Investigating the Use of Miniaturized Electrodynamınic Tethers to Enhance the Capabilities of Femtosatellites and other Ultra-small Satellites

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Presentation Outline

- Ultra-small satellite introduction
- Electrodynamic tether introduction
- Dual femto/picosatellite tether concept
- Trade study results
  - Estimating power needed for propulsion
  - Estimating thrust
  - Estimating tether performance as antenna
Ultra-small satellites: the pico- and femtosat concepts

- 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.

<table>
<thead>
<tr>
<th>Name</th>
<th>Weight</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprite chipsat</td>
<td>7.5 mg</td>
<td>1×1×0.025 cm</td>
</tr>
<tr>
<td>Picosat 1 and 2</td>
<td>250 g</td>
<td>few cm length</td>
</tr>
<tr>
<td>PocketQub</td>
<td>~250 g</td>
<td>5×5×5 cm</td>
</tr>
<tr>
<td>PCBSat</td>
<td>~300 g</td>
<td>9×9.5×2.5 cm</td>
</tr>
<tr>
<td>PalmSat</td>
<td>Few 100 g</td>
<td>several cm length</td>
</tr>
<tr>
<td>CubeSat</td>
<td>1 kg</td>
<td>10×10×10 cm</td>
</tr>
</tbody>
</table>
What are some applications for picosat or femtosat fleets?

- Planetary monitoring
  - Global monitoring of natural disaster
  - Potentially useful on other planetary bodies

- *In situ* measurements of the ionosphere/thermosphere
  - Gaining insight into the temporal evolution of ionosphere at smaller scale
  - Studying the structure and dynamics of ionosphere scintillation events (gradients in ion density)

- Fractionated system architecture
**The Need for Propulsion**

- Small Size & mass enable large *swarms* or *fleets* to be launched.
- Missions using “fleets” of pico- and femtosats would require coordination/maneuverability (propulsion).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>3 kg CubeSat</th>
<th>8 g ChipSat</th>
<th>7.5 mg ChipSat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration</td>
<td>3-1000 cm(^3) cubes, stacked upright</td>
<td>Low drag</td>
<td>High Drag</td>
</tr>
<tr>
<td>Ballistic Coeff.</td>
<td>45</td>
<td>95</td>
<td>2.5</td>
</tr>
<tr>
<td>Alt = 300 km</td>
<td>a month</td>
<td>a month</td>
<td>hours</td>
</tr>
<tr>
<td>Alt = 400 km</td>
<td>several months</td>
<td>several months</td>
<td>days</td>
</tr>
<tr>
<td>Alt = 500 km</td>
<td>~1 year</td>
<td>~1-2 years</td>
<td>weeks</td>
</tr>
</tbody>
</table>

*Early concepts also have no propellant and a high area/mass ratio, so the orbital lifetime is short.*
Electrodynamic Tethers (EDTs) are Capable of Thrusting

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

\[ \mathbf{F}_{\text{Lorentz}} = \int_{0}^{\text{Wire Length}} (I_{\text{wire}} d\mathbf{L}) \times \mathbf{B}_{\text{Permanent magnet}} \]

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

\[ \mathbf{F}_{\text{Electrodynamic Tether}} = \int_{0}^{\text{Tether Length}} (I_{\text{tether}} d\mathbf{L}) \times \mathbf{B}_{\text{Earth}} \]

Connected to a satellite, this force can be used to overcome atmospheric drag and change the satellite’s altitude or inclination.
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.
Motivation for using Electrodynamic Tethers (EDTs) for Thrusting

- EDT 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

Research questions:
Can electrodynamic tethers provide ultra small satellites with lifetime enhancement and maneuverability? Can it provide other capabilities?
Trade Study System Concept

System is capable of boost, deboost, and inclination change

Both satellites have
- solar panel
- power supply
- electron emitter
- capable of collecting electrons on the surface

Four satellites are considered in the trade study

Electron emitter
Pico/femtosat
Power source
Insulated tether (1–12 m long)
Conductive coating
Nearly identical pico/femtosat

\[
F_{\text{EDT Thrust}} = \int_0^L (I_{\text{tether}} dL) \times B
\]

Both satellites have
- 250 g Satellite
- 5 cm × 5 cm × 5 cm
- 50 g Satellite
- 5 cm × 5 cm × 1 cm
- 2 g Satellite
- 1 cm × 1 cm × 1 cm
- 400 mg Satellite
- 1 cm × 1 cm × 0.2 cm

System is capable of boost, deboost, and inclination change
Estimate of Power Needed and Available for Drag Make-up

