Capitalizing on Relative Motion in Electrostatic Detumble of Axi-Symmetric GEO Debris

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Space Utilization!
Debris Removal, Satellite Servicing


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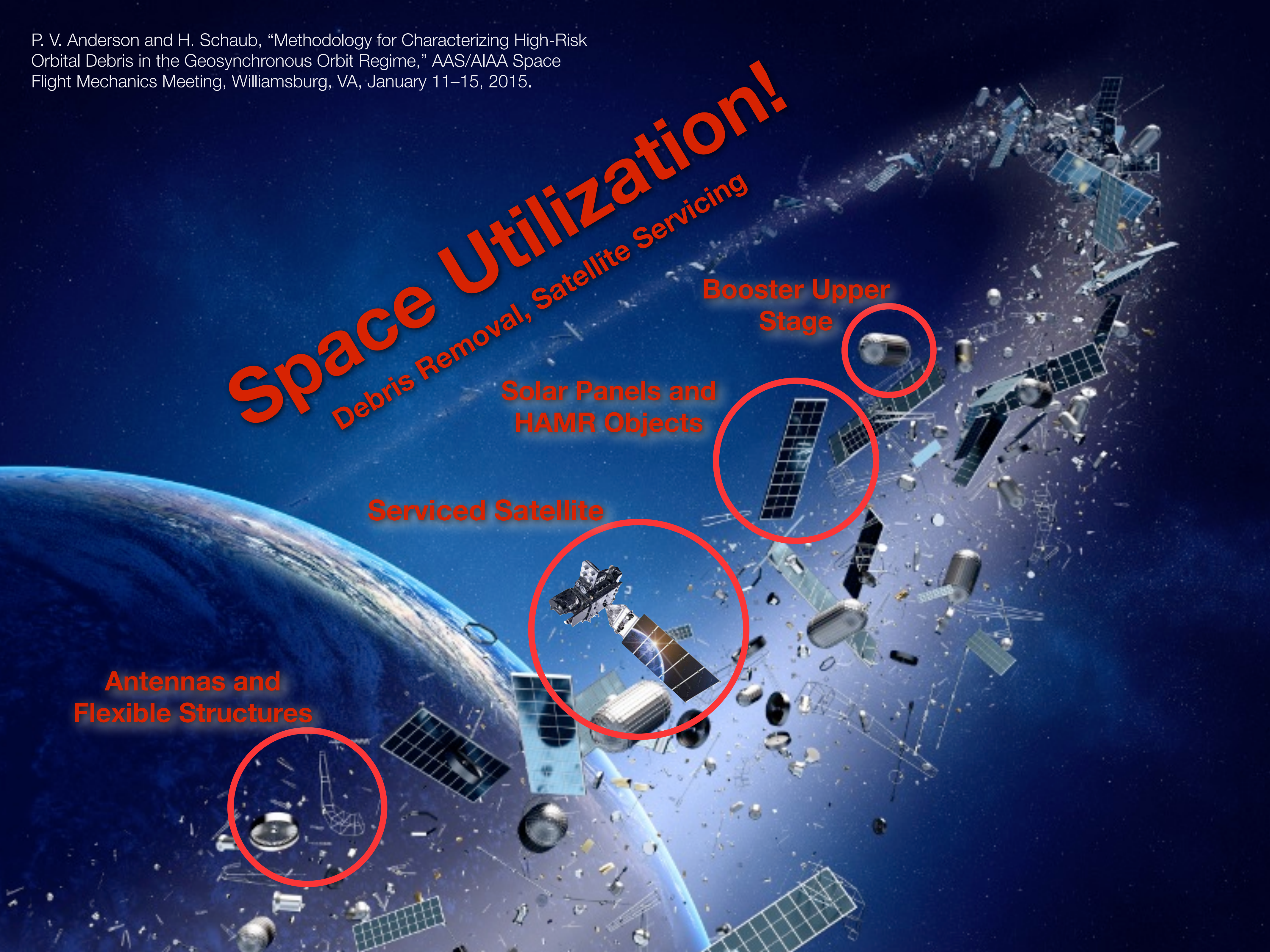
Debris Removal, Satellite Servicing
Booster Upper Stage
Solar Panels and HAMR Objects
Serviced Satellite
Antennas and Flexible Structures


P. V. Anderson and H. Schaub, “Methodology for Characterizing High-Risk Orbital Debris in the Geosynchronous Orbit Regime,” AAS/AIAA Space Flight Mechanics Meeting, Williamsburg, VA, January 11–15, 2015.
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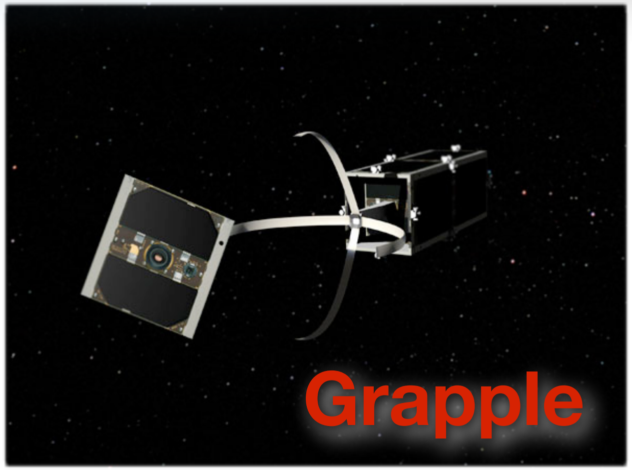
Target Capture Techniques

Conventional Grapple

Current docking techniques or arm capture can only achieve slow rotation rates.



