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Advanced Space Propulsion Laboratory

Control of Spacecraft Swarms Using Coulomb Forces

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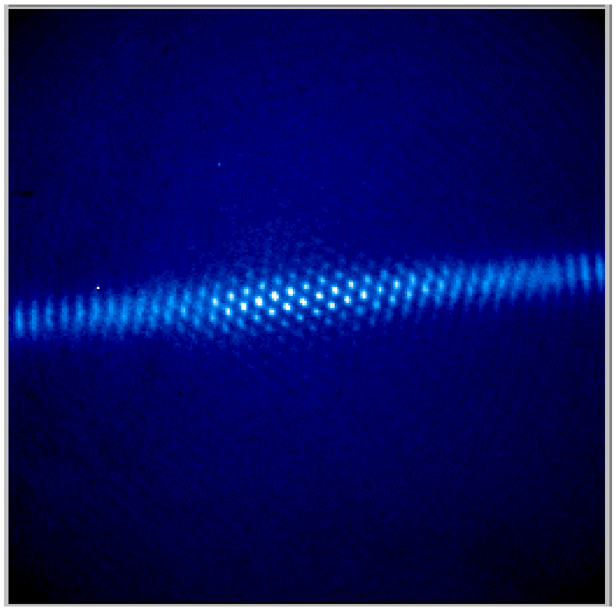
Motivation: Coulomb Clusters

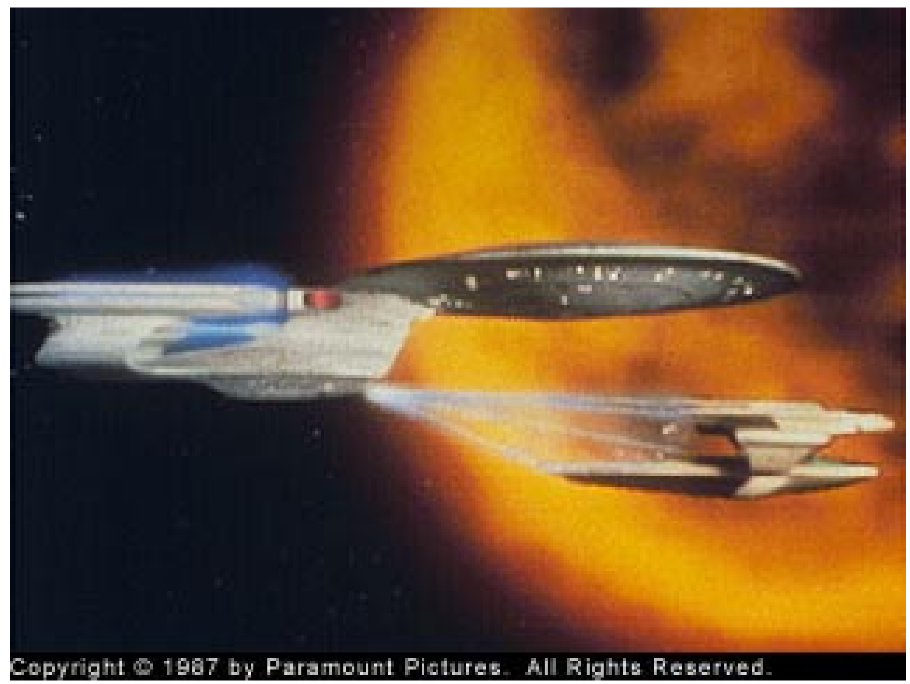
Laser-cooled trapped ion research at NIST



- Ions in $1/r^2$ confining potential form stable crystal formations

- What would charged spacecraft do in a gravity potential?

"How to build a tractor beam
Without gravitons"



Presentation Overview

- Introduction to formation flying
- Space-based imaging and interferometry
- Formation propulsion requirements
- Spacecraft charging as control force
- Coulomb force metrics
- Coulomb formation orbital dynamics

Space-based Imaging Concepts

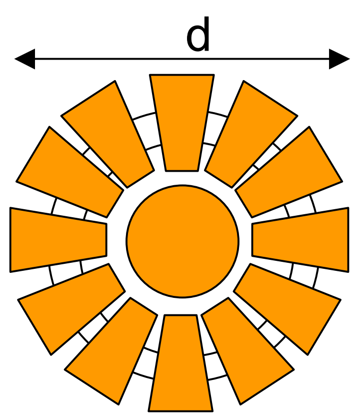
<u>Space-based imaging problem:</u>

- Image resolution limited by size of aperture: $\theta = \lambda / d$

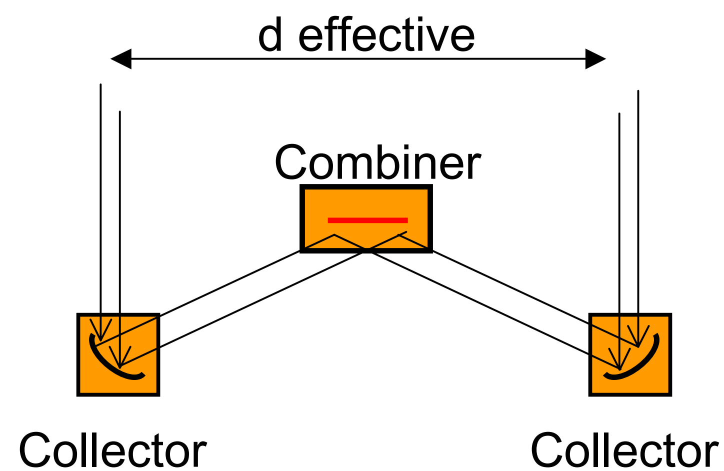
  …but…

- Spacecraft size limited by launch vehicle fairing (~ 4m)

