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The Next Little Thing: Femtosatellites

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Small Satellite Classification

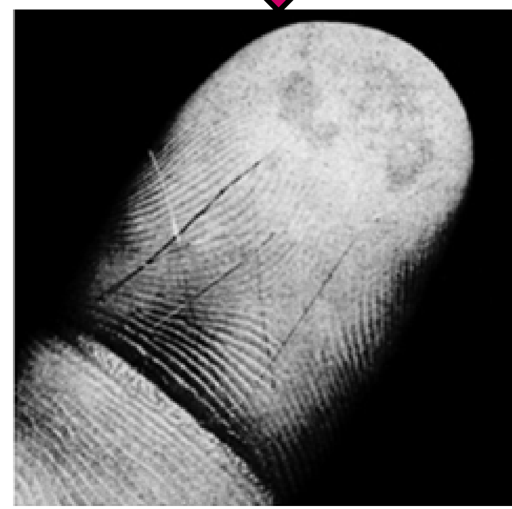
Microsatellite:	**10-to-100 kg**
Nanosatellite:	**1-to-10 kg**
Picosatellite:	**0.1-to-1 kg**
Femtosatellite:	**< 100 g**

Echo-1
(1960)

Photograph courtesy of NASA

Size: 30.5-m diameter sphere
Mass: 75.5-kg

West Ford
Needles
(1963)



Size: 1.78-cm long, 17.8-μm dia.
Mass: 48-μg x 480 million dipoles

"Small" satellites have ranged from huge to barely visible.

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Femtosatellite Flight History:

- **West Ford needles (1963)**
  - 480 million, 1.78-cm long by 1.8-micron diameter copper wires
  - They created an artificial ionosphere for X-band communications
  - Another 1960's-era experiment that will never happen again (e.g., above-ground nuclear tests)

- **Orbital Debris Radar Calibration Spheres-2 (1995)**
  - Multiple 5 to 0.5-kg mass spheres ejected from STS-63, plus
  - Two 13.3-cm long by 0.102-cm diameter dipoles (1.5-gram mass)
  - One 4.42-cm long by 0.102-cm diameter dipole (0.5-gram mass)

- **Cornell Sprites (2011)**
  - Mounted on Materials on International Space Station Experiment – 8
  - 3.8-cm square, ~10-gram mass

Before 2011, femtosatellites were passive; literally "dead as a door nail".
In 2011, active "ChipSat" femtosatellites were put into orbit .

Why Bother with Femtosatellites?

- **Spacecraft can cost $100 to $10,000**
  - Mass production drives individual costs down
  - $1,000 bought a KickSat Sprite and development kit on KickStarter.com

- **Launch costs of $100 to $10,000**
  - Based on ~$100,000 for a 1.3-kg 1U CubeSat

- **High area/mass ratios enables new propulsion options**
  - Rapid deorbit (weeks)
  - Aerodynamic rephasing, altitude, and RAAN changes
  - Solar sailing (chipsats a few microns thick)
  - Electrodynamic propulsion using multi-meter tethers

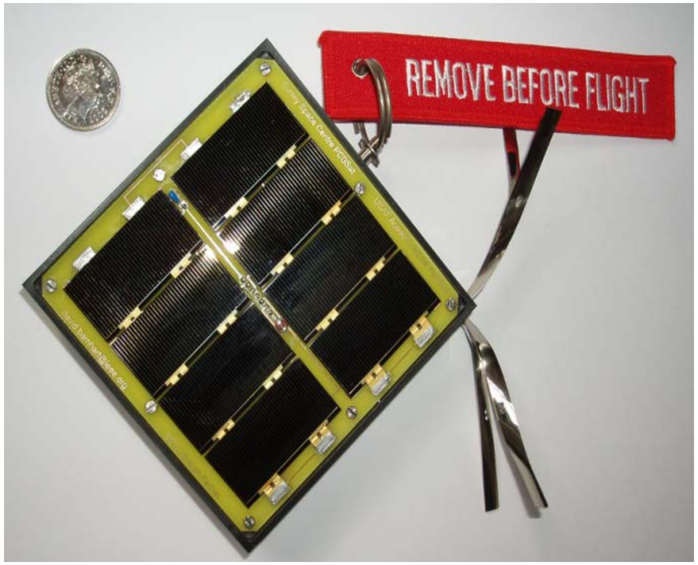
- **An entire constellation in a CubeSat**
  - Distributed, simultaneous measurements

Femtosatellites offer inexpensive access to space and the ability to fly entire constellations for under a few hundred thousand dollars.

What Has Changed?

- **Transistors continue to shrink in size**
  - You can fit 128-Gbytes of data in a 15 x 11 x 1-mm volume
- **Microelectromechanical Systems (MEMS)**
  - You can buy a 4 x 4 x 1.1-mm volume 3-axis rate gyro or magnetometer
- **"Do less with more" rather than "Do more with less"**
  - Use many inexpensive spacecraft
  - Don't try to put too much capability into a single spacecraft

A <$10,000 PC board satellite: PCBSat



Micro/nanofabrication technologies make active femtosatellites possible.

