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Exploring the Potential of Miniaturized Electrodynamic Tethers to Enhance Femtosatellites and Picosatellites Capabilities

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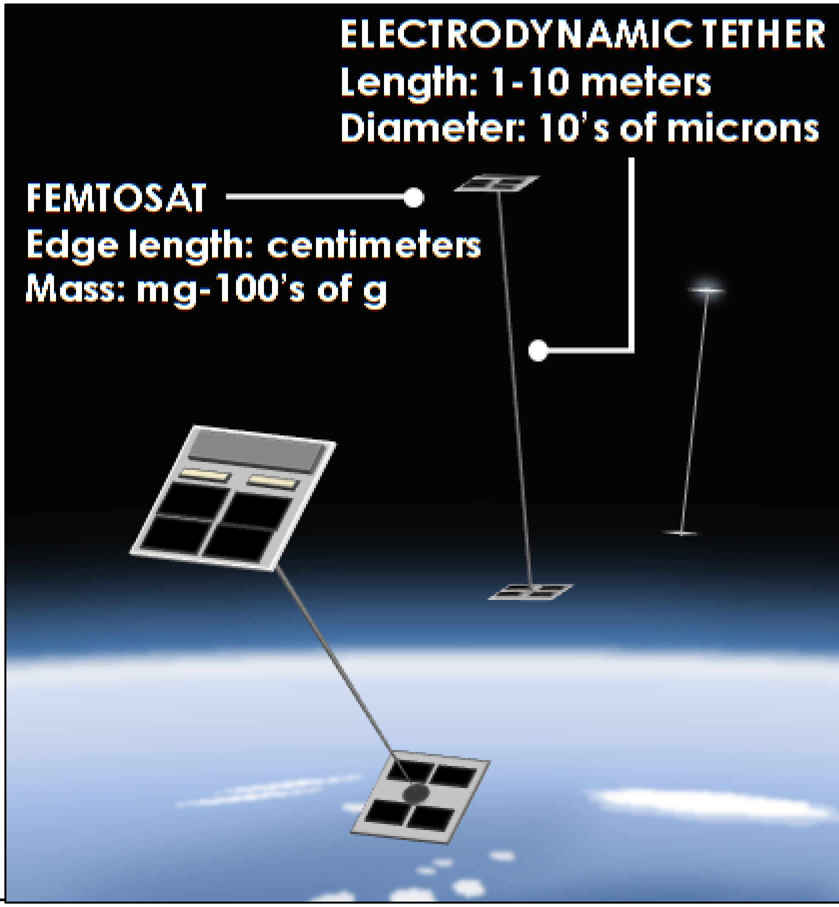
Miniature Electrodynamic Tethers (EDTs)



- EDT can provide propellantelss propulsion
  - ✓ Drag make-up
  - ✓ Change inclination, altitude, etc.
  - ✓ No consumable propellant
- Additional benefits of tether:
  - ✓ Provided gravity gradient stability
  - ✓ Tether as antenna
  - ✓ Ionospheric plasma probe
- EDT miniaturization means
  - ✓ Scaled to the size needed (shorter)
  - ✓ Lower power: lower current & voltage

Research questions:
Can electrodynamic tethers provide ultra-small satellites with lifetime enhancement and maneuverability? Can it provide additional benefits?

- Picosatellite and femtosatellite background

Picosatellites and Femtosatellites

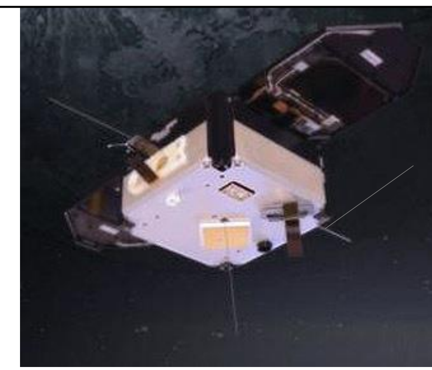
- Picosats (0.1–1 kg) and femtosats (<100 g)
- Think flying your iPhone or Android

LG Nexus 5 Smartphone

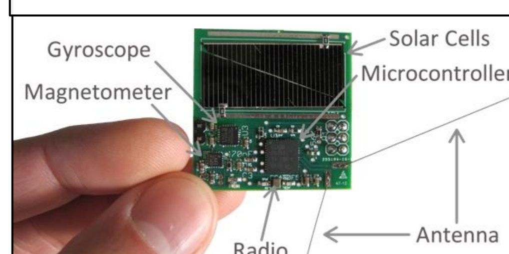
- Radio transceiver
- CPU
- Battery
- Cameras
- GPS
- Accelerometer
- Magnetometer
- 130 g (14x7x0.8 cm)

Picosat 1 and 2
250 g, few cm length

AeroCube 6a and 6b
0.5 U



Sprite ChipSat
5 g, 3.5×3.5×0.25 cm



The Potential of Picosats and Femtosats

- Due to small size and mass, they can be launched in large numbers

- Fleets of picosats or femtosats could enable:
  - Global monitoring for disaster detection/response
  - Studying large-scale space weather phenomena
  - Synthesizing virtual apertures
  - Spacecraft fractionization

- Features of picosats and femtosats with propellantless propulsion
  - Lifetime enhancement
  - Dynamically reconfigurable constellations

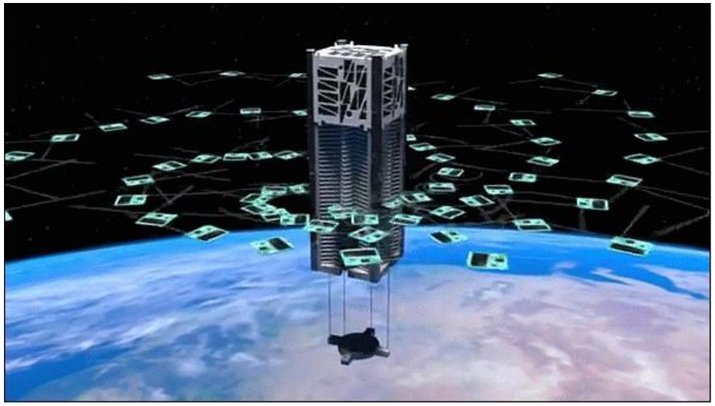


Illustration of KickSat mission concept

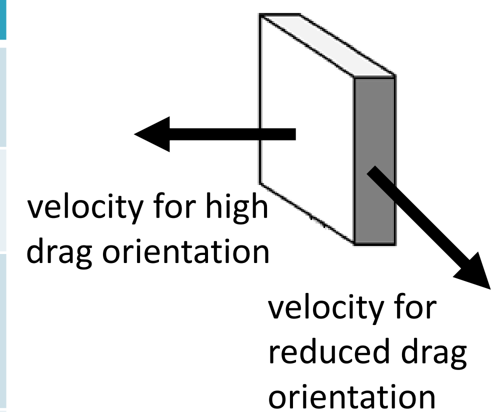
Challenges for Picosats and Femtosats

1. Missions **requiring** coordination and maneuverability

1. Short orbital lifetime

A *Rough* Estimate of Satellite Lifetime due to Atmospheric Drag

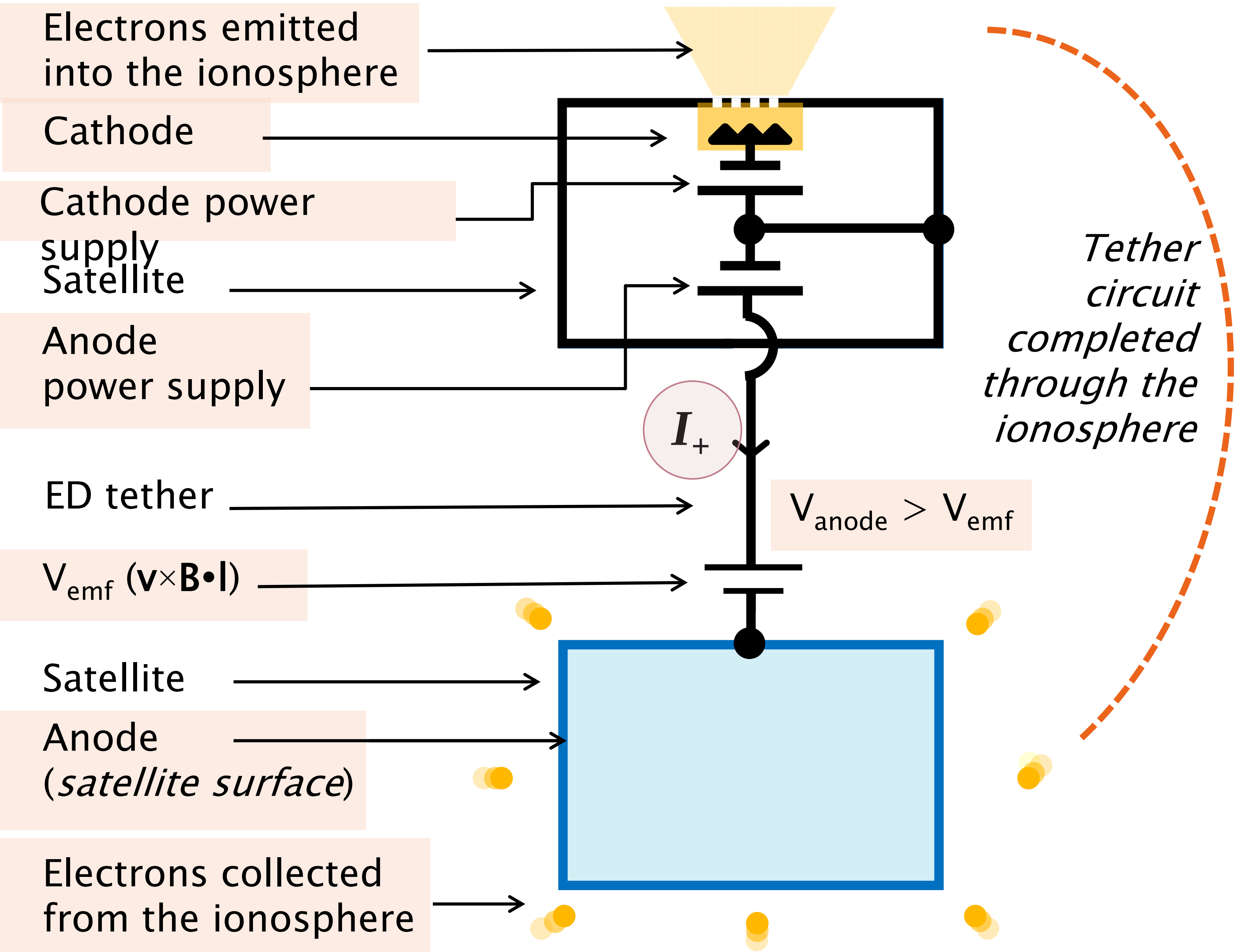
Parameters	1-kg CubeSat	200-g PicoSat		8-g FemtoSat	
Dimensions	10×10×10 cm	10×10×2 cm		3.8×3.8×0.1 cm	
Configuration	1 face in ram direction	Low drag	High drag	Low drag	High drag
Ballistic Coeff. ($kg \cdot m^{-2}$)	45	45	9	95	2.5
Alt = 300 km	weeks	weeks	days	a month	hours
Alt = 400 km	months	months	weeks	several months	days
Alt = 500 km	~1 year or more	~1 year or	months	~years	weeks



