Space Tethers and Small Satellites: Formation Flight and Propulsion Applications

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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

Propellantless propulsion enables large ΔV missions with low mass impact.
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, demonstrated 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 $\Delta V \approx 32 \text{ m/sec} \text{ PER DAY}$ for stationkeeping

- Nanosatellites can easily have orbital lifetimes exceeding 25 years
  
  • Commonly launched as secondary payloads => little control over insertion orbit
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

[Diagram showing the flow of forces and currents in the electrodynamic tether system.]
Propellantless ED Tether Propulsion

Propulsion for Microsatellites
- Large total $\Delta V$ 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 Launch Costs ($M$)

Star 48V
PAM-D (DeltaIV)
MR-502 Resistojet
IUS (Titan IV)
Hybrid
J2
Centaur
Advanced Cryo
Ammonia Arcjet
Solar Thermal
Derated Ion (1500 s)
SPT Thruster
Ion (3800 s)
Tether

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

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

- 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, 0.01m² cross sectional area, ballistic coefficient ≈ 45 kg/m²
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
- **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
Orbital Lifetime simulation for a CubeSat with nanoTerminator™

- Single (1U) CubeSat has 1kg mass, 0.06m² 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 1 km 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
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
- 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

![Graph showing monthly number of cataloged objects in Earth orbit by object type.](image.png)