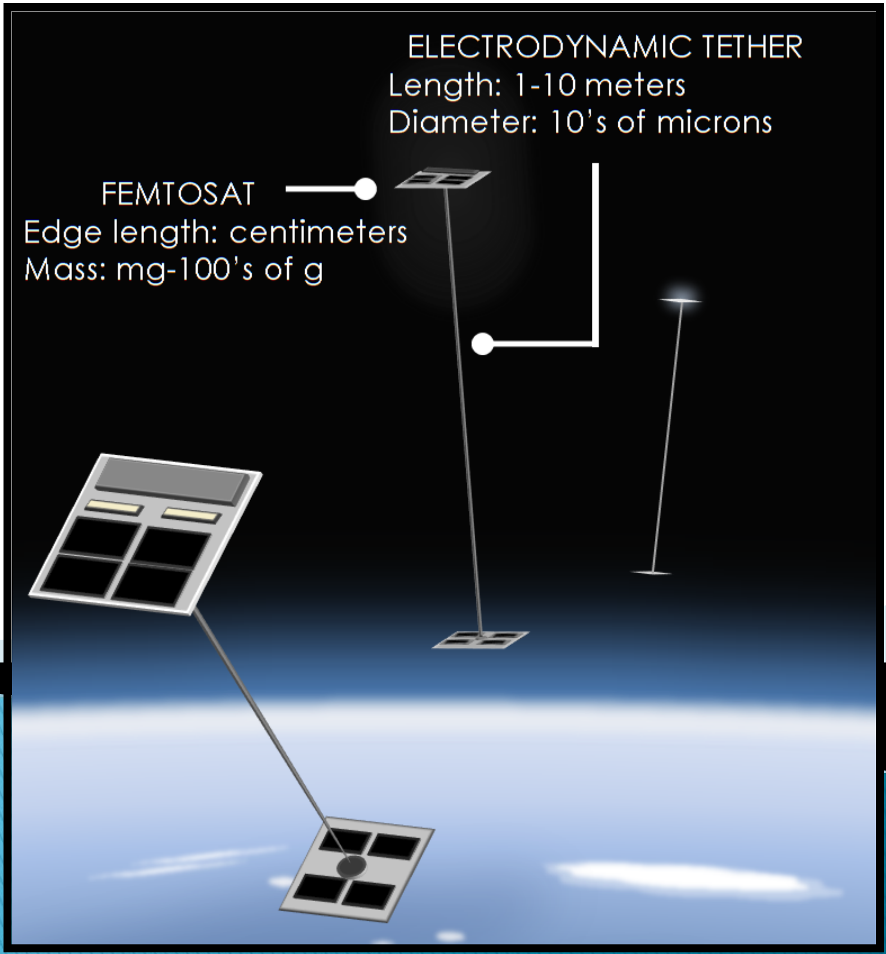
Exploring the Use of Miniaturized Electrodynamic Tethers to Enhance the Capabilities of Ultra-small Satellites

Iverson C. Bell, III
Brian E. Gilchrist
The University of Michigan



Presentation Outline

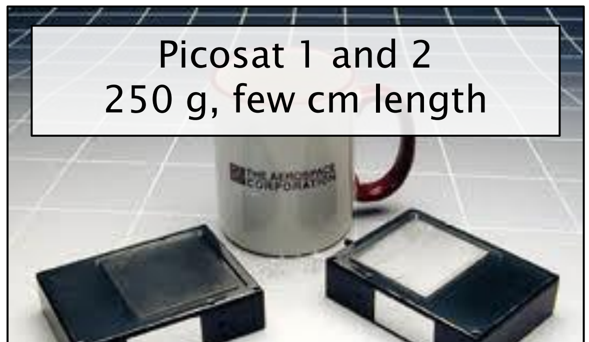
- Ultra-small satellites
- Miniaturized electrodynamic tethers
- Dual femto/picosatellite tether concept
- Trade study results
  - Estimating power needed for propulsion
  - Estimating thrust
  - Estimating tether performance as antenna

Picosats, Femtosats, ChipSats, and *Ultra-small* Sats

- Picosatellites (1 kg–100 g) and femtosatellites (<100 g) are the next steps in satellite miniaturization. Think of flying your iPhone or Android with highly capable, enhanced MEMS sensors.

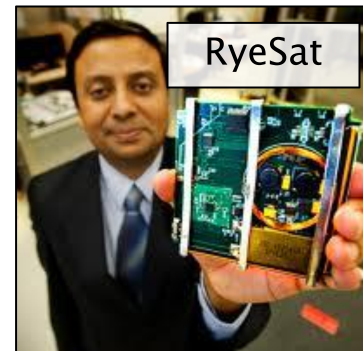
Sprite Chipsat
7.5 mg, 1×1×0.025 cm

Cornell University



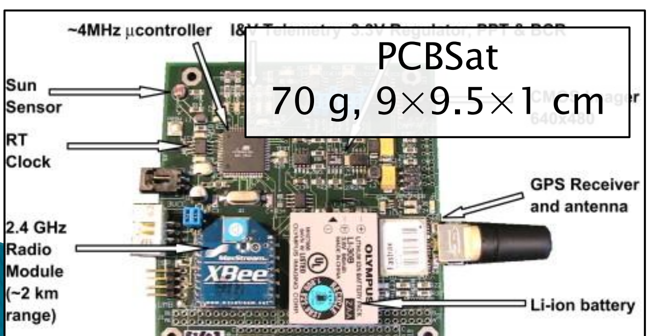
Picosat 1 and 2
250 g, few cm length

DARPA/Aerospace Corp.



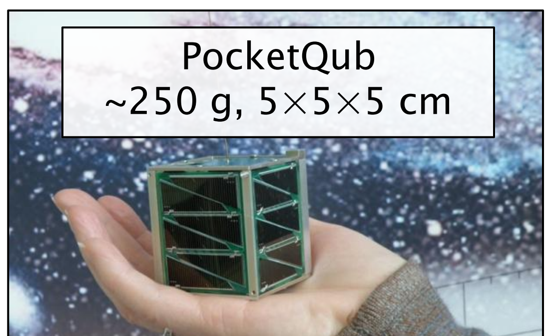
RyeSat

Ryerson University



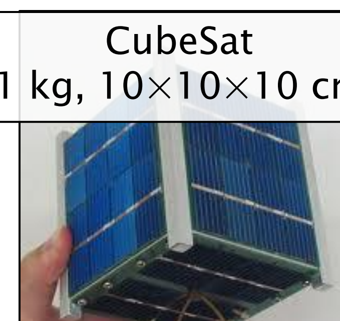
PCBSat
70 g, 9×9.5×1 cm

University of Surrey



PocketQub
~250 g, 5×5×5 cm

Morehead State University



CubeSat
1 kg, 10×10×10 cm

U of M, Everywhere

What are some applications for ultra-small sat *fleets*?

