

Coulomb Formation Flying

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Outline

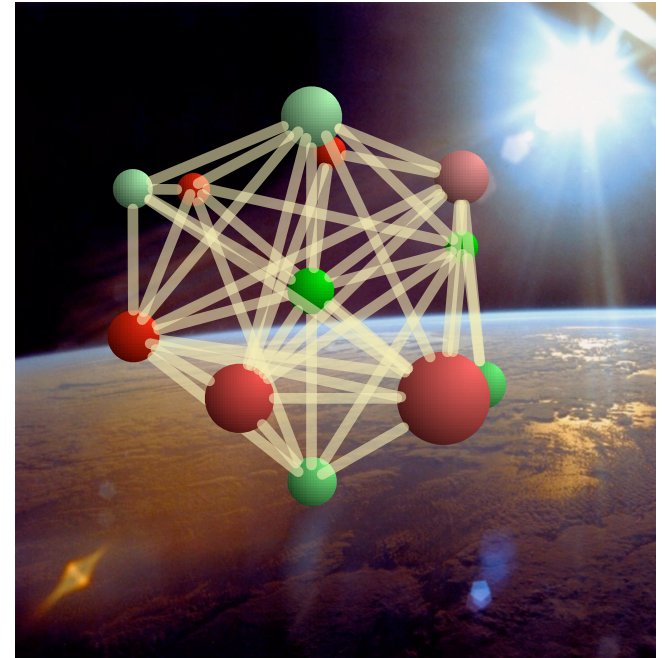
➔ Concepts and Background

- Intercraft Coulomb Forces
- Research History

➔ Applications

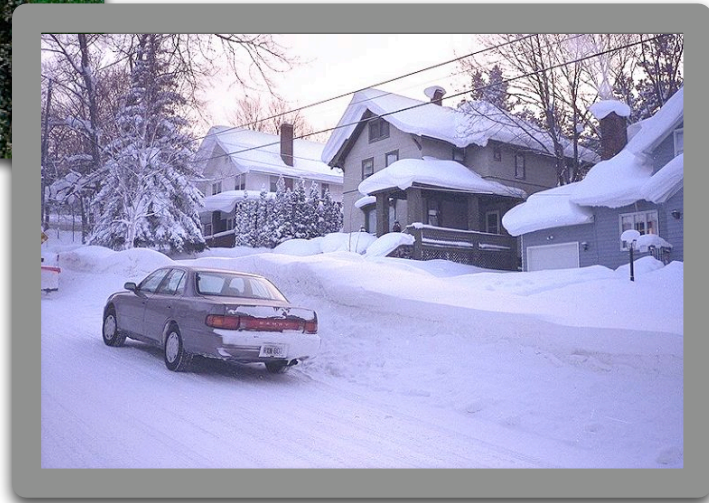
- Spacecraft Deployment
- Virtual Structures