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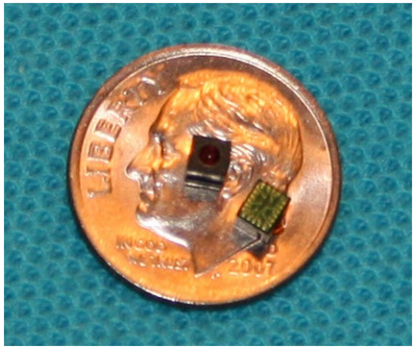
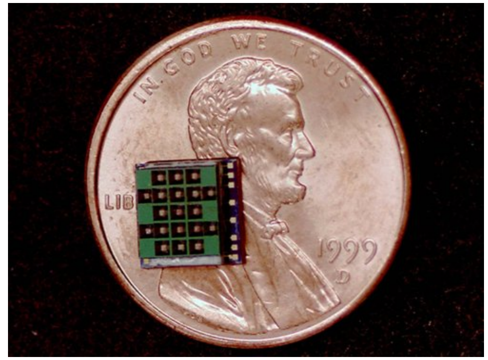
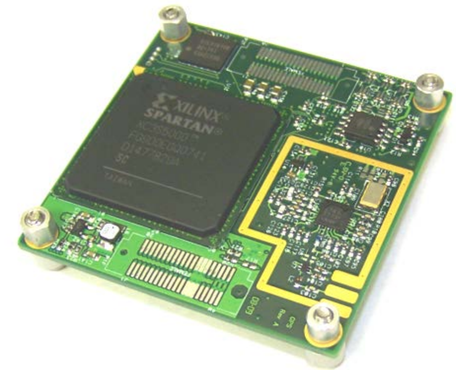
Potential Small Subsystems for FemtoSatellites:



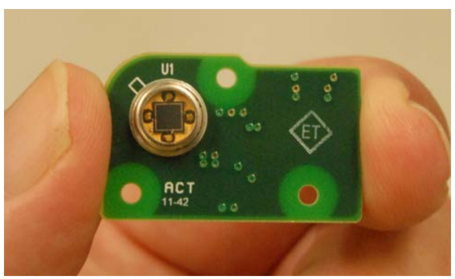
- 640 x 480 Camera
  - 3 x 3 x 3 mm



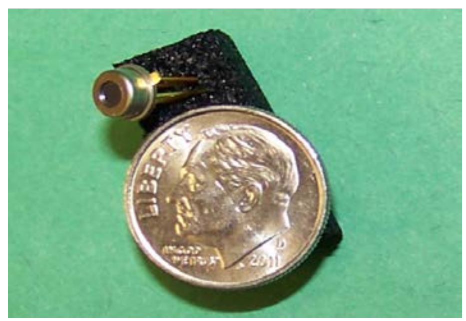
- Solid microthruster array
  - 12 x 10 x 4 mm



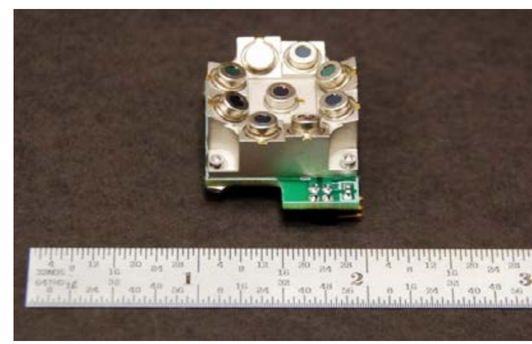
- GPS receiver
  - 56 x 56 x 13 mm



- 2-axis sun sensor
  - 25 x 14 x 6 mm



- Optical thermometer
  - 5 x 9-mm diameter



- Earth nadir sensor
  - 25 x 25 x 14 mm

All of these have flown on CubeSats, except for the VGA (640 x 480 pixel) CameraCube that includes an integrated lens.

