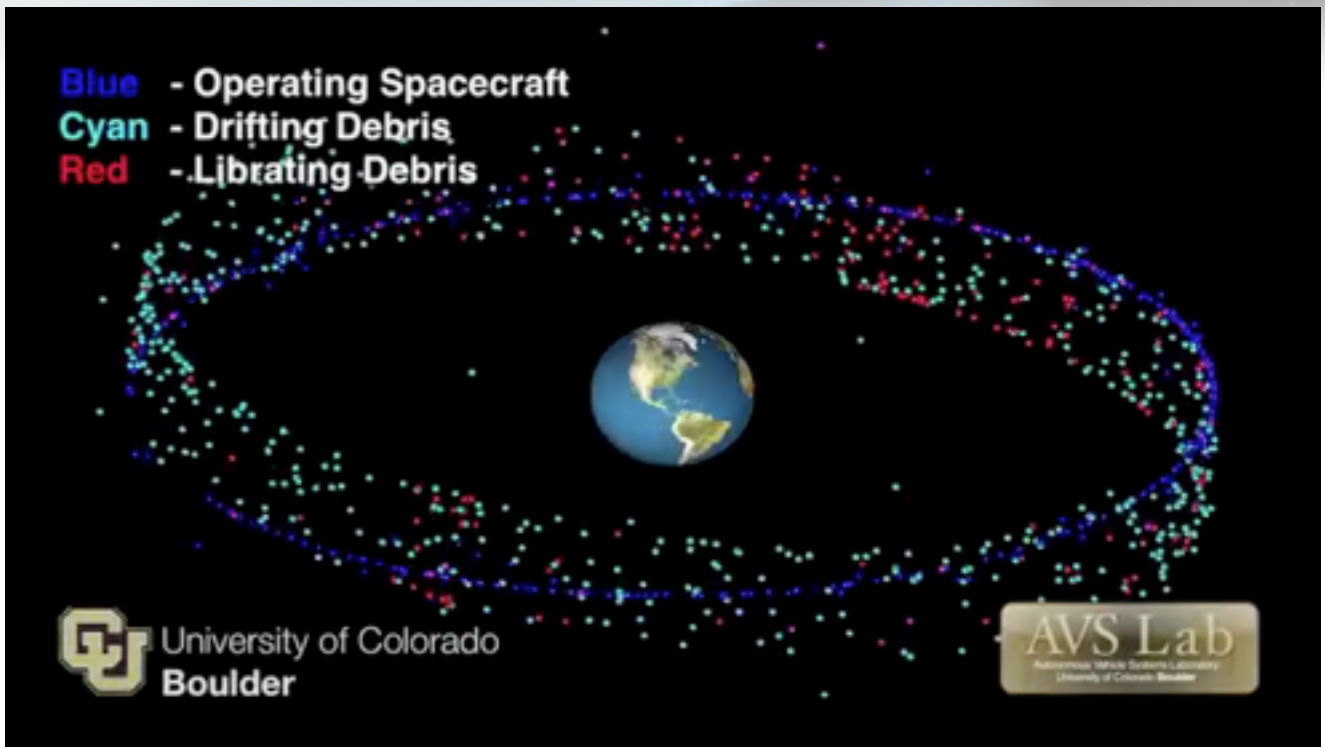


Concept Discussion



Outline

- E-Tractor Performance
- MSM E-Force/Torque Modeling
- 3D Detumbling of a Cylinder
- Exploring Relative Orbital Motion
- Conclusions

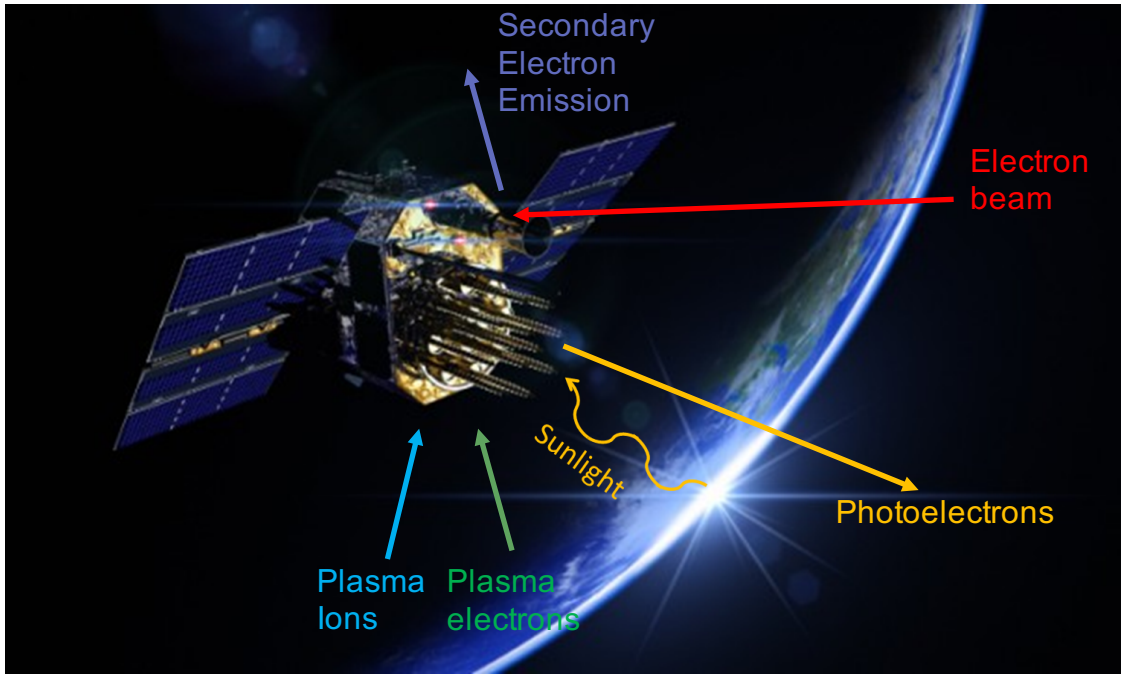


Voltage and Force Model

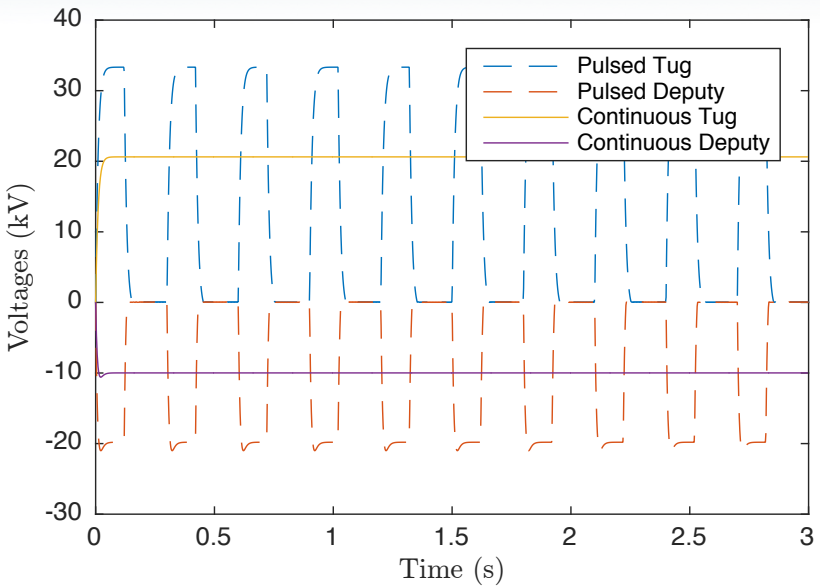
$$\frac{\mathrm{d}q}{\mathrm{d}t} = I_b(t) + \sum I_{env}(\phi)$$
$$= I_e(\phi, A) + I_i(\phi, A) + I_p(V, A) + I_{SEE}(\phi_{eff}) + I_{beam}(\phi, t)$$