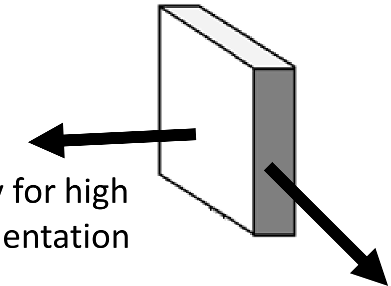
- Planetary monitoring
  - Fleet of satellites equipped with small cameras
  - Could enable global monitoring of forest fires, earthquakes, tsunamis, etc… and mapping other planetary bodies

- *In situ* multipoint measurements of the ionosphere/thermosphere
  - Fleet of satellites equipped with simple plasma probes
  - Investigating the temporal evolution of the ionosphere
  - Enabling validation of space weather forecasting models and the structure and dynamics of plasma bubbles

- *Fractionated* system architecture

Some Big Challenges for Small Sats

1. Missions using *fleets* of pico/femtosats **require** coordination/maneuverability (propulsion).
2. Ultra-small satellites have a short orbital lifetime



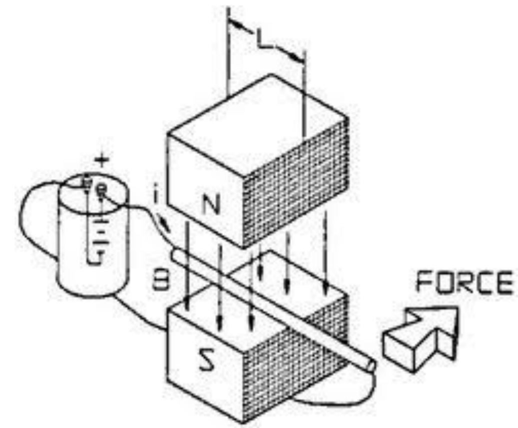
A *Rough* Estimate of Satellite Lifetime due to Atmospheric Drag					
Parameters	3 kg CubeSat	8 g ChipSat		7.5 mg ChipSat	
Configuration	3-1000 cm^3 cubes, stacked upright	Low drag	High Drag	Low Drag	High Drag
Ballistic Coeff.	45	95	2.5	13.6	0.03
Alt = 300 km	a month	**a month**	hours	**several days**	~
Alt = 400 km	several months	**several month s**	days	**several weeks**	hours
Alt = 500 km	~1 year or more	**~1-2 years**	weeks	**several months**	hours

Early concepts also have no propellant so the orbital lifetime is *short*

3. Limited power and size for comm system
4. Their size makes them difficult to track

Electrodynamic Tethers (EDTs) are Capable of Propellantless Thrusting

A force is produced when electric current travels in a conductor in the presence of a magnetic field.



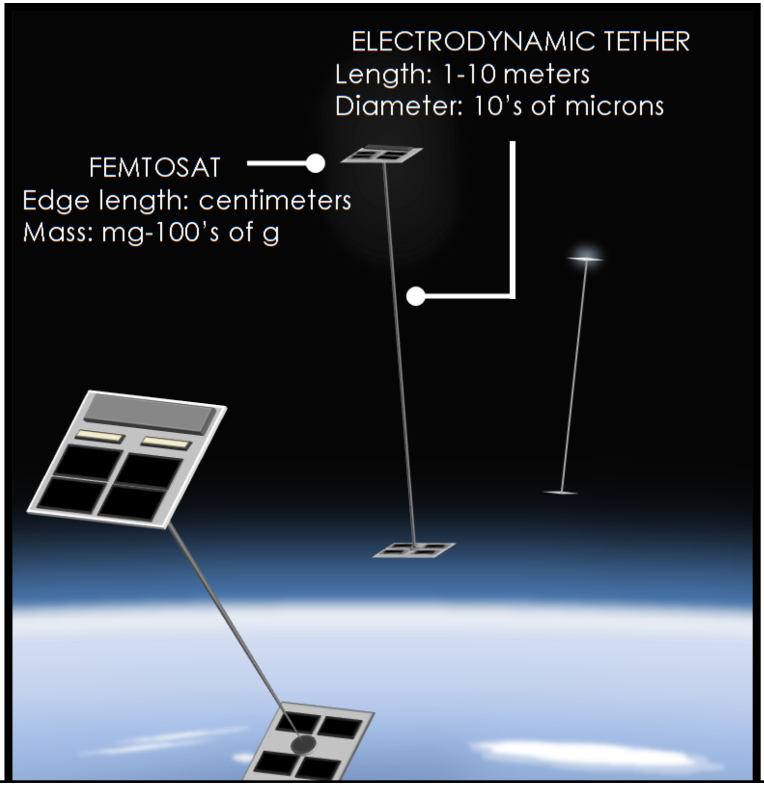
$$\mathbf{F}_{\mathrm{Lorentz}} = \int_{0}^{Wire\_Length} \left(I_{\mathrm{wire}} d\mathbf{L} \right) \times \mathbf{B}_{\mathrm{Permanent\,magnet}}$$

An electrodynamic tether is a current-carrying conductor that can generate force in a planetary magnetic field.

$$\mathbf{F}_{\mathrm{ElectrodynamicTether}} = \int_{0}^{Tether\_Length} \left(I_{\mathrm{tether}} d\mathbf{L} \right) \times \mathbf{B}_{\mathrm{Earth}}$$

Connected to a satellite, this force can be used to overcome atmospheric drag and change the satellite's altitude or inclination.

