Exploring the Potential of Miniature Electrodynamic Tethers and Developments in the Miniature Tether Electrodynamics Experiment

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SSC14-WK-4
Picosatellites and Femtosatellites

- Picosats (0.1–1 kg) and femtosats (<100 g), are an emerging class of “ultra-small” satellites
  - Smartphone sized satellites with enhanced MEMS sensors
- Can fly low-cost constellations of satellites
  - Multi-point, simultaneous measurements

**Sprite chipsat**
7.5 mg, 1×1×0.025 cm

**PhoneSat 1.0**
~1 kg, ~10×10×10 cm
### Challenges for Ultra-small Sats

1. Missions requiring coordination and maneuverability (*fleets of s/c*)
2. Short orbital lifetime.
3. Limited power and size

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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>1-kg CubeSat</th>
<th>200-g PicoSat</th>
<th>8-g FemtoSat</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimensions</strong></td>
<td>10x10x10 cm</td>
<td>10x10x2 cm</td>
<td>3.8x3.8x0.1 cm</td>
</tr>
<tr>
<td><strong>Configuration</strong></td>
<td>1 face in ram direction</td>
<td>Low drag</td>
<td>High Drag</td>
</tr>
<tr>
<td><strong>Ballistic Coeff. (kg·m(^{-2}))</strong></td>
<td>45</td>
<td>45</td>
<td>9</td>
</tr>
<tr>
<td>Alt = 300 km</td>
<td>weeks</td>
<td>weeks</td>
<td>days</td>
</tr>
<tr>
<td>Alt = 400 km</td>
<td>months</td>
<td>months</td>
<td>weeks</td>
</tr>
<tr>
<td>Alt = 500 km</td>
<td>~1 year or more</td>
<td>~1 year or more</td>
<td>months</td>
</tr>
</tbody>
</table>

Early concepts have no propellant so the orbital lifetime is short.
Motivation for using Miniature Electrodynamic Tethers (EDTs)

- EDT can provide 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

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

MiTEE: Miniature Tether Electrodynamics Experiment

- Technology demonstration mission
- Primary mission: verify a 10 meter long tether can provide drag makeup for a femtosatellite (smartphone sized satellite)

- Secondary mission: Can the tether be used as an antenna?
- Use as a plasma probe
Electrodynamic Tether Propulsion

- Exploits the Lorenz force generated by current flow in a magnetic field

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

Electrons emitted into the ionosphere
Cathode
Cathode power supply
Anode power supply
ED tether
Anode (satellite surface)

Electrons collected from the ionosphere

Tether circuit completed in the ionosphere
The gravity gradient force generates tension in the tether.

The gravity gradient torque helps align the tether along the local vertical.
Tether Overview

• Requirements for Tether Material
  o High tensile strength to prevent tether from breaking
  o Conductive with insulating overlay
  o Semi-rigid

• Investigating various materials for use
  o Conducting testing on gold plated Nitinol as main material base

Bent Nitinol

Springs back to original shape
Deployment System

• **Tether Storage**
  o Coiled in a figure 8 pattern in spool to minimize tip off dynamics

• **Deployment**
  o Thermal knife cuts fiber that holds back end body
  o Spring loaded pegs push end body away
  o Investigating methods to prevent bounce back at end of tether

• **Micro-Gravity Testing**
  o Initial testing conducted in house
  o Constructed drop chamber to deploy tether
  o Will conduct further testing on parabolic flight
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Cathode

- Emits electrons from main body of satellite
- Flying two types of cathodes
  - Thermionic cathode
    - Hot cathode for primary emission
  - Field emission array cathode
    - Low TRL, cold cathode for demonstration and redundancy

Thermionic cathode

FEAC Cathode
• High-Voltage Power Supply (HVPS) supplies voltage bias for anode and cathode
• Low TRL item never tested in a CubeSat
• Requirements
  o 200 V drop, supplying up to 5 mA
  o Low power (< 2 W)
  o Small form factor
• Powered by on-board battery/solar cells
Communications Overview

