FORMATION FLYING WITH SHEPHERD SATELLITES

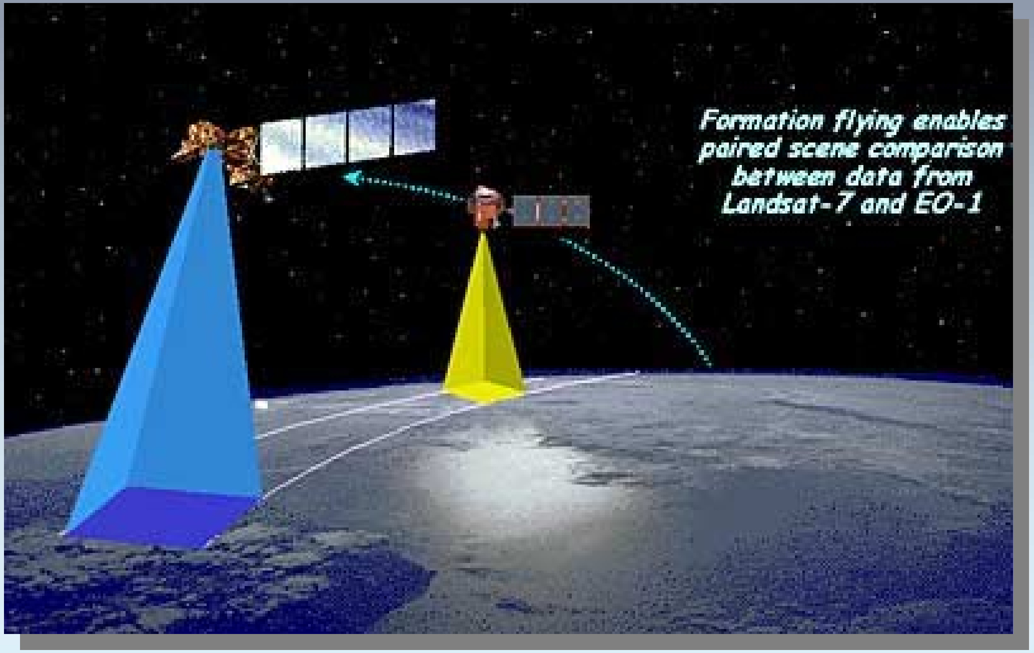
2001 NIAC Fellows Meeting

Michael LaPointe

Ohio Aerospace Institute

WHAT IS FORMATION FLYING?

Two or more satellites flying in prescribed orbits at a fixed separation distance for a given period of time



NASA -GSFC

Example:

EO-1 and Landsat-7 satellites are currently formation flying in LEO to provide high resolution images of Earth's environment

Planned Formation Flying Missions

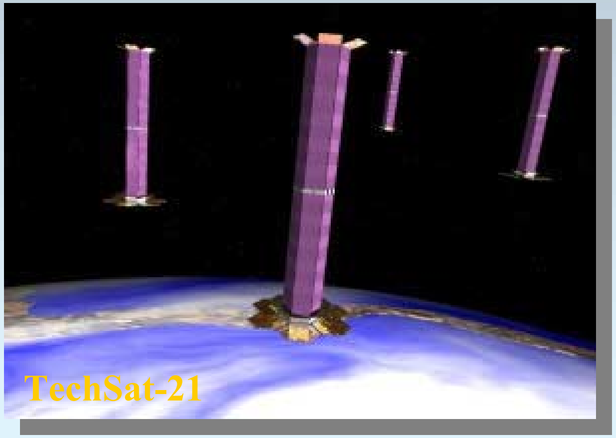
NASA


ST3: Starlight

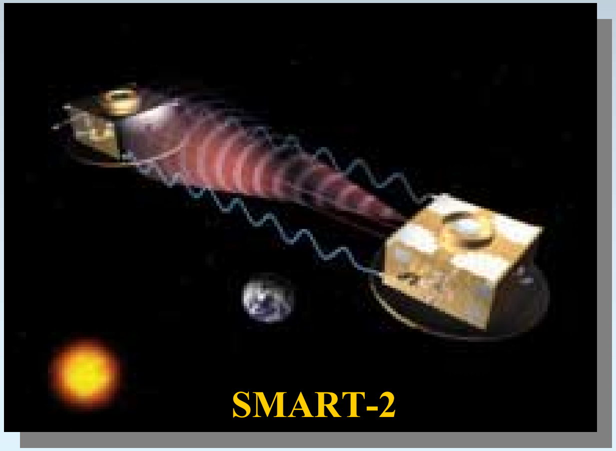

ST5: Nanosat Trailblazer

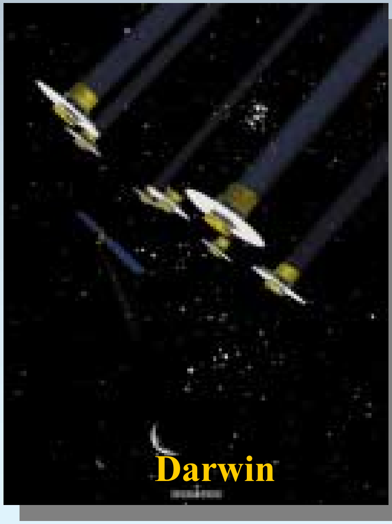

Terrestrial Planet Finder

USAF


TechSat-21

ESA


SMART-2


Darwin

…And Future Arrays Are Predicted With Multiple (10 – 100) Nanosatellites

WHAT ARE THE BENEFITS?