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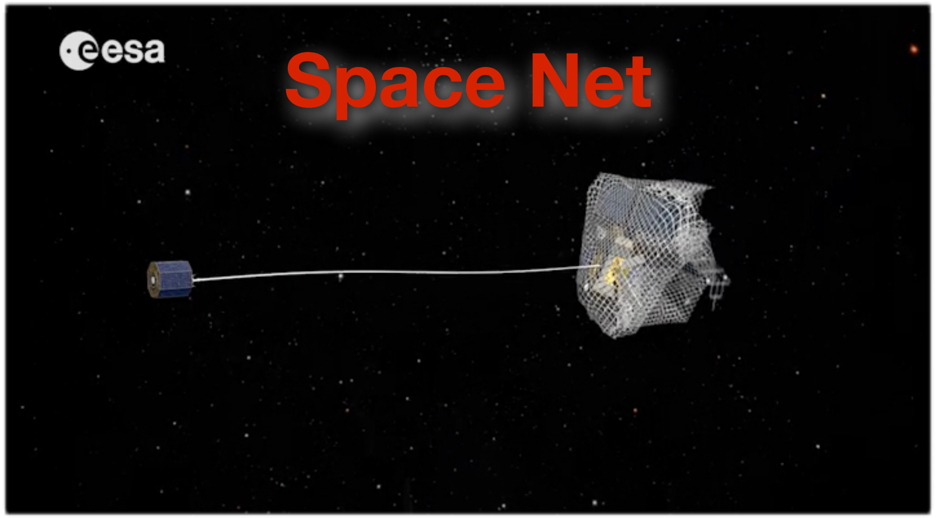
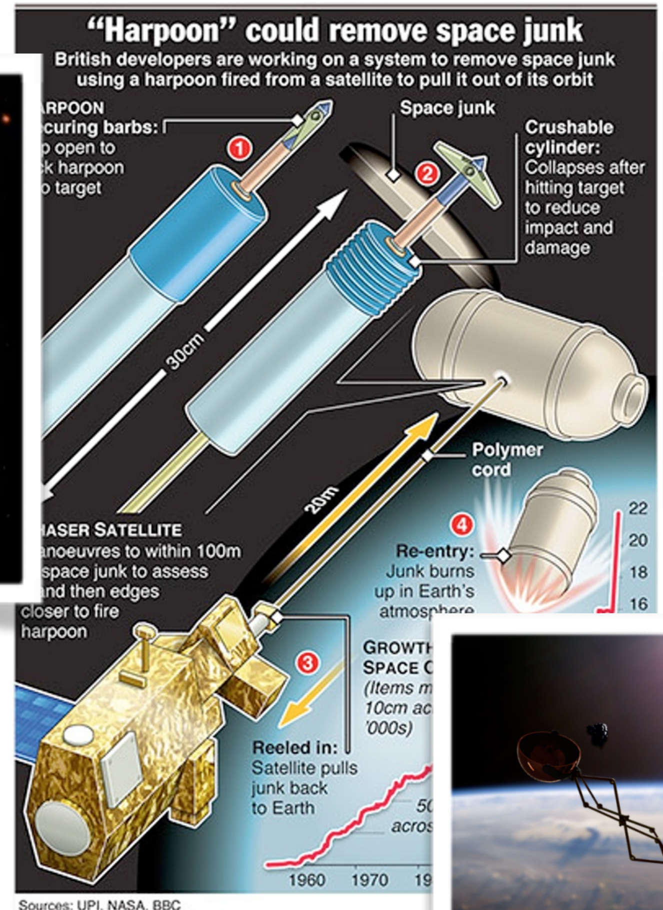
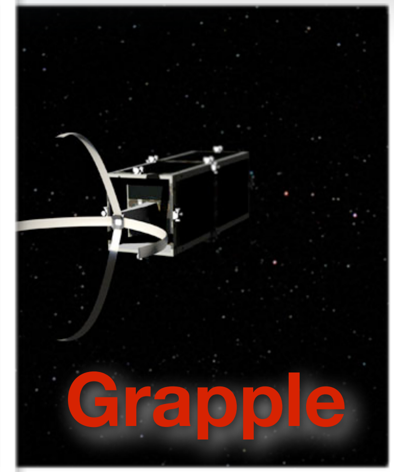


