Electromagnetic Formation Flight (EMFF)

NIAC Phase I Review

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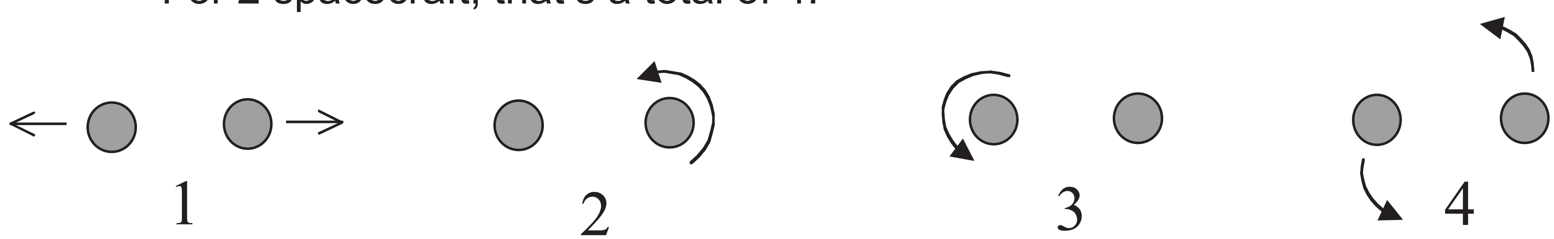
Motivation

- Traditional propulsion uses propellant as a reaction mass
- Advantages
  - Ability to move center of mass of spacecraft
    (Momentum conserved when propellant is included)
  - Independent (and complete) control of individual spacecraft
- Disadvantages
  - Propellant is a limited resource
  - Momentum conservation requires that propellant mass increase exponentially with the velocity increment (ΔV)
  - Some propellants can be a surface contaminant to precision optics and solar arrays
  - Lingering propellant clouds can obscure or blind infrared telescopes
- Is there an alternative ??

A Candidate Solution

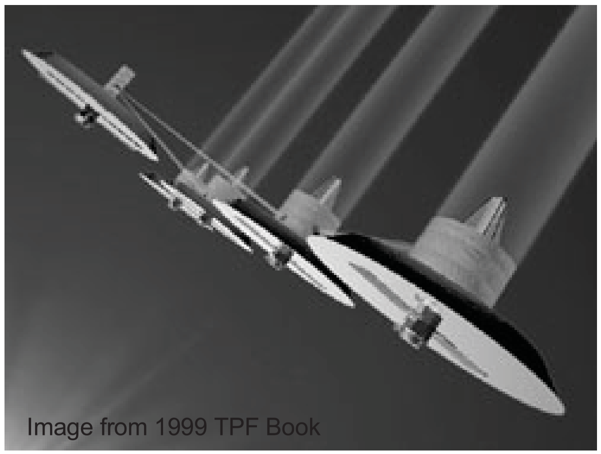
- Yes… inter-spacecraft forces can be used…
  - …provided it is not necessary to alter the center of mass motion of the system
- What forces must be transmitted between satellites to allow for all relative degrees of freedom to be controlled?
  - In *2* dimensions, *N* spacecraft have 3*N* DOFs, but we are at most able to control 3*N*-2 (no translation of the center of mass)
  - For 2 spacecraft, that's a total of 4:



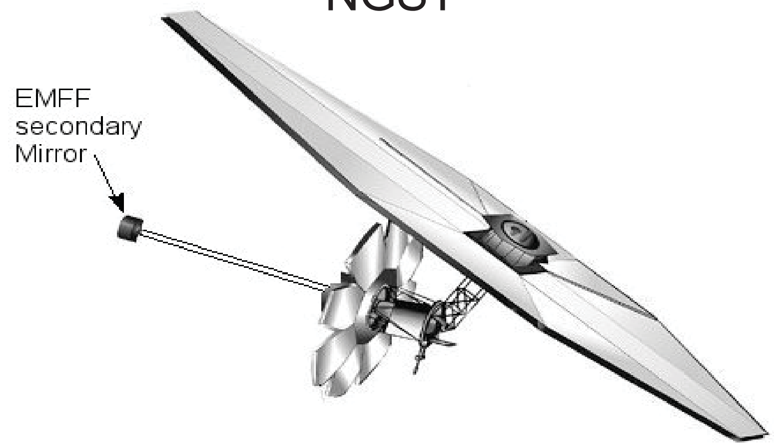
- DOFs 1-3 can be controlled with inter-spacecraft axial forces and on-board torques, but 4 requires a transverse force
- Electrostatic monopoles cannot provide this type of force, but Electromagnetic and electrostatic dipoles can!
- Tethers attached away from the center of mass of the spacecraft will also work, but that's a different project…
- So, are there missions where controlling cluster center of mass doesn't matter?