Lower Life Cycle Cost

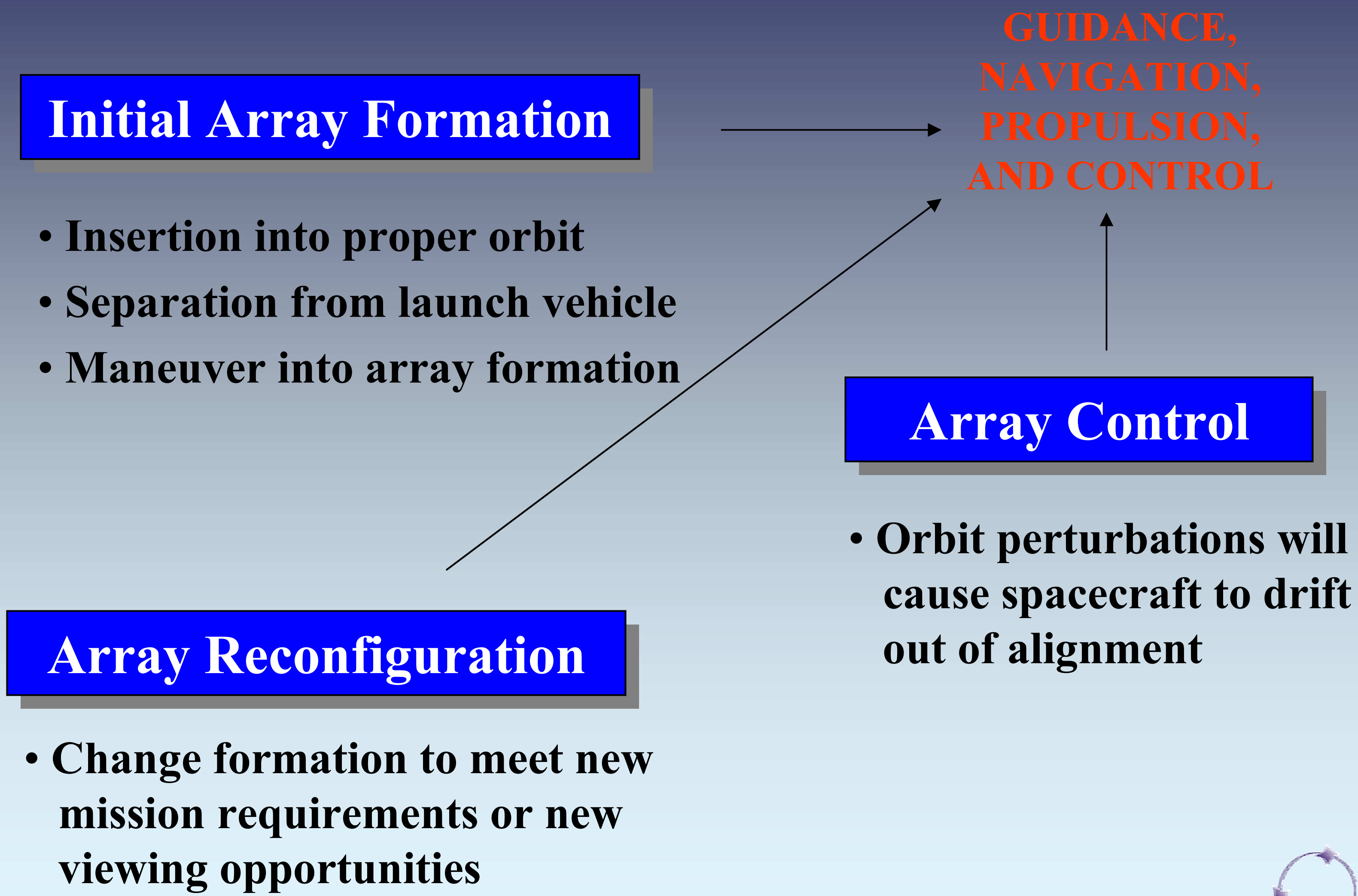
Enhance/Enable Missions

BUT THERE ARE SIGNIFICANT CHALLENGES…

Reduce Mission Risk

Adapt to Changing Missions

KEY ISSUES



GUIDANCE, NAVIGATION, PROPULSION, AND CONTROL

Initial Array Formation

- Insertion into proper orbit
- Separation from launch vehicle
- Maneuver into array formation

