Exploring the Potential of Miniature Electrodynamic Tethers to Provide Propulsion and other Capabilities to Femtosatellites and Picosatellites

Iverson C. Bell, III

Research Advisor: Professor Brian E. Gilchrist
The University of Michigan

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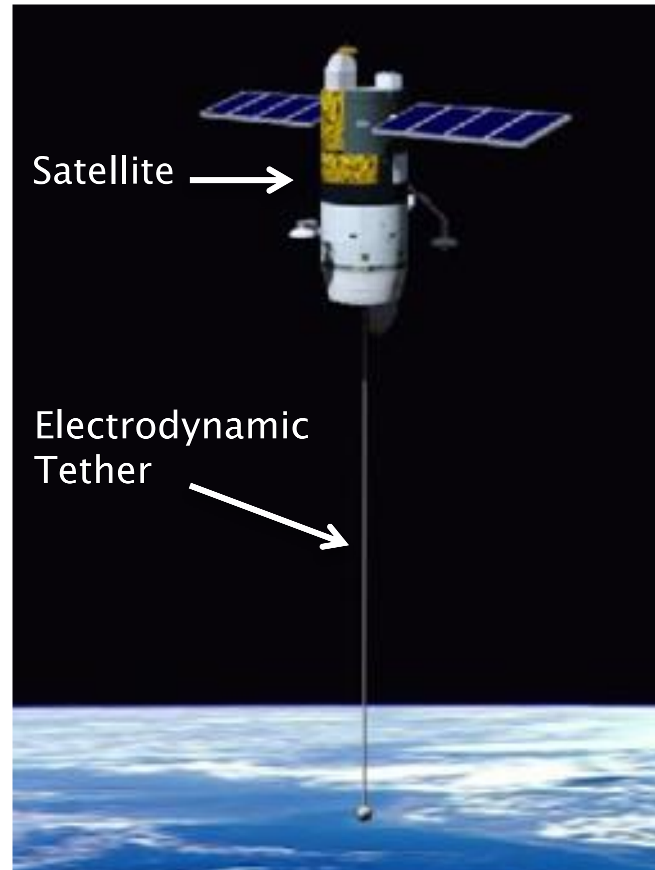
Overview of Research

- Electrodynamic tether propulsion technology has potential to enable small satellites
- Potential of the technology
  - Enable *maneuverable, coordinated fleets* of spacecraft
  - Extend satellite lifetime
  - Enable controlled de-orbiting to ***prevent*** satellites from becoming "space junk" or orbital debris
  - The same system can operate as an antenna and a scientific instrument



Electrodynamic Tether Illustration

The Next Generation of Small Sats: Picosatellites and Femtosatellites

- Picosats (0.1–1 kg) and femtosats (<100 g)
- Think flying your iPhone or Galaxy smartphone in space

iPhone 6

- Radio transceiver
- CPU
- Battery
- Cameras
- GPS
- Accelerometer
- Magnetometer
- 129 g (14x7x0.7 cm)

Modern smartphones have <u>many</u> of the same capabilities as satellites!

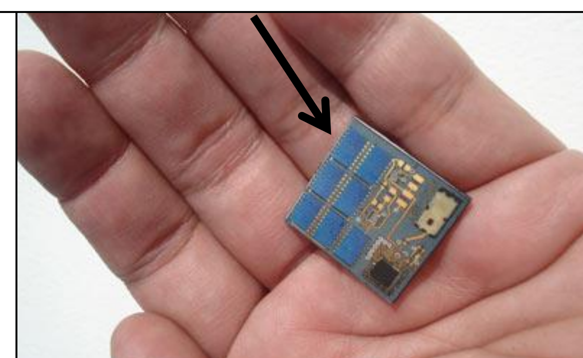
Example Picosatellites and Femtosatellites

PhoneSat 2.4
1 kg, 10x10x10 cm

Picosat 1 and 2
250 g, few cm length

AeroCube 6a and 6b
0.5 U

Sprite "Satellite-on-a-Chip"
5 g, 3.5×3.5×0.25 cm



The Potential of Picosats and Femtosats

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

- *Fleets* of picosats or femtosats could enable:
  - Earth monitoring for rapid emergency disaster response
  - Understanding phenomena that cause GPS signal interruptions and errors
  - Spacecraft to fly together to make up an entirely new class of sophisticated virtual spacecraft

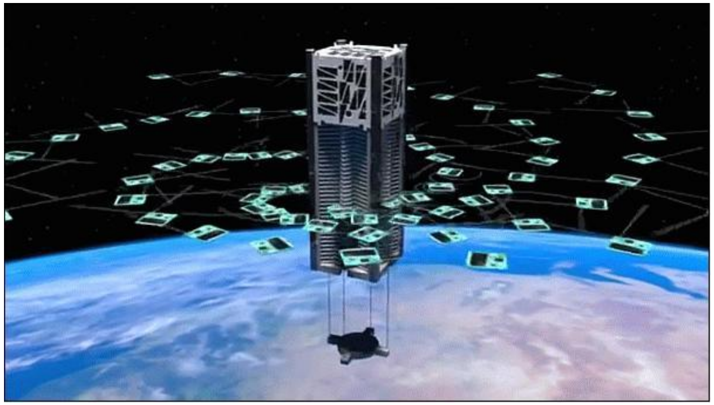
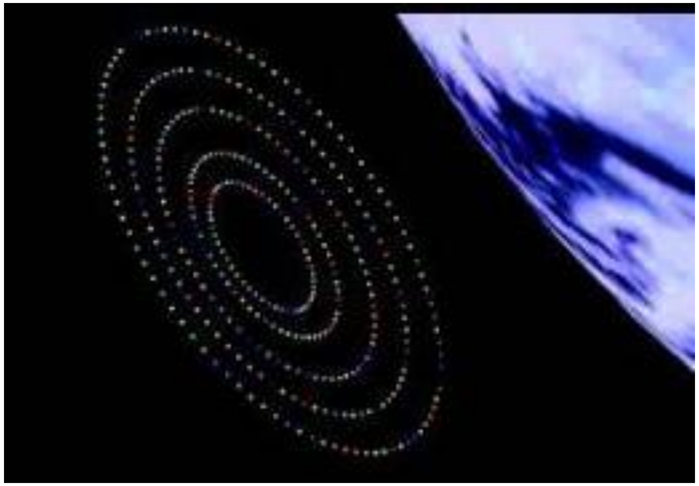


Illustration of KickSat mission concept



Small satellites in formation

Challenges for Picosats and Femtosats

1. Space missions <u>requiring</u> coordination and maneuverability

1. Short orbital lifetime- very small sats re-enter the atmosphere days to months after launch

Electrodynamic Tethers (EDTs)

- An electrodynamic tether (EDT) is an advanced propulsion technology.
- EDTs are long conducting wires.
- EDTs can provide spacecraft maneuverability and extend mission lifetime.
- Note: EDTs do not require fuel. Solar panels can provide energy for propulsion.