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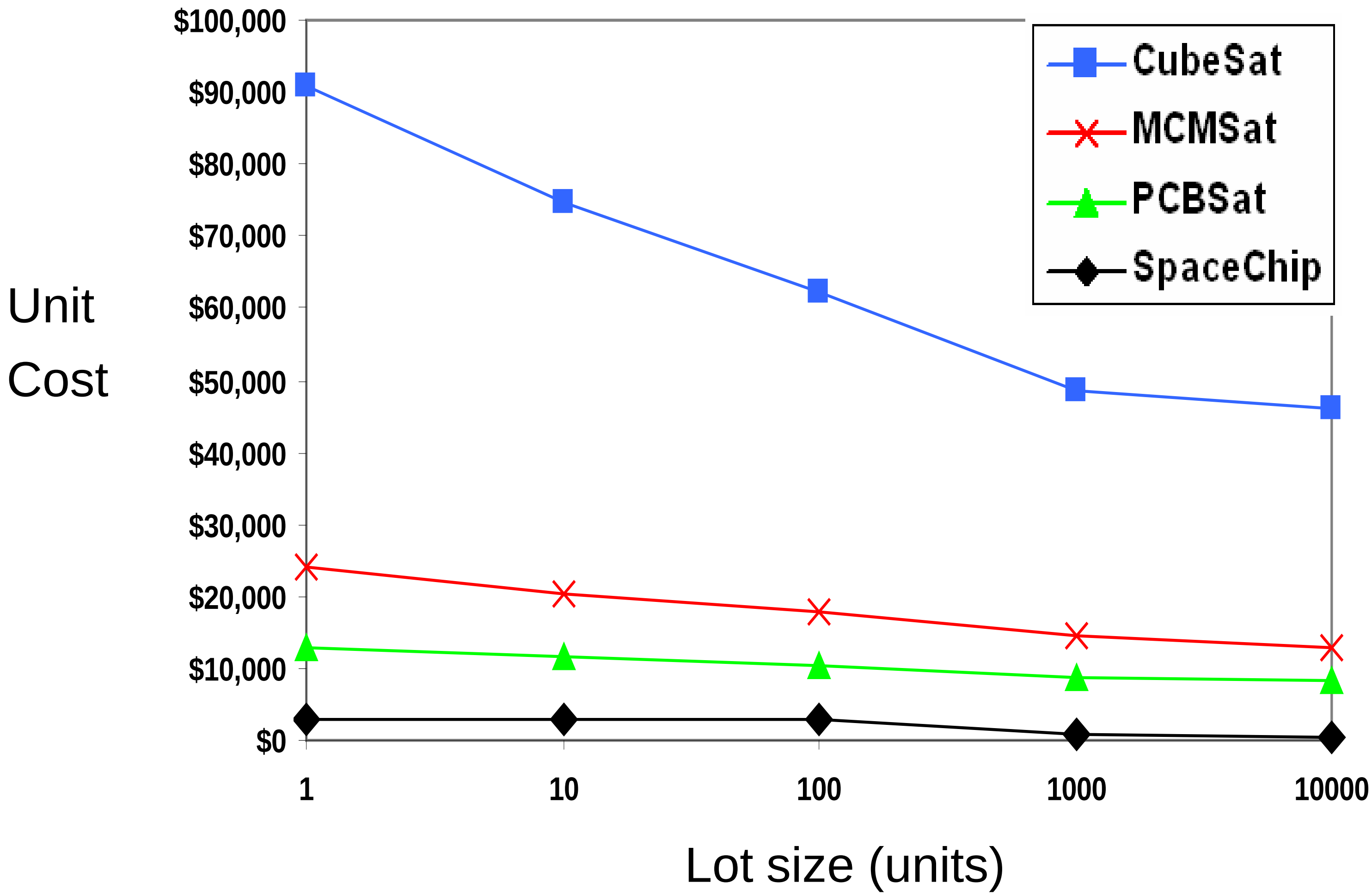
1U CubeSat and Femtosatellite Unit Costs vs. Lot Size



These costs are for spacecraft without specialized payload development costs.

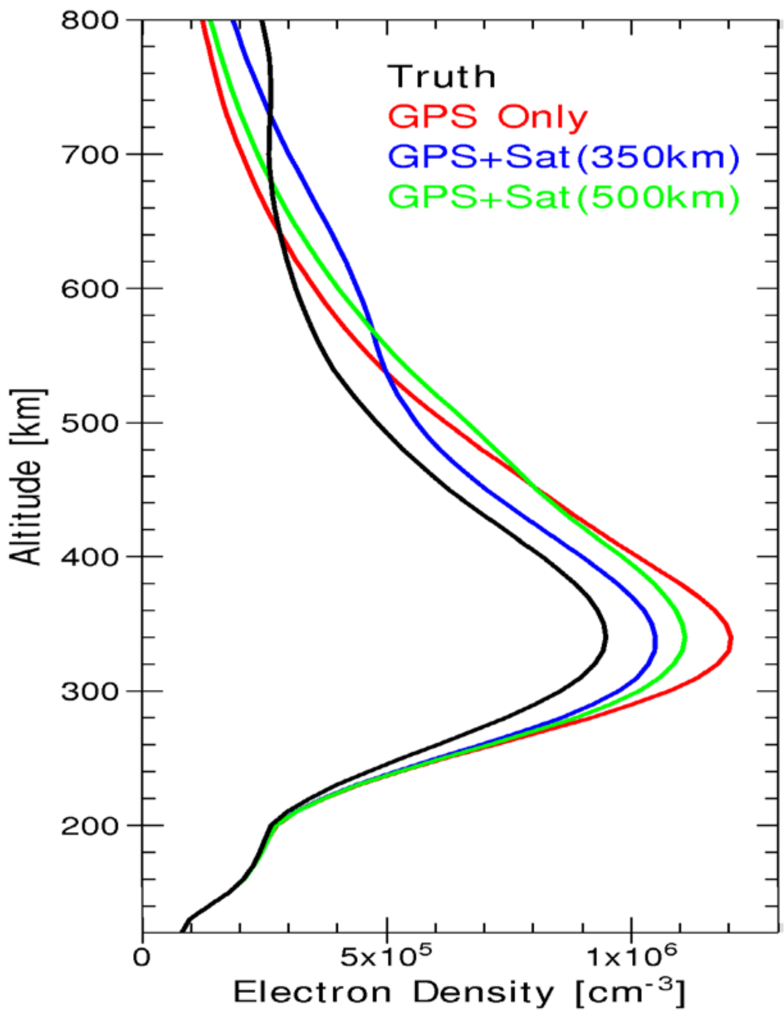
Potential FemtoSatellite Missions:

