Space Tethers and Small Satellites: Formation Flight and Propulsion Applications

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Engineering the Future

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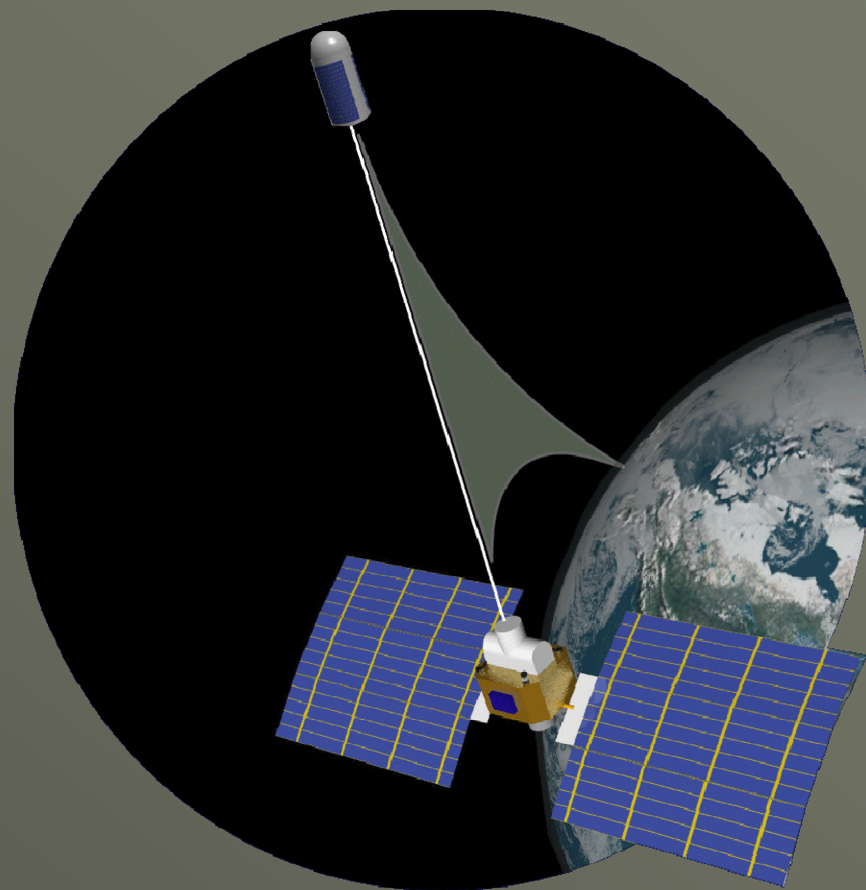
Space Tether Applications & Benefits

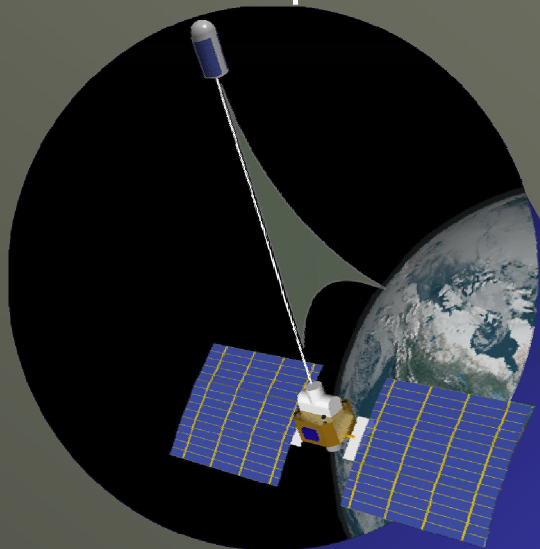
- Enable high ΔV missions by using mechanical or electrodynamic propulsion and motion control
- Reduce system mass by eliminating complex subsystems
- Minimize formation flying system complexity and risks
- Enable new missions by non-Keplerian motion of tethered satellites



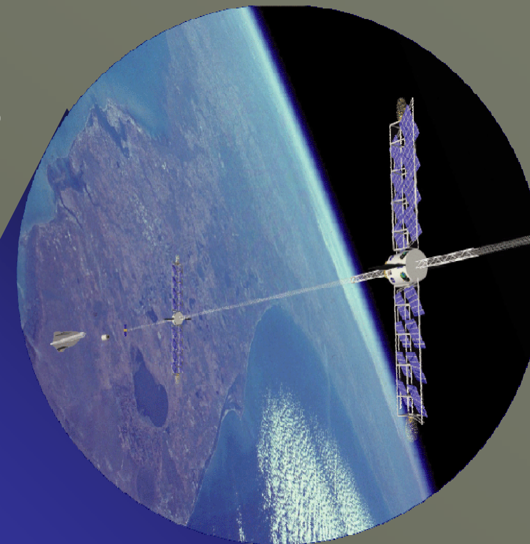
Provide new and improved system capabilities by exploiting unique motion of tethered satellite system

Space Tethers for Propellantless Propulsion

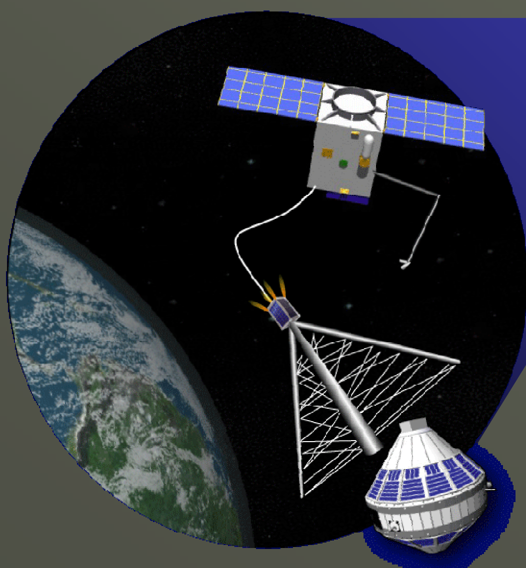
Orbit-Raising and Repositioning of LEO Spacecraft



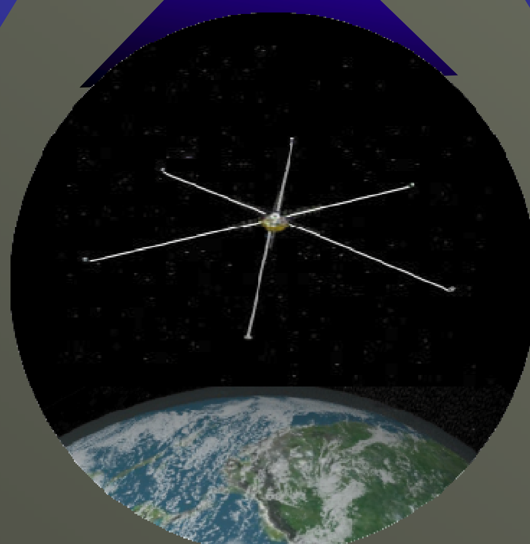
Launch-Assist & LEO to GTO Payload Transfer



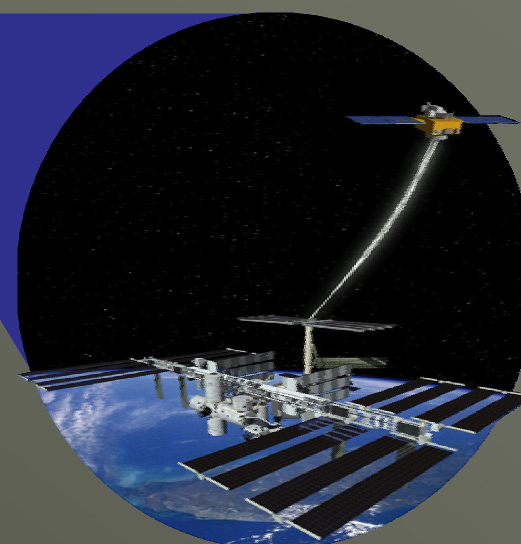
Propellantless propulsion enables large ΔV missions with low mass impact



Capture & Deorbit of Space Debris



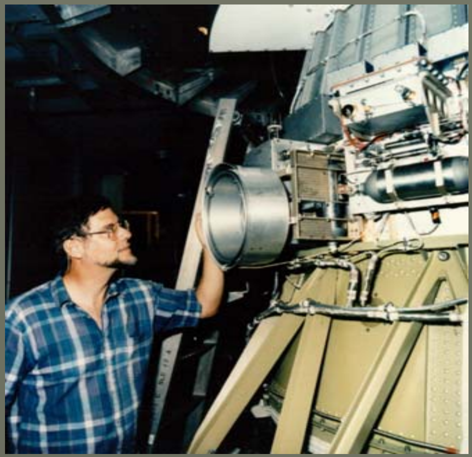
Formation Flying for Long-Baseline SAR & Interferometry