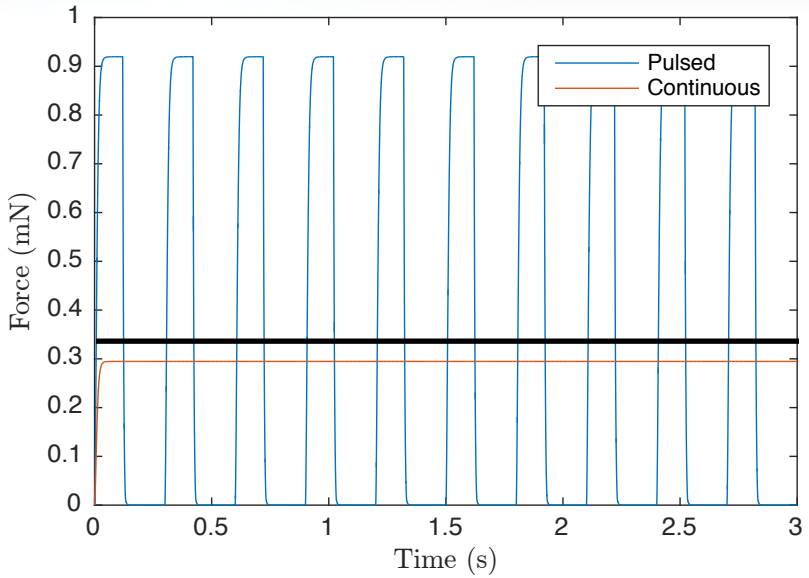
$$\begin{bmatrix} \phi_T \\ \phi_D \end{bmatrix} = \frac{1}{4\pi\epsilon_0} \begin{bmatrix} 1/R_T & 1/\rho \\ 1/\rho & 1/R_D \end{bmatrix} \begin{bmatrix} q_T \\ q_D \end{bmatrix}$$

$$\boldsymbol{F} = \frac{q_d\, q_t}{4\pi\epsilon_0 \rho^2} \hat{\boldsymbol{\rho}}$$