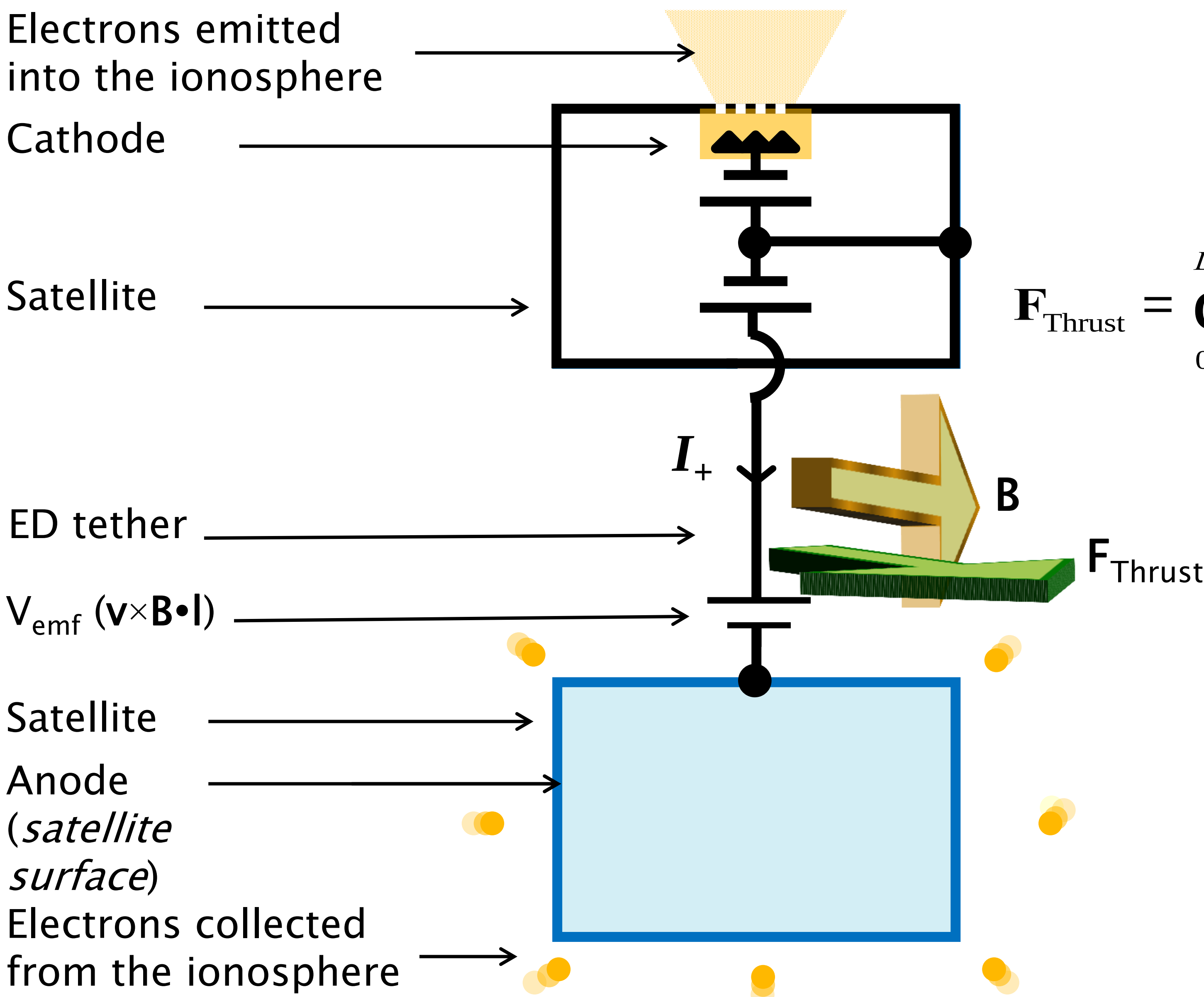
The orbital lifetime is *short* without propulsion

- Electrodynamic tether background

Key Elements of EDT Electrical System



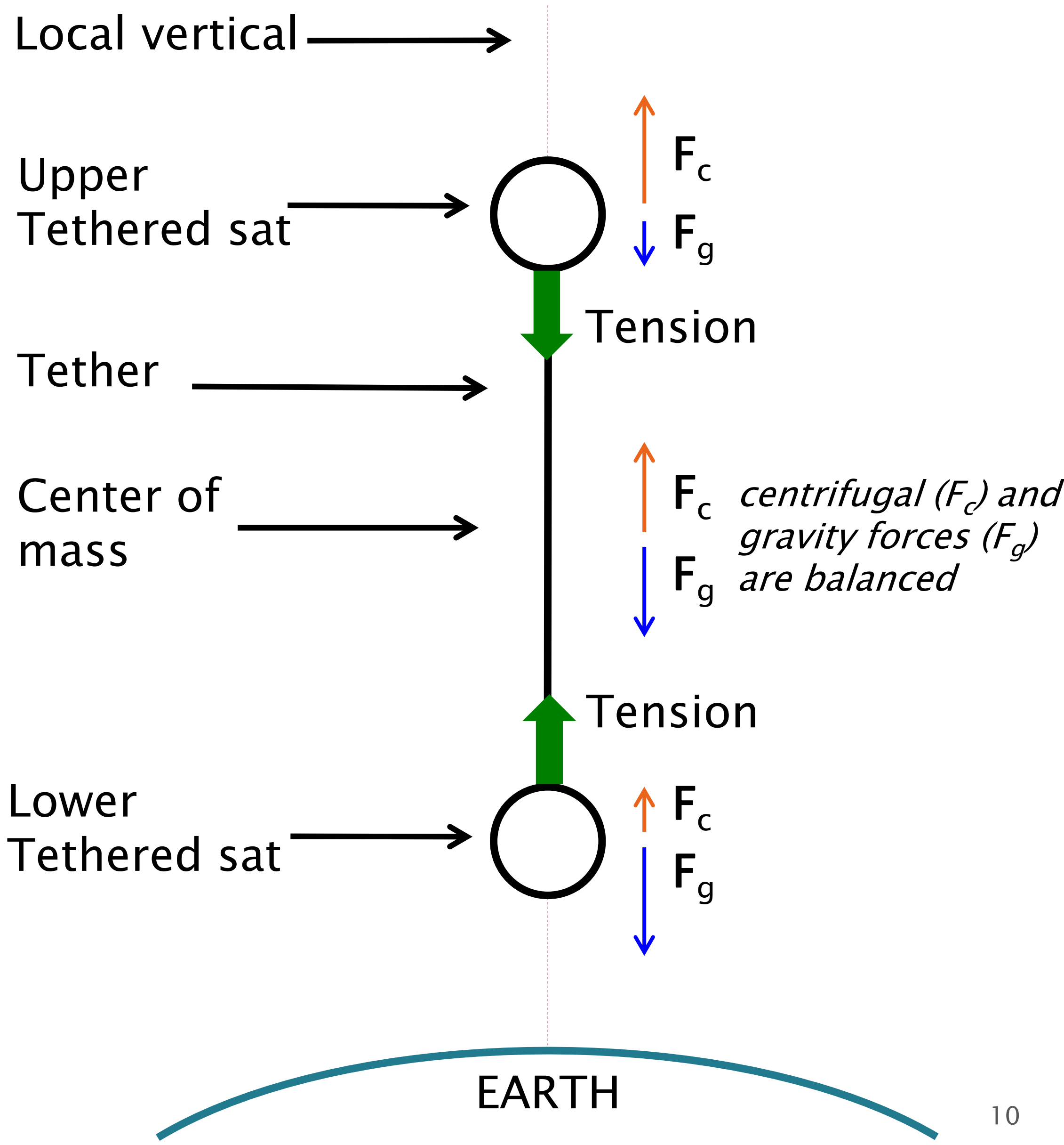
EDTs Provide Propellantless Propulsion



$$\mathbf{F}_{\text{Thrust}} = \int_0^L I_{\text{tether}} \, d\mathbf{L} \times \mathbf{B}$$

EDTs Provide Attitude Stability

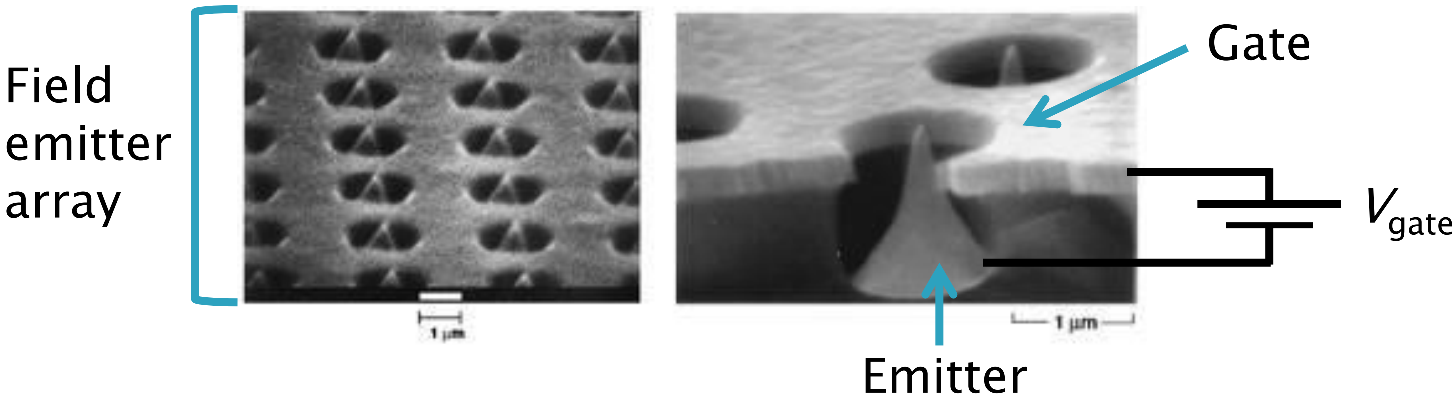
- The gravity-gradient force generates tension in the tether
- The gravity-gradient torque helps align the tether along the local vertical



System Concept Trade Study

Electron Emission

- Cathode current
  - Electrons are emitted using field emitter arrays



  - Advantages: low power and low mass
  - Fowler–Nordheim expression:

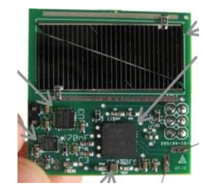
$$I_{cathode} = a_{FN} V_{gate}^{\ 2} \exp(-b_{FN}/V_{gate})$$

$$a_{FN} = 0.03\ \mathrm{A \cdot V^{-2}}$$
$$b_{FN} = 487\ \mathrm{V}$$

Electron Collection: the challenge of estimating collection current

- Electron collection current is hard to estimate
  - high-speed plasma flow
  - sat size comparable to Debye length, gyroradius
  - sat shape (cuboid)





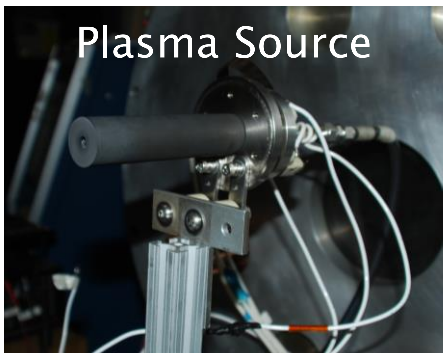
- Approximating collection current
  - sat approximated as a sphere
  - Used wide-sweeping Langmuir probe (WLP) model

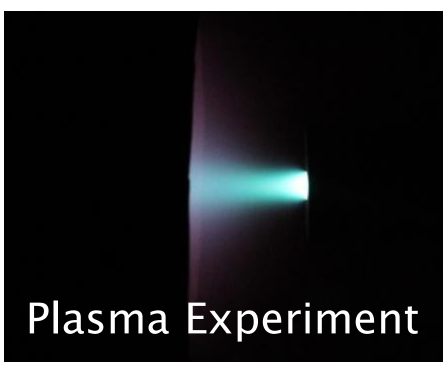
$$I_{\mathrm{WLP}} = \frac{I_{\mathrm{thermal}}}{2}\left(1 + \frac{q\left(V_{\mathrm{anode}} - \phi_p\right)}{kT_e}\right)^{\beta}$$

we use $\beta = 0.85$

Electron Collection Experiment

- Goal: improve collection current estimate
  - simulate the plasma environment in LEO
  - test probes representative of actual sat shapes and sizes