Drag-Makeup Stationkeeping for LEO Assets

Past Tether Flight Experiments

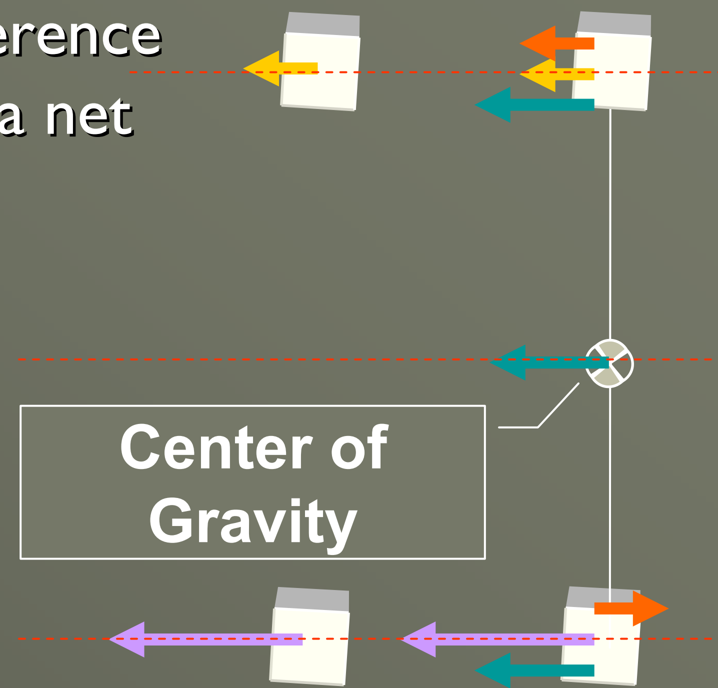
- ≥ 17 tether experiments flown, starting with Gemini capsule tether

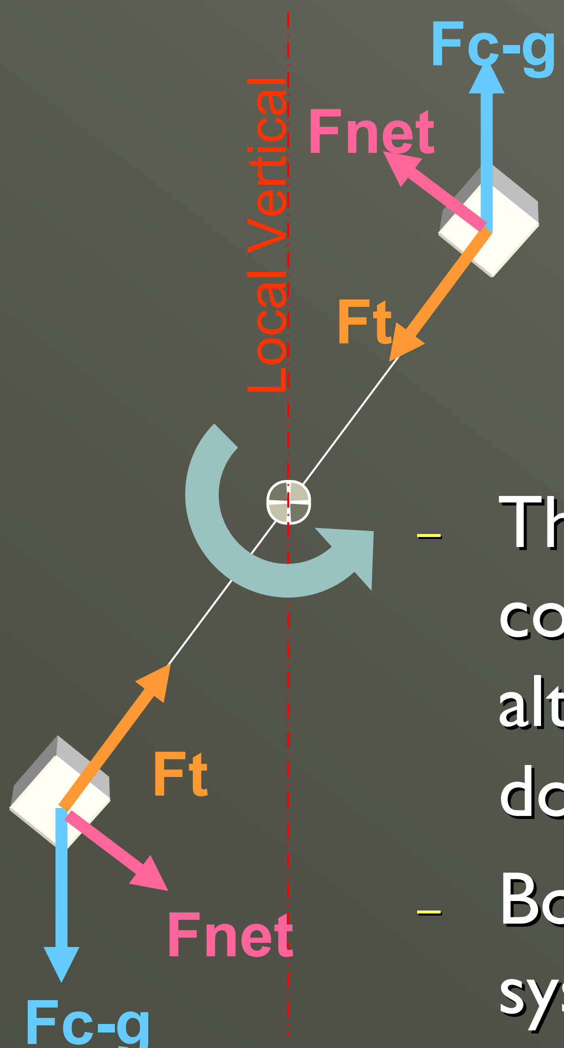


- Small Expendable Deployer System (SEDS)
  - SEDS 1&2: successfully deployed 20km tethers
  - PMG: 500m conducting tether
    - 7 hour lifetime, currents up to 300mA observed
- Shuttle Tethered Satellite System (TSS)
  - 20 km insulated conducting electrodynamic tether
  - TSS-1: 200m deployed, demostrated stable dynamics
    - Bolt that was too long caused deployer jam (engineering process failure)
  - TSS-1R: 19.9km deployed, >5 hours of excellent data validating ED tether physics
    - Arc caused tether to fail (tether fabrication/design/handling flaw)
- TiPS
  - 4km non-conducting tether
  - On orbit since June 1996

Intro to Gravity Gradient Tether System

- The gravity gradient and centrifugal force difference creates tension in the tether which results in a net local vertical restoring force

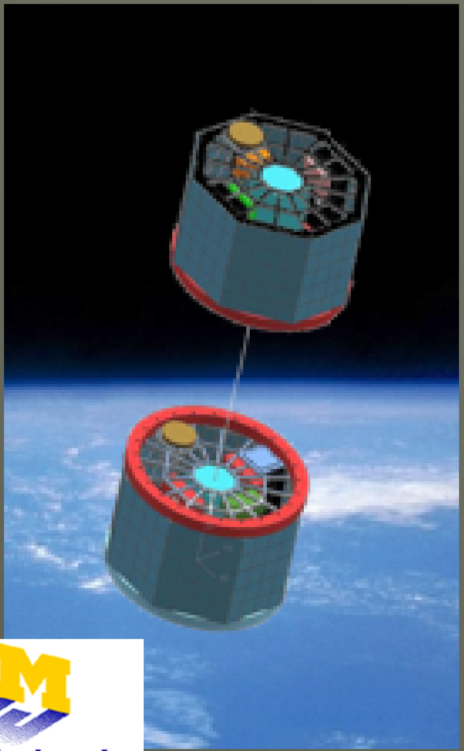




- The tension caused by the physical connection couples the motion of two satellites at different altitudes, speeding up the higher mass and slowing down the lower mass
- Both satellites travel at the orbital velocity of the system’s center of gravity

Nanosatellites & Space Tethers?

- Formation Flight without expending propellant
  - Two freeflyers separated by 100 vertical meters @ 700km would require *$\Delta V \approx 32$ m/sec PER DAY* for stationkeeping
- Nanosatellites can easily have orbital lifetimes exceeding 25 years
  - Commonly launched as secondary payloads => little control over insertion orbit