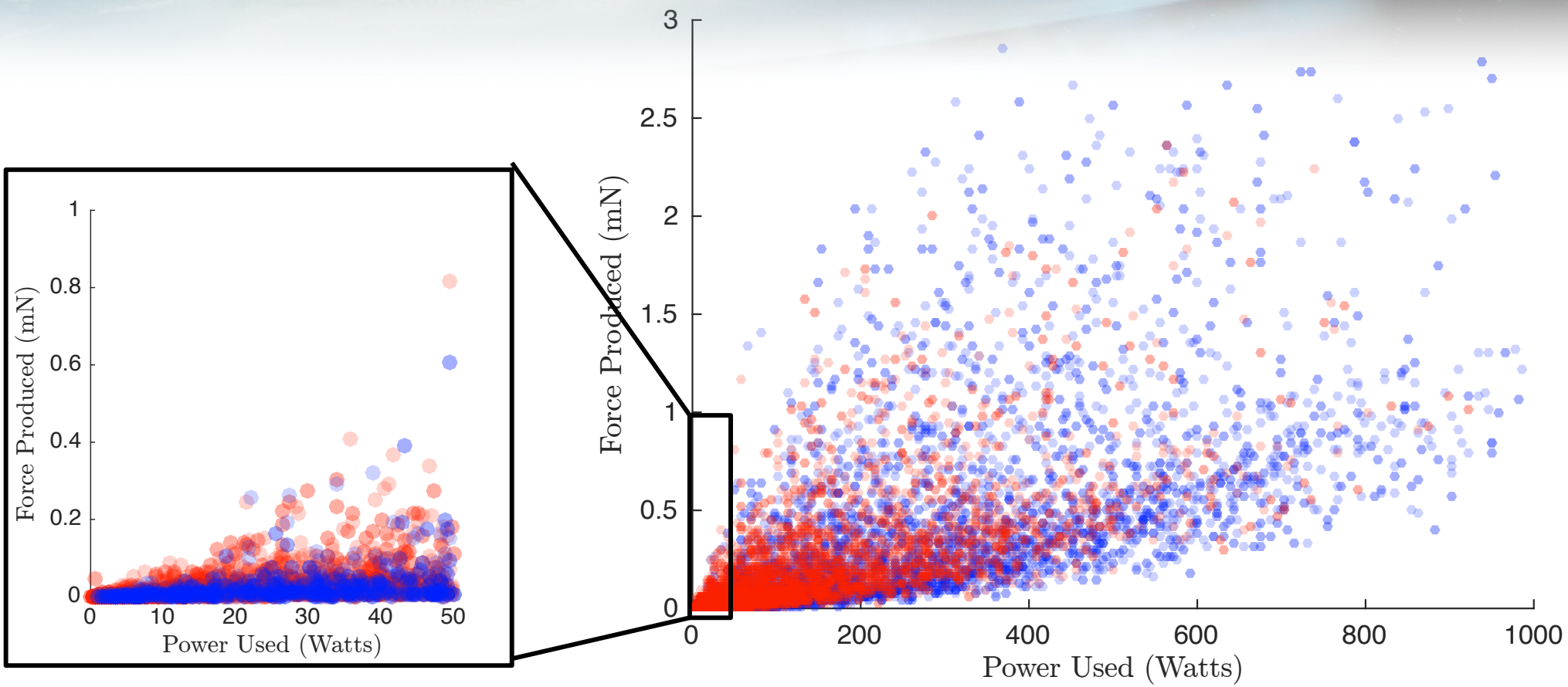
Pulsed Beaming Simulation





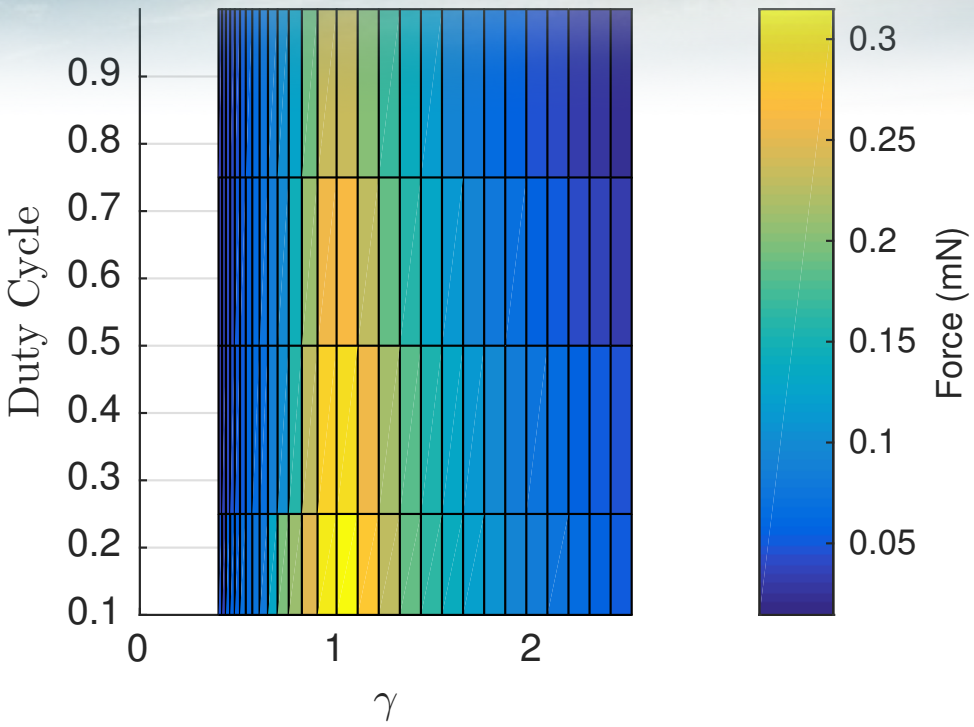
Parameter	Lower Limit	Upper Limit
R_{T}	1.5 m	5m
R_{D}	1.5 m	5m
V_{b}	5 kV	100 kV
I_{b}	50 μA	10 mA
T_{p}	100 ms	1 s
d	0.01	0.99

Force Analysis



J. Hughes and H. Schaub, "Monte-Carlo Analysis Of The Pulsed Electrostatic Tractor Strength," Spacecraft Charging Technologies Conference, Space Research and Technology Centre of the European Space Agency (ESA/ESTEC), Holland, April 4–8, 2016.