➔ Conclusions and Future Work



MichiganTech

Houghton Michigan



Michigan Tech

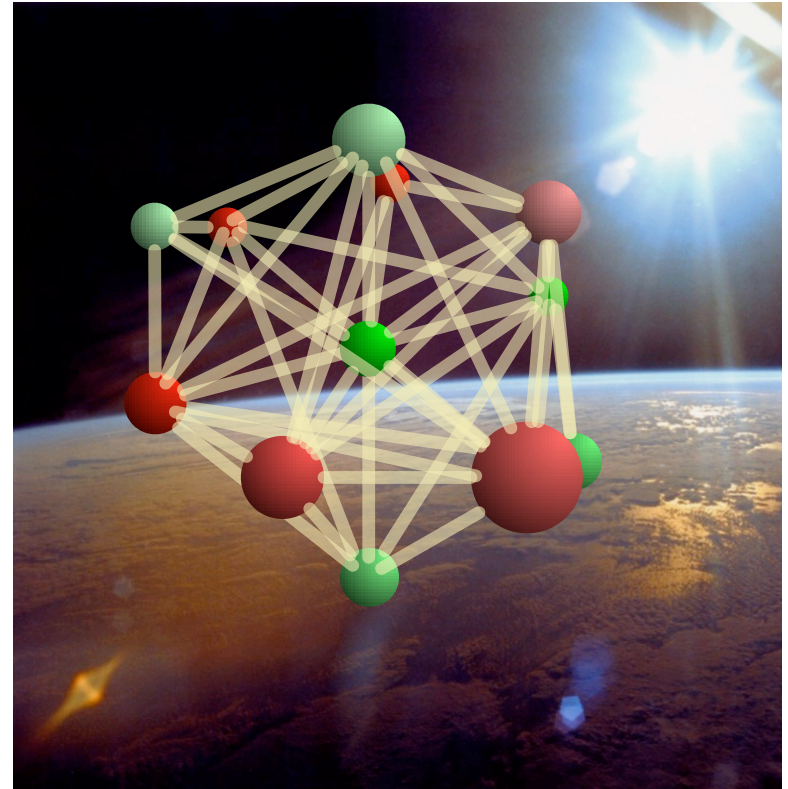
University

- About 6500 students
- Engineering, Sciences, Business

Mechanical Engineering

- 43 faculty
- 1140 undergraduate, 210 graduate students

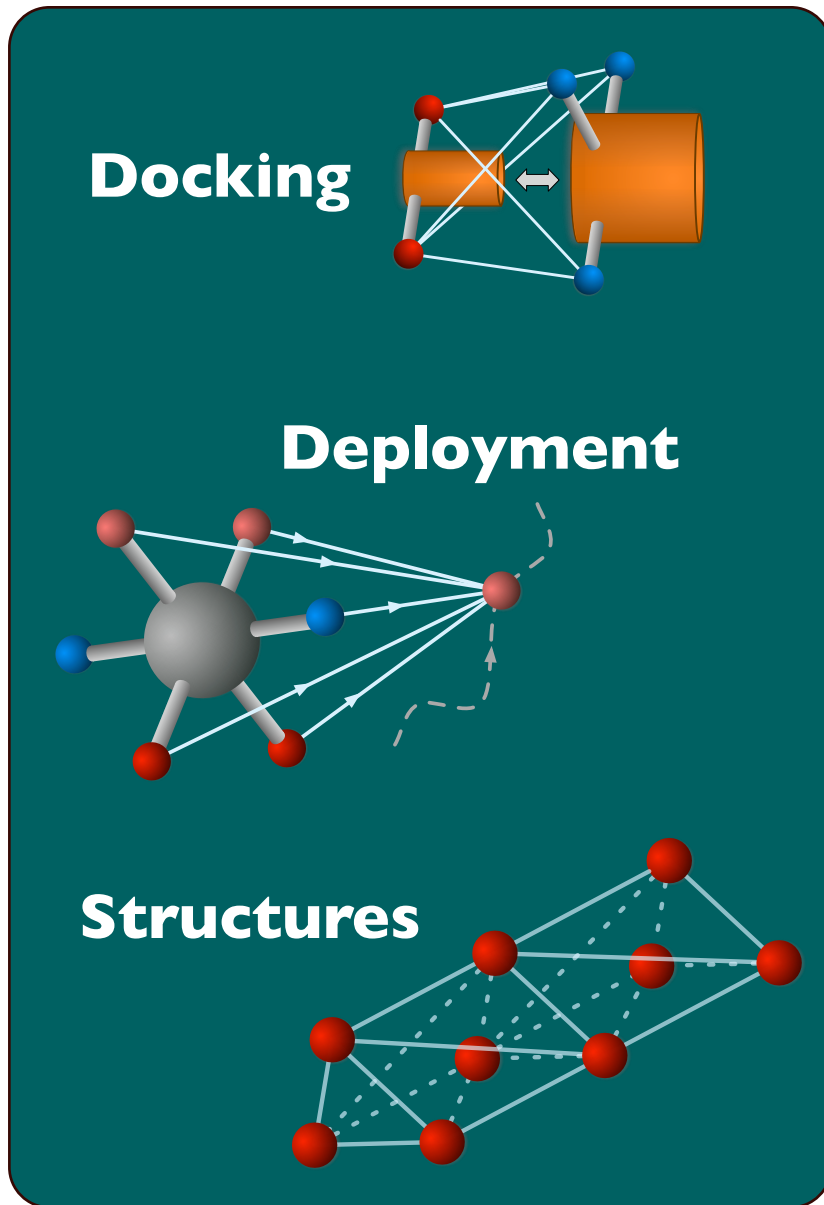
Concepts and Background



Coulomb Force Concept

Controlled charging of Coulomb “thrusters” to create interspacecraft forces.

- ➔ Formation flying
- ➔ Nanosat deployment
- ➔ Reconfigurable structures
- ➔ Docking
- ➔ Attitude Control

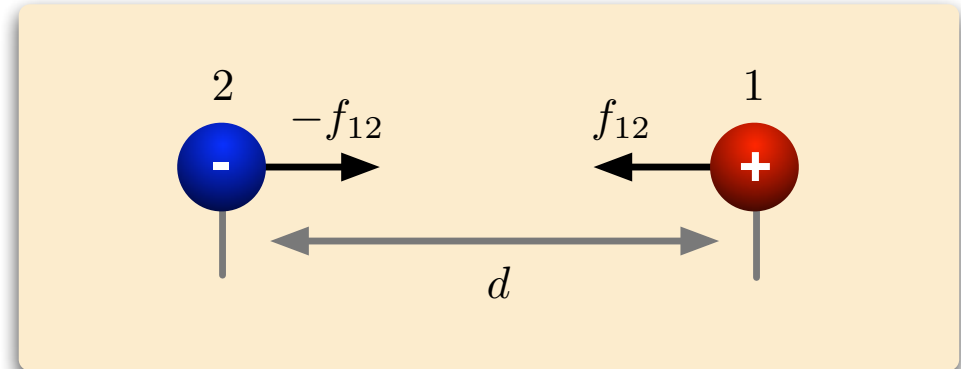


Coulomb Thrusting Research History

- ➔ 2000-2001: MTU
Proof of concept, static formations
- ➔ 2002-2004: VPI and MTU
Shape constraints, bounded motion control
- ➔ 2005: VPI and MTU
Coulomb tethers, virtual structures, deployment, charge sensing
- ➔ 2006: VPI and MTU
Formation control and virtual structures
- ➔ 2006: ESA and Ariadna

Related Work:
D. Miller, MIT
electromagnetic
thrusting

Coulomb Forces: Vacuum



$$f_{12} = k_c \frac{q_1 q_2}{d^2} = \frac{V_1 V_2}{k_c} \left(\frac{r_{sc}}{d} \right)^2$$

r_{sc} – charge sphere radius

q_i – i^{th} charge

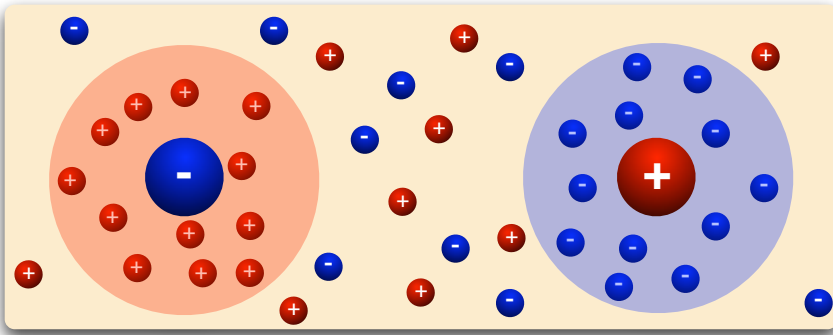
V_i – i^{th} voltage

$k_c \approx 8.99 \times 10^9$

| V (volts) | q (μC) | f_{12} (mN) |
|-------------|-----------------|---------------|
| 1000 | 0.06 | 0.01 |
| 5000 | 0.3 | 0.3 |
| 10000 | 0.6 | 1.2 |

**Typical Force-Volts Relationship
(radius = 0.5m, separation = 1.5m)**

Coulomb Forces: Plasma



$$f_{12} = \frac{V_1 V_2}{k_c} \left(\frac{r_{sc}}{d} \right)^2 e^{-d/\lambda_d}$$

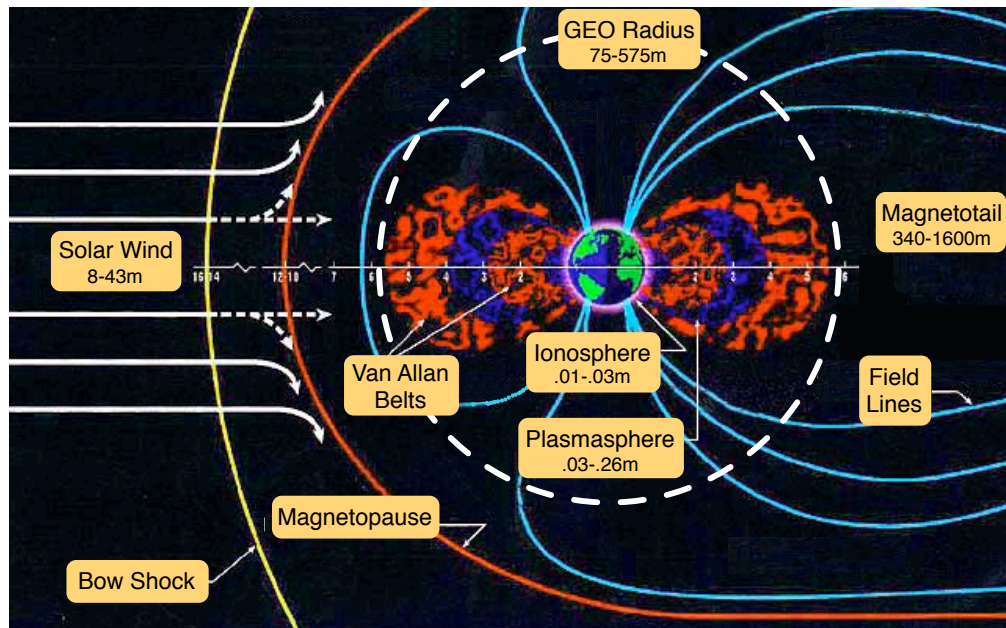
Typical Force vs Debye Length

| $\lambda_d(m)$ | $f_{12}(\mu N)$ |
|----------------|-----------------|
| 5 | 0.94 |
| 10 | 2.56 |
| 100 | 6.29 |