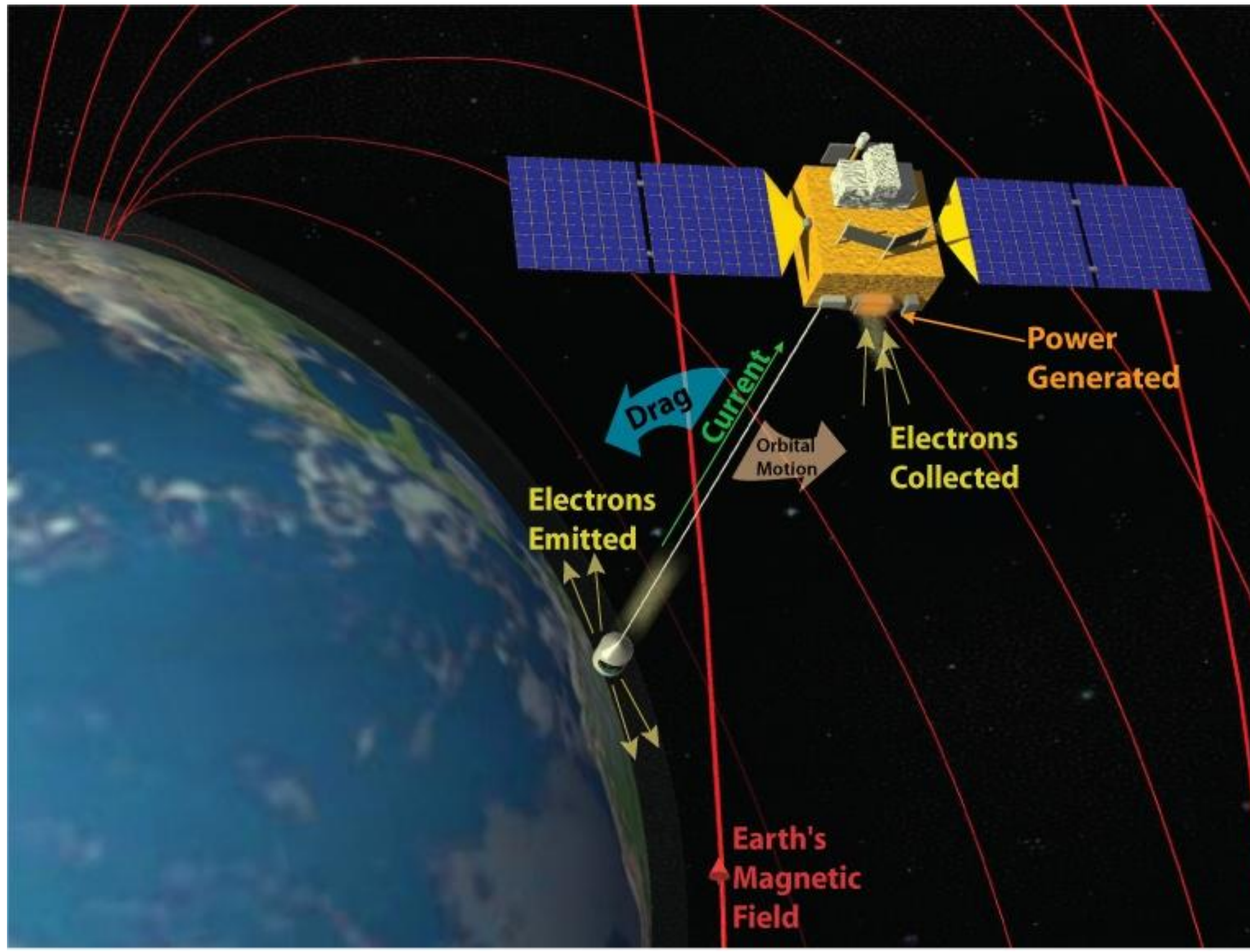
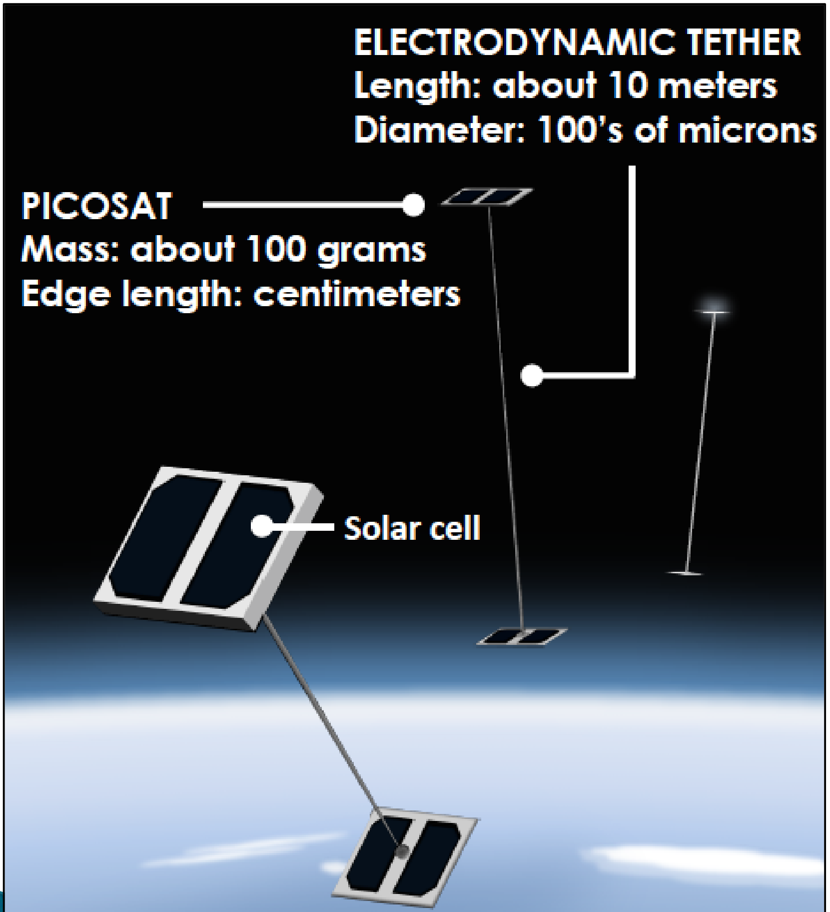