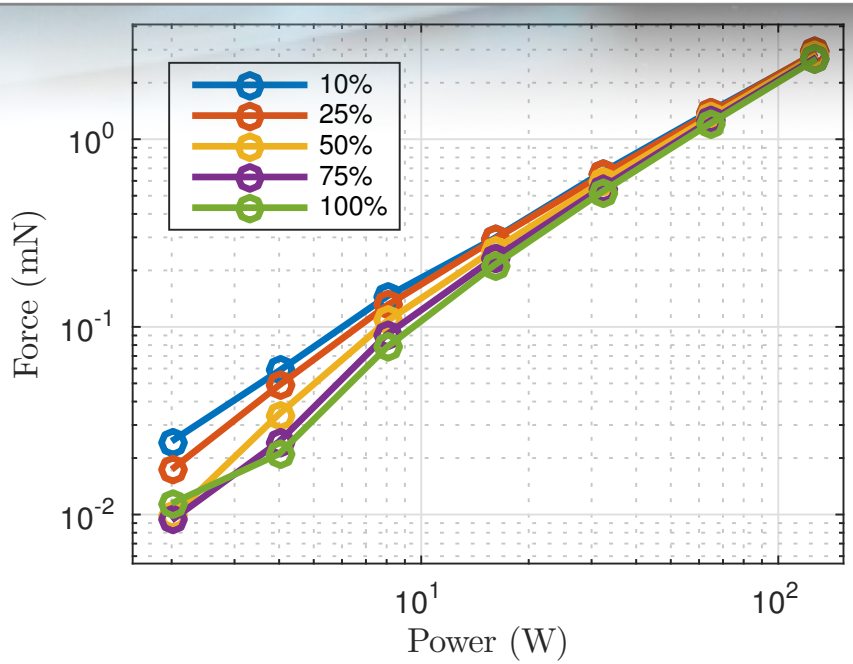
Duty Cycle Analysis

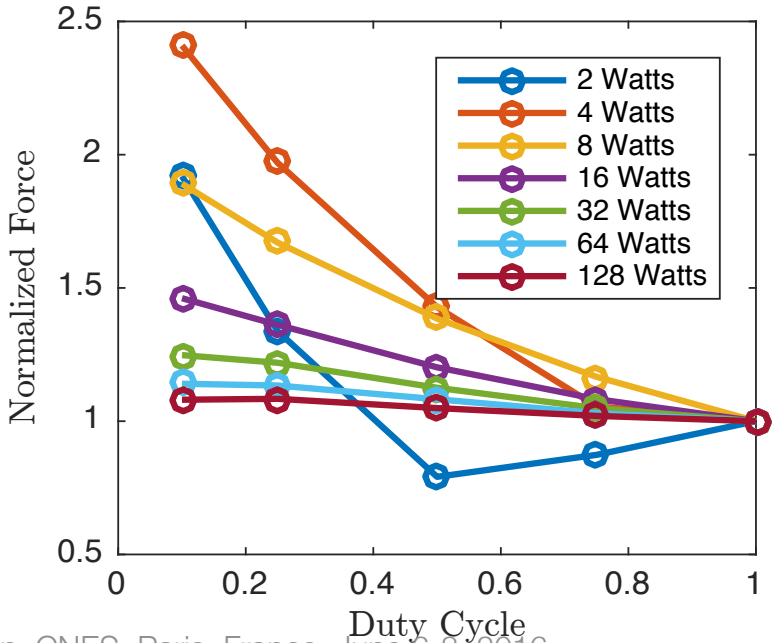


$$P = I_{b_0} V_{b_0} = I_b V_b \; d$$

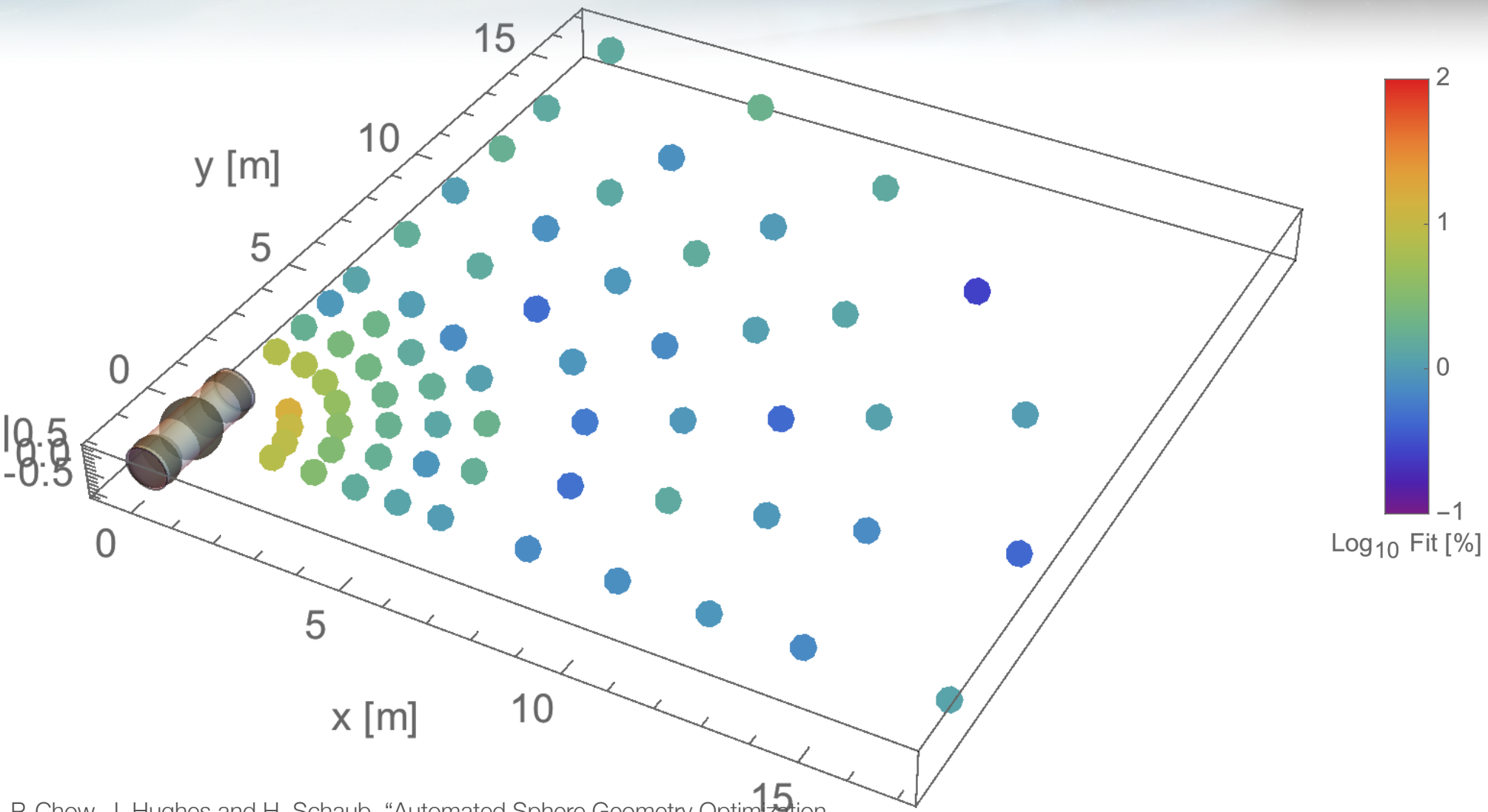
$$I_b = \frac{I_{b_0}}{\sqrt{d}} \qquad V_b = \frac{V_{b_0}}{\sqrt{d}}$$

$$I_b = \frac{\gamma I_{b_0}}{\sqrt{d}} \qquad V_b = \frac{V_{b_0}}{\gamma\sqrt{d}}$$





Multi-Sphere Method (MSM)



P. Chow, J. Hughes and H. Schaub, "Automated Sphere Geometry Optimization For The Volume Multi-Sphere Method," AAS Spaceflight Mechanics Meeting, Napa Valley, California, February 14–18, 2016. Paper No. 16-472.

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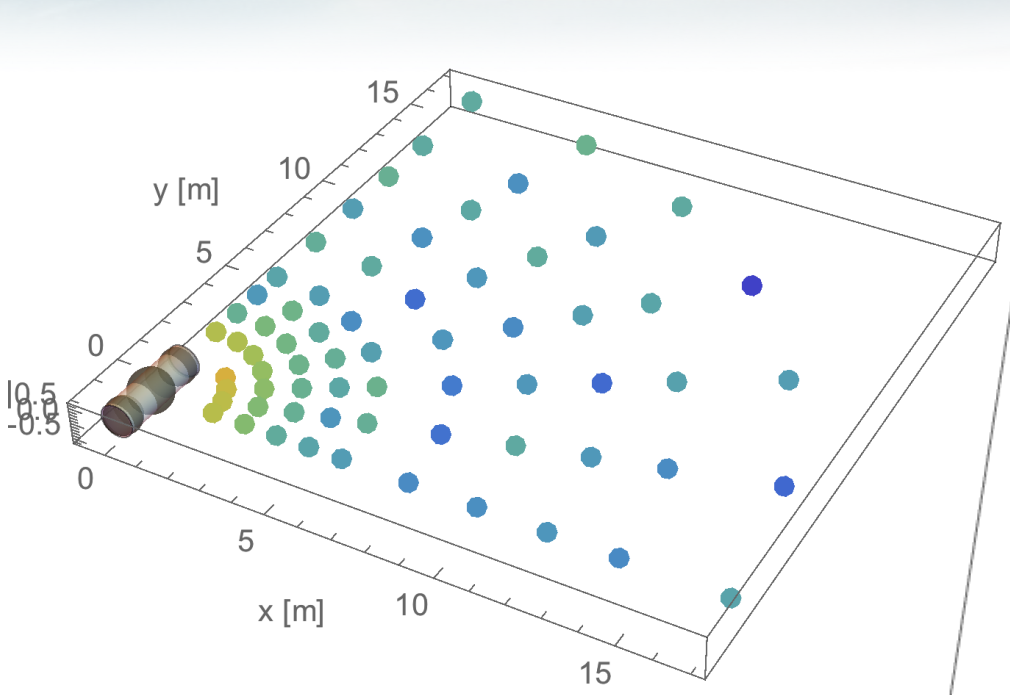
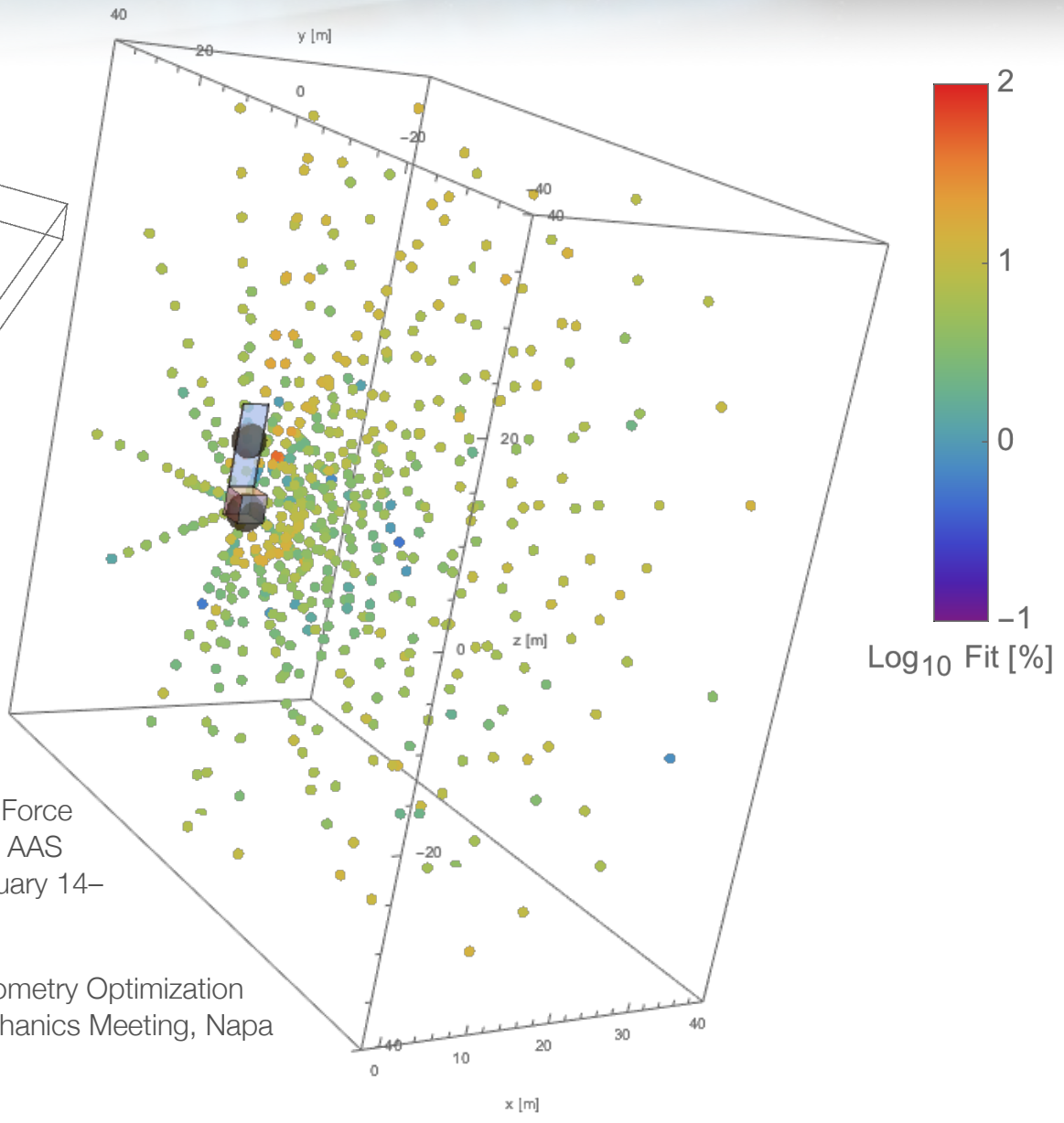