- Estimated that solar cells provide $4.4 \text{ mW} \cdot \text{cm}^{-2}$ for propulsion

- If more power is available than required for thrust, the EDT can boost

- Figures to the right show power needed for drag make-up at
  - 400 km (black)
  - 500 km (green)
  - 600 km (blue)

as well as the power available for propulsion (red)
A 1m EDT gives peak thrust for 400 mg femtosat at 500 km and 600 km. The gravity gradient force is also well below other forces.
Velocity

A 12 m EDT gives peak thrust for 250 g picosat at 400 km, 500 km, and 600 km. The gravity gradient force is also comparable to other forces.
Potential of ED Tether to Enhance Communication

Possible ED Tether Architecture for Communication

- 1.75 m tether
- 0.25 m tether

Simulated ED Tether Radiation Pattern

- Radiation pattern cross section
- 3D pattern

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

\[ F = 295 \text{ MHz} \]
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
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>400 mg</th>
<th>2 g</th>
<th>50 g</th>
<th>250 g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite Dimensions</td>
<td>1 cm × 1 cm</td>
<td>1 cm × 1 cm</td>
<td>5 cm × 5 cm</td>
<td>5 cm × 5 cm</td>
</tr>
<tr>
<td></td>
<td>1 cm × 1 cm</td>
<td>1 cm × 1 cm</td>
<td>5 cm × 5 cm</td>
<td>5 cm × 5 cm</td>
</tr>
<tr>
<td></td>
<td>0.2 cm</td>
<td>1 cm</td>
<td>1 cm</td>
<td>5 cm</td>
</tr>
<tr>
<td>Tether</td>
<td>1 m long, 24 μm diam.</td>
<td>4 m long, 70 μm diam.</td>
<td>5 m long, 80 μm diam.</td>
<td>12 m long, 200 μm diam.</td>
</tr>
<tr>
<td>Mass</td>
<td>2 mg</td>
<td>12 mg</td>
<td>0.18 g</td>
<td>3 g</td>
</tr>
<tr>
<td>Thrust Power</td>
<td>9 mW</td>
<td>27 mW</td>
<td>318 mW</td>
<td>672 mW</td>
</tr>
<tr>
<td>Where is gravity gradient significant?</td>
<td>~600 km</td>
<td>~500 km, 600 km</td>
<td>~400 km, 500 km, 600 km</td>
<td>400 km, 500 km, 600 km</td>
</tr>
</tbody>
</table>
Thank you
Additional Slides
## More Detailed System Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>400 mg</th>
<th>2 g</th>
<th>50 g</th>
<th>250 g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Current Needed for Drag</td>
<td>400 km</td>
<td>0.66</td>
<td>1.24</td>
<td>2.89</td>
</tr>
<tr>
<td>Make-up (mA)</td>
<td>500 km</td>
<td>0.12</td>
<td>0.22</td>
<td>0.52</td>
</tr>
<tr>
<td>Estimated Sphindt</td>
<td>600 km</td>
<td>0.03</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>Cathode Base-Gate Voltage (V)</td>
<td>400 km</td>
<td>45</td>
<td>49</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>500 km</td>
<td>38</td>
<td>43</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>600 km</td>
<td>35</td>
<td>36</td>
<td>38</td>
</tr>
<tr>
<td>Dimensions</td>
<td>1 cm × 1 cm × 0.2 cm</td>
<td>1 cm × 1 cm × 1 cm</td>
<td>5 cm × 5 cm × 1 cm</td>
<td>5 cm × 5 cm × 5 cm</td>
</tr>
<tr>
<td>Surface area of largest sat face (cm²)</td>
<td>1</td>
<td>1</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Total surface area of each sat (cm²)</td>
<td>2.8</td>
<td>6</td>
<td>70</td>
<td>150</td>
</tr>
</tbody>
</table>
- 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

- Electrodynamical 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 \((F_{RE})\)

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

\[
y_{\text{max}} = \frac{-5L^4}{384EI_{\text{inertia}}} \left( \frac{F_{RT}}{L} \right)
\]
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, $f_{\text{nat}}$

If rigidity is important, increasing EDT length requires increasing the radius.
We aim to find the minimum radius so the tether can be coiled without distorting the straight, elongated equilibrium shape

- High $E \sim$ more rigid
- Euler–Bernoulli Beam Theory…
  - $\rho_{\text{min}} = \frac{Ec}{\sigma_Y}$
  - $\rho_{\text{min}}$ is minimum radius of elastic curvature, $c$ is wire/beam radius, $\sigma_Y$ is yield stress

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