Illustration of electrodynamic tether (EDT) system in orbit

Miniaturized Electrodynamic Tethers



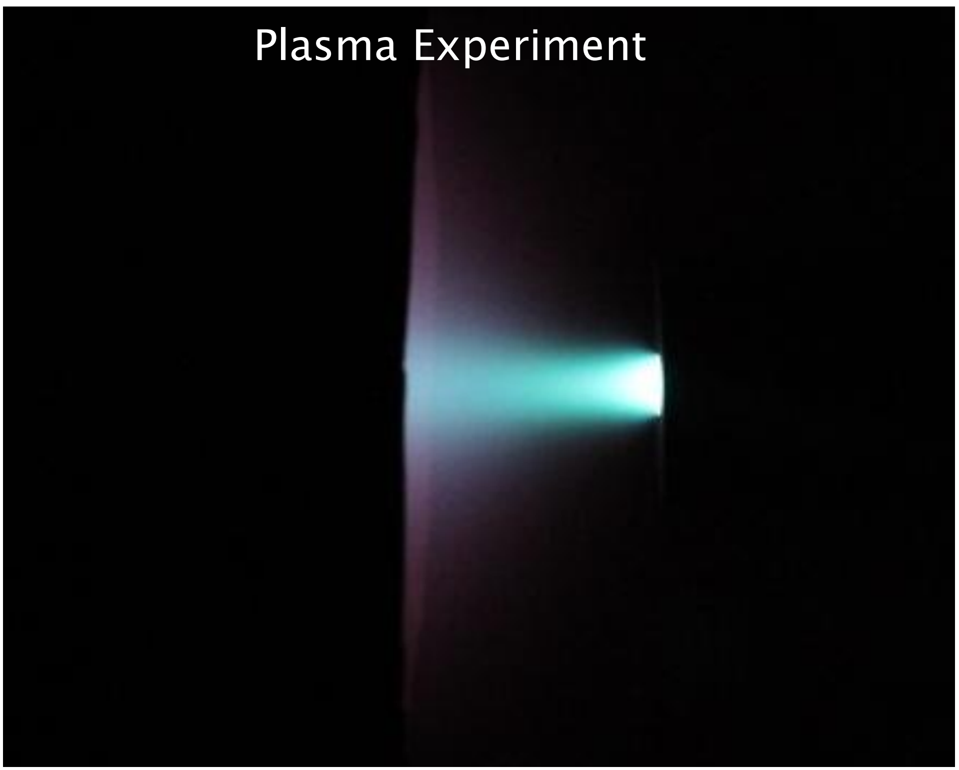
Concept of EDTs with 3 pairs of thin, smartphone-sized picosats in a maneuverable fleet.

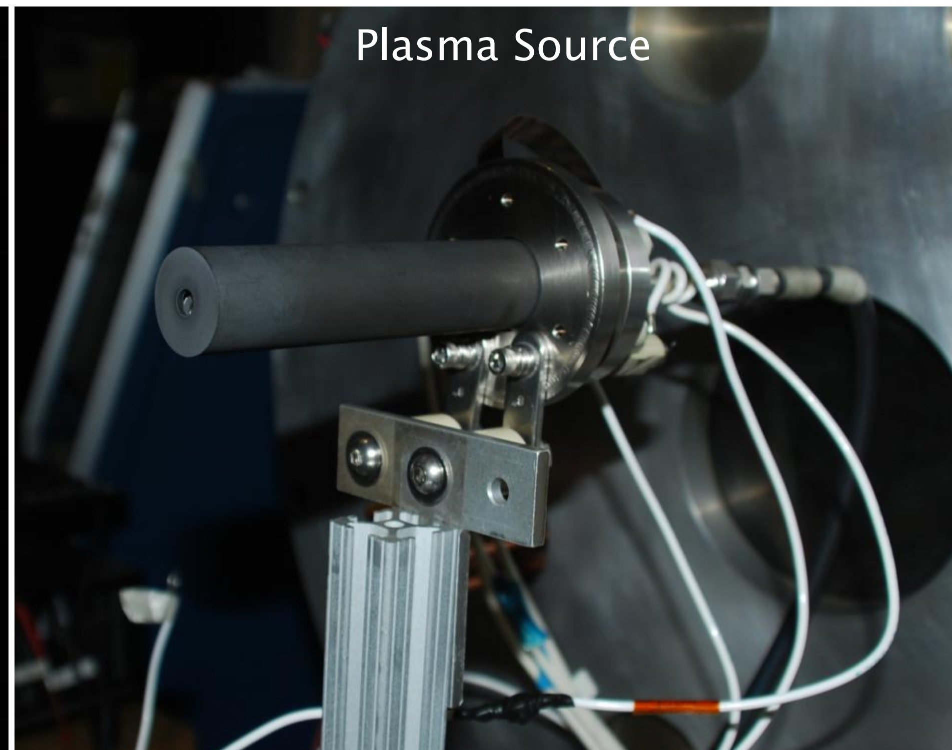
- Conventional EDTs can provide propulsion
- EDTs can be miniaturized for picosats and femtosats
- Additional benefits include:
  - ✓ EDTs can function as antennas
  - ✓ EDTs can function as useful scientific instruments
- Research goals: explore how EDTs could enable picosats and femtosats

» RESEARCH

Simulating the Space Environment

- Simulate the environment in orbit to better understand how propulsion system works in orbit