J. Hughes and H. Schaub, “Appropriate Fidelity Electrostatic Force Evaluation Considering A Range Of Spacecraft Separations,” AAS Spaceflight Mechanics Meeting, Napa Valley, California, February 14–18, 2016. Paper No. 16-486.

P. Chow, J. Hughes and H. Schaub, “Automated Sphere Geometry Optimization For The Volume Multi-Sphere Method,” AAS Spaceflight Mechanics Meeting, Napa Valley, California, February 14–18, 2016. Paper No. 16-472.

3D Detumble Kinematics

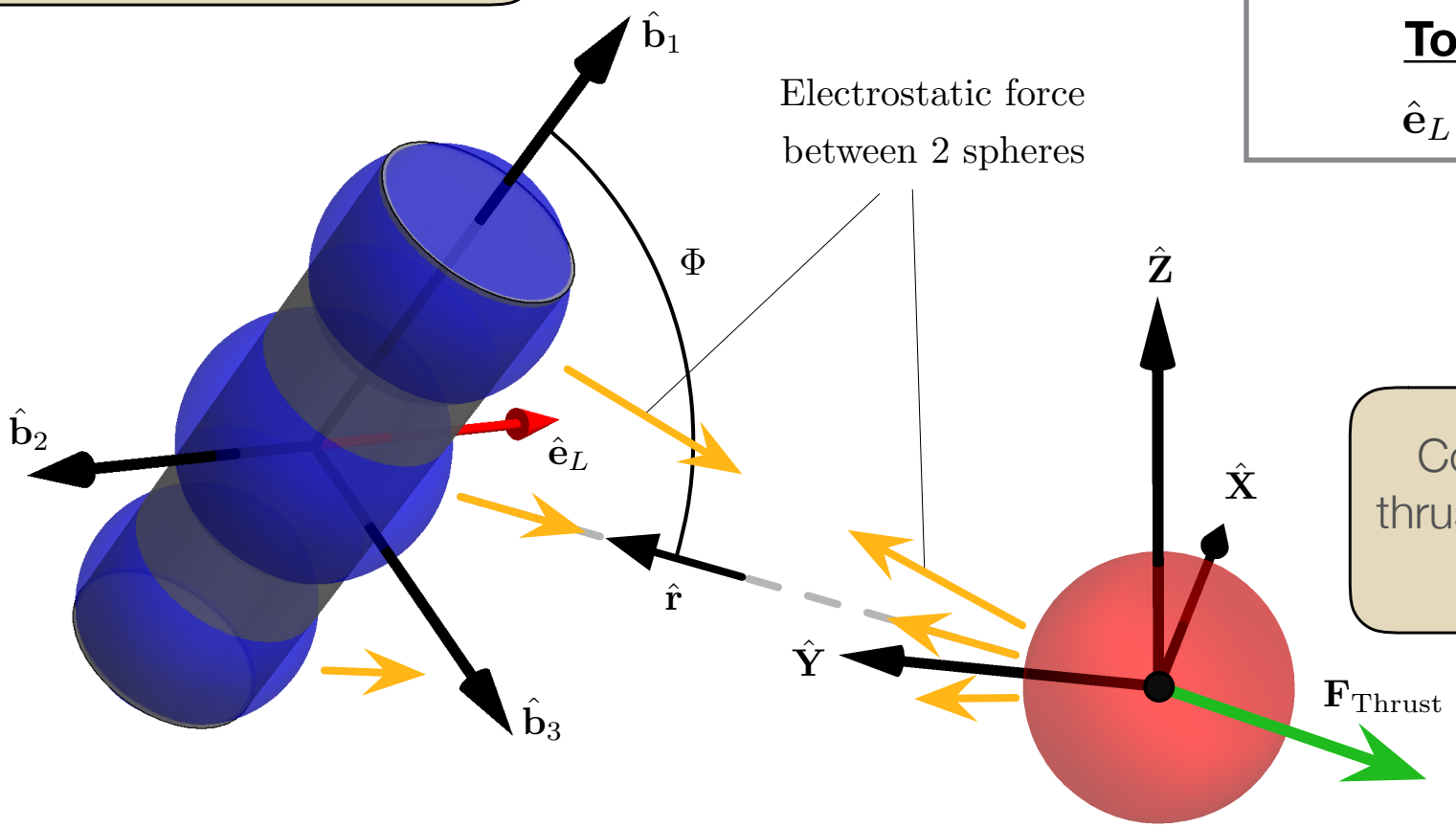
Multi-Sphere Method (MSM) used to obtain real-time charging dynamics.

Projection Angle

$$\Phi = \arccos\left(\hat{\mathbf{b}}_1 \cdot (-\hat{\mathbf{r}})\right)$$

Torque Axis

$$\hat{\mathbf{e}}_L = \hat{\mathbf{b}}_1 \times -\hat{\mathbf{r}}$$



Command craft inertial thrusting maintains desired separation.