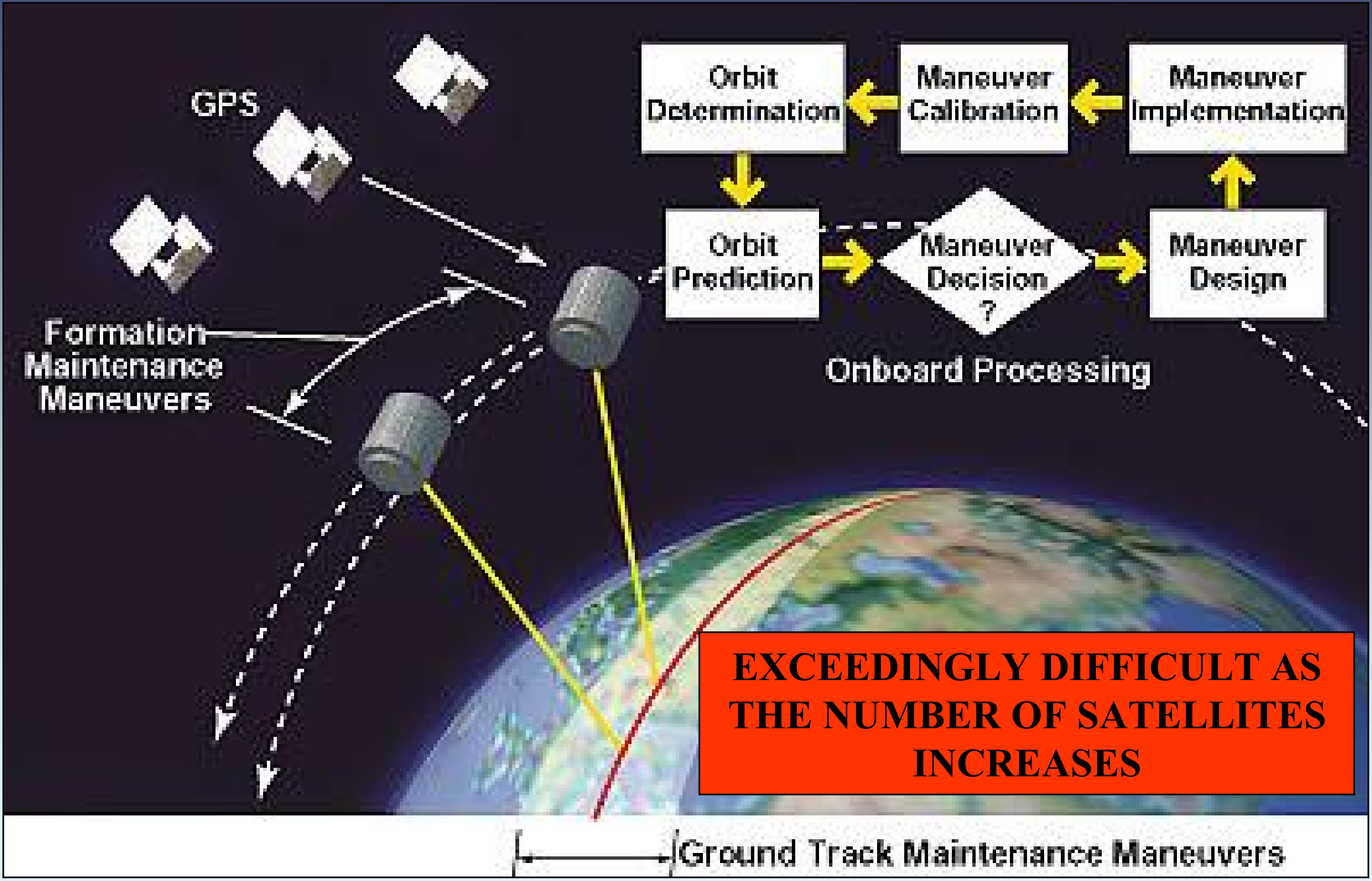
Array Control

- Orbit perturbations will cause spacecraft to drift out of alignment

Array Reconfiguration

- Change formation to meet new mission requirements or new viewing opportunities

CURRENT APPROACH TO SATELLITE GNC USES GPS AND ON-BOARD ALGORITHMS



EXCEEDINGLY DIFFICULT AS THE NUMBER OF SATELLITES INCREASES

J. Guinn, JPL, NASA Tech Briefs, July 1998

SOME OF THE CHALLENGES

- GPS is not sufficiently accurate for interferometer applications
- Closed-loop algorithms for autonomous N-body control are not yet developed
- Propulsion system exhaust may interfere with instrumentation of neighboring microsatellites in the array
- Propellant mass required for continuous array control reduces the microsatellite mass allotted to instrumentation
- Power system mass for higher specific impulse electric thrusters also reduces available mass for instrumentation
- Proposed solutions, such as tethering satellites to form an array, may be difficult to implement for arrays with several satellites or for arbitrary array geometries

NIAC PHASE I PROPOSAL

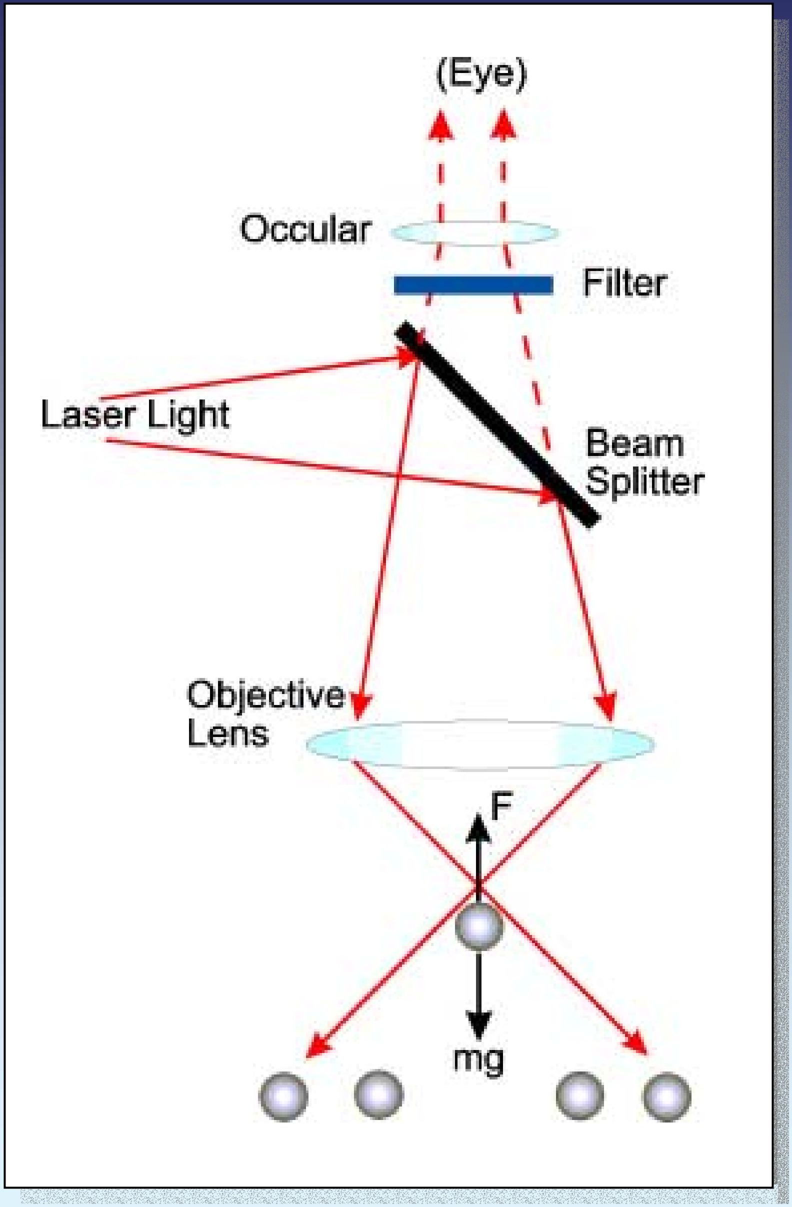
Use “shepherd satellites” flying outside the array to provide guidance, navigation and control functions