Motivation for Using Miniaturized EDTs with Ultra-small Satellites



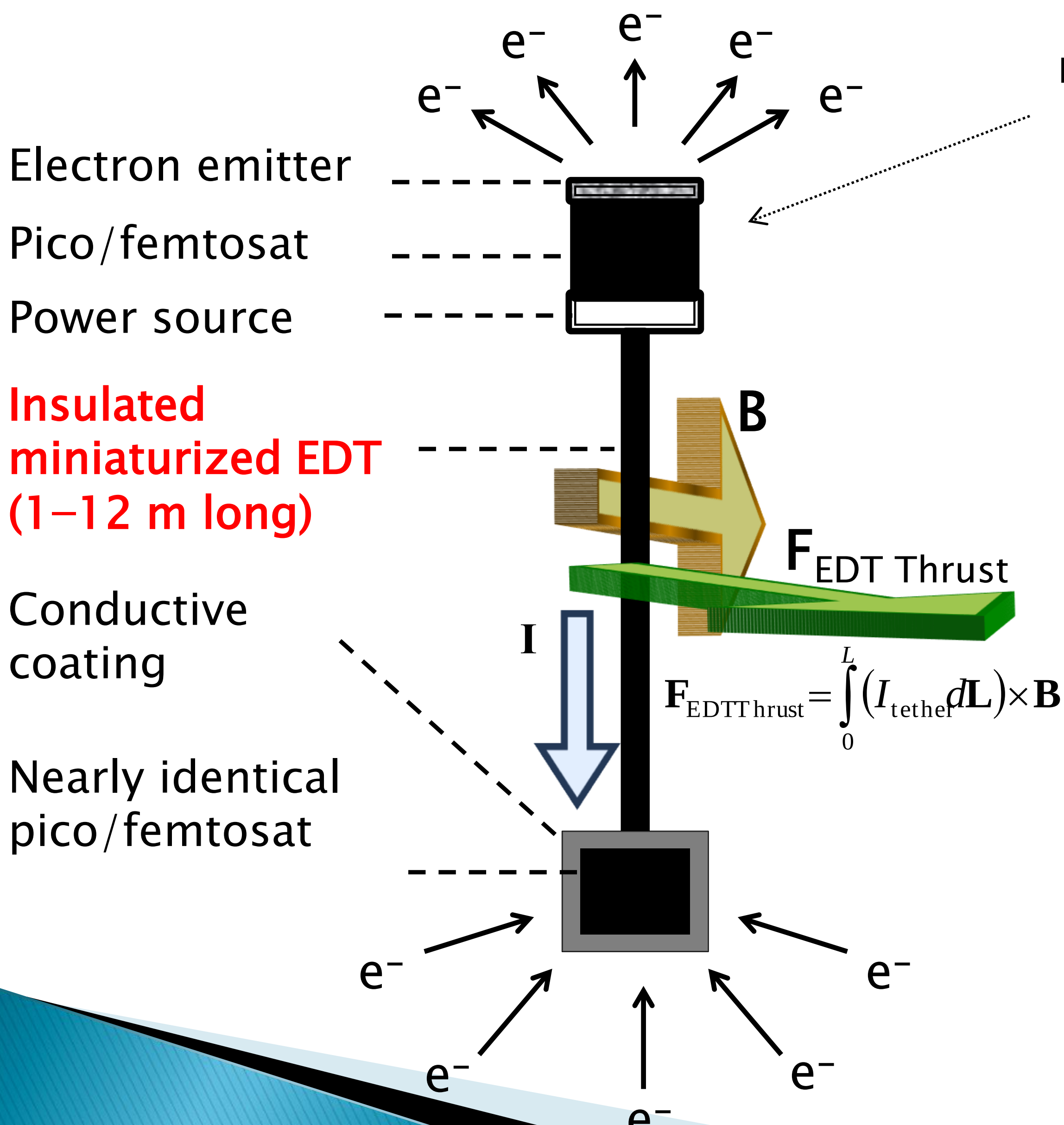
Concept of ED tethers with pairs of femtosats as a maneuverable and coordinated fleet.

- Conventional EDTs can provide propulsion
  - ✓ Change inclination, altitude, etc.
  - ✓ Reboost and deboost
  - ✓ No consumable propellant
- Additional benefits may include:
  - ✓ Providing gravity gradient stability
  - ✓ Transmitting and sending data as a VHF or UHF antenna
  - ✓ Measuring properties of the ionospheric plasma as a Langmuir probe
- EDT miniaturization means
  - ✓ Shorter & thinner than other EDTS
  - ✓ Lower power: lower current & voltage

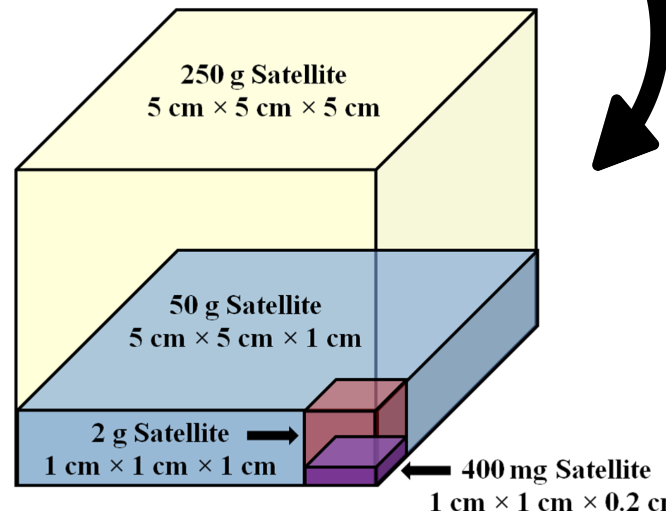
My research questions:

Can electrodynamic tethers provide ultra-small satellites with lifetime enhancement and maneuverability? Can it provide other capabilities?

Trade Study System Concept



Four satellites were considered in the trade study, but we show analysis for the 250 g sat



Both satellites have

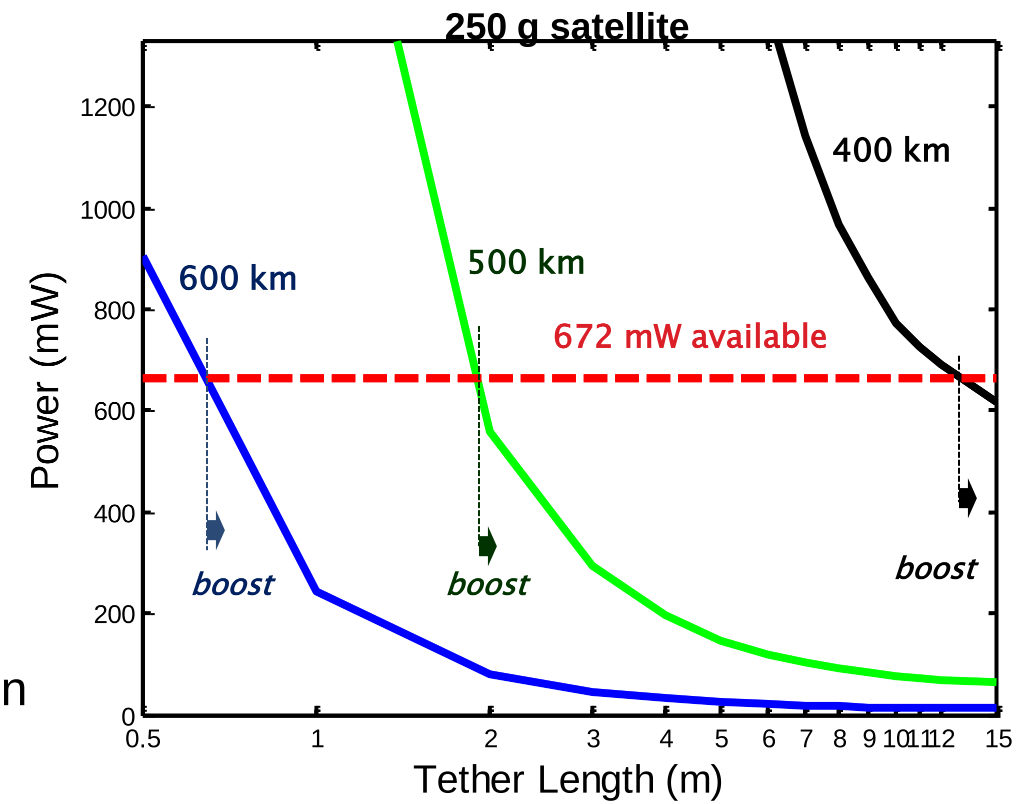
- *solar panel*
- *power supply*
- *electron emitter*
- *capable of collecting electrons on the surface*