New Attitude Equations of Motion

$$I_a\dot{\omega}_1 = 0$$

$$I_t\dot{\eta} - I_a\omega_1\dot{\Phi}\sin\Phi = 0$$

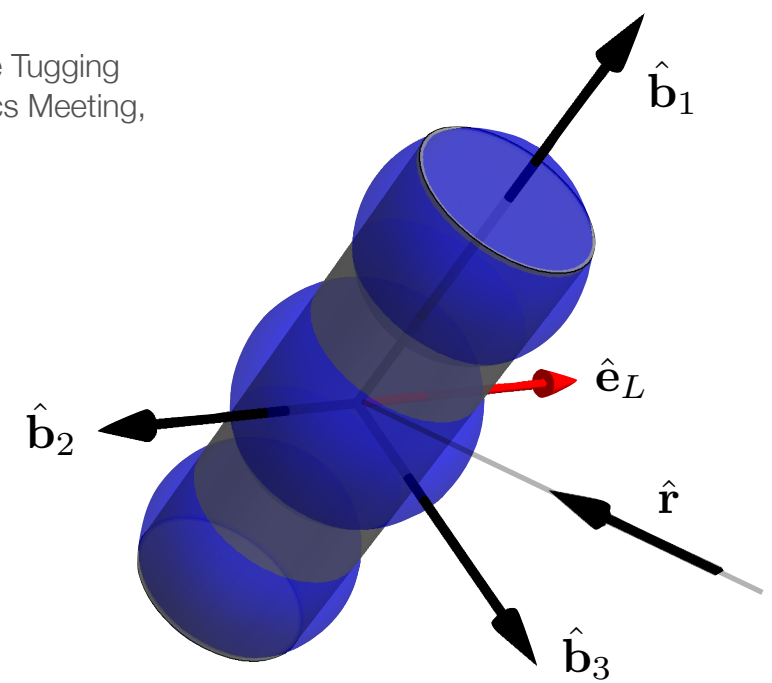
$$I_t\left(\ddot{\Phi}\sin\Phi - \eta^2\frac{\cos\Phi}{\sin^2\Phi}\right) + I_a\omega_1\eta = L$$

$$\eta \equiv -\omega_2(\hat{\mathbf{r}}\cdot\hat{\mathbf{b}}_2) - \omega_3(\hat{\mathbf{r}}\cdot\hat{\mathbf{b}}_3)$$

$$\dot{\Phi}\sin\Phi = -\omega_2(\hat{\mathbf{r}}\cdot\hat{\mathbf{b}}_3) + \omega_3(\hat{\mathbf{r}}\cdot\hat{\mathbf{b}}_2)$$

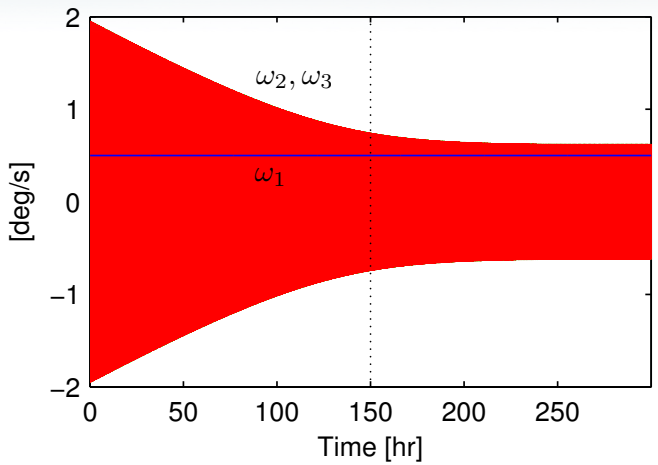
$$\mathbf{L} = -L\hat{\mathbf{e}}_L = -f(\phi)\sum_{m=1}^{n}\gamma_m g_m(\Phi)\,\hat{\mathbf{e}}_L$$

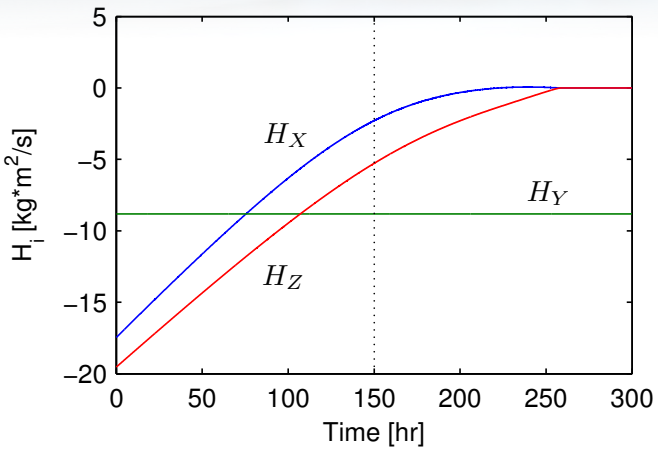
T. Bennett and H. Schaub, "Touchless Electrostatic Detumbling While Tugging Large Axi-Symmetric GEO Debris," AAS/AIAA Space Flight Mechanics Meeting, Williamsburg, VA, January 11–15, 2015.



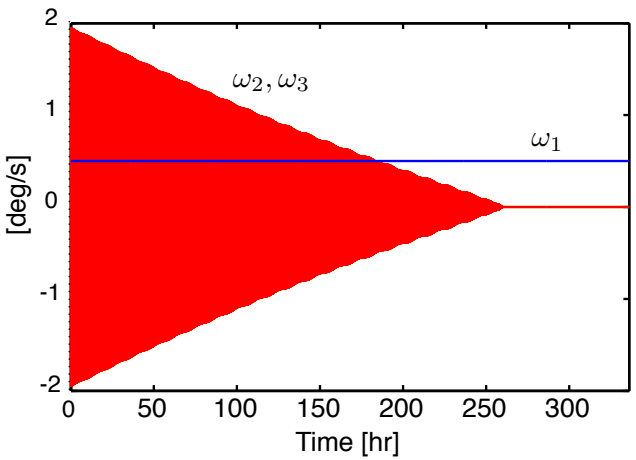
Detumble Performance

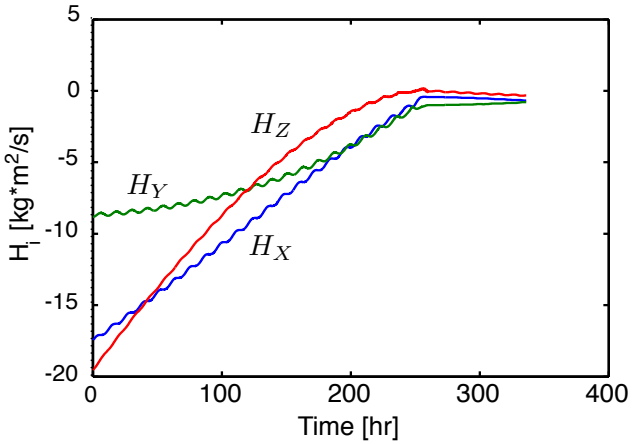
Deep Space





Lead-Follower





Relative positioning effects momentum removal.

↓

Momentum dumping can be analytically predicted as a function of relative motion.