Solution #1:
Deployable structure

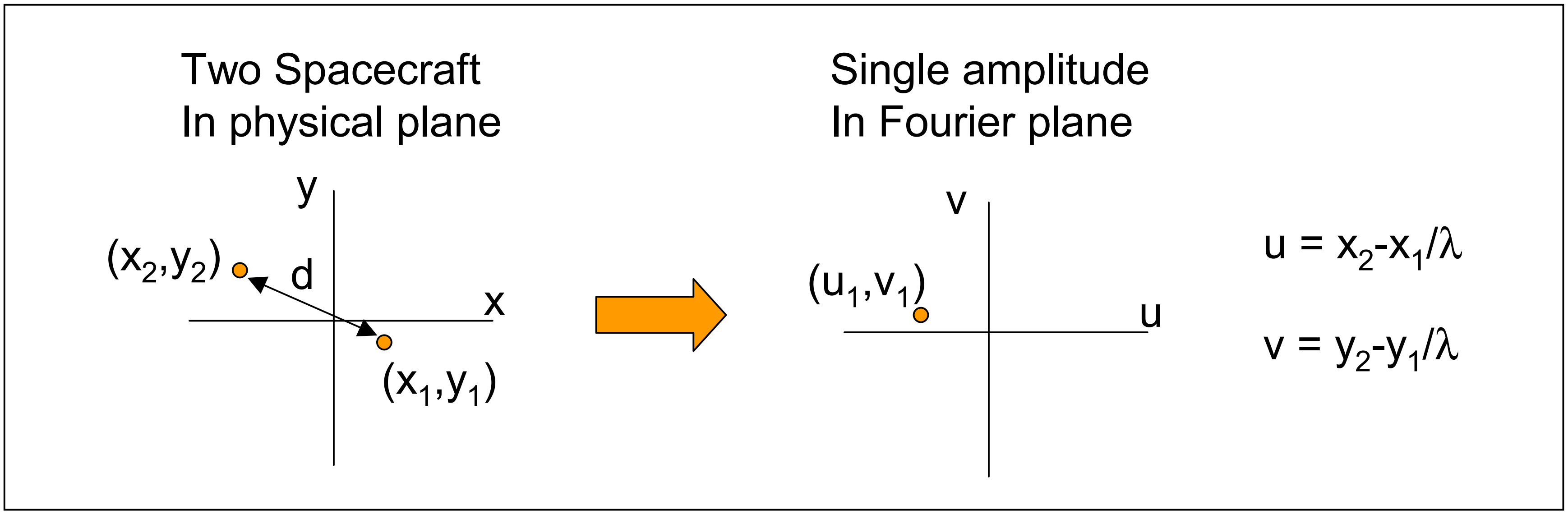


Solution #2:
Separated Interferometer



Interferometry Basics

- Spatial frequencies in the image are given by u,v points
- Each unique physical separation yields amplitude at one u,v point



Inverting Spatial Frequency → Spatial Amplitude → Image

To perform the inversion we need to fill the u,v plane

Finite apertures can fill-in Holes in u-v plane

Physical Plane | Fourier Plane

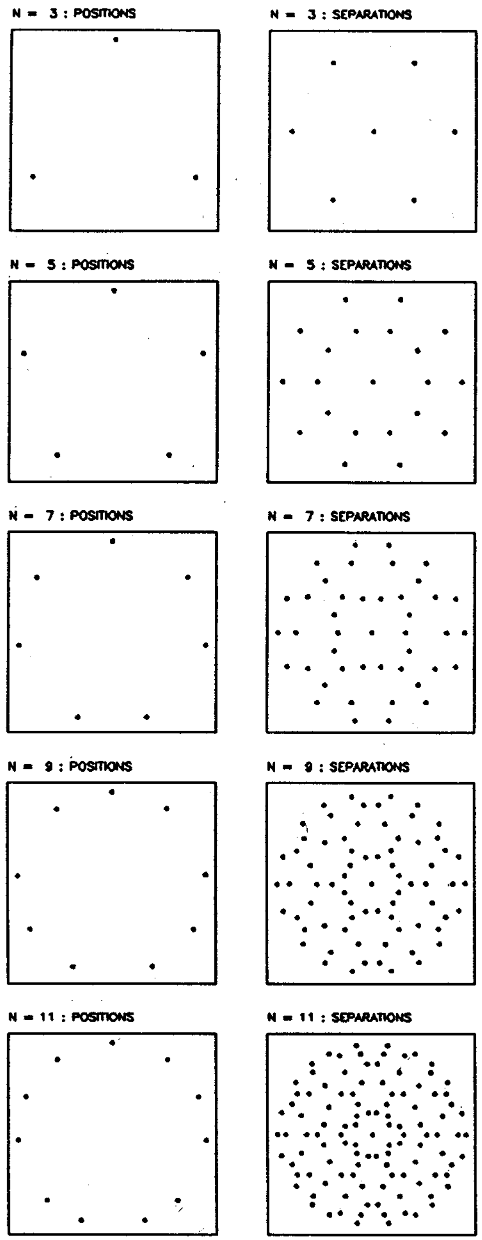
3 Spacecraft

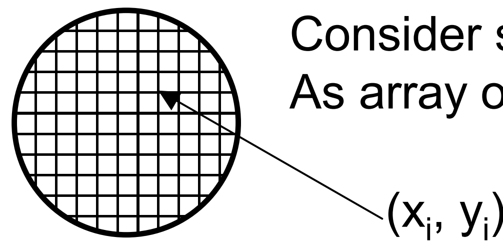
5 Spacecraft

7 Spacecraft

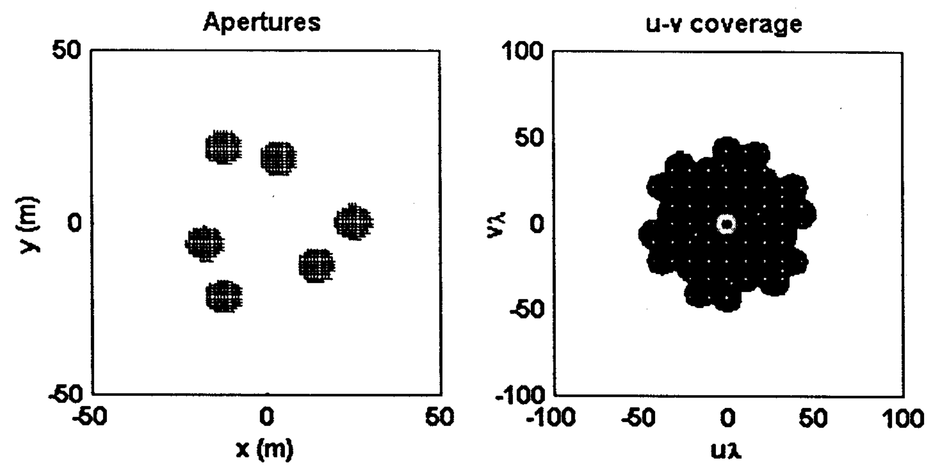
9 Spacecraft

11 Spacecraft





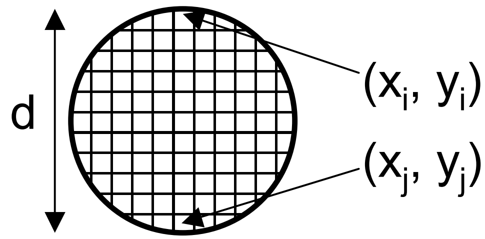
Consider single aperture
As array of sub-apertures