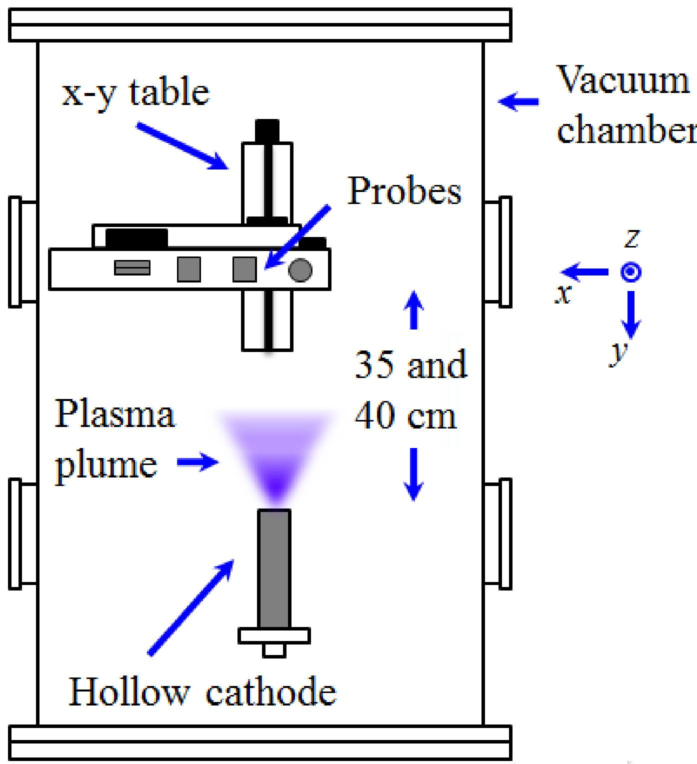


Illustration showing experimental setup

Spherical Reference Probe

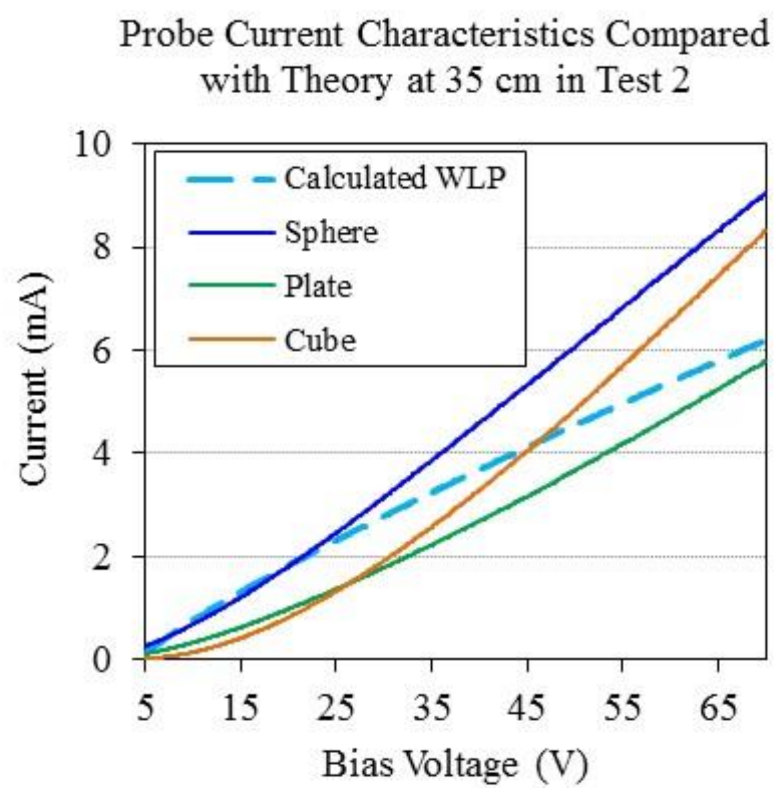
Planar satellite-shaped Probe

Cubic satellite-shaped Probe

Electron Collection Experiment Results

- Comparison with WLP model
  - Planar and cubic probe current magnitudes are comparable with WLP model
  - Shapes of the I–V characteristic are different

Bottom line: WLP model is a conservative estimate for electron current collection



Estimating Dissipated Power

Cathode

$P_{\text{cathode}} = IV_{\text{cath}}$

Tether resistance

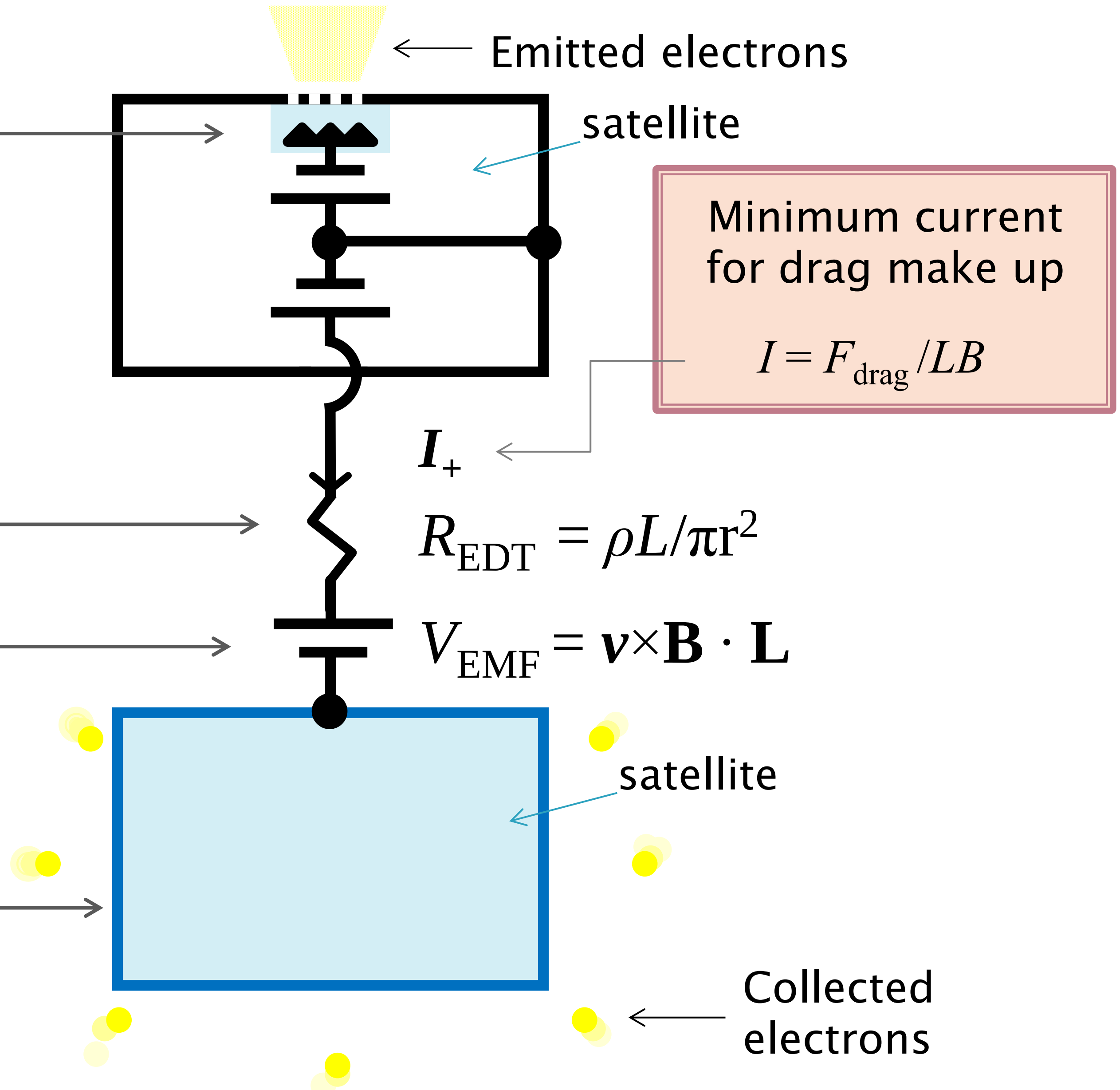
$P_{\text{EDT}} = I^2 R_{\text{EDT}}$

Overcoming induced EMF

$P_{\text{EMF}} = IV_{\text{EMF}}$

Anode

$P_{\text{ANODE}} = IV_{\text{anode}}$



Estimating Available Thrust Power

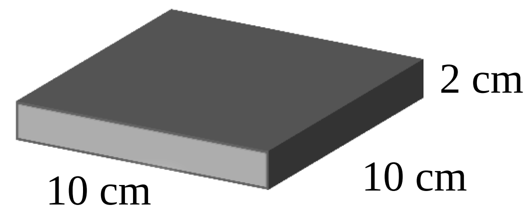
Solar Flux Density in LEO
136.8 mW·cm^{-2}

Est. Solar Cell Output
9.4 mW·cm^{-2}

Est. Power for Propulsion
2.8 mW·cm^{-2}

475 mW

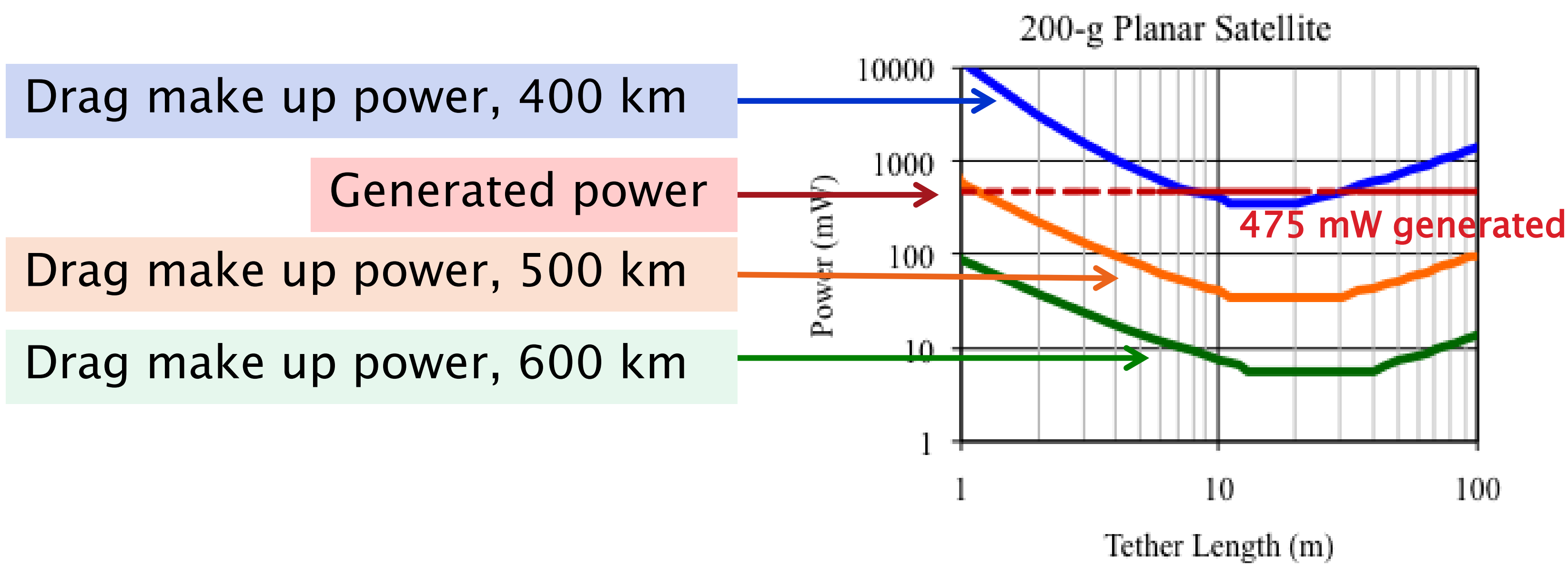
200-g Planar Picosatellite



<u>EDT propulsion is propellantless</u>. The generated power is adequate for EDT propulsion.