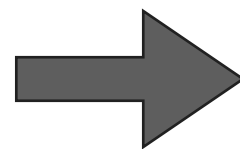
radius = 0.5m
V = 5000 volts
d = 10m

- ➔ Plasma: cloud of positively and negatively charged particles
- ➔ Debye Length (λ_d): Characteristic length over which charged particles in a plasma influence each other - an exponential effect.
- ➔ Beyond a few Debye lengths, a charged particle appears to have no charge and thus no “Coulomb thrust.”

Earth's Debye Length "Map"



Max charge sphere separation for practical Coulomb thrusting is about 2 Debye lengths



- Submeter Separation: MEO
- 10x m. Separation: GEO



Applications

N-Craft Dynamic Equations

$$m(\ddot{x}_i - 2n\dot{y}_i - 3n^2x_i) = k_c \sum_{j=1}^N \frac{x_i - x_j}{d_{ij}^3} q_i q_j e^{-\frac{d_{ij}}{\lambda_d}}$$

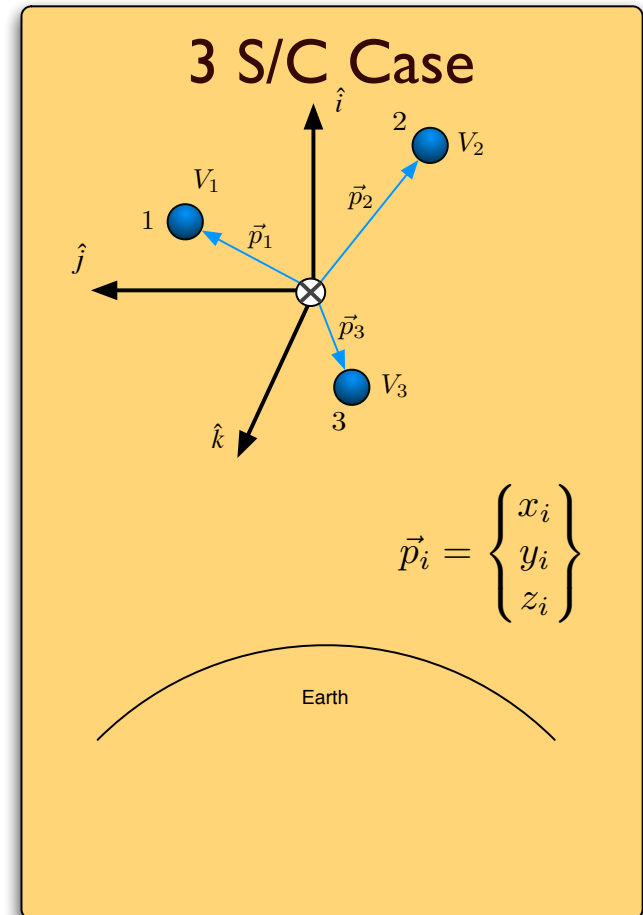
$$m(\ddot{y}_i + 2n\dot{x}_i) = k_c \sum_{j=1}^N \frac{y_i - y_j}{d_{ij}^3} q_i q_j e^{-\frac{d_{ij}}{\lambda_d}}$$

$$m(\ddot{z}_i + n^2\dot{z}_i) = k_c \sum_{j=1}^N \frac{z_i - z_j}{d_{ij}^3} q_i q_j e^{-\frac{d_{ij}}{\lambda_d}}$$

$$q_i = \frac{r_{sc}}{k_c} V_i$$

Assumptions

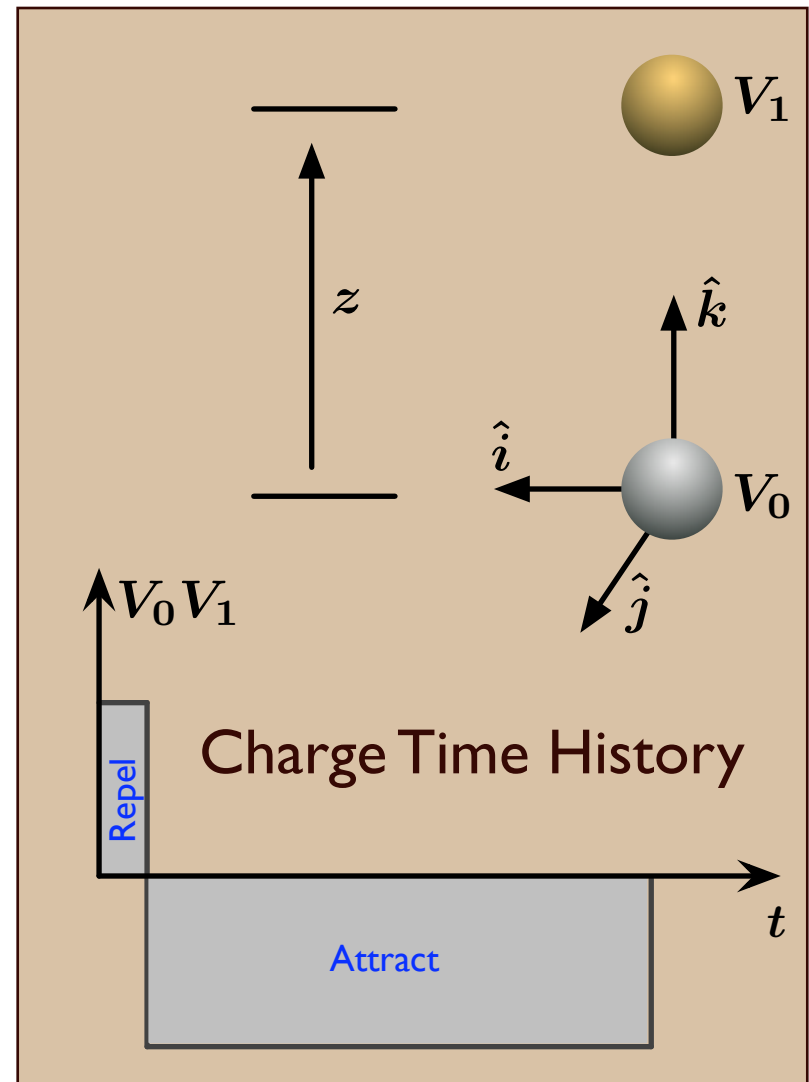
- Reference frame origin in a circular orbit
- S/C motions are small compared to orbit radius
- High order gravity terms are neglected
- External perturbations are neglected
- All S/C have the same mass