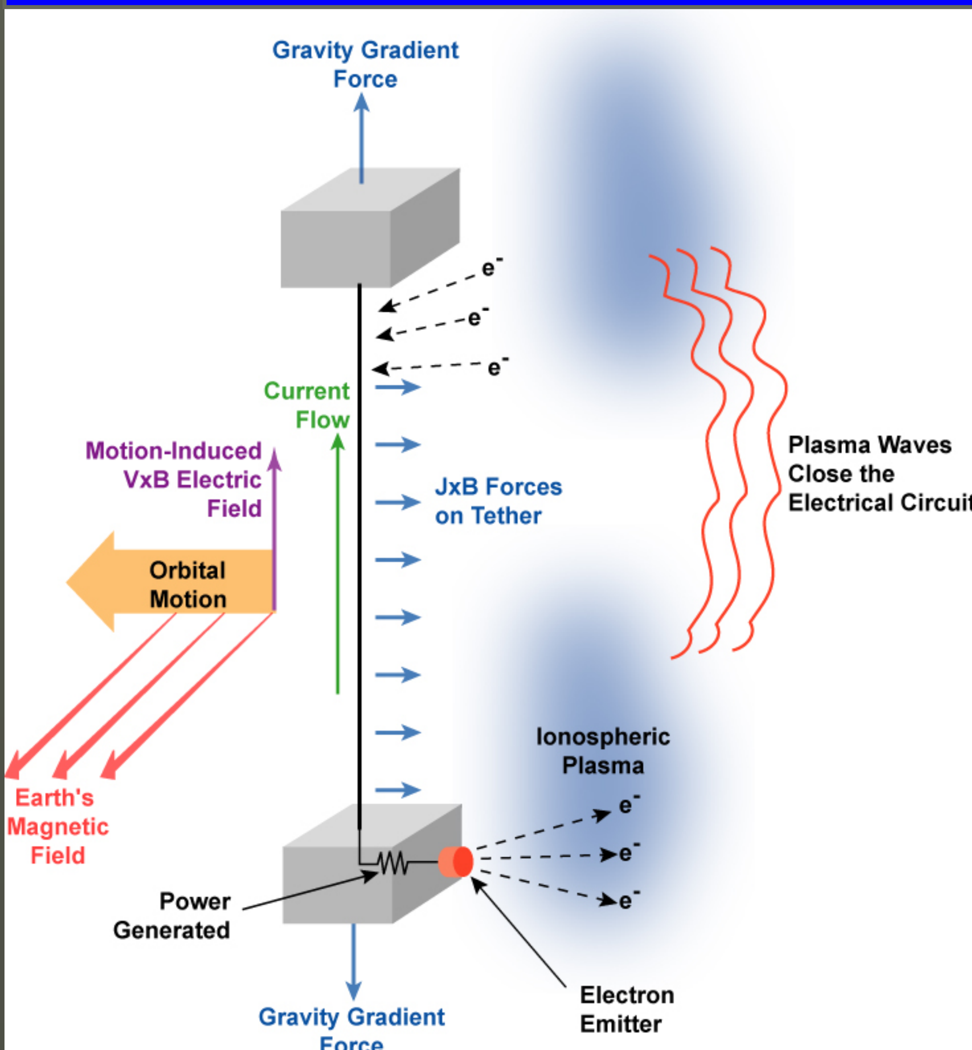


Michigan Engineering

Electrodynamic Tethers

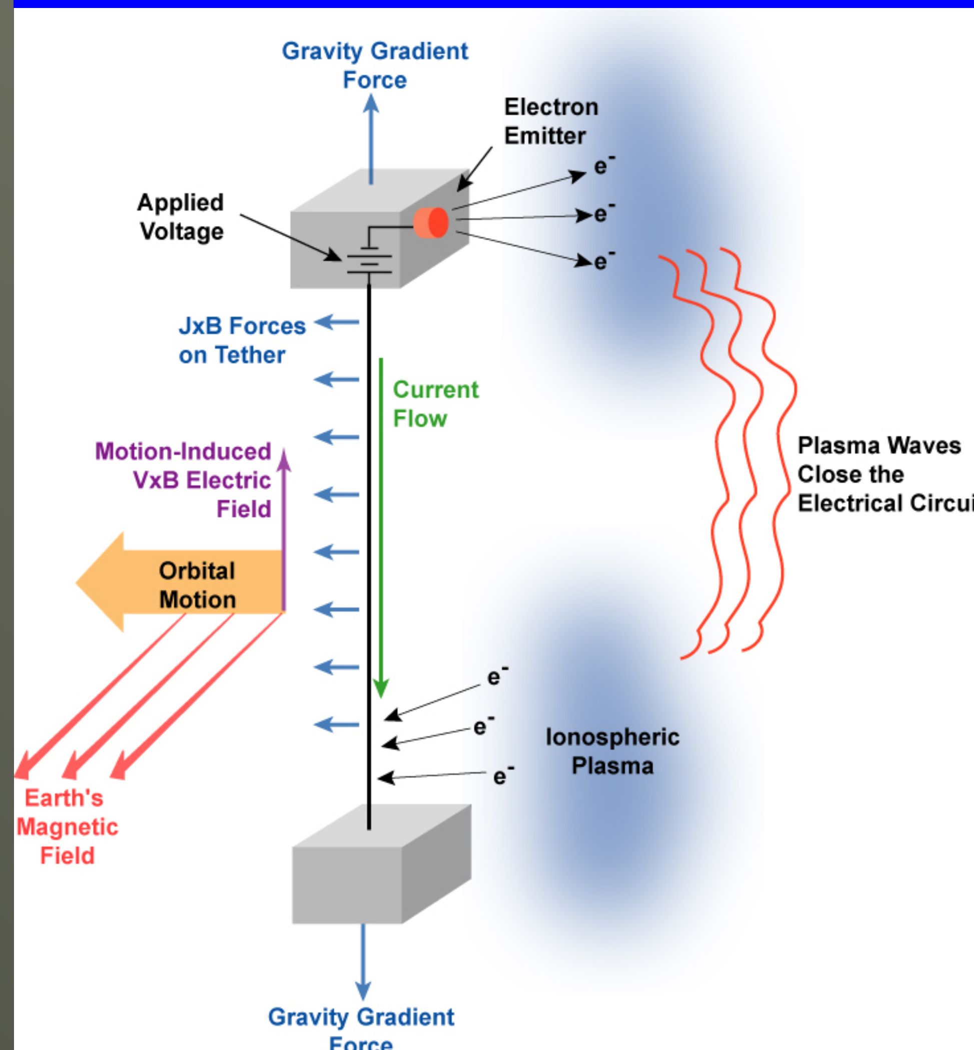
Drag/Power Generation Mode

- Motion-induced electric field drives current up the tether
- Current flowing across magnetic field induces drag force
- Tether voltage & current can be used to provide peak power to spacecraft
  - Orbital energy converted to electrical energy



Propulsive Mode

- Apply voltage to overcome motion-induced electric field and drive current across magnetic field
- Current flowing down tether produces thrust force
- Plasma waves close the electrical circuit



Propellantless ED Tether Propulsion

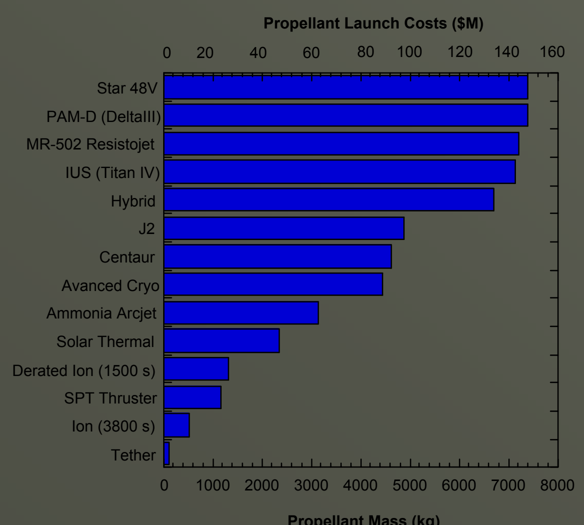
Propulsion for Microsatellites

- Large total ΔV with very low mass requirements
- 5 kg to boost 100 kg s/c from 350->1500 km

Deorbit of LEO Space Debris

- Autonomous assured disposal at end-of-mission with low mass penalty (~1-2% of s/c)

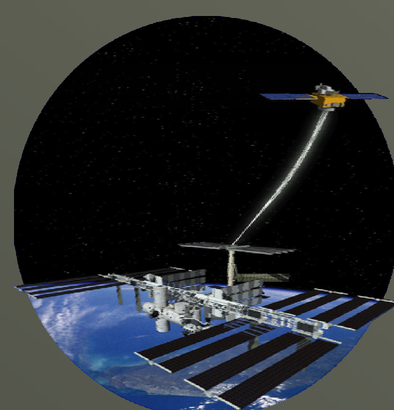
Orbital Tug for Satellite Deployment & Repositioning

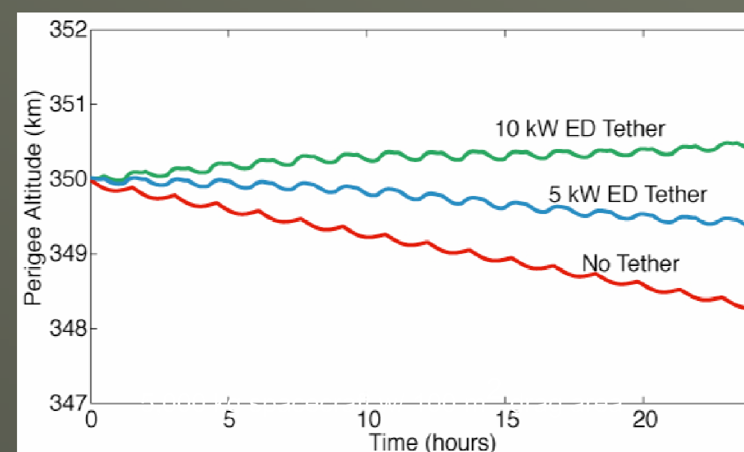


Propellant mass and propellant launch costs for reusable upper stages based on various chemical and advanced propulsion technologies. Mission analyzed is to boost ten 3000 kg satellites from a 300 km holding orbit to a 1400 kg operational orbit.