Estimating the Power Needed for Drag Make-up

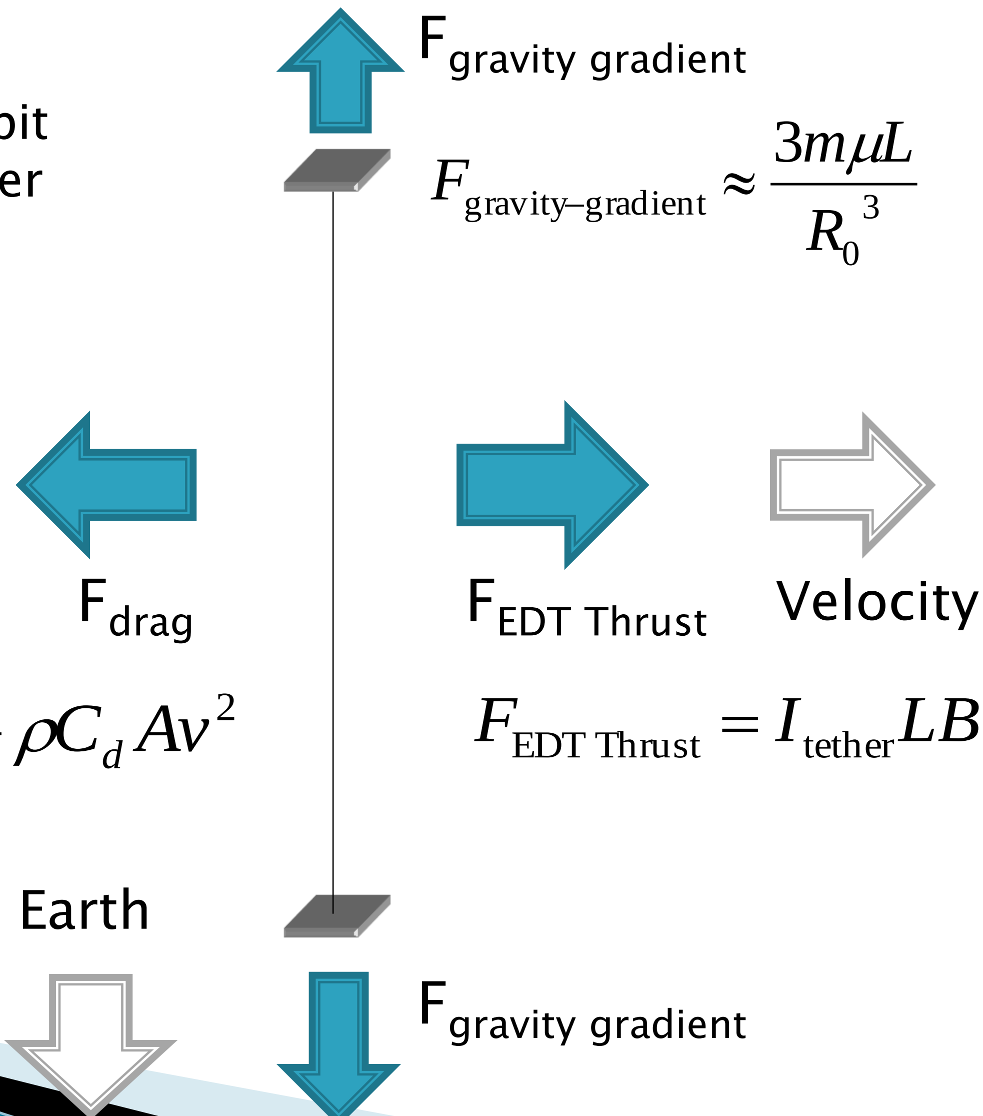
- More available power = boost capable



Dominant Forces acting on a Tethered System

Simplifying assumptions:

- Circular, equatorial orbit
- Vertically-aligned tether

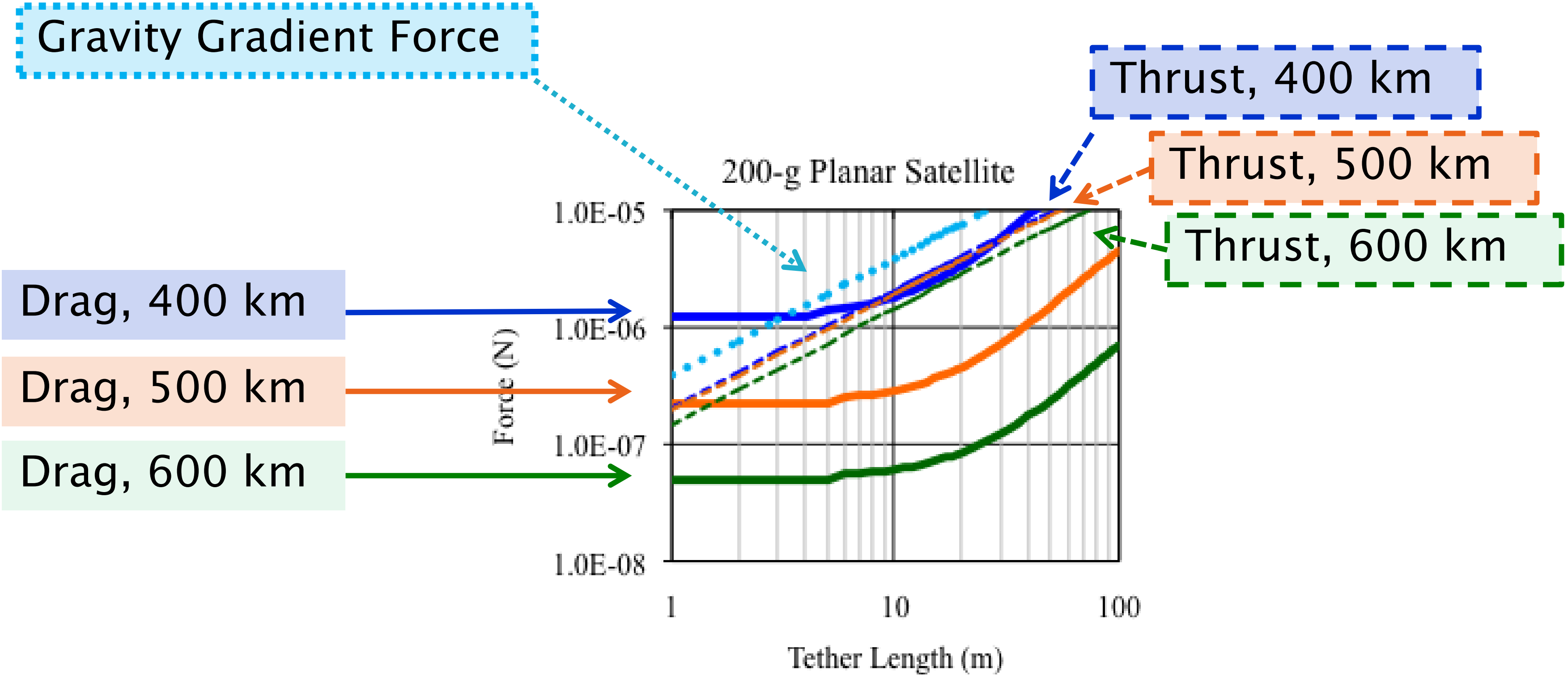


$$F_{\text{gravity-gradient}} \approx \frac{3m\mu L}{R_0^{\;3}}$$

$$F_{\text{drag}} = \tfrac{1}{2}\rho C_d A v^2$$

$$F_{\text{EDT Thrust}} = I_{\text{tether}} L B$$

Estimating the Dominant Forces on Dual 200 g Satellites with ED tether

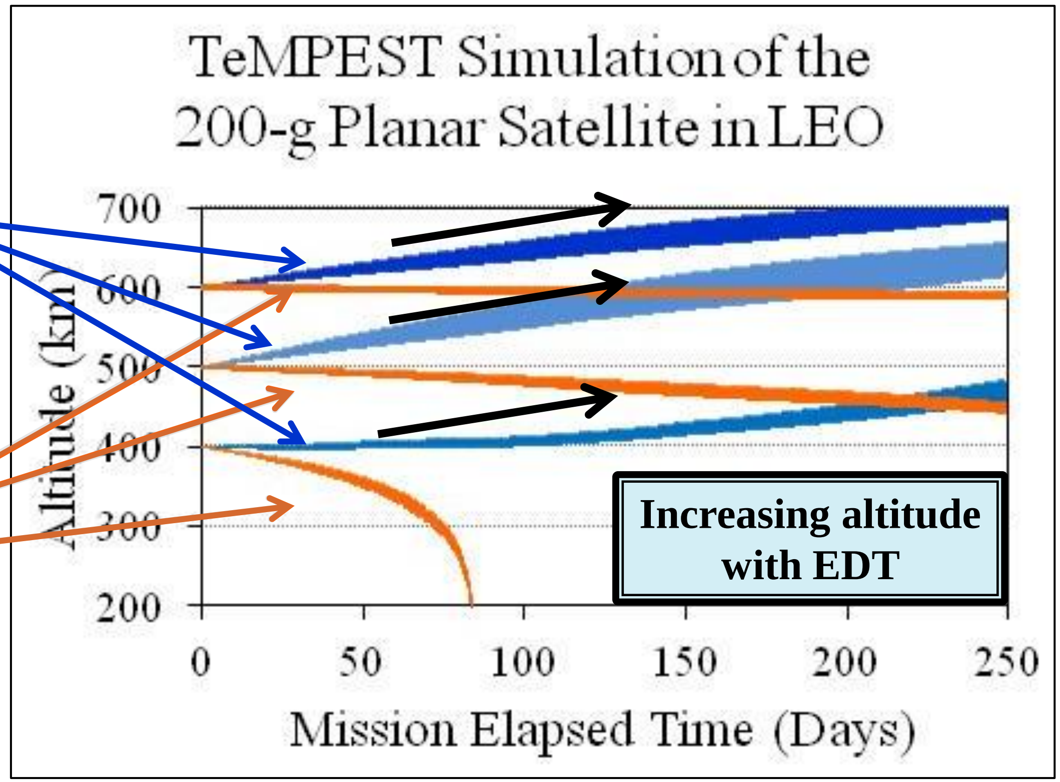


A 10 m EDT can generate thrust that exceeds drag at 400 km, 500 km, and 600 km. The gravity gradient force is also comparable to other forces.

Simulation of Performance

Dual satellites with an ED tether

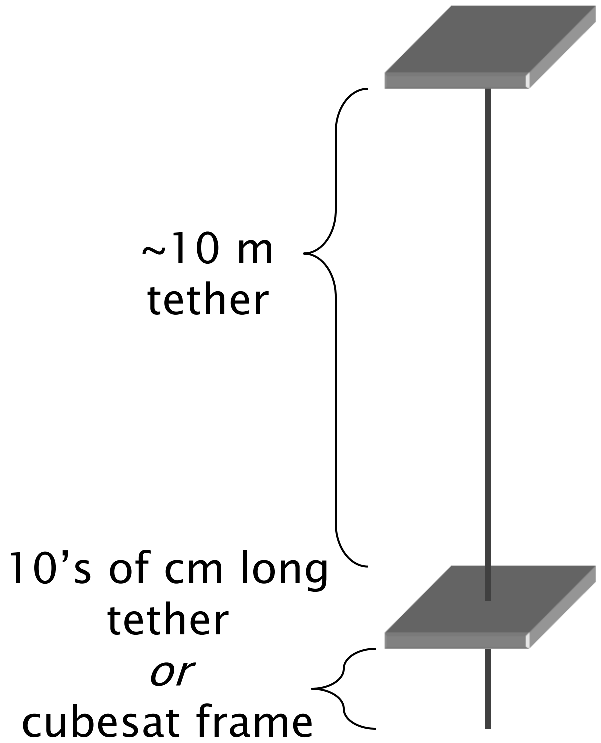
Single 100-g satellite starting at 400 km, 500 km, and 600 km



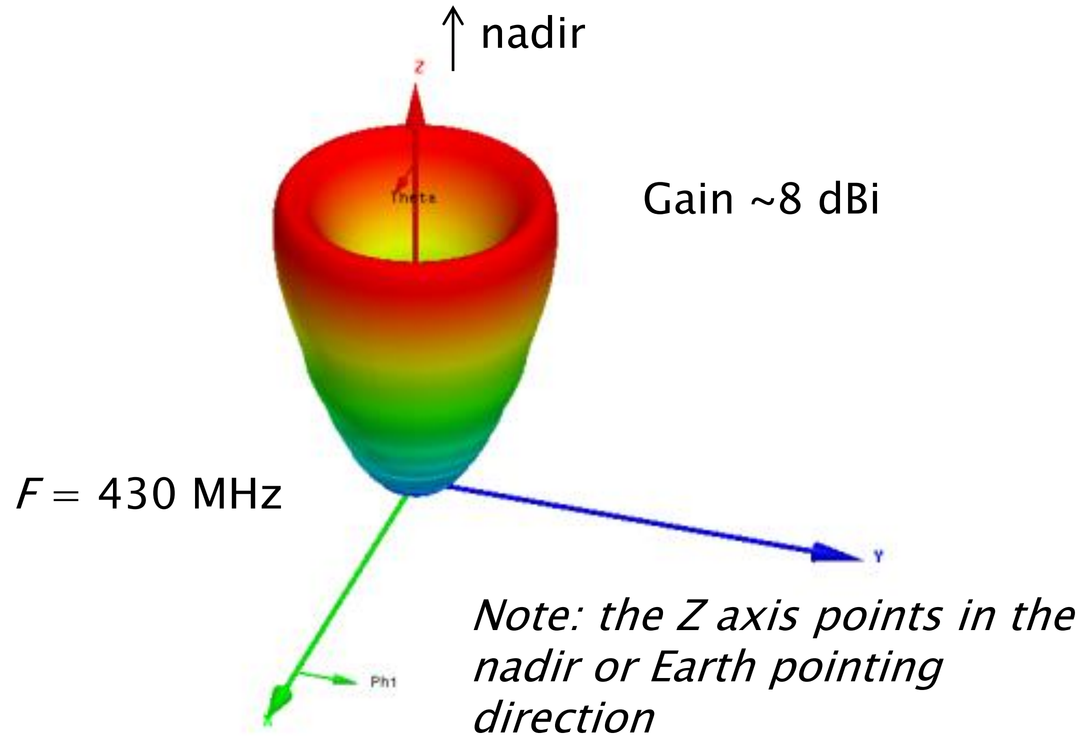
The satellite can boost at 400 km, 500 km, and 600 km