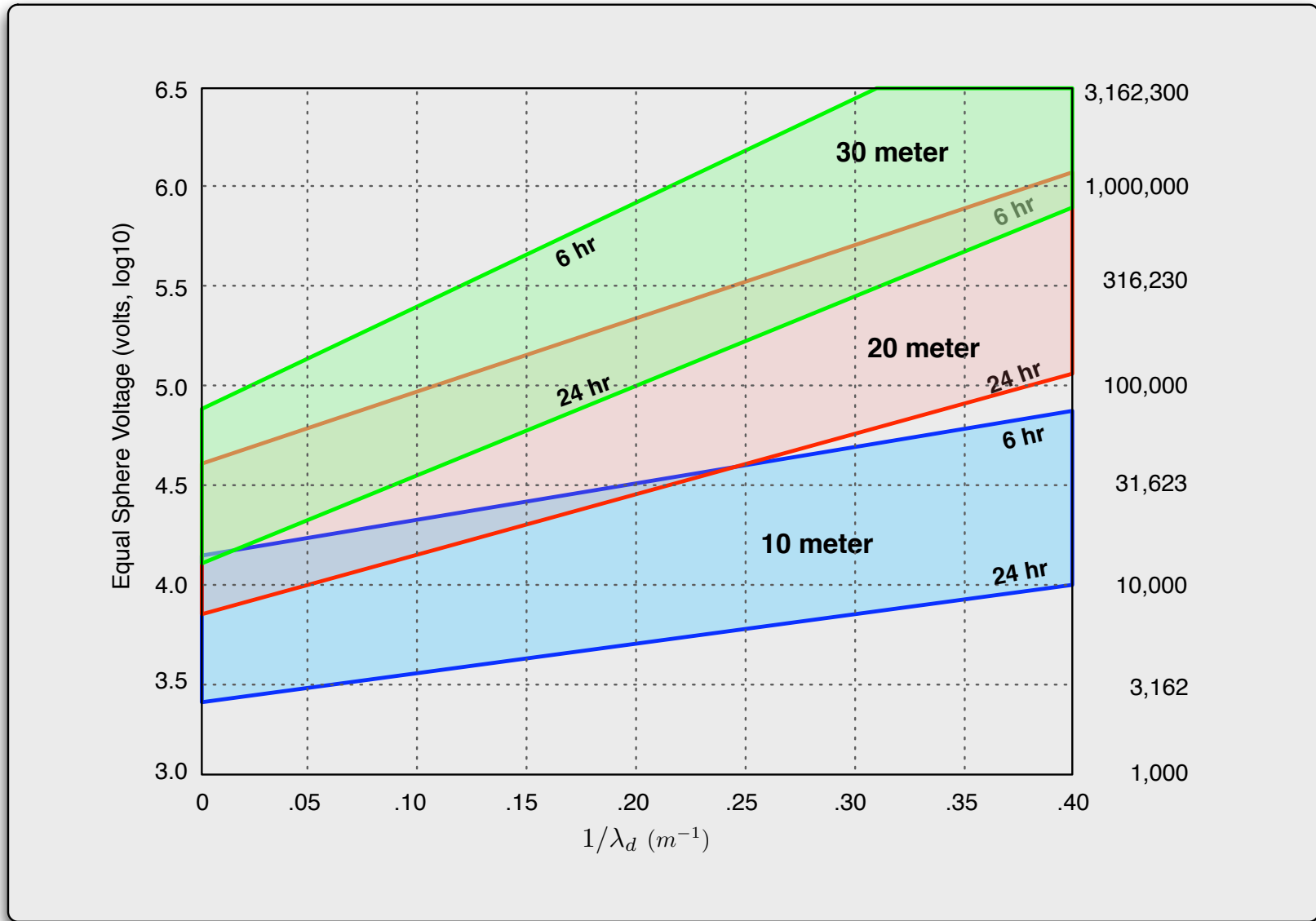
Open Loop, Z-Axis Rest-to-Rest Maneuver

$$m(\ddot{z}_i + n^2 z_i) = \frac{r_{sc}^2}{k_c z^2} V_0 V_1 e^{-\frac{z}{\lambda_d}}$$

- ➔ A single deputy s/c pushes off a chief having a fixed orbit
- ➔ Goal: deputy moves from an initial center-to-center distance of 1.5 meters to X meters in a specified time such that its speed is zero at the final time.
- ➔ Bang-bang charge time history.
- ➔ What final distances are “reasonable?”