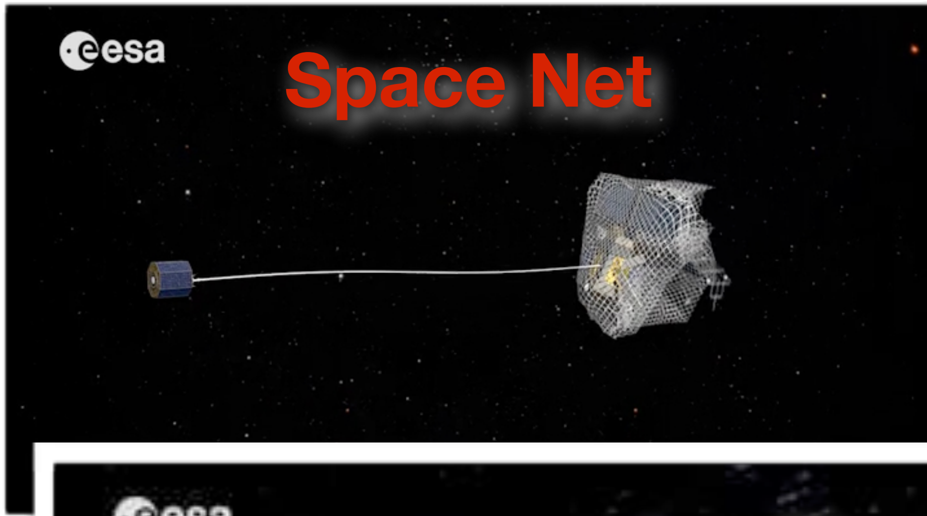


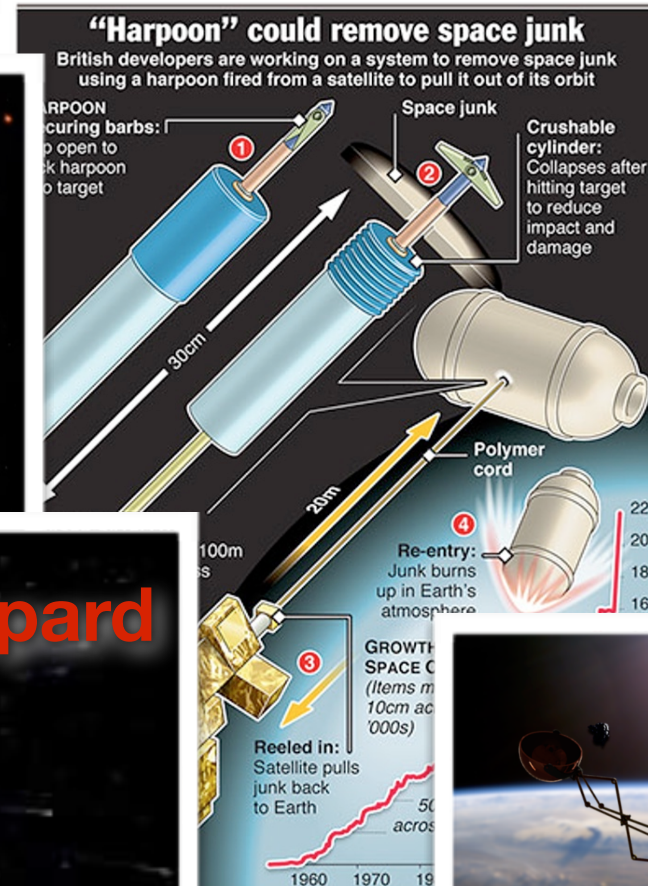


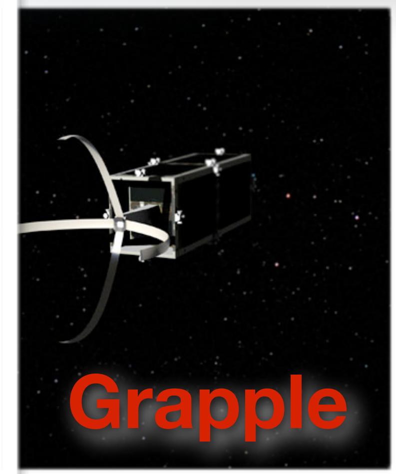
Tethered Capture

Subject to tether dynamics and deployment challenges.

Target Capture Techniques







Electrostatic Actuation Applications

Opportunities exist for many space-based applications of electrostatic actuation. Concepts have been explored as early as 1960s.

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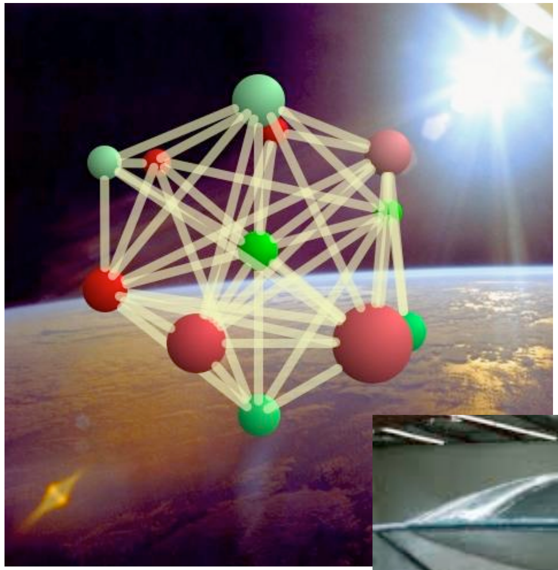

Tethered and Inflatable Structures

J. H. Cover, W. Knauer, and H. A. Maurer, "Lightweight Reflecting Structures Utilizing Electrostatic Inflation", US Patent 3,546,706, October 1966

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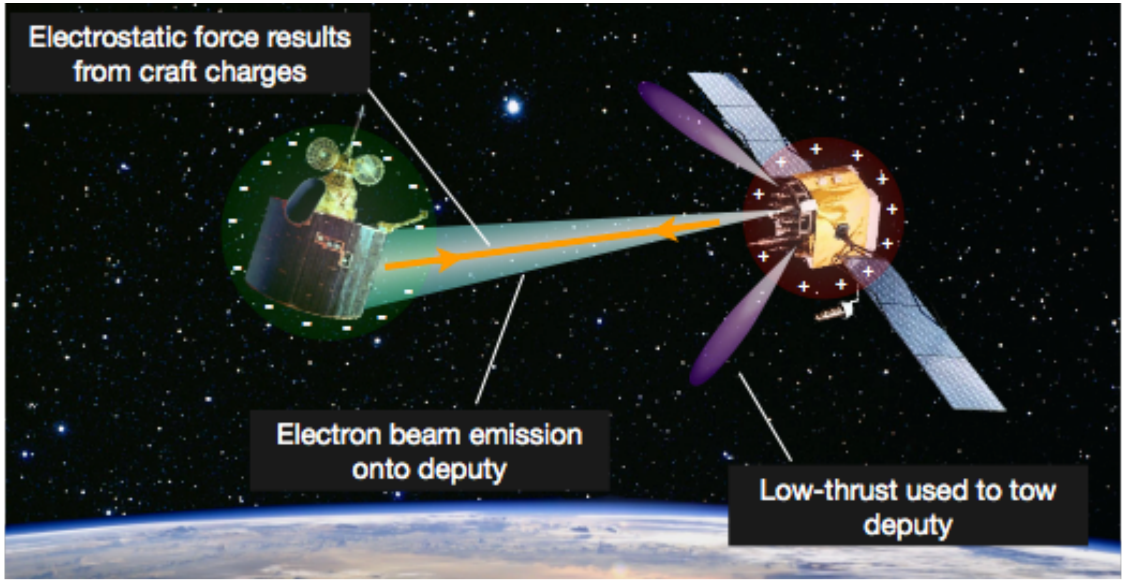
Debris Re/De-Orbiting



E. A. Hogan and H. Schaub, "Space Debris Reorbiting Using Electrostatic Actuation," AAS Guidance, Navigation and Control Conference, Breckenridge, February 3–8, 2012.