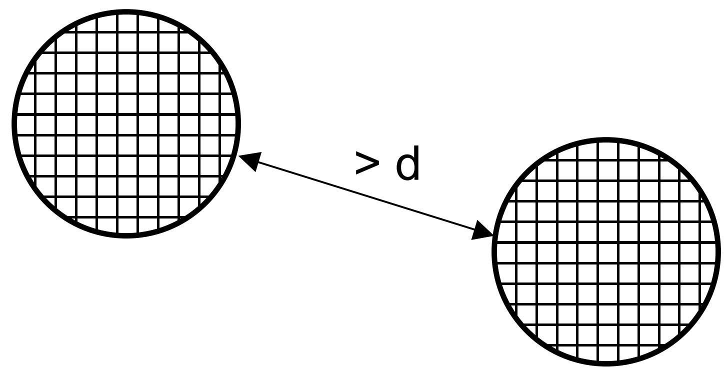
•Kong, E.M., *"Optimal Trajectories and Orbit Design for Separated Spacecraft Interferometry," Master's Thesis, MIT Dept. of Aeronautics and Astronautics, November, 1998.*
•Cornwell, T.J., *"A Novel Principle for Optimization of the Instantaneous Fourier Plane Coverage of Correlation Arrays," IEEE Trans. On Antennas and Propagation, Vol. 36, No. 8, 1165-1167.*

Interferometry for Formations

All separations (u,v points) less
Than d are covered by a single aperture



Separations (u,v points) greater than d
Must come from separated spacecraft



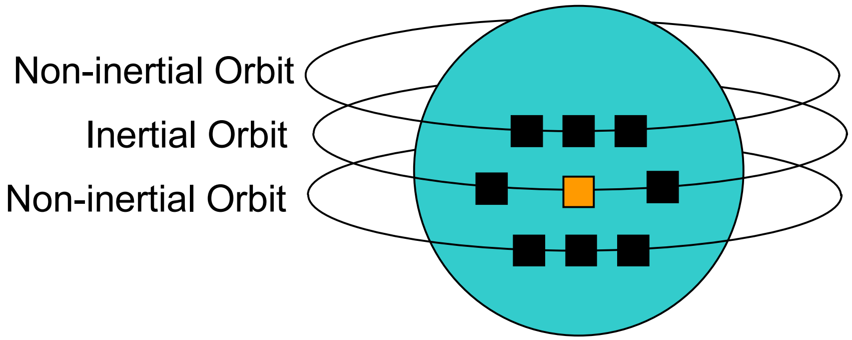
<u>Implication:</u>

- To provide seamless u,v coverage spacecraft must fly within close proximity (~ d) of each other

Formation Flying Introduction

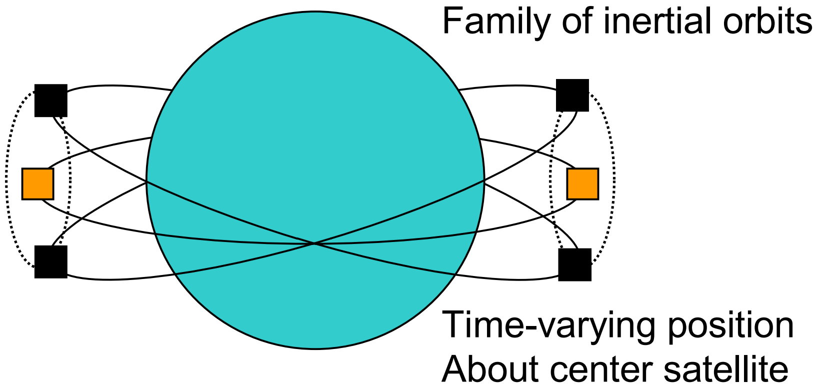
Optimal imaging configurations yield non-optimal orbital trajectories

Rigid Formation



- Requires constant thrust
- Good imaging properties

Dynamic Formation



- Thrust only for error correction
- Complicated imaging

Propulsion Requirements

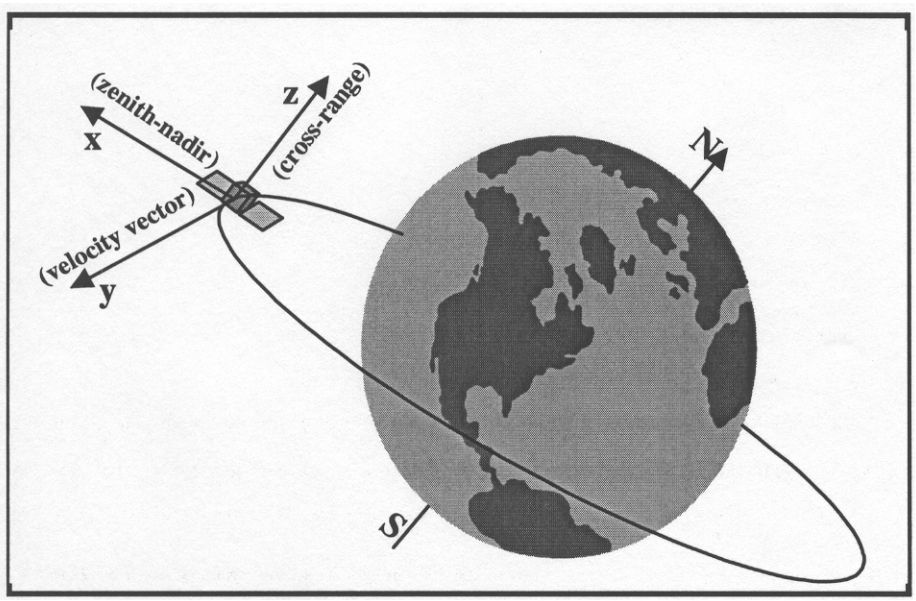


Figure reprinted from Kong, E.M., "Optimal Trajectories and Orbit Design for Separated Spacecraft Interferometry," Master's Thesis, MIT Dept. of Aeronautics and Astronautics, November, 1998.

Hill's Equations for Formation

$$\frac{F_x}{m} = \ddot{x} - 3\Omega^2 x - 2\Omega\dot{y}$$

$$\frac{F_y}{m} = \ddot{y} + 2\Omega\dot{x}$$

$$\frac{F_z}{m} = \ddot{z} + \Omega^2 z$$

Ω = angular velocity (for GEO Ω =7.3x10^{-5} rad/sec)