EMFF Applications in 10-20 Years

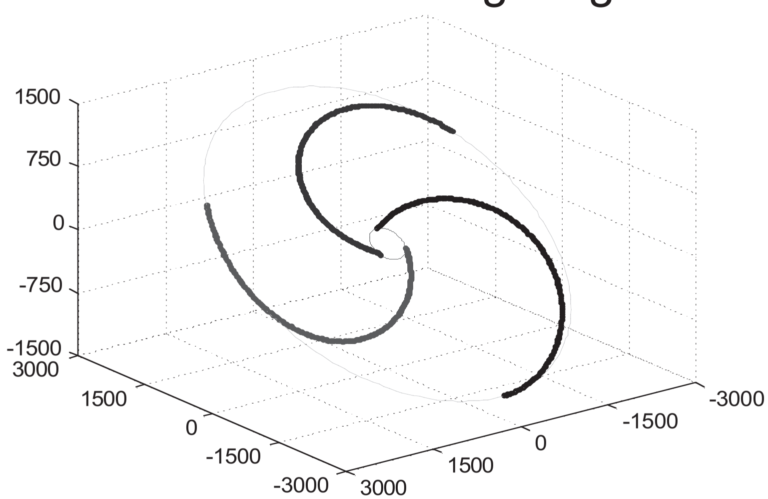
Terrestrial Planet Finder



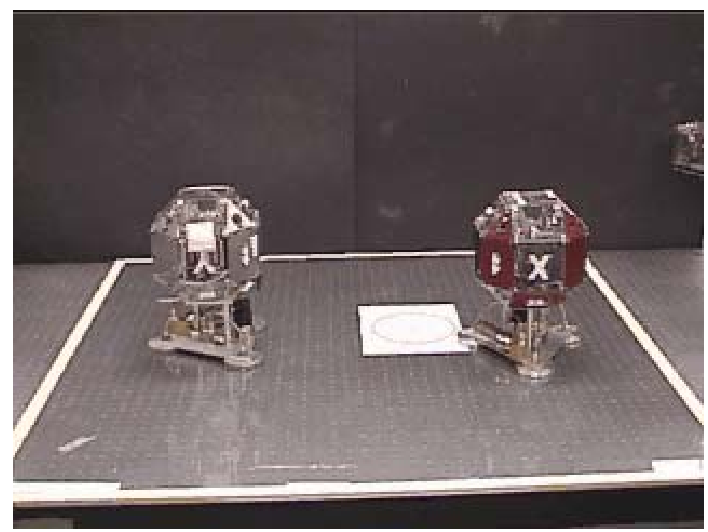
NGST



Cluster Reconfiguring

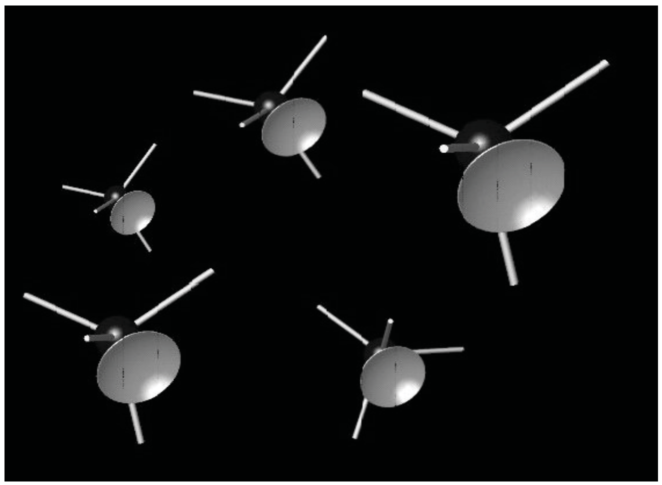


Docking



EMFF Applications in 30-40 Years

Reconfigurable Arrays & Staged Deployment



Planet Imager

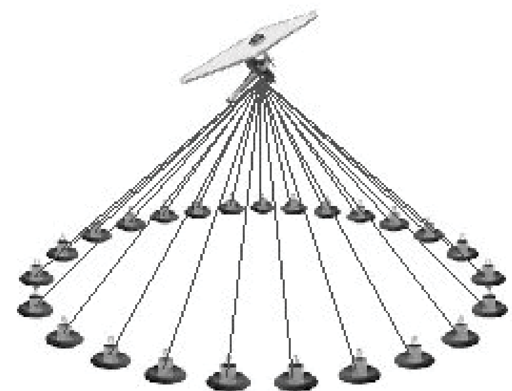
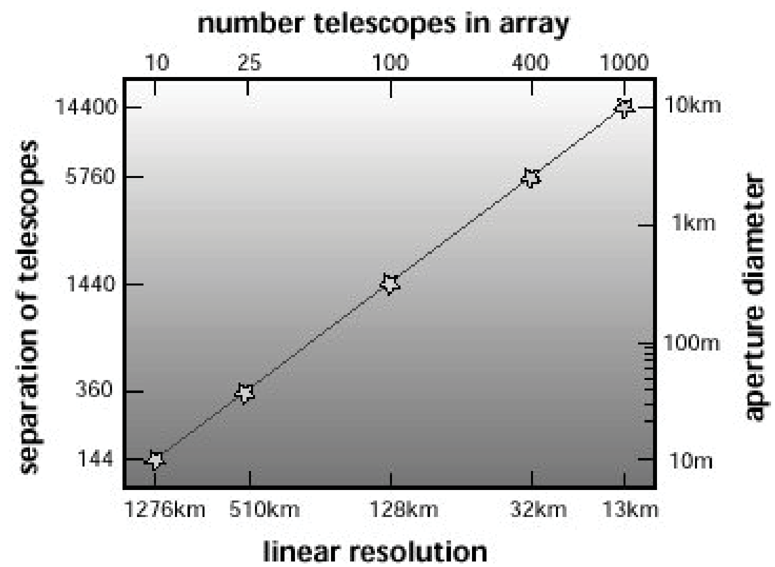
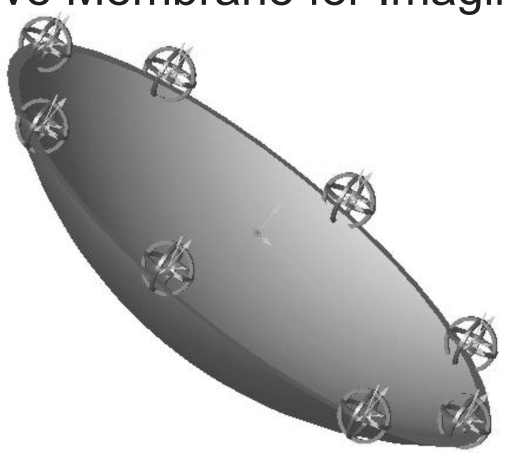