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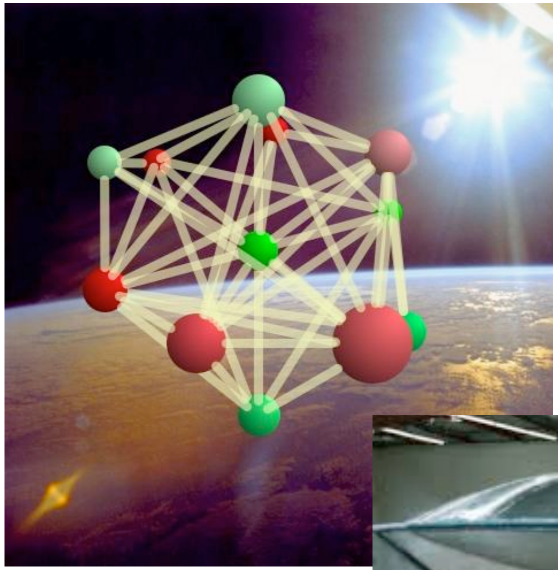

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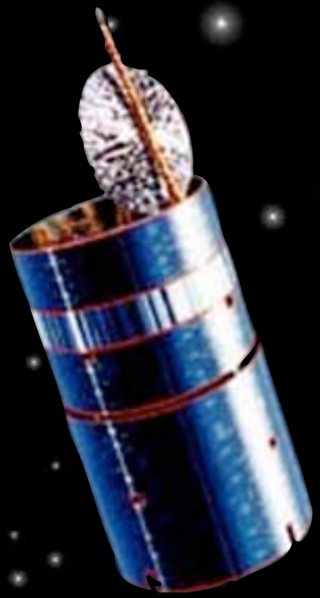
Electrostatic Actuation

Consider a GEO debris object



Electrostatic Actuation

Consider a GEO debris object

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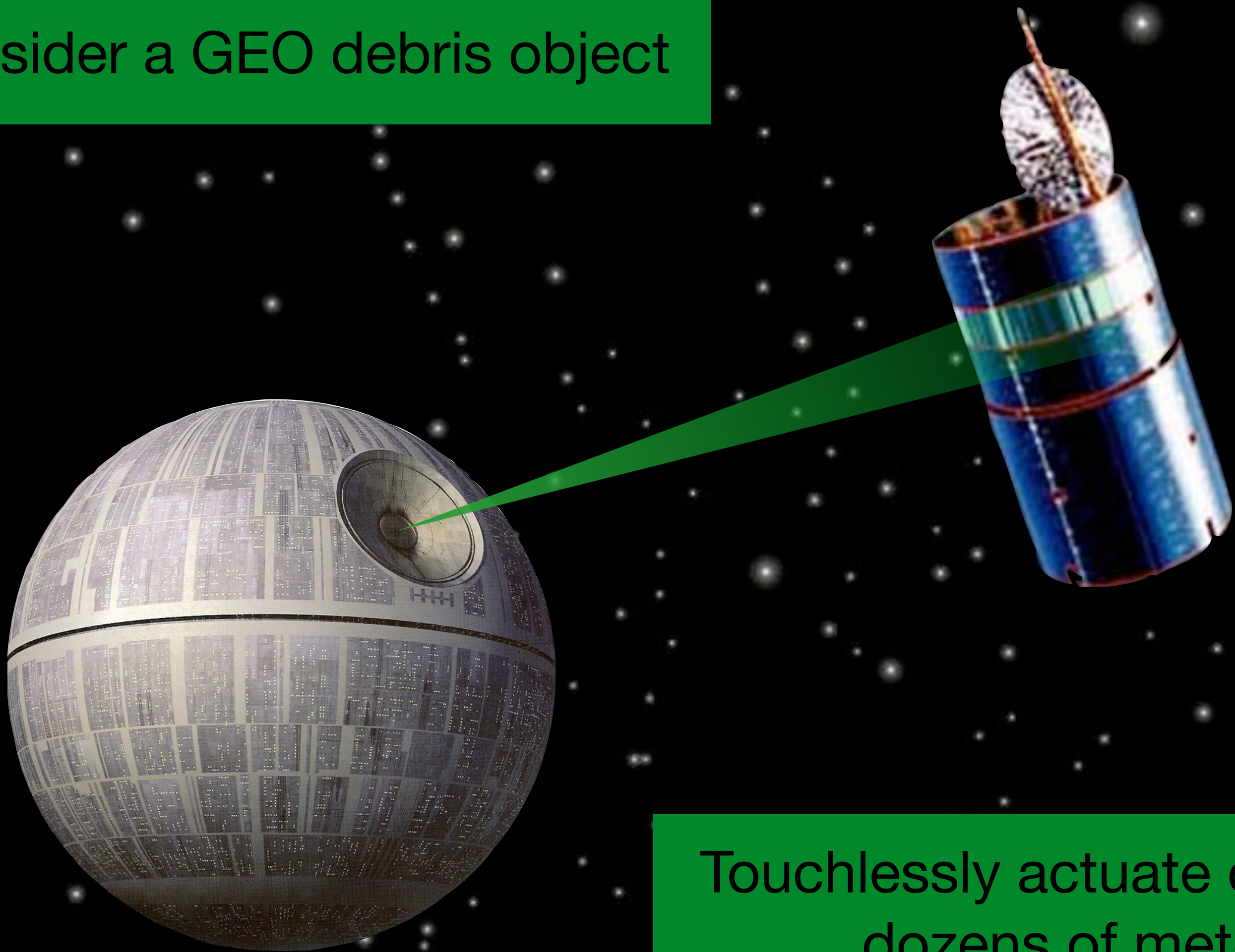
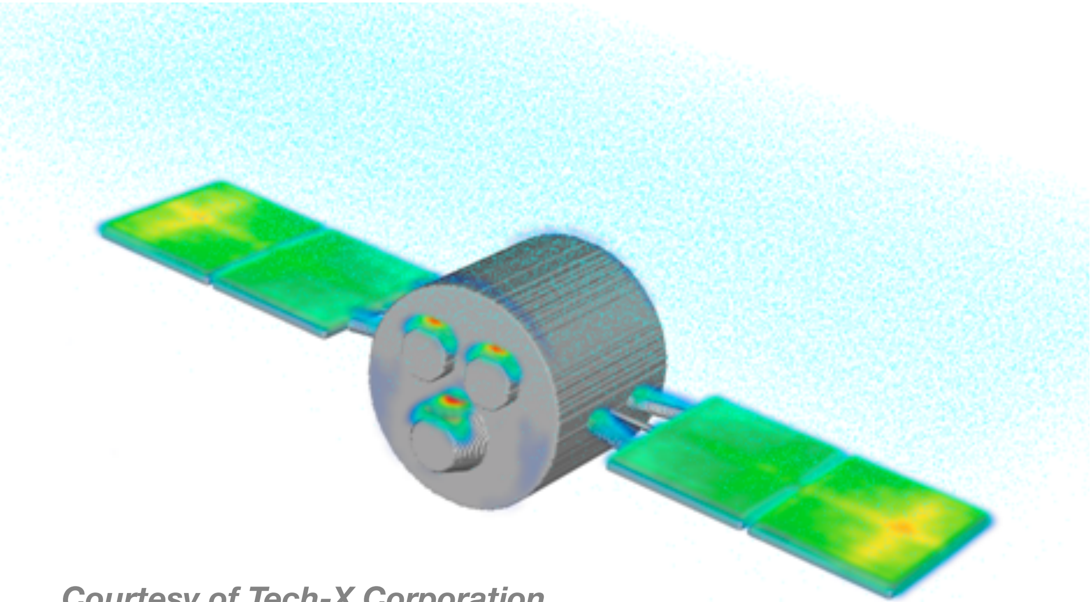