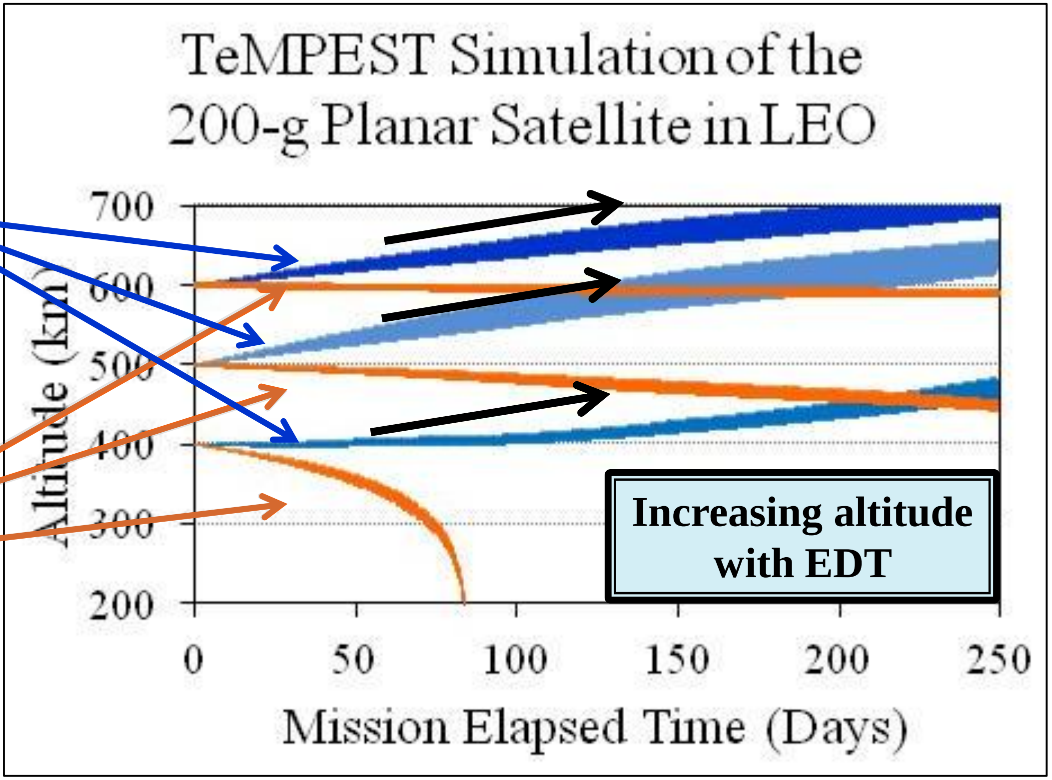


Note: this is like a wind tunnel for spacecraft

Simulating Performance

Dual satellites with an ED tether

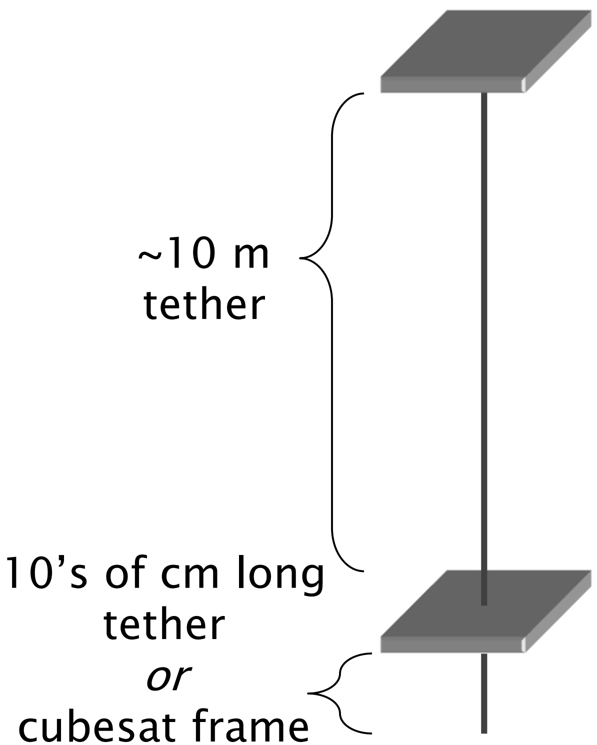
Single 100-g satellite starting at 400 km, 500 km, and 600 km



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

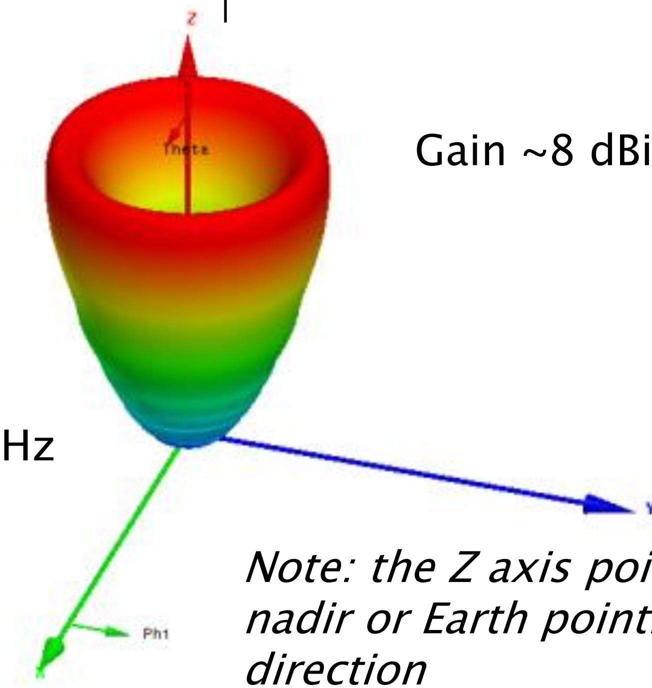
Simulating the EDT as an antenna

Possible ED Tether Architecture for Communication



Simulated ED Tether Radiation Pattern

↑ nadir



Gain ~8 dBi

F = 430 MHz

Note: the Z axis points in the nadir or Earth pointing direction

HFSS antenna model

Tether provides directional, traveling wave type radiation pattern

Testing the Concept in Space: The Miniature Tether Electrodynamics Experiment (MiTEE)

Goal of MiTEE: demonstrate a miniature EDT in space

This mission is being developed by ~30 undergraduate and Master's level students at the University of Michigan in collaboration with Penn State, so we are <u>educating</u> and <u>enriching</u> students