For rigid formation: $\ddot{x} = \dot{x} = \ddot{y} = \dot{y} = \ldots = 0$

$$F_x = -3\Omega^2 xm$$

$$F_z = \Omega^2 zm$$

→ m = 100 kg, x, z ~ 10 m → $F_x \sim 16\ \mu N$, $F_z \sim 6\ \mu N$

Coulomb Control Forces

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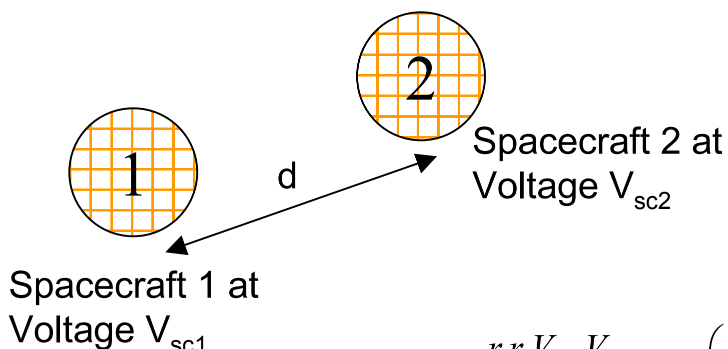
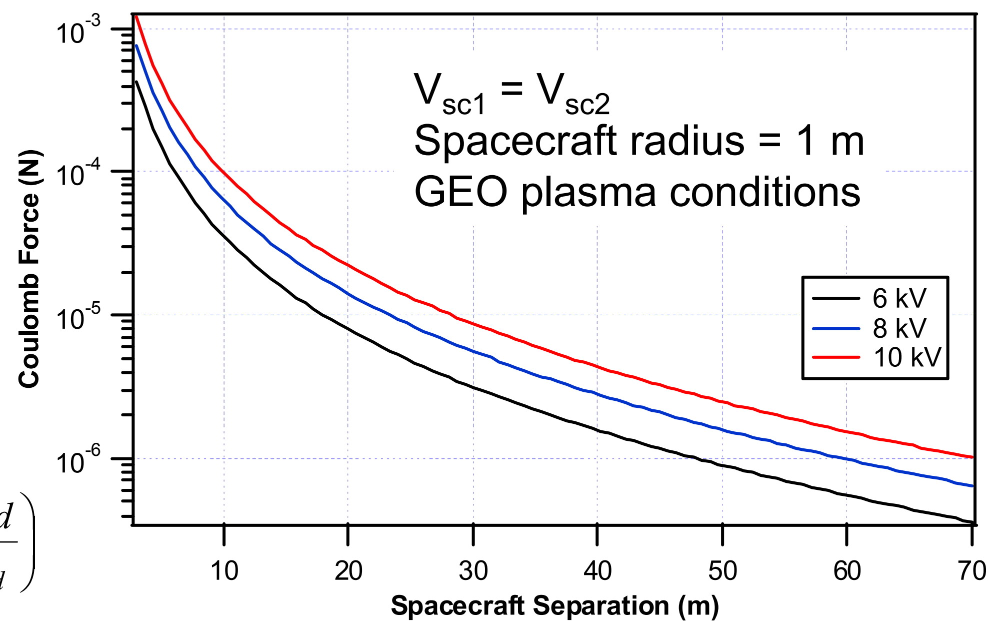
- Engineering throttleable thrusters for 10 µN is tough
- Current candidates (FEEP, Colloid) exhaust contaminants
- Collisions are of paramount concern

Is there a better way to control the formation? **Maybe!**

If the plasma Debye length is larger than spacecraft separation, Coulomb forces could be used

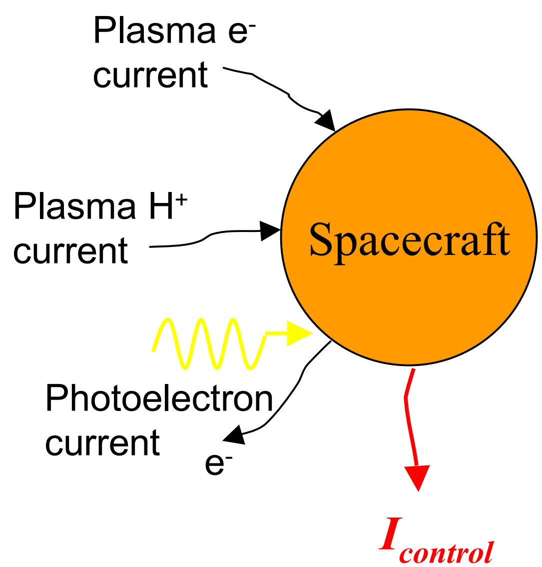


$$F_{1,2} = 4\pi\varepsilon_o \frac{r_1 r_2 V_{sc1} V_{sc2}}{d^2} \exp\left(\frac{-d}{\lambda_d}\right)$$



Spacecraft Charging

For equilibrium, Mother Nature adjusts spacecraft voltage such that net current is zero.



$$I_{sc} = I_e + I_i + I_{ph}$$

$$I_e = A_{sc} e n_e \left[\frac{k_B T_e}{2\pi m_e}\right]^{\frac{1}{2}} \exp\left[\frac{eV_{sc}}{k_B T_e}\right]$$

$$I_i = -A_{sc} e n_i \left[\frac{k_B T_i}{2\pi m_i}\right]^{\frac{1}{2}} \exp\left[\frac{-eV_{sc}}{k_B T_i}\right]$$

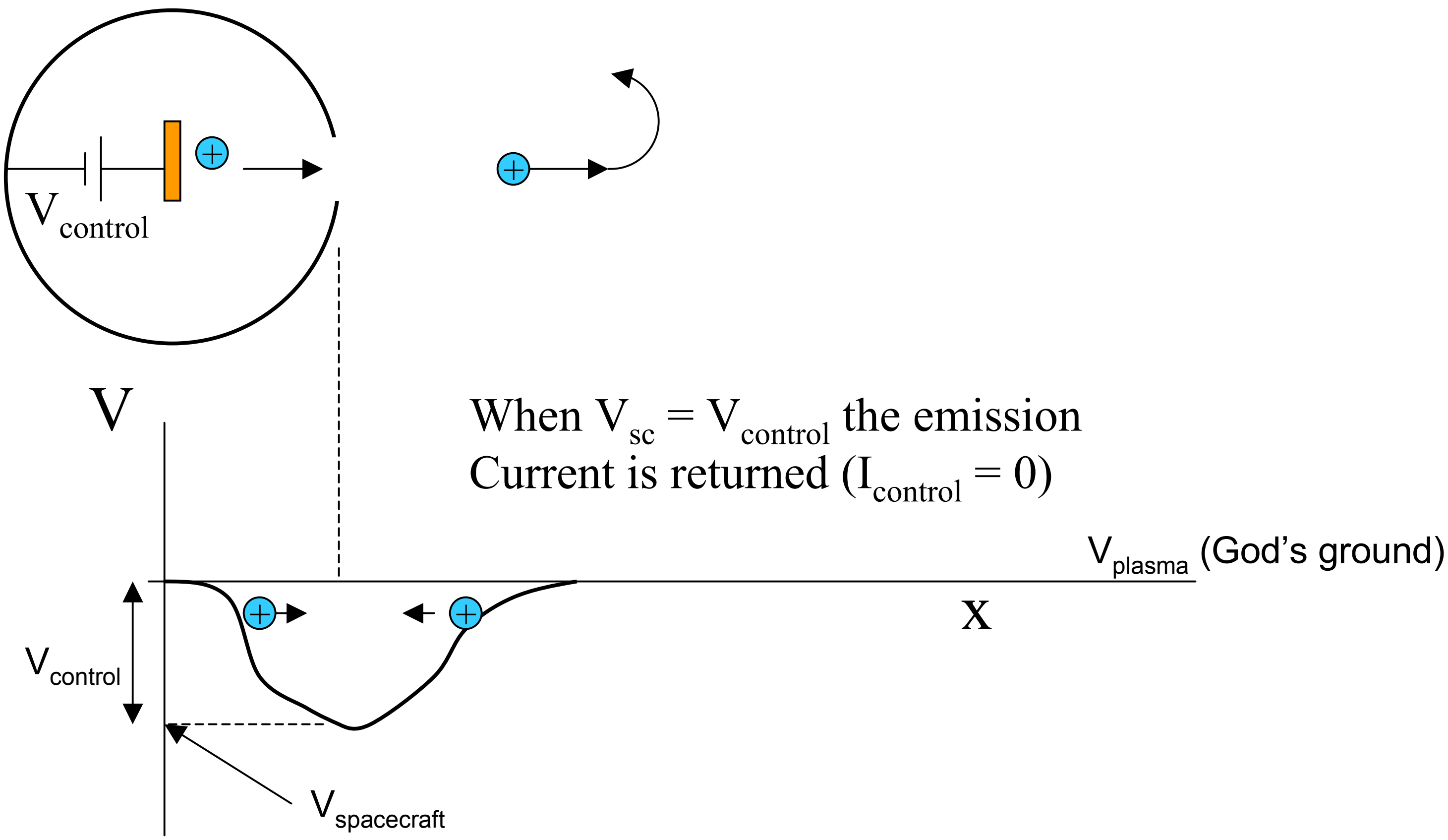
$$I_{ph} = -A_{sc} e \alpha_w I_{pe} \exp\left(\frac{-eV_{sc}}{k_B T_{pe}}\right)$$