Touchlessly actuate objects separated by dozens of meters. Proposed:

Electrostatic Detumble of GEO Debris

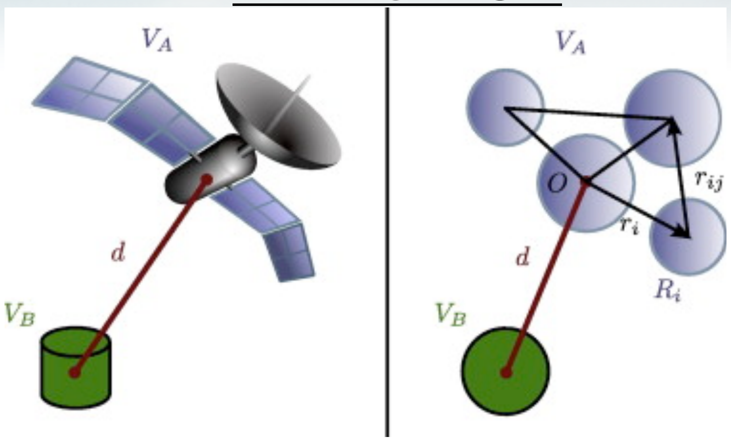
Charge Distribution and the Multi-Sphere Method (MSM)



Courtesy of Tech-X Corporation

Charge Distribution and the Multi-Sphere Method (MSM)

FEM vs. MSM



MSM is a lumped charge representation

D. Stevenson, and H. Schaub, Optimization of Sphere Population for Electrostatic Multi Sphere Model, 12th Spacecraft Charging Technology Conference, Kitakyushu, Japan, May 14–18, 2012

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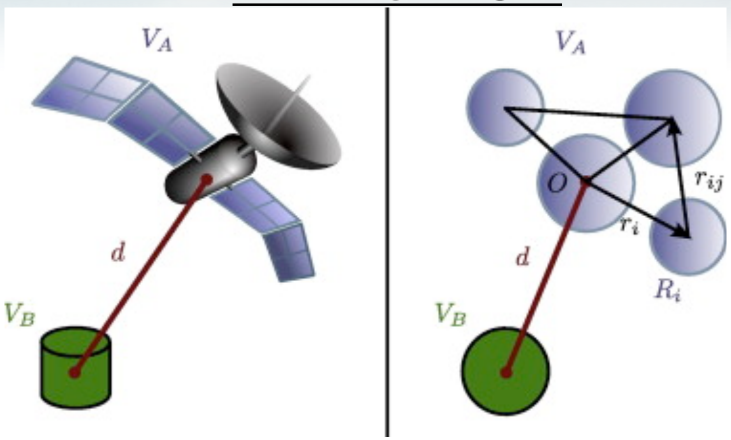

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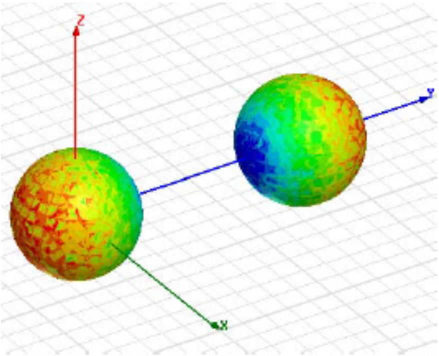