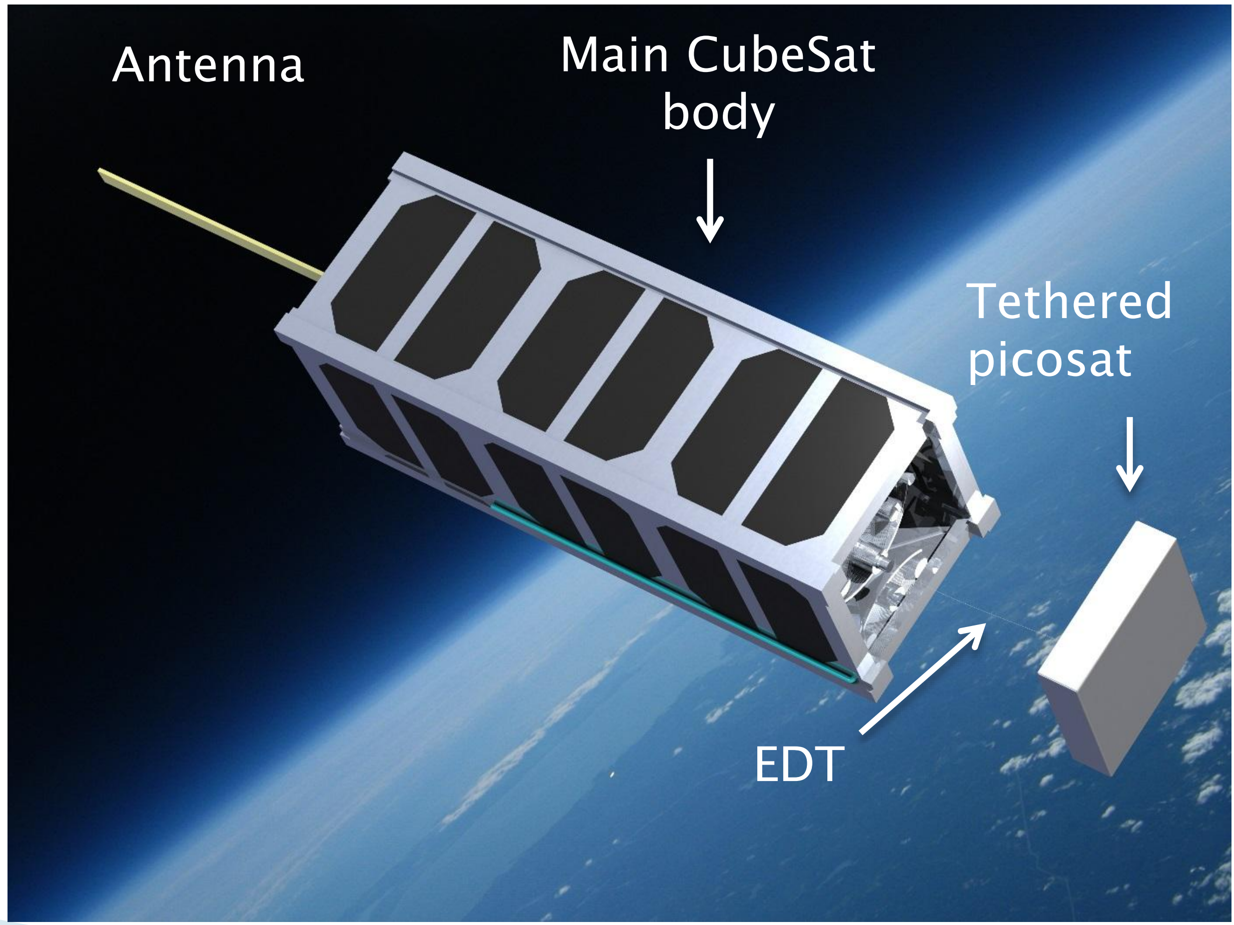
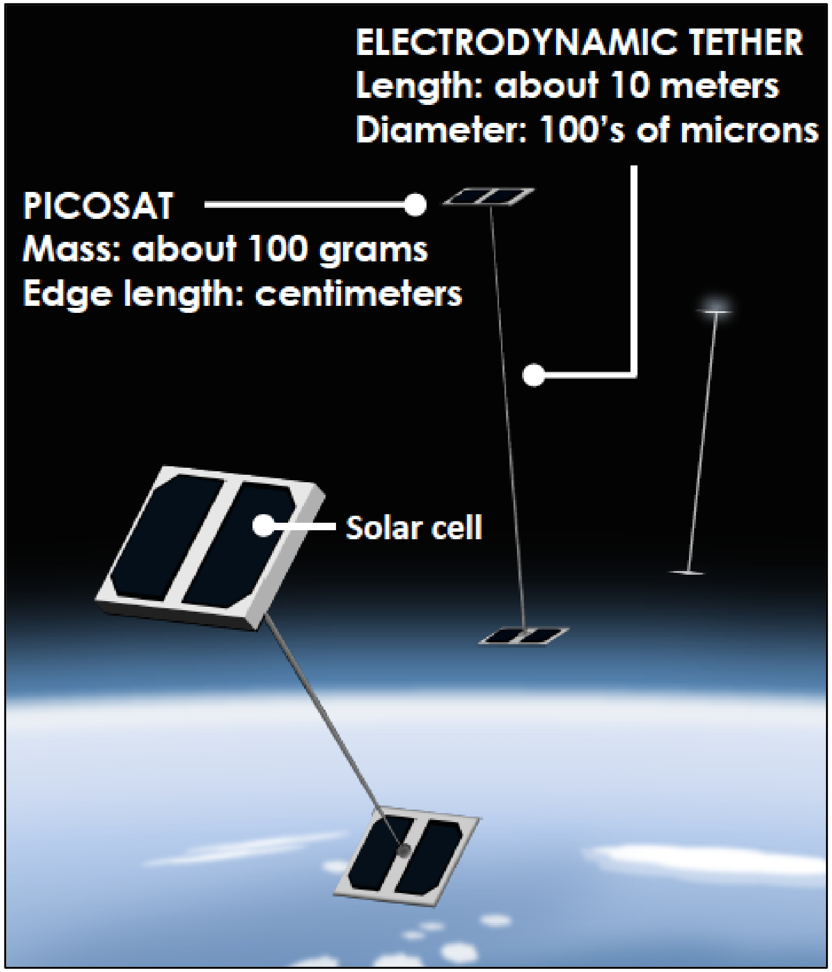


Illustration of the MiTEE space mission

Conclusions

- A short, few-meter tether shows potential for stable, propellantless pico- and femtosat propulsion
- The tether may also function as an enhanced antenna
- Potential impact:
  - Lifetime enhancement
  - Enable coordinated, controllable fleets of small satellites
  - Debris mitigation