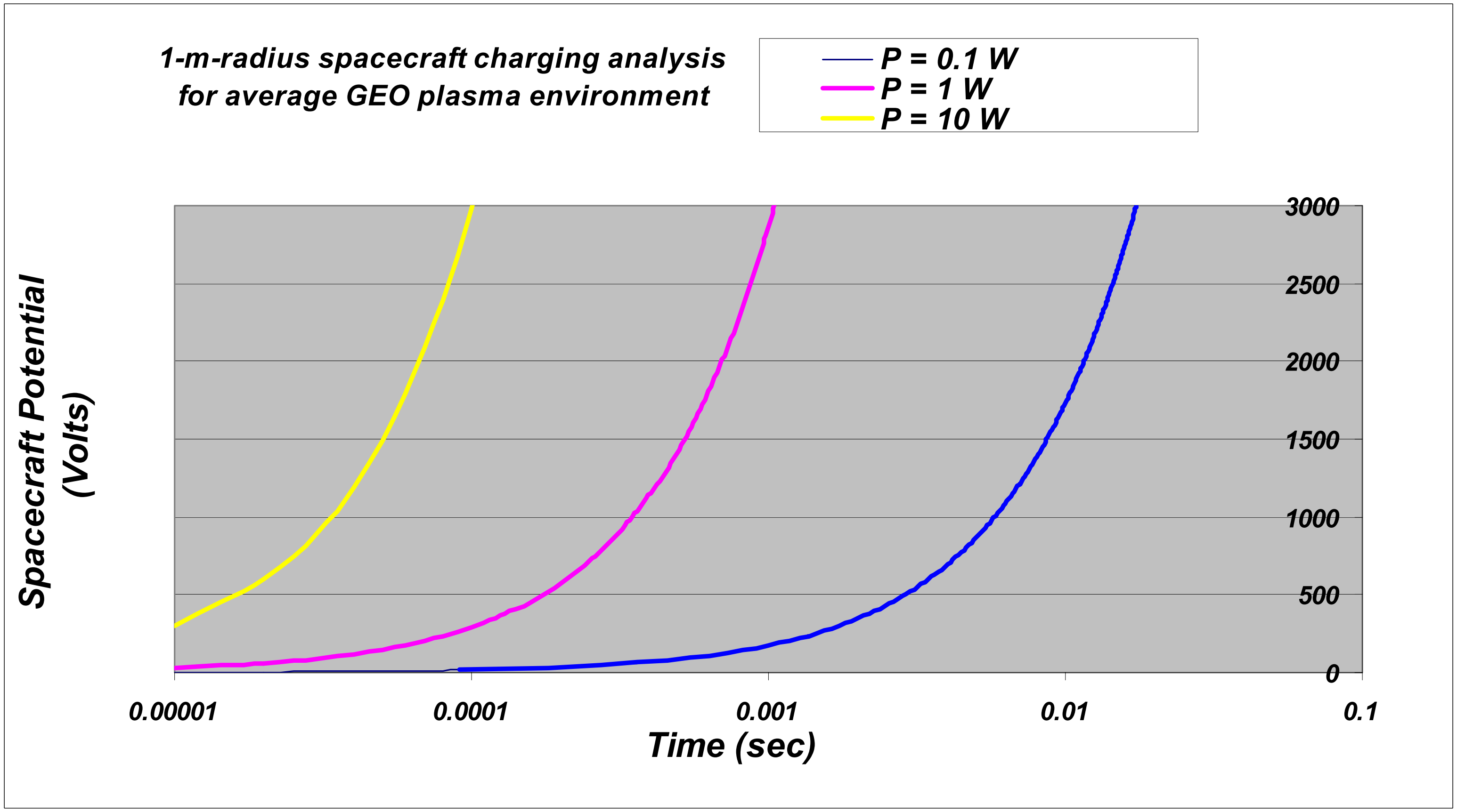
We can change the spacecraft voltage by creating a current imbalance

$$\frac{dV_{sc}}{dt} = \frac{I}{C} = \frac{I_e + I_i + I_{ph} + I_{control}}{4\pi\varepsilon_o r} \neq 0$$

Spacecraft Charge Control

- Electron emission drives V_{sc} positive
- Ion emission drives V_{sc} negative
- Spacecraft potential control is naturally stable

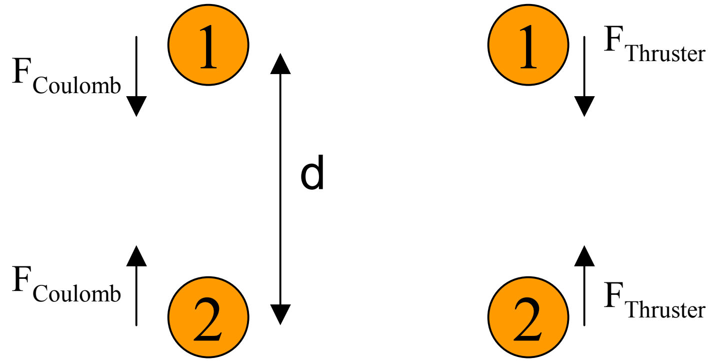




$$I_{control} = \frac{P}{V_{control}}$$

$$\frac{dV_{sc}}{dt} = \frac{I}{C} = \frac{I_{control} + 4\pi r^2 \left\{ en_e \left[\frac{k_B T_e}{2\pi m_e}\right]^{\frac{1}{2}} \exp\left[\frac{eV_{sc}}{k_B T_e}\right] - en_i \left[\frac{k_B T_i}{2\pi m_i}\right]^{\frac{1}{2}} - e\alpha_w I_{ph} \right\}}{4\pi \varepsilon_0 r}$$