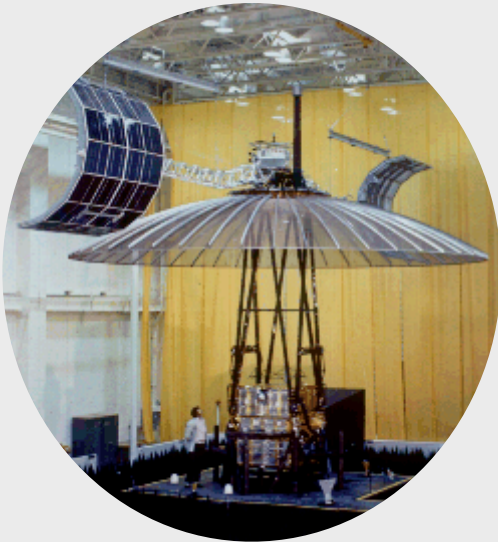


Rest-to-Rest Maneuver



Charging Capability

ATS-5,ATS-6, SCATHA



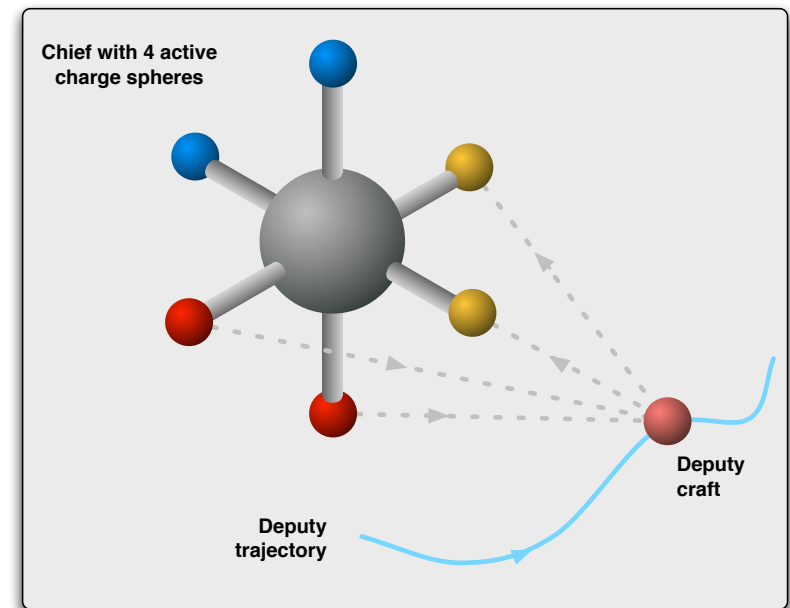
- ➔ **ATS-5, ATS-6:** Illustrated that s/c charging up to 10kV occurs.
(launchs: 1969 & 1974, orbits: GEO)
- ➔ **SCATHA:** demonstrated electron gun to modulate s/c charge within -2kv to -8kV range.
(launch: 1979, orbit: 5.5Re to 7.5Re)
- ➔ kV range, controlled “charge sphere” charging may be feasible with proper regard for isolation and differential charging.

Multiple Charge Chief

Closed-loop Deployment

- ➔ The Coulomb thrust chief craft has several charge spheres distributed around it.
- ➔ The chief has its own station keeping control system, thus the deputies that it steers can push against it.
- ➔ A switched charge strategy is used to create near-simultaneous, multiple deputy motion.

- Orbital dynamics are considered
- Debye length shielding is considered



Closed Loop Control

Any desired force vector can be applied to a deputy. A force control law that provides specifiable closed loop performance is:

$$\vec{f}_d = \begin{Bmatrix} -2n\dot{y}_1 - 3n^2x_1 \\ 2n\dot{x}_1 \\ n^2z_1 \end{Bmatrix} + K_p (\vec{p}_{1d} - \vec{p}_1) - K_d \vec{v}_1$$

Since there can be more than 3 spheres on the chief, the charge solution is in general underdetermined. A minimum norm solution can be used to help reduce the charge needed.

$$\vec{q} = W^{-1} B^T (B W^{-1} A^T)^{-1} \vec{f}_d$$

The j th column of B is derived from the N craft Coulomb equations.

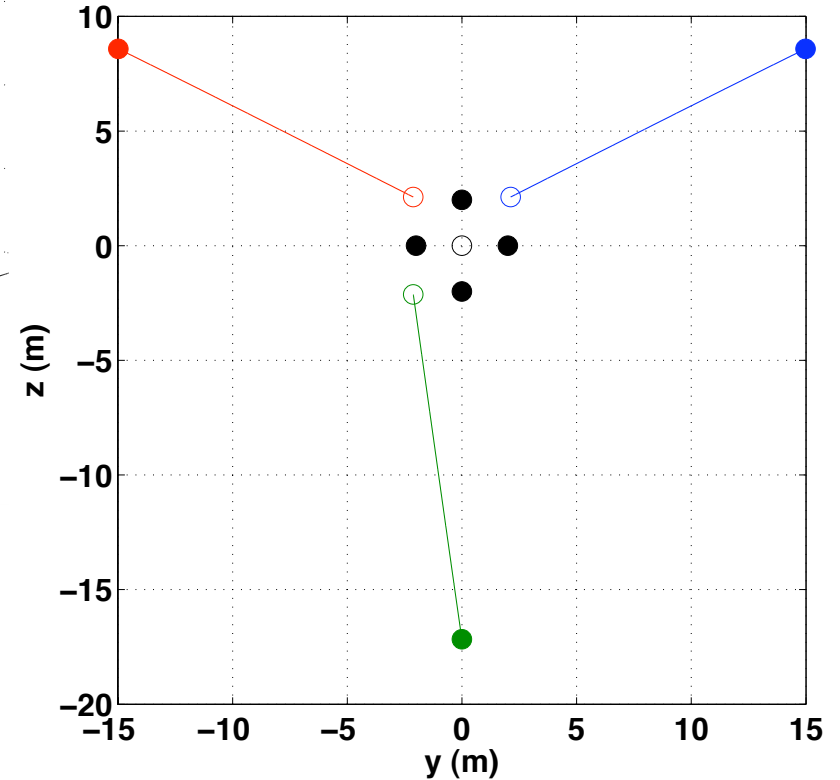
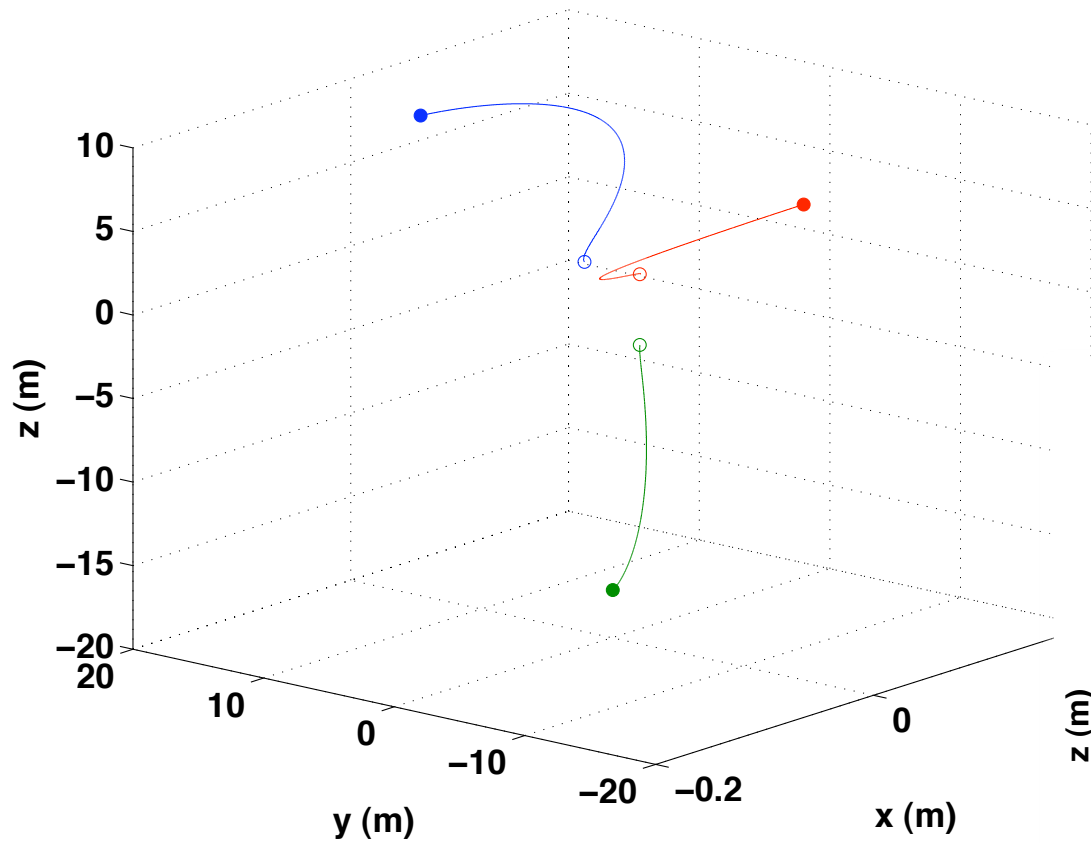
$$\vec{B}_j = k_c (\vec{p}_1 - \vec{p}_j) \cdot \left(\frac{d^{-\frac{d_{ij}}{\lambda_d}}}{d_{ij}^3} \right) q_1$$