• **Primary Antenna**
  o Monopole antenna
  o Omnidirectional in azimuth plane
  o 90° beamwidth in elevation plane

• **Secondary Antenna**
  o Travelling wave antenna
  o Gain 8 dBi at 435 MHz
  o Doughnut shaped radiation pattern directed towards nadir

• **Ground stations**
  o Ann Arbor, MI
  o TBD backup station
  o HAM community
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Diagnostics Tools

- **Langmuir Probe**
  - Plasma diagnostics tool to measure ambient plasma characteristics
  - Deployed off of primary antenna boom
- **Camera**
  - Verifies deployment, end body location
- **GPS**
  - Position data
Summer Progress Summary

• Successfully completed a high-altitude balloon flight
  ○ Tested communications and integration of components
Summer Progress Summary

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- Decision to have distributed network of MSP430s control CubeSat
Summer Progress Summary

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  o Tested communications and integration of components
• Decision to have distributed network of MSP430s control CubeSat
• In-house microgravity chamber and thermionic cathode testing system
Future Plans

• Heading towards a Preliminary Design Review in Fall 2014
• Plan to submit a proposal for launch position
• Submit proposal for reduced gravity flight with NASA
Questions?

Thank you for your time!
Backup Slides
Picosatellites and Femtosatellites

- Can be launched to form low cost constellations if propulsion source was on board
  - Multi-point, simultaneous measurements
  - Take *in-situ* measurements

DARPA System F6 Constellation Concept$^3$
Operations Overview

Launch from PPOD

Primary Antenna Deployment and De-tumble

Science Mission Starts

Tether Deployment when Nadir Facing
• Assumptions – UHF downlink at 435Mhz Reception using 436CP2UG Antenna from M2inc at ground station, 10dB Eb/No requirement to get a BER of 1e-06 using FSK modulation from an orbit of 500km altitude.