System is capable of boost, deboost, and inclination change

Estimate of Power Needed and Available for Drag Make-up

- Estimated that solar cells provide 4.4 $mW \cdot cm^{-2}$
- If more power is available than required, the EDT can boost
- Right, power needed for drag make-up at
  - 400 km (**black**)
  - 500 km (**green**)
  - 600 km (**blue**)

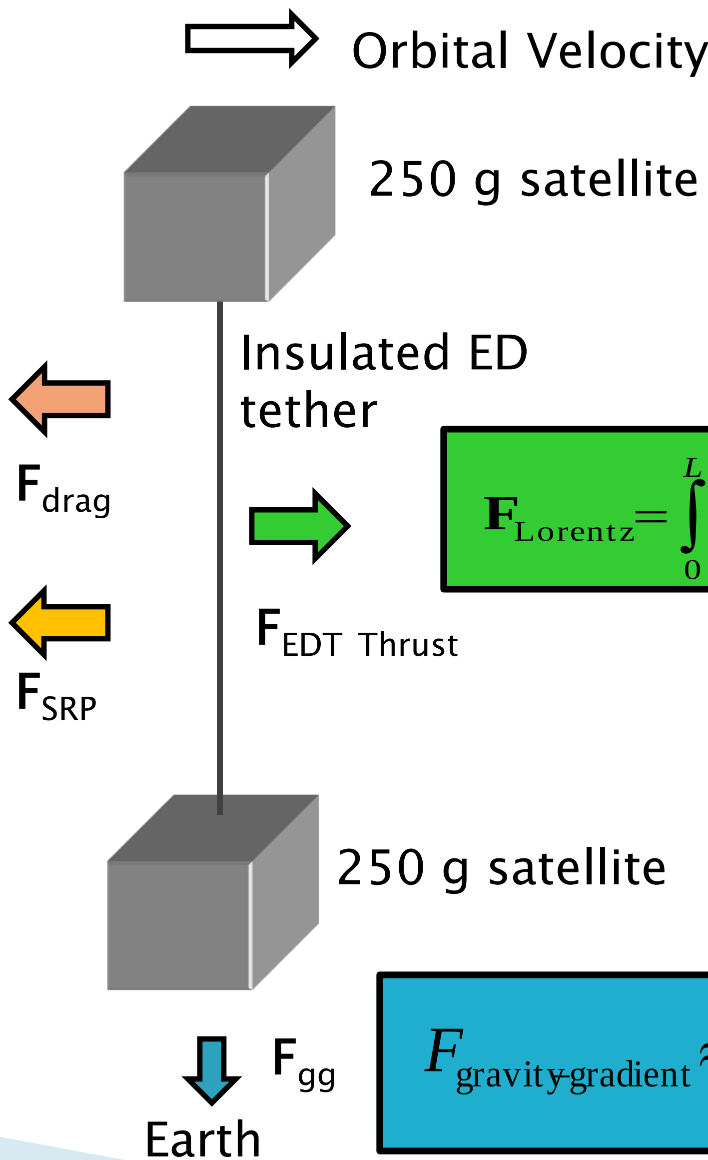
  and power available for propulsion (**red**)



Considerations for estimating available power
- Solar angle, time in sunlight, total PV area
- Conversion and distribution inefficiencies
- Demands from other loads

Considerations for estimating needed power
- Orbital conditions (atmospheric, plasma density)
- Ram area (drag make-up force)
- EDT propulsion power demands

Dominant Forces on Dual 250 g Satellites with ED tether



$$\mathbf{F}_{drag} = \tfrac{1}{2}\rho C_d A v^2 \hat{\mathbf{v}}$$

$$\mathbf{F}_{Lorentz} = \int_0^L (I_{tether}\, d\mathbf{L}) \times \mathbf{B}$$

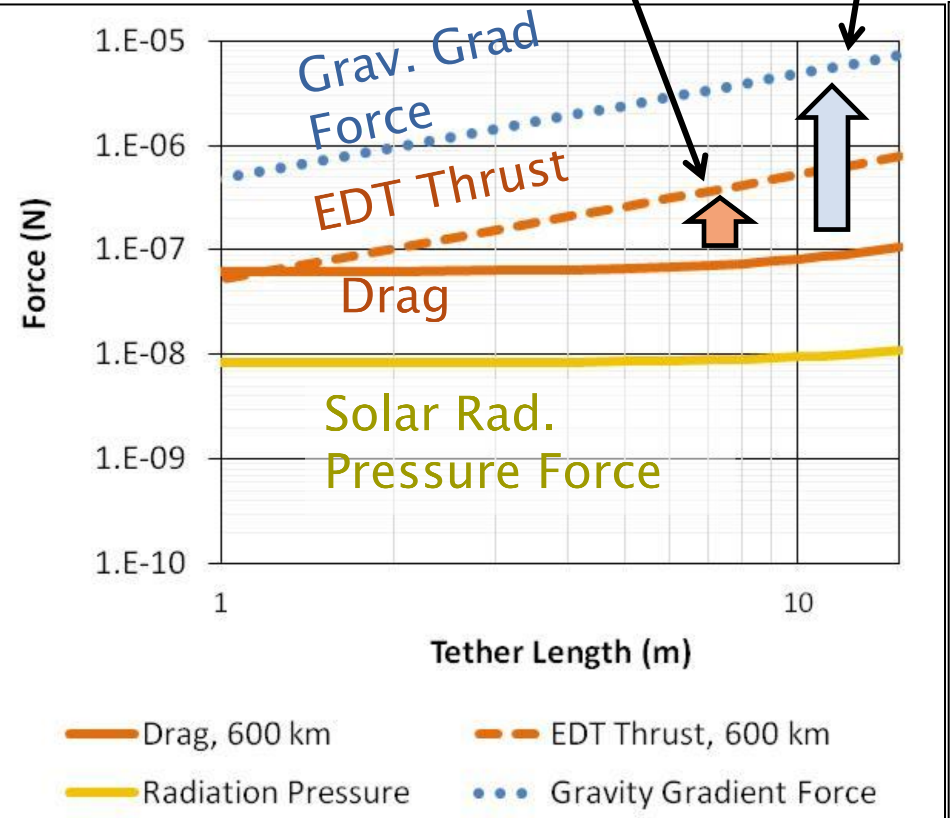
$$F_{SRP\_MAX} = \frac{Area\_\Phi_{direct}}{c}\left[\frac{1+\Gamma_{spec}}{\pi} + \frac{\Gamma_{diffuse}}{2} + (1-\Gamma_{spec}) + 2\left(\frac{\Gamma_{diffuse}}{3} + \Gamma_{spec}\right)\right]$$