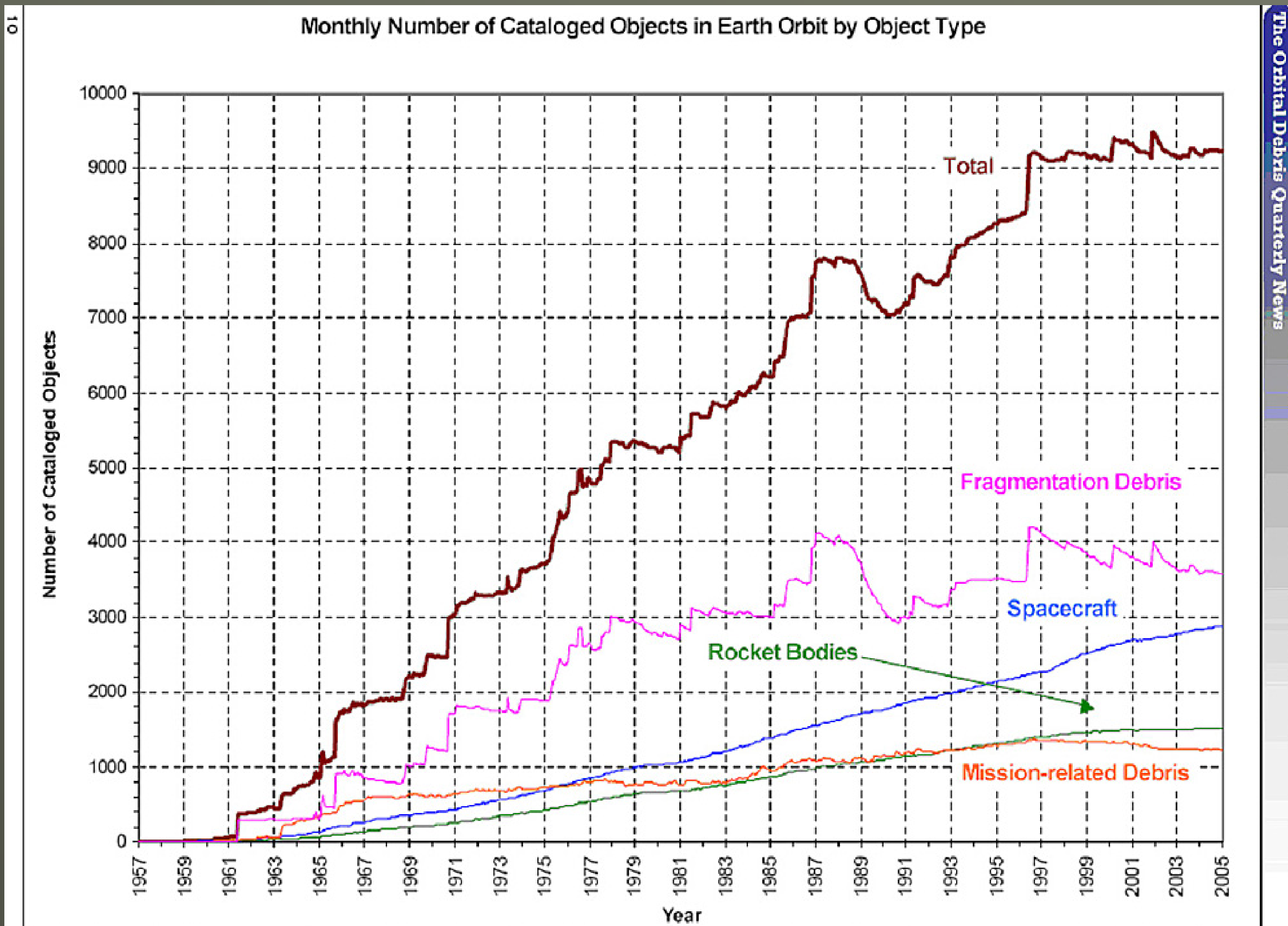
Stationkeeping for LEO Assets

- >$1B cost savings possible for ISS reboost
- Fly assets at lower altitudes





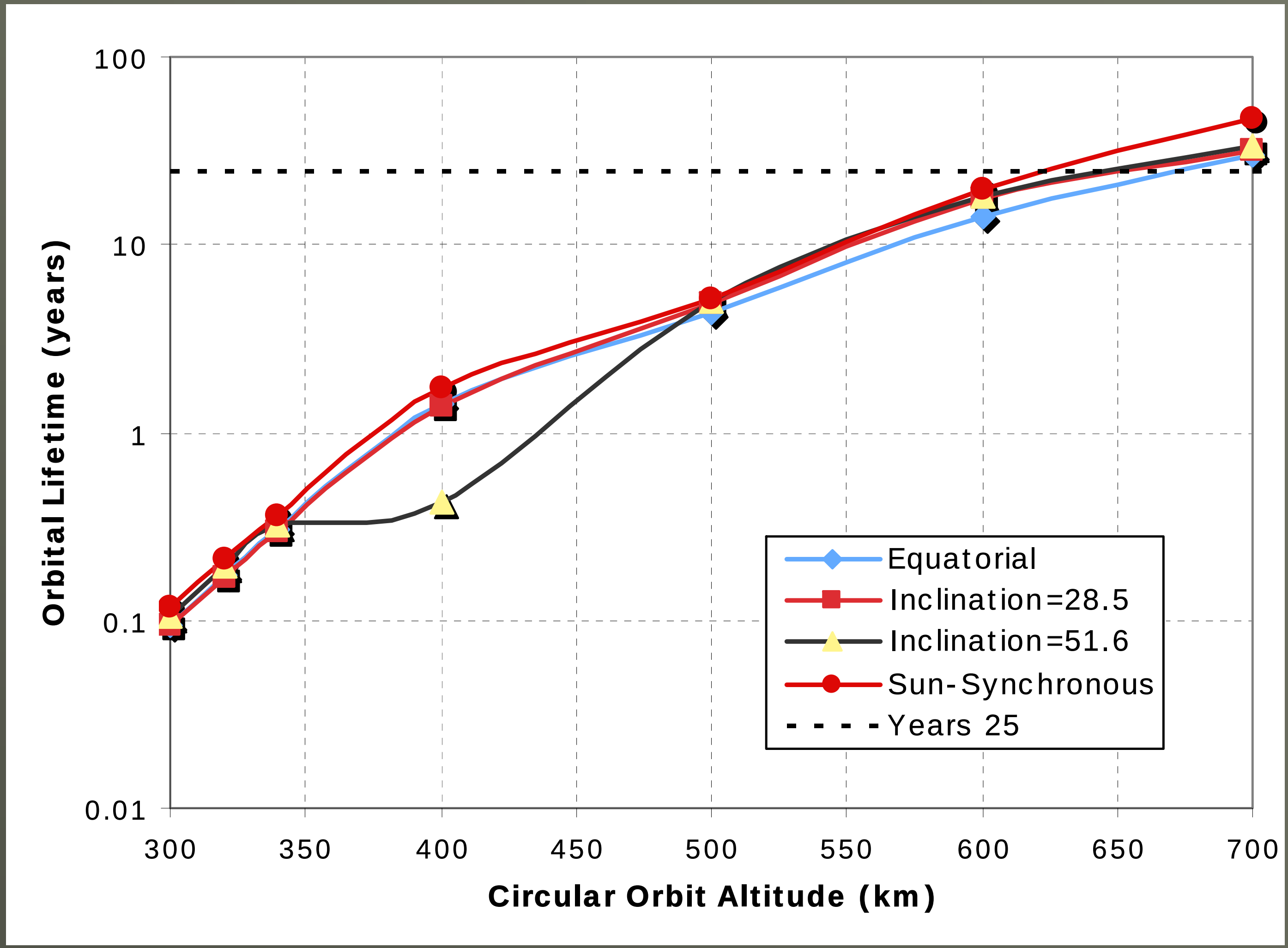
Is Orbital Debris a Problem?



Monthly Number of Cataloged Objects in Earth Orbit by Object Type: This chart displays a summary of all objects in Earth orbit officially cataloged by the US Space Surveillance Network. "Fragmentation debris" includes satellite breakup debris and anomalous event debris, while "mission-related debris" includes all objects dispensed, separated, or released as part of the planned mission.