- **Active West Ford**
  - 100's to 1,000's of femtosatellites, not 100,000,000's
  - Amplifying cloud (femtosats act like excited atoms in a laser)
- **Space weather monitoring**
- **Upper atmospheric density monitoring**
  - Add ~20-gram GPS receivers and low-power rf transmitters as beacons
  - Spherical spacecraft with different surface textures
  - Dual-use as radar calibration targets like ODERACS
- **One-way satellite inspector**
- **Terrestrial gamma-ray flash monitoring**

This is just a subset of possible missions.

Space Weather Monitoring:

- **Distributed sensor platforms**
  - Improve spatial resolution
  - Data for input into global atmospheric models like GAIM
- **Small in-situ sensors**
  - Micro ElectroStatic Analyzer (MESA)
  - Langmuir probes
  - Radiation dosimeters



Extra plasma sensors, especially at low altitudes, improves ionospheric models.

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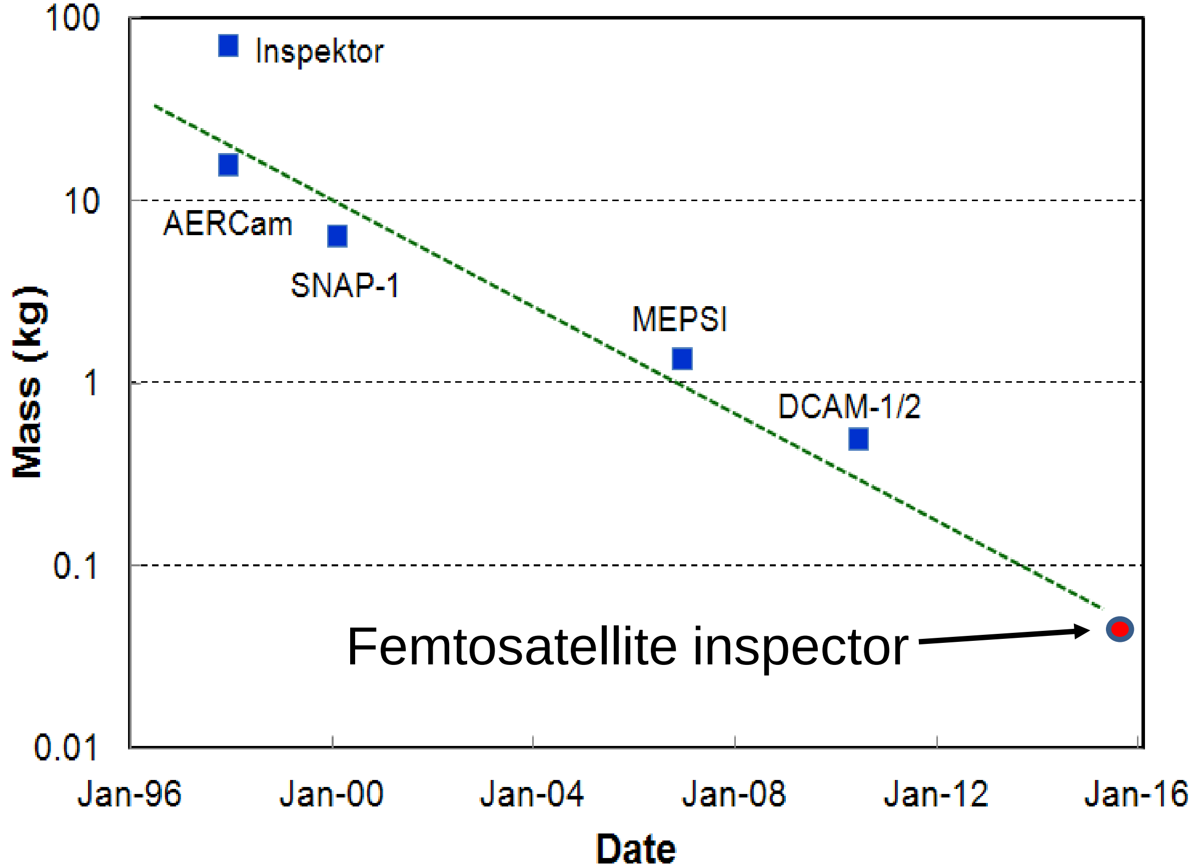
Satellite Inspectors:

- **Satellite inspectors are ejected from a cooperative host**
  - Provide imagery of host for anomaly resolution or publicity
  - Can carry other sensors/sources for on-orbit calibration of host systems
- **~1-kg mass experimental inspectors have flown**
  - MEMS-Enabled Picosatellite Inspector (MEPSI, 2006)
- **Concept makes many satellite owners nervous**
  - Co-orbiting spacecraft could collide with host vehicle
  - Control issues occurred with Inspecktor and Mir (1997)
- **One-way inspectors are easier to implement, and lighter**
  - Japanese DCAM-1/2 were ~0.5-kg in mass (2010)
  - 40-gram mass one-way inspectors are feasible

One-way picosatellite inspectors have been flown.

Satellite Inspectors: Mass History and Future

- **40-gram inspector:**
  - VGA CameraCube
  - Hope RFM22B transmitter, ~1-gram
  - 1.2-gram lithium polymer battery
  - 0.3-gram brushless DC motors
  - 2.5-gram torque coils



One-way femtosatellite inspectors can be fabricated today.

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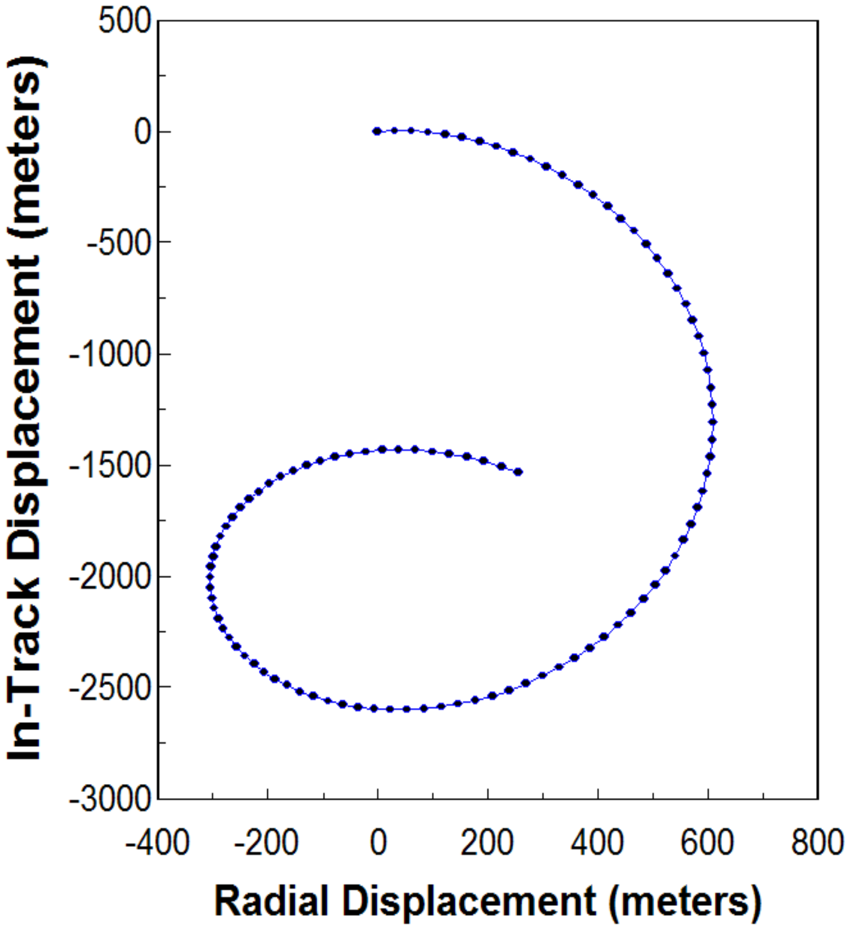
One-Way Satellite Inspector Trajectory:

- **Example trajectory from a LEO host satellite:**
  - Host in 360-km altitude orbit
  - 0.5-m/s ejection speed
  - Ejected 10º from nadir direction
  - Dots are 1-minute apart
  - Maximum range of 2.5 km over first 92 minutes of flight



One-way trajectories from spacecraft in LEO can provide collision avoidance and km-scale ranges for an hour or more to enable low-power communications between inspector and host.