Maxwell FEM

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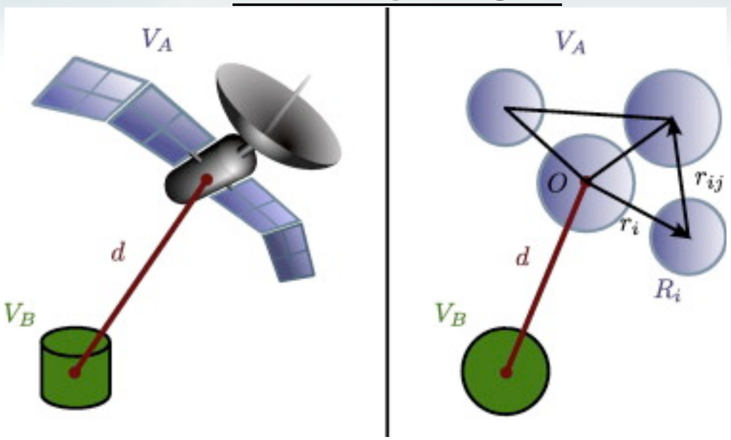

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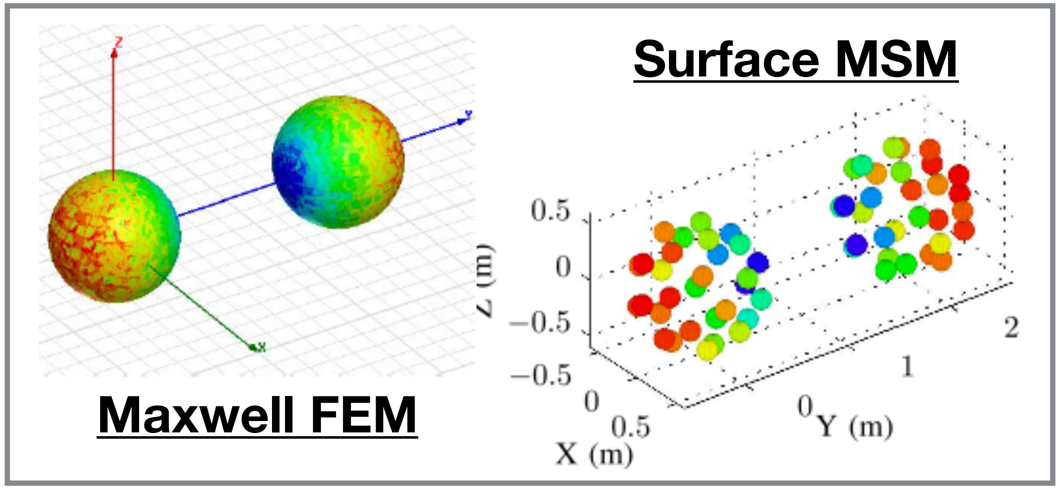

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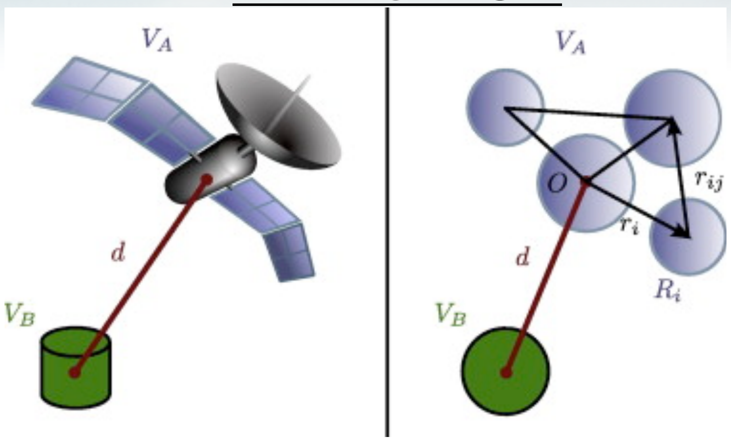

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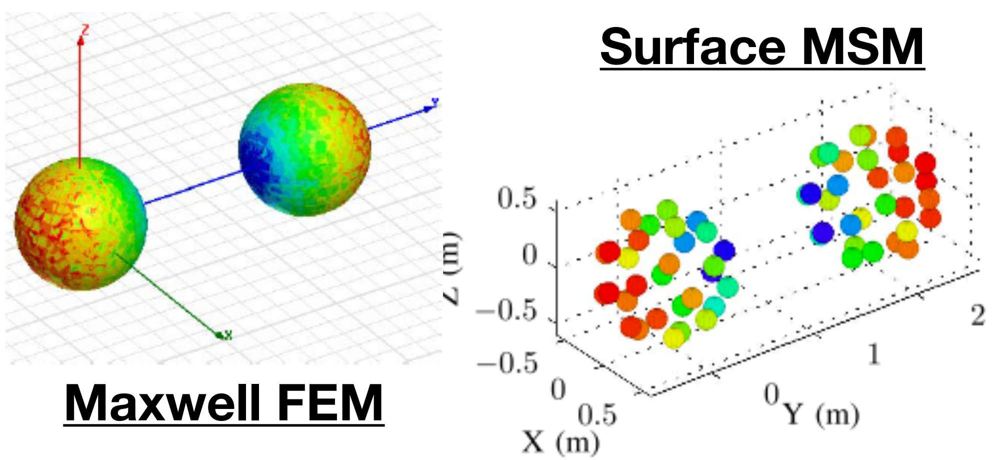