↓

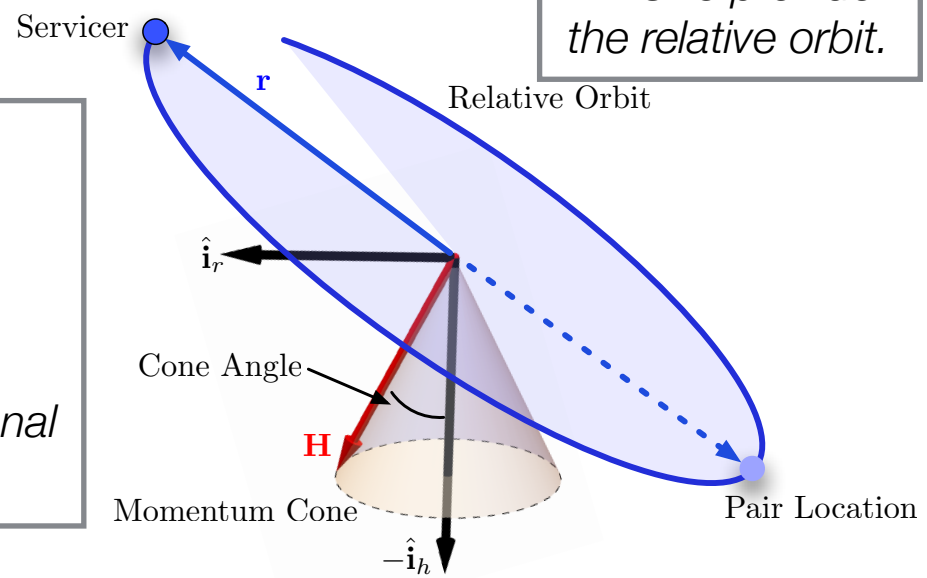
Relative motion now becomes a design parameter.

T. Bennett and H. Schaub, "Touchless Electrostatic Detumbling While Tugging Large Axi-Symmetric GEO Debris," AAS/AIAA Space Flight Mechanics Meeting, Williamsburg, VA, January 11–15, 2015.

Relative Orbit Optimization Approach

Desire: *Relative orbit that will improve detumble performance from lead-follower the angular momentum.*

LROEs provide the relative orbit.



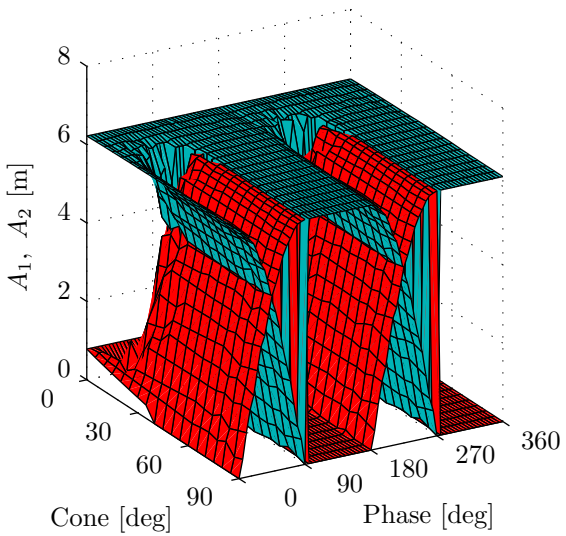
Detumble Torque Axis

$$\hat{\mathbf{e}}_L = \hat{\mathbf{b}}_1 \times -\hat{\mathbf{r}}$$

where torque is inversely proportional to r^2.

Hill frame optimization

LROE Optimums for Particular Momentum Geometries

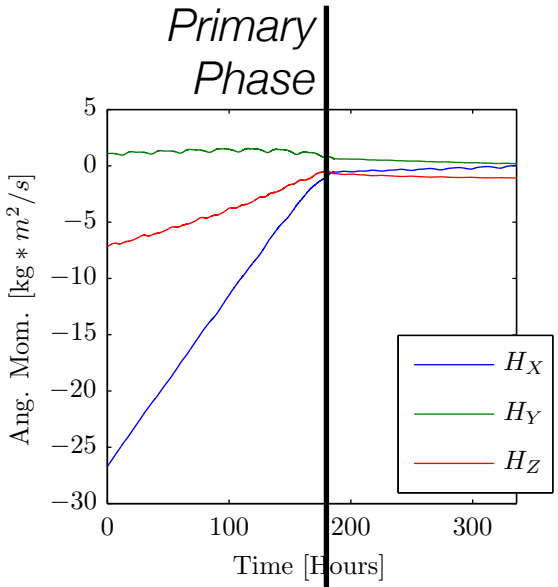


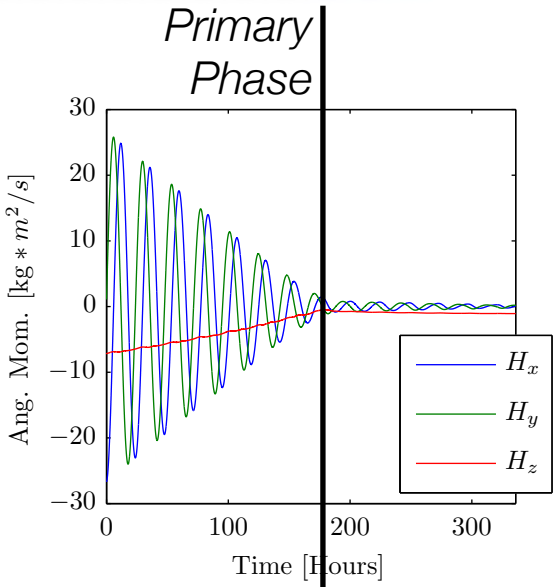
LROEs provide improved relative orbit guidance for electrostatic detumble mission applications.

T. Bennett and H. Schaub, "Capitalizing on Relative Motion in Electrostatic Detumble of Axi-Symmetric GEO Objects," 6th International Conference on Astrodynamics Tools and Techniques (ICATT), ESOC, Darmstadt, Germany, March 14–17, 2016.