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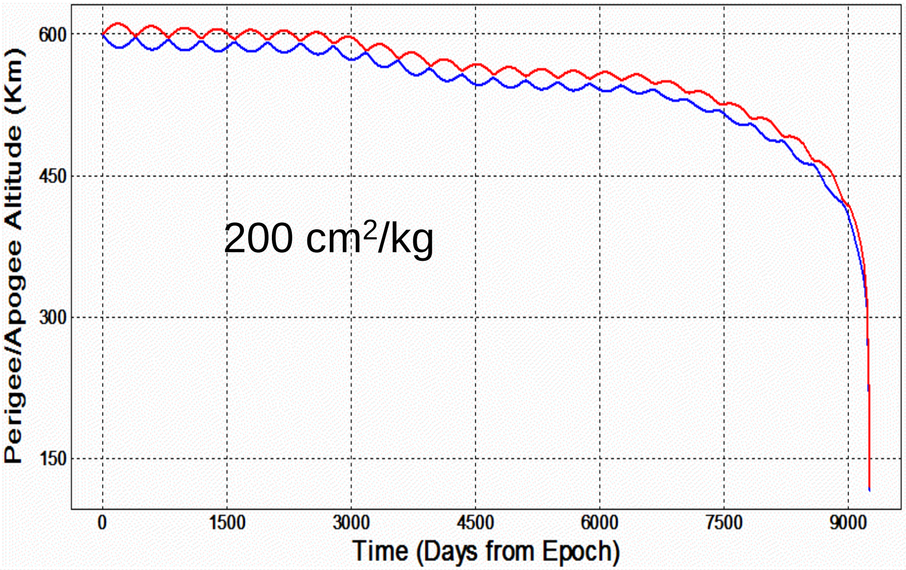
Terrestrial Gamma-Ray Flash Monitoring:

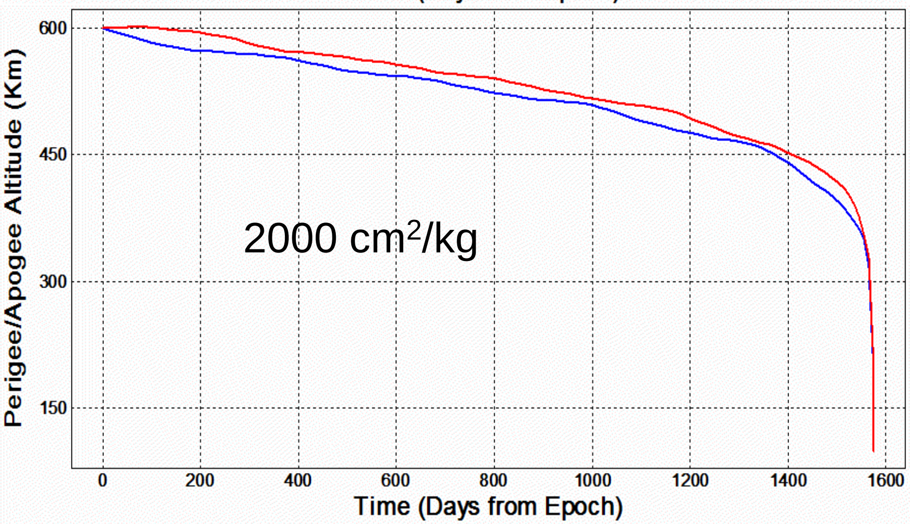
- **Terrestrial gamma-ray flashes (TGFs)**
  - Occur during lightning strikes
  - Origin is 10 to 20-km altitude
  - 0.1 to 100-MeV gamma ray energies
  - TGFs occur during ~0.01% of lightning flashes
  - Thousands have been observed by NASAs SWIFT and other spacecraft
  - Gamma ray detection area is a few hundred kilometers in diameter at ~500-km altitude
  - TGF burst lasts up to 2 milliseconds
  - Mechanism not completely understood
- **Femtosatellite detection?**
  - CdZnTe detector mass ~30-grams
  - Hundreds of femtosatellites would offer better detection statistics and data

Terrestrial gamma ray flashes occur randomly in the tropics. This is a good application for hundreds of distributed simple detectors in low Earth orbit.

Orbital Evolution Using Variable Drag:

- **Thin rectangular femtosatellites:**
  - 100-gram mass
  - 1 x 10 x 10-cm dimensions
  - C_d A/m ranges from 200 to 2000 cm^2/kg
  - 600 km starting altitude
- **Low-drag mode has 26 years of orbital lifetime**
- **High-drag mode has 4.3 years of orbital lifetime**
- **Difference in drag enables significant orbit control**
  - Orbit rephasing
  - Altitude changes
  - Changes in RAAN





A 10 x 10 x 1-cm femtosatellite can carry four 1-W triple-junction solar cells and provide a 10:1 range in ballistic coefficient for significant orbital maneuvering; assuming you're patient.