- Most Lethal population: objects 1-10cm(!) in size

Nanosatellite Orbital Lifetime

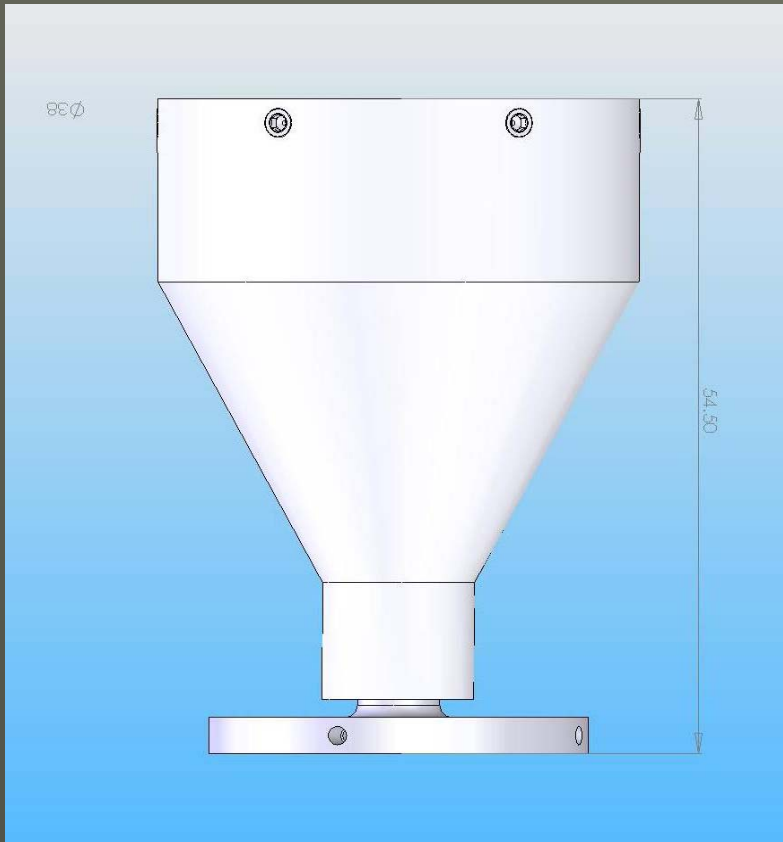


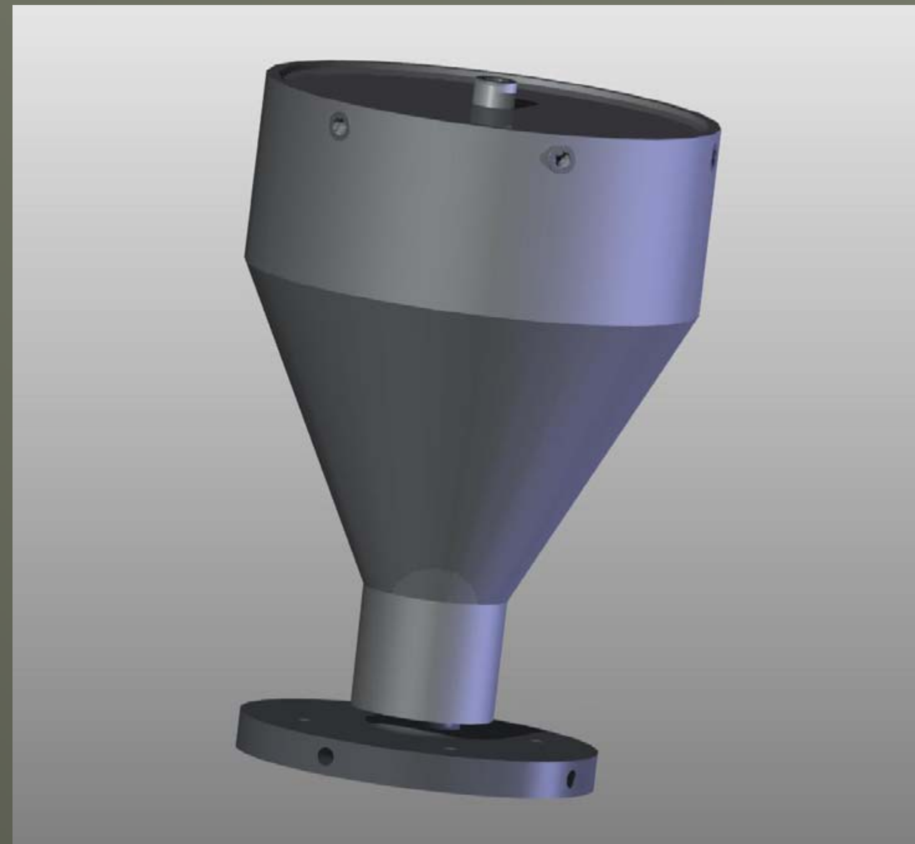
- Orbital Lifetime simulation for a CubeSat without deployables
  - Single (1U) CubeSat has 1kg mass, 0.01m^2 cross sectional area, ballistic coefficient ≈ 45 kg/m^2

TUI's Solution: nanoTerminator™

- A completely passive deorbit system
  - No avionics, no command and control capabilities
- Low mass, volume, and power deorbit system that simply meets 25 year lifetime requirement/ recommendation for orbital debris mitigation

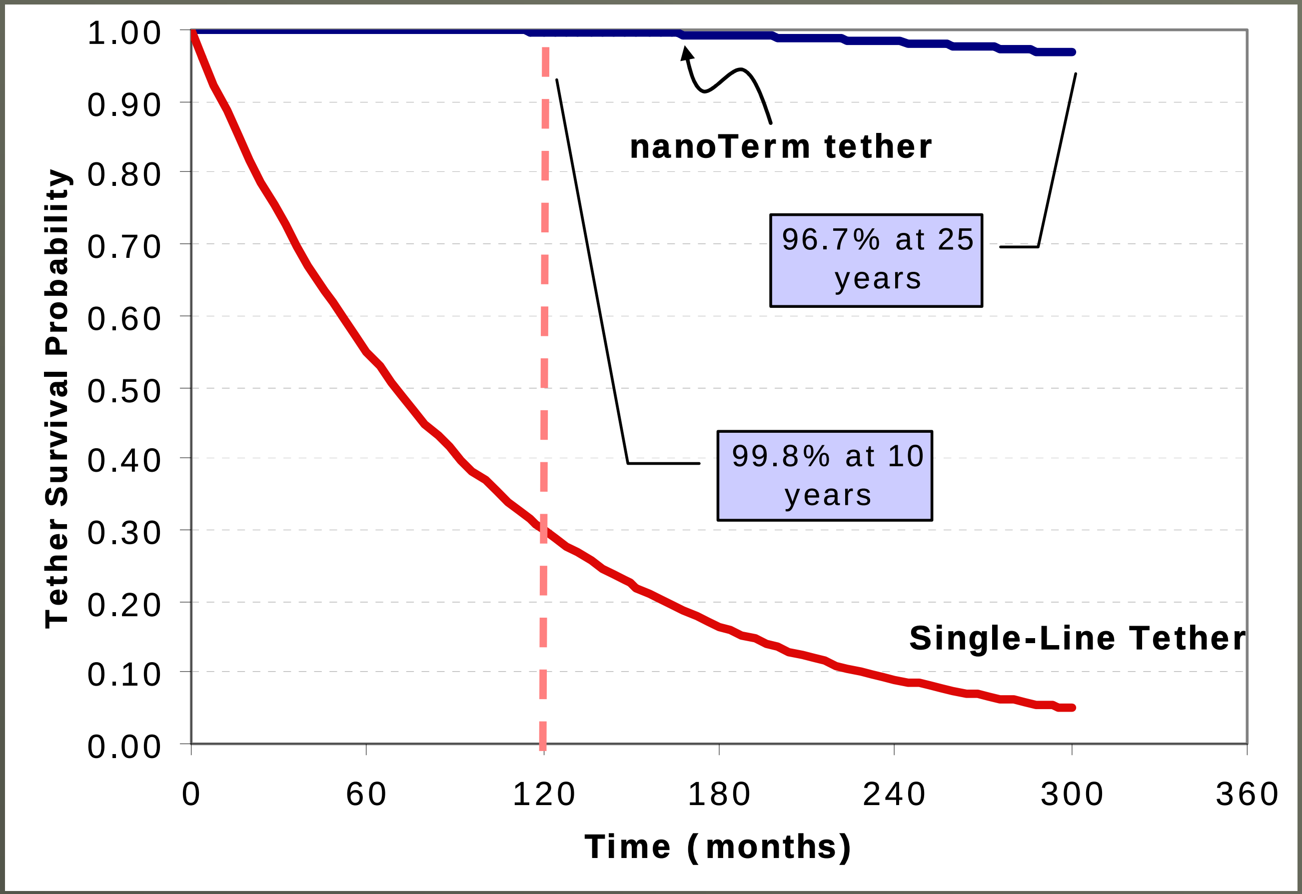
nanoTerminator™ Module

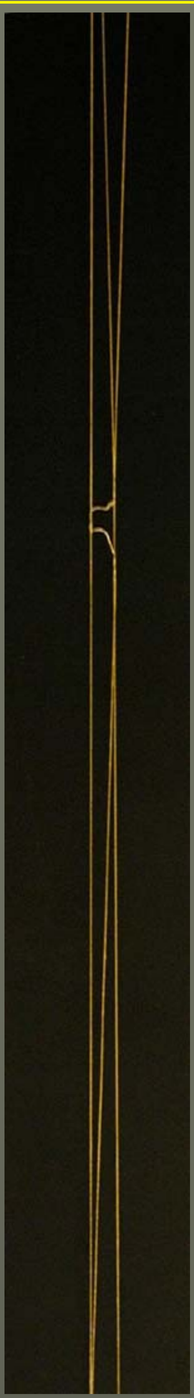




- Design targeted for single (1U) CubeSat (1kg, 100x100x100mm) and RocketPod CubeSat Plus (2kg, 100x100x164mm)
- nanoTerminator™ envelope: 54.5 x 38 mm diameter, mass: 56g
  - Equivalent volume of a D-cell alkaline battery
- Consists of tether (nominally 100 meters), spindle & shroud, spring ejection deployer & mount

Long-Life Multi-strand Hoytether™

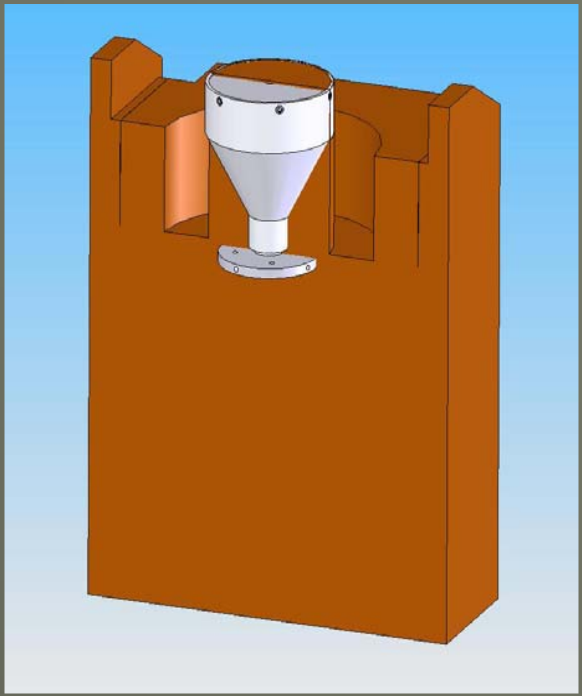




- Multi-strand braided tether construction
  - 2 primary lines nominally spaced 25mm apart, with one secondary
  - Secondary line providing redundant load paths every 0.5 meters
  - Dupont's Aracon™ used for the conductive element – copper and nickel clad Kevlar™ (9180Ω/km)
  - Fine denier DSM Dyneema™ used to complete tether structure