Example

- ➔ The chief has 6 charge spheres.
- ➔ 3 deputies (mass = 50kg) are initially located near the chief and are to be deployed to lie on a circle as viewed from Earth with s/c separations of 30 meters.
- ➔ The piecewise constant deputy charge is 20kV
- ➔ Deputies and charge sphere radii are all 0.5 meters
- ➔ Debye length is 100 meters
- ➔ Control authority is cycled between deputies every 5 minutes

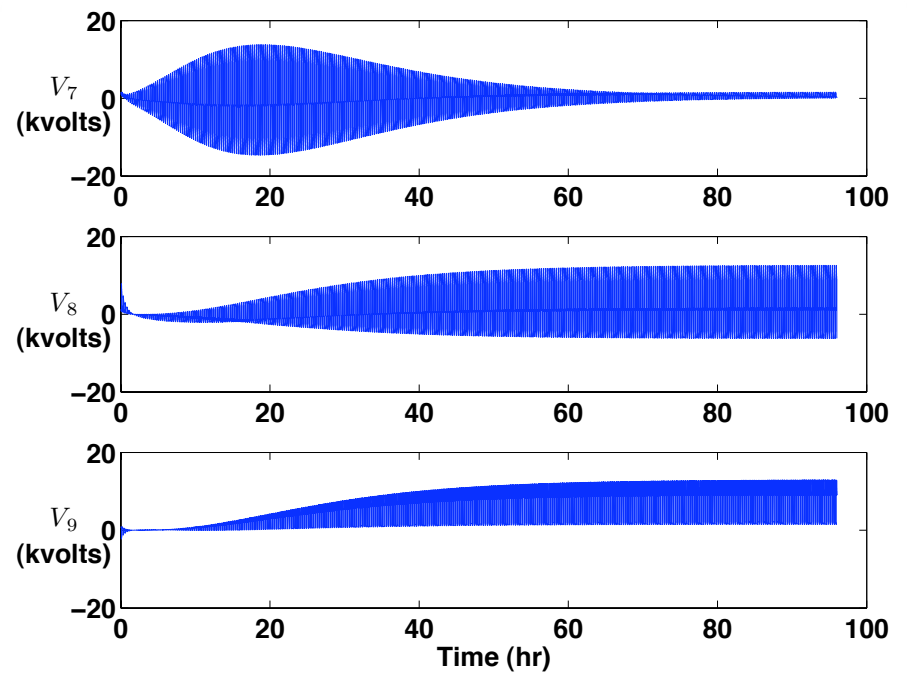
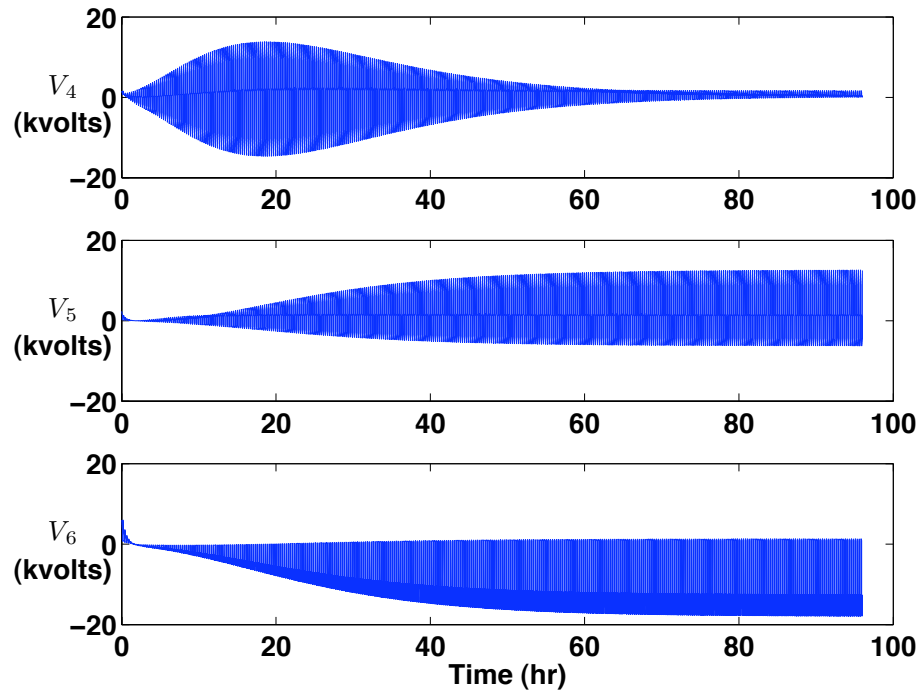
Simulation Results