Apply external forces to hold array in place

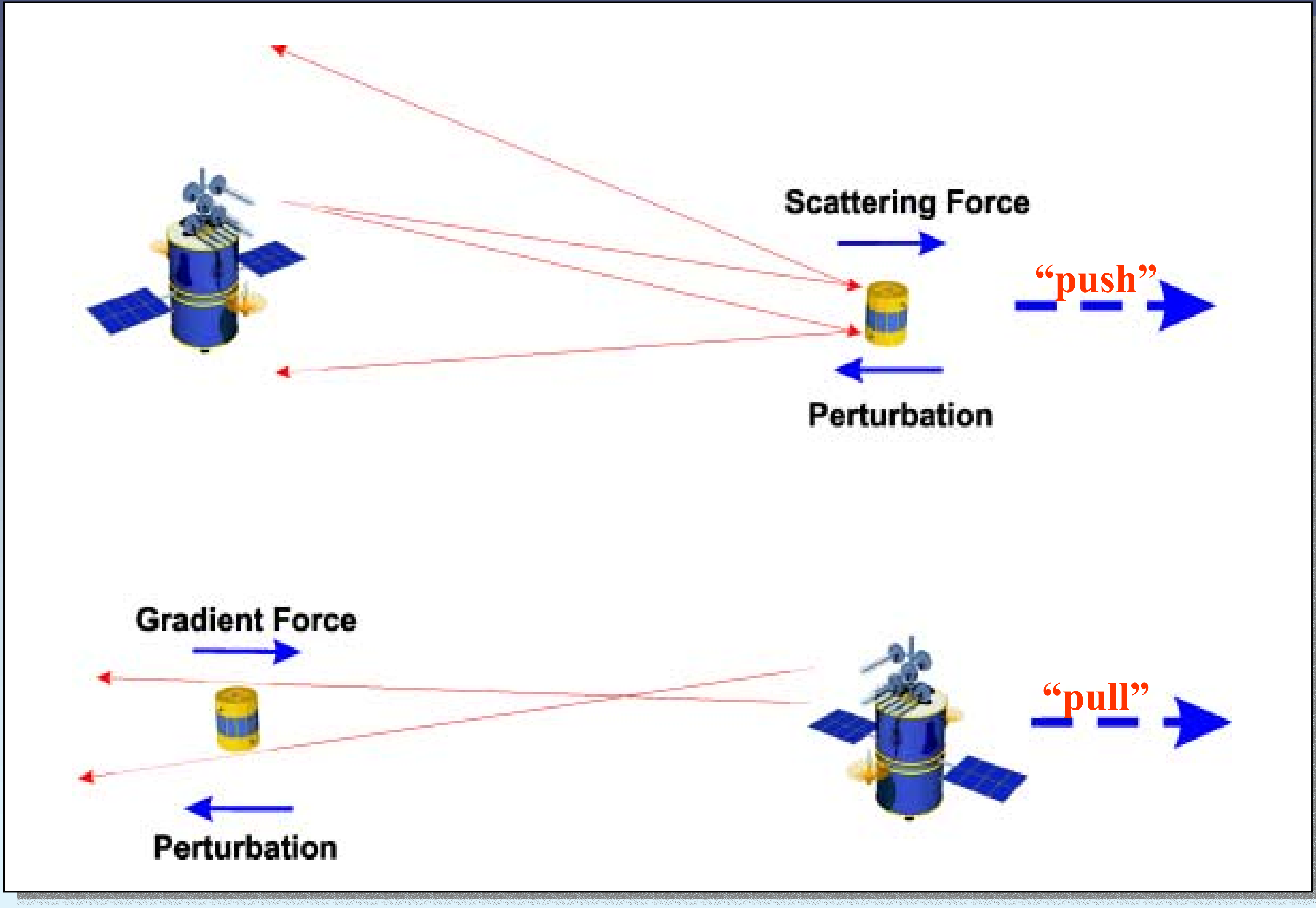
CONCEPT BASED ON OPTICAL SCATTERING FORCE AND GRADIENT FORCE TECHNIQUES

- Stable levitation and trapping of microscopic particles using mW lasers
- Techniques used in biology, material science, etc.

Idea is to extend method to higher powers, longer wavelengths, and larger objects (microsatellites)…



RADIATION FORCES FOR MICROSATELLITE ARRAY CONTROL



BASIC FEASIBILITY QUESTIONS

- How would it work?
  - Can we extend optical techniques to longer wavelengths and larger "particle" sizes?
- What are the required force levels?
  - Overcome orbit perturbations
  - Maneuver or reconfigure array
- What are the required power levels?
  - Use solar arrays to power beams
  - Don't fry the science microsatellites
- How many shepherd satellites are required?
  - Depends on array formation (number, geometry)
  - Require significantly fewer shepsats than microsats

ANALYTIC MODELS

Rayleigh Approximation:
Diameter << Wavelength
(Electromagnetic Wave Theory)

Mie Approximation:
Diameter ≥ Wavelength
(Geometric/Ray Optics Theory)

Dielectric Material

Metallic Material

- Analysis can be extended to arbitrary EM wavelengths
- Emphasis placed on Mie approximation (microwaves)
- Models used to predict radiation force per unit power

ELECTROMAGNETIC SCATTERING FORCES

$$F_s = \frac{n_1 Q_s P}{c}$$

$$Q_s = \left\{ 1 + R\cos(2\Theta_1) - \frac{T^2[\cos 2(\Theta_1 - \Theta_2) + R\cos(2\Theta_1)]}{1 + R^2 + 2R\cos\Theta_2} \right\}$$

dielectric

$$Q_s = \{1 + R\cos(2\Theta_1)\}$$

metallic

R = Reflection Coefficient, T = Transmission Coefficient
➔$_1$ = incident angle, ➔$_2$ = refraction angle, c= speed of light,
n_1 = refractive index (vacuum), P = incident beam power