$$F_{gravity\text{-}gradient} \approx \frac{3m\mu L}{R_0^{\ 3}}$$

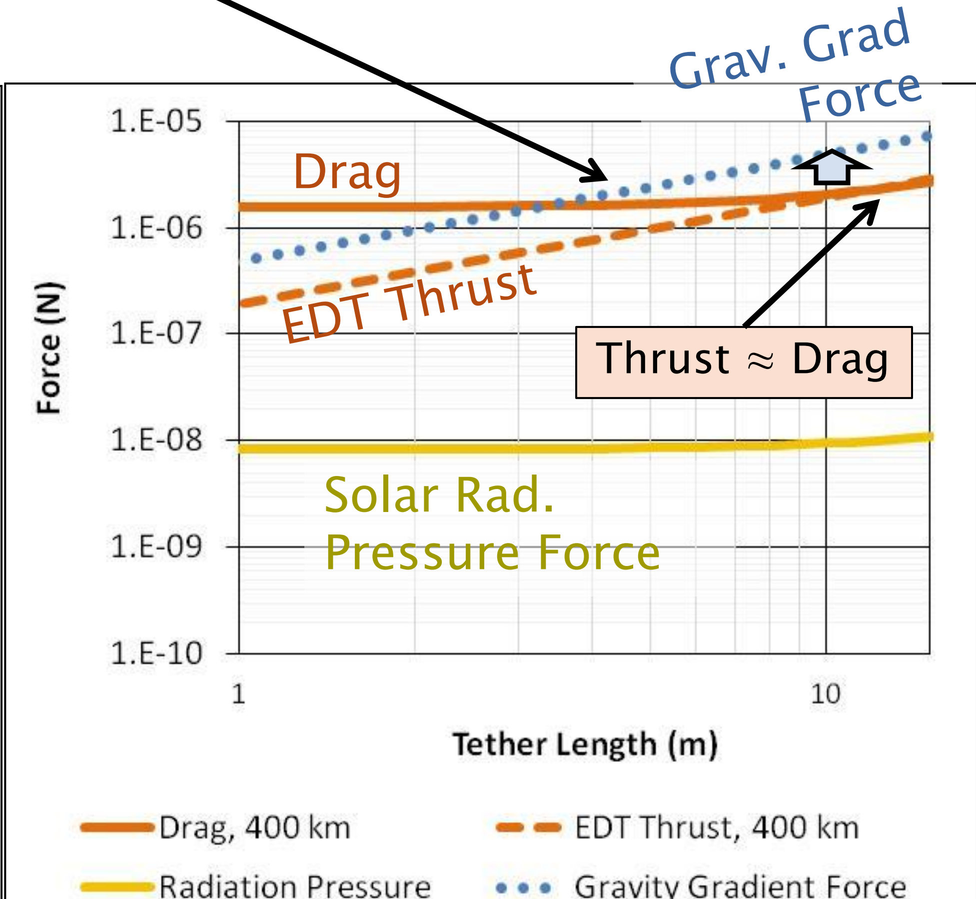
Zero-order Force Estimate

Gravity gradient stability is feasible when the gravity gradient force is greater than other forces

Drag make-up force (thrust is greater than drag)



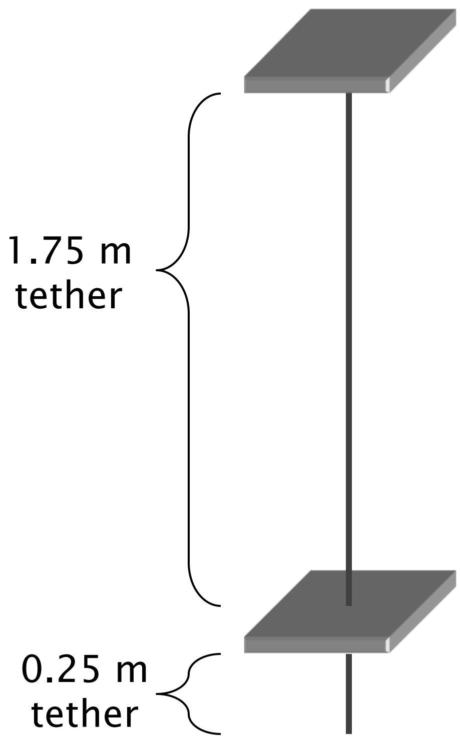
600 km Equatorial Orbit



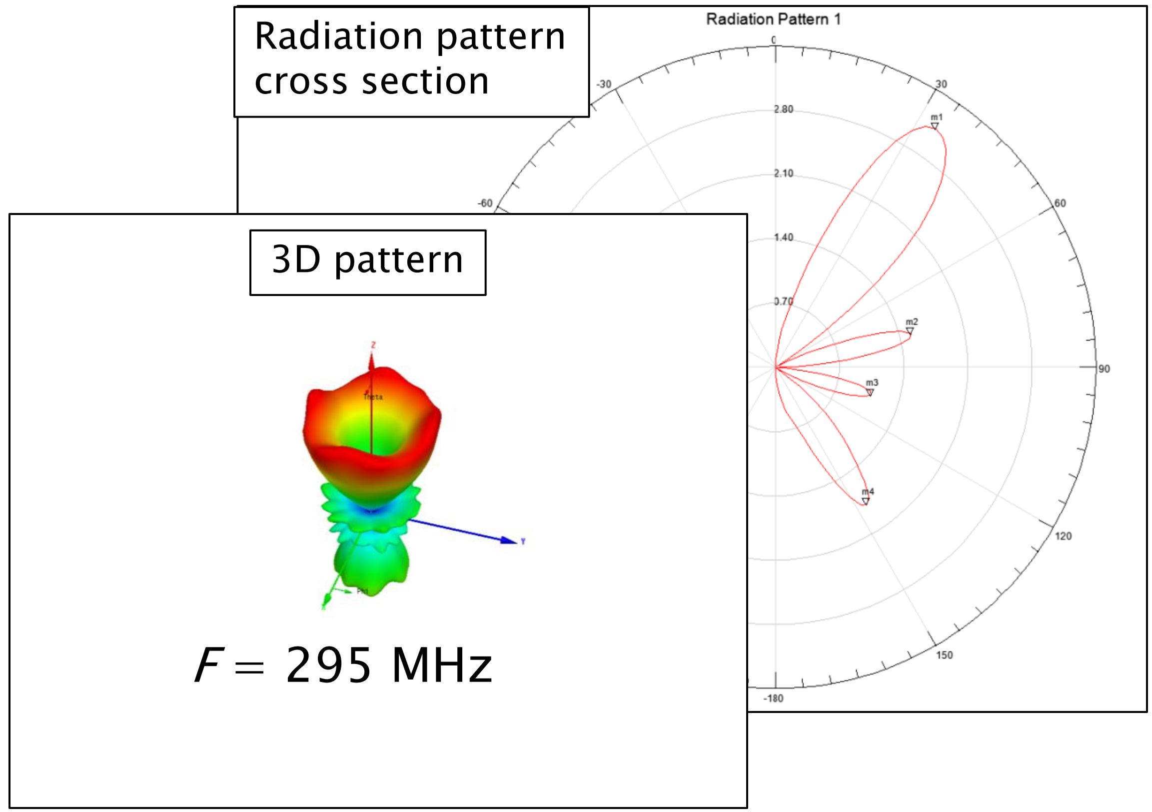
400 km Equatorial Orbit

Potential of ED Tether to Enhance Communication

Possible ED Tether Architecture for Communication



Simulated ED Tether Radiation Pattern



HFSS was used to model the ED tether as an antenna. We have considered an off-center dipole configuration.