Acknowledgements

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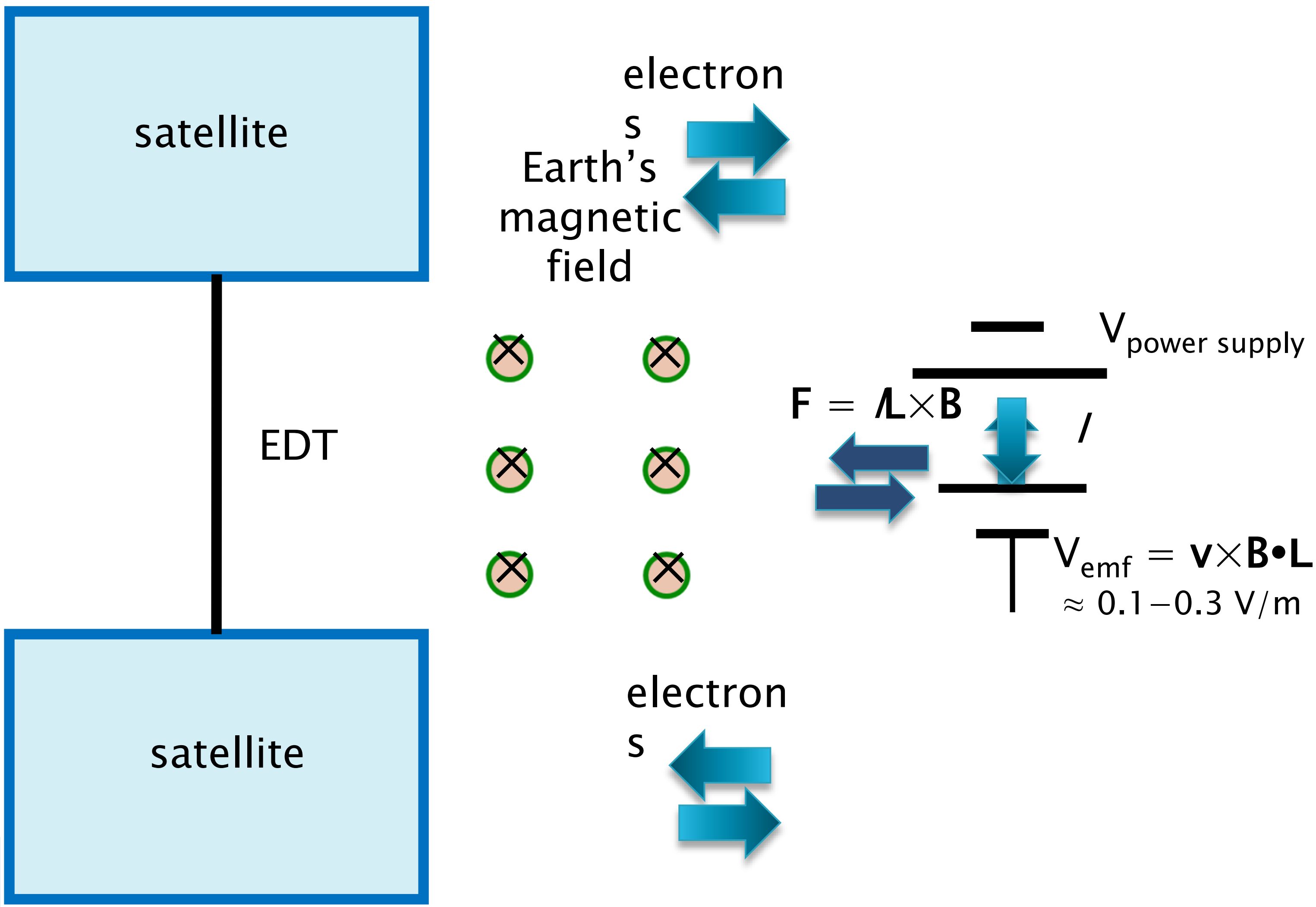
- Thank You!

- Backup slides

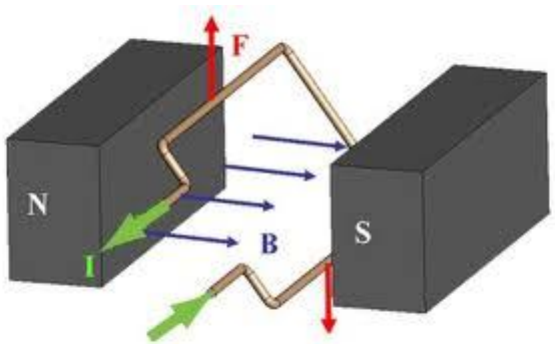
EDT Background

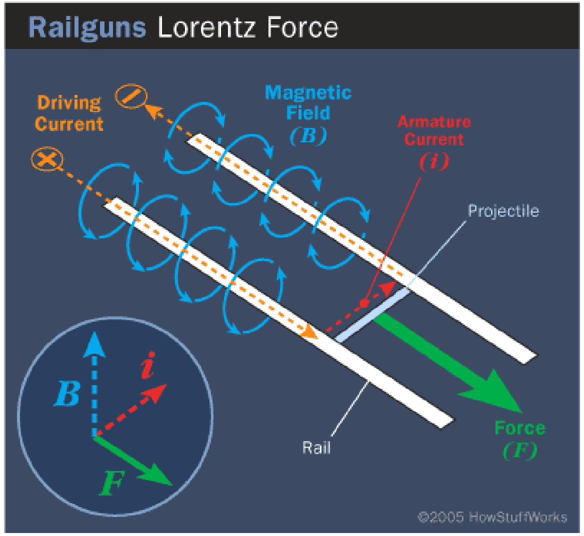
1. An EDT is a long wire
2. The EDT crosses magnetic field lines
3. V_{emf} generated
4. Ionosphere completes circuit
5. Force opposes motion
6. A power supply in series can reverse EDT current
7. Force is now in direction



The Lorentz Force at Work

- Electric motor
- Speakers
  - Link: http://www.physics-chemistry-interactive-flash-animation.com/mechanics_forces_gravitation_energy_interactive/lorentz_laplace_force_speaker.htm
- Rail gun
- Linear actuator
- Electrodynamic tether