Using a Short Conducting Tether to Enhance Communication

Possible ED Tether Architecture for Communication



Simulated ED Tether Radiation Pattern



HFSS antenna model

Tether provides directional, traveling wave type radiation pattern

The Miniature Tether Electrodynamics Experiment (MiTEE)

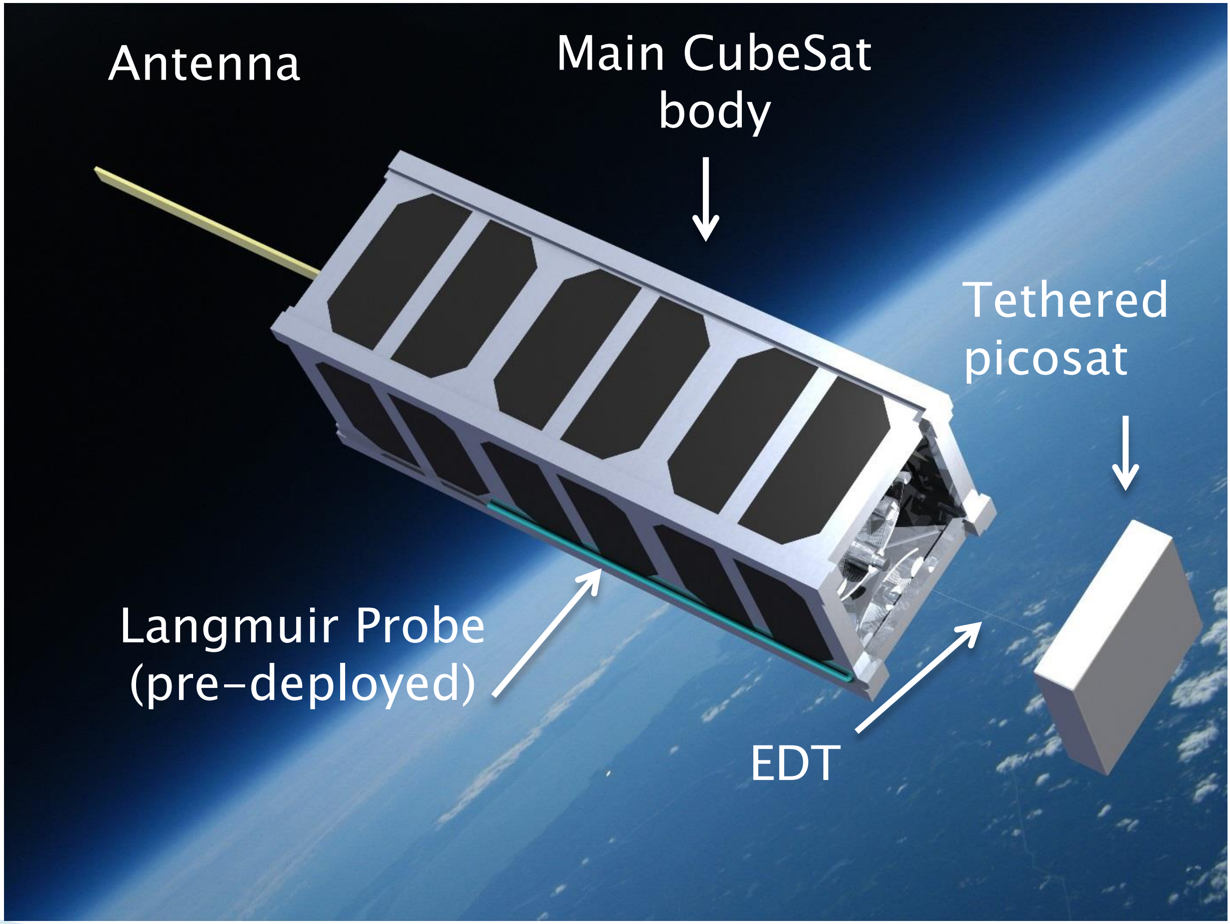
The Miniature Tether Electrodynamics Experiment (MiTEE)

Goal: demonstrate miniature tether technology and study the attitude dynamics and measure the current in a miniature tethered system

Additionally:

- If EDT is pointing toward Earth, secondary goal is to assess EDT as an antenna

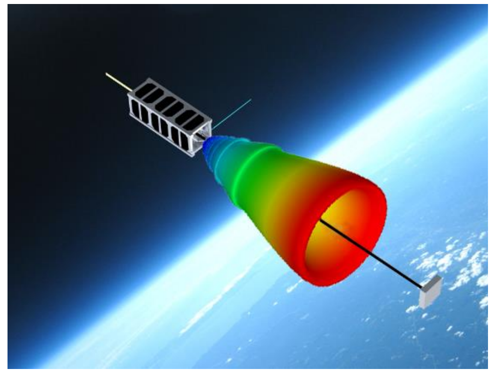
- Educating and enriching students is a central goal of MiTEE (team of ~30 undergrad/Master's students)



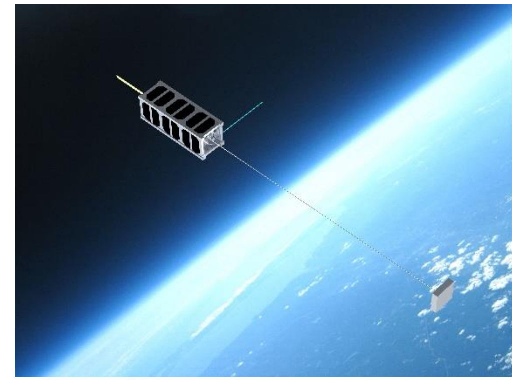
MiTEE Concept of Operations Overview

Launch from PPOD

Secondary Science Mission Starts



Primary Science Mission Starts



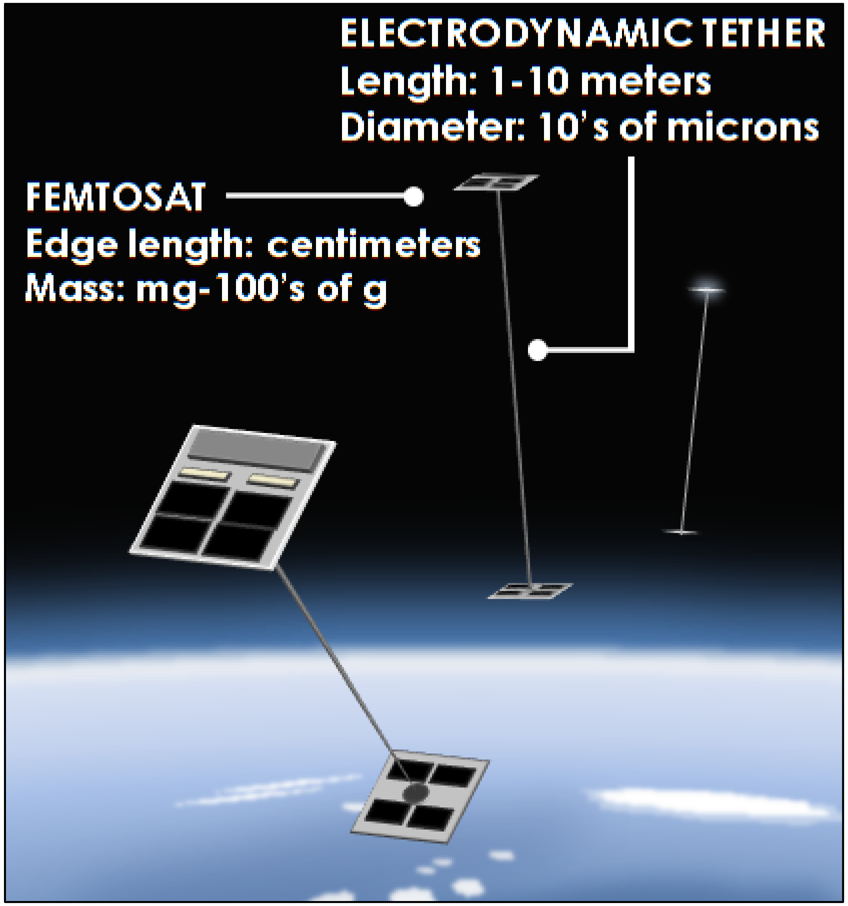
Primary Antenna Deployment and Start to De-tumble

Tether Deployment when Nadir Facing

Conclusions

Conclusions

- A short, few-meter tether shows potential for stable, propellantless pico- and femtosat propulsion
- The tether may also function as an enhanced antenna aperture
- Potential impact:
  - lifetime enhancement
  - enabling reconfigurable constellations



Acknowledgements

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  - Michigan Space Grant Consortium graduate fellowship

- Thank You!

Questions?

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Extra slides

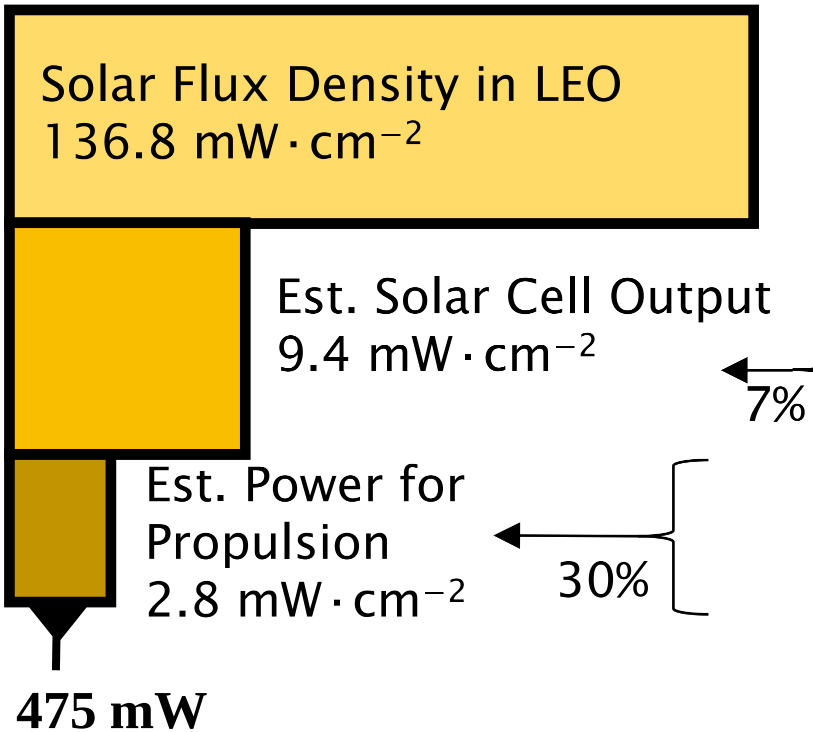
Summary of First Iteration of Trade Study

An appropriate tether length and width has been defined for a range of satellite sizes

Confirmed gravity gradient exceeds drag and thrust

Parameter		200-g planar satellite	150-g cubic satellite	10-g ChipSat
Tether length		11 m	12 m	4 m
Tether radius		105 μm	110 μm	45 μm
Tether mass		2.7 g	3.4 g	150 mg
Available power		475 mW	230 mW	22 mW
Tether Current	400 km	5.9 mA	*2.8 mA*	*400 μA*
	500 km	0.9 mA	1 mA	230 μA
	600 km	0.2 mA	0.2 mA	5 μA
Thrust Force	400 km	2.3 μN	*1 μN*	*47 nN*
	500 km	2.1 μN	0.9 μN	44 nN
	600 km	1.6 μN	0.7 μN	33 nN
Gravity-gradient Force		4 μN	3.5 μN	77 nN

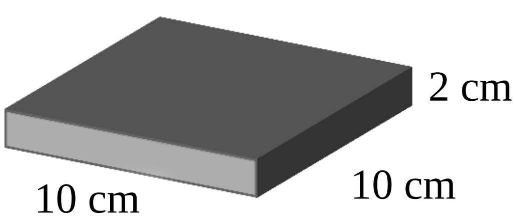
Estimating Available Thrust Power



Assumptions for estimating thrust power

- Body mounted PV cells
- PV cell efficiency: 18.5%
- PV coverage of each face: 80%
- Number of sunlight faces: 3
- Inherent degradation: 72%
- Life degradation in 1 year: 3%
- Efficiency loss due to ITO coating: 95%
- Average solar angle: 45°
- X_e, power conversion efficiency: 0.60
- X_d, power conversion efficiency: 0.80
- Fraction of total power generated for propulsion: 70%

200-g Planar Picosatellite



<u>EDT propulsion is propellantless</u>. The generated power is adequate for EDT propulsion.