Deputy Trajectories



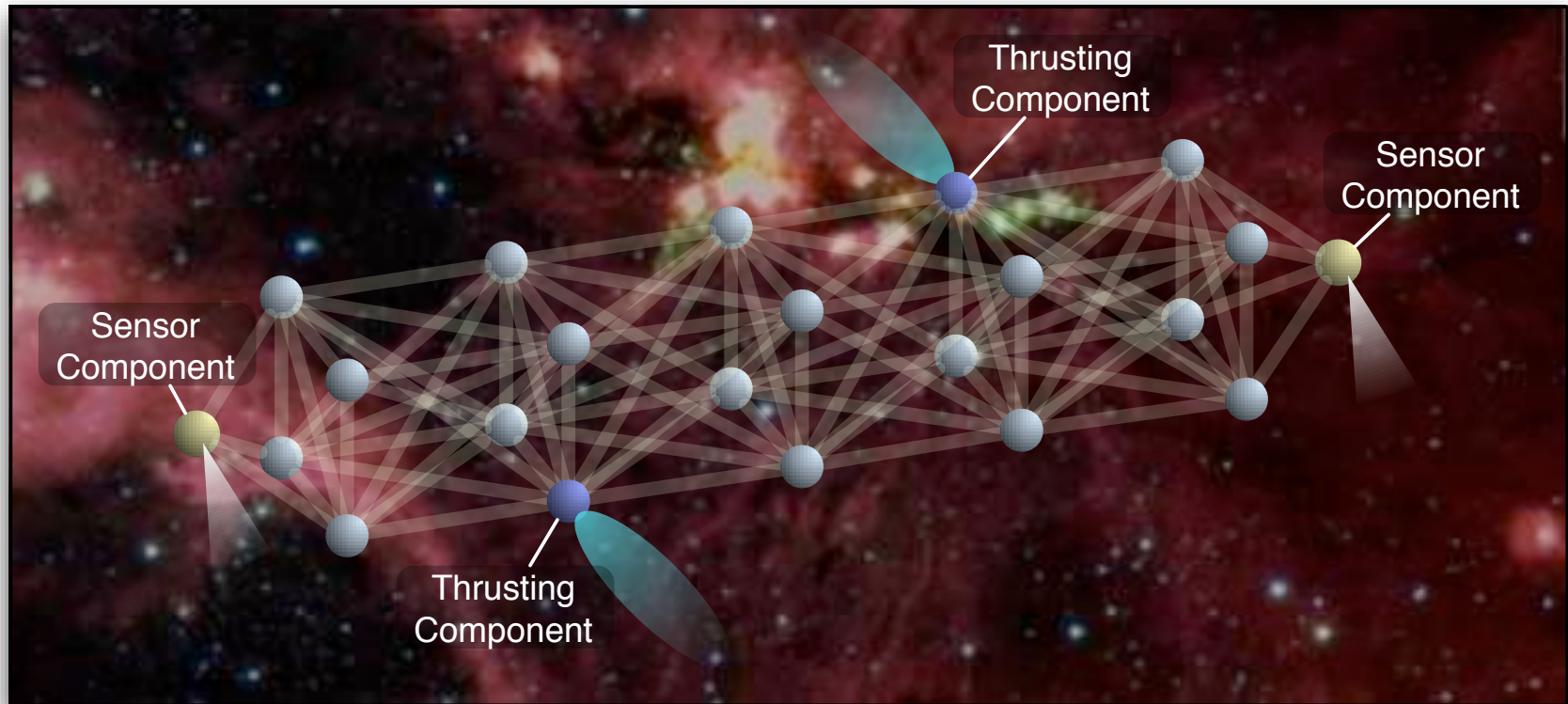
Simulation Results

Sphere Charges



Multiple Charge Chief Summary

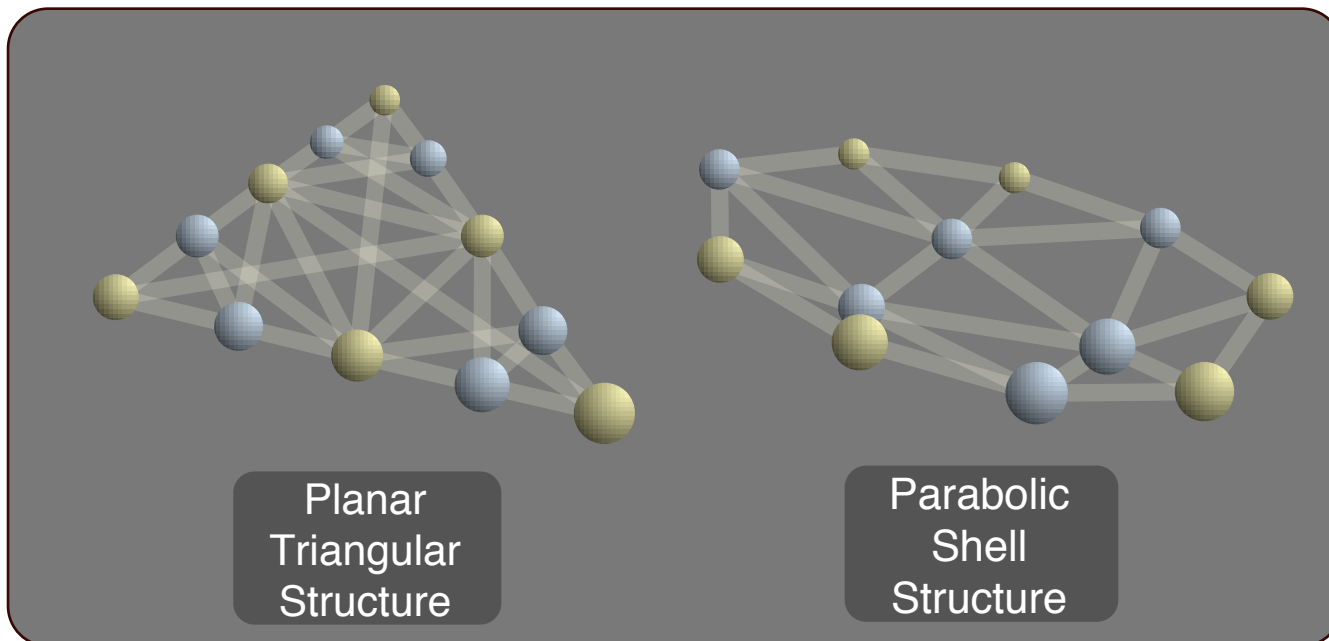
- ➔ Increasing the number of charge spheres decreases the maximum required charge -- larger distances can be achieved without increased control law complexity
- ➔ Attitude control can also be implemented to **deputies** with multiple charge spheres.



Static Structures

Virtual Structures

Conventional space structures use physical connections. A Coulomb force structure uses Coulomb forces alone to maintain the shape. By changing the charges, reconfiguration can be achieved.



In general, a Coulomb structure requires more “charge nodes” than a conventional structure.