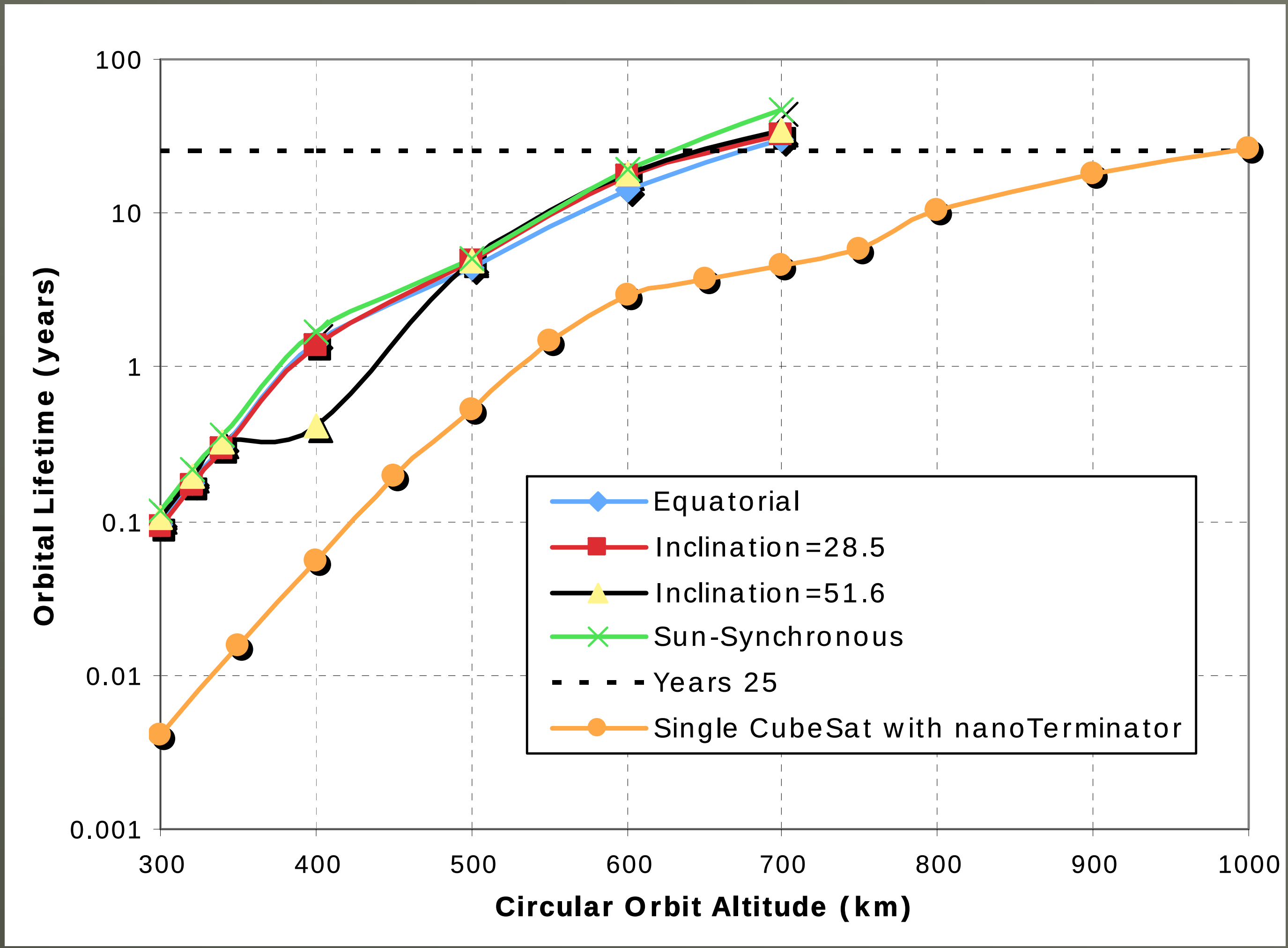
nanoTerminator™ Operation

- At end of nominal mission operations, tether deployment initiated
  - Satellite operator command
  - Watchdog timer expiration



- Restraints released, and integral deployer spring ejects spool
- Spring ejection velocity tuned for full tether deployment
- Combination of electrodynamic and aerodynamic drag change deorbit

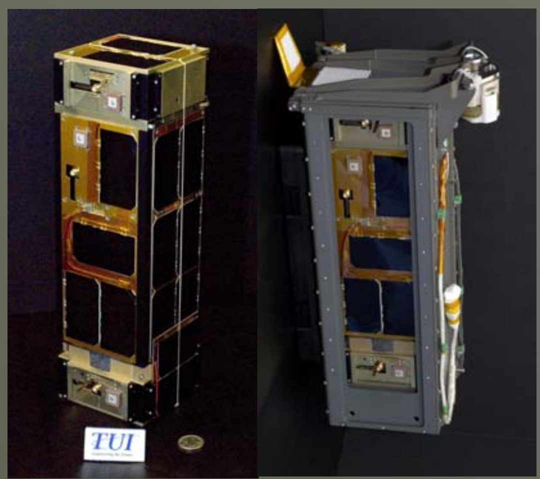
nanoTerminator™ Deorbit Times



– Orbital Lifetime simulation for a CubeSat with nanoTerminator™
  - Single (1U) CubeSat has 1kg mass, $0.06m^2$ area, and ED tether!

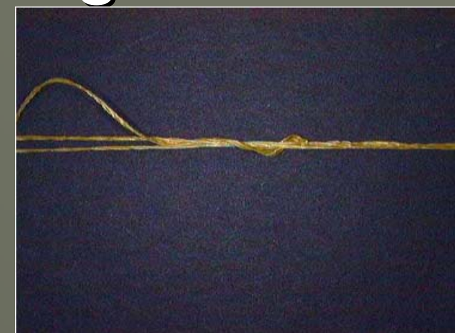
MAST Experiment

- Multi-Application Survivable Tether
- PRIMARY Mission Objective
  - Deploy multi-strand space tether
  - Inspect multi-strand for micrometeorite impact damage
    - Image tether which is a multi-strand 1 kilometer Hoytether™
- SECONDARY Mission Objective
  - Collect data on passive tether dynamics for study of formation dynamics and validation of tether dynamics models
    - Measure relative position of tether endpoints, and crawling body