Zeroth order estimate: ΔV

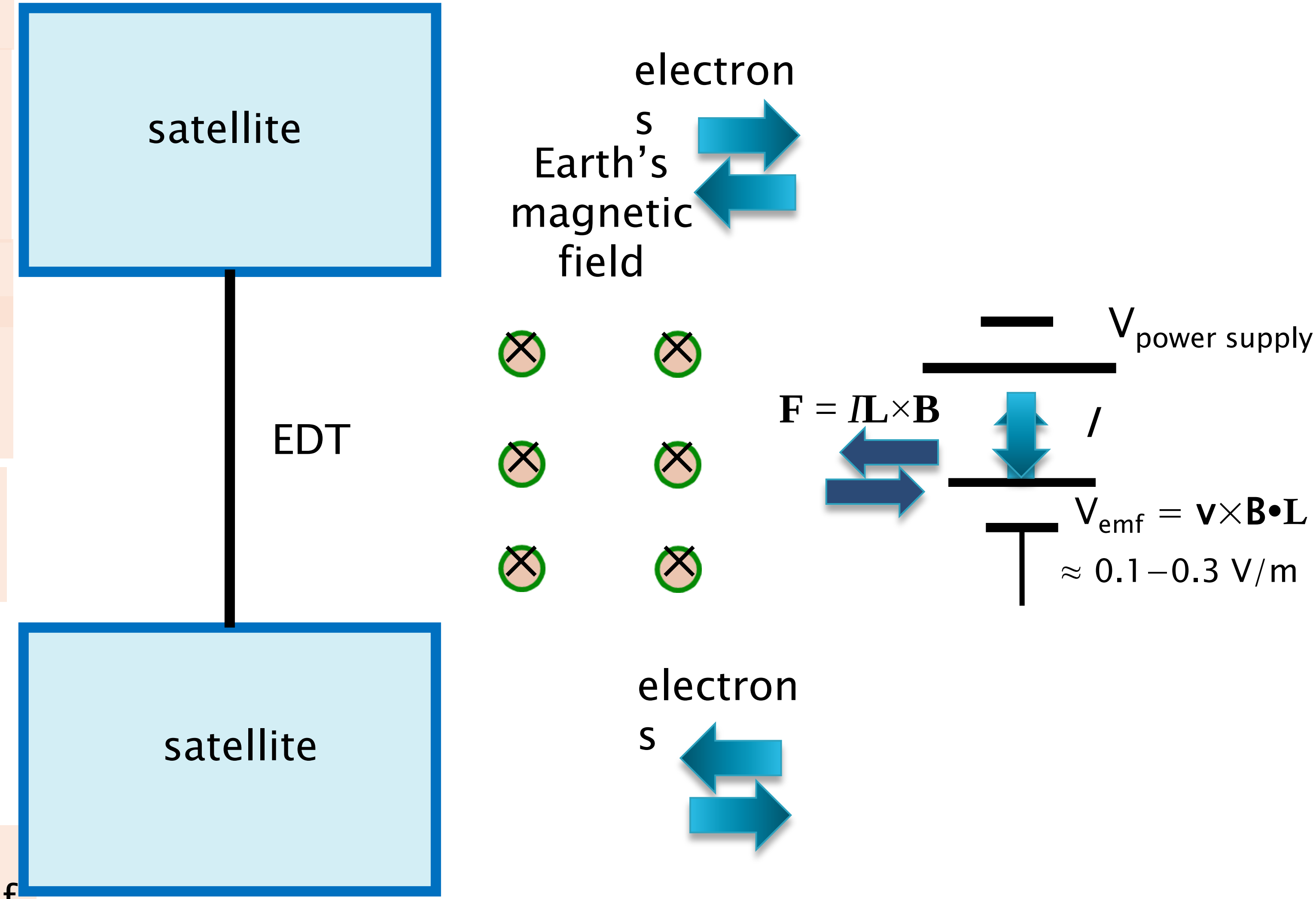
- For a pair of 200-g planar satellites connected with a 10-m tether
  - Mass = 0.403 kg
  - Mass/area = 67.2 kg/m2
  - Thrust ≈ 2 μN (400 km)
  - Estimated ΔV per year is 157 m/s
    - *assuming nearly continuous thrust, vertical tether, equatorial orbit, and 5-6 mA of tether current*

- From SMAD, ΔV to maintain altitude for 50 kg/m^2
  - 154 m/s per year at 300 km (solar min)
  - 140 m/s per year at 400 km (solar max)

Tethered system appears capable of generating ΔV needed to maintain altitude and even boost in a range of altitudes

EDT Background

1. An EDT is a long wire
2. The EDT crosses magnetic field lines
3. V_{emf} generated
4. Ionosphere completes circuit
5. Force opposes motion
6. A power supply in series can reverse EDT current
7. Force is now in direction of motion



Explaining the "Semi-rigid" tether: Part 1

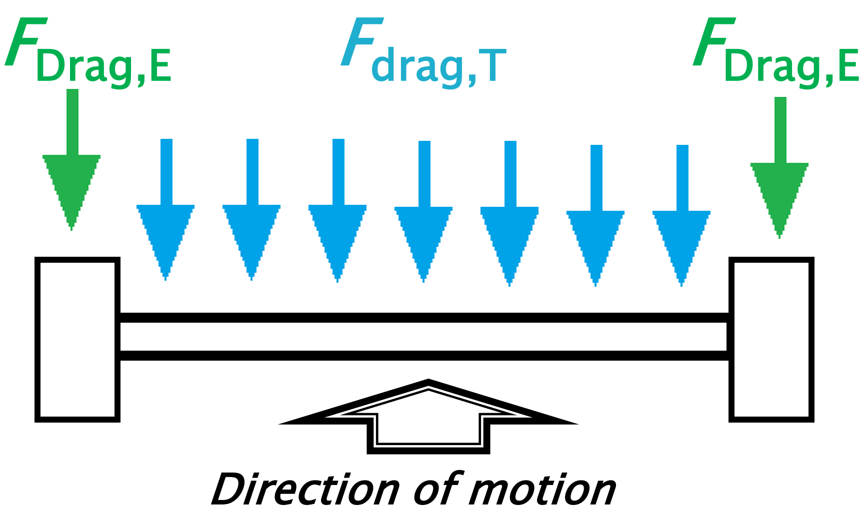
- Drag may cause bending due to the relative acceleration of the high area-to-mass ratio tether compared to the end-bodies.

- Courtesy Wikipedia: *D'Alembert showed that one can transform an accelerating rigid body into an equivalent static system by adding the so-called "inertial force" and "inertial torque" or moment. The inertial force must act through the center of mass.*

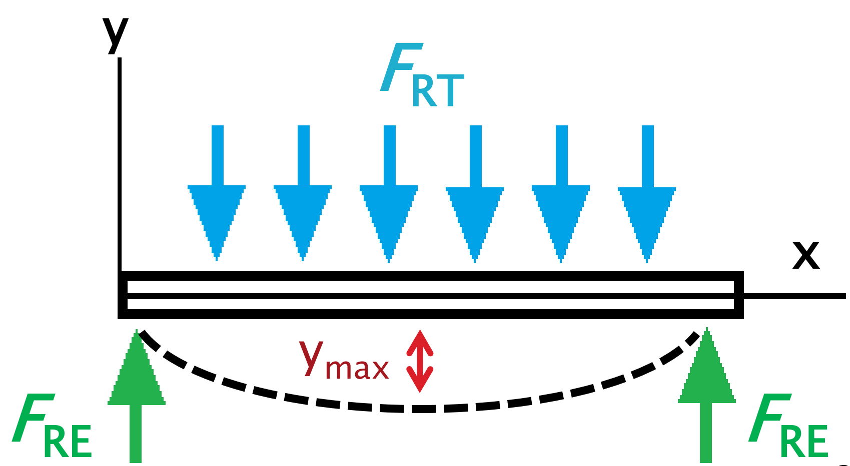
$$F_{\mathrm{RT}} = -2\left(\frac{F_{\mathrm{Drag,E}}\,m_{\mathrm{EDT}} - F_{\mathrm{Drag,T}}\,m_{\mathrm{endbody}}}{m_{\mathrm{EDT}} + 2m_{\mathrm{endbody}}}\right) = -2F_{\mathrm{RE}}$$