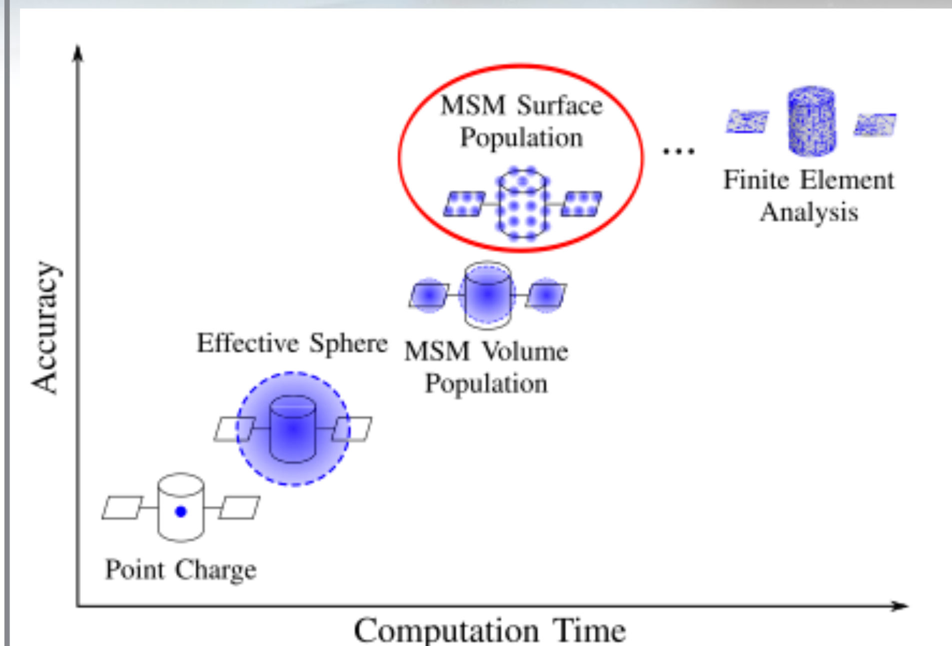

Finite element methods require minutes to solve the charge for a particular configuration.

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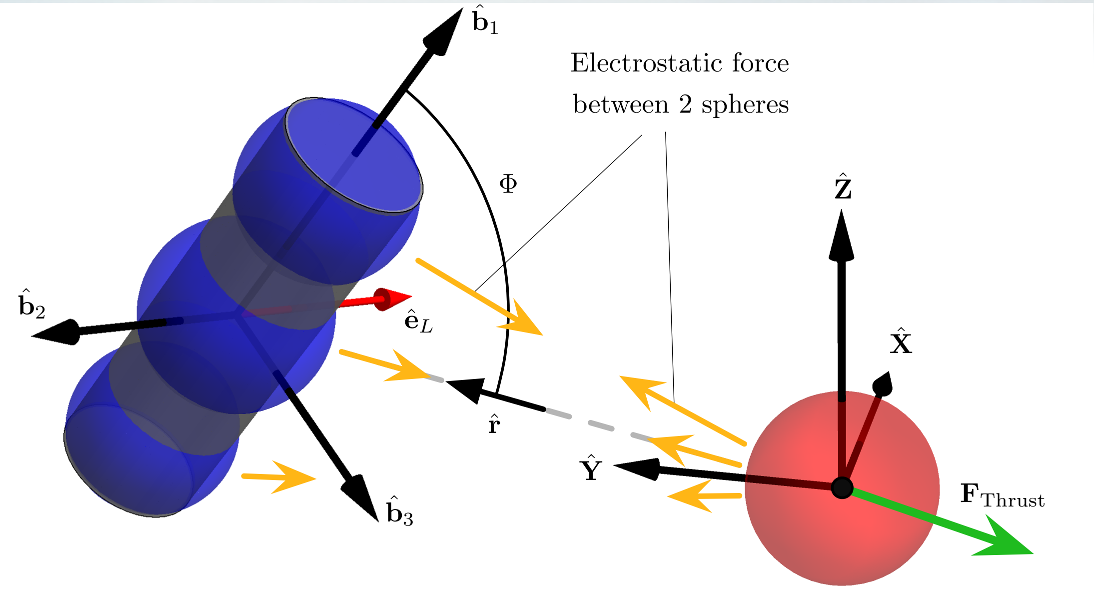
Electrostatic Detumble Equations of Motion



Projection Angle

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

Torque Axis

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

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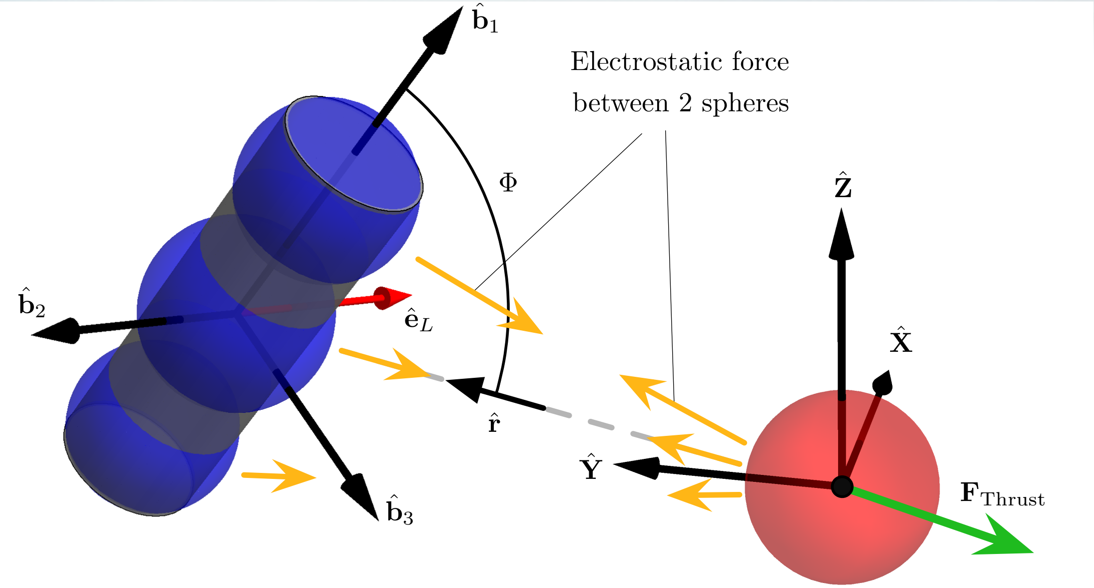