ELECTROMAGNETIC GRADIENT FORCES

ARISE FROM INTERACTION OF INCIDENT ELECTRIC FIELD WITH INDUCED DIPOLE MOMENT OF OBJECT

$$U(r,t) = -\tfrac{1}{2}(\vec{p}\cdot\vec{E}) = -\tfrac{1}{2}\,\mathrm{pE}\cos\Theta$$

$$\vec{F}_{\mathrm{grad}}(r,t) = -\nabla U(r,t) = \tfrac{1}{2}\nabla(\vec{p}\cdot\vec{E})_{\Theta=\mathrm{fixed}}$$

U=potential energy, p=dipole moment, E=external electric field

ELECTROMAGNETIC GRADIENT FORCES

Geometric Optics Approximation:

$$F_G = \frac{n_1 Q_G P}{c}$$

$$Q_G = \left\{ R\sin(2\Theta_1) - \frac{T^2[\sin 2(\Theta_1 - \Theta_2) + R\sin(2\Theta_1)]}{1 + R^2 + 2R\cos\Theta_2} \right\}$$

dielectric

$$Q_G = \{R\sin(2\Theta_1)\}$$ metallic

Integrate over incident angles for total force

PRELIMINARY RESULTS

Analytic Models Predict Scattering and Gradient Forces of ~ 10^{-11} N/W to ~ a few 10^{-9} N/W

Based on these results…

- Assume 10^{-9} N/W can be achieved
- Assume 10-kW to 100-kW power levels
- Provides restoring forces of 10^{-5} N to 10^{-4} N

WHAT CAN WE DO WITH THIS?

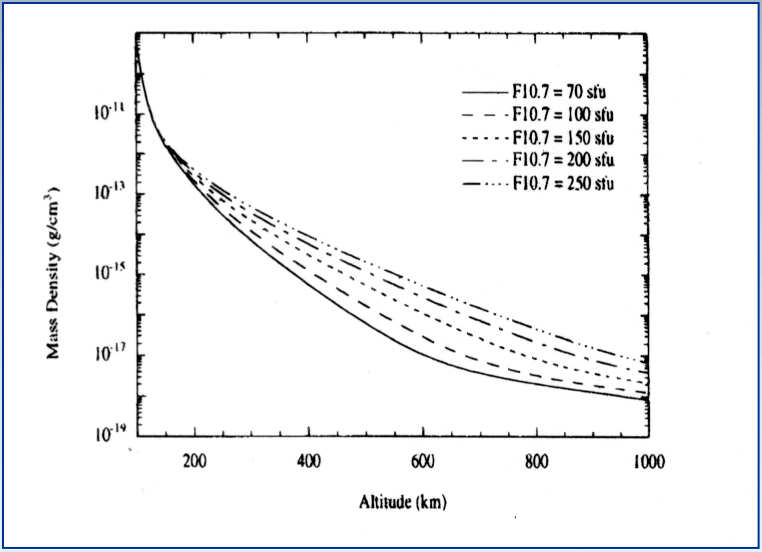
MISSION APPLICATIONS

LOW EARTH ORBIT

Drag Force:

$$F_D = \frac{1}{2} M \rho V^2 B^{-1}$$

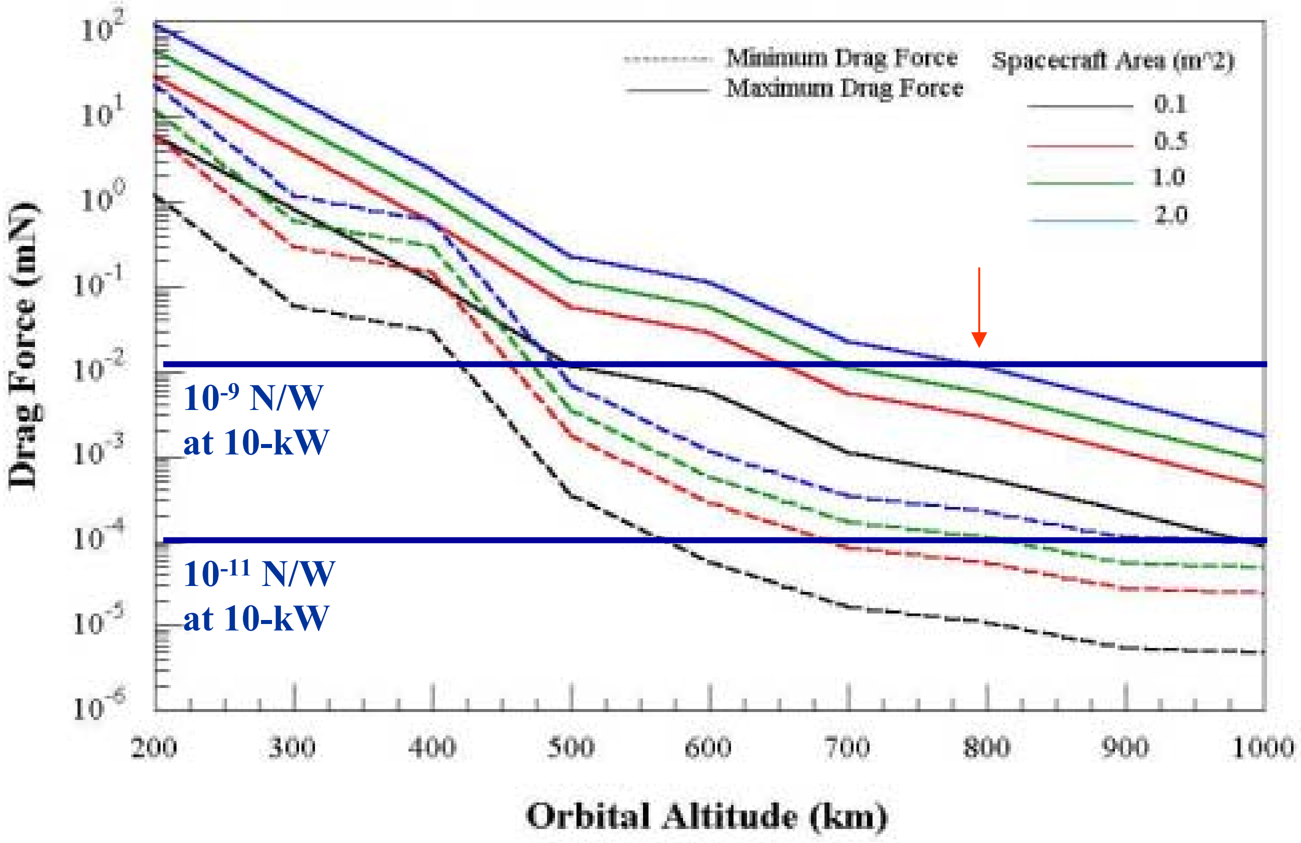
M = spacecraft mass (kg)
ρ = atmospheric density (kg/m^3)
V = orbital velocity (m/s)
B = ballistic coefficient = $M/(C_D A)$
A = cross-sectional area (m^2)
C_D = drag coefficient; $2 \le C_D \le 4$