Future work

- Laboratory experiments scaled to capture the critical characteristics of the LEO environment could provide a more accurate estimate of

  - current collection and emission *(plasma electrodynamics modeling and experiment*)

  - attitude and tether bending (*dynamics modeling and experiment*)

- We will also be working towards an orbital experiment

Developing an orbital experiment

- The objective of the *Miniature Tether Electrodynamics Experiment* (MiTEE) will be a technology demonstration mission that will utilize CubeSat capabilities to deploy a PicoSat–tether system and assess the key dynamics and electrodynamics fundamental to the tether system's successful operation.
- 15 students (undergraduate and graduate)
- Currently developing requirements and selecting the mission concept

Conclusions

- Insulated EDTs only a few meters long show potential to be used for femtosat and picosat lifetime enhancement and maneuverability.
  - Capable of nN to μN thrust levels

- The ED tether is less able to overcome drag at lower altitudes
  - Due to increased neutral density and decreased plasma density-to-neutral density ratio

Parameter	400 mg	2 g	50 g	250 g
Satellite Dimensions	1 × 1 × 0.2 cm	1 × 1 × 1 cm	5 × 5 × 1 cm	5 × 5 × 5 cm
Tether	1 m long, 24 μm diam.	4 m long, 70 μm diam.	5 m long, 80 μm diam.	12 m long, 200 μm diam.
Mass	2 mg	12 mg	0.18 g	3 g
Thrust Power	9 mW	27 mW	318 mW	672 mW
Where is gravity gradient significant?	~600 km	600 km, ~500 km	600 km, 500 km, ~400 km,	600 km, 500 km, 400 km,

Acknowledgements

- We are grateful for support from:
  - AFOSR grant FA9550-09-1-0646
  - National Science Foundation Graduate Student Research Fellowship under Grant No. DGE 1256260
  - Michigan Space Grant Consortium graduate fellowship

Thank you

Additional Slides

Rationale Behind Reducing Satellite Size

- Reduce (↓) mass = ↓ rocket size & fuel = ↓ $
- In some cases, ↓ size = ↓ assembly/test time = ↓ $

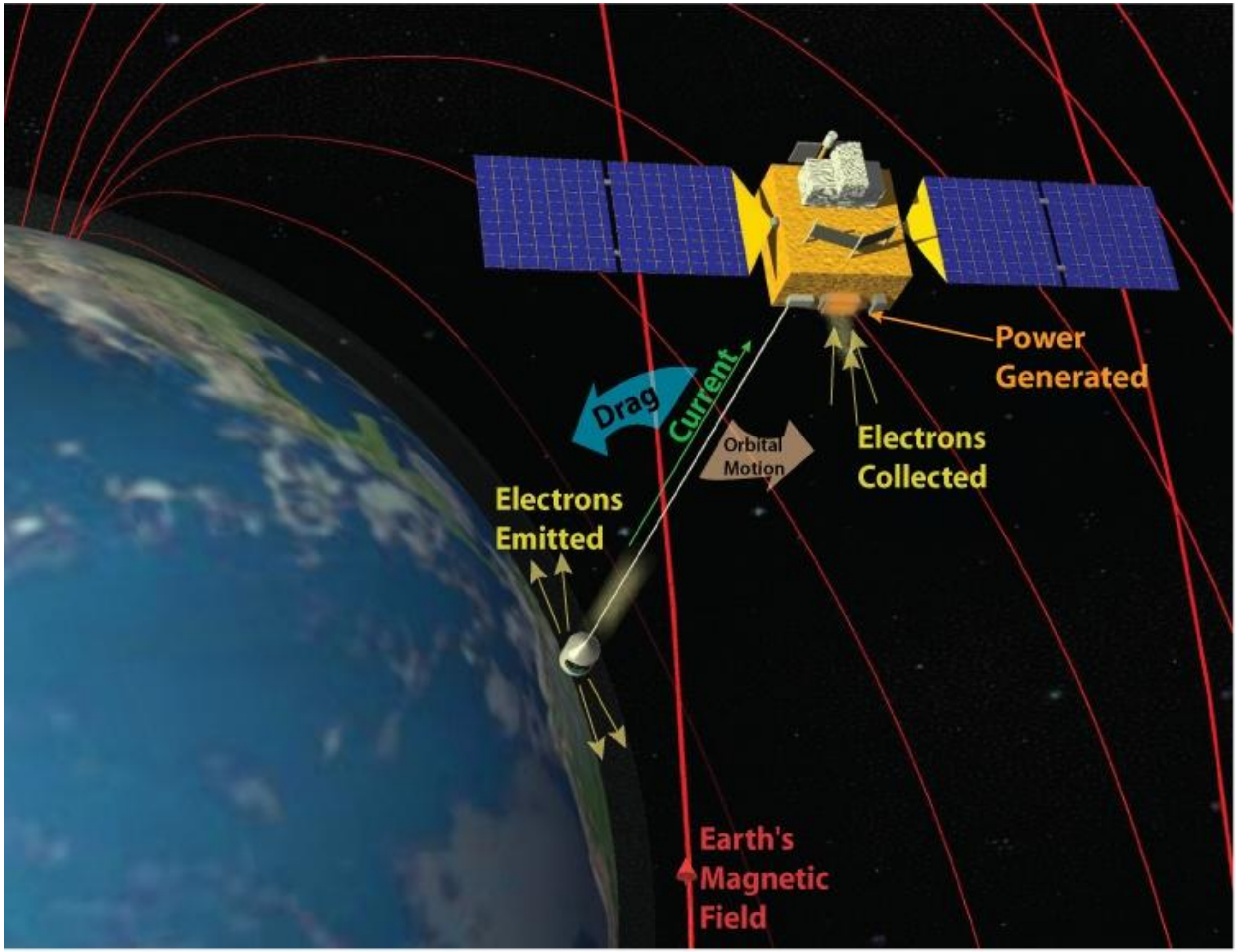
- Launch as secondary payload, i.e., "piggy-back"

- **Potential game changing technology**
  - Simultaneous, multi-point data collection
  - Rapid design, test, assembly, & deployment
  - High risk missions- provide redundancy
  - In-space communication links
  - Reconfigurable antenna arrays
  - *Things we cannot imagine*

EDT plasma electrodynamics

The tether electrical circuit is closed by collecting electrons from the Earth's ionosphere at one end and emitting them at the other end, with final circuit closure occurring in the ambient plasma.