Detumble Performance

Optimized





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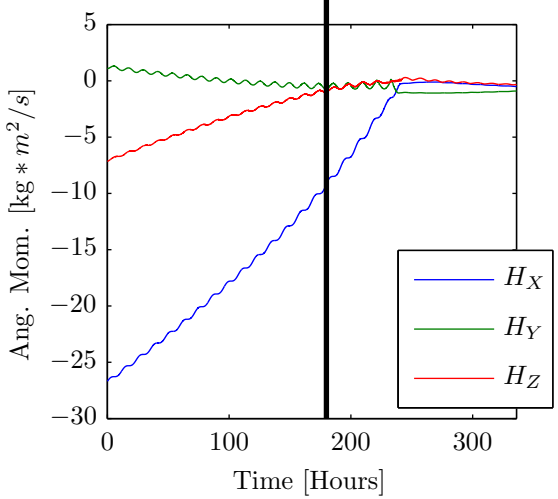
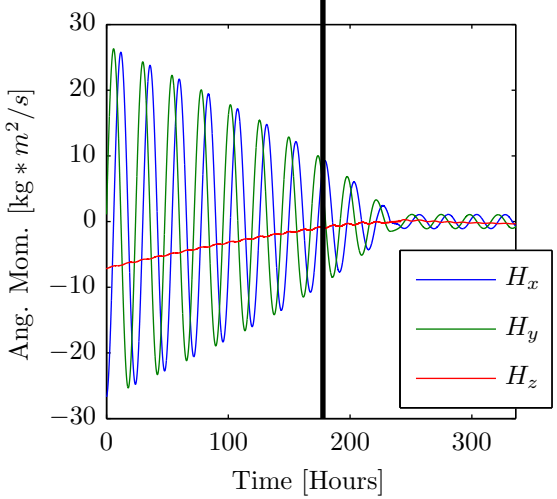
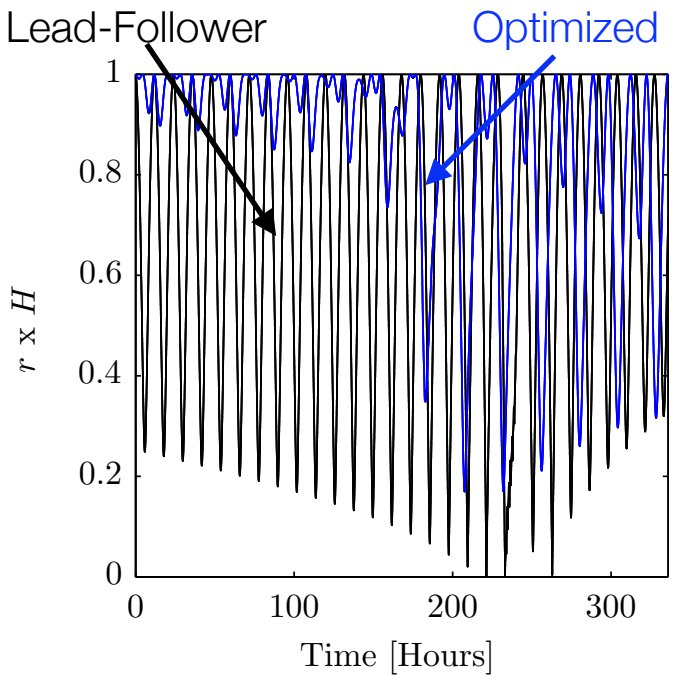




The optimization approach provides the improved detumble geometry.



Particular relative orbits using LROE guidance do improve electrostatic detumble.

Conclusions

- Pulsed charging can yield strong E-Tractor forces for a given power level, and provides windows to apply inertial thrusting.
- The MSM E-force and torque modeling method is providing very fast numerical solutions with percent level loss in accuracy.
- Modulated E-Tractors can detumble an object with predictable convergence properties
- The relative orbital motion can be exploited to improve the detumble performance.

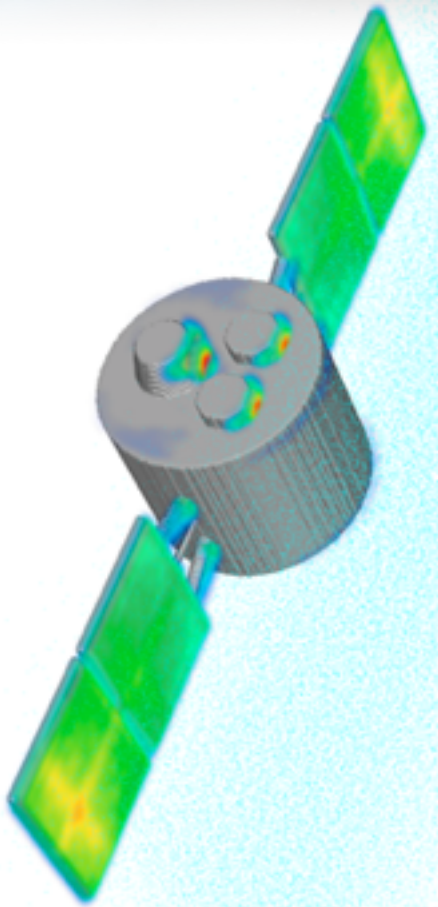
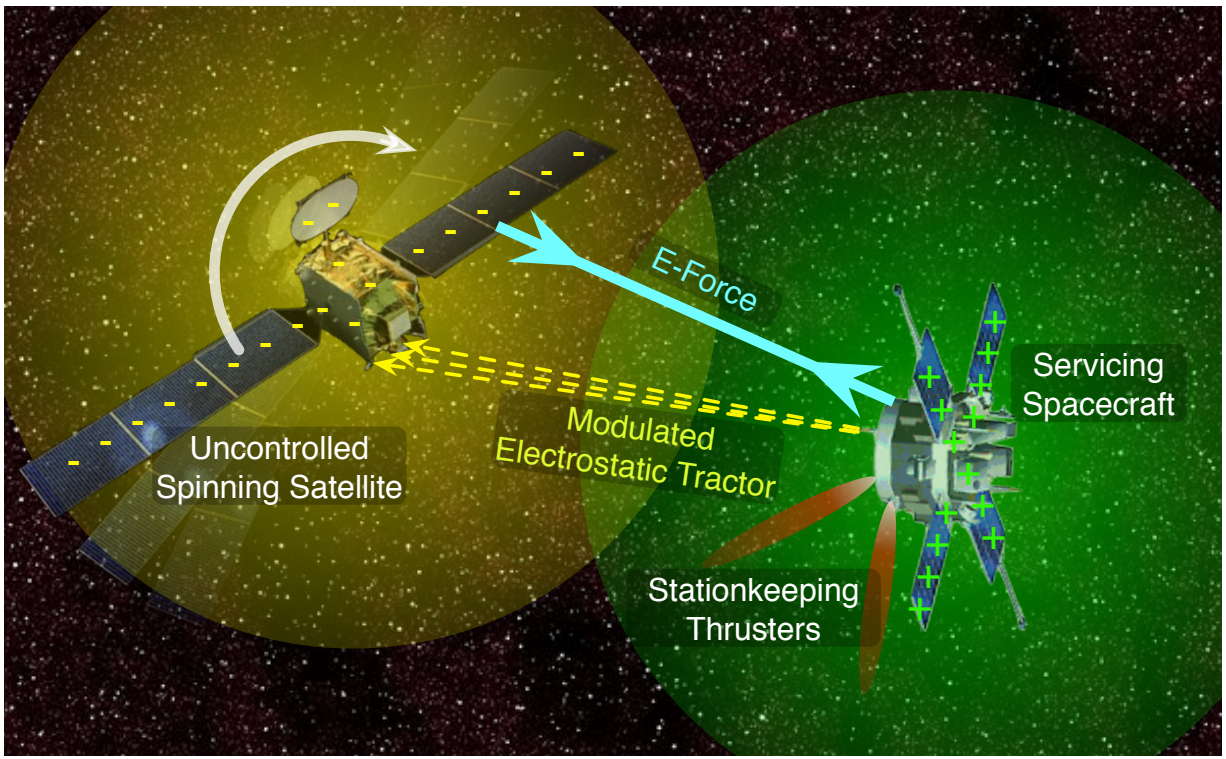


Image courtesy of
Tech-X Corporation

Questions?



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