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

EDT with drag forces

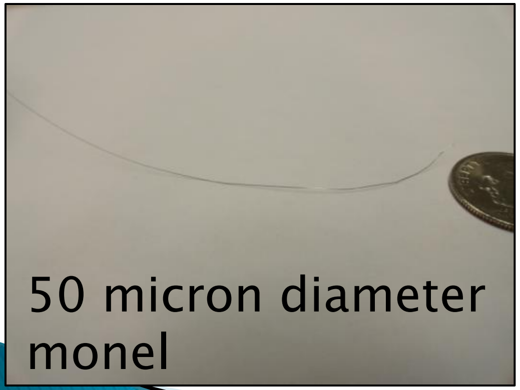


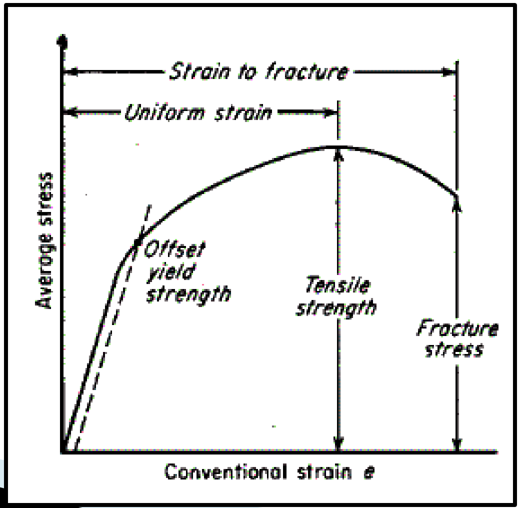
EDT modeled as a static system

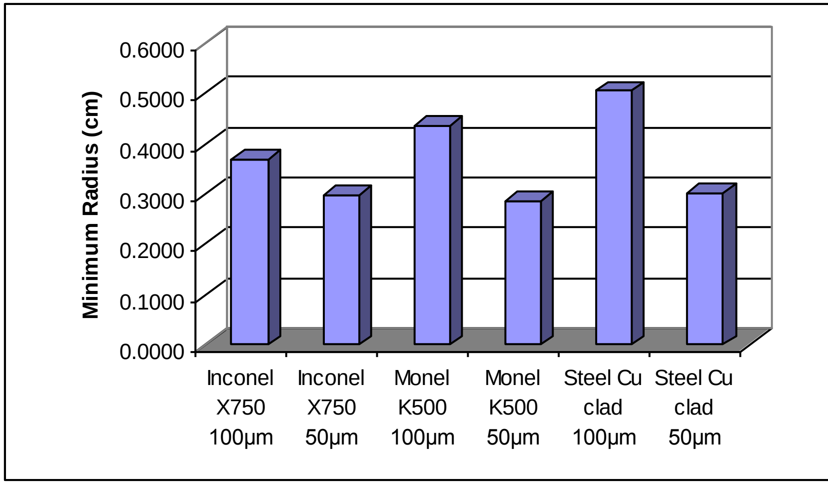


Explaining the "Semi-rigid" tether: Part 2

- 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





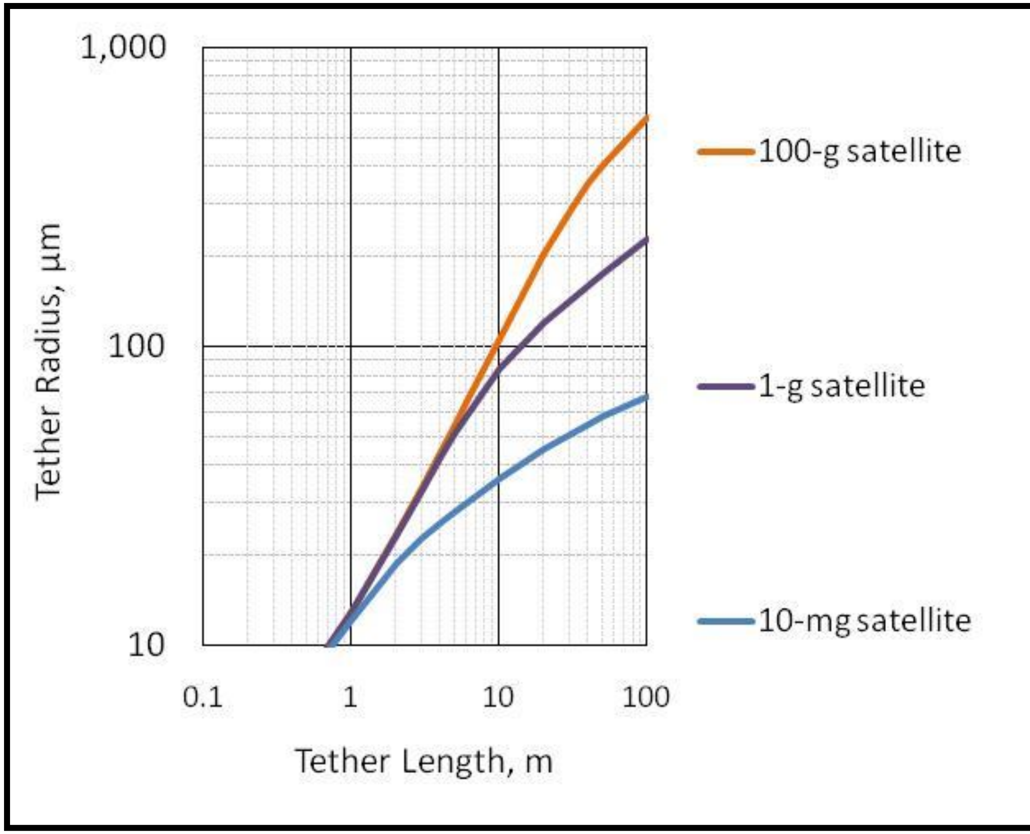


Due to problems in the test set -up, these values are rough approximations

Explaining the "Semi-rigid" tether: Part 3

- To limit bending, the tether radius increases with length

- Tether has a Monel™ core and thin Teflon insulation
    - EDT has a high Young's Modulus, *E*

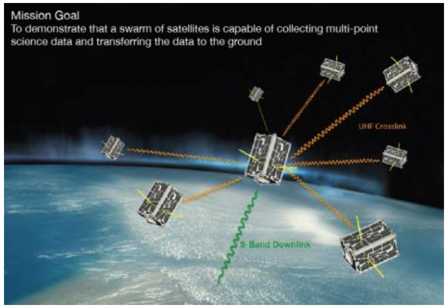


***If* rigidity is important, increasing EDT length requires increasing the radius**

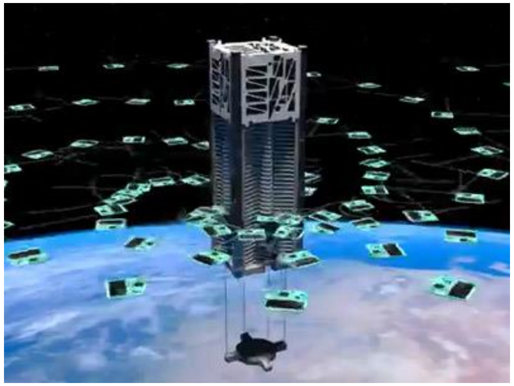
Constellations of Small Sats

- Flock (planet labs)

- EDSN



- KickSat 2



Satellite Mass Classifications

- Mass impacts cost
  - High mass sats require high thrust rockets, increasing launch cost
- Advantages of smaller sats:
  - Reduced lunch cost (per sat)
  - Can launch multiple sats (constellations)
  - Can rideshare or “piggy back” with other sats

Satellite Classification	Wet Mass
Large Satellite	>1000 kg
Medium Satellite	500–100 kg
Mini-satellite or “small satellite”	100–500 kg
Microsatellite	10–100 kg
Nanosatellite	1–10 kg
Picosatellite	0.1–1 kg
Femtosatellite	<0.1 kg

Generally categorized as small satellite

Tether Prior History

■ = Met All Mission Goals ■ = Did Not Meet All Mission Goals

Year	Mission	Type	Description	Lessons Learned
1966	**Gemini-11**	Dynamics	• 15-m tether between capsules • Tethered capsules set in rotation	+ Successful deployment and stable rotation
1966	**Gemini-12**	Dynamics	• 30-m tether between capsules • Tethered capsules set in rotation	+ Successful deployment and stable rotation
1989	**OEDIPUS-A**	ED/Plasma Physics	• Sounding rocket experiment • 958-m conducting tether, spinning	+ Successfully demonstrated strong EM coupling between the ends of conducting tether t + Obtained data on behavior of tethered system as large double electrostatic probe
1992	**TSS-1**	ED/Plasma Physics	• 20-km insulated conducting tether to study plasma-electrodynamic processes and tether orbital dynamics	– Too-long bolt added without proper review caused jam in tether deployer + Demonstrated stable dynamics of short tethered system + Demonstrated controlled retrieval of tether
1993	**SEDS-1**	Momentum Exchange	• Deployed payload on 20-km nonconducting tether and released it into suborbital trajectory	+ Demonstrated successful, stable deployment of tether + Demonstrated deorbit of payload
1993	**PMG**	ED	• 500-m insulated conducting tether • Hollow cathode contactors at both ends	+ Demonstrated ED boost and generator mode operation • Did **not** measure thrust
1994	**SEDS-2**	Dynamics	• Deployed 20-km tether to study dynamics and survivability	+ Demonstrated successful, controlled deployment of tether with minimal swing
1995	**OEDIPUS-C**	ED/Plasma Physics	• Sounding rocket experiment • 1174-m conducting tether, spinning	+ Successfully obtained data on plane and sheath waves in ionospheric plasma
1996	**TSS-1R**	ED/Plasma Physics	• 20-km insulated conducting tether to study plasma-electrodynamic processes and tether orbital dynamics	+ Demonstrated electrodynamic efficiency exceeding existing theories + Demonstrated ampere-level current – Flaw in insulation allowed high-voltage arc to cut tether • Tether was not tested prior to flight
1996	**TiPS**	Dynamics	• Deployed 4-km nonconducting tether to study dynamics and survivability	+ Successful deployment + Tether survived over 10 years on orbit
1999	**ATEx**	Dynamics	• Tape tether deployed with pinch rollers	– "Pushing on a rope" deployment method resulted in unexpected dynamics, experiment terminated early
2000	**Picosats 21/23**	Formation	• 2 picosats connected by 30-m tether	+ Demonstrated tethered formation flight
2001	**Picosats 7/8**	Formation	• 2 picosats connected by 30-m tether	+ Demonstrated tethered formation flight
2002	**MEPSI-1**	Formation	• 2 picosats connected by 50-ft tether • Deployed from Shuttle	+ Tethered formation flight
2006	**MEPSI-2**	Formation	• 2 picosats connected by 15-m tether • Deployed from Shuttle	+ Tethered formation flight of nanosats with propulsion and control wheels
2009	**AeroCube-3**	Formation	• 2 picosats connected by 61-m tether • Deployed from Minotaur on TacSat-3 launch	+ Tethered formation flight with tether reel and tether cutter
2007	**MAST**	Dynamics	• 3 tethered picosats to study tether survivability in orbital debris environment	– Problem with release mechanism resulted in minimal tether deployment; + Obtained data on tethered satellite dynamics
2007	**YES-2**	Momentum Exchange	• Deployed payload on 30-km nonconducting tether and released it into suborbital trajectory	+ Tether did deploy, but: – Controlling computer experienced resets during tether deployment, preventing proper control of tether deployment
2010	**T-REX**	ED/Plasma Physics	• Sounding rocket experiment • 300-m bare tape tether	+ Successfully deployment of tape and fast ignition of hollow cathode

>70% of Tether Missions Have Been Fully Successful

Early Rocket Test History

TETHERS UNLIMITED
Advanced Propulsion, Power, & Comm. for Space, Sea, & Air

Rocket #	Date	Successes/Failures
2	18 Mar 1942	• Gyro & propellant feed failures
3	16 Aug 1942	• Nose broke off
4	3 Oct 1942	• Success
5	21 Oct 1942	• Steam generator failure
6	9 Nov 1942	• Success
7	28 Nov 1942	• Tumbled
9	9 Dec 1942	• Hydrogen peroxide explosion
10	7 Jan 1943	• Explosion on ignition
11	25 Jan 1943	• Trajectory failure
12	17 Feb 1943	• Trajectory failure
13	19 Feb 1943	• Fire in tail
16	3 Mar 1943	• Exploded in flight
18	18 Mar 1943	• Trajectory failure
19	25 Mar 1943	• Tumbled, exploded
20	14 Apr 1943	• Crashed
21	22 Apr 1943	• Crashed
22	14 May 1943	• Cut off switch failed
25	26 May 1943	• Premature engine cutoff
26	26 May 1943	• Success
24	27 May 1943	• Success
23	1 Jun 1943	• Premature engine cutoff
29	11 Jun 1943	• Success
31	16 Jun 1943	• Premature engine cutoff
28	22 June 1943	• Exploded in flight

80% Failure Rate

Prior Art for Miniature EDTs for Small Satellites

Missions using short (≤ 500 m) tethers

Mission	Deployed Length	EDT?	Small sat?
Gemini 11	30 m	No	No
Gemini 12	30 m	No	No
H-9M-69	500 m	Yes	No
S-520-2	500 m	Yes	No
Charge-1	500 m	Yes	No
Charge-2	500 m	Yes	No
Charge-2B	500 m	Yes	No
TSS-1	260 m	Yes	No
PMG	500 m	Yes	No
PICOSAT 1.0	30 m	No	Yes
PICOSAT 1.1	30 m	No	Yes
T-Rex	300 m	Yes	No
ESTCube-1	10 m	No	Yes
Aalto-1	10/100 m	No	Yes

← *Almost*

There have been **no previous missions** demonstrating 1-50 m EDTs for pico- or femtosats

Small Sat Propulsion Concepts

- Propulsion concepts
  - Microthruster
  - Digital Propulsion
  - Scaled down ion engine
  - FEEP

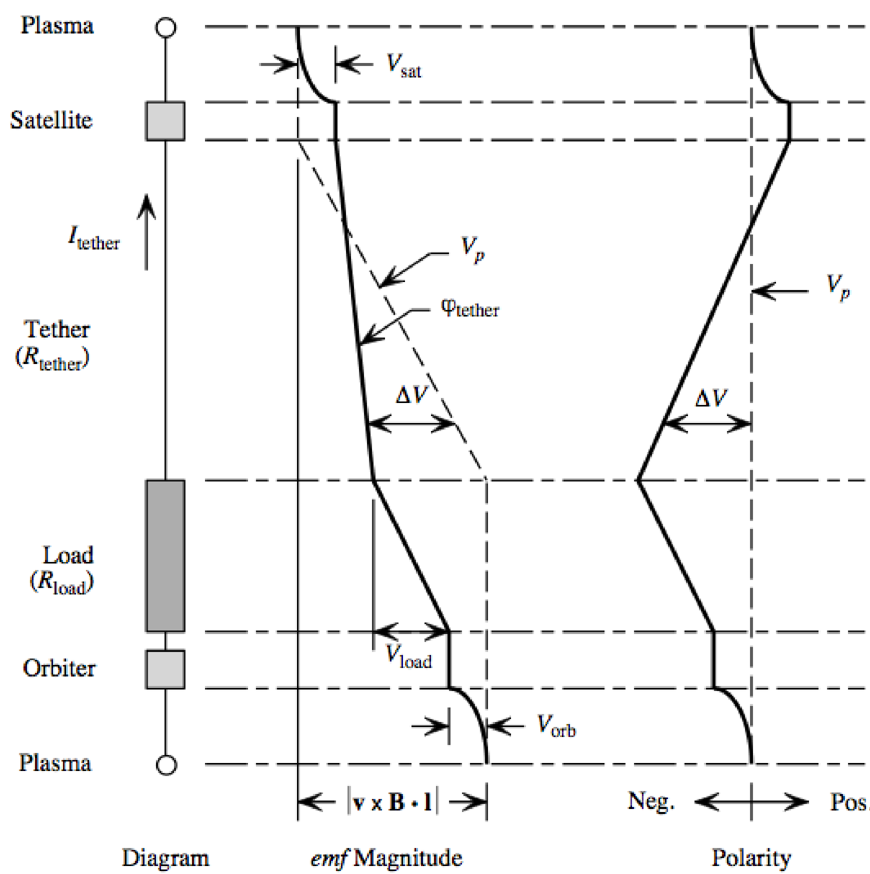
- Propellantless propulsion
  - Lorentz augmented propulsion
  - Solar sail