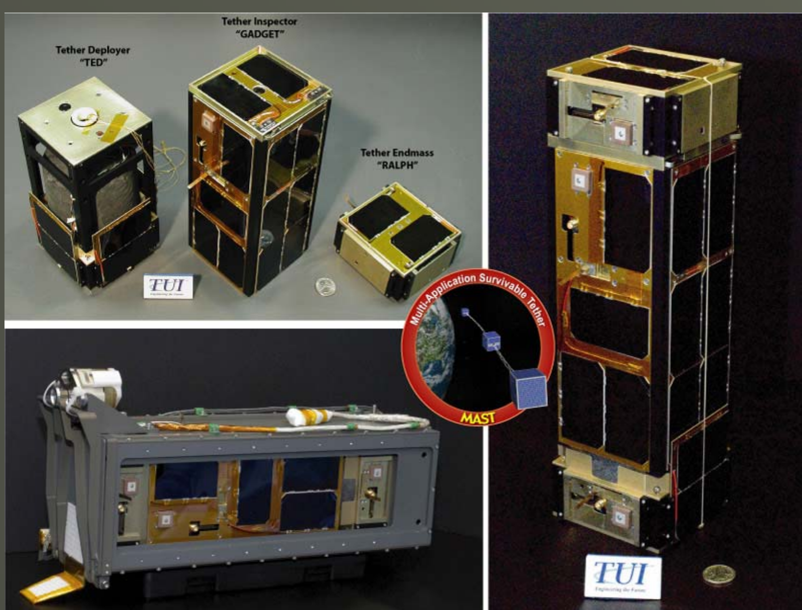


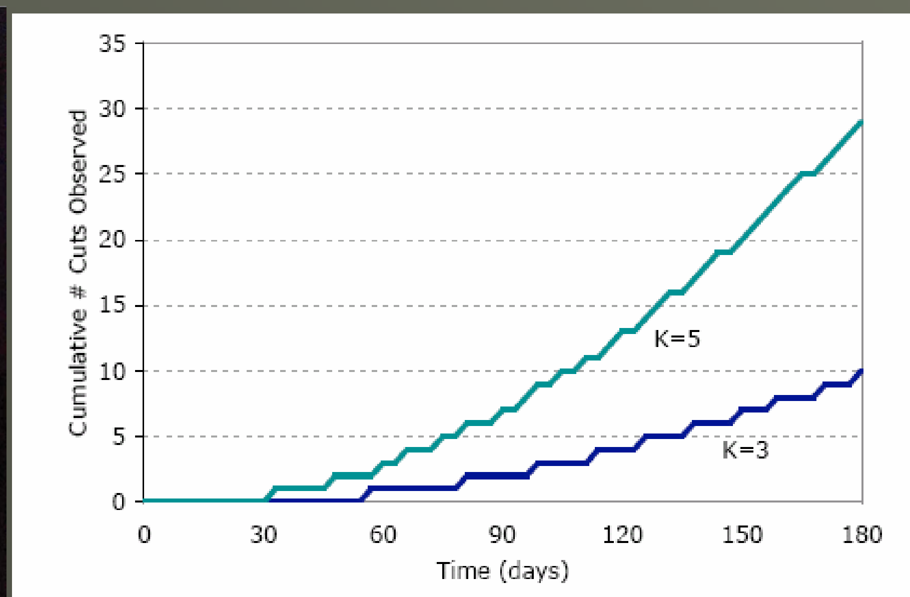
MAST Operations

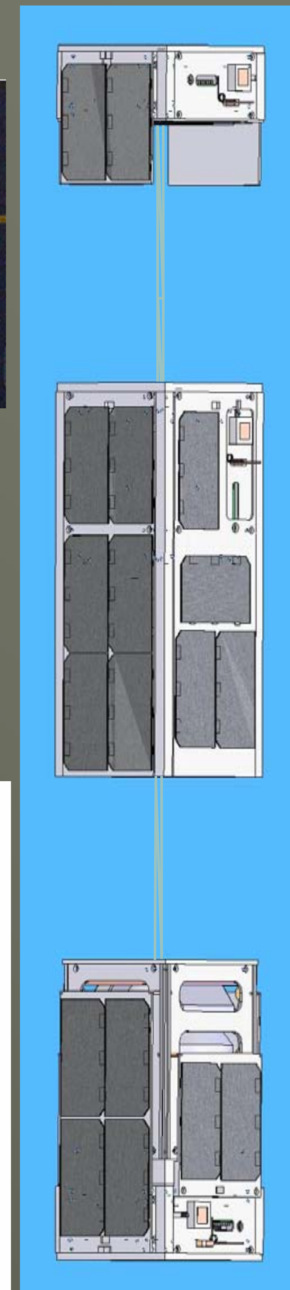
- Inspector crawls along tether taking images
  - 45,500 images per 1km of tether!
  - Expect to see 3.3 to 9.3 cuts/month!



- All satellites gather dynamics data
  - GPS Position, Ambient Magnetic Field, Coarse Sun Sensing
- Downlink Images and Telemetry Data using 2.4GHz downlink (20kbps)

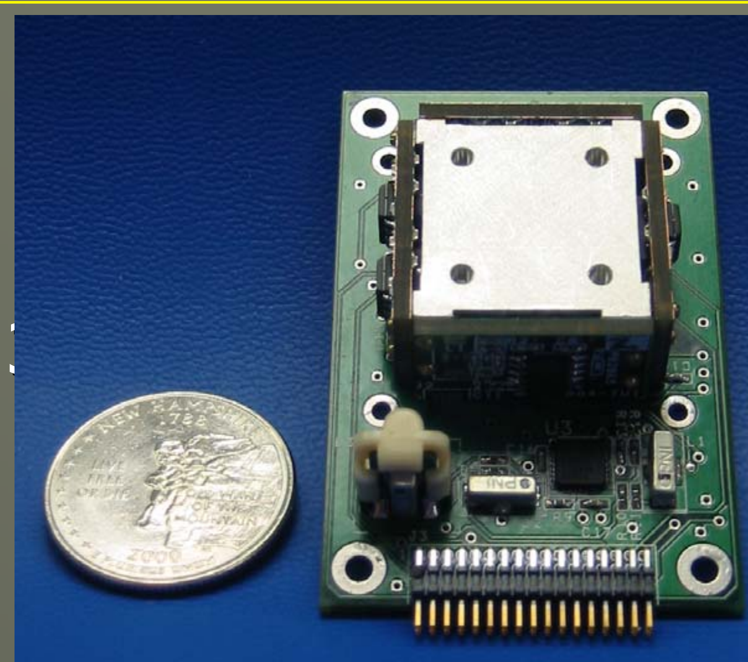




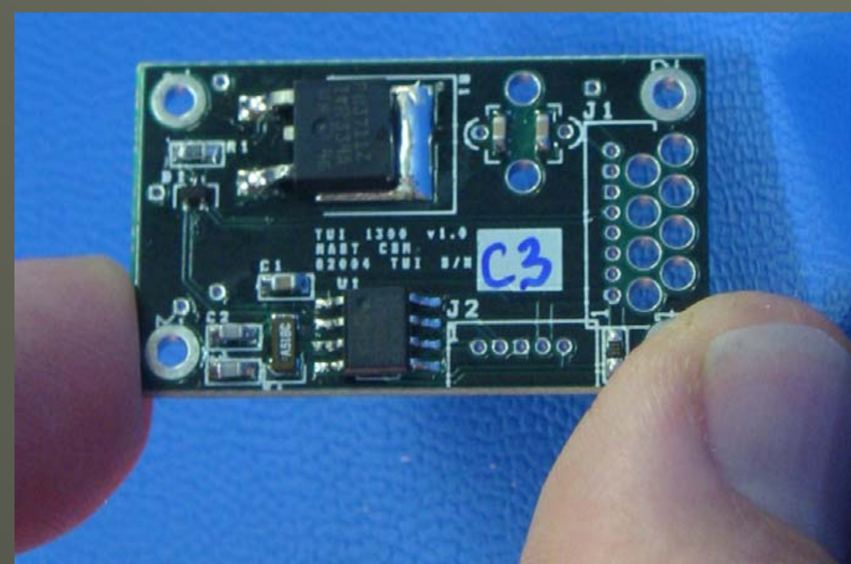


Other TUI nanosat Technologies

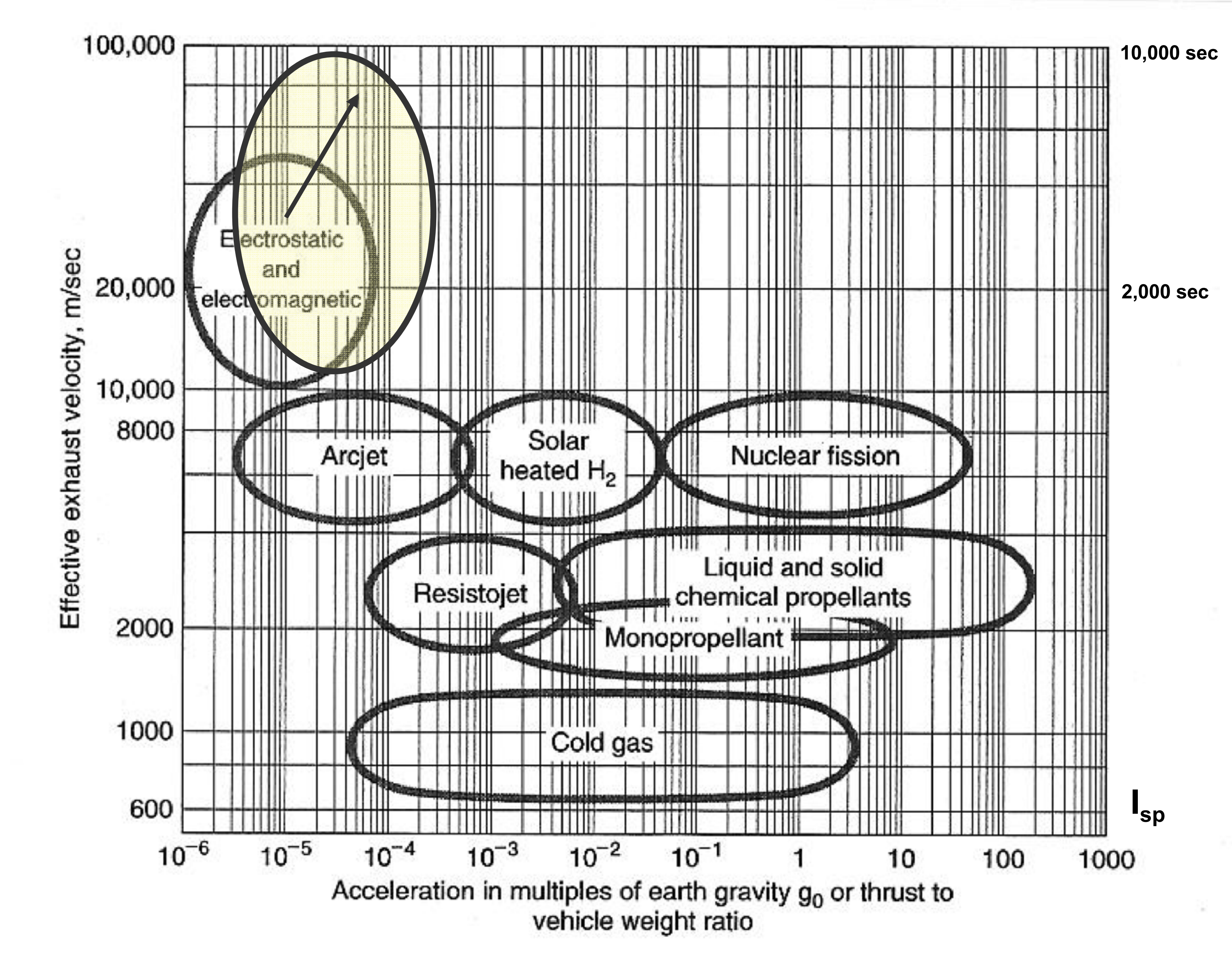
- nanosat IMU
  - 6DOF with integrated 3-axis magnetometer
  - VERY compact:
    x 50.8 x 15.2 mm, 34 grams