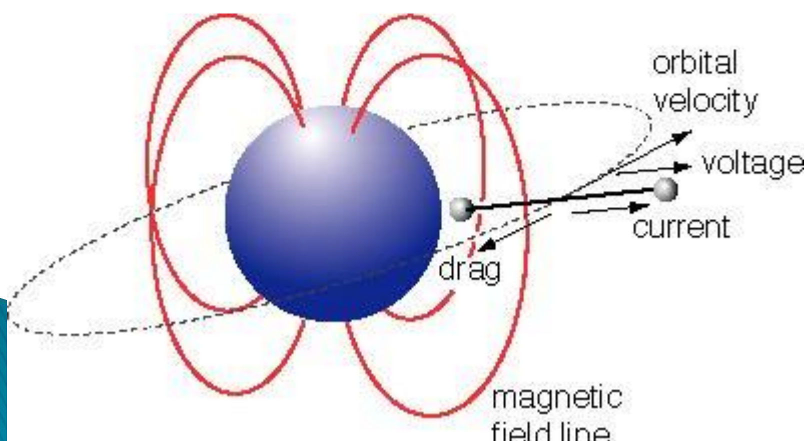


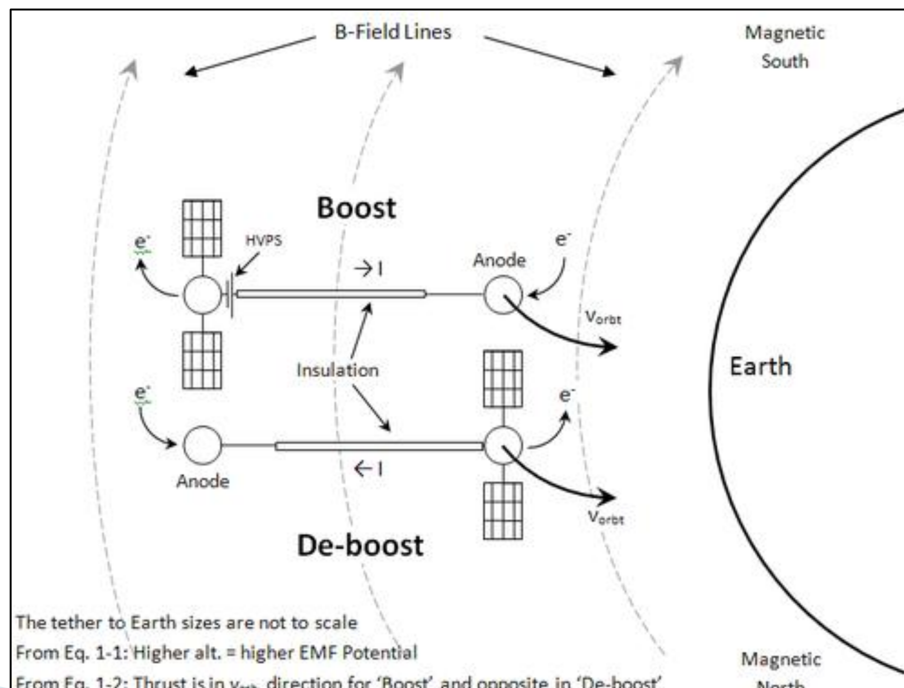


Electrodynamic Tether Introduction: Propellantless Propulsion

- An electrodynamic tether (EDT) is a current-carrying conductor that can generate force in a planetary magnetic field
- Connected to a satellite, this force can be used to overcome atmospheric drag and change the satellite's altitude or inclination.

$$\mathbf{F}_{\text{Electrodynamic Tether}} = \int_0^{Tether\_Length} \left(I_{\text{tether}} d\mathbf{L}\right) \times \mathbf{B}_{\text{Earth}}$$



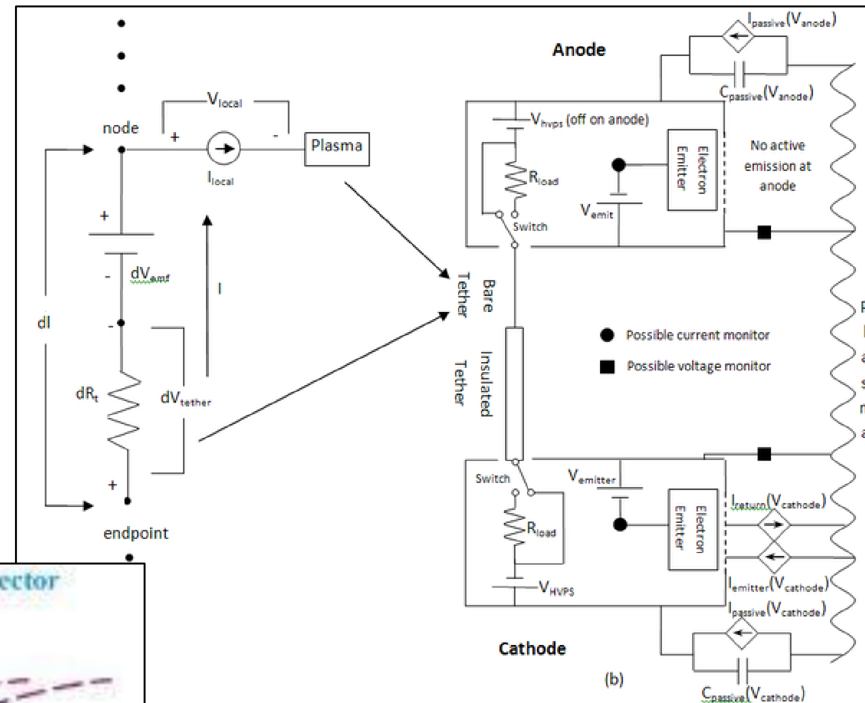


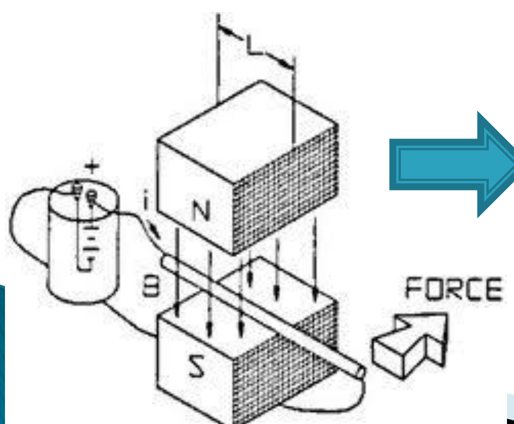
Electrodynamic Tether Introduction: Closing the Circuit

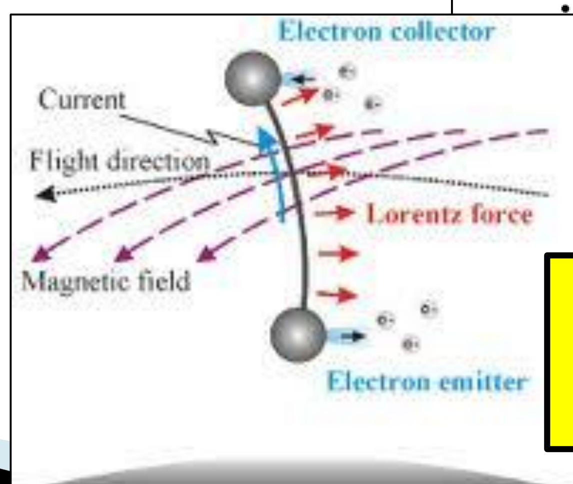
- The circuit must be closed at either end of the tether for current to flow

$$\mathbf{F}_{\text{Electrodynamic Tether}} = \int_0^{Tether\_Length} (I_{\text{tether}} d\mathbf{L}) \times \mathbf{B}_{\text{Earth}}$$