MSIS Density Model, Hedin, *JGR* 96, 1999

MISSION APPLICATIONS

LOW EARTH ORBIT



MISSION APPLICATIONS

LOW EARTH ORBIT

Drag make-up at orbital altitudes above 800-km

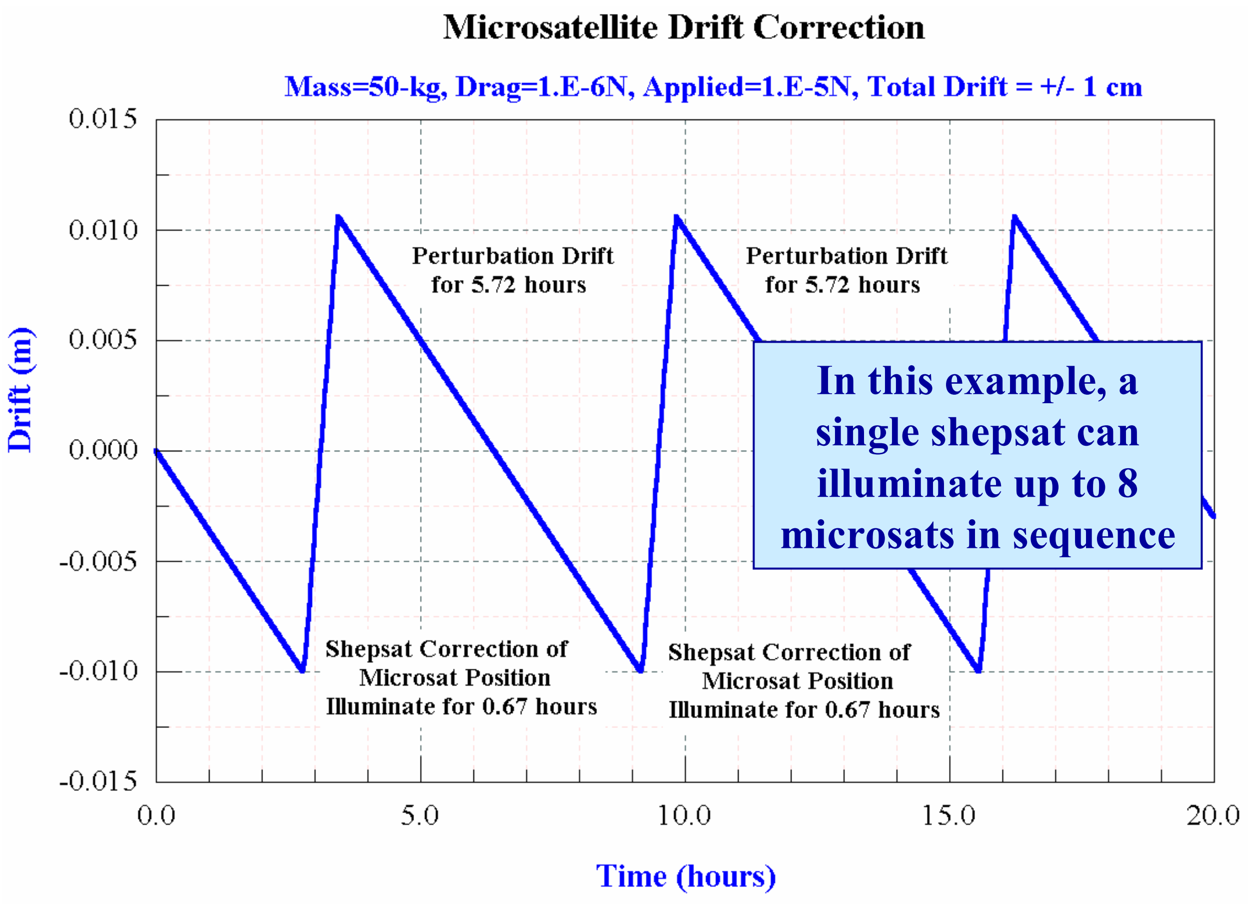
$$F_{net} = F_{rad} - F_{drag}$$

Example:

- 50-kg microsatellite
- 1000-km orbit
- Cross-sectional area = 1-m^2
- 10^{-5} N restoring force
  - ⬇ 10^{-9} N/W @ 10-kW
- Maintain position ± 1-cm

MISSION APPLICATIONS

LOW EARTH ORBIT



In this example, a single shepsat can illuminate up to 8 microsats in sequence

MISSION APPLICATIONS

LOW EARTH ORBIT

- Drag correction appears feasible at higher altitudes (>800-km)
- Single shepsat can illuminate several microsats in sequence
- Time on target depends on required force, degree of correction
    - less drag for smaller satellite areas and higher satellite orbits