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Units</th>
<th>Source</th>
<th>Spacecraft to Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>( f )</td>
<td>GHz</td>
<td>Input Parameter</td>
<td>0.44</td>
</tr>
<tr>
<td>Transmitter Power (DC)</td>
<td>( P )</td>
<td>Watts</td>
<td>Input Parameter</td>
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<tr>
<td>Transmitter Power Amplifier Efficiency</td>
<td>( h_p )</td>
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<td>Transmitter Power (RF)</td>
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<td>Watts</td>
<td>( P_{\text{RF}} )</td>
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<td>Transmitter Power (RF)</td>
<td>( P )</td>
<td>dBW</td>
<td>( 10 \log_{10}(P) )</td>
<td>-3.468</td>
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<tr>
<td>Transmitter Line Loss</td>
<td>( L_u )</td>
<td>dB</td>
<td>Input Parameter</td>
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<td>Transmit Antenna Beamwidth</td>
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<td>deg</td>
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<td>48.276</td>
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<td>Transmit Antenna Efficiency</td>
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<td>Input Parameter</td>
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<tr>
<td>Peak Transmit Antenna Gain</td>
<td>( G_p )</td>
<td>dBi</td>
<td>Eq. (13-18b)</td>
<td>12.21</td>
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<tr>
<td>Transmit Antenna Diameter</td>
<td>( D_t )</td>
<td>m</td>
<td>Input Parameter</td>
<td>1.0</td>
</tr>
<tr>
<td>Transmit Antenna Pointing Error</td>
<td>( e_t )</td>
<td>deg</td>
<td>Input Parameter</td>
<td>0.000</td>
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<tr>
<td>Transmit Antenna Pointing Loss</td>
<td>( L_{\text{pt}} )</td>
<td>dB</td>
<td>Eq. (13-21)</td>
<td>-0.515</td>
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<td>Transmit Antenna Gain (net)</td>
<td>( G_{\text{pt}} )</td>
<td>dBi</td>
<td>( G_p + L_{\text{pt}} )</td>
<td>11.70</td>
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<tr>
<td>Equiv. Isotropic Radiated Power</td>
<td>EIRP</td>
<td>dBW</td>
<td>( P + L + G_t )</td>
<td>6.23</td>
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<td>Propagation Path Length</td>
<td>( S )</td>
<td>km</td>
<td>Input Parameter</td>
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<tr>
<td>Space Loss</td>
<td>( L_s )</td>
<td>dB</td>
<td>Eq. (13-23a)</td>
<td>-139.19</td>
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<tr>
<td>Propagation &amp; Polarization Loss</td>
<td>( L_a )</td>
<td>dB</td>
<td>Fig. 13-10</td>
<td>-0.5</td>
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<tr>
<td>Receive Antenna Diameter</td>
<td>( D_r )</td>
<td>m</td>
<td>Input Parameter</td>
<td>2.0</td>
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<tr>
<td>Receive Antenna Efficiency</td>
<td>( h_r )</td>
<td>--</td>
<td>Input Parameter</td>
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<tr>
<td>Peak Receive Antenna Gain</td>
<td>( G_{\text{rp}} )</td>
<td>dBi</td>
<td>Eq. (13-18b)</td>
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<tr>
<td>Receive Antenna Beamwidth</td>
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<td>Receive Antenna Pointing Loss</td>
<td>( L_{\text{pr}} )</td>
<td>dB</td>
<td>Eq. (13-21)</td>
<td>0.000</td>
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<tr>
<td>Receive Antenna Gain (net)</td>
<td>( G_r )</td>
<td>dBi</td>
<td>( G_{\text{rp}} + L_{\text{pr}} )</td>
<td>16.60</td>
</tr>
<tr>
<td>System Noise Temperature</td>
<td>( T_s )</td>
<td>K</td>
<td>Table 13-10 or DSN table</td>
<td>135</td>
</tr>
<tr>
<td>Data Rate</td>
<td>( R )</td>
<td>bps</td>
<td>Input Parameter</td>
<td>9600</td>
</tr>
<tr>
<td>Modulation Rate</td>
<td>--</td>
<td>--</td>
<td>Input Parameter</td>
<td>1.0</td>
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<tr>
<td>Computer Implementation Efficiency</td>
<td>--</td>
<td>--</td>
<td>Input Parameter</td>
<td>0.90</td>
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<tr>
<td>Effective Data Rate</td>
<td>( R )</td>
<td>bps</td>
<td>*See cell</td>
<td>10667</td>
</tr>
<tr>
<td>( E_b/N_0 ) (1)</td>
<td>( E_b/N_0 )</td>
<td>dB</td>
<td>Eq. (13-13)</td>
<td>50.16</td>
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<tr>
<td>Carrier-to-Noise Density Ratio</td>
<td>( C/N_0 )</td>
<td>dB-Hz</td>
<td>Eq. (13-15a)</td>
<td>90.44</td>
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<td>Bit Error Rate</td>
<td>BER</td>
<td>--</td>
<td>Input Parameter</td>
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<tr>
<td>Required ( E_b/N_0 ) (2)</td>
<td>( E_b/N_0 )</td>
<td>dB</td>
<td>Fig. 13-9</td>
<td>12.0</td>
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<tr>
<td>Implementation Loss (3)</td>
<td>--</td>
<td>dB</td>
<td>Input Parameter</td>
<td>-2.0</td>
</tr>
<tr>
<td>Rain Attenuation (4)</td>
<td>--</td>
<td>dB</td>
<td>Fig. 13-11</td>
<td>-1.0</td>
</tr>
<tr>
<td>Margin</td>
<td>--</td>
<td>dB</td>
<td>( (1) - (2) + (3) + (4) )</td>
<td>35.161</td>
</tr>
</tbody>
</table>
OADCS Overview

• Pre-Deployment nadir pointing accuracy of 10°
• Post-Deployment will rely on gravity gradient for nadir pointing stability
• Rotational stability in-plane to less than 0.2 rad/s
  o Out of plane rotation should be less than 0.01 rad/s
• Actuator
  o Magnetorquers with active control
• Position and attitude determination sensors
  o GPS
  o IMU
  o Magnetometer
  o Sun sensor