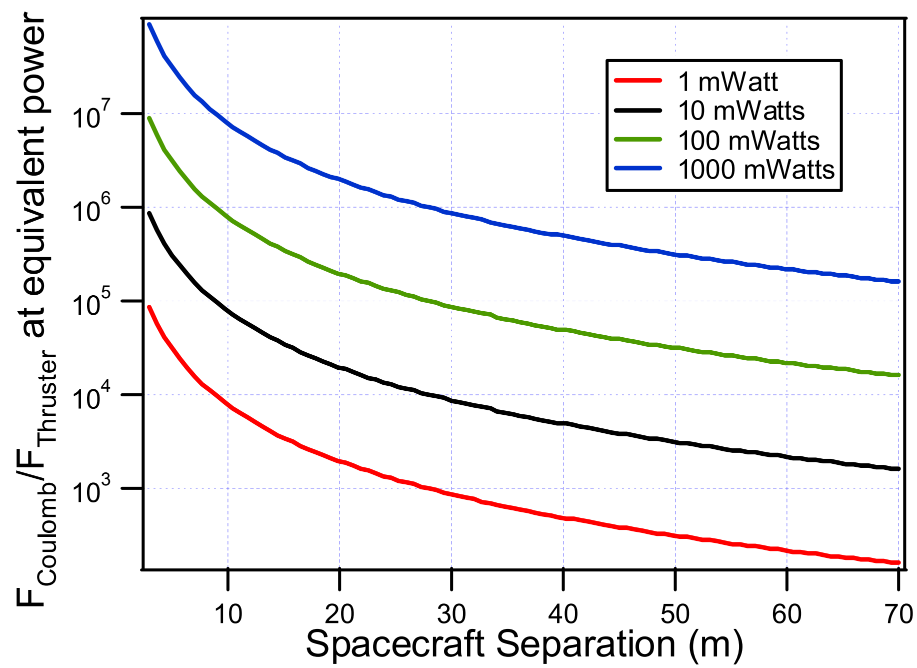
Coulomb vs. Electric Propulsion



$$F_{Coulomb} = \frac{\pi \varepsilon_o r^2 P_{Total}^2}{d^2 I_{control}^2}$$

$$F_{Thruster} = \frac{\eta P_{Total}}{2 g I_{sp}}$$

Comparison of Coulomb Control for 1-m-radius Spacecraft in average GEO plasma with FEEP Thruster technology (I_{sp} = 10,000 sec, η = 0.65)



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Mission design parameters for two-spacecraft flying in 20-m formation (located on Hill's z-axis)

MEANS OF CONTROL	COULOMB CONTROL	MICROPPT	COLLOID THRUSTER	FEEP
SPECIFIC IMPULSE (sec)	1×10^7 $I_{sp} = \frac{F}{\dot{m}g}$	500	1000	10000
EFFICIENCY	0.65	0.026	0.65	0.65
MASS OF FUEL FOR 10 YEARS (kg)	0.00003 (using H_2 for Ion source)	0.089	0.045	0.004
INPUT POWER (W)	0.031	0.261	0.021	0.209
MASS/POWER RATIO (kg/W)	0.22	0.37	0.216	0.1125
INERT MASS (kg)	0.0068	0.097	0.005	0.024
TOTAL PROPULSION SYSTEM MASS (kg)	0.00683	0.186	0.050	0.028

Coulomb Orbit Dynamics

Do formations exist for forces acting only along position vectors?

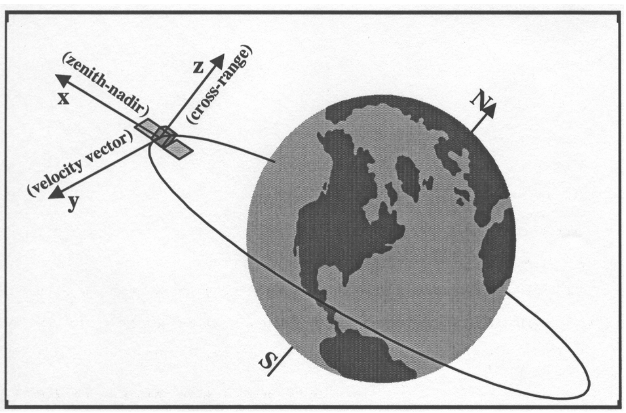
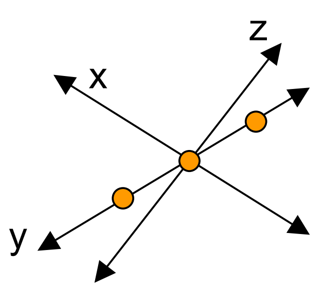
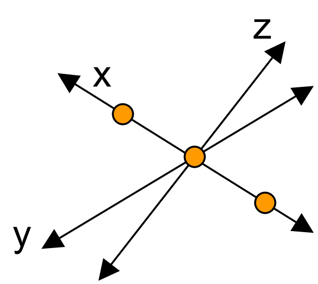


Figure reprinted from Kong, E.M., "Optimal Trajectories and Orbit Design for Separated Spacecraft Interferometry," Master's Thesis, MIT Dept. of Aeronautics and Astronautics, November, 1998.

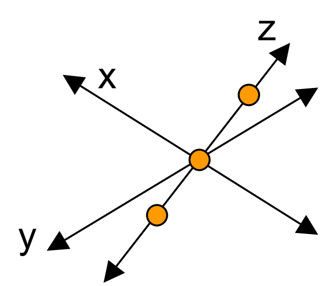
- 3-spacecraft formations considered
- 3 canonical orientations
- Hill's equations for relative motion
- GEO orbit with 10-m separation



Along-track
"leader-follower"



Zenith-nadir
"Coulomb tether"



Z-axis stack

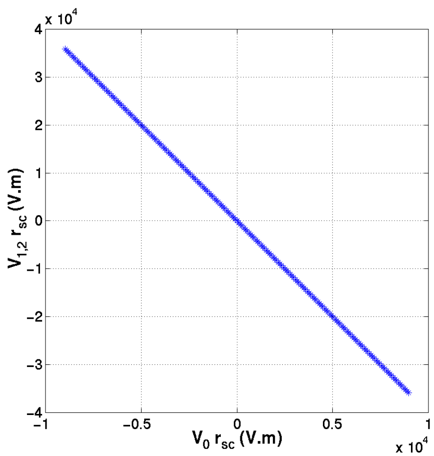
3-Spacecraft Orbital Analysis

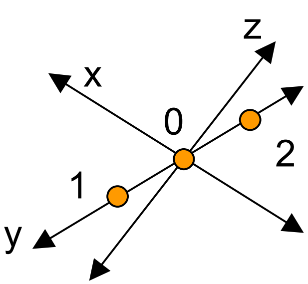
Equilibrium solutions to Hill's equations