Equation Normalization

- ➔ The optimization process must select both distance and voltage variables which are different by several orders of magnitude
- ➔ Generate families of solutions over arbitrary Debye length and node-to-node distance

$$\tilde{x}_i = \frac{x_i}{M\lambda_d} \quad \tilde{y}_i = \frac{y_i}{M\lambda_d}$$

$$\tilde{z}_i = \frac{z_i}{M\lambda_d}$$

$$\tilde{V}_i = \frac{r_{s/c}}{n\sqrt{m}(M\lambda_d)^3 k_c} V_i$$

$$0 = \sum_{j=1}^N \frac{\tilde{y}_i - \tilde{y}_j}{\tilde{d}_{ij}^3} \tilde{V}_i \tilde{V}_j e^{-M\tilde{d}_{ij}}$$

$$-3\tilde{x}_i = \sum_{j=1}^N \frac{\tilde{x}_i - \tilde{x}_j}{\tilde{d}_{ij}^3} \tilde{V}_i \tilde{V}_j e^{-M\tilde{d}_{ij}}$$

$$\tilde{z}_i = \sum_{j=1}^N \frac{\tilde{z}_i - \tilde{z}_j}{\tilde{d}_{ij}^3} \tilde{V}_i \tilde{V}_j e^{-M\tilde{d}_{ij}}$$

Cost Function

Keeps the node charges similar

Encourages the correct shape

$$J = \left(\frac{\max |\tilde{V}_i|}{\min |\tilde{V}_i|} \right) \sum_{i=1}^N |\tilde{R}_i| + w_1 S(\tilde{p}_i, L_p) + w_2 \{ |I_{xy}| + |I_{xz}| + |I_{yz}| \}$$

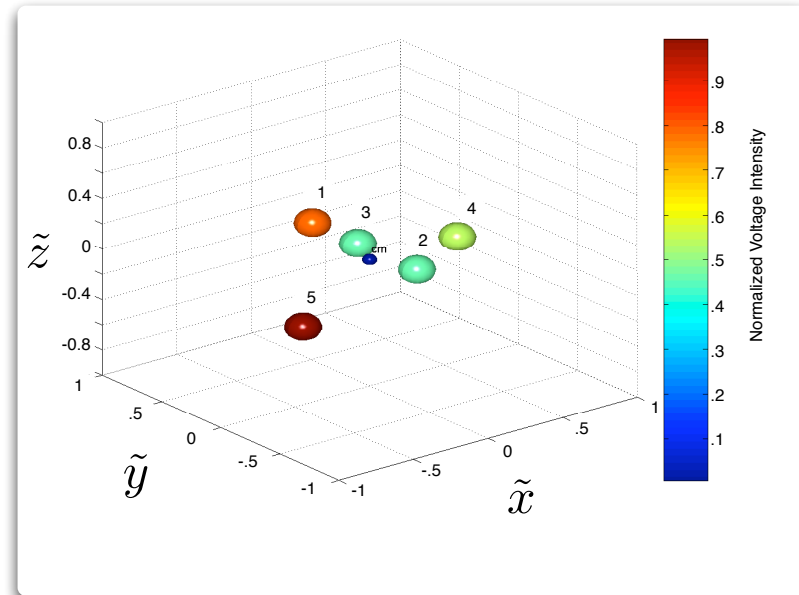
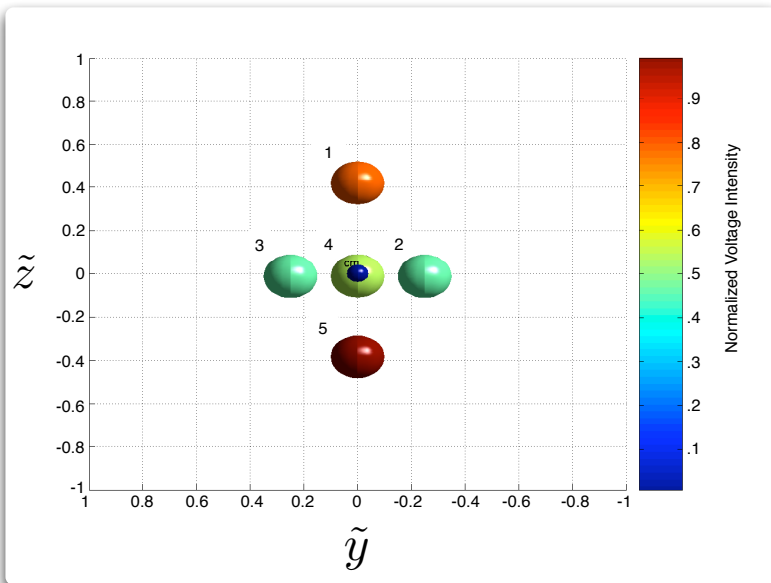
Encourages satisfaction of the equilibrium equations by reducing residuals

Helps convergence by encouraging principal axis necessary condition

Example

➔ Create a structure such that 3 nodes form an equilateral triangle when projected onto the y - z Hill frame.

➔ 5 nodes



With a node radius of 0.5 meters, the max. voltage across all nodes, as a function of side length, was:

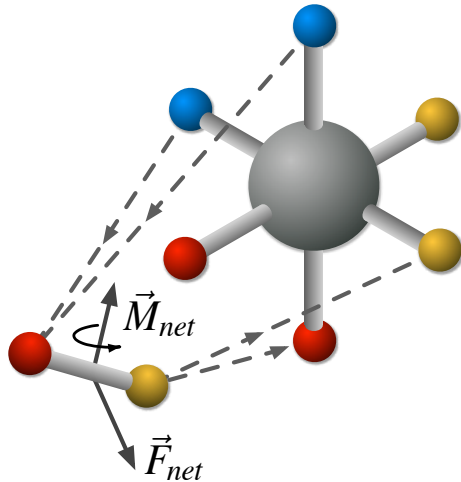
12 meters --> 16kV

25 meters --> 56kV

Summary

- ➔ Coulomb charge forces can be used for several applications including
 - ➔ reconfigurable structures
 - ➔ nanosat deployment
- ➔ At GEO altitudes, Coulomb operations are possible with 10s of meters of s/c separation
- ➔ Coulomb operations are not practical in LEO
- ➔ The coupled s/c dynamic equations are nonlinear. However, control approaches are made tractable by sequencing control authority between pairs of s/c

Future Work: Deployment

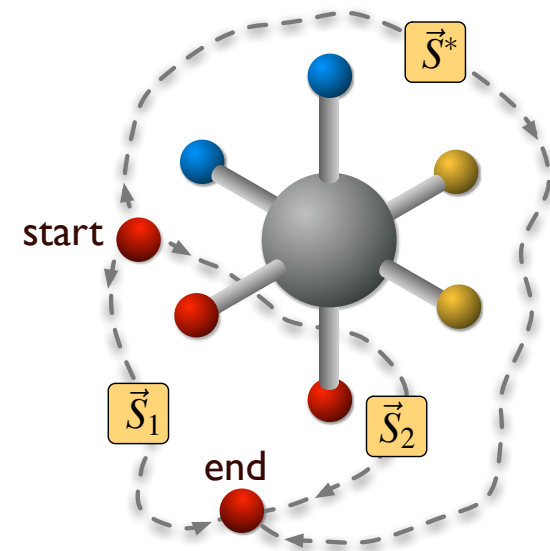


Transition to more realistic S/C geometries, and incorporate attitude deployment (e.g. spin or fixed attitude).

- control law development
- simulation and analysis tools for nonuniform charged bodies

Deployment envelope can be enlarged (lower voltages) by using optimal paths exploiting orbital dynamics.

- *a priori* trajectory optimization
- real-time trajectory optimization using nonlinear receding horizon control



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