- nanosat Release Mechanism
  - Used to initiate mechanism release
  - Cuts Spectra® loop with NiCr wire
  - Integrated Watchdog Timer
  - VERY compact:
    34.4 x 20.2 x 7.3 mm, 5 grams



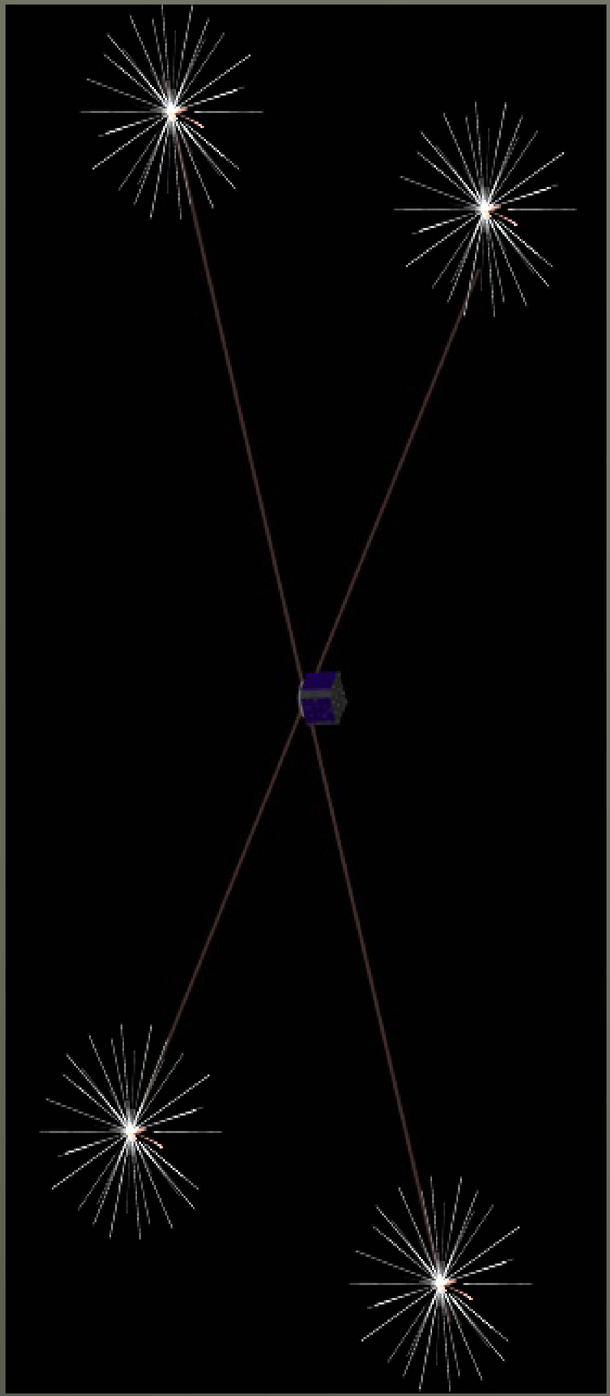
Space Propulsion Landscape



Courtesy Gallimore, A., UMich

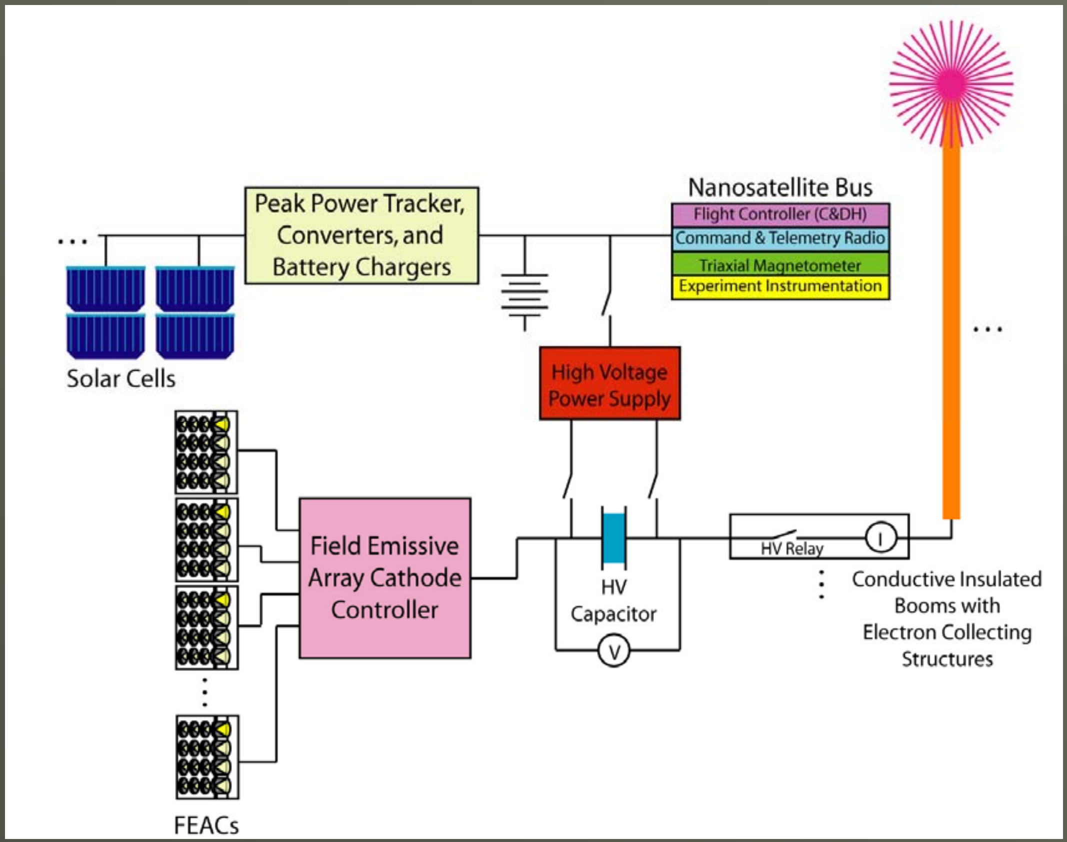
ED Propulsion Experiment

- Primary Experiment Objectives
  - Generate directly detectable torque
  - Generate directly measurable thrust
- Secondary Experiment Objectives
  - Validate performance of Field Emissive Electron device(s)
  - Validate performance of lightweight electron collectors
- **GOAL**: Drive 1 Ampere of current through lightweight deployable, conductive 10-20 meter booms
  - 0.2-1.0 second impulses > 0.5 mN



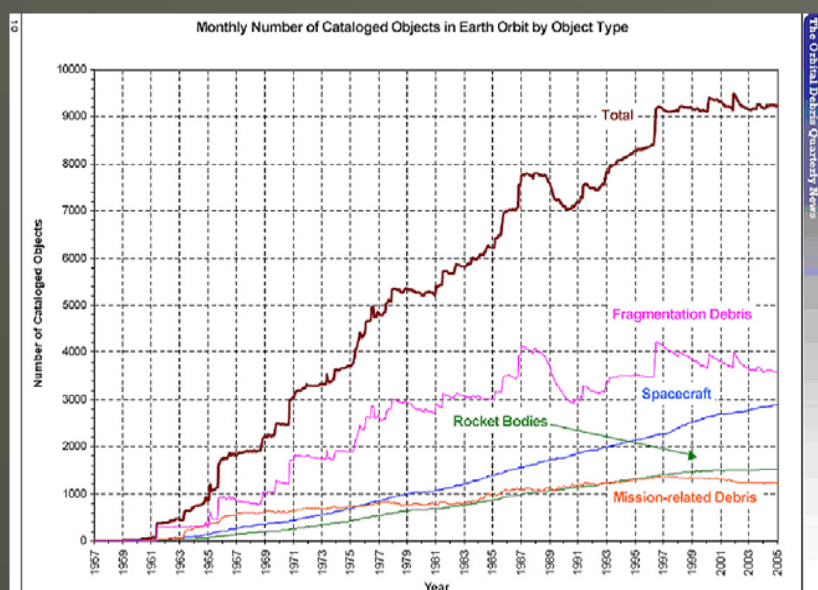
Experiment Conops

- Converted Solar Energy is stored onboard in capacitor bank
  - Allow for thrust pulse every 4-6 orbits
- At desired B-field alignment, discharge capacitor to generate 1 Ampere pulse
- Measure Thrust with onboard accelerometers
- Measure Torque with body attitude rate change



Summary

- Tethers in Space are an enabling technology – even for nanosatellites!
- Tethers enable persistent formation flight without any expenditure of propellant
- ED Tethers are suitable for low-mass, low-volume, deorbit system where deorbit time requirements are simply 25 years (nanoTerminator™)
  - Can expand the altitude ceiling for a single CubeSat/RocketPod class satellite from 620-680 km to almost 1000km
  - Help control the growth of the orbital debris population



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