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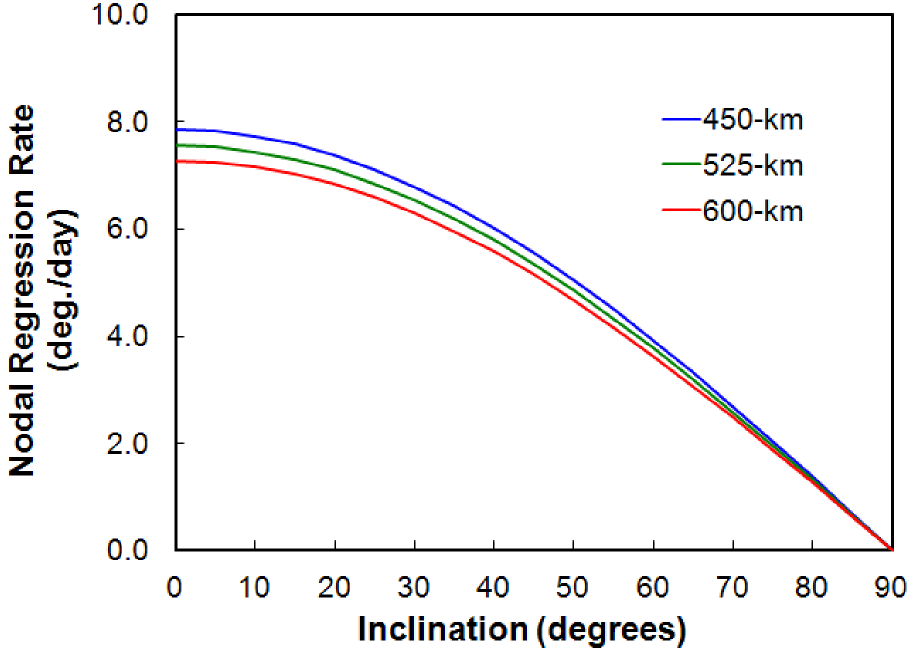
Changing RAAN for Creating Distributed Constellations

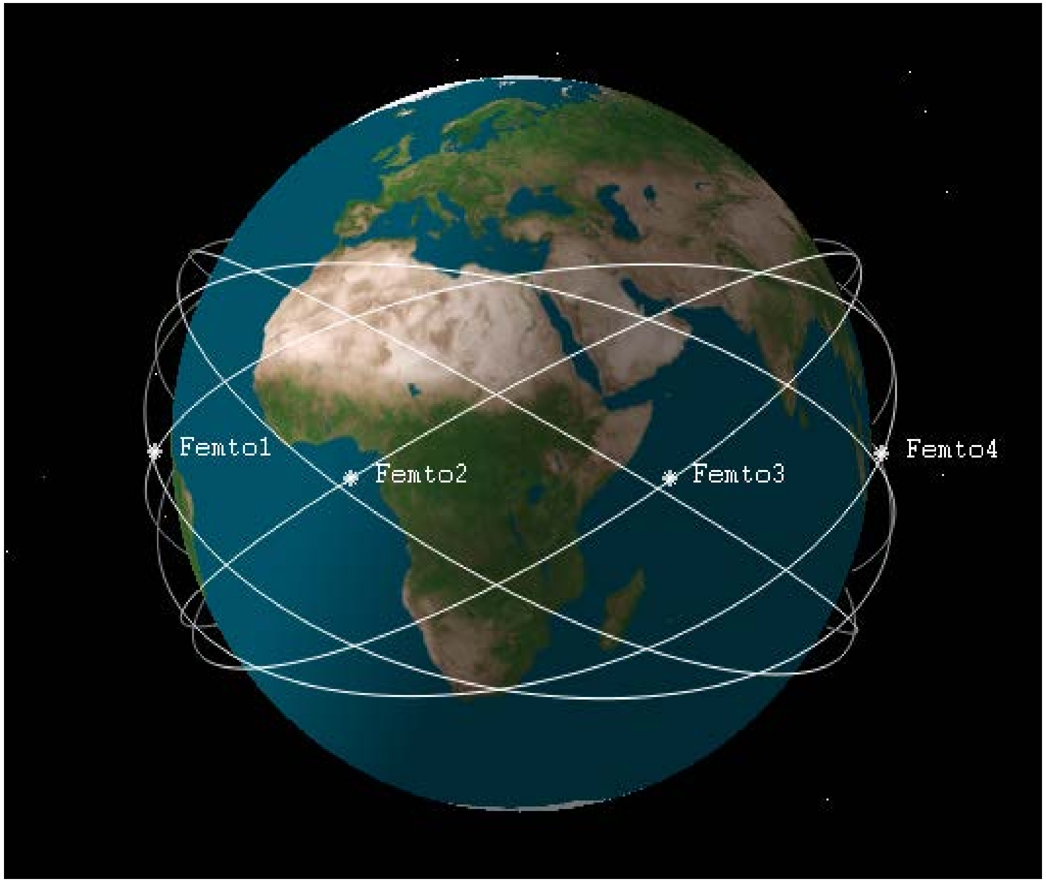
- **Nodal regression rate is a function of altitude:**
  - Changing altitude changes the nodal regression rate
  - Orbit planes can disperse if the altitudes are different
- **Deploying two orbit planes:**
  - Deploy femtosatellites from a common carrier (CubeSat)
  - 50% go into high-drag mode, 50% in low-drag mode
  - After a fixed time, high-drag sats enter low-drag mode at lower altitude
  - Both sets wait as RAAN differences increase over time
  - Higher altitude set repeats process to drop to altitude of lower set