Image from 1999 TPF Book



Adaptive Membrane for Imaging



Electromagnetics vs. Electrostatics

- Electromagnetic Dipoles
  - Force Scaling:

$$F_{EM} \sim \frac{3\pi}{2}\mu_0\left(\frac{a}{x}\right)^4 I^2 \qquad \mu_0 = 4\pi(10^{-7}) \quad [N/A^2]$$

  - a = coil radius, x = separation distance, I = current (Amp-turns)

- Electrostatic Dipoles
  - Force Scaling:

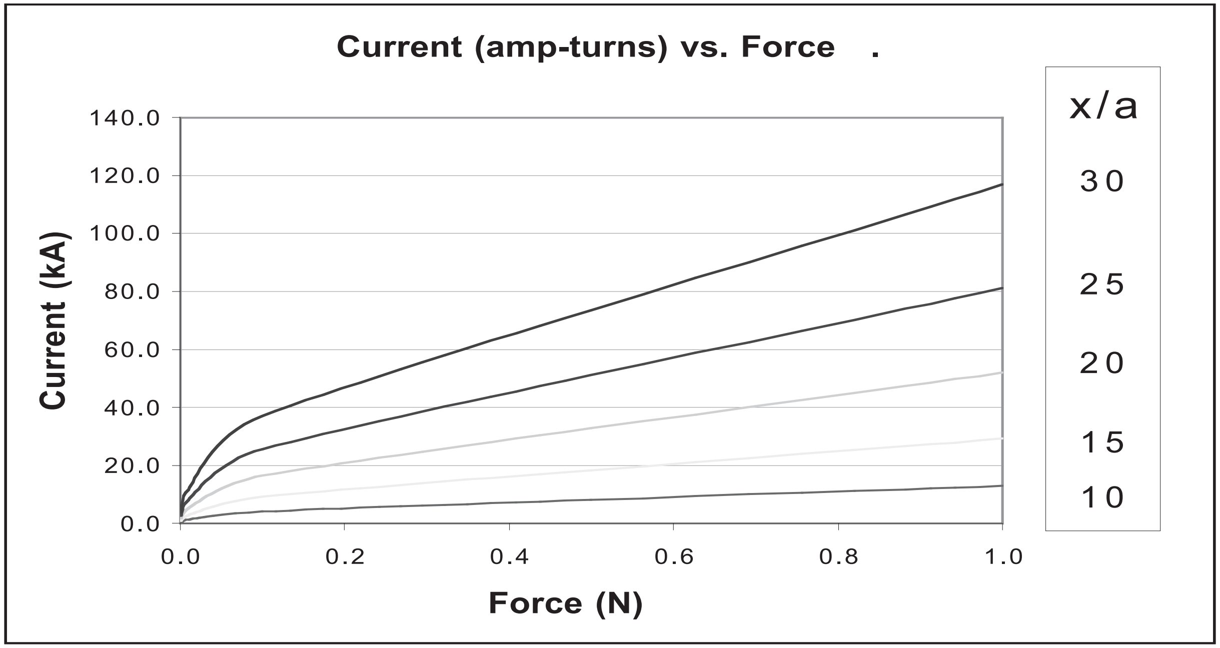
$$F_{ES} \sim 24\,\alpha^2\pi\varepsilon_0\left(\frac{a}{x}\right)^4 V^2 \qquad \varepsilon_0 = 8.85(10^{-12}) \quad [N/V^2]$$

  - a = electrode spacing, α = electrode radius / a, V = Voltage difference

$$\frac{F_{EM}}{F_{ES}} = \frac{1}{16\alpha^2}\frac{\mu_0}{\varepsilon_0}\left(\frac{I}{V}\right)^2 \quad \Rightarrow \quad V \approx \left(\frac{94}{\alpha}\right) I$$