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$$I\dot{\omega} + \omega \times I\omega = \mathbf{L}$$

New Basis Equations of Motion

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

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

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

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

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

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

Linearized Relative Orbit Elements

Clohessy-Wiltshire (CW) Equations

$$x(t) = A_1 \cos(nt) - A_2 \sin(nt) + x_{\text{off}}$$

$$y(t) = -2A_1 \sin(nt) - 2A_2 \cos(nt) - \frac{3}{2} n t x_{\text{off}} + y_{\text{off}}$$

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$$\mathbf{X}_{\text{NS}} = (A_1, A_2, x_{\text{off}}, y_{\text{off}}, B_1, B_2)$$

The collection of CW invariants become the state vector for relative motion. This new state vector becomes the Linearized Relative Orbit Element (LROE) state.

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***Lagrange Brackets** provides evolution of the invariants given a perturbation acceleration.*

$$\dot{\mathbf{X}}_{\text{NS}} = \underbrace{\frac{1}{n}\begin{bmatrix} -\sin(nt) & -2\cos(nt) & 0 \\ -\cos(nt) & 2\sin(nt) & 0 \\ 0 & 2 & 0 \\ -2 & 3nt & 0 \\ 0 & 0 & -\sin(nt) \\ 0 & 0 & -\cos(nt) \end{bmatrix}}_{B(\mathbf{X},t)} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}$$

$$\dot{\mathbf{X}}_k = \mathbf{F}(\mathbf{X}(t_k), t_k) = B(\mathbf{X}(t_k), t_k)\mathbf{a}_d$$

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LROEs can be propagated with any acceleration rotated into the relative orbit frame.

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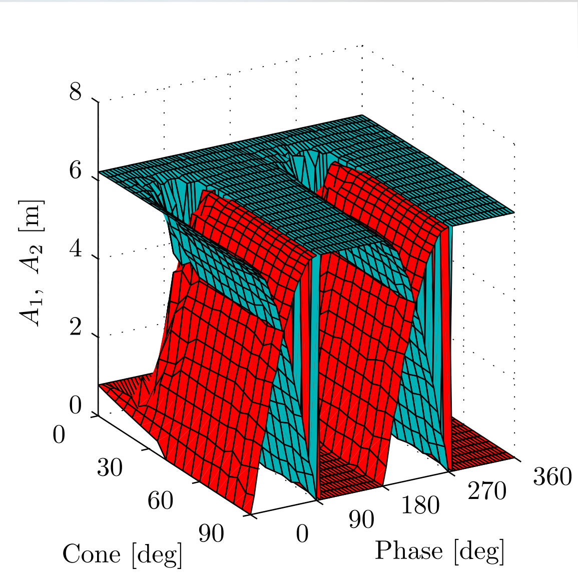
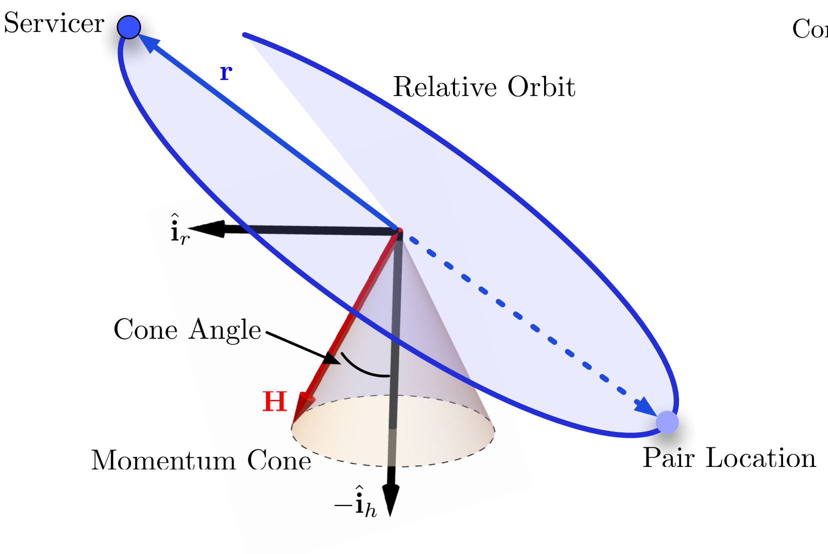
Optimization Approach

$$J = \sum_{i=0}^{N} \left(-1000 \ln[|\mathbf{r}_i| - r^* + 1] - 10 \ln \left[\left| \frac{\mathbf{r}_i \cdot \mathbf{H}_i}{\|\mathbf{r}_i\| \|\mathbf{H}_i\|} \right| + 1 \right] \right)$$





Optimization Design Output

A movie will be included here.

Numerical Simulations

- parameters, conditions, time, etc.

Optimized State Provides a Performance Increase

A movie will be included here.

Conclusions and Future Work

Conclusions:

- The choice of relative orbit provides substantial increase/decrease in detumble performance.
- The Linearized Relative Orbit Element (LROE) approach provides insightful approaches to optimizing the servicer relative orbit.
- Without significant loss in performance, the relative orbit may be selected for operational simplicity using a leader-follower or for operational safety where a safety ellipse orbit is available.

Future Work:

- Expand the relative motion detumble analysis to include objects that are not axi-symmetric.

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The authors would like to thank the NASA Space Technology Research Fellowship (NSTRF) program, grant number NNX14AL62H, for support of this research.

Questions?

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