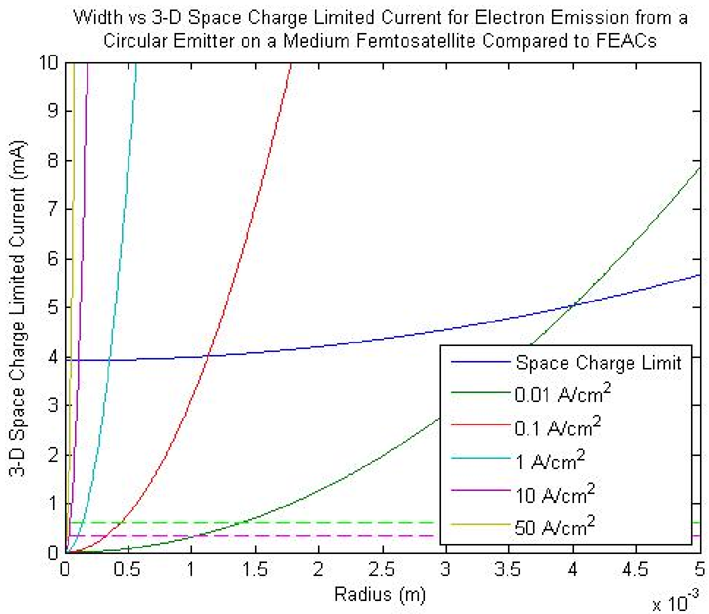
Solar panels mounted on the spacecraft provide the ED tether with the power necessary to drive current in the tether and to emit and collect electrons.

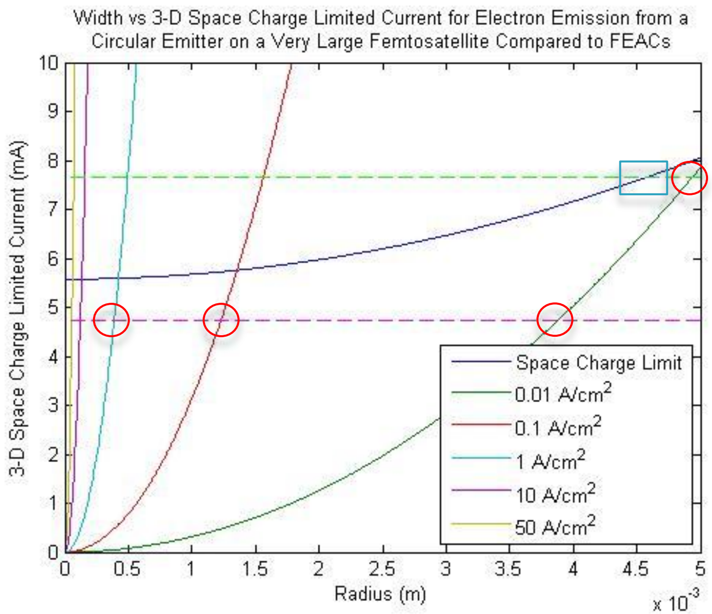


More Detailed System Summary

Parameter		400 mg	2 g	50 g	250 g
Estimated Current Needed for Drag Make-up (mA)	400 km	0.66	1.24	2.89	6.36
	500 km	0.12	0.22	0.52	1.14
	600 km	0.03	0.05	0.12	0.25
Estimated Sphindt Cathode Base-Gate Voltage (V)	400 km	43	45	49	52
	500 km	38	40	43	45
	600 km	35	36	38	40
Dimensions		1 cm × 1 cm × 0.2 cm	1 cm × 1 cm × 1 cm	5 cm × 5 cm × 1 cm	5 cm × 5 cm × 5 cm
Surface area of largest sat face (cm^2)		1	1	25	25
Total surface area of each sat (cm^2)		2.8	6	70	150

Emission Current vs Emission Area





- Tether emission current needed – horizontal dotted lines, green is for 350 km and magenta is for 500 km
- Depending on the femtosatellite emission current constraints, there may be a minimum emitter size simply due to space charge limit constraints (blue square)
- However, there can be an even larger minimum emitter size due to emitter capability (red circle)
- For all femtosatellite sizes and altitudes, the necessary emission area <2% of available emission area even for worst emission technology

Factors Impacting EDT Dynamical Interactions

- Tether Rigidity and Flexibility
  - While flexible, EDTs will have some stiffness and shape memory at the low tensions expected
- Electrodynamic and disturbance force/moments analysis
  - Exp: gravity gradient torques, aerodynamic drag, solar radiation pressure, Lorentz force

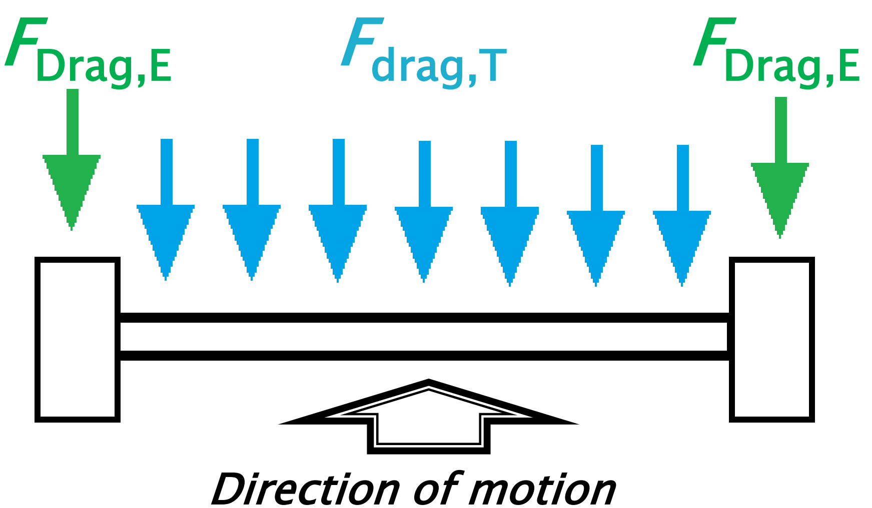
Tether Bending and Stiffness

- Forces along the tether may cause the tether to bend
  - Tension from the gravity-gradient force will not be large
- Bending is due to relative forces on the tether (F_{RT}) and the end-bodies (F_{RE})