Parameter $V_{sc}r$ is like equivalent charge:

$$V_{sc} = \frac{1}{4\pi\varepsilon_o}\frac{q_{sc}}{r}$$

$$V_{sc}r = \frac{q_{sc}}{4\pi\varepsilon_o}$$





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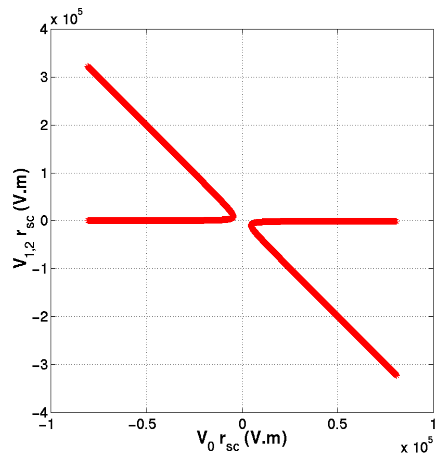

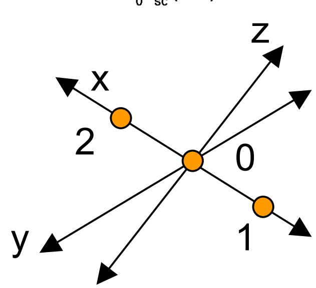

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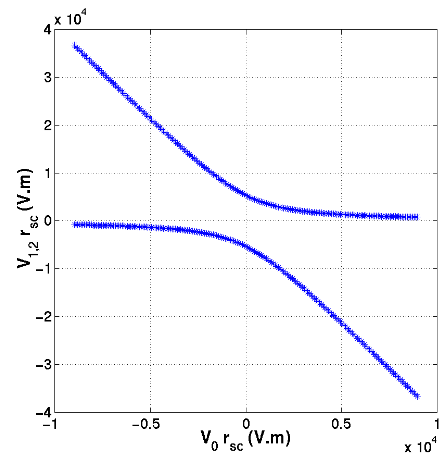
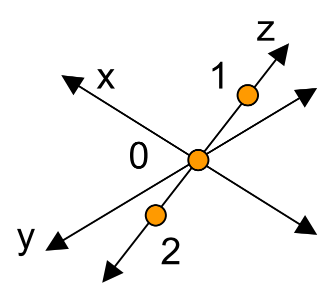
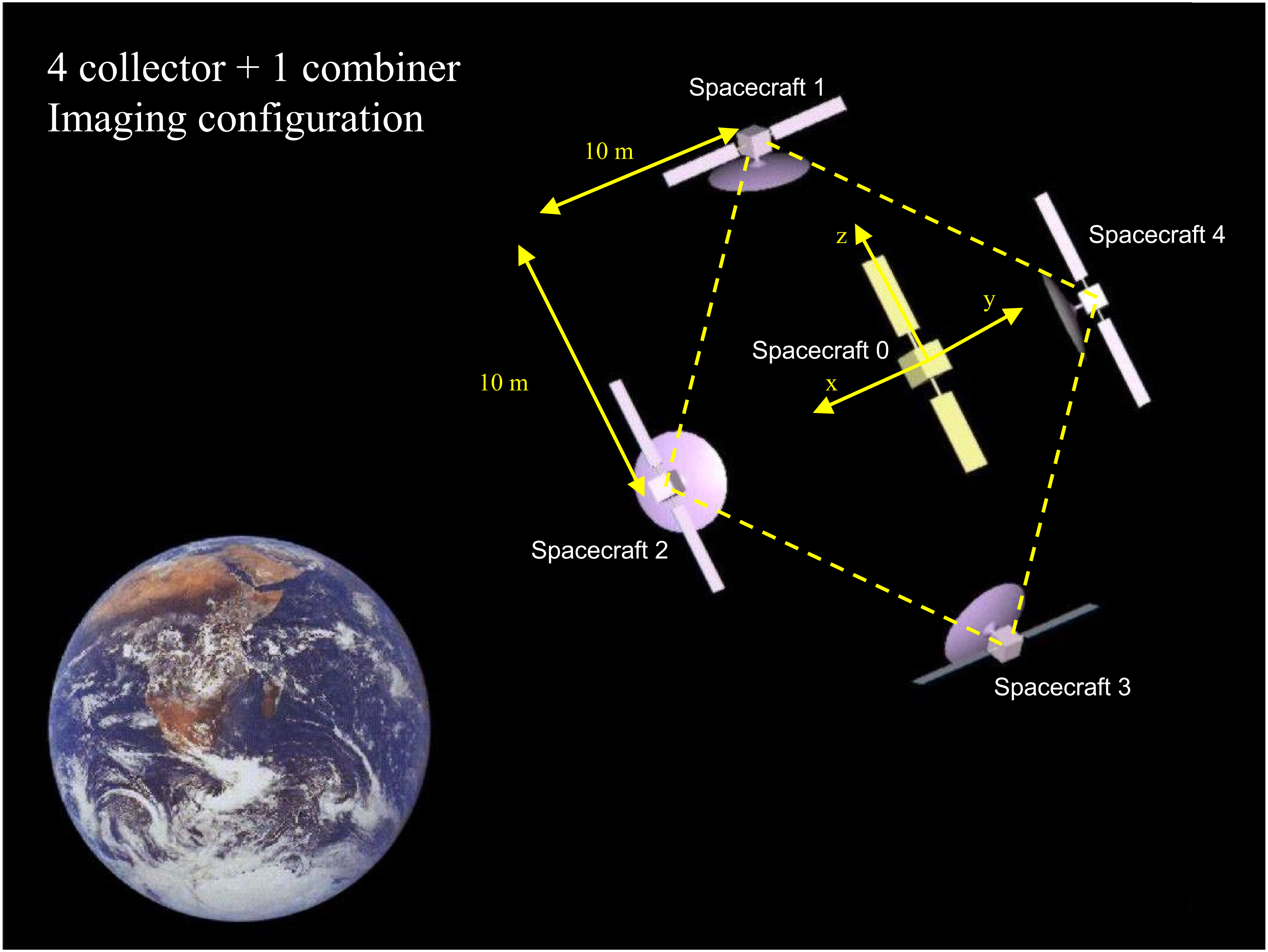
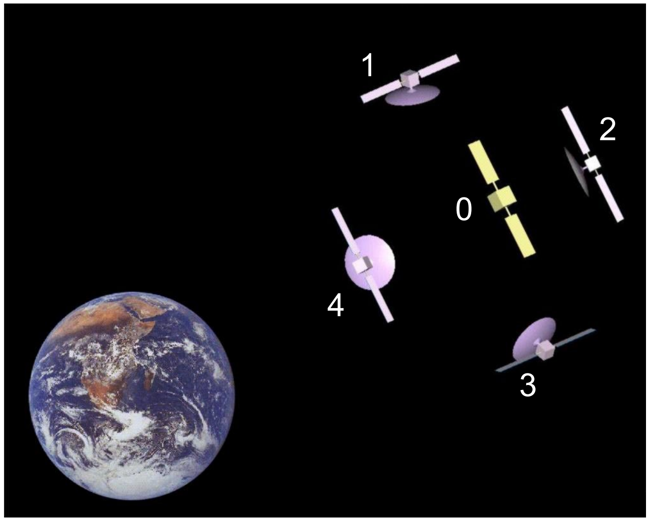