Comparing Collection Models

This model includes or takes into consideration:	OML	Parker-Murphy	TSS-1R modified Parker-Murphy	WLP model
Expression	$I_{\mathrm{OML}} = I_{\mathrm{thermal}}\left(1+\frac{q\left(V_{\mathrm{anode}}-\varphi_p\right)}{kT_e}\right)^{\beta}$	$I_{\mathrm{PM}} = \frac{I_{\mathrm{thermal}}}{2}\left(1+\left(\frac{V_{\mathrm{anode}}-\varphi_p}{\varphi_0}\right)^{1/2}\right)$	$I_{\mathrm{TSS-1R}} = \alpha\frac{I_{\mathrm{thermal}}}{2}\left(1+\left(\frac{V_{\mathrm{anode}}-\varphi_p}{\varphi_0}\right)^{\beta}\right)$	$I_{\mathrm{WLP}} = \frac{I_{\mathrm{thermal}}}{2}\left(1+\frac{q\left(V_{\mathrm{anode}}-\varphi_p\right)}{kT_e}\right)^{\beta}$
An Explanation for Current Collection Behavior	Yes	Yes	Yes, but may need more experiments…	No– "β" variation unexplained
Magnetic Field Effects	No	Yes	Yes	Yes
Plasma Flow	No	No	Yes	Yes
Relative Size of Satellite to Debye length	No	No	No	Yes
Relative Size of Satellite to Electron Gyroradius	No	No	No	Yes
Non-spherical Satellite Shape	No	No	No	No

Tether Circuit Model

- Kirchoff's Voltage Law: the sum of voltages around a closed loop is zero.



Approximating Collection Current

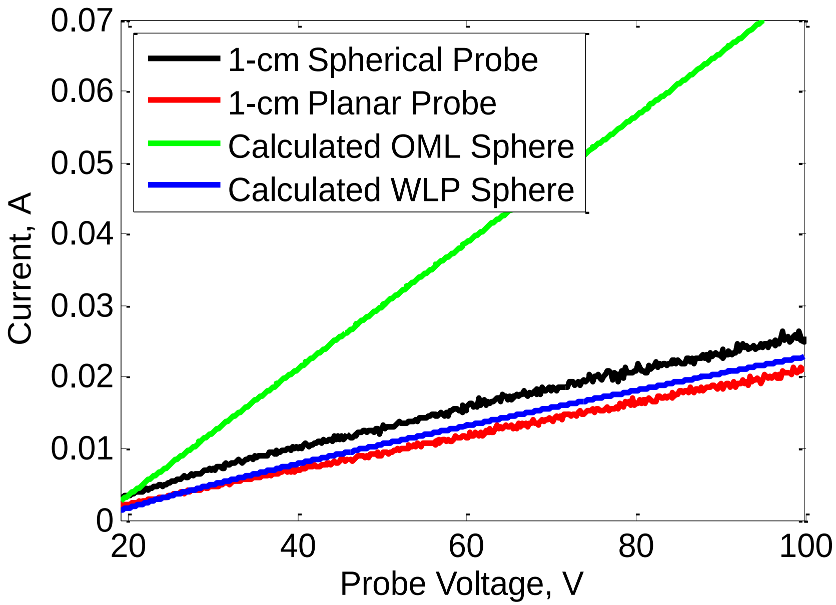
- Sat approximated as a sphere
- Wide-sweeping Langmuir probe (WLP) model used
  - probe size comparable to some of the sats
  - probe size comparable to gyroradius

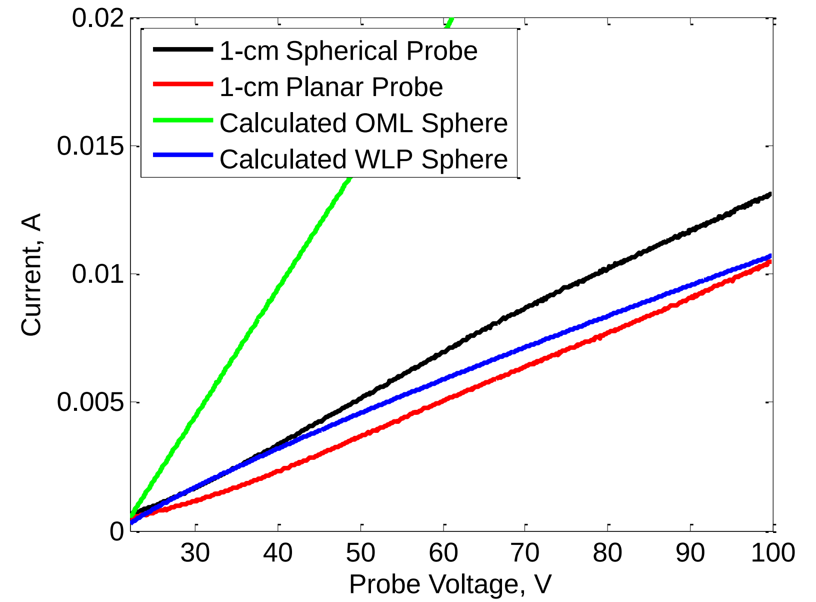
$$I_{\mathrm{WLP}} = \frac{I_{\mathrm{thermal}}}{2}\left(1 + \frac{q\left(V_{\mathrm{anode}} - \phi_p\right)}{kT_e}\right)^{\beta}$$

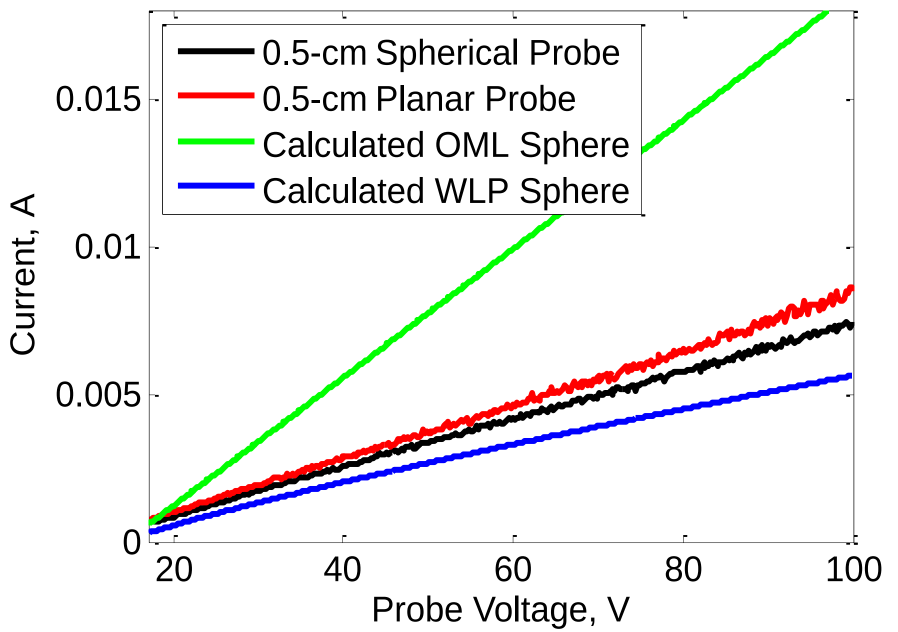
we use $\beta = 0.85$

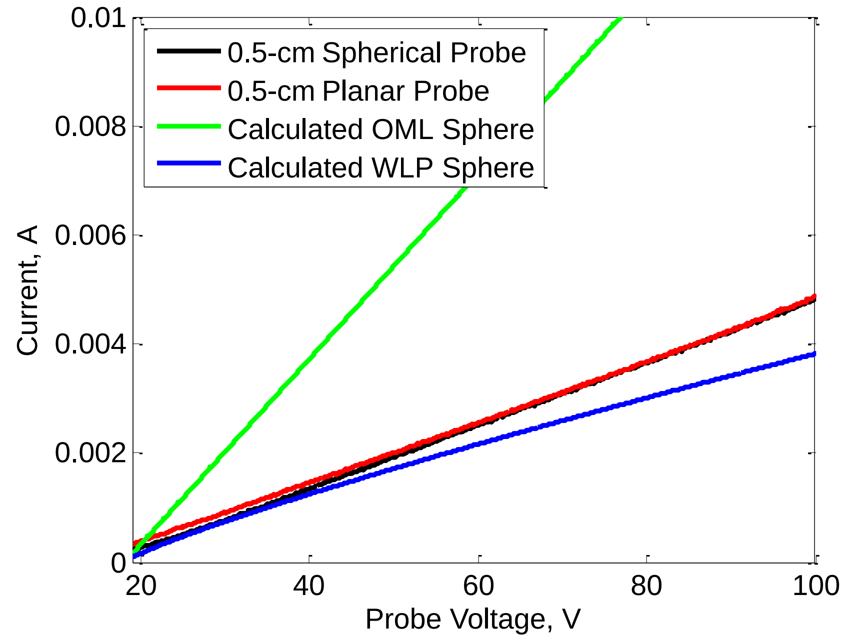
Barjatya, Swenson, Thompson, and Wright (2009)

Comparing Experiments





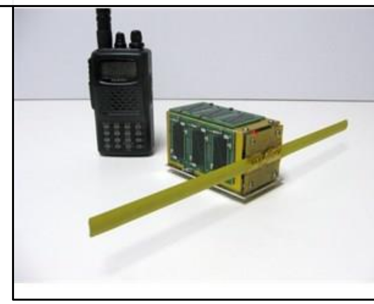




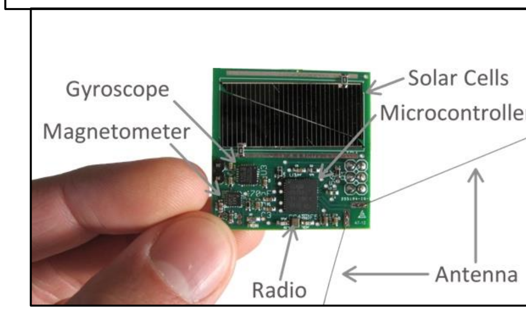
Example Picosats and Femtosats

Picosat 1 and 2
250 g, few cm length

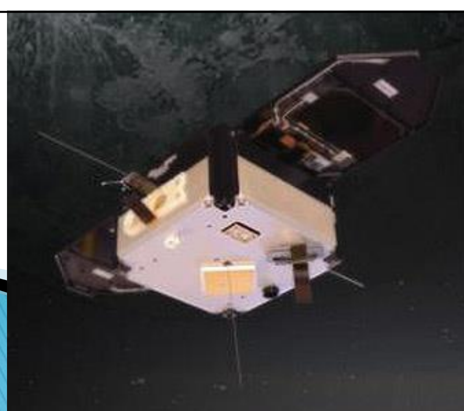
Eagle 2 ($50sat)
210 g, 5×5×7.5 cm



Sprite ChipSat
5 g, 3.5×3.5×0.25 cm



AeroCube 6a and 6b
0.5 U



<u>Capability at the small scale</u>

- Conventional subsystems
  - Computer, transceiver, attitude control and sensing, GPS, etc…
- Compelling science
  - Miniaturized radiation dosimeter
  - Inter-sat cross-link comm