- The EDT connects to the ionospere at each end to close the circuit





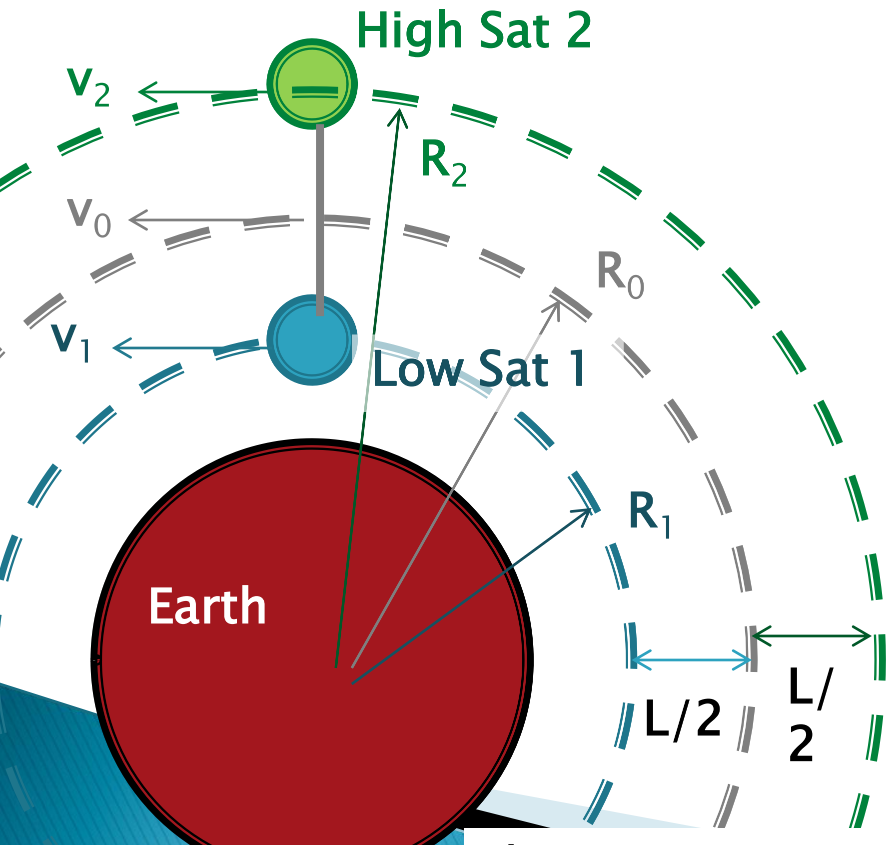


The ionosphere is a sea of charged particles (plasma) that helps close the circuit.

Gravity Gradient Stabilization, Part 1

Old Fashioned Video (1:39–19:50)
http://www.youtube.com/watch?v=tRciKLI7U2E

Shared orbital $v_0 = (GM/R_0)^{1/2}$
If disconnected, $v_1 > v_2$
$R_2 = R_0 + L/2$
$R_1 = R_0 - L/2$



Forces	High Sat 2	Low Sat 1
Centrifugal "Force"	mv_0^2/R_2	mv_0^2/R_1
Gravity Force	GMm/R_2^2	GMm/R_1^2
Comparison	Centrifugal "force" dominates	Gravity force dominates
Net direction of Vertical Forces		

Tether tension

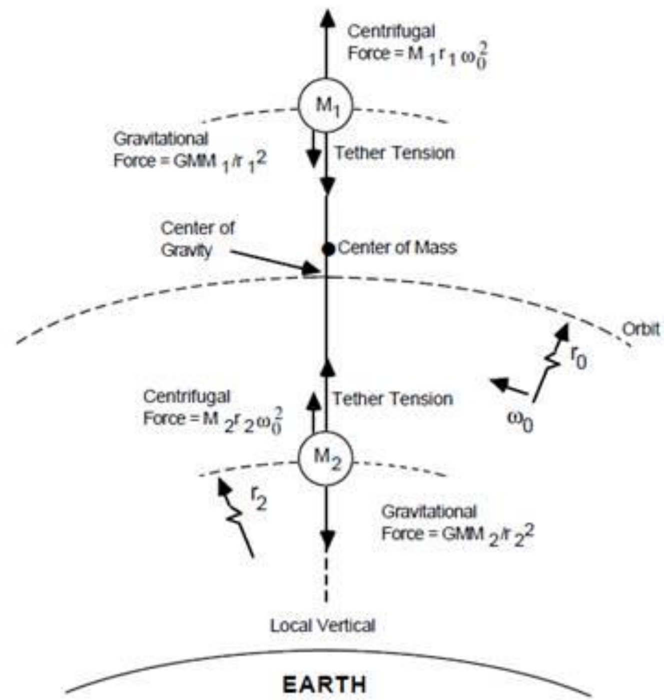
Assume $m_1 = m_2 = m$ & massless

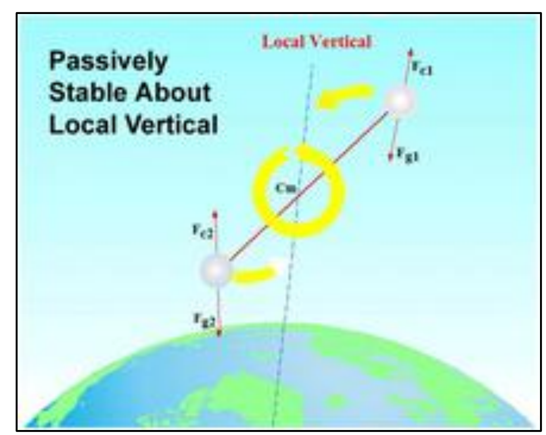
Gravity Gradient Stabilization, Part 2

- Gravity gradient torques are caused when the s/c center of gravity is not aligned with the center of mass wrt the local vertical
- GG torque increases with angle between local vertical and spacecraft's principal axis, trying to align principal axis with vertical

$$\boldsymbol{\tau}_{gg} = \frac{3\mu}{R_0^{\;3}} \mathbf{u}_e \times \left(\mathbf{I}_{\text{spacecraft}} \bullet \mathbf{u}_e \right)$$

$$\boldsymbol{\tau}_{gg} \approx \frac{3\mu}{2R_0} \left| I_z - I_y \right| \sin(2\theta)$$





Tether History *Courtesy Robert Hoyt, Tethers Unlimited*

Tether Prior History

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

= 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

Questions?

- Iverson Bell: icbell@umich.edu
- Professor Brian Gilchrist: brian.gilchrist@umich.edu