Z-axis stack

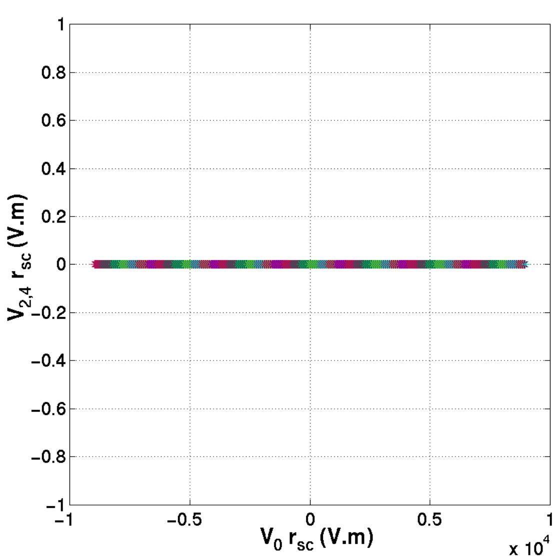

4 collector + 1 combiner
Imaging configuration
Spacecraft 1
10 m
Spacecraft 4
z
y
Spacecraft 0
x
10 m
Spacecraft 2
Spacecraft 3

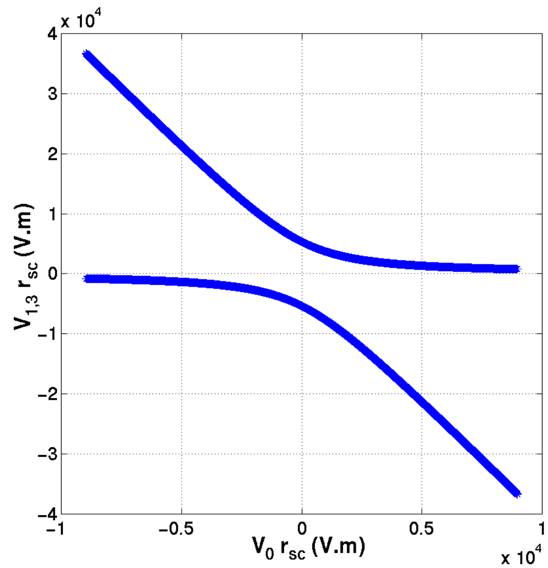
5-Spacecraft Formation



Solution Family 1

- Special case of 3-spacecraft z stack
- Vehicle 2 and 4 remain neutral

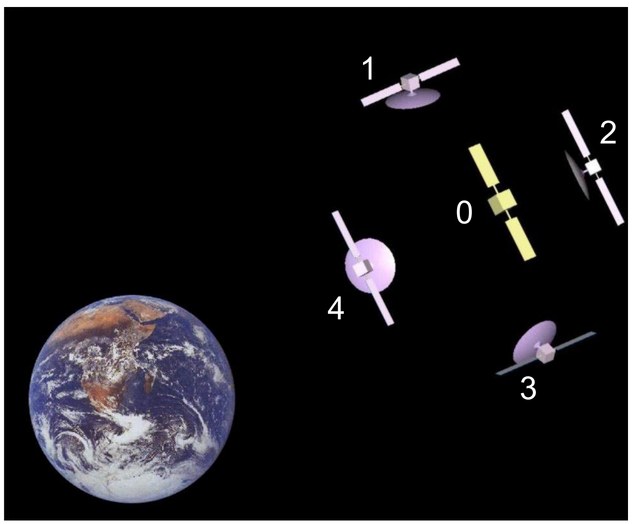


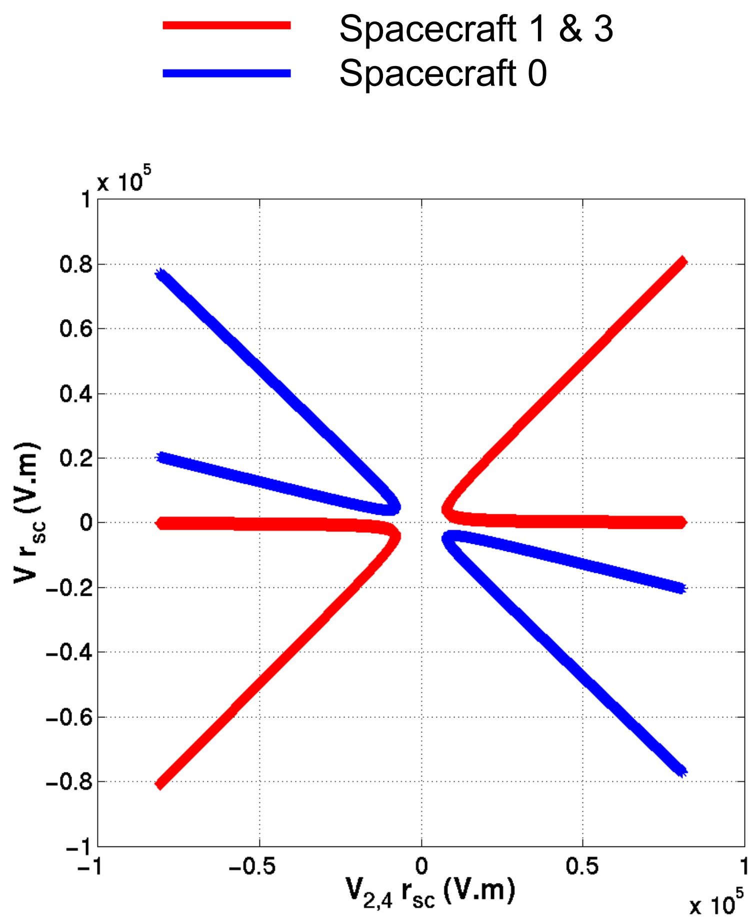


5-Spacecraft Formation

Solution Family 2

- All 5 Spacecraft charged
- Minimum $V_{sc}r$ identified





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Phase I Summary

Conclusions

- Coulomb forces comparable with best thrusters
- Continuous force dither/variation is possible
- Required charge control demonstrated as early as 1979 (SCATHA)
- Rich family of orbital solutions possible
- Particularly suited to Fizeau interferometry (visible GEO imager?)
- Coulomb control works best where thrusters work worst => synergistic control
- Coulomb control can help with collision avoidance
- Even if Coulomb is not used for control……

  natural charging will be significant perturbation that must be addressed!

On-going tasks

- Examine formations for stability
- Develop dynamic simulation
- Formulate control laws
- Search for more complicated formation solutions
- Perform vehicle sizing analysis for canonical mission