Potential Uses in LEO below 800-km

- Provide positioning beacons for array formation
    - Single shepsat can provide discrete EM intensity “matrix”
    - Sensors position microsats at points of maximum intensity
    - Microsats require propulsion, but simpler GNC routines
    - Ground/autonomous control of shepsat vs. full array

MISSION APPLICATIONS

GEOSYNCHRONOUS EARTH ORBIT

- **Orbital altitude = 37,786 km (Geostationary Orbit)**
- **Atmospheric drag is negligible**
- **Other perturbations become important:**
  - **North-South perturbations due to Sun and Moon**
  - **East-West perturbations due to solar radiation**
  - **East-West perturbations due to Earth triaxiality**

Sufficient Force to Overcome These Perturbations?

MISSION APPLICATIONS

GEOSYNCHRONOUS EARTH ORBIT

North-South perturbations due to Sun and Moon

- **Changes satellite inclination over time**

$$\frac{di}{dt} = \frac{r\cos\varphi}{\omega a^2\sqrt{1-e^2}} W \approx \frac{0.85^\circ}{\text{year}}$$

$$W = \left(\frac{1.45\times10^{-6}}{\cos\varphi}\right)\frac{m}{s^2}$$

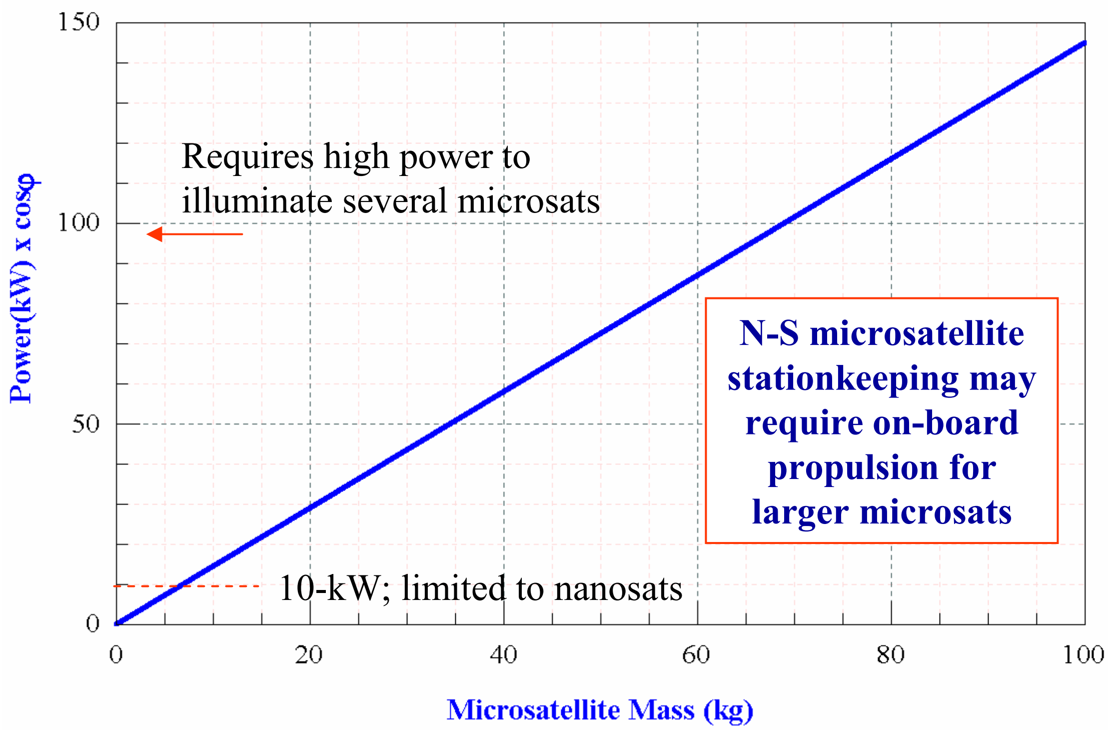
- **Need to supply restoring force to overcome perturbing acceleration:**

$$P\times10^{-9}\,\tfrac{N}{W} \geq M\left(\frac{1.45\times10^{-6}}{\cos\varphi}\right) \rightarrow$$

MISSION APPLICATIONS

GEOSYNCHRONOUS EARTH ORBIT

Power required to compensate for changes in inclination



Requires high power to illuminate several microsats

10-kW; limited to nanosats

N-S microsatellite stationkeeping may require on-board propulsion for larger microsats

MISSION APPLICATIONS

GEOSYNCHRONOUS EARTH ORBIT

East-West Perturbations from Solar Radiation Forces

- **Changes orbital eccentricity and orientation of apsidal line:**

Results in an acceleration:

$$\boxed{\Delta a = S(1+\sigma)\frac{A}{M}}$$

S = solar constant, A = area, M = microsat mass, σ = average reflectivity

- **Assuming shepsat restoring force of 10^{-5} N yields condition:**

$$\boxed{(1+\sigma)A \leq 2.2\mathrm{m}^2}$$

Easily met for most planned microsats

MISSION APPLICATIONS

GEOSYNCHRONOUS EARTH ORBIT

North-South Perturbations due to Earth's Triaxiality

- Equatorial cross-section is approximately elliptical
- Minor ellipse axis passes through 75°E, 105°W longitude
  - Stable points; satellites at these locations will stay there
  - At any other longitude, satellite will drift toward and oscillate around the nearest equilibrium point