(For break-even and comparable size)

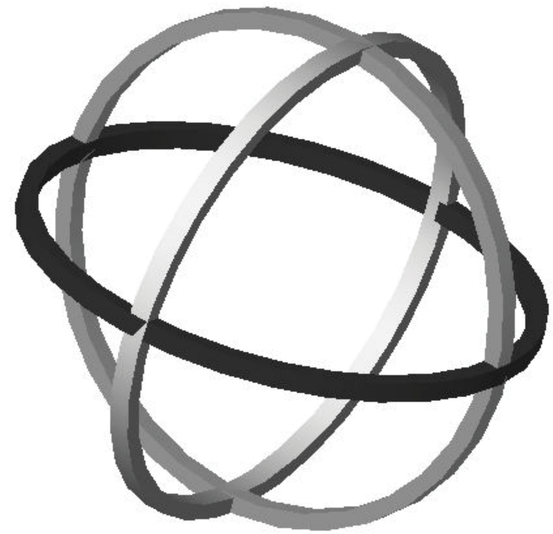
Is This a Lot?



- For regular wire… yes (except for low force or close operations)
- For high temperature superconducting wire… no!
  - Commercially available wire will carry 13 kA/cm^2
  - Laboratory demonstrations up to 6 MA/cm^2 (even in high B-field)
- However, voltages required for Electrostatics are prohibitive
- Debye shielding in LEO also a problem for electrostatics

EM Design: Steerable Dipoles

- Using ferromagnetic cores in a tetrahedron, the dipole direction can be steered by energizing different combinations
- Tend to be heavy for a given force

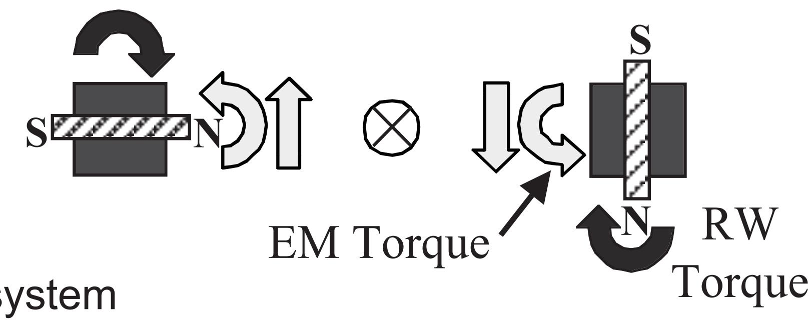


- Likewise, a set of 3 orthogonal coils can achieve the same effect
- Much lighter weight

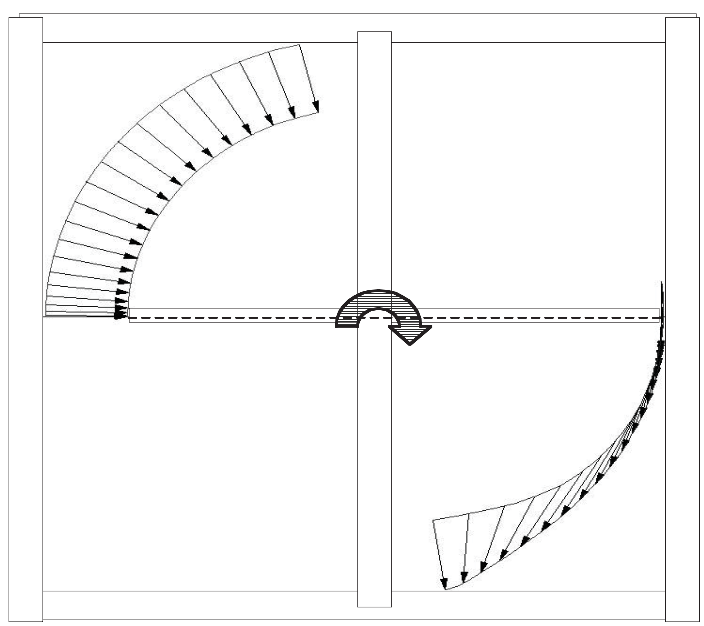
- A set of 3 orthogonal gimbaled reaction wheels used in conjunction with these steerable dipoles will decouple spacecraft orientation from EM control
- Gimbals could be locked during spin-up maneuver, and unlocked during steady-state spin to eliminate gyroscopic stiffening

Satellite Formation Spin-Up

- Electromagnets exert forces/torques on each other
  - Equal and opposite “shearing” forces
  - Torques in the same direction
- Reaction wheels counteract EM torques
  - Resultant is shearing force
  - Angular momentum conserved by spin of the system

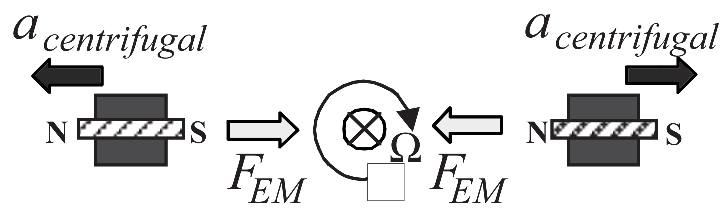


- There are many possible combinations of EM strength and dipole orientation, causing different distributions of angular momentum storage.



Steady-State Spin

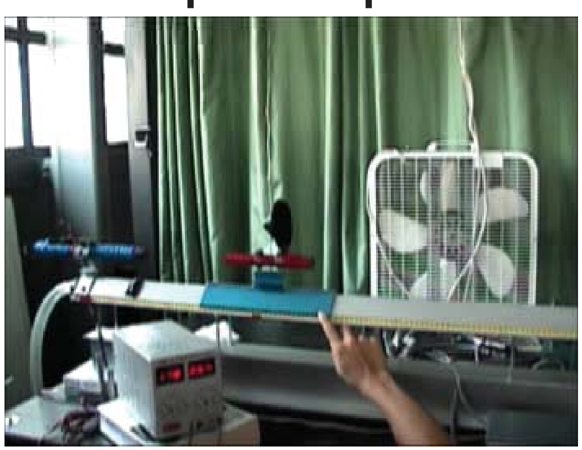
- Steady-state spin
  - Constant spin rate for data collection
  - Relative position and orientation maintenance
  - Disturbance rejection
  - Linearized dynamics about nominal spin
- Optimal control design
  - Choose ratio of penalties on state and control $(\frac{\lambda}{\rho})$
  - Can stabilize dynamics and reject disturbances
- Experimental validation on linear air track
  - Similar unstable dynamics
  - Stabilized using optimal control



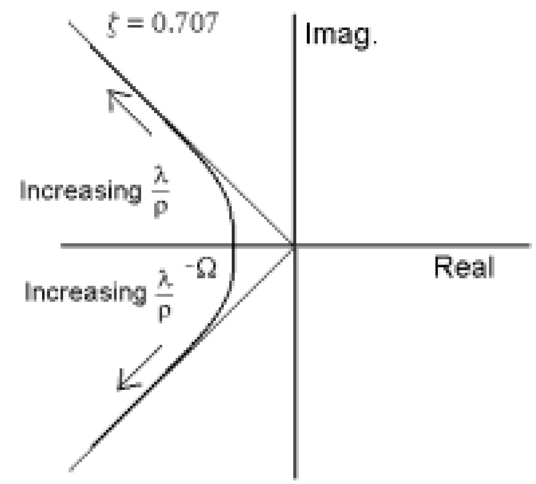
Unstable poles:

$$s_{1,2} = \pm\Omega$$

Open-Loop:



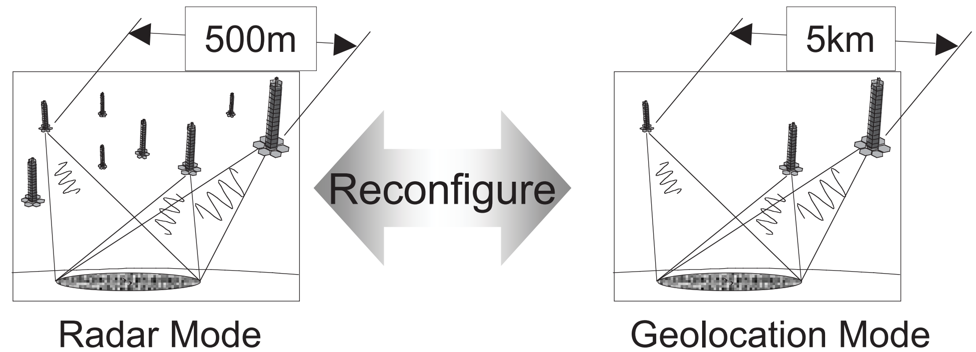
Closed-Loop:



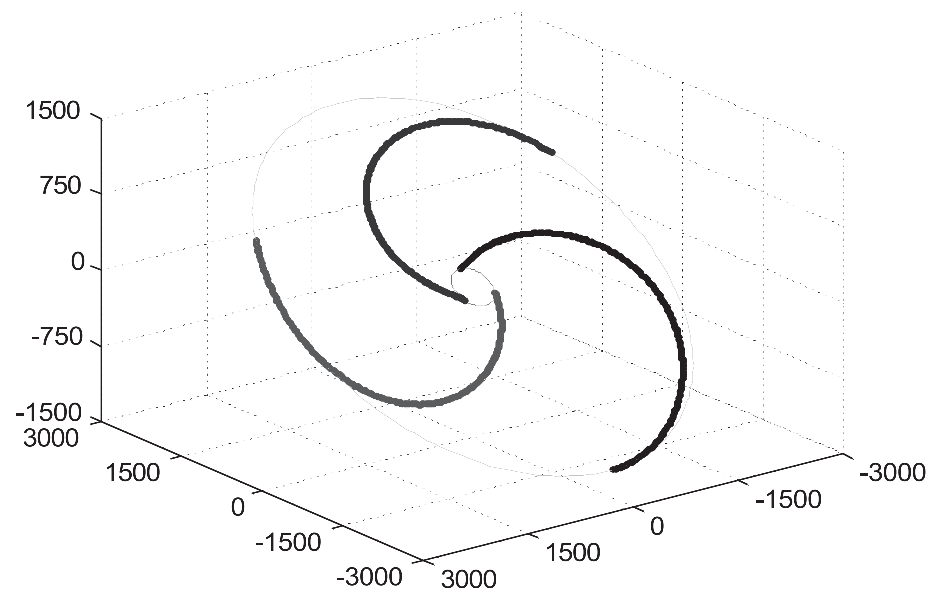
Optimal Cluster Reconfiguration

- Multiple trajectories to initialize or resize the EMFF cluster
- Can be framed as an optimal control problem with Quadratic cost function (Energy) and Linear dynamics (Hill Equations)

- Balancing between power requirements for reaction wheels and electromagnets
- Reaction wheel torques and power constraints must also be considered
- Previous work applied to TechSat 21 clusters for both cluster initialization and geo-location problems



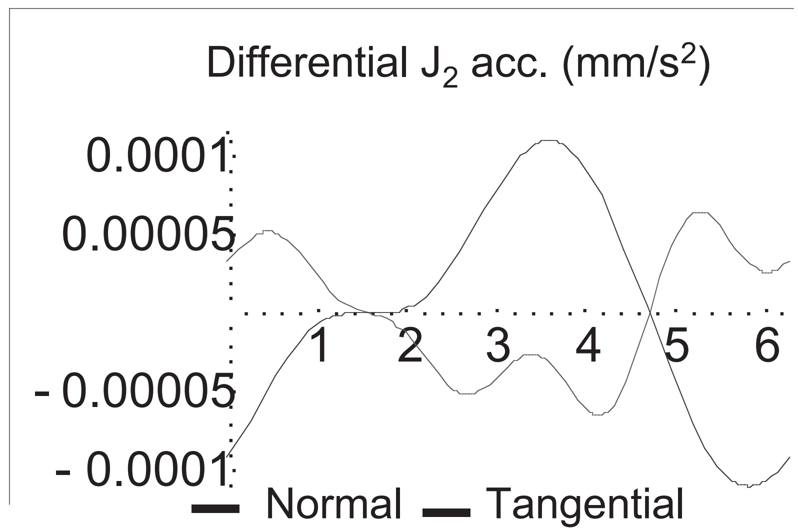
* *Figure courtesy of AFOSR Techsat21 Research Review (29 Feb - 1 Mar 2000)*



Optimal Techsat21 Cluster Re-sizing

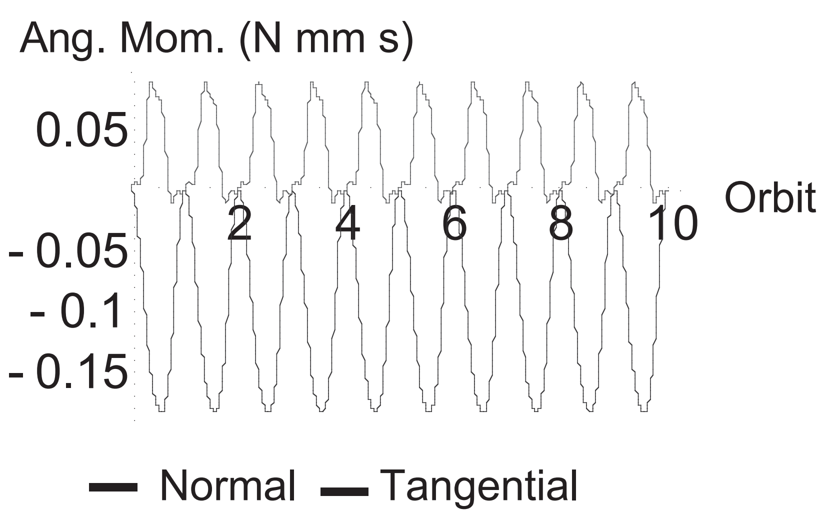
Disturbance Rejection

- EMFF must counteract the disturbances present in LEO
  - Earth's Gravitational Potential (J2)
    - Differential forces causes satellite formations to separate
    - Causes Satellite Formations to 'Tumble'
  - Differential Drag
  - Earth's Magnetic Field
- When counteracting the disturbances, EMFF produces unwanted torques on each spacecraft.
- Reaction wheels are used to temporarily store the change in the angular momentum
- The reaction wheels must be de-saturated by means other than traditional propulsion

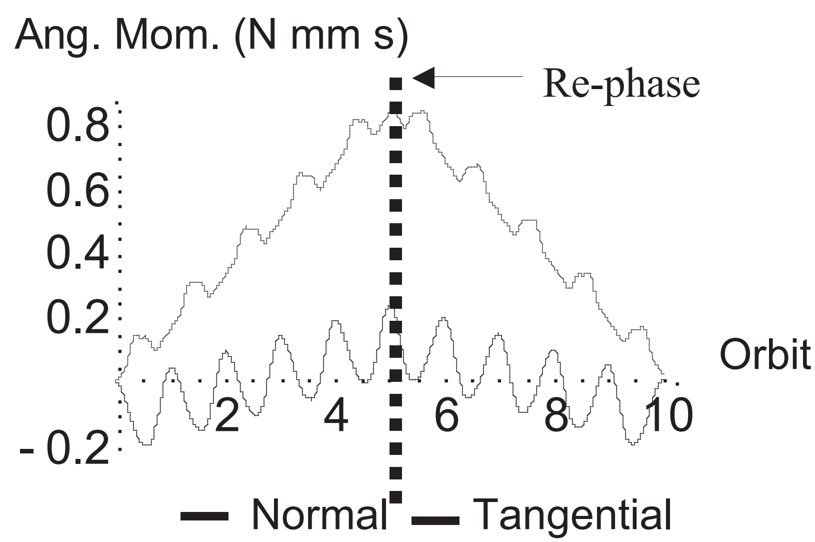


Angular Momentum Management

- Zero net angular momentum gain
  – There is a limited subset of formation designs that produce zero net angular momentum gain

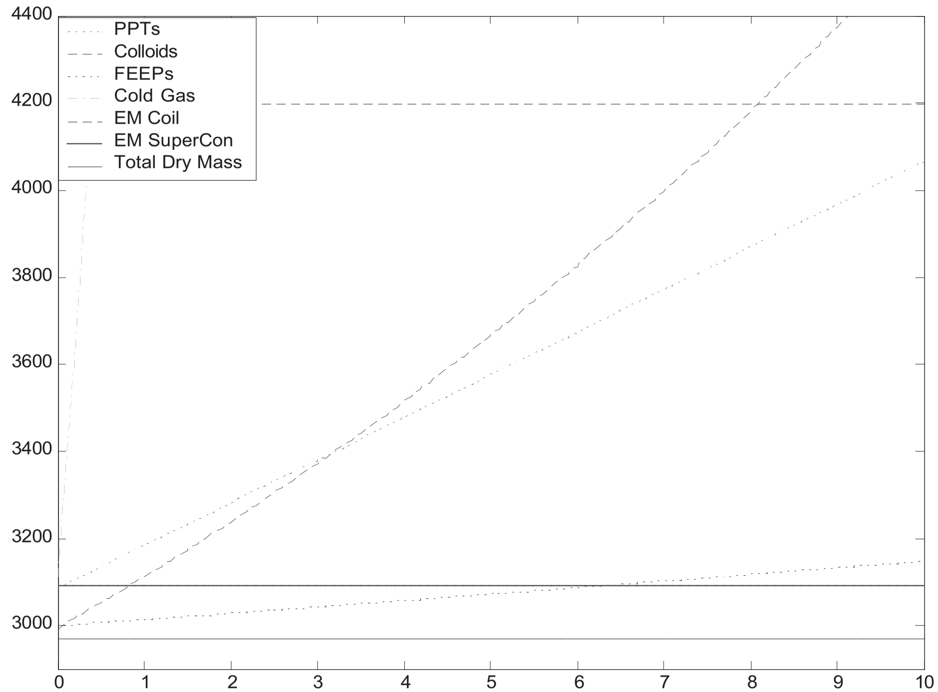


- Re-phasing of the formation
  – Re-phasing causes the torques to be applied in the opposite direction. Thus de-spinning the wheels.



- Earth's magnetic field
  – By varying the dipole strength, the torque distribution can be varied without affecting the resulting forces.
  – If the Earth is considered as another dipole, some of the torques can be preferentially distributed to the earth

Case Study: TPF Retrofit



- Cold Gas and Colloids
  - Low I_{sp} systems translate to high propellant requirements
  - Not viable options

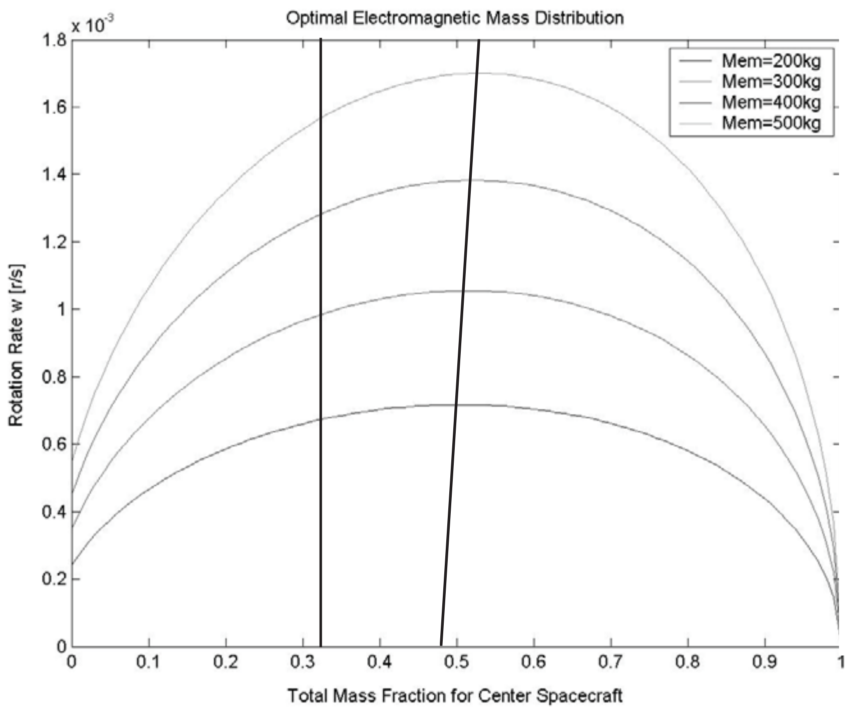
- PPTs
  - Higher efficiency system but still requires significant propellant over a 10 year mission lifetime
- FEEPs
  - Ideal for very short mission lifetime systems (less than 6 yrs)
  - Must consider contamination issue
- EM coil (R = 4 m) (M_{tot} = 4198 kg)
  - Less ideal option when compared to FEEPs even for long mission lifetime
- EM Super Conducting Coil (R = 2 m) (M_{tot} = 3089 kg)
  - Best option if mission lifetime of greater than 6.2 years is desired
  - No additional mass is required to increase mission lifetime

EMFF System Trades

- Identical or Mother-Daughter Configuration for spinning case?
  - Define Mass Fractions:

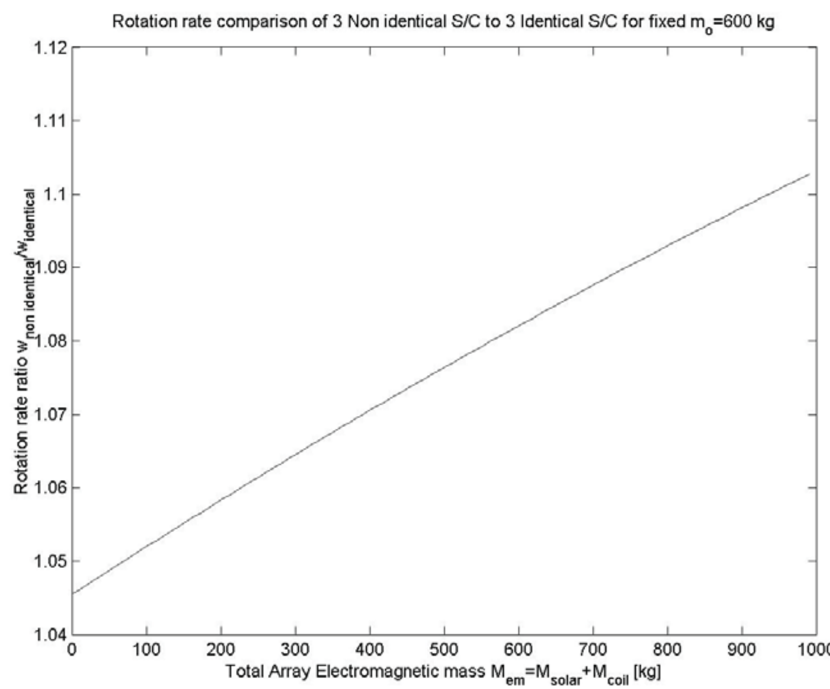
$$M_{inner} = \gamma M_{total_{array}}$$

$$M_{outer} = \frac{\gamma - 1}{2} M_{total_{array}}$$



- Identical Configuration is non-optimal

Center Spacecraft experiences no translation → no mass penalty → suggests larger center spacecraft



- Higher rotation rate for mother-daughter configuration for fixed masses

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NASA Institute for Advanced Concepts

Phase II Objectives

- Conduct more in-depth systems trades using various NASA missions
  - Terrestrial Planet Finder
  - Life Finder
  - Constellation-X
- Analyze impact on various subsystems
  - Tolerance of avionics
  - Inter-vehicle power coupling
  - Inter-vehicle communications
  - Angular momentum redistribution for enabling precision operations
- Formulate arbitrary n-body dynamics to analyze control complexity growth as a function of array growth
- Build a prototype to test simultaneous control in translation and rotation
  - Coordinate with undergraduate design-build class
  - Previous classes developed SPHERES and ARGOS testbeds
  - Provides opportunity for undergraduates to participate in, and have impact on, space research

Conclusions (1)

- Lifetime and contamination are two compelling reasons to seek alternate solutions to using propellants
- Dipole fields and reaction wheels can produce all of the necessary actuation for complete controllability of relative degrees of freedom
- There are many missions where relative DOF control is all that is necessary
  - Agencies that have interest: JPL, GSFC, LMCO, NRO
- Debye shielding in LEO, and problems with high E-fields in general make electrostatic dipoles less attractive (no pun intended)
  - Electrostatic monopoles could provide a stronger attractive force for constant spin rate, but charge exchange between spacecraft is an issue

Conclusions (2)

- Constrained Steady-state spin control has been demonstrated in hardware
- In LEO, disturbance rejection is the main concern and angular momentum management is the biggest problem
  - Three approaches: Zero not torque solution, Re-phasing, Using Earth's Field
- EMFF retrofit of TPF looks like the best solution if FEEP contamination is a high risk
- Optimal distribution of Torque for TPF-like maneuver is not necessarily to have identical spacecraft