A coordinated routine of high-drag/low-drag operation can split an initial cluster of spacecraft into two groups orbiting at lower altitude in different orbital planes

8-Femtosatellite Walker Constellation in a CubeSat

- **8-planes from a single CubeSat:**
  - Eight 100-gram femtosatellites in a single 1U CubeSat (Femto5 through Femto8 are behind the Earth)
  - 30º orbit inclination for TGF constellation (tropics coverage)
  - 4-years to establish
  - 4-years of remaining lifetime
  - Satellites can be rephased within each orbit as required



A fully-distributed Walker constellation can be launched inside a CubeSat without requiring on-orbit propulsion. Attitude control, however, is required over many years of operation.

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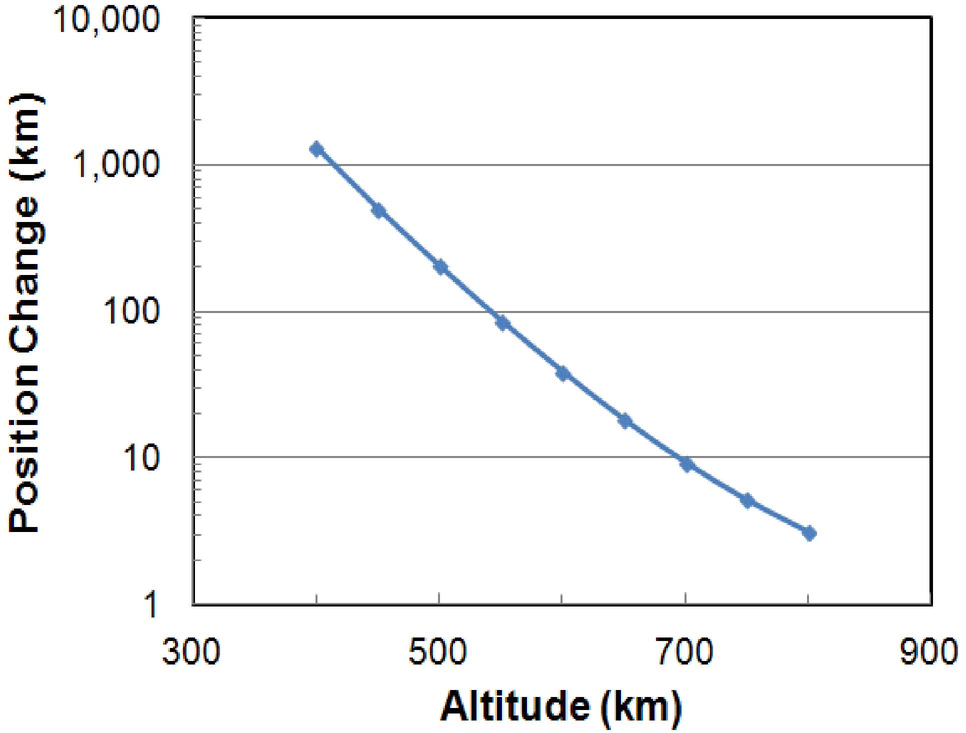
Femtosatellites Don't Have to be DebriSats

- **Thin femtosatellites can be fairly maneuverable without propulsion**
  - 100-gram mass
  - 1 x 10 x 10-cm dimensions
  - Min/Max drag control

Position change after 3-days between spacecraft in high-drag and low-drag attitude.



With attitude control and a 10:1 range in ballistic coefficient, a femtosatellte can avoid a collision with another space object for altitudes below 700-km if given at least 3-days notice.

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Summary

- **Femtosatellites are coming!**
  - Experimental “Sprites” are on orbit
  - 40-gram mass satellite inspectors are possible
- **Femtosatellite missions exist**
  - Active West Ford
  - Space weather monitoring
  - Upper atmospheric density monitoring
  - One-way satellite inspector
  - Terrestrial gamma-ray flash monitoring
- **Highly-capable femtosatellites are possible**
  - Attitude control using micro reaction wheels
  - Orbit control using variable drag

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