$$\Delta V(\tfrac{\mathrm{m}}{\mathrm{s}} / yr) = 1.75\,|\sin(2\gamma_o)|$$

Need to correct this annual change in ΔV

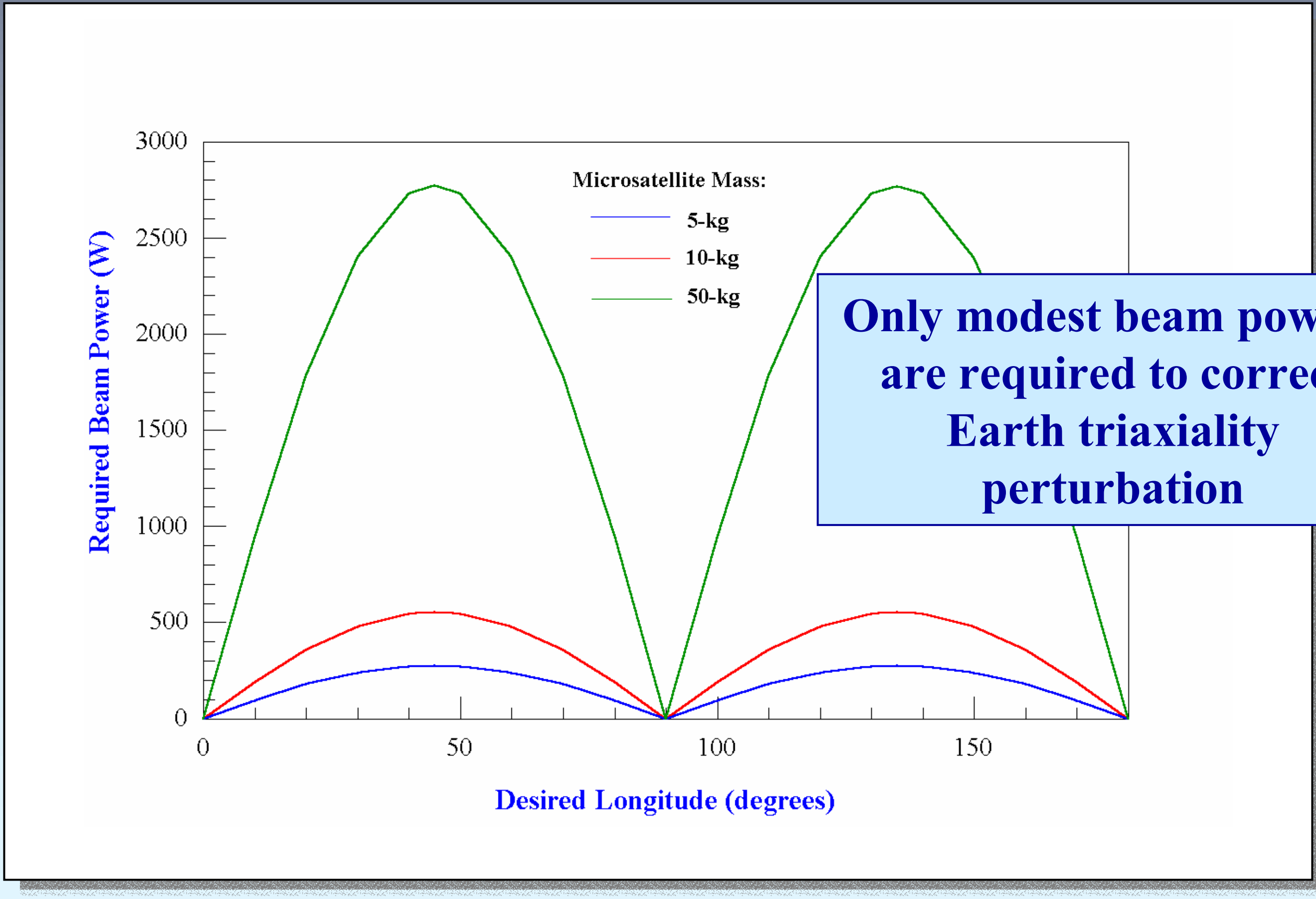
Leads to condition on required beam power:

$$\mathrm{P(W)} \geq 55.45 \times \mathrm{M} \times |\sin(2\gamma_{\mathrm{o}})|$$

MISSION APPLICATIONS

GEOSYNCHRONOUS EARTH ORBIT

North-South Perturbations due to Earth’s Triaxiality



Only modest beam powers are required to correct Earth triaxiality perturbation

OTHER MISSION APPLICATIONS

Middle Earth Orbit

- Repeat ground track missions
- Reduced atmospheric drag
- Smaller ΔV from solar pressure
- Sun/Moon and triaxial still exist

Deep Space Arrays

- Long-baseline observations
- Minimal orbit perturbations
- “Fine control” provided by an intensity matrix holding the microsatellites in place

SUMMARY

- Formation flying enhances/enables science missions
  - Lower life cycle cost, reduced risk, mission adaptable

- Shepherd satellite concept may provide a useful technique for controlling microsatellite positions within the array
  - Provide restoring forces ≈ 10^{-9} N/W per beam

- Low Earth Orbit

  ≥ 800-km, provide drag compensation and position control

  < 800-km, provide intensity markers for microsat positions

- Geosynchronous Earth Orbit
  - Control orbital perturbations for nanosatellites (≤ 10-kg)
  - Larger microsatellites may require on-board propulsion

- Deep Space Arrays
  - Accurate position control using intensity force matrix

NEXT STEPS…

- **Additional system definition studies:**
  - **Shepsat power, propulsion, communications…**
  - **Microwave power generation (10-kw to 100-kW)**
  - **Beam formation and pointing accuracy**
    - Antenna design: variable focus, ability to scan, etc…
  - **Microwave beam interaction with microsatellites**
    - Dielectric or reflective “shells” for surface interactions?
    - Protect electronics, instruments, inter-satellite communications
  - **Microsatellite reaction control/pointing systems**

- **Refine numerical models for better force predictions**
  - **Material interactions, off-angle beam corrections,…**

- **Experimental validation of force predictions**
  - **Demonstrate electromagnetic scattering and trapping forces on representative microsatellite test mass**

ACKNOWLEDGEMENTS

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