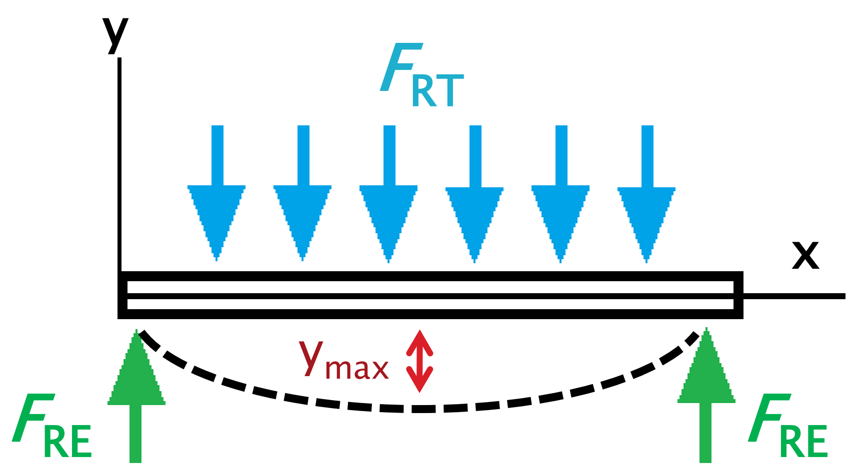
$$F_{RT} = -2\left(\frac{F_{Drag,E}\, m_{EDT} - F_{Drag,T}\, m_{endbody}}{m_{EDT} + 2m_{endbody}}\right) = -2F_{RE}$$

$$y_{max} = \frac{-5L^4}{384EI_{inertia}}\left(F_{RT}/L\right)$$

EDT with drag forces

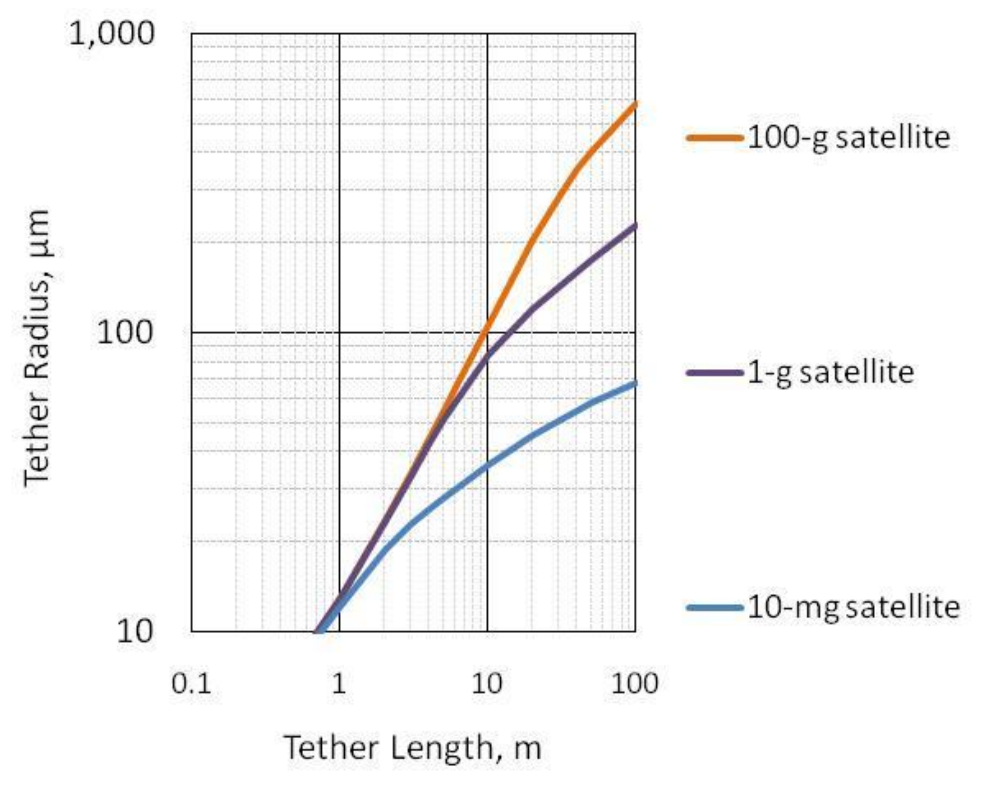


EDT modeled as simply supported beam



Tether Stiffness Continued…

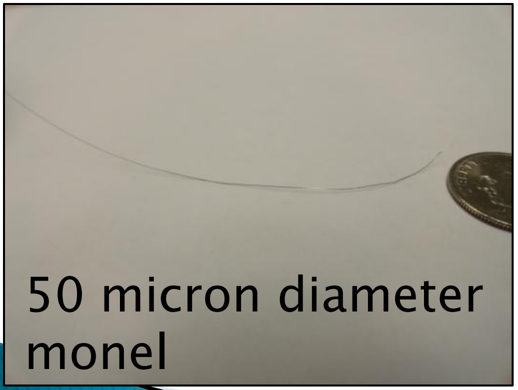
- To limit bending, the tether radius increases with length
- Tether has a Monel™ core and thin Kapton insulation
  - EDT has a high Young's Modulus, *E*
- *We have not yet studied resonant frequency,* f_{nat}

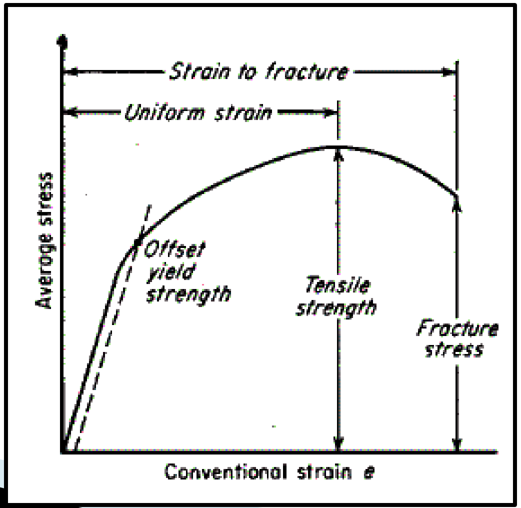


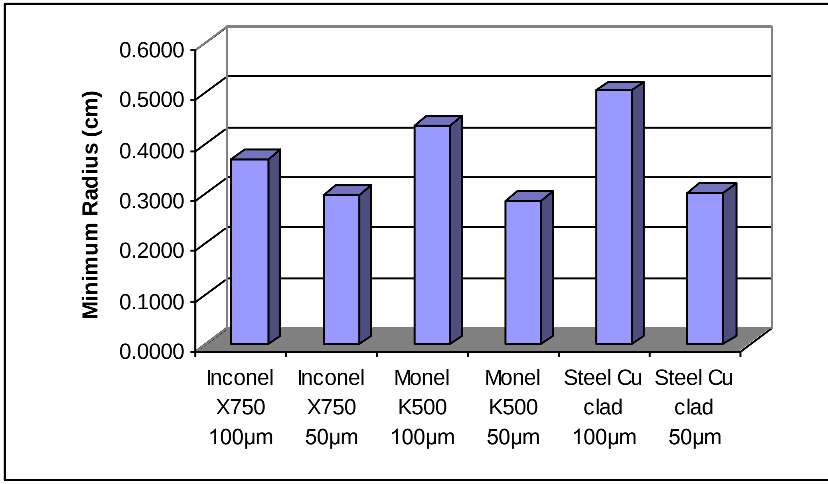
***If* rigidity is important, increasing EDT length requires increasing the radius**

Tether Flexibility: Minimum Bending Radius

- We aim to find the minimum radius so the tether can be coiled without distorting the straight, elongated equilibrium shape
  - High E ~ more rigid
  - Euler-Bernoulli Beam Theory…
    - $\rho_{min} = Ec/\sigma_Y$
    - ρ_{min} is minimum radius of elastic curvature, c is wire/beam radius, σ_Y is yield stress







Due to problems in the test